Near-touching holes in a Dirichlet screen: the retained-segment heat profile, repulsive contact and the exact static Casimir constant

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Abstract

As two holes in a Dirichlet screen approach each other, their connected scalar Casimir interaction is governed by a single planar observable: the heat integral $J(t)$ of Brownian bridges that hit both exterior rays of a retained Dirichlet segment of unit length while avoiding the segment. We determine this observable completely and use it to describe the near-touching interaction with and without surface contact. At short time $J(t) \sim t^{5/2}e^{-1/t}/(32\pi^{3/2})$, with its first correction, by a half-line factorization of the relative determinant; at long time $J(t) \to 1/8$ with an inverse-logarithmic expansion. A translation argument expresses J through the gaps in the screen trace of the bridge and gives exact small- and large-gap counting laws. For two interval apertures we compute the static (zero-mode) heat integral in closed form,

$$Q_g^{\mathrm{stat}} = -2\sum_{n\geq 1} \log\tanh\Big(\pi n \frac{K(k')}{K(k)}\Big) = -\tfrac{1}{4}\log(1-q) - \log\frac{2K(k)}{\pi},$$

by mapping the loops that visit both apertures to the two seams of a flat cylinder. This fixes the finite static constant $\log\pi - \frac{1}{4}\log(\ell_-^{-1}+\ell_+^{-1})$ and attributes the entire double logarithm to loops of nonzero winding. We then add a common repulsive contact of strength ρ_g on both apertures: bounded $g\rho_g$ gives a weighted bridge profile; strong contact gives explicit vacuum constants and a thermal sum of squared boundary kernels for curved and finite-type tangencies in every dimension; and for intervals an unbounded contact with $g\rho_g \to 0$ cuts off the static logarithm at length $1/\rho_g$ while retaining its double-logarithmic correction. The gap-scale free energy and both endpoints of its nonzero Matsubara profile are determined. Finally we let the two contact strengths scale independently. When one scaled strength diverges and the other has a finite limit, including zero, we prove the connected vacuum and thermal limits; with a transparent limiting side a causal half-line factorization gives exact momentum and heat formulas and explicit static and vacuum constants in every dimension. We also treat bounded and doubly divergent strengths, and for intervals with both scaled strengths vanishing a single-ray local-time bound gives the logarithmic crossover uniformly in the ratio of the strengths. We extend the strong-contact limits to contact profiles that vary with depth and to strengths vanishing like a power at the contact point, where three regimes appear and a quadratic interior zero produces an Airy coefficient, and we treat two independently strong degenerate contacts. For interval apertures with weak contact we obtain the joint static limit with an exact determinant, and the vacuum-to-temperature crossover. When the strong contact itself vanishes at a power-law zero, the weak static response splits exactly into a singly logarithmic term from the zero and a two-logarithm term from the far depths, with an explicit balance between them, a vacuum response linear in the weak amplitude and a

thermal limit that adds the static zero mode. Finally, at curved quadratic and separable finite-type tangencies in every dimension we determine the leading connected interaction of strong contacts that vanish at prescribed depths, with the gap and both strengths scaling independently: one strong side integrates its normal response against the frozen column of the opposite aperture, and two strong sides pair their two normal response measures against the squared separated kernel. When the zero of a strong contact moves periodically in depth on the scale of its normal confinement width, the leading connected trace per unit tangential area factors into a forced fractional cell response and a separated weak-side factor; the cell response decreases strictly with the ratio r of confinement width to period, from the average of the local vertical responses to the response of the averaged potential, and its small-r loss is quadratic for an interior zero and of exact order $r^2 \log(1/r)$ at the aperture edge, with both coefficients computed explicitly. Finally, for a strong contact vanishing to order p along a compact smooth submanifold of codimension k, we determine the leading inverse in every regime: the reciprocal contact is integrable for $p < k$, produces a logarithm at $p = k$, and for $p > k$ the coefficient comes from a forced k-dimensional fractional oscillator at finite scaled floor or from a multiplication inverse when the floor dominates; this covers directional normal potentials and zero sets inside a smooth aperture boundary, and gives the connected vacuum and thermal laws with one or two independently strong contacts. When the contact instead vanishes over a smooth set in the slow tangential coordinates of a shrinking gap, with the gap and the contact strength scaling independently, the power $p = k$ (slow normal directions plus inward depth) again gives a logarithm, while for $p > k$ at finite scaled floor the coefficient integrates a forced one-dimensional fractional inverse over the slow normal directions and strictly exceeds the full k-dimensional oscillator response. For parallel aperture edges and a homogeneous confining profile, a small tangential kinetic ratio τ lowers the normalized connected determinant at the exact order $\tau^2 \log(1/\tau)$, with an explicit positive coefficient given by the tangential gradient of the depth-integrated optimizer; replacing the half-space openings by bounded windows of radius M changes this correction only by boundary errors of order M^{-d}, with matching lower bounds, and for homothetic windows with parallel flat facing sides the shape-dependent coefficient at each order is identified as the exterior energy of an explicit Bessel profile, giving the vacuum and thermal corrections.

Keywords. Scalar Casimir effect, Dirichlet screen, near-contact asymptotics, Brownian loop measure, elliptic integrals, Robin contact, Matsubara sum.

Overview

Sections 1–4 determine the retained-segment profile and the gap-scale free energy of transparent intervals. Sections 5–9 add repulsive contact and prove the exact static formula. Sections 10–13 let the two contact strengths scale independently. Sections 14–17 treat variable and degenerate contact, and Sections 18–21 weak contact and the temperature crossover at interval apertures. Section 22 combines a degenerate strong contact with weak contact, and Sections 27–31 carry degenerate strong contacts to curved tangencies in every dimension. Sections 32–37 treat a strong contact whose zero is periodically corrugated in depth, and Sections 38–42 contacts vanishing along submanifolds of any codimension, and Sections 43–50 zeros in the slow coordinates of a shrinking gap, and Sections 51–55 the tangential kinetic correction, with its bounded-window errors in Sections 56–60 and their shape coefficients in Sections 61–64. The near-contact law for transparent windows, of which J is the local kernel, and the separated many-hole interaction are proved in the companion paper [2]; the underlying connected heat trace is that of [1].

1 The planar observable

Let H_- and H_+ be the two open rays in the horizontal axis outside the retained segment $[-h/2, h/2]$. A planar bridge of duration t, generator Δ, and base point (S, X) contributes when it hits the axis in both rays and avoids the retained segment. Write $J_h(t)$ for the integral of this probability against $(4\pi t)^{-1} dS\, dX$, and write $J(t) = J_1(t)$. This is the local two-aperture kernel in the near-contact theorem of [2]. Brownian scaling gives $J_h(t) = J(t/h^2)$. At $h = 0$ the two slit-edge defects give $J_0(t) = 1/8$ [2, 9, 10]. In particular $0 \le J(t) \le 1/8$. Bridges that hit both rays have lateral range at least h, giving a Gaussian small-time bound up to a constant by one-dimensional bridge range and reflection estimates.

The interaction of two Dirichlet obstacles occupying the exterior rays involves bridges hitting both rays, as in the whisker geometry of [7, Section 3]. The event defining J_h also excludes paths hitting the central segment. The closest classical comparison for finite apertures is the collinear *Neumann* needle calculation [3, Eq. (15)]. Reflection across the axis in the aperture problem leaves an unchanged odd Dirichlet sector and gives N on the openings and D elsewhere in the even sector. Neumann needles occupying the same intervals leave the even Neumann sector unchanged and yield the same mixed sector in the odd component. Thus the connected classical observable is the same in the two models, by cancellation of the unchanged sectors [5]. The known equal-needle force already gives the first two static logarithmic terms. For infinite rays the complementary Neumann half-plane scattering representation of [4, Eqs. (6)–(7)] contains both displayed positive-real-frequency coefficients of Q in its lowest odd channel. We determine the complex-frequency expansion needed for time inversion, the bridge gap law, and the nonzero-frequency thermal response, and match the arbitrary-length finite-interval expansion at the heat level.

2 Half-line determinant and exact short-time equivalent

Theorem 1. *With the principal root $w = \sqrt{z}$,*

$$Q(z) := \int_0^\infty e^{-zt} J(t)\, \frac{dt}{t} = \frac{e^{-2w}}{32\pi w^3} \left(1 - \frac{15}{4w} + O(|w|^{-2})\right)$$

uniformly for $\operatorname{Re} z > 0$*, as* $|z| \to \infty$*. Consequently*

$$J(t) = \frac{t^{5/2}}{32\pi^{3/2}} e^{-1/t} \left(1 - \frac{21}{4} t + O(t^2)\right) \qquad (t \downarrow 0).$$

Proof. For two bounded transparent apertures the relative determinant identity of [2] identifies their connected heat transform with minus the connected log determinant of the compressed response $2\sqrt{D^2 + z}$, where $D = -i\partial_u$ on $\mathbb{R}$. The factor two cancels. Put $r = |w|$ and $\mu = w/r$, and dilate the tangential coordinates by r. The isolated operators become, after removing the common scale factor, the form compression A_μ of $\sqrt{D^2 + \mu^2}$ to the positive half-line. The form domain is the subspace of $H^{1/2}(\mathbb{R})$ supported there. In coordinates $u, v > 0$ that increase into either ray, the equal off-diagonal blocks B have kernel

$$-\frac{\mu}{\pi(r + u + v)} K_1\big(\mu(r + u + v)\big).$$

This follows by square-root subordination, with the identity term supported on the diagonal, or the Bessel formula in [2]. Uniform accretivity of A_μ in the form norm follows from $\operatorname{Re} \sqrt{\xi^2 + \mu^2} \ge$

$c\sqrt{1+\xi^2}$ for $|\arg\mu| \le \pi/4$. Indeed the modulus of $\xi^2+\mu^2$ is at least $(1+\xi^2)/\sqrt{2}$ and the root argument has magnitude at most $\pi/4$.

On the positive axis, pass from bounded intervals to rays by increasing their lengths. The heat side converges by monotone convergence. For the determinant, variational approximation gives strong convergence of the extended inverses, since compact cutoffs approximate in the half-line form space and the restricted forms are uniformly coercive. The cross kernels converge in Hilbert–Schmidt norm by truncation. Uniform boundedness and strong convergence of the inverses and their adjoints preserve this norm convergence under multiplication, by finite-rank approximation. The small norm of B at large r permits the block determinant expansion

$$Q(z) = \sum_{j\ge 1} j^{-1} \operatorname{Tr}[(A_\mu^{-1} B A_\mu^{-1} B)^j].$$

For complex z, form the same product in the original unscaled coordinates. The inverse depends holomorphically on z by local coercive form inversion. The separated Bessel kernel is Hilbert–Schmidt holomorphic on the right half-plane by local exponential domination. The scaled norm bounds below make the series holomorphic throughout its connected large-$|z|$ region. The identity theorem extends the equality from its positive real segment.

Set $f_\mu(u) = e^{-\mu u}$. Use the bilinear rank-one kernel $f_\mu(u) f_\mu(v)$. The fixed-order Bessel asymptotic [12, Eq. 10.40.2] gives

$$B = -\frac{\sqrt{\mu}\, e^{-w}}{\sqrt{2\pi}\, r^{3/2}} f_\mu \otimes f_\mu + E, \qquad \|E\|_2 \le C e^{-\operatorname{Re} w} r^{-5/2}.$$

Indeed for $s = u+v$ the change in the algebraic factor $(1+s/r)^{-3/2}$ is $O(s/r)$, the Bessel remainder is $O((r+s)^{-1})$, and $|e^{-\mu s}| \le e^{-s/\sqrt{2}}$. Terms with $j \ge 2$ are exponentially smaller. For the first trace it remains to compute $q(\mu) = \int_0^\infty f_\mu(u)(A_\mu^{-1} f_\mu)(u)\, du$.

For positive real μ, the multiplier $L = (\mu + \partial_u)^{1/2}$ factors the full energy as $\|Lf\|_2^2$. Its inverse is convolution by $\mathbf{1}_{s>0} e^{-\mu s}/\sqrt{\pi s}$, which maps half-line L^2 into the supported form space. Conversely $L = (\mu+\partial_u) L^{-1}$ preserves half-line support in distributions. Thus L is a bijective form isometry onto half-line L^2. The adjoint of the causal inverse maps f_μ to $f_\mu/\sqrt{2\mu}$. Taking its squared norm gives $q(\mu) = 1/(4\mu^2)$. Local form inversion and the holomorphic exponential extend the bilinear pairing to a sector containing the unit-circle arc $|\arg\mu| \le \pi/4$, and the identity theorem gives the same formula there. The leading trace is $\mu e^{-2w} r^{-3} q(\mu)^2/(2\pi)$. The Hilbert–Schmidt error and the uniform inverse norm give a relative $O(r^{-1})$ contribution since the leading coefficient is nonzero with constant modulus on the arc.

To one further order, the rank-one kernel after removal of its scalar prefactor is

$$f_\mu \otimes f_\mu + r^{-1}\left[\frac{3}{8\mu} f_\mu \otimes f_\mu - \frac{3}{2}(u f_\mu \otimes f_\mu + f_\mu \otimes u f_\mu)\right] + O_2(r^{-2}),$$

where O_2 is in Hilbert–Schmidt norm. The next Bessel error and the Taylor remainder of the distance factor are bounded after integration by the same exponential majorant times $C(1+(u+v)^2)$. The adjoint of the causal inverse applied to $u f_\mu$ gives $(u + 1/(4\mu)) f_\mu/\sqrt{2\mu}$, first for positive real μ. Consequently the pairing of $u f_\mu$ with $A_\mu^{-1} f_\mu$ is $3q(\mu)/(4\mu)$, and again extends holomorphically. The cross term in the first trace gives relative correction $r^{-1}(3/(4\mu) - 6 \cdot 3/(4\mu)) = -15/(4w)$.

The correction in the transform can be inverted term by term. The inverse of $z^{-p} e^{-2\sqrt{z}}$ for $p > 0$ is

$$\frac{1}{\sqrt{\pi}\Gamma(p)} \int_0^t u^{p-1}(t-u)^{-3/2} e^{-1/(t-u)}\, du = \frac{t^{2p-3/2} e^{-1/t}}{\sqrt{\pi}} (1 + p(1/2-p)t + O(t^2)).$$

The integral is the convolution of the inverse of z^{-p} with that of $e^{-2\sqrt{z}}$. To expand it, put $u = t^2 v$. The first-order factor multiplying $v^{p-1}e^{-v}$ is $1 + t(3v/2 - v^2)$. Taylor expansion on $v \le t^{-1/4}$ bounds the error by t^2 times an integrable polynomial against e^{-v}. On the omitted tail the exponential $e^{-v/(1-tv)}$ absorbs both the factor $(1-tv)^{-3/2}$ and any fixed power of $1/t$.

For the transform remainder invert on $z = t^{-2} + iy$. Its vertical tail is integrable, and continuity of J, also given by the gap identity below, gives pointwise inversion. The exponent is bounded in modulus after taking out $e^{-1/t}$ by $\exp[-c(yt^2)^2/t]$ for $|yt^2| \le 1$ and by $\exp[-c|yt^2|^{1/2}/t]$ outside. This follows by taking the real part of $\sqrt{1+iyt^2} - 1$. The factor $|z|^{-5/2} \le t^5$ and integration in y give $O(t^{7/2}e^{-1/t})$ for the inverse remainder. Taking $p = 3/2$ and $p = 2$ in the two leading inverse terms and multiplying by t proves the asserted expansion. □

3 Large times and the screen-trace gap law

Theorem 2. *Put $a = \gamma - \log 64$, where γ is Euler's constant. At large time,*

$$J(t) = \frac{1}{8} - \frac{1}{\log t} - \frac{a}{(\log t)^2} - \frac{a^2 - \pi^2/6}{(\log t)^3} + O((\log t)^{-4}).$$

The difference $1/8 - J(t)$ has the full inverse-logarithmic expansion of the planar isolated-segment heat defect.

Proof. At duration one, $J_0(1) - J_h(1)$ counts loops hitting the short segment $[-h/2, h/2]$ and both zero-gap rays, up to polar endpoint events. Its difference from the isolated-segment heat defect counts loops hitting the segment while missing at least one zero-gap ray. Missing a zero-gap ray implies avoiding the corresponding exterior ray at gap h. The relevant loops therefore hit the disk of radius h about the endpoint of that exterior ray while avoiding the ray. Time reversal and the first-half bridge density bound $p_{1/2}(z,q)/p_1(q,q) \le 2$ let us use the Brownian-motion probability to hit that disk before the slit boundary. In the slit exterior wedge of opening 2π, for radius $r \ge 2h$ this probability is $O((h/r)^{1/2})$. Separation of variables gives terms $\sin(n\theta/2)(h/r)^{n/2}$ with bounded coefficients from the constant-one data on the circular arc. Independently, the free bridge reaching the disk has a Gaussian bound for r above a fixed constant. The geometric mean of the two estimates is integrable over starting points and gives $O(h^{1/4})$. The inner disk has area $O(h^2)$. The other ray gives the same bound.

By scaling, the isolated-segment defect at this duration is the unit-segment defect at time h^{-2}, and the missing-ray error becomes $O(t^{-1/8})$. McGillivray's pinned-sausage expansion [6, Theorem 1.2 and Eq. (8.1)], divided by $4\pi t$, is the free-minus-killed heat trace. In its convention $C(K) = 2\log \mathrm{cap}(K)$. The conformal map of the unit segment complement to the exterior unit disk has derivative 4 at infinity in the sense that its leading term is $4z$, hence the capacity is $1/4$. The second coefficient is $C(K) + \gamma - \log 4 = a$, and the third is $a^2 - \pi^2/6$. The arbitrary-order expansion gives the stated remainder and the full transfer. □

Let B_1, B_2 be independent unit-duration one-dimensional bridges of generator Δ from zero to zero. For a fixed initial normal coordinate X, define

$$Z_X = \{t : X + B_2(t) = 0\}, \qquad Y_X = \{B_1(t) : t \in Z_X\}.$$

Let $\mathcal{G}_X$ be the bounded complementary intervals of the compact set Y_X. Empty and singleton traces have no such gaps. Vary the initial lateral coordinate S. The translated trace $S + Y_X$ avoids the retained segment and meets both exterior rays exactly when the segment lies in a translated

bounded gap, apart from zero-measure endpoint placements. A gap of length ℓ permits lateral shifts of measure $(\ell - h)_+$. Thus

$$4\pi J_h(1) = \int_{\mathbb{R}} \mathbb{E} \sum_{I \in \mathcal{G}_X} (|I| - h)_+ \, dX = \int_h^\infty M(u) \, du, \qquad M(u) = \int_{\mathbb{R}} \mathbb{E}\#\{I \in \mathcal{G}_X : |I| > u\} \, dX. \tag{1}$$

Tonelli applies. For a normal bridge that reaches zero, the total gap length is bounded by the lateral bridge range, which is independent of the normal event. The latter has integrable probability e^{-X^2}. This proves continuity at $h > 0$ by dominated convergence. Planar point polarity and Fubini also give $|Y_X| = 0$ almost surely for every $X \neq 0$. At $h = 0$, the integrated expected range of Y_X therefore equals $4\pi J_0(1) = \pi/2$.

Theorem 3. *The integrated gap count satisfies*

$$M(h) \sim \frac{2\pi}{h \log^2(1/h)} \quad (h \downarrow 0), \qquad M(h) \sim \frac{h^{-4}}{4\sqrt{\pi}} e^{-h^2} \quad (h \to \infty).$$

For the dimensional coefficient $D_d = (4\pi)^{-(d-1)/2}(4\sqrt{\pi})^{-1} \int_0^\infty t^{-(d+2)/2} J(t) \, dt$ *of [2],*

$$D_d = \frac{(4\pi)^{-(d+1)/2}}{2\sqrt{\pi}\, d(d+1)} \int_{\mathbb{R}} \mathbb{E} \sum_{I \in \mathcal{G}_X} |I|^{d+1} \, dX, \qquad \int_0^\infty t^{-(d+2)/2} J(t) \, dt \sim \frac{\Gamma(d/2 - 5/2)}{32\pi^{3/2}} \quad (d \to \infty).$$

Proof. By (1), the two secants of the decreasing function $4\pi J_h(1)$ across h bound $M(h)$, since M is decreasing. At small h use endpoints $h/q, h, qh$, with $q > 1$ fixed. In Theorem 2 and $J_h(1) = J(h^{-2})$, the second inverse-log term changes by $O(\log^{-3}(1/h))$; the leading difference across each secant is $\log q/(2\log^2(1/h))$ for $J_h(1)$. Send $q \downarrow 1$ after $h \downarrow 0$. At large h, Theorem 1 gives $J_h(1) \sim h^{-5} e^{-h^2}/(32\pi^{3/2})$. With endpoints $h - b/h, h, h + b/h$ for fixed $b > 0$, the ratios of the shifted values to the central value tend to e^{2b} and e^{-2b}. Send $b \downarrow 0$ after $h \to \infty$.

For the moment identity, set $h = t^{-1/2}$ and integrate (1), using $2\int_0^\ell h^{d-1}(\ell - h) \, dh = 2\ell^{d+1}/[d(d+1)]$. For large d, instead set $v = 1/t$; the large-v integrand is $v^{d/2-7/2} e^{-v}/(32\pi^{3/2})$ up to arbitrarily small relative error, by Theorem 1. The integral on a fixed bounded v-interval is negligible at the gamma scale. This proves both claims. □

4 Gap-scale free energy of finite intervals

Let the two transparent intervals have fixed lengths $\ell_-, \ell_+ > 0$, with gap g centered at zero. Let $\mathcal{I}_g(t)$ denote their connected all-hit heat gain. At $g = 0$ retain the interval labels and disregard the polar common endpoint. Fix a common unit of length in logarithms. Define

$$\begin{aligned} C_* &= \lim_{L \to \infty} \left[\int_0^{L^2} J(t) \frac{dt}{t} - \frac{1}{4} \log L + \log \log L \right], \\ C_{\ell_-, \ell_+} &= C_* + \int_0^1 (\mathcal{I}_0(t) - 1/8) \frac{dt}{t} + \int_1^\infty \mathcal{I}_0(t) \frac{dt}{t}, \\ N_\lambda &= 2 \sum_{n \geq 1} Q((2\pi n/\lambda)^2). \end{aligned}$$

Theorem 4. *At inverse temperature* $\beta = \lambda g$*, locally uniformly for* $\lambda > 0$*, the connected free energy is*

$$\mathcal{F}_{g, \lambda g} = -\frac{\log(1/g)}{8\lambda g} + \frac{\log\log(1/g)}{2\lambda g} - \frac{C_{\ell_-, \ell_+} + N_\lambda}{2\lambda g} + o(g^{-1}).$$

The nonzero Matsubara function obeys

$$N_\lambda \sim \frac{\lambda^3}{128\pi^4} e^{-4\pi/\lambda} \qquad (\lambda \downarrow 0),$$

$$N_\lambda = 2\lambda D_1 - \tfrac{1}{4}\log\lambda + \log\log\lambda - C_* + \tfrac{\gamma}{8} - \frac{a+\gamma}{2\log\lambda} + O((\log\lambda)^{-2}) \qquad (\lambda \to \infty).$$

Proof. The bounded intervals are contained in the infinite rays of gap g. For small physical times,

$$0 \le J(t/g^2) - \mathcal{I}_g(t) \le Ce^{-c/t}$$

uniformly in sufficiently small g. A bridge in the difference visits a ray beyond an outer endpoint and also visits the opposite ray. Its contact-axis range in unit-duration coordinates is at least $\min(\ell_-, \ell_+)/\sqrt{t}$. Integrate over contact-axis starts using the lateral range to bound their measure, over the normal starts by the reflection probability, and then apply the Gaussian range tail. For each fixed $t > 0$, the all-hit event converges as $g \downarrow 0$, outside the zero-probability event of hitting one of the limiting endpoints. Gaussian localization gives convergence of the spatial integral. At large time use the enclosing-window $O(t^{-1})$ bound [2, 1].

Split the zero-mode integral as

$$\int_0^\infty \mathcal{I}_g(t)\frac{dt}{t} = \int_0^{g^{-2}} J(T)\frac{dT}{T} + \int_0^1 [\mathcal{I}_g(t) - J(t/g^2)]\frac{dt}{t} + \int_1^\infty \mathcal{I}_g(t)\frac{dt}{t}.$$

The last two terms converge by the preceding bounds. The first is $\frac{1}{4}\log(1/g) - \log\log(1/g) + C_* + o(1)$ by Theorem 2. In the nonzero modes the substitution $t = g^2T$ gives $\mathcal{I}_g(g^2T) \uparrow J(T)$. The Gaussian bounds on $J(T)$ at zero and on the nonzero-mode sum at infinity give dominated convergence locally uniformly in $\lambda > 0$. The free-energy prefactor is $-1/(2\lambda g)$ [2]. The first nonzero Matsubara pair dominates as $\lambda \downarrow 0$ by Theorem 1, which also bounds the higher-mode tail.

For large λ, Poisson summation as in [8] gives

$$2\lambda D_1 - N_\lambda = \int_0^\infty J(t)W(t/\lambda^2)\frac{dt}{t}, \qquad W(x) = (4\pi x)^{-1/2} - 2\sum_{n\ge1} e^{-4\pi^2 n^2 x}.$$

Equivalently $W(x) = 1 - 2(4\pi x)^{-1/2}\sum_{n\ge1} e^{-n^2/(4x)}$. Thus $k(x) = W(x) - \mathbf{1}_{x<1}$ has all finite absolute logarithmic moments against dx/x. Its zeroth moment is $-\gamma$, by

$$\int_0^\infty x^{s-1}W(x)\,dx = -2\Gamma(s)(2\pi)^{-2s}\zeta(2s) \qquad (0 < \operatorname{Re} s < 1/2).$$

Indeed the positive n-sum has its termwise Mellin transform for $\operatorname{Re} s > 1/2$. Subtract $(4\pi x)^{-1/2}$ on $(0,1)$ and continue its integral $1/(\sqrt{4\pi}(s-1/2))$. In the indicated strip this term equals minus the integral of the same power over $(1,\infty)$. The constant term at $s = 0$ of the displayed expression is $-\gamma$, since $\zeta(0) = -1/2$ and $\zeta'(0) = -\frac{1}{2}\log(2\pi)$. The pole $1/s$ is exactly the Mellin transform of the indicator.

The sharp cutoff contribution is

$$\int_0^{\lambda^2} J(t)\frac{dt}{t} = \tfrac{1}{4}\log\lambda - \log\log\lambda + C_* + \frac{a}{2\log\lambda} + O((\log\lambda)^{-2}).$$

Set $t = \lambda^2 x$ in the difference. For $\lambda^{-1} < x < \lambda$, Theorem 2 gives

$$J(\lambda^2 x) = \frac{1}{8} - \frac{1}{2\log\lambda} + O\Big(\frac{1+|\log x|}{(\log\lambda)^2}\Big).$$

The bounds on k and J make the omitted tails $O(\lambda^{-1/2})$. Thus the difference is $-\gamma/8 + \gamma/(2\log\lambda) + O((\log\lambda)^{-2})$, giving the stated large-period law. □

For comparison, the noncompact Dirichlet–Neumann boundary four-point function [11, Appendix A] gives the normalized expression

$$(1-q)^{-1/8}[2K(\sqrt{q})/\pi]^{-1/2}, \qquad q = \frac{\ell_-\ell_+}{(\ell_-+g)(\ell_++g)},$$

where K is the complete elliptic integral of the first kind. Identifying twice its logarithm with the static heat integral would give $C_{\ell_-,\ell_+} = \log\pi - \frac{1}{4}\log(\ell_-^{-1}+\ell_+^{-1})$. Theorem 4 gives a heat-level definition and proof of the finite limit. Theorem 8 below proves this identification and the stated value of C_{ℓ_-,ℓ_+}.

5 Contact and local geometry

Let two bounded apertures in the plane of a Dirichlet screen in $\mathbb{R}^{d+1}$ have gap $g > 0$. In each aperture impose a common repulsive surface form $\rho_g \int |f|^2$, $\rho_g \geq 0$. Across the screen the openings allow transmission. Reflection leaves an odd full-Dirichlet half-space problem and an even half-space problem with Robin coefficient $\rho_g/2$ on the openings and Dirichlet on the rest. The factor $1/2$ follows from the unitary restriction of an even full-space function to the half-space. It also appears as the ratio of the contact term to the two-arm response $2\sqrt{|D|^2+z}$.

Karabali and Nair [13, Section 3] develop the square-root boundary action for general boundary conditions and apply it to a plate and a parallel half-plate. Fosco and Mazzitelli [14] study variable delta interactions between parallel thin plates. The derivative expansion for facing imperfect mirrors [15] and the curved delta arc in a wedge [16, Section 6] treat different geometries. Frank and Geisinger [17] and Sher [18] analyze large Robin parameters at smooth boundaries, including the scale $\rho\sqrt{t}$ in the heat kernel. We use the connected interaction of apertures in one screen. Inclusion–exclusion cancels the individual aperture terms, and the relevant $\rho_g\sqrt{t}$ scale becomes $g\rho_g$ at the gap diffusion time. The previous transparent near-contact laws [2] answer the approach question of [19, Section V] in several geometries. Here we vary the contact through the competing gap scale and obtain a separate squared-kernel limit when $g\rho_g$ diverges.

Take $s \in \mathbb{R}$ along the gap and $y \in \mathbb{R}^{d-1}$ tangential to it in the screen, with x normal to the screen. Before translating the apertures by $\mp g/2$ in s, suppose their closures have unique contact at zero and lie on opposite sides of $s = 0$. For $d \geq 2$, assume bounded convex apertures with facing graphs $s = -a_-(y)$ and $s = a_+(y)$ near zero. The interiors are respectively on the left and right. We use either of the following hypotheses from [2].

- The graphs are C^2 with positive definite sum $B_- + B_+$ of their Hessians at zero. Put $\alpha = (d-1)/2$ and $H(w) = 1 + \frac{1}{2}w^{\mathsf{T}}(B_- + B_+)w$.
- For $p_j > 1$, $a_i(y) = \sum_j b_{ij}|y_j|^{p_j} + o(\sum_j |y_j|^{p_j})$ in orthonormal coordinates, where $b_{ij} \geq 0$ and $b_{-j} + b_{+j} > 0$. Set $\alpha = \sum_j p_j^{-1}$ and $H(w) = 1 + \sum_j (b_{-j}+b_{+j})|w_j|^{p_j}$.

In $d = 1$ take fixed interval lengths $\ell_-, \ell_+ > 0$, put $\alpha = 0$ and $H = 1$, and interpret the zero-dimensional integral as evaluation.

Let $\mathcal{I}_{g,\rho}(t)$ be the connected heat gain obtained by the two-opening relative heat trace minus the two one-opening relative traces, each relative to the cut half-spaces. Denote by L_t the normal local time at the plane, in the occupation-density convention for generator Δ. The connected gain is the free diagonal integral of bridges that avoid the retained screen and hit both openings,

with weight $e^{-\rho L_t}$ [1]. The weight is common to all surviving subsets, so the same inclusion–exclusion applies. The scalar vacuum and thermal observables in units $\hbar = c = k_{\mathrm{B}} = 1$ are [2]

$$\mathcal{E}_g = -\frac{1}{4\sqrt{\pi}} \int_0^\infty t^{-3/2} \mathcal{I}_{g,\rho_g}(t)\, dt, \tag{2}$$

$$\mathcal{F}_{g,\beta} = -\frac{1}{2\beta} \int_0^\infty \mathcal{I}_{g,\rho_g}(t) \sum_{n\in\mathbb{Z}} e^{-t(2\pi n/\beta)^2}\, \frac{dt}{t}. \tag{3}$$

6 Planar estimates and bounded scaled contact

Let $J_h^b(t)$ be the planar all-hit gain for the exterior rays of a retained segment of length h, with bridge weight e^{-bL_t}. For $b = 0$, write $J_h(t)$ and $J(t) = J_1(t)$. The zero-gap rays have $J_0(t) = 1/8$ [2] and Sections 1–4. Brownian scaling gives

$$J_h^b(t) = J_{h/\sqrt{t}}^{b\sqrt{t}}(1) = J_1^{bh}(t/h^2) \quad (h > 0).$$

For later use set $Q_b(z) = \int_0^\infty J_1^b(t) e^{-zt}\, dt/t$ for $z > 0$, also for $z = 0$ when $b > 0$.

At duration one, vary the lateral base point of the ray bridge while keeping the lateral increments and normal path fixed. The available lateral length is bounded by the full lateral bridge range Sections 1–4, which has finite expectation and is independent of the normal bridge. The occupation local time of a generator-Δ normal unit bridge from X to X satisfies

$$\Pr_X(L_1 > u) = e^{-(|X|+u)^2} \quad (u \geq 0).$$

Indeed the reflected joint bridge density for variance-one Brownian motion with local time above l is $p_1(|x|+|y|+l)$ before conditioning on the endpoint y. Divide by $p_1(y-x)$ at $x = y = X/\sqrt{2}$ and use that variance-two semimartingale local time is twice its occupation local time. Integration over X gives $2e^{-u^2}\, du$ for the positive part of the local-time density. Hitting the line and acquiring positive local time are almost surely the same event for these bridges. The bound on the lateral range and $1 - e^{-s} \leq s$ give

$$J_h^b(t) \leq C \min(1, (b\sqrt{t})^{-1}), \qquad 0 \leq J_h(t) - J_h^b(t) \leq C \min(1, b\sqrt{t}). \tag{4}$$

These estimates are uniform in $h \geq 0$ and apply to the respective interval observables by event inclusion. The separate Gaussian estimate $J_1(T) \leq Ce^{-\eta/T}$ at $T \leq 1$ follows from the lateral range needed to meet both rays.

Set $c_g = g\rho_g$. For $b \geq 0$ define

$$D_d(b) = \frac{(4\pi)^{-(d-1)/2}}{4\sqrt{\pi}} \int_0^\infty T^{-(d+2)/2} J_1^b(T)\, dT.$$

Theorem 5. *If $c_g \to c < \infty$, then*

$$g^{d-\alpha} \mathcal{E}_g \longrightarrow -\int_{\mathbb{R}^{d-1}} H(w)^{-d} D_d(cH(w))\, dw.$$

For $d \geq 2$, and also $d = 1$ when $c > 0$, one has locally uniformly for $\lambda > 0$

$$g^{d-\alpha} \mathcal{F}_{g,\lambda g} \longrightarrow -\frac{(4\pi)^{-(d-1)/2}}{2\lambda} \int_{\mathbb{R}^{d-1}} \int_0^\infty T^{-(d+1)/2} J_{H(w)}^c(T) \sum_{n\in\mathbb{Z}} e^{-T(2\pi n/\lambda)^2}\, dT\, dw. \tag{5}$$

Proof. For $t = g^2T$, dilation in the two fast bridge coordinates changes the weight to $e^{-c_g L_T}$. The slow tangential freezing in [2, proof of the near-contact theorem] uses the uniform continuity of a scaled bridge and point polarity at the two limiting endpoints. Multiply the converging all-hit indicators by this bounded weight, which converges pointwise for fixed T. Every spatial and time majorant of the transparent proof still applies, since the weight is at most one. For the additional $d = 1, c > 0$ zero mode use (4) at large T with c_g bounded below. The small-time Gaussian bound and the Matsubara sum control the other terms uniformly for λ in compact positive sets. For the vacuum integral use $J_h^c(T) = J_1^{ch}(T/h^2)$ and substitute $T = h^2u$. This gives the factor h^{-d} and the asserted result. The limiting integrals are strictly positive, by a positive-probability bridge tube that forces two visits and by strict positivity of the local-time factor. □

7 Strong scaled contact

Write n_{κ^2} for the off-diagonal kernel of $2\sqrt{|D|^2 + \kappa^2}$ in dimension d, in the convention of [2]. Define, for $h > 0$,

$$V_d(\kappa, h) = \int_0^\infty \int_0^\infty \int_{\mathbb{R}^{d-1}} |n_{\kappa^2}(h + u + v, x)|^2 \, dx \, du \, dv, \qquad A_d = \frac{2\Gamma(d/2+1)^2\Gamma(d/2+2)}{\pi^{d/2+2}\Gamma(d+4)}.$$

Theorem 6. *If $c_g \to \infty$, then*

$$g^{d-\alpha} c_g^2 \mathcal{E}_g \longrightarrow -A_d \int_{\mathbb{R}^{d-1}} H(w)^{-d-2} \, dw,$$
$$g^{d-\alpha} c_g^2 \mathcal{F}_{g,\lambda g} \longrightarrow -\frac{1}{2\lambda} \int_{\mathbb{R}^{d-1}} \sum_{n \in \mathbb{Z}} V_d(2\pi|n|/\lambda, H(w)) \, dw.$$

The second limit is locally uniform for $\lambda > 0$. The static kernel integral is

$$V_d(0, h) = \frac{4\Gamma((d+1)/2)^2\Gamma((d+3)/2)}{\pi^{(d+3)/2}\Gamma(d+3)} \, h^{-d-1}.$$

In particular $A_1 = 1/(64\pi)$ and $V_1(0, 1) = 2/(3\pi^2)$.

Proof. Let $\gamma_* = d - 1 - \alpha$ and let $K_{i,g}$ be the apertures dilated by $1/g$ in the screen. At scaled momentum κ the relative response, after removing a common factor, has isolated diagonal forms $A_{i,g} + c_g$, with $A_{i,g}$ the compression of $2\sqrt{|D|^2 + \kappa^2}$. The cross block B_g acts by n_{κ^2} between the two scaled domains. Their separation is at least one. Subordination gives

$$|n_{\kappa^2}(x)| \le C|x|^{-d-1} e^{-b\kappa|x|} \quad (|x| \ge 1).$$

Differentiating its integral gives $|\nabla n_{\kappa^2}(x)| \le C_\kappa |x|^{-d-1}$ there for fixed κ. The Schur test on $|x - y| \ge 1$ also gives $\|B_g\| \le Ce^{-b\kappa}$ uniformly in g.

In the facing charts use the physical tangential coordinates $y_j = g^{1/p_j} w_j$ and $y' = y + gx$, with $p_j = 2$ in the quadratic case. The two inward depths are gu, gv. The pair separation divided by g is $(1 + (a_-(y) + a_+(y'))/g + u + v, x)$, which tends to $(H(w) + u + v, x)$. In the finite-type case a_+ is convex and $a_+(y) = o(|y|)$. Its Lipschitz constants on shrinking centered neighborhoods tend to zero: bound its slope in any direction between points in a small ball by its oscillation on a concentric ball of twice the radius divided by that radius. This gives

$(a_+(y') - a_+(y))/g \to 0$ at fixed chart variables. For a fixed local chart, bounded Lipschitz constants and $a_-(y) + a_+(y) \gtrsim \sum_j |y_j|^{p_j}$ give a lower bound for the scaled pair distance by

$$C^{-1}\left(1 + u + v + |x| + \sum_j |w_j|^{p_j}\right).$$

In fact the nonnegative graph heights give the bound in u, v, the lateral difference gives the bound in $|x|$, and replacing $a_+(y')$ by $a_+(y)$ costs at most $Cg|x|$.

The local Jacobian is $g^{d+1+\alpha}$ for the two physical variables together, hence $g^{-\gamma_*}$ in the scaled aperture spaces. The aperture indicators tend to one at fixed positive u, v by the local interior graph description. The squared radial decay exponent $2(d+1)$ exceeds the effective volume exponent $d + 1 + \alpha$ of the chart variables. Outside the local charts compactness and unique contact give a positive physical distance lower bound. This part gives $O(g^2 e^{-b\kappa})$ in the squared scaled kernel integral, using the bounded physical volumes. Dominated convergence gives

$$g^{\gamma_*}\|B_g\|_2^2 \longrightarrow \int_{\mathbb{R}^{d-1}} V_d(\kappa, H(w))\, dw, \qquad g^{\gamma_*}\|B_g\|_2^2 \le Ce^{-b\kappa}. \tag{6}$$

It remains to control the diagonal inverse in this same limit. Put $R_{i,g} = c_g(A_{i,g} + c_g)^{-1}$, a positive contraction. For either output side of the cross block, multiply its kernel in the output variable by

$$\chi_{i,g,\delta}(x) = \min(1, \operatorname{dist}(x, K_{i,g}^c)/\delta), \qquad \delta > 0.$$

At a fixed chart tuple with positive output depth, the scaled boundary distance is bounded below by a positive constant times that depth for small g, by the graph's bounded Lipschitz constant. The majorant for (6) therefore shows the removed kernel has negligible normalized squared Hilbert–Schmidt norm when $g \downarrow 0$ and then $\delta \downarrow 0$. The cutoff columns have zero extensions in H^1. Their normalized integrated squared gradients are bounded by $C_{\kappa,\delta}$ by differentiating the kernel in the output variable and using the bound on the cutoff gradient. The normalized integrated $A_{i,g}$ form of these columns is bounded by the same type of constant, since $2\sqrt{|\xi|^2 + \kappa^2} \le C_\kappa(1 + |\xi|^2)$. The spectral bound

$$(I - R_{i,g})^2 \le c_g^{-1} A_{i,g}$$

then shows that the action of $I - R_{i,g}$ on the cutoff columns is negligible in the normalized Hilbert–Schmidt norm. First send $g \downarrow 0$ and then $\delta \downarrow 0$, using contractivity for the removed part.

Define $q_g(\kappa) = \int_0^\infty e^{-\kappa^2 T}\mathcal{I}_{g,\rho_g}(g^2T)\, dT/T$. The pair relative determinant identity from [2] expands this as a positive trace logarithm. Its first term times c_g^2 is $\operatorname{Tr}(R_{-,g}B_gR_{+,g}B_g^*)$. The preceding cutoff bound and Hilbert–Schmidt Cauchy–Schwarz show its difference from $\|B_g\|_2^2$ is $o(g^{-\gamma_*})$. After multiplication by c_g^2, the remaining trace series is bounded by $Cc_g^{-2}\|B_g\|_2^2\|B_g\|^2$, by bounding all but the first normalized cross-pair factor in operator norm. Thus $g^{\gamma_*}c_g^2 q_g(\kappa)$ has the pointwise limit in (6) and is bounded by $Ce^{-b\kappa}$. It is a decreasing function of κ by the positive heat representation. Continuity of the limit and a finite mesh give uniform convergence on compact κ-intervals. The exponential bound controls the upper tails when integrating in κ or summing Matsubara frequencies. In (2) the corresponding momentum formula is $-(2\pi g)^{-1}\int_0^\infty q_g(\kappa)d\kappa$; in (3) the prefactor at $\beta = \lambda g$ is $-(2\lambda g)^{-1}$. Both have scaling $g^{\alpha-d}$ once $g^{-\gamma_*}$ is included.

Tangential Plancherel gives

$$V_d(\kappa, h) = (2\pi)^{-(d-1)}\int_{\mathbb{R}^{d-1}} V_1(\sqrt{\kappa^2 + |k|^2}, h)\, dk, \qquad V_1(\kappa, h) = h^{-2}V_1(h\kappa, 1).$$

The planar kernel is $-2\kappa K_1(\kappa r)/(\pi r)$ at separation r. Radially integrating the κ, k variables gives the vacuum factor h^{-d-2} times

$$\frac{|S^{d-1}|}{2(2\pi)^d}\frac{4}{\pi^2}\int_0^\infty \frac{s\,ds}{(1+s)^{d+4}}\int_0^\infty q^{d+1}K_1(q)^2\,dq.$$

The first integral is $1/[(d+2)(d+3)]$. The second is $2^{d-1}\Gamma(d/2+1)^2\Gamma(d/2)\Gamma(d/2+2)/\Gamma(d+2)$. To see this, use $K_1(q)=\frac{q}{4}\int_0^\infty x^{-2}e^{-x-q^2/(4x)}dx$ twice and integrate in q first. In the remaining two variables x, y, substitute $x+y$ and $x/(x+y)$. Their gamma and beta integrals give the stated moment. This yields A_d. At $\kappa = 0$ the kernel is $-2\Gamma((d+1)/2)\pi^{-(d+1)/2}|x|^{-d-1}$. Integrate its square over the $d-1$ tangential coordinates first, by the radial beta integral, and then integrate $\int_0^\infty s(h+s)^{-d-3}ds = h^{-d-1}/[(d+1)(d+2)]$. This proves the static formula. □

In Theorems 5 and 6, the leading law at fixed $\beta > 0$ is the vacuum law. Indeed the scaled momentum step is $\Delta = 2\pi g/\beta$. For a positive decreasing function, the half-weighted mesh sum after multiplication by Δ differs from its integral by at most Δ times its value at zero. Use $g^{\gamma_*}c_g^2 q_g$ in the strong case, bounded at zero by (6). In the bounded case use $g^{\gamma_*}q_g$. Its value at zero is bounded by the transparent Matsubara sum at the scaled period one, which is $O(1)$ in $d \geq 2$ and $O(\log(1/g))$ in $d = 1$ by [2]. Multiplication by Δ makes the error negligible in both cases. Positivity of the limiting vacuum constants permits comparison of equivalents.

8 Interval zero mode with weak scaled contact

For $d = 1$, write

$$Z_g = \int_0^\infty \mathcal{I}_{g,\rho_g}(t)\,\frac{dt}{t}, \qquad N_\lambda = 2\sum_{n\geq 1} Q_0((2\pi n/\lambda)^2).$$

At $g = 0$ retain the two interval labels, with the common endpoint omitted as a polar set. In fixed units of length, set

$$\begin{aligned} C_* &= \lim_{L\to\infty}\left[\int_0^{L^2} J(T)\frac{dT}{T} - \frac{1}{4}\log L + \log\log L\right], \\ C_R &= \int_0^1 [J_0^1(s) - 1/8]\frac{ds}{s} + \int_1^\infty J_0^1(s)\frac{ds}{s}, \\ C_{\ell_-,\ell_+} &= \log\pi - \tfrac{1}{4}\log(\ell_-^{-1} + \ell_+^{-1}). \end{aligned}$$

The constant C_* exists by the retained-segment heat expansion Sections 1–4; C_R is finite by (4).

Theorem 7. *Suppose $d = 1$ and $c_g \to 0$. If $\rho_g \to \rho < \infty$, then*

$$\begin{aligned} Z_g = \tfrac{1}{4}\log(1/g) - \log\log(1/g) + C_{\ell_-,\ell_+} \\ + \int_0^\infty [\mathcal{I}_{0,\rho}(t) - \mathcal{I}_{0,0}(t)]\,\frac{dt}{t} + o(1). \end{aligned}$$

If $\rho_g \to \infty$, then

$$Z_g = \tfrac{1}{4}\log(1/c_g) - \log\log(1/c_g) + C_* + C_R + o(1).$$

In both cases

$$\mathcal{F}_{g,\lambda g} = -\frac{Z_g + N_\lambda + o(1)}{2\lambda g}$$

locally uniformly for $\lambda > 0$. In particular $\rho_g = g^{-\sigma}$ with $0 < \sigma < 1$ reduces the coefficient of $\log(1/g)$ in Z_g to $(1-\sigma)/4$.

Proof. If the physical coefficients are bounded, subtract the transparent finite-interval integral. At fixed $t > 0$ the gain difference converges by polarity at the limiting endpoints and continuity of the weight in ρ_g. The small-time bound in (4) is $O(\sqrt{t})$ for this difference. At large time use the fixed enclosing transparent window's $O(t^{-1})$ heat gain [1, 2]. Dominated convergence gives the stated finite shift. The transparent constant follows from Theorem 8 below.

If $\rho_g \to \infty$, truncate the infinite rays to the actual intervals. The unweighted heat loss at small physical time is bounded by $Ce^{-b/t}$, uniformly for small g, since a lost all-hit bridge reaches beyond an outer endpoint and must have lateral range at least $\min(\ell_-, \ell_+)$. The weighting can only decrease this loss, and (4) also bounds it by $C/(\rho_g\sqrt{t})$. Use dominated convergence below $t = 1$ and integrate directly above $t = 1$ to get $Z_g = Q_{c_g}(0) + o(1)$.

For $c > 0$ split that ray integral at $T = c^{-2}$. Insert the transparent ray integral below the cutoff and rescale the resulting difference by $s = c^2T$. This gives the exact identity

$$Q_c(0) = \int_0^{c^{-2}} J(T)\frac{dT}{T} + \int_0^1 [J_c^1(s) - J_c(s)]\frac{ds}{s} + \int_1^\infty J_c^1(s)\frac{ds}{s},$$

where the subscripts c on J_c^1, J_c denote the retained segment lengths. By point polarity, as $c \downarrow 0$ the last two integrands converge to the corresponding zero-gap ones; (4) supplies integrable majorants. The first integral equals the two logarithms plus $C_* + o(1)$ by its definition.

Finally at each fixed $T > 0$, the expanding intervals in scaled coordinates and $c_g \to 0$ give $\mathcal{I}_{g,\rho_g}(g^2T) \to J(T)$. Insert this in the nonzero Matsubara modes. The unweighted small-time Gaussian bound and the exponential large-T Matsubara bound give a majorant locally uniformly in λ. This proves the last formula. □

9 Exact transparent static calibration

Let the transparent interval endpoints be $a < b < c < d_0$, and put

$$q = \frac{(b-a)(d_0-c)}{(c-a)(d_0-b)}, \qquad k = \sqrt{q}, \quad k' = \sqrt{1-q}.$$

Section 4 compared the finite interval constant to a boundary four-point expression from [11, Appendix A]. The following argument fixes the normalization in the aperture heat observable. The classical Neumann needle geometry has the same connected static observable by reflection parity (Section 1) [3]. In that geometry [3, Eq. (15)] already gives the equal-length leading and double logarithms. Dubédat's crosscut transfer formula [20, Section 2.2] also gives the cylinder product below, since the transfer between the seams has eigenvalues $\operatorname{sech}(\pi nW/H_0)$. We derive it directly from the connected heat trace to track its winding classes.

Theorem 8. *For transparent intervals the zero-mode heat integral is exactly*

$$Q_g^{\mathrm{stat}} = -2\sum_{n\ge1} \log\tanh\left(\pi n\,\frac{K(k')}{K(k)}\right) = -\frac{1}{4}\log(1-q) - \log\frac{2K(k)}{\pi}.$$

Thus its finite constant as $g \downarrow 0$ is C_{ℓ_-,ℓ_+} above. In the decomposition by cylinder winding, the nonzero class of signed winding m has mass $1/[|m|(e^{s|m|}-1)]$ with $s = 2\pi K(k')/K(k)$. The zero-winding all-hit mass is $2\sum_{n\ge1}\log(1+e^{-sn})$. The nonzero classes give the entire double logarithm.

Proof. Let Ω be the plane cut along the screen retained outside both intervals. By the killed heat diagonal and its conditional bridge, the measure dt/t times that diagonal and bridge law is the Brownian loop measure of Ω after forgetting the root. The all-hit static integral is its mass of loops visiting both apertures. The generator normalization agrees with [21] because changing from $\Delta/2$ to Δ simply changes the integration variable in dt/t. The event is independent of the time parametrization, so the conformal invariance of the unrooted loop measure applies [21, Proposition 6], including for the cylindrical surface [22, Theorem 2.2].

A real Möbius map sends a, b, c, d_0 cyclically to $0, q, 1, \infty$. The Schwarz–Christoffel integral in the upper half-plane has derivative proportional to $[z(z-q)(z-1)]^{-1/2}$. Its rectangle has its opposite aperture sides of height $H_0 = 2K(k)$ and its gap side of width $W = 2K(k')$ [12, Section 19.32]. These lengths follow by substituting $z = q\sin^2\theta$ on $(0, q)$ and $z = 1-(1-q)\sin^2\theta$ on $(q, 1)$. Schwarz reflection across either open aperture maps the lower half-plane to a reflected rectangle. The two reflections differ by the translation $2W$ across the pair of parallel aperture sides. Taking this horizontal coordinate modulo $2W$ therefore gives one conformal map from Ω to the flat cylinder $(\mathbb{R}/2W\mathbb{Z}) \times (0, H_0)$, with two seams $x = 0, W$. The two half-planes map to the two half-cylinders. The remaining sides give the two Dirichlet circles, and the four endpoints lie on their boundary.

Cutting the cylinder at one seam gives a rectangle of width $2W$; cutting both gives two rectangles of width W. Inclusion–exclusion on the loop event separates the common vertical Dirichlet heat trace. Horizontally, with P_L the period-L and D_L the Dirichlet-interval length-L traces, the factor is

$$P_{2W}(t) - 2D_{2W}(t) + 2D_W(t) = \frac{4W}{\sqrt{4\pi t}} \sum_{m\in\mathbb{Z},\ m\ \text{odd}} e^{-m^2W^2/t}.$$

This is the image sum for the circle and the Poisson formula $D_L(t) = L(4\pi t)^{-1/2}\sum_m e^{-m^2L^2/t} - 1/2$. Multiply by the vertical sum $\sum_{n\ge1} e^{-(\pi n/H_0)^2 t}$. Integration using $\int_0^\infty t^{-3/2}e^{-A^2/t-B^2t}dt = \sqrt{\pi}e^{-2AB}/A$ gives $4\sum_{n\ge1}\sum_{m\ge1,\ m\ \text{odd}} e^{-snm}/m$. The series converges for $s > 0$ and summing in m yields the first formula. With nome $p = e^{-s/2}$, Jacobi's products [12, Sections 20.4 and 20.9] give

$$\prod_{n\ge1}\frac{1+p^{2n}}{1-p^{2n}} = [\vartheta_3(0,p)\vartheta_4(0,p)]^{-1/2} = (1-q)^{-1/8}[2K(k)/\pi]^{-1/2}.$$

The first equality follows by collecting the even and odd factors; the second uses $2K(k)/\pi = \vartheta_3^2$ and $k' = \vartheta_4^2/\vartheta_3^2$. This proves the elliptic expression.

Every loop of horizontal winding $m \neq 0$ visits both seams. Select just the m-th periodic image in the uncut cylinder before integrating. Its coefficient is $2W$ instead of $4W$, and summing the vertical factor gives $1/[|m|(e^{s|m|}-1)]$, in agreement with the general annular formula [22, Eq. (4.3)]. Summing the nonzero classes gives $-2\log P(s)$ with $P(s) = \prod_{n\ge1}(1-e^{-sn})$. Subtraction from the first formula leaves $2\log[P(2s)/P(s)]$ for the zero-winding loops. Put $L = \log(16/(1-q))$. Then $s = 2\pi^2/L + O((1-q)/L)$ by the elliptic endpoint expansion. The eta transformation [12, Chapter 23] gives

$$\log P(s) = -\frac{\pi^2}{6s} + \tfrac{1}{2}\log(2\pi/s) + \frac{s}{24} + O(e^{-4\pi^2/s}).$$

Consequently the contributions near contact are

$$Q_{\text{wound}} = \frac{L}{6} - \log L + \log\pi - \frac{s}{12} + o(L^{-1}), \qquad Q_{\text{zero}} = \frac{L}{12} - \log 2 + \frac{s}{12} + o(L^{-1}).$$

This gives the winding claim. Finally $1-q = g(\ell_-^{-1}+\ell_+^{-1}) + O(g^2)$ and $2K(k) = \log(16/(1-q)) + O((1-q)|\log(1-q)|)$. Inserting these in the exact heat integral gives C_{ℓ_-,ℓ_+}. □

For clarity, the transparent cylinder result concerns the static heat integral. Positive contact would pull back to a spatially varying coefficient along the seams under the same conformal map. Under zero contact, put $A = \ell_-^{-1}+\ell_+^{-1}$ and $L_g = \log(1/g)$. The elliptic expression refines the static expansion by the next term $-\log(16/A)/L_g + O(L_g^{-2})$ in Q_g^{stat}. The nonzero-mode discrepancy with N_λ is exponentially small in $1/g$ for λ in compact positive sets. Indeed at small physical time t it is bounded in the heat integral by $Ce^{-b/t}\sum_{n\neq 0} e^{-t(2\pi n/(\lambda g))^2}$, and at $t \geq 1$ the sum itself is exponentially small. Splitting the small-time exponential in half and using $b/t + t(2\pi n/(\lambda g))^2 \geq c|n|/g$ gives the claimed bound after integration with dt/t. Thus the next term in $\mathcal{F}_{g,\lambda g}$ beyond that of Sections 1–4 is $+\log(16/A)/(2\lambda g L_g)$, with remainder $O(1/(gL_g^2))$ locally uniformly in $\lambda > 0$.

10 Independent contact strengths: geometry and observables

We take the near-contact geometry from [2] and Sections 5–9. Two bounded convex apertures lie in opposite closed half-spaces of a d-dimensional screen, with unique contact of their closures at the origin before translation. Their facing graphs are $s = -a_-(y)$ and $s = a_+(y)$, where s is the gap direction and $y \in \mathbb{R}^{d-1}$ is tangential to the contact. The interiors lie on the outer sides of the respective graphs. Translate the apertures by $\mp g/2$ along s. For a quadratic contact the two graphs are C^2 and $B_- + B_+$ is positive definite, with B_i their Hessians at zero. Put $\alpha = (d-1)/2$ and $H(w) = 1 + \frac{1}{2}w^{\mathsf{T}}(B_- + B_+)w$. For separable finite type assume $a_i(y) = \sum_j b_{ij}|y_j|^{p_j} + o(\sum_j |y_j|^{p_j})$ in orthonormal coordinates, where $p_j > 1$, $b_{ij} \geq 0$, and $b_{-j} + b_{+j} > 0$. Then $\alpha = \sum_j p_j^{-1}$ and $H(w) = 1 + \sum_j (b_{-j}+b_{+j})|w_j|^{p_j}$. For $d = 1$ use intervals of fixed lengths $\ell_-, \ell_+ > 0$, with $\alpha = 0$, $H = 1$, and zero-dimensional integration interpreted as evaluation.

Write $\rho_{i,g} \geq 0$ for the constant repulsive coefficient added to the aperture form on side i, and $c_{i,g} = g\rho_{i,g}$. The connected heat gain $\mathcal{I}_g(t)$ is the two-opening relative heat trace minus the two one-opening relative heat traces, each relative to the cut half-spaces. It is the all-hit integral of bridges of generator Δ that avoid the retained screen and visit both apertures, with weight $\exp[-\sum_i \rho_{i,g} L_t^i]$ [1]. Here L_t^i is the normal occupation local time accumulated at hits in aperture i. Define the gap-scaled positive transform

$$q_g(\kappa) = \int_0^\infty e^{-\kappa^2 T}\mathcal{I}_g(g^2 T)\,\frac{dT}{T}, \qquad \kappa \geq 0.$$

The vacuum energy is $-(2\pi g)^{-1}\int_0^\infty q_g(\kappa)d\kappa$, and the free energy at inverse temperature β is $-(2\beta)^{-1}\sum_{n\in\mathbb{Z}} q_g(2\pi|n|g/\beta)$ [2]. In gap coordinates the diagonal boundary response is the form compression of $2\sqrt{|D|^2+\kappa^2}$ plus $c_{i,g}$, and the off-diagonal kernel is that of the two-arm square root. The normalized pair determinant equals the positive transform q_g after taking minus the logarithm.

The common-strength theory Sections 5–9 uses a trace of two separated kernels for large contact. With unequal strengths there is a regime in which only one diagonal inverse tends to a scalar. Mixed-boundary half-plane Green functions [23, 10] and the diffraction basis for the massive half-line square root [19, Appendix A.1] are antecedents for the flat profile. Explicit Dirichlet Green functions for fractional half-space powers [24] describe the massless local inverse, while small Robin patches on a fixed boundary [25] give a different perturbation of a local

potential. The problem here is a connected trace on varying apertures, including an unbounded inverse on the remaining transparent side. We estimate its cross-kernel sandwich, track the collapsing geometry, and evaluate the resulting flat coefficient when that side is transparent.

11 One strong contact

Let A_κ be the positive-ray compression of $2\sqrt{D^2+\kappa^2}$ in one tangential dimension, and let $B_{\kappa,h}$ on two inward half-lines have symmetric kernel

$$-\frac{2\kappa K_1(\kappa(h+x+y))}{\pi(h+x+y)}, \qquad x,y>0, \quad h>0.$$

At $\kappa=0$ the kernel is $-2/[\pi(h+x+y)^2]$. Put

$$W_{1,b}(\kappa,h)=\operatorname{Tr}\big[B_{\kappa,h}(A_\kappa+b)^{-1}B_{\kappa,h}^*\big], \tag{7}$$

$$W_{d,b}(\kappa,h)=(2\pi)^{-(d-1)}\int_{\mathbb{R}^{d-1}} W_{1,b}(\sqrt{\kappa^2+|k|^2},h)\,dk. \tag{8}$$

At $\kappa=b=0$, the inverse in (7) is understood through the form-dual variational supremum. Its trace is finite, as shown below.

Theorem 9. *Suppose $c_{-,g}\to\infty$ and $c_{+,g}\to b\in[0,\infty)$. Then, with $\gamma_*=d-1-\alpha$,*

$$g^{\gamma_*}c_{-,g}q_g(\kappa)\longrightarrow\int_{\mathbb{R}^{d-1}} W_{d,b}(\kappa,H(w))\,dw.$$

The convergence is uniform on compact subsets of $[0,\infty)$, with a common exponential upper bound at infinity. Hence the vacuum limit after multiplication by $g^{d-\alpha}c_{-,g}$ is minus the integral of the displayed limit against $d\kappa/(2\pi)$. At $\beta=\lambda g$ the same normalization gives minus its Matsubara sum with prefactor $1/(2\lambda)$, locally uniformly for $\lambda>0$. For fixed $\beta>0$ the free energy has the vacuum equivalent.

For $b=0$ the planar expression and the static value in all dimensions are

$$W_{1,0}(\kappa,h)=\frac{1}{2\pi}\int_h^\infty (r-h)r^{-3}e^{-2\kappa r}\,dr,$$

$$W_{d,0}(0,h)=\frac{\Gamma(d/2)}{2^d\pi^{(d+2)/2}d(d+1)}\,h^{-d}.$$

The vacuum limit is then $-A_d^{(1)}\int H(w)^{-d-1}dw$, where

$$A_d^{(1)}=\frac{\Gamma((d+1)/2)}{2^{d+2}\pi^{(d+3)/2}(d+1)(d+2)}.$$

11.1 The half-line sandwich

For $\kappa>0$ the form of A_κ is $2\|Lf\|_2^2$ with $L=(\kappa+\partial_x)^{1/2}$. Its causal inverse is convolution by $\mathbf{1}_{s>0}e^{-\kappa s}/\sqrt{\pi s}$. The inverse maps half-line L^2 into the supported form domain, and $L=(\kappa+\partial_x)L^{-1}$ preserves support. Thus L maps the form space bijectively onto half-line L^2 as in Sections 1–4. The zero-contact sandwich equals $T_{\kappa,h}^*T_{\kappa,h}/2$ with $T_{\kappa,h}=L^{-*}B_{\kappa,h}^*$. Evaluate the convolution by using

$$\frac{\kappa K_1(\kappa r)}{r}=\int_\kappa^\infty e^{-sr}\sqrt{s^2-\kappa^2}\,ds.$$

The backward convolution on an exponential of rate s gives $(s+\kappa)^{-1/2}$, leaving $\sqrt{s-\kappa}$ in the integral. Hence $T_{\kappa,h}$ has kernel $-e^{-\kappa r}/(\sqrt{\pi}\, r^{3/2})$ at $r = h + x + y$. This is Hilbert–Schmidt and gives the first explicit expression in the theorem.

At $\kappa = 0$ regularize the diagonal form by $2\sqrt{D^2 + m^2}$ while keeping the massless cross block. As $m \downarrow 0$, the forms decrease to $2|D|$ with discrepancy at most $2m\|f\|_2^2$. The inverse quadratic form converges to the variational supremum by taking the limit on each compactly supported test. The backward convolutions are dominated in absolute value by the positive convolution with $\mathbf{1}_{s>0}/\sqrt{\pi s}$, so their sandwiched kernels converge in Hilbert–Schmidt norm to $T_{0,h}$. This identifies the variational limit as the trace-class sandwich. The static planar value $W_{1,0}(0,h) = 1/(4\pi h)$ also follows from the classical mixed Laplace Green function [23, Eq. (4.12)]. By variational comparison the sandwich for $b \geq 0$ is bounded by that for $b = 0$, including its exponentially decaying trace bound.

11.2 Bounded intervals in dimension one

Let $P_{i,g}$ restrict the corresponding ray to its scaled interval. The diagonal contractions $R_{-,g} = c_{-,g}(A_{-,g} + c_{-,g})^{-1}$, extended by zero, tend strongly to the identity. On a smooth compactly supported interior test this follows by the resolvent identity, since the compressed square root of that test is the restriction of its full-line image; then use contractivity and density. With $C_g = B_g(A_{+,g} + c_{+,g})^{-1}B_g^*$ and $B_g = P_{-,g}B_{\kappa,1}P_{+,g}$, the variational comparison gives $0 \leq C_g \leq P_{-,g}C_{\kappa,0}P_{-,g}$, where $C_{\kappa,0} = T_{\kappa,1}^* T_{\kappa,1}/2$.

At any fixed left coordinate the diagonal form on the right cross column converges to the full right-ray value with contact b. The lower limit follows by eventual admissibility of every compactly supported form test. For the upper limit use the full-ray contact $b - \varepsilon > 0$ if $b > 0$ and then send $\varepsilon \downarrow 0$ using its gap. If $b = 0$, use the massless-compatible zero-contact variational bound. The dominating trace density from the transparent half-line sandwich is integrable, so the traces converge to $W_{1,b}(\kappa, 1)$. The first determinant term times $c_{-,g}$ is $\operatorname{Tr}(R_{-,g}C_g)$. The difference from $\operatorname{Tr} C_g$ is at most $\operatorname{Tr}[(P_{-,g} - R_{-,g})C_{\kappa,0}]$, which tends to zero by trace class and strong convergence. The normalized cross product before multiplication has operator norm and trace at most $W_{1,0}(\kappa, 1)/c_{-,g}$. The higher trace terms therefore tend to zero after multiplication by $c_{-,g}$, with the same uniform exponential bound. This proves the planar transform limit.

11.3 Localization of the weak inverse in dimension $d \geq 2$

Let $K_{i,g}$ be the aperture domains dilated by $1/g$, $A_{i,g}$ the compressed two-arm square root at κ, and B_g its kernel $n_{\kappa^2}(X - Y)$ between the two domains. At a left point Y, the diagonal of $C_g = B_g(A_{+,g} + c_{+,g})^{-1}B_g^*$ is the quadratic form of the right inverse on

$$f_{g,Y}(X) = \mathbf{1}_{K_{+,g}}(X) n_{\kappa^2}(X - Y).$$

For $p = 2d/(d+1)$, the homogeneous Sobolev estimate $\|v\|_{2d/(d-1)} \leq C\|v\|_{\dot{H}^{1/2}(\mathbb{R}^d)}$ [26, Theorem 6.5] gives the column-form bound $C\|f_{g,Y}\|_p^2$. Indeed dualize and take the supremum of $2\operatorname{Re}\langle f_{g,Y}, v\rangle$ minus the response form. No positive spectral gap is needed. The kernel is bounded for $|Z| \geq 1$ by $C|Z|^{-d-1}e^{-a\kappa|Z|}$ by Sections 5–9. If L is the distance from Y to the right aperture, integration over $|Z| \geq L \geq 1$ gives $Ce^{-a\kappa}L^{-d-1}$ for the column bound, after reducing a if needed. The same decay power holds for derivatives in Y at fixed κ, by differentiating the kernel.

In the left chart use $y_j = g^{1/p_j} w_j$ with $p_j = 2$ in the quadratic case, and physical inward depth gu. The pair-distance estimate of Sections 5–9 gives $L \gtrsim 1 + u + \sum_j |w_j|^{p_j}$ against points of the right chart. For a left point in a smaller chart, any point outside the right chart is at

positive physical distance by uniqueness of contact. Since $u + \sum_j |w_j|^{p_j} \lesssim g^{-1}$ in the left chart, the bound holds against the entire right aperture. For a left point outside its smaller chart the distance to every right point is at least c/g, and the total off-chart column estimate is $O(ge^{-a\kappa})$, using the scaled volume $O(g^{-d})$. The scaled left volume element in the chart is $g^{-\gamma_*} dw\, du$. The localized majorant is integrable because the effective dimension in these variables is $1+\alpha < d+1$.

Fix (w, u) with $u > 0$, and translate Y to the origin. At any bounded tangential offset the right graph converges uniformly to the half-space boundary $s = H(w)+u$. This is the graph limit in Sections 5–9, where the local Lipschitz constants tend to zero on shrinking neighborhoods of contact. Other parts of the right boundary leave each compact set. The translated columns converge strongly in L^p by dominated convergence, since the support is at distance at least one and the kernel has the stated radial decay.

The inverse forms on these columns converge by the variational formula. For the lower bound, every smooth test compactly supported inside the limiting half-space is admissible for all small g. Such tests are dense in the supported energy space. In the massless homogeneous case, translate a function inward, apply a compact cutoff, and smooth without crossing the boundary. To justify removing the cutoff, let $\chi_R(X) = \chi(X/R)$ with smooth χ equal to one near zero. The difference-quotient norm of $\chi_R v$ is bounded by the norm of v plus a term $C \int |v(Y)|^2 h_R(Y) dY$, where

$$h_R(Y) = \int_{\mathbb{R}^d} |\chi_R(X) - \chi_R(Y)|^2 |X - Y|^{-d-1}\, dX.$$

This term is bounded by $C\|v\|^2_{\dot{H}^{1/2}}$ by Hölder and the Sobolev estimate, since h_R has uniformly bounded L^d norm. Indeed $h_R(Y) = R^{-1} h_1(Y/R)$ and h_1 is bounded and decays as $|Y|^{-d-1}$ at infinity. Whole-space test density and this uniform cutoff bound give convergence. For the inhomogeneous energy also use convergence in L^2.

For the upper bound take near-maximizing tests. They have bounded homogeneous energy by the dual bound on the columns and the quadratic cost. If $\kappa > 0$ or $b > 0$, they are also bounded in L^2 by coercivity. Take a weak subsequential limit in the relevant space. It vanishes strictly below the limiting plane by the convergence of the domains on compact sets. The pairing converges by strong L^p convergence, and energy is lower semicontinuous. When $b > 0$ use the eventual form bound with contact $b - \varepsilon$, followed by $\varepsilon \downarrow 0$; when $b = 0$ drop the nonnegative contact part. This proves the variational upper bound, including $\kappa = b = 0$.

The column majorant now permits integration, giving the limit of $g^{\gamma_*} \operatorname{Tr} C_g$. Tangential Plancherel on the limiting half-space separates the right inverse into the half-line forms of (7) with momentum $\sqrt{\kappa^2 + |k|^2}$. Integration of the left depth at each w gives $W_{d,b}(\kappa, H(w))$. This separation also holds in the massless form-dual sense by positive diagonal mass regularization followed by monotone convergence. The planar fiber trace is finite at zero, and its trace decays exponentially in the fiber momentum for $h \geq 1$.

11.4 The strong inverse and the trace remainder

Put $T_g = (A_{+,g} + c_{+,g})^{-1/2} B_g^*$. The difference between $\operatorname{Tr} C_g$ and $\operatorname{Tr}(R_{-,g} C_g)$ equals $\|(I - R_{-,g})^{1/2} T_g^*\|_2^2$. Cut off T_g^* near the left boundary using the multiplier $\min(1, \operatorname{dist}(Y, K^c_{-,g})/\delta)$. The squared normalized Hilbert–Schmidt norm removed by the cutoff is at most the left column-form integral times the squared removed multiplier. It vanishes as $g \downarrow 0$ and then $\delta \downarrow 0$, by the majorant above and the uniform scaled boundary distance at fixed positive depth in the Lipschitz chart. For fixed δ the cutoff kernel has zero extensions with normalized integrated H^1 norms bounded. To see this, differentiate the cross column in Y under the bounded finite-domain weak inverse square root and use the derivative column estimate and the Lipschitz cutoff. The cutoff

$A_{-,g}$ form is thus bounded after normalization by g^{γ_*}. The bound $I - R_{-,g} \le A_{-,g}/c_{-,g}$ shows that the trace error is $o(g^{-\gamma_*})$.

For the higher traces we also need an operator norm bound for C_g independent of its growing trace. Both apertures are contained in facing supporting half-spaces at separation one in scaled coordinates. By the weak variational formula, the finite-domain C_g is dominated by the compression of the zero-contact facing-half-space sandwich. Its tangential Fourier fibers are the positive planar operators with norm at most their traces $W_{1,0}(\sqrt{\kappa^2 + |k|^2}, 1) \le W_{1,0}(0, 1)$. This is a uniform operator norm bound even at zero. The positive normalized cross product has norm $O(c_{-,g}^{-1})$ and trace $O(c_{-,g}^{-1} g^{-\gamma_*} e^{-a\kappa})$. Thus the remainder after multiplication by $g^{\gamma_*} c_{-,g}$ is $O(c_{-,g}^{-1} e^{-a\kappa})$. This finishes the pointwise transform limit in $d \ge 2$.

In every dimension the limiting transform is continuous, from the explicit $b = 0$ formula and from the positive inverse gap and kernel continuity if $b > 0$, followed by dominated convergence in the tangent variables. The normalized transforms decrease with κ by their heat definition, so a finite mesh gives compact uniformity. The exponential bound permits vacuum integration and Matsubara summation. For fixed physical temperature the scaled mesh is $2\pi g/\beta$. The error of its half-weighted sum, after multiplication by the mesh step, is at most the step times the value at zero, by monotone comparison with the integral. That value is uniformly bounded in the normalization of the theorem. This proves the fixed-temperature assertion.

To compute the coefficients, insert $W_{1,0}$ into (8) and integrate radially. The static tangential integral gives a gamma factor from $e^{-2|k|r}$ and then $\int_h^\infty (r-h) r^{-d-2} dr = h^{-d}/[d(d+1)]$. For the vacuum integrate over $\kappa \ge 0$ and the $d-1$ momenta. At $h = 1$ this gives

$$\frac{|S^{d-1}|}{2(2\pi)^d} \int_0^\infty q^{d-1} W_{1,0}(q, 1)\, dq.$$

Substitute the planar formula, use $\int_0^\infty q^{d-1} e^{-2qr} dq = \Gamma(d)/(2r)^d$, and then $\int_1^\infty (r-1) r^{-d-3} dr = 1/[(d+1)(d+2)]$. Gamma duplication yields $A_d^{(1)}$; the same duplication simplifies the static expression. Dilation gives the height factor h^{-d-1} in the vacuum integral.

11.5 Time representation for the transparent limit

When $b = 0$, the positive transform limit is the Laplace transform with measure $j(T)dT/T$, where

$$j(T) = \frac{T^{-d/2}}{2^d \pi^{(d+2)/2}} \int_{\mathbb{R}^{d-1}} \int_{H(w)}^\infty (r - H(w)) r^{-2} e^{-r^2/T}\, dr\, dw.$$

Indeed the inverse Laplace transform of $e^{-2r\sqrt{z}}$ is $r\, e^{-r^2/T}/(\sqrt{\pi} T^{3/2})$. The tangential momentum integral contributes $(4\pi T)^{-(d-1)/2}$ by the Gaussian integral after the shift $z + |k|^2$. Integrating the positive formula yields the expression. Convergence of the finite-measure Laplace transforms including total mass at $\kappa = 0$ proves weak convergence of $g^{\gamma_*} c_{-,g} \mathcal{I}_g(g^2 T) dT/T$ to this measure.

Write $v_H = |\{w : H(w) - 1 < 1\}|$, with $v_H = 1$ in $d = 1$. The sublevel volumes of $H - 1$ are $v_H s^\alpha$ at level $s > 0$. Thus the double integral may be replaced by

$$\frac{v_H}{\alpha + 1} \int_1^\infty (r-1)^{\alpha+1} r^{-2} e^{-r^2/T}\, dr.$$

At small T, substitute $r = 1 + Ts$ and apply dominated convergence to get the equivalent $\frac{v_H}{\alpha+1} \Gamma(\alpha+2) 2^{-\alpha-2} T^{\alpha+2} e^{-1/T}$ for this integral. At large T and $\alpha > 0$, substituting $r = \sqrt{T} s$ gives $\frac{v_H}{2(\alpha+1)} \Gamma(\alpha/2) T^{\alpha/2}$. If $d = 1$ and $\alpha = 0$, the integral instead has leading term $\frac{1}{2} \log T$, since its integrand differs from $r^{-1} e^{-r^2/T}$ by an integrable function. In that case $j(T) \sim T^{3/2} e^{-1/T}/(8\pi^{3/2})$ at

zero and $j(T) \sim \log(T)/(4\pi^{3/2}\sqrt{T})$ at infinity. The interval vacuum equivalent is $-1/(48\pi^2 g c_{-,g})$; at gap-scale temperature the interval equivalent is

$$-\frac{1}{4\pi\lambda g c_{-,g}} \int_1^\infty (r-1) r^{-3} \coth(2\pi r/\lambda)\, dr,$$

by summing the elementary exponentials in $W_{1,0}$.

12 Independent bounded and divergent strengths

Let $J_h^{a,b}(T)$ be the planar all-hit relative heat gain for the two rays outside a retained segment of length h, with weight $\exp(-aL_T^- - bL_T^+)$ as in Section 1. Its unweighted version is $J_h(T)$; write $J = J_1$. At the gap-scale short-time limit the weights act on the fixed normal bridge local time. We first estimate the large-time effect of a single positive strength.

Theorem 10. *For $a, b, h \geq 0$ and $T > 0$, writing $m = \max(a, b)$, one has*

$$J_h^{a,b}(T) \leq C(1 + m\sqrt{T})^{-1/4}, \qquad 0 \leq J_h(T) - J_h^{a,b}(T) \leq C \min(1, m\sqrt{T}).$$

If $c_{-,g} \to a < \infty$ and $c_{+,g} \to b < \infty$, the limits after multiplication by $g^{d-\alpha}$ are

$$-\frac{(4\pi)^{-(d-1)/2}}{4\sqrt{\pi}} \int_{\mathbb{R}^{d-1}} \int_0^\infty T^{-(d+2)/2} J_{H(w)}^{a,b}(T)\, dT\, dw \quad \text{for the vacuum,}$$

$$-\frac{(4\pi)^{-(d-1)/2}}{2\lambda} \int_{\mathbb{R}^{d-1}} \int_0^\infty T^{-(d+1)/2} J_{H(w)}^{a,b}(T) \sum_{n\in\mathbb{Z}} e^{-T(2\pi n/\lambda)^2}\, dT\, dw \quad \text{at } \beta = \lambda g.$$

The thermal limit holds locally uniformly for $\lambda > 0$ in $d \geq 2$ and also in $d = 1$ if $m > 0$. At fixed positive physical inverse temperature the leading law is the vacuum law.

If both $c_{i,g} \to \infty$, the strong common-strength vacuum and thermal laws of Sections 5–9 hold with the product $c_{-,g}c_{+,g}$ replacing the squared common strength.

Proof. For the first inequality scale to $T = 1$ and take $a = m \geq 2$ by symmetry. At a fixed normal starting coordinate X the normal zero times give the compact lateral trace of the lateral increments. In the all-hit event the minimum of this trace plus the lateral base point lies in the left ray. The placements for which that minimum is within distance δ of the left endpoint have lateral measure at most δ. Integrating the normal hit probability e^{-X^2} bounds this part by $C\delta$.

All other contributing bridges have a contact at least δ inside the left ray. By time reversal it suffices to handle such a hit by $1/2$, at a cost of two. The bridge law up to time $3/4$ is bounded by four times planar Brownian motion from the same base point, by the Gaussian transition density. Stop the motion at its first such contact before $1/2$. During the following $U \leq 1/4$ time units it can exit the left ray in lateral coordinate only by a displacement of at least δ, whose probability is at most $Ce^{-\delta^2/(4U)}$ by reflection. Otherwise all normal local time during that time stays in the left ray. Starting normally at zero, its occupation local time has the law of a constant times $\sqrt{U}$ times a half-normal variable by the standard reflected Brownian local-time identity. Hence the strong Markov property bounds the weighted expectation by $C[(1 + a\sqrt{U})^{-1} + e^{-\delta^2/(4U)}]$, uniformly in the base point. Independently, the all-hit event has Gaussian bound $Ce^{-c(S^2+X^2)}$ from the two independent bridge coordinates. Use the geometric mean of the bounds and integrate in (S, X). With $\delta = a^{-1/4}$ and $U = a^{-3/4}/4$ the deep term is $O(a^{-5/16})$ and the shallow term $O(a^{-1/4})$. Scaling the retained gap and local time proves the assertion. The second inequality follows from

$1-e^{-aL^- -bL^+} \le m(L^- + L^+)$ and the integrated unit normal local-time moment in Sections 5–9, with the same range bound over lateral placements.

For finite scaled limits, $T = t/g^2$ gives the two limiting local-time weights in the near-contact bridge proof [2]. Off the polar limiting endpoints the compact trace at normal-zero times has positive distance from the endpoints. The tangential freeze converges uniformly along each path, so aperture labels agree on the whole normal-zero set for all small g. Integration against its local-time measure therefore gives convergence of both weights. The transparent majorants from [2] apply to the weighted integrals. In $d = 1$ the first estimate of the theorem adds $O(T^{-1/8})$ at infinity when $m > 0$, which makes the thermal zero mode integrable. This proves the limits including local uniformity in λ. At fixed physical temperature the same monotone mesh comparison as in Theorem 9 applies. For $d \ge 2$ the appropriately normalized zero mode is uniformly bounded by the transparent Matsubara sum at $\lambda = 1$. For $d = 1$ it is at most $O(\log(1/g))$, again sufficient against the $O(g)$ step.

If both strengths diverge, the leading trace term becomes $\mathrm{Tr}(R_{-,g}B_gR_{+,g}B_g^*)/(c_{-,g}c_{+,g})$, with $R_{i,g} = c_{i,g}(A_{i,g} + c_{i,g})^{-1}$. The strong kernel localization and two boundary-cutoff estimates in Sections 5–9 apply to each factor with its own $c_{i,g}$, both tending to infinity. The higher traces have an extra operator norm factor $O((c_{-,g}c_{+,g})^{-1})$ by the separated kernel Schur bound. Thus the same limits and temperature estimates follow with the product normalization. □

13 The marginal interval regime

Suppose $d = 1$ and both scaled strengths vanish. Write $Z_g = q_g(0)$ and put $r_g = \max_i \rho_{i,g}$, $\epsilon_g = gr_g$. As in Sections 1–4 and Sections 5–9, define

$$\begin{aligned} C_* &= \lim_{L\to\infty}\left[\int_0^{L^2} J(T)\frac{dT}{T} - \tfrac{1}{4}\log L + \log\log L\right], \\ C_{\ell_-,\ell_+} &= \log\pi - \tfrac{1}{4}\log(\ell_-^{-1} + \ell_+^{-1}), \\ N_\lambda &= 2\sum_{n\ge 1}\int_0^\infty e^{-(2\pi n/\lambda)^2 T} J(T)\frac{dT}{T}. \end{aligned}$$

The time limit in C_* exists by the retained-segment inverse-logarithmic law Sections 1–4. The finite geometric constant is the heat-normalized elliptic result of Sections 5–9.

Theorem 11. *If the physical pair $(\rho_{-,g}, \rho_{+,g})$ tends to a finite (ρ_-, ρ_+), then*

$$Z_g = \tfrac{1}{4}\log(1/g) - \log\log(1/g) + C_{\ell_-,\ell_+} + \int_0^\infty [\mathcal{I}_{0;\rho_-,\rho_+}(t) - \mathcal{I}_{0;0,0}(t)]\frac{dt}{t} + o(1).$$

At gap zero the intervals retain their two labels. If $r_g \to \infty$ while $\epsilon_g \to 0$, set $\theta_{i,g} = \rho_{i,g}/r_g$. Then

$$Z_g = \tfrac{1}{4}\log(1/\epsilon_g) - \log\log(1/\epsilon_g) + C_* + C_R(\theta_g) + o(1),$$

where

$$C_R(\theta) = \int_0^1 [J_0^{\theta_-,\theta_+}(s) - 1/8]\frac{ds}{s} + \int_1^\infty J_0^{\theta_-,\theta_+}(s)\frac{ds}{s}.$$

This is uniform in the contact ratios θ_g on $\max_i \theta_i = 1$, including an exactly transparent side. In both cases the free energy at gap-scale temperature is $-(Z_g + N_\lambda + o(1))/(2\lambda g)$, locally uniformly in $\lambda > 0$.

Proof. For a finite limiting physical pair, take the difference from the transparent finite-interval heat integral. It converges at fixed physical time by polarity of the limiting endpoints and by local-time label convergence. The small-time difference is $O(\sqrt{t})$ by Theorem 10; the large-time bound is the fixed enclosing window's $O(t^{-1})$ heat gain [1, 2]. Dominated convergence and the transparent expansion prove the first formula.

When $r_g \to \infty$, replace the finite apertures by their infinite rays of gap g. At small physical times the truncation changes the heat gain by at most $Ce^{-c/t}$, because a removed all-hit bridge must cross past an outer endpoint and have lateral range at least the shorter interval length. Independent of this bound, its difference is bounded by $C(1+r_g\sqrt{t})^{-1/4}$ by Theorem 10. Dominated convergence below time one and direct integration above one show the integrated truncation error is $o(1)$.

In gap units split the ray integral at $T = \epsilon_g^{-2}$, and use $s = \epsilon_g^2 T$ in the difference from its transparent sharp-cutoff part. The resulting static integral is

$$\int_0^{\epsilon_g^{-2}} J(T)\frac{dT}{T} + \int_0^1 [J_{\epsilon_g}^{\theta_{-,g},\theta_{+,g}}(s) - J_{\epsilon_g}(s)]\frac{ds}{s} + \int_1^\infty J_{\epsilon_g}^{\theta_{-,g},\theta_{+,g}}(s)\frac{ds}{s}.$$

The transparent cutoff term equals the stated logarithms plus $C_* + o(1)$. The two matching terms converge to those defining $C_R(\theta_g)$, uniformly in θ_g. At each fixed s the origin is polar, so the all-hit indicators and aperture labels agree eventually with their zero-gap limits on each eligible path, independently of the contact strengths. The weights are bounded by one, and the all-hit probability has an integrable spatial majorant. The time majorants are $O(\sqrt{s})$ for the difference at zero and $O(s^{-1/8})$ at infinity, uniformly by Theorem 10. This also shows continuity of C_R.

For every fixed scaled time the weights tend to one because both $c_{i,g} \to 0$, and the scaled finite intervals exhaust their rays. Thus the nonzero Matsubara sum converges to N_λ, by the small-time Gaussian crossing bound and exponential large-time suppression from the nonzero Matsubara frequencies. The domination is uniform on compact positive λ-intervals. □

14 Variable and degenerate contact: problem and normalization

We use the connected scalar heat trace and boundary determinant of [1], Sections 5–9 and Sections 10–13. The apertures approach across a gap g; $u, v \geq 0$ denote inward aperture depths in units of g, and $\kappa \geq 0$ is the gap-scaled mass. The normalized transform $q_g(\kappa)$ is the minus-log determinant of I minus the positive cross product obtained by inserting the two diagonal form inverses. The diagonal operator before a contact is the supported compression of $2\sqrt{|D|^2+\kappa^2}$. A contact is a nonnegative multiplication term in the form, and the gap-scaled contact is g times the physical coefficient. The connected vacuum energy is $-(2\pi g)^{-1}\int_0^\infty q_g(\kappa)\,d\kappa$. At inverse temperature β the free energy is $-(2\beta)^{-1}\sum_{j\in\mathbb{Z}} q_g(2\pi|j|g/\beta)$.

In the curved and separable finite-type setting, write the facing depths before translation as $a_-(y)$ and $a_+(y)$. In smooth quadratic contact let $B_\pm$ be their Hessians at the tangency, with $B_- + B_+$ positive definite, and put $\alpha = (d-1)/2$ and $H(w) = 1 + w^{\mathsf{T}}(B_- + B_+)w/2$. For separable finite type the leading profiles are $\sum_j b_{\pm,j}|y_j|^{p_j}$, $p_j > 1$, $b_{-,j}+b_{+,j} > 0$; put $\alpha = \sum_j p_j^{-1}$ and $H(w) = 1 + \sum_j (b_{-,j}+b_{+,j})|w_j|^{p_j}$. In the quadratic case take $p_j = 2$ for the depth estimate. The geometry and full hypotheses are those in Sections 5–9 and Sections 10–13. In dimension $d = 1$ take two intervals, $\alpha = 0, H = 1$.

Inhomogeneous repulsive boundary strengths and their determinant representation are used in [14, 27] for thin mirrors. The interface here is a Dirichlet screen with two apertures and the

connected subtraction is essential. The constant-contact near-tangency results in Sections 5–9 and Sections 10–13 supply the geometric estimates and the transparent separated column. The new limits address varying depths, zeros that make the reciprocal nonintegrable, and two strong profiles with independent rates. The finer zero-layer laws below apply to flat geometries and to physical intervals.

15 Depth-dependent contact on moving apertures

Use the geometry in Sections 10–13 and Sections 5–9, $\gamma_* = d-1-\alpha$, height $H(w)$, and positive transform q_g. In the facing charts let $y_j = g^{1/p_j} w_j$ and write inward depths as gu on the left and gv on the right. In dimension one omit w, and use $H = 1$, $\gamma_* = 0$. Take bounded continuous nonnegative profiles $a(w,u)$, $b(w,v)$ on $\mathbb{R}^{d-1} \times [0,\infty)$. Give the left aperture scaled strength $M_g[a(w,u)+\epsilon_g]$ in its chart and M_g outside, with

$$M_g \to \infty, \qquad \epsilon_g \downarrow 0, \qquad M_g \epsilon_g \to \infty.$$

On the right prescribe the scaled strength $b(w,v)$ in the chart and any uniformly bounded nonnegative measurable strength outside it. These are scaled strengths, so the physical coefficients are divided by g. We use one fixed facing chart per side, and only its local representation enters the limit.

For $q \ge 0, \ell > 0$, let

$$f_{q,\ell}(v) = -2qK_1(q(\ell+v))/[\pi(\ell+v)]$$

with $f_{0,\ell}(v) = -2/[\pi(\ell+v)^2]$. Let A_q be the zero-exterior right-ray compression of $2\sqrt{|D|^2+q^2}$. Set

$$C_b(\kappa,w,u) = (2\pi)^{-(d-1)} \int_{\mathbb{R}^{d-1}} \langle f_{q,\ell}, (A_q + b(w,\cdot))^{-1} f_{q,\ell} \rangle \, dk.$$

Here $q = \sqrt{\kappa^2+|k|^2}$ and $\ell = H(w)+u$. The zero-energy inverse denotes the form-dual variational expression.

Theorem 12. *The transform limit below holds under* (9)*, and at any fixed $\kappa \ge 0$ where its right side is infinite:*

$$g^{\gamma_*} M_g q_g(\kappa) \longrightarrow \Phi_{a,b}(\kappa) := \int_{\mathbb{R}^{d-1}} \int_0^\infty \frac{C_b(\kappa,w,u)}{a(w,u)} \, du \, dw.$$

A sufficient hypothesis for uniform convergence on compact κ-intervals, an exponential upper bound, and vacuum and thermal limits is

$$\int \frac{(1+u+\sum_j |w_j|^{p_j})^{-(d+1)}}{a(w,u)} \, du \, dw < \infty. \tag{9}$$

Under (9)*, multiply the energy and free energy by $g^{d-\alpha} M_g$. The vacuum limit and the free-energy limit at $\beta = \lambda g$ are respectively*

$$-\frac{1}{2\pi} \int_0^\infty \Phi_{a,b}(\kappa) \, d\kappa, \qquad -\frac{1}{2\lambda} \sum_{n \in \mathbb{Z}} \Phi_{a,b}(2\pi|n|/\lambda).$$

The latter convergence is locally uniform in $\lambda > 0$. At fixed positive physical β, the normalized free energy has the vacuum limit. The case $b \equiv 0$ is included.

15.1 Weak inverse and separated columns

At each fixed left point in the scaled local chart, translate tangentially to its tangency coordinate. The right domain converges locally to the half-space at distance $H(w) + u$. Every fixed local tangential offset changes w_j by $O(g^{1-1/p_j})$, while the scaled facing graph becomes flat on bounded sets. Thus the right potential converges locally uniformly in the limiting interior to $b(w, v)$. At $d \geq 2$ use the homogeneous Sobolev dual bound $C\|f_{g,Y}\|^2_{2d/(d+1)}$ for each separated column and its spatial derivatives. Compactly supported tests give the variational lower limit. Near-maximizers have bounded homogeneous energy by this dual bound. Their zero extensions are bounded in local $H^{1/2}$ after smooth cutoff, using Sobolev for local L^2 bounds and the difference-quotient multiplier estimate in Sections 10–13. Rellich compactness gives strong L^2_{loc} and weak energy convergence along a subsequence. The weak limit vanishes off the limiting right half-space. On compact subsets of that half-space the potential integrals converge by the local L^2 convergence and boundedness. Exhausting the interior and dropping the nonnegative potential cost elsewhere proves lower semicontinuity of the potential term, including profiles with zeros and no positive gap. For $\kappa > 0$, there is in addition a global L^2 bound from the mass. The pairing passes by the strong $L^{2d/(d+1)}$ column convergence. The limit energy-plus-potential domain has compactly supported test density: first cut off at infinity using the homogeneous multiplier argument and dominated convergence in the potential norm, then translate inward and smooth on bounded sets where the potential is bounded.

For $d = 1$, the translated weak domains are intervals $(0, \ell_+/g)$, and the massless energy completion of the supported ray has norm $2\|L_0 v\|_2^2$ where $L_0 = \partial_x^{1/2}$. Its inverse on the completion is the causal half-integral

$$(I_0 h)(x) = \int_0^x \frac{h(y)}{\sqrt{\pi(x-y)}}\, dy.$$

Here is one justification of surjectivity in the completion. For smooth h compactly supported in the open ray, put $I_m h = \mathbf{1}_{x>0} e^{-mx}/\sqrt{\pi x} * h$ after zero extension. These are supported form functions for $m > 0$. Their Fourier transforms are $(m + i\xi)^{-1/2}\widehat{h}(\xi)$, so they converge in homogeneous energy to $I_0 h$ by dominated convergence against $|\xi|\, d\xi$. Hardy control on the ray identifies this limit in local L^2. Inversion by L_0 follows by the Fourier multiplier identity and hence extends by density of such h in L^2. The restriction of I_0 to any bounded interval is compact on L^2: the part of its kernel with $x - y < \delta$ has L^1 convolution norm $O(\sqrt{\delta})$, and the remainder is Hilbert–Schmidt there. Thus the same local compactness, potential lower semicontinuity, and weak form argument apply even at $\kappa = 0$. For density with a bounded potential, the support condition gives the elementary Hardy bound $\int_0^\infty |v(x)|^2 dx/x \leq C\mathfrak{a}_0[v]$ by retaining interactions with the negative ray in the homogeneous difference-quotient form. Smooth cutoffs $\chi(x/R)$ on the line act uniformly in energy since their difference-quotient multiplier $h_R(x)$ satisfies $h_R(x) \leq C/x$ for $x > 0$. This follows by scaling from boundedness near zero and $O(x^{-2})$ decay at infinity. Density in the completed energy then gives energy cutoff convergence, while the potential norm converges by domination. The compactly supported restriction can be translated inward and mollified, as in higher dimension. For $\kappa > 0$, the same cutoff convergence includes the L^2 norm. The full-ray column pairing is bounded by the causal adjoint $I_0^* f$ in L^2. Restricted and moving columns converge in this dual norm by dominated convergence, applied first pointwise to I_0^* and then in L^2 using the massless column at separation bounded below. This also applies to their depth derivatives, dominated by a constant times the massless column at separations at least one.

Consequently the diagonal column forms of

$$C_g = B_g(A_{+,g} + c_{+,g})^{-1}B_g^*$$

have pointwise limit C_b. Fiber decomposition follows by tangential Plancherel since the frozen potential only depends on depth. At mass zero it follows by monotone removal of a positive diagonal mass using the variational expression. In every dimension, these columns obey

$$C_g(Y,Y) \le Ce^{-c\kappa}(1 + u + \sum_j |w_j|^{p_j})^{-(d+1)}$$

in the left chart by the column estimates in Sections 10–13, and the off-chart contribution after g^{γ_*} normalization is $O(ge^{-c\kappa})$. In dimension one use the pointwise I_0^* factorization, which gives a column-square bound $C(H+u)^{-2}$. For fixed κ, the same normalized integrated bound holds for the squared norms of the spatial derivatives of the weak-inverted cross columns. The operator bound $\|C_g\| \le C$ at all $\kappa \ge 0$ is the transparent supporting-half-space comparison in Sections 10–13, which uses only nonnegativity of $c_{+,g}$.

15.2 The weighted strong inverse

Let $a_g = a + \epsilon_g$ in the left chart and $a_g = 1$ off it. Then $R_g = M_g(A_{-,g} + M_g a_g)^{-1} = (M_g^{-1}A_{-,g} + a_g)^{-1}$, and $R_g \le a_g^{-1}$ in form order. For $F = (A_{+,g} + c_{+,g})^{-1/2}B_g^*$, the difference between $\mathrm{Tr}(a_g^{-1}C_g)$ and $\mathrm{Tr}(R_gC_g)$ is nonnegative. The variational formula bounds it above, for any admissible Hilbert–Schmidt trial kernel V on the left, by

$$\|a_g^{1/2}(V - a_g^{-1}F^*)\|_2^2 + M_g^{-1}\|A_{-,g}^{1/2}V\|_2^2. \tag{10}$$

Choose $V = m(w,u)F^*$, where a real smooth multiplier m compactly supported in $u > 0, a > 0$ approximates $1/a$ on an inner compact set. This suffices to make the limsup of the first term after normalization by g^{γ_*} arbitrarily small. Indeed use an exhaustion of $u > 0, a > 0$, a smooth cutoff $0 \le \eta \le 1$ equal to one on the selected compact set, and uniform approximation of $1/a$ on the cutoff support. The lost part is dominated by the integrable weighted column bound from (9). The off-chart contribution is negligible. The normalization of the energy term in (10) is bounded for each chosen multiplier, since the scaled Lipschitz constants of the slow coordinates and inward depth are uniformly bounded, and the multiplier vanishes at the actual left edge. The derivative-column estimate controls the zero-extended H^1 norm of V. This proves that the weighted multiplication upper bound is asymptotically attained. Dominated convergence evaluates the weighted trace.

The relative determinant and all-hit identity hold for these bounded multiplication contacts at each fixed g. In the Galerkin/Poisson proof of [1] and Sections 10–13 the contact is independent of the resolvent variable, and it adds a nonnegative trace-form term to the energy. All differentiated Poisson factors are unchanged, and strong Galerkin inverse convergence uses the same form density. The corresponding bridge weight is the exponential of the integral of the bounded coefficient against normal occupation local time. Thus it preserves positivity, monotonicity in κ, and comparison under increasing a coefficient. The positive normalized cross product has operator norm $O((M_g\epsilon_g)^{-1})$ and trace $M_g^{-1}\,\mathrm{Tr}(R_gC_g)$. Its higher trace terms are negligible relative to the first by the determinant power series. This proves the limit under (9), including exponential domination. Limiting spectral continuity follows from variational convergence as the mass varies: on $\kappa > 0$ use the mass gap and strong dual convergence of cross columns. At zero use compact tests for the lower bound, and for the upper bound drop the nonnegative mass

increment and use dual convergence in the massless space, with the common column majorant. Tangential and depth integrations preserve continuity by (9). The monotone mesh and sum bounds of Sections 10–13 now give the stated energy limits.

For a divergent pointwise profile without (9), the determinant first term and $R_g \le a_g^{-1}$ yield domination if the weighted column envelope is integrable, but this sufficient criterion need not be necessary at positive κ or for large weak profiles. The divergence can be shown by comparison with a raised profile. Since b is globally bounded, the transparent column form and the bounded-contact column form have comparable local positive lower bounds on every compact (w,u)-set. Thus if $\int C_b/a = \infty$, regardless of where divergence occurs, increase the left profile to $a+\delta$ in the chart. The proved limit gives $\liminf g^{\gamma_*} M_g q_g(\kappa) \ge \int C_b/(a+\delta)$, and monotone convergence sends this to infinity. When (9) fails but $\int C_b/a < \infty$, no limit is claimed here because upper tightness of the finite-gap weighted columns has not been established. In particular the extended pointwise assertion above applies under (9) and in the divergent case, with this intermediate case unasserted.

For example if $a(w,u) \asymp u^\nu$ for u near zero and is bounded below away from the edge, then $\nu < 1$ gives (9), and $\nu \ge 1$ gives divergence for every κ by a single compact tangential patch. Likewise a zero set of codimension m with local strength comparable to distance to the power ν has threshold $\nu = m$ wherever the corresponding tubular volume is comparable to r^m. When $b \equiv 0$, the massless unweighted column obtained from the causal factorization in Sections 10–13 is exactly a positive constant times $(H(w)+u)^{-(d+1)}$. Thus (9) gives the precise threshold for a finite normalized static limit in that case. These conclusions concern the M_g normalization. Section 16 gives the finer laws in the flat and interval settings.

15.3 Strong profiles with a zero floor

All the preceding claims under (9) still hold with $\epsilon_g = 0$ if $M_g g^{\gamma_*} \to \infty$, or if the strong profile has the uniform lower bound

$$a(w,u) \ \ge c \min(1, u^\nu), \qquad 0 \le \nu < 1. \tag{11}$$

In the first case the normalized cross product has norm at most its trace, bounded by $C M_g^{-1} g^{-\gamma_*}$ from (9) and the weighted form inequality. This includes arbitrary integrable reciprocal profiles in $d = 1$, with no extra condition on M_g. A vanishing floor does not affect any other part of the variational trace proof, since $a > 0$ almost everywhere under (9) and weighted multiplication is interpreted through its quadratic form. For each finite g the bounded-domain compressed square-root response has a strictly positive lower bound even where contact vanishes.

For (11), weighted Schur gives a uniform operator bound on $a_g^{-1/2} C_g a_g^{-1/2}$, which handles every $M_g \to \infty$. First, the kernel of C_g is nonnegative and is bounded pointwise by the facing-half-space transparent sandwich C_κ^{H}. Indeed the cross columns have one sign and the compressed square-root inverses preserve positivity. The enlarged-domain inverse comparison on nonnegative forcing follows by subtracting the form equations on the smaller domain and testing with the positive part of the difference. This is an admissible supported test since the larger-domain solution is nonnegative and the difference's positive part vanishes off the smaller domain. The square-root form has the jump difference representation from subordination plus a nonnegative mass term, so this test gives the order as in the standard disjoint-sign argument. The same comparison drops a nonnegative contact. Form-dual limits at mass zero follow by positive mass regularization. The kernel $C_\kappa^{\mathrm{H}}(x,x',t)$ uses flat depths $x, x' \ge 0$ and tangential difference t. It decreases in each depth, since each positive cross column does by radial subordination and the inverse preserves order.

The integral in t is the zero-tangential-momentum planar sandwich $C_\kappa^{(1)}(x,x')$. To justify integrability before taking Fourier value zero, first integrate the nonnegative kernel against $e^{-|t|^2/R^2}$. On the Fourier side this is a positive approximate identity acting on the continuous planar fibers. Continuity and boundedness follow from their explicit causal columns, and monotone convergence in R now proves the asserted integral. The factorization in Sections 10–13 gives

$$0 \le C_\kappa^{(1)}(x,x') \le C_0^{(1)}(0,x') = \frac{1}{2\pi}\int_0^\infty (1+z)^{-3/2}(1+x'+z)^{-3/2}\,dz.$$

Its integral against $1+\mathbf{1}_{x'<1}(x')^{-\nu}$ is bounded for $\nu<1$: near zero the kernel is bounded, and for the unweighted tail one can integrate in x' first. Inside the left aperture chart, the flat depth x' is at least the actual inward depth u', so monotonicity allows replacing x' by u' in the kernel. The shear between the flat and actual depth coordinates has Jacobian one. Outside the chart the multiplier is one and the entire flat half-space bound suffices. We conclude

$$\sup_Y \int C_g(Y,Y')a_g(Y')^{-1}\,dY' \le C.$$

The weighted Schur test with positive testing function $a_g^{-1/2}$ proves the desired operator norm bound, by approximation if the multiplier is unbounded. Equivalently it bounds $C_g^{1/2}a_g^{-1}C_g^{1/2}$. The form inequality therefore bounds the normalized cross product's norm by C/M_g. Its logarithmic higher powers are negligible as before.

Finally the divergence conclusion when $\int C_b/a = \infty$ also needs no floor. Increasing the coefficient by a fixed δ in the chart gives the already proved lower estimate for the original gain by positivity of the bridge comparison. In particular the edge threshold $\nu = 1$ for the M_g normalization holds at actual zero edge strength with no regularization and arbitrary $M_g \to \infty$.

16 A power-law zero of the strong contact

Use depth $x \ge 0$ on a half-line or on $(0, L_M)$, $L_M \to \infty$, with zero extension in the kinetic form. Let a be a continuous nonnegative profile with one zero $x_0 \ge 0$. Assume $a(x)$ is bounded below by a positive constant outside each neighborhood of x_0, and

$$a(x) = c|x-x_0|^p(1+o(1)), \qquad c>0, \quad p>0.$$

Limits at $x_0 = 0$ are from the right. Set $M \to \infty$, floor $\varepsilon_M \to 0$, $\varepsilon_M \ge 0$, and take the compressed form

$$H_M = 2\sqrt{D^2+\kappa_M^2} + M(a+\varepsilon_M)$$

with $\kappa_M \to \kappa \ge 0$. If f is an L^2 source continuous near x_0, put $Q_M(f) = \langle f, H_M^{-1} f\rangle$. The proof also works for Hilbert-valued sources. In the logarithmic and power regimes it covers varying sources uniformly bounded in L^2 and locally uniformly continuous near x_0, with a limit of their squared norms at x_0. In the integrable regime the varying-source version additionally uses pointwise norm convergence, uniform L^2 tails, and uniform local H^1 bounds away from the zero, all available for the columns below.

Theorem 13. *Let $s_0 = 2$ for an interior zero and $s_0 = 1$ for a boundary zero, and let $D_0 = \mathbb{R}$ in the interior and $D_0 = \mathbb{R}_+$ at the boundary. All operators on $\mathbb{R}_+$ below use zero extension in the full-line Fourier form.*

- *If $0 < p < 1$, $MQ_M(f) \to \int_0^\infty \|f(x)\|^2/a(x)\,dx$.*
- *If $p = 1$, put $\rho_M = \max(M^{-1/2}, \varepsilon_M)$. Then*

$$\frac{M}{\log(1/\rho_M)} Q_M(f) \longrightarrow \frac{s_0}{c}\|f(x_0)\|^2.$$

For zero floor this is $Q_M = (s_0/(2c))M^{-1}\log M\,\|f(x_0)\|^2 + o(M^{-1}\log M)$.

- *If $p > 1$, put $\ell = M^{-1/(p+1)}$, $\lambda_M = M\ell\,\varepsilon_M$. If $\lambda_M \to \lambda < \infty$, then*

$$\ell^{-2} Q_M(f) \longrightarrow \|f(x_0)\|^2\, \mathcal{C}_{p,c}^{D_0}(\lambda),$$

where

$$\mathcal{C}_{p,c}^{D_0}(\lambda) = \sup_v \left(2\,\mathrm{Re}\int_{D_0} v - \langle v, (2|D| + c|y|^p + \lambda)v\rangle \right),$$

with the supremum over smooth compactly supported tests in D_0, equivalently its weighted form completion. The constant is finite and positive. If $\lambda_M \to \infty$, then

$$M\varepsilon_M^{1-1/p} Q_M(f) \longrightarrow \|f(x_0)\|^2 \int_{D_0} \frac{dy}{1 + c|y|^p} = \|f(x_0)\|^2\, \frac{s_0 \pi}{p c^{1/p} \sin(\pi/p)}.$$

The assertions concern normalized limits, including $f(x_0) = 0$. As $\lambda \to \infty$ the critical profile satisfies $\lambda^{1-1/p}\mathcal{C}_{p,c}^{D_0}(\lambda) \to \int_{D_0}(1 + c|y|^p)^{-1} dy$, matching the last regime.

16.1 Proof of the three regimes

The quadratic inverse is the form supremum

$$Q_M(f) = \sup_v (2\,\mathrm{Re}\langle f, v\rangle - \langle v, H_M v\rangle).$$

It is bounded by the quadratic inverse of the positive multiplication part wherever the latter is finite. Also uniformly in $\kappa_M \geq 0$,

$$H_M \succeq c_1\, \ell^{-1} I, \qquad \ell = M^{-1/(p+1)}.$$

Indeed set $x = x_0 + \ell y$. The scaled potential $\ell M a(x_0 + \ell y)$ is bounded below by $c_2 \min(|y|^p, 1)$ on the scaled domain for large M, by the assumed local behavior and the positive lower bound away from the zero. The operator $2|D| + c_2 \min(|y|^p, 1)$ has a positive L^2 lower bound: split into frequencies $|\xi| \leq r$ and $|\xi| > r$. The former part has mass in $[-1, 1]$ at most $Cr\|v\|_2^2$ by Fourier Cauchy–Schwarz, and the latter has total squared norm bounded by $\langle v, |D|v\rangle / r$. Choose r fixed small. The potential bounds mass outside $[-1, 1]$, so absorb the low-frequency term. Zero extension gives the same inequality on the half-line or on expanding bounded intervals. The floor additionally gives $H_M \succeq M\varepsilon_M I$.

For $p < 1$, the multiplication inverse upper bound is integrable by local continuity of f and the bound on a away from zero. For the lower bound use the form of $M^{-1}H_M$ against fixed compact smooth tests and let $M \to \infty$. The limiting multiplication variational supremum is the integral, by cutoffs avoiding the zero and density on the truncated sets. Varying Hilbert-valued sources for the trace application below can also be treated without assuming strong global convergence: truncate away from the zero and the far edge, use smooth scalar cutoffs times the sources divided

by a approximated by a continuous bounded function, and use uniform H^1 bounds of the sources on compact intervals. This permits convergence to the pointwise norm integral.

For $p = 1$, split f at $|x - x_0| = \rho_M$. The inner inverse quadratic form is $O(M^{-1})$, using $\|f\|^2_{\text{inner}} = O(\rho_M)$ and $\|H_M^{-1}\| \le CM^{-1/2}$ when $\rho_M = M^{-1/2}$, or $\|H_M^{-1}\| \le (M\varepsilon_M)^{-1}$ otherwise. The outer inverse is bounded by $M^{-1}\int_{\text{outer}} \|f\|^2/(a + \varepsilon_M)$. Its leading logarithm is at most $(s_0/c)M^{-1}\log(1/\rho_M)\|f(x_0)\|^2$, with the coefficient verified by integrating $1/r$ on each side between ρ_M and fixed small depth and then shrinking the upper depth. The inner-outer cross term is of smaller order by Cauchy–Schwarz for the positive inverse. For a lower test, choose

$$v(x) = \frac{f(x_0)}{Mc|x - x_0|}$$

with smooth cutoffs to depths between ρ_M and a small fixed upper depth. Its potential and linear terms produce the same logarithm, up to an arbitrarily small relative error by continuity of f and the asymptotic of a. The additional floor energy is $O(\varepsilon_M/(M\rho_M)) = O(M^{-1})$. The compressed kinetic cost satisfies $\langle v, |D|v\rangle \le \|v\|_2\|v'\|_2 = O(M^{-2}\rho_M^{-2}) = O(M^{-1})$, and the fixed bounded mass adds at most $2\kappa_M\|v\|^2 = o(M^{-1})$. This proves the logarithmic coefficient including its one-sided boundary factor.

For $p > 1$ and finite λ, the inverse quadratic form divided by ℓ^2 is that of the rescaled operator

$$2\sqrt{D_y^2 + (\ell\kappa_M)^2} + \ell M a(x_0 + \ell y) + \lambda_M$$

on the source $f(x_0 + \ell y)$, by unitary dilation. On every bounded scaled interval the potential converges uniformly to $c|y|^p + \lambda$. The form inverses converge on compactly supported scalar sources: for the lower limit use compact smooth tests, which eventually belong to the scaled domains. For the upper limit their maximizing vectors have bounded energy and L^2 norm by uniform coercivity, hence weak $H^{1/2}$ and strong local L^2 subsequences. The supported limit belongs to the full-line or half-line form space, and restricting potentials to compact sets then growing the sets gives the lower semicontinuity of the limiting energy. The mass change is bounded in form by $2\ell\kappa_M\|v\|^2$. Smooth compact tests are dense in the limit form: cut off at infinity with a smooth scaled cutoff in $H^{1/2}$ and weighted L^2; for a supported ray translate the cut-off function slightly inward and mollify without crossing the boundary. Translation and approximation are valid in full-line $H^{1/2}$, and on the compact support the potential is bounded. This proves equality of the variational limits.

For the rescaled inverse quadratic form, the part of the source outside $|y| \le R$ has squared dual norm at most $CR^{1-p} + C\ell^{p-1}\|f\|_2^2$, by the multiplication bound. In the local region use $\ell M a(x_0 + \ell y) \ge c_3|y|^p$, and on the remaining region use the lower bound $c_4\ell^{-p}$. Cross terms tend uniformly to zero as $R \to \infty$. On each fixed scaled compact set the source differs in L^2 by $o(1)$ from the constant vector $f(x_0)$, so vector-valued sources reduce there to the scalar variational comparison. The same tail estimate proves that the constant source is in the dual form space of the limit, and the constant is strictly positive by a nonzero nonnegative test. For the large-λ limit of the limiting constant, rescale $y = \lambda^{1/p}z$; the kinetic coefficient relative to λ becomes $\lambda^{-1-1/p}$, giving the multiplication limit by the same upper bound and compact tests.

When $\lambda_M \to \infty$, rescale instead $x = x_0 + \varepsilon_M^{1/p}y$ and divide the kinetic plus potential by $M\varepsilon_M$. The kinetic coefficient $1/(M\varepsilon_M^{1+1/p}) = \lambda_M^{-(p+1)/p}$ tends to zero, and the mass coefficient $\kappa_M/(M\varepsilon_M)$ tends to zero. The potential tends to $1 + c|y|^p$ uniformly on compacts, and the exact multiplication upper bound and compact smooth lower tests give its inverse integral. The omitted portion outside scaled radius R is again bounded in squared dual norm by $CR^{1-p} + C\varepsilon_M^{1-1/p}\|f\|^2$, using the fixed positive bound away from x_0. This proves the floor-dominated formula.

16.2 The connected trace and energy

Between two inward rays at separation $h > 0$, let $B_{\kappa,h}(x,y) = f_{\kappa,h+x}(y)$ be the separated column kernel defined in Section 15. The diagonal response A_κ is the supported compression of $2\sqrt{D^2+\kappa^2}$. For weak constant $b \geq 0$ let

$$F_{\kappa,h,b}(x) = (A_\kappa + b)^{-1/2} B^*_{\kappa,h}\delta_x, \qquad w_{\kappa,h,b}(x) = \|F_{\kappa,h,b}(x)\|^2.$$

Use the form-dual interpretation at $\kappa = b = 0$. Then the first connected determinant trace with strong profile $M(a+\varepsilon_M)$ is $Q_M(F)$, acting on the left depth with a Hilbert-valued source. The transparent half-line factorization in Sections 10–13 gives

$$w_{\kappa,h,b}(x) \leq w_{\kappa,h,0}(x) = \frac{1}{2\pi}\int_{h+x}^{\infty} e^{-2\kappa r} r^{-3}\, dr.$$

It also bounds the source derivative norm in x by differentiating the explicit backward-convolved separated kernel, and hence gives uniform local equicontinuity and global L^2 bounds with exponential mass decay for fixed h. The same statements hold for finite right interval compressions, by the variational upper bound on each column and every difference or derivative column. The compressed column norms converge pointwise when the right interval expands and its constant contact tends to b, by the variational comparison in Sections 10–13. This remains true along $\kappa_M \to \kappa$: for a positive limiting mass or contact use fixed test convergence and lower comparison with the nearby positive mass or contact; at zero mass and contact use the transparent massless upper bound and fixed compact tests for the lower bound. Cross columns converge in the transparent dual norm by the same factorization or dominated backward convolution. For the $p < 1$ lower bound with a varying source, the column derivative estimates make compact cutoff tests $v = \chi(x)F_M(x)/a_{\mathrm{appr}}(x)$ uniformly bounded in H^1, where a_{appr} is a smooth positive approximation to a on the support away from its zero. This validates the source condition used above.

The normalized connected cross product has norm at most $C\ell$ times the bound on the weak-side sandwich, by the strong spectral gap, uniformly for finite left/right intervals. Its higher trace terms are at most $O(\ell)$ times its first trace, so all source limits apply to the full minus-log determinant. The three normalized strong-side profiles are therefore respectively a weighted integral of w, a logarithmic coefficient times $w(x_0)$, and a fractional-oscillator coefficient times $w(x_0)$, with the additional floor crossover as above. Exponential mass domination follows from the column bound and the upper estimates in the source proof, with uniform constants.

For fixed gap-scaled separation h, the flat density per unit tangent area in a screen of dimension d follows by tangential Fourier integration of these formulas with mass $\sqrt{\kappa^2+|k|^2}$, as in Sections 10–13. For transparent weak contact the static point coefficient is

$$w_{d,0}(0,h;x_0) = \frac{\Gamma(d/2)}{2^d \pi^{(d+2)/2}(d+1)}(h+x_0)^{-d-1},$$

and its integral against $d\kappa/(2\pi)$ is

$$\frac{\Gamma((d+1)/2)}{2^{d+2}\pi^{(d+3)/2}(d+2)}(h+x_0)^{-d-2}.$$

These are minus the separation derivatives of the static and vacuum transparent constants, since its full trace integrates the depth density from zero to infinity.

In the physical $d = 1$ interval model at gap g, use $h = 1$ and prescribe the strong gap-scaled contact $M_g(a(x)+\varepsilon_g)$ in inward depth x measured in units of g, with $M_g \to \infty$. The

opposing contact converges to finite b. Let S_g be the normalizing factor from the corresponding source regime (M_g, $M_g/\log(1/\rho_g)$, ℓ_g^{-2}, or $M_g\varepsilon_g^{1-1/p}$). Then $S_g q_g(\kappa) \to P(\kappa)$ from the preceding trace formulas, along compact κ-converging sequences and with a common exponential tail. The vacuum limit is $gS_gE_g \to -(2\pi)^{-1}\int_0^\infty P(\kappa)\,d\kappa$. At inverse temperature $\beta = \lambda g$, the same normalization gives $-(2\lambda)^{-1}\sum_{m\in\mathbb{Z}} P(2\pi|m|/\lambda)$. At fixed positive β, monotone mesh comparison for the positive transformation of the all-hit heat formula gives the same vacuum equivalent: the mesh is $2\pi g/\beta$ and its error is bounded by the mesh times the uniformly bounded normalized value at $\kappa = 0$. The nonnegative variable contact enters the all-hit formula through the exponential of its local-time integral. Curved higher-dimensional apertures with a shrinking strong-side zero layer require a separate simultaneous geometry limit; the flat-tangent density above does not claim that extension.

16.3 The Airy coefficient for a quadratic interior zero

For $p = 2$ and an interior zero, the full-line constant $\mathcal{C}^{\mathbb{R}}_{2,c}(\lambda)$ admits an exact Airy expression. The form solution v to

$$(2|D| + cx^2 + \lambda)v = 1$$

is L^1 by its L^2 and $xv \in L^2$ bounds. With Fourier convention $\hat{v}(\xi) = \int e^{-ix\xi}v(x)\,dx$ it satisfies

$$-c\hat{v}'' + (2|\xi| + \lambda)\hat{v} = 2\pi\delta_0.$$

For $\xi > 0$ the decaying solution is a multiple of $\mathrm{Ai}(a\xi + b)$, $a = (2/c)^{1/3}$, $b = \lambda/(ca^2)$. The solution is even by uniqueness of the form solution. The derivative jump $-2c\hat{v}'(0+) = 2\pi$ gives

$$\mathcal{C}^{\mathbb{R}}_{2,c}(\lambda) = \hat{v}(0) = -\frac{\pi}{2^{1/3}c^{2/3}}\,\frac{\mathrm{Ai}(\lambda/(2^{2/3}c^{1/3}))}{\mathrm{Ai}'(\lambda/(2^{2/3}c^{1/3}))}.$$

This directly gives

$$\mathcal{C}^{\mathbb{R}}_{2,c}(0) = \frac{\pi\,\Gamma(1/3)}{6^{1/3}c^{2/3}\Gamma(2/3)}, \qquad \mathcal{C}^{\mathbb{R}}_{2,c}(\lambda) \sim \pi/\sqrt{c\lambda}.$$

The Airy spectral problem for the full-line massless relativistic oscillator is treated by [28]. Here the Fourier source is a point mass and its forced resolvent value is the aperture coefficient. The values at zero and the asymptotics used here are given in [12, Sections 9.2 and 9.7]. The boundary-zero coefficient corresponds to a different supported half-line form.

17 Two independently strong degenerate contacts

On each inward ray (or each expanding finite interval in scaled depth), take a profile a_i with one zero x_i, exponent $p_i > 0$, leading coefficient $c_i > 0$, and floor $\epsilon_i \to 0$ as in the source theorem. Let $M_i \to \infty$ independently. In any of the allowed regimes of that theorem let S_i denote the normalization of Theorem 13, let $G_i = (A_\kappa + M_i(a_i + \epsilon_i))^{-1}$, and define a positive measure σ_i on the closed inward ray $[0,\infty)$ as follows.

- For $p_i < 1$, $\sigma_i(dx) = a_i(x)^{-1}\,dx$.
- For $p_i = 1$, $\sigma_i = (s_{0,i}/c_i)\delta_{x_i}$, with the logarithmic normalization $M_i/\log(1/\rho_i)$.
- For $p_i > 1$ and a finite scaled floor, $\sigma_i = \mathcal{C}^{D_i}_{p_i,c_i}(\lambda_i)\delta_{x_i}$.

- In the floor-dominated power regime, $\sigma_i = (\int_{D_i}(1 + c_i|y|^{p_i})^{-1}\,dy)\delta_{x_i}$.

Theorem 14. *The first connected trace has the joint limit*

$$S_-S_+\ \mathrm{Tr}(G_-B_{\kappa,h}G_+B_{\kappa,h}^*) \longrightarrow \iint |B_{\kappa,h}(x,y)|^2\,\sigma_-(dx)\sigma_+(dy). \tag{12}$$

The rates M_-, M_+ need no coupling. The same holds for the full minus-log determinant. This gives the flat density per tangential area by Fourier integration in all screen dimensions, and physical interval vacuum and thermal laws in dimension one with the energy factors of Section 16, with $S_g = S_{-,g}S_{+,g}$.

We use a positive-kernel argument that includes point evaluations at the boundary. Fix $w(x) = (1+x)^{-1}$, and define the finite measure $d\mu_i^{(M)}(x,x') = S_i w(x)G_i(x,x')w(x')\,dx\,dx'$. The kernel is nonnegative. Indeed the restricted square-root form is the zero-exterior part of the subordinate Brownian jump form with a nonnegative mass term. Its semigroup with additional nonnegative multiplication is positive and dominated on nonnegative functions by the full-line translation-invariant semigroup. The domination can also be obtained by testing resolvent differences with positive parts as in the depth-profile proof, followed by the semigroup product limit. The full-line semigroup has a density for each positive time, by the usual square-root subordination of the heat kernel. Thus the dominated semigroup and its positive resolvent have nonnegative kernels, with no pointwise bound at their diagonal needed for the weighted finite measure. The total mass of $\mu_i^{(M)}$ is $S_iQ_{M_i}(w)$, uniformly bounded by the source theorem.

For compact continuous tests ϕ, ψ of the two variables, polarization of the source theorem shows that $\int \phi(x)\psi(x')\,d\mu_i^{(M)} \to \int \phi(x)\psi(x)w(x)^2\,d\sigma_i(x)$. The measures are tight: for $R > x_i + 1$, the first marginal on $x > R$ is at most

$$[S_iQ_{M_i}(w1_{x>R})]^{1/2}[S_iQ_{M_i}(w)]^{1/2},$$

and the first term under the square root is bounded by $(S_i/M_i)\int_{x>R} w^2/a_i = O(\int_{x>R} w^2)$. Here S_i/M_i stays bounded in all regimes. The second marginal is the same by symmetry. The product tests and tightness give weak convergence of the measures to the weighted diagonal measure, including its possible point concentration.

The trace is the tensor-product quadratic form of the real L^2 cross kernel for $G_- \otimes G_+$. Its kernel integrand uses the two positive Green kernels times $B(x',y)\overline{B(x,y')}$. This product is nonnegative since the cross kernel has a single real sign; the formula follows first for rectangle step kernels and then by monotone nonnegative approximations to $|B|$ and convergence in L^2. Divide each B by its two depth weights to express the normalized trace as an integral against $\mu_-^{(M)} \otimes \mu_+^{(M)}$. The new test

$$\frac{B_{\kappa,h}(x',y)\overline{B_{\kappa,h}(x,y')}}{w(x)w(x')w(y)w(y')}$$

is bounded and continuous. Indeed for $r = h + x + y$, the Bessel Laplace representation gives

$$|B_{\kappa,h}(x,y)| \le Ce^{-\kappa r/2}r^{-2}$$

uniformly in $\kappa \ge 0$, by bounding $\sqrt{s^2-\kappa^2} \le s$ and integrating. Also $(1+x)(1+y) \le C_h r^2$. This test is continuous as κ varies, uniformly on compact depth sets, and retains a common exponential bound in mass. Thus weak product convergence proves (12) along compact κ-converging sequences, with exponential domination by the uniformly bounded measure masses.

The norm of the positive connected product is at most $C_h \ell_- \ell_+$, where $\ell_i = M_i^{-1/(p_i+1)}$, by the two strong inverse spectral gaps and bounded B. Hence the determinant remainder is relatively $O(\ell_- \ell_+)$ compared to the first trace. Tangential Fourier integration for the flat model and the interval vacuum and Matsubara limits follow from the exponential bound. At fixed physical temperature use the same monotone mesh comparison of the all-hit heat transform as in the source theorem.

When both limiting measures are point masses with weights m_-, m_+, the static coefficient in a one-dimensional screen is $m_- m_+ \cdot 4/(\pi^2 r_0^4)$, $r_0 = h + x_- + x_+$. The vacuum integral of the positive trace coefficient is

$$m_- m_+ \frac{3}{16\pi r_0^5}.$$

To check the latter, $\int_0^\infty t^2 K_1(t)^2 \, dt = 3\pi^2/32$. Indeed insert $K_1(t) = (t/4) \int_0^\infty u^{-2} e^{-u - t^2/(4u)} du$, integrate the resulting t^4 Gaussian, then use the sum and proportion of the two Schwinger variables. The remaining product is $\Gamma(5/2)\Gamma(1/2)\mathrm{B}(3/2, 3/2) = 3\pi^2/32$. Multiplying by $4/(\pi^2 r_0^5)$ and $1/(2\pi)$ gives the expression. The physical vacuum energy carries the minus sign of the connected determinant convention.

18 Weak contact at interval apertures: setup and main limits

Use the connected scalar Dirichlet-screen model of Section 10. The two interval apertures have inward depth variables in $(0, L_-)$, $(0, L_+)$, in units of a length g; their separation is $h > 0$ in those units. In the physical fixed-length example with actual gap g, $h = 1$ and $L_\pm = \ell_\pm / g$. At mass κ, $A_\pm$ are the compressed operators $2\sqrt{D^2 + \kappa^2}$, with zero extension, and the cross operator B has kernel

$$-\frac{2\kappa K_1(\kappa(h + u + v))}{\pi(h + u + v)}$$

for $\kappa > 0$, and $-2/[\pi(h + u + v)^2]$ at zero. The contact strengths here are scaled by g. For left strength M and right strength b, set

$$Q_{M,b} = (A_- + M)^{-1/2} B (A_+ + b)^{-1} B^* (A_- + M)^{-1/2}, \qquad q_{M,b}(\kappa) = -\log\det(I - Q_{M,b}).$$

The vacuum energy is $-1/(2\pi g)$ times the integral of q over positive mass. At physical inverse temperature β the free energy is $-(2\beta)^{-1} \sum_{j \in \mathbb{Z}} q_{M,b}(2\pi |j| g/\beta)$.

Theorem 15. *Let $L_\pm \to \infty$, $\eta \downarrow 0$, and $M \to \infty$, at independent rates. Put*

$$T = \min\{L_+, \eta^{-1}\}, \qquad l = \log(T/h), \qquad m = \log((h + L_-)/h), \qquad D_* = l^2 - (l - m)_+^2.$$

For the first trace $W(\eta) = \mathrm{Tr}[B(A_+ + \eta)^{-1} B^*]$ at $\kappa = 0$,

$$W(0) - W(\eta) \sim \eta D_*/(2\pi^2). \tag{13}$$

For the exact transform,

$$M[q_{M,0}(0) - q_{M,\eta}(0)] \sim \eta D_*/(2\pi^2). \tag{14}$$

The joint vacuum energy difference satisfies

$$\frac{gM}{\eta}(E_{M,\eta} - E_{M,0}) \longrightarrow \frac{1}{8\pi^3 h}.$$

With $\lambda_g = \beta/g$, if $\lambda_g \to \infty$, the free-energy difference satisfies

$$\frac{gM}{\eta}(\mathcal{F}_{M,\eta} - \mathcal{F}_{M,0}) = \frac{1}{8\pi^3 h} + \frac{D_*}{4\pi^2 \lambda_g} + o(1 + D_*/\lambda_g).$$

If λ_g is bounded above, the second term alone is the leading equivalent for the normalized difference.

For comparable scaled lengths $D_* \sim \log^2(T/h)$. The static formula and exact determinant comparison remain valid if the left length instead stays bounded below by a positive constant. The short interval can then limit the leading logarithm through m. The vacuum and temperature formulas above use both lengths tending to infinity.

General delta-profile boundary determinants occur for inhomogeneous parallel mirrors [14], and perturbations about a constant background are studied for a single inhomogeneous mirror [27]. The finite-interval inverse below uses the fractional Poisson kernel [29]. In the present separated connected trace it cuts off a static long-depth response. The relative error from the strong side is estimated after taking the weak-contact difference. This is what permits independent rates.

19 Weak-contact response on the half-line

The depth profiles in this section are defined on the full rays. For the limiting static half-line model, write $W_{\eta p}(0,h)$ for the trace profile with weak multiplication contact $\eta p(v)$, with p bounded, measurable and nonnegative. The parameter $\eta \downarrow 0$ is the weak amplitude.

If $p(v) \to p_\infty$ as $v \to \infty$, then

$$\frac{W_0(0,h) - W_{\eta p}(0,h)}{\eta \log^2(1/(\eta h))} \longrightarrow \frac{p_\infty}{2\pi^2}. \tag{15}$$

If instead p is integrable against the weight in (16), the correct first variation is finite and exact:

$$\lim_{\eta \downarrow 0} \frac{W_0(0,h) - W_{\eta p}(0,h)}{\eta} = \frac{1}{\pi^2} \int_0^\infty \frac{p(v)}{v} \left[\log(1 + v/h) - \frac{v}{v+h} \right] dv. \tag{16}$$

In particular this holds for compactly supported p. For general bounded $p \geq 0$ the limit in (16) holds in the extended positive reals.

19.1 Exact column and variational deficit

Let A_q be the zero-extension ray compression of $2\sqrt{D^2 + q^2}$ and $\mathfrak{a}_q$ its quadratic form. Write $f_{q,\ell}$ for the cross column at separation $\ell = h + u$, with u the left depth. Its transparent inverse is

$$V_{q,\ell}(v) := A_q^{-1} f_{q,\ell}(v) = -\frac{\sqrt{v}}{\pi \sqrt{\ell}(\ell + v)} e^{-q(\ell+v)}. \tag{17}$$

In the half-line factorization of Section 11, $L_q^{-*} f_{q,\ell}(v) = -e^{-q(\ell+v)}/[\sqrt{\pi}(\ell+v)^{3/2}]$, and $A_q^{-1} f = \frac{1}{2} L_q^{-1} L_q^{-*} f$. Multiply out the two exponentials and use

$$\int_0^v (v-s)^{-1/2} (\ell + s)^{-3/2} \, ds = \frac{2\sqrt{v}}{\sqrt{\ell}(\ell + v)}.$$

This also directly yields the supported massless energy representative. The per-column loss $D_{\eta p}(q,\ell)$ is exactly

$$D_{\eta p}(q,\ell) = \inf_z \{\mathfrak{a}_q[z - V_{q,\ell}] + \eta \int_0^\infty p|z|^2\}, \tag{18}$$

from the variational supremum by completing the energy square. For each column $D_{\eta p}/\eta$ increases as $\eta \downarrow 0$, by taking the infimum of $\mathfrak{a}_q/\eta + \int p|z|^2$. If $\int p|V_{q,\ell}|^2 < \infty$, testing with $V_{q,\ell}$ gives the upper bound. For a finite bounded subsequential ratio, near-minimizing z converges in energy to $V_{q,\ell}$, hence in local L^2 by Hardy or the mass gap. Fatou gives the lower bound even if the response integral is infinite. Therefore the limit is the integral of $p|V_{q,\ell}|^2$, finite or infinite. Monotone convergence in left depth proves the integrated response, and integration of the explicit squared massless column uses

$$\int_h^\infty \frac{d\ell}{\ell(\ell+v)^2} = v^{-2}\left[\log(1+v/h) - \frac{v}{v+h}\right].$$

19.2 Truncation bounds

Write

$$S_p(R) = \frac{1}{\pi^2}\int_0^R \frac{p(v)}{v}\left[\log(1+v/h) - \frac{v}{v+h}\right] dv, \qquad L = \log(1/\eta).$$

For η sufficiently small the integrated loss satisfies

$$\frac{\eta S_p(\eta^{-1}L^{-2})}{1+CL^{-2}} \le W_0(0,h) - W_{\eta p}(0,h) \le \eta S_p(2\eta^{-1}L^2) + O(\eta/L). \tag{19}$$

The constants may depend on h and the profile bound. This estimates nonconstant and vanishing tails directly.

For the lower bound in (19), keep only $(0,R)$ in the weighted contact term for each column. Write $B_\ell = \|p^{1/2}V_{0,\ell}\|_{L^2(0,R)}$, $y = \mathfrak{a}_0[z - V_{0,\ell}]^{1/2}$ and $c_R = (C\|p\|_\infty R)^{1/2}$. Hardy and the reverse triangle inequality bound the objective in (18) below by $y^2 + \eta(B_\ell - c_R y)_+^2$, whose minimum for $y \ge 0$ is $\eta B_\ell^2/(1+\eta c_R^2)$. Integrate over ℓ, then set $R = \eta^{-1}L^{-2}$.

For the upper bound take $z = \chi(v/R)V_{0,\ell}$ at $h \le \ell \le R$ and $z = 0$ for $\ell > R$, with $0 \le \chi \le 1$ equal to one up to one and zero past two. The lost energy for $\ell \le R$ is $O(1/(R\ell))$. Indeed after $v = Ry$ the omitted tail has amplitude factor $(R\ell)^{-1/2}$ times a function zero below one, bounded by $Cy^{-1/2}$, with derivative bounded by $Cy^{-3/2}$ at infinity, uniformly for $\ell/R \in [0,1]$. Its difference-quotient seminorm is uniformly bounded: for $|x-y| \le x/2$ use the derivative bound and integrate $O(x^{-2})$ in x away from zero. On the complementary positive quadrant $|x-y| \gtrsim x, y$, so the squared values integrate against dx/x. Interactions with the negative half-line also integrate against dx/x. Homogeneous energy at this order is invariant under scaling the argument, leaving the squared amplitude $1/(R\ell)$. For $\ell > R$ the whole-column loss is at most $1/(4\pi\ell^2)$ by the causal column trace of Sections 10–13. Thus the integrated energy error is $O((1+\log R)/R)$. The potential error is at most $\eta S_p(2R)$. Take $R = \eta^{-1}L^2$ to finish (19).

If $p(v) \to p_\infty$, then $S_p(R)/\log^2 R \to p_\infty/(2\pi^2)$ by the elementary logarithmic integral and tail comparison. Since both cutoff logarithms in (19) equal $L + O(\log L)$, this gives (15), including $p_\infty = 0$. More generally if $p(v) \sim p_0(\log v)^{-\sigma}$ at infinity with $p_0 > 0$, then the deficit has equivalents

$$\frac{p_0}{\pi^2(2-\sigma)}\eta L^{2-\sigma} \quad (0 \le \sigma < 2), \qquad \frac{p_0}{\pi^2}\eta \log L \quad (\sigma = 2).$$

For $\sigma > 2$, (16) supplies a finite linear derivative. These coefficients come from S_p, whose tail integrand is asymptotic to $p_0(\log v)^{1-\sigma}/(\pi^2 v)$.

20 The joint static limit

20.1 The finite-interval inverse column

Write $\ell = h + u$, $R = L_+$. The right forcing is $f_\ell(v) = -2/[\pi(\ell + v)^2]$ for $0 < v < R$. Its transparent inverse has zero exterior extension and the explicit formula

$$V_\ell^R(v) = (A_+)^{-1} f_\ell(v) = -\frac{\sqrt{v}}{\pi\sqrt{\ell}(\ell + v)}\sqrt{\frac{R - v}{R + \ell}}, \qquad 0 < v < R. \tag{20}$$

Indeed the positive of (20) is the interval Poisson kernel at the exterior point $-\ell$. The ball formula with $n = 1, s = 1/2$, recentered at $R/2$, gives the square-root factor and $1/\pi$. For rigor, take a smooth unit-mass exterior source supported in a shrinking neighborhood of $-\ell$, solve the homogeneous real-line half-Laplacian problem with that exterior value, and subtract the source to leave the zero extension. The zero-interior source enters the inner equation with kernel $-2/(\pi|v - y|^2)$, so the remaining interior solution solves the compressed problem with its opposite sign. The forcing converges in $L^2(0, R)$ and the compressed inverse is bounded for each finite R, by the exterior part of the energy. The Poisson formula converges pointwise to its value at $-\ell$. Hence it gives (20) with the sign shown. The Poisson formula and its exterior-data theorem are [29, Eq. (1.14) and Theorem 2.10].

The limiting half-line column is $V_\ell^\infty(v) = -\sqrt{v}/[\pi\sqrt{\ell}(\ell + v)]$, also given directly by the two causal integrals in Section 19. For every $b > 0$, the weak-inverted finite-interval column $v_{b,\ell} = (A_+ + b)^{-1} f_\ell$ is nonpositive and

$$|v_{b,\ell}| \le \left|(A_{\mathbb{R}_+} + b)^{-1} f_\ell^\infty\right|$$

on the finite interval. To see the order use positive forcing and test the difference of the form equations by the positive part of the finite-interval solution minus the half-line solution. This test is supported in the finite interval by nonnegativity of the half-line solution. The cross energy of positive and negative parts is nonpositive for the jump form, and adding mass b preserves the inequality. Inverses preserve positivity by energy contraction under absolute values. The same argument also applies at $b = 0$ in the supported homogeneous space, or follows here from (20).

20.2 Matching cutoffs for the first trace

Let

$$S_L(X) = \int_h^{h+L} \int_0^X |V_\ell^\infty(v)|^2 \, dv \, d\ell.$$

By explicit integration in v,

$$\begin{aligned} S_L(X) &= \frac{1}{\pi^2} \int_h^{h+L} \left[\log(1 + X/\ell) - \frac{X}{X + \ell}\right] \frac{d\ell}{\ell} \\ &= \frac{l_X^2 - (l_X - m_L)_+^2}{2\pi^2} + O(1 + \min\{l_X, m_L\}), \end{aligned} \tag{21}$$

Here $l_X = \log(X/h)$ and $m_L = \log((h + L)/h)$. The estimate is uniform for $X > h$. For $\ell \le X$ the bracket is $\log(X/\ell) + O(1)$, and its integral for $\ell > X$ is $O(1)$ using the bound $O((X/\ell)^2)$. Evaluating (21) at $X = T \log^{\pm 2} T$, or at twice that value, changes its leading term by relative $o(1)$. In fact the main expression is of order $l_X \min(l_X, m_L)$, its slope in l_X is $2\min(l_X, m_L)$ before the factor $1/(2\pi^2)$, and the change of l_X is $O(\log\log T)$.

For the lower bound on the per-column loss, use the finite-interval identity

$$D_\eta^R(\ell) = \inf_z \{\mathfrak{a}[z - V_\ell^R] + \eta\|z\|^2\},$$

where $\mathfrak{a}$ is the zero-extension form of $2|D|$. The ray Hardy bound, obtained by retaining interactions against the negative ray, gives $\|z - V_\ell^R\|_{L^2(0,U)} \le (CU\mathfrak{a}[z - V_\ell^R])^{1/2}$ if $U < R$. Minimize $y^2 + \eta(\|V_\ell^R\|_{L^2(0,U)} - \sqrt{CU}\, y)_+^2$ over $y \ge 0$. This gives

$$D_\eta^R(\ell) \ge \frac{\eta}{1 + C\eta U} \int_0^U |V_\ell^R(v)|^2\, dv.$$

Set $U = T/\log^2 T$ and restrict to $\ell \le U$. The squared finite-to-infinite column ratio on this region is $1 + O(U/R) = 1 + O(1/\log^2 T)$. In $S_{L_-}(U)$ the part with $\ell > U$ is bounded by a constant, because its integrand is at most $v/(\pi^2\ell^3)$. Thus the finite loss integrated in ℓ has lower bound $\eta(1 - O(1/\log^2 T))(S_{L_-}(U) - O(1))$.

For the upper bound when $T = R$, use the trial $z = V_\ell^R$, giving total loss at most $\eta S_{L_-}(R)$. When $T = \eta^{-1}$, comparison of the positive weak inverses gives $D_\eta^R(\ell) \le D_\eta^\infty(\ell)$. In detail, for $b > 0$ the derivative of the per-column quadratic inverse is minus the squared column norm. The cumulative loss integrates these norms over $0 < b < \eta$, by the resolvent identity and continuity at zero in the form-dual expression. The finite-domain norm is bounded by the full-ray norm by positivity. Now take the half-line cutoff used in (19), but integrate only over $h \le \ell \le h + L_-$. With $X = \eta^{-1}\log^2(1/\eta)$ this gives the bound $\eta S_{L_-}(2X) + O(\eta/\log(1/\eta))$, since the integrated cutoff energy is $O((1+\log X)/X)$ even over the whole ray. The lower and upper bounds with (21) prove (13). The same argument permits L_- to stay bounded away from zero without tending to infinity, using the displayed two-log expression.

20.3 The exact determinant

Let $D_- = A_- + M$ and $Q_b = D_-^{-1/2} B(A_+ + b)^{-1} B^* D_-^{-1/2}$. The positive transparent full-ray sandwich bounds the compressed sandwich in operator norm by the transparent trace $1/(4\pi h)$ of Theorem 9, even when the right interval grows. Thus $0 \le Q_b \le (C_h/M)I$. For M large one can differentiate the Fredholm logarithm on $b \in [0, \eta]$, at fixed finite intervals. The identity

$$-\partial_b q_{M,b}(0) = \operatorname{Tr}\left[(I - Q_b)^{-1} D_-^{-1/2} B(A_+ + b)^{-2} B^* D_-^{-1/2}\right]$$

has positive trace factors. The bound $I \le (I - Q_b)^{-1} \le (1 - C_h/M)^{-1} I$ therefore gives a relative $1 + O(M^{-1})$ error between $M[q_{M,0}(0) - q_{M,\eta}(0)]$ and

$$\operatorname{Tr}(R_- \Delta_\eta), \quad R_- = M(A_- + M)^{-1}, \quad \Delta_\eta = \int_0^\eta B(A_+ + b)^{-2} B^*\, db.$$

Here $\operatorname{Tr} \Delta_\eta = W_{L_-,L_+}(0) - W_{L_-,L_+}(\eta)$. This comparative estimate scales with the deficit itself.

To control $I - R_-$, use the Hilbert–Schmidt columns of $\Delta_\eta = VV^*$, with right input labels v, b, $0 < b < \eta$. The kernel of V is $v_{b,\ell}(v)$, with left coordinate $\ell = h + u$. By positivity and the pointwise bound $|\partial_\ell f_\ell| \le (2/h)|f_\ell|$,

$$|\partial_\ell v_{b,\ell}(v)| \le (2/h)|v_{b,\ell}(v)|.$$

The derivative statement can first be taken in $L^2(0, R)$, since f_ℓ is smooth there in ℓ and the finite inverse is bounded. The pointwise inequality then follows from applying the positive inverse to

the two forcing inequalities. In particular the integrated squared left-derivative norm is at most $(2/h)^2 \operatorname{Tr} \Delta_\eta$.

The diagonal loss density satisfies, uniformly for $\ell \geq h$,

$$\int_0^\eta \|v_{b,\ell}\|_2^2 \, db \ \leq C_h \eta (1 + \log T).$$

When $T = R$, bound it by the transparent norm integrated only to R, using (20) and positivity in b. When $T = \eta^{-1}$, compare to the half-line column at $\ell = h$ by forcing monotonicity and the domain comparison. For this single column the half-line energy cutoff at $X = \eta^{-1}$ has lost energy $O_h(\eta)$ and potential norm cost $O_h(\eta(1 + \log(1/\eta)))$, by the same tail bound as in (19).

Choose $0 \leq \chi \leq 1$ on the left interval, zero on its endpoints, and equal to one outside depth δ of both endpoints, with derivative bounded by C/δ. For $L_- \to \infty$ take $\delta = 1$ eventually. The removed squared norm is $O_h(\delta\eta(1 + \log T))$, which is $o(\operatorname{Tr} \Delta_\eta)$ for fixed δ since $\min(l, m) \to \infty$. The retained columns extend by zero to H^1, with squared form cost at most $C_h(1 + \delta^{-2}) \operatorname{Tr} \Delta_\eta$ using the derivative estimate and $2|\xi| \leq 1 + |\xi|^2$. Finally

$$\operatorname{Tr}[(I - R_-)\Delta_\eta] = \|(I - R_-)^{1/2} V\|_{\mathrm{HS}}^2 \leq 2\|(1 - \chi)V\|_{\mathrm{HS}}^2 + 2M^{-1}\|A_-^{1/2}\chi V\|_{\mathrm{HS}}^2.$$

Both terms are relatively negligible. If L_- is merely bounded below, take $\delta = M^{-1/4}$ eventually and use that $\operatorname{Tr} \Delta_\eta \gtrsim_h \eta \log T$ with a constant depending on the lower left length. The two terms are still relatively negligible. This proves (14).

21 Vacuum and temperature crossover

21.1 Positive mass and vacuum

For the current parameter sequence put

$$F(\kappa) = \frac{M}{\eta}[q_{M,0}(\kappa) - q_{M,\eta}(\kappa)], \qquad G_- = (A_- + M)^{-1}.$$

The forcing $f_{\kappa,\ell}(v)$ is the cross column at left depth $\ell - h$.

For $\kappa > 0$, the half-line column at separation $\ell = h + u$ is

$$V_{\kappa,\ell}(v) = -\frac{\sqrt{v}}{\pi\sqrt{\ell}(\ell + v)} e^{-\kappa(\ell+v)}.$$

Along converging positive masses and any geometric/contact rates as above,

$$F(\kappa) \longrightarrow J(\kappa) = \int_h^\infty d\ell \int_0^\infty |V_{\kappa,\ell}(v)|^2 \, dv. \tag{22}$$

For proof, differentiate the exact connected determinant in right strength b, as in Section 20. The derivative is the trace of $(I - Q_b)^{-1}$ against the positive form $G_-^{1/2} B (A_+ + b)^{-2} B^* G_-^{1/2}$. The norm bound $\|Q_b\| \leq C_h/M$, uniform in mass, removes the first factor at relative error $O(M^{-1})$. The scaled derivative is then the trace of $R_- = M(A_- + M)^{-1}$ against the Gram operator of $v^g_{b,\kappa,\ell} = (A_+ + b)^{-1} f_{\kappa,\ell}$ on the finite right interval, ℓ restricted to the finite left interval.

For each fixed positive κ, expanding right supports give strong L^2 convergence of the zero-contact columns by form exhaustion and the mass gap. The same holds along $\kappa_g \to \kappa > 0$, since the square-root form difference has L^2 operator bound $2|\kappa_g - \kappa|$, and the forcing kernels converge

in L^2. Right strength $0 \le b \le \eta$ changes the column in L^2 by at most $b\|v^g_{0,\kappa,\ell}\|/(2\kappa)$, by the resolvent identity. These convergences give the convergence in Hilbert–Schmidt norm of the full cross-column kernels on the expanding supports, by dominated convergence in left depth using the positive inverse comparison with the full-ray column at any fixed smaller positive mass. The contractions R_-, extended by zero, converge strongly to the identity. For compact interior tests this follows from the resolvent identity and uniform boundedness of the applied square root for bounded κ; extend to all L^2 by density. Combining both convergences gives the stated trace limit uniformly for $b \in [0, \eta]$ along such mass sequences, and then (22) after averaging over b.

The same positivity comparison and determinant bound give the exact majorant

$$0 \le F(\kappa) \le (1 - C_h/M)^{-1} J(\kappa) \qquad (\kappa > 0).$$

The positive function J decreases in κ and is integrable. Indeed integration of the exponential and then $\int_0^\infty v/(\ell + v)^3\, dv = 1/(2\ell)$ gives

$$\int_0^\infty J(\kappa)\, d\kappa = \frac{1}{4\pi^2 h}.$$

The joint vacuum difference is therefore linear:

$$\frac{gM}{\eta}(E_{M,\eta} - E_{M,0}) \longrightarrow \frac{1}{8\pi^3 h},$$

where g is the length used in the dimensionless gap scaling. For physical fixed-length intervals at gap g use $h = 1$, $L_\pm = \ell_\pm/g$. The vacuum change is positive because the weak contact reduces the magnitude of the attraction in this scalar convention.

21.2 The zero and nonzero thermal modes

Let $\lambda_g = \beta/g$, where β is physical inverse temperature. The exact scaled free-energy difference is

$$\frac{gM}{\eta}(\mathcal{F}_{M,\eta} - \mathcal{F}_{M,0}) = \frac{F(0)}{2\lambda_g} + \frac{1}{\lambda_g} \sum_{j \ge 1} F(2\pi j/\lambda_g).$$

If $\lambda_g \to \infty$, the mesh $a_g = 2\pi/\lambda_g$ tends to zero. Equation (22) is uniform on compact positive mass intervals by the converging-sequence assertion. The nonzero sum therefore converges to the vacuum constant after multiplication by $1/\lambda_g$, including at the moving endpoints: the positive integrable decreasing majorant J bounds $a_g \sum_{0 < j a_g < d} F(j a_g)$ by a fixed multiple of $\int_0^d J$, and the analogous upper tail by the integral above a nearby cutoff. Thus

$$\frac{gM}{\eta}(\mathcal{F}_{M,\eta} - \mathcal{F}_{M,0}) = \frac{1}{8\pi^3 h} + \frac{D_*}{4\pi^2 \lambda_g} + o(1 + D_*/\lambda_g).$$

The nonzero modes and the zero mode are comparable at λ_g of order D_*. For comparable scaled interval lengths, $D_* \sim \log^2(\min(L_+, \eta^{-1})/h)$. Fixed positive physical β in the fixed-length physical intervals gives $D_*/\lambda_g \to 0$, since $D_* = O(\log^2(1/g))$ and $\lambda_g = \beta/g$.

For λ_g bounded above, including $\lambda_g \downarrow 0$, the same J majorant with its exponential tail at positive mass bounds the whole nonzero contribution after multiplication by λ_g by $O(1)$. Since $D_* \to \infty$, the zero mode alone gives the leading difference $\eta D_*/(4\pi^2 \lambda_g g M)$. The result concerns constant strong and weak contacts. A strong profile with a vanishing layer would require control of the weak-loss columns on that layer, which is not supplied by the separate fixed-contact estimates.

22 Weak response at a degenerate strong contact

Let $A_\pm$ be the zero-extension compressions of $2\sqrt{D^2+\kappa^2}$ on the gap-scaled interval depths. Their separated cross operator B has kernel $-2\kappa K_1(\kappa(h+x+v))/[\pi(h+x+v)]$, with value $-2/[\pi(h+x+v)^2]$ at $\kappa = 0$. We use the connected scalar determinant and the vacuum and Matsubara normalization of Sections 10–13. The dimensionless separation is $h > 0$, with g the length unit. For fixed physical interval lengths and actual gap g, one has $h = 1$ and $L_\pm = \ell_\pm/g$.

The previous weak-contact result Sections 18–21 treats an independently diverging constant strong contact, while Sections 14–17 treats a strong contact with a zero and a fixed limiting weak contact. The present calculation requires a further split in depth: the static weak-loss source has one logarithm at any fixed depth, and a second appears in its total squared norm over the long depths. Applying the single-source strong limit to a globally normalized source would discard one of these contributions. The fractional localization identity and the positivity of the separated inverse permit a joint limit. Related boundary-diffraction and thermal logarithms in scalar Casimir models are discussed in [7, 8].

22.1 Main limits

Use two finite gap-scaled intervals of lengths $L_-, L_+ \to \infty$, fixed separation $h > 0$, and the scalar connected transform $q_b(\kappa)$ with weak constant $b \geq 0$ on the right. On the left use $M[a(x)+\varepsilon_M]$, where $M \to \infty$, $\varepsilon_M \geq 0$ tends to zero, and the continuous strong profile has exactly one zero x_0, satisfies $a(x) \sim c|x-x_0|^p$ there for $c > 0, p \geq 1$, and is bounded below away from every neighborhood of the zero. Assume $a(x) \to a_\infty > 0$ as $x \to \infty$. The weak amplitude is $\eta \downarrow 0$, with no relative rate imposed on $M, \eta, L_\pm$. Let S be the strong normalization and $m_0 > 0$ the corresponding weight from Theorem 13. Write $s_0 = 2$ for an interior zero and $s_0 = 1$ for a boundary zero.

- If $p = 1$, use $\rho_M = \max(M^{-1/2}, \varepsilon_M)$, $S = M/\log(1/\rho_M)$, and $m_0 = s_0/c$.
- If $p > 1$, set $\ell_{\mathrm{sc}} = M^{-1/(p+1)}$ and $\lambda_M = M\ell_{\mathrm{sc}}\varepsilon_M$. For $\lambda_M \to \lambda_0 < \infty$, use $S = \ell_{\mathrm{sc}}^{-2}$ and the weight $m_0 = \langle 1, (2|D| + c|y|^p + \lambda_0)^{-1}1\rangle$ in the dual form sense. Its domain is the full line for an interior zero and the zero-extension half-line for a boundary zero. For $\lambda_M \to \infty$, use $S = M\varepsilon_M^{1-1/p}$ and $m_0 = s_0\pi/[pc^{1/p}\sin(\pi/p)]$.

In all cases $S/M \to 0$.

Set

$$T = \min(L_+, \eta^{-1}), \quad l = \log(T/h), \quad m = \log((h+L_-)/h), \quad D = l^2 - (l-m)_+^2, \quad \ell_0 = h + x_0.$$

Theorem 16. *Then the exact static deficit has the additive asymptotic*

$$q_0(0) - q_\eta(0) = \frac{\eta\, m_0 l}{\pi^2 \ell_0 S} + \frac{\eta D}{2\pi^2 a_\infty M} + o\Big(\frac{\eta l}{S} + \frac{\eta D}{M}\Big). \tag{23}$$

Both terms are positive. The first term comes from the contact zero. The second comes from the far depths. The dimensionless balance is $(S/M)D/l$. For comparable scaled lengths the two terms have the same order when l has order M/S, which equals $\log(1/\rho_M)$ at a linear zero and $M^{(p-1)/(p+1)}$ at a power zero with finite scaled floor.

The joint vacuum difference is

$$\frac{gS}{\eta}(E_\eta - E_0) \longrightarrow \frac{m_0}{8\pi^3\ell_0^2}. \tag{24}$$

Write $\mathcal{F}_b$ for the free energy at right strength b. At $\lambda = \beta/g \to \infty$, the difference $(gS/\eta)(\mathcal{F}_\eta - \mathcal{F}_0)$ is the same vacuum constant plus

$$\frac{1}{2\lambda}\left[\frac{m_0 l}{\pi^2 \ell_0} + \frac{SD}{2\pi^2 a_\infty M}\right] + o\Big(1 + \frac{l + (S/M)D}{\lambda}\Big). \tag{25}$$

For λ bounded above the displayed zero-mode term is the leading equivalent. In the physical fixed-length interval setting $h = 1, L_\pm = \ell_\pm/g$, fixed positive physical β gives the vacuum equivalent.

23 From determinant difference to a positive source

Let $G_- = (A_- + M[a + \varepsilon_M])^{-1}$ for the left supported square-root form and $Q_b = G_-^{1/2} B (A_+ + b)^{-1} B^* G_-^{1/2}$ for the connected cross product. At any mass κ, differentiate the right strength b in the exact determinant at fixed finite intervals, as in Sections 18–21. The negative derivative of q_b is the trace of $(I - Q_b)^{-1}$ against the positive operator $G_-^{1/2} B (A_+ + b)^{-2} B^* G_-^{1/2}$. The strong form gap gives $\|G_-\| \le C\ell_{\mathrm{sc}}$, $\ell_{\mathrm{sc}} = M^{-1/(p+1)}$, uniformly in mass and floor. The transparent sandwich bounds $\|Q_b\| \le C\ell_{\mathrm{sc}}$. Therefore the determinant deficit is the first-trace deficit to a relative $1 + O(\ell_{\mathrm{sc}})$, independently of η:

$$q_0(\kappa) - q_\eta(\kappa) = (1 + O(\ell_{\mathrm{sc}}))\langle F_\kappa, (G_- \otimes I) F_\kappa\rangle, \qquad F_\kappa(x)(b, v) = (A_+ + b)^{-1} f_{\kappa, h+x}(v), \quad 0 < b < \eta. \tag{26}$$

The Hilbert space in the source labels is $L^2((0, \eta) \times (0, L_+))$. Its kernel has one sign by positivity of the compressed inverse. Its spatial derivative satisfies the relative bound uniformly at static mass,

$$\|\partial_x F_0(x)\| \le (2/h)\|F_0(x)\|,$$

by $|\partial_x f_{0,h+x}| \le (2/h)|f_{0,h+x}|$ and applying the positive weak inverse. The norm squares integrate in x to the unweighted static first-trace deficit of Sections 18–21, which is $\eta D/(2\pi^2)(1 + o(1))$.

24 Local weak-loss coefficient

Uniformly on every compact left depth set,

$$\frac{\|F_0(x)\|^2}{\eta l} \longrightarrow \frac{1}{\pi^2 (h + x)}. \tag{27}$$

For $R = L_+$ the transparent interval inverse column and the ray column are

$$V_\ell^R(v) = V_\ell^\infty(v)\sqrt{(R - v)/(R + \ell)}, \qquad V_\ell^\infty(v) = -\frac{\sqrt{v}}{\pi\sqrt{\ell}(\ell + v)}.$$

For fixed ℓ in a compact positive interval, $\int_0^X |V_\ell^\infty|^2 = \log(X/h)/(\pi^2 \ell) + O(1)$. The finite Hardy lower test from Sections 18–21, truncated at $U = T/\log^2 T$, gives the same integral times $\eta(1 + o(1))$ because $\eta U = o(1)$ and the finite-column ratio is $1 + o(1)$ on this test. For the upper bound when $T = R$, trial with V_ℓ^R gives $\eta \int_0^R |V_\ell^\infty|^2$. When $T = \eta^{-1}$, use the half-line domain comparison for the integrated derivative and the half-line cutoff at $X = \eta^{-1} \log^2(1/\eta)$, with energy cost $O_h(1/(X\ell))$. These bounds match (27). The same upper comparison at $\ell = h$ and forcing monotonicity give $\|F_0(x)\|^2 \le C_h \eta(1 + l)$ for all left depths.

25 Adding the zero layer and the bulk

We use two static bounds that retain constant accuracy across arbitrary ratios of η and M. First, for any fixed smooth $0 \le \chi_0 \le 1$ compactly supported in left depth and equal to one in a neighborhood of x_0, apply the source theorem Theorem 13 to $\chi_0 F_0/\sqrt{\eta l}$. These sources are uniformly bounded in L^2 since the left support is fixed, and locally uniformly continuous at x_0 by the relative derivative estimate and local bound above. Their value norm squares tend to $1/(\pi^2 \ell_0)$ by (27). This applies also to an edge zero with $\chi_0(0) = 1$, since the source need not be a form test there. It gives

$$Q_H(\chi_0 F_0) \sim \eta l \, m_0/(\pi^2 \ell_0 S),$$

where Q_H denotes the inverse quadratic form with $G_- \otimes I$.

Second, for sources supported away from the zero, multiplication bounds and a far-depth test give the bulk term. Fix any cutoff χ_1 zero near the zero and equal to one beyond a fixed sufficiently large depth. The upper bound

$$Q_H(\chi_1 F_0) \le M^{-1} \int \frac{\|\chi_1 F_0\|^2}{a + \varepsilon_M}$$

has limsup coefficient $1/(2\pi^2 a_\infty)$ under normalization $M/(\eta D)$. To see it, all fixed bounded depths away from the zero cost $O(\eta l)$, smaller than ηD since $D/l \to \infty$ when both lengths grow. On the remaining far depths use $a(x) \to a_\infty$ and the full unweighted trace norm. For the lower bound take a nonnegative scalar cutoff ψ which vanishes up to fixed depth R_0 beyond the zero and at the far endpoint, and equals one between $R_0 + 1$ and the last unit of the left interval. Choose R_0 large enough that $|a(x) - a_\infty| \le \delta$ there. For the source restricted to those far depths, the trial

$$v = \frac{\psi F_0}{M(a_\infty + 2\delta)}$$

is in the zero-extension H^1 form domain. For sufficiently small floor its potential and linear terms give at least $1/[M(a_\infty + 2\delta)]$ times the integrated source norm except in the two cutoff layers. The discarded layers cost $O_{R_0}(\eta l)$ by the pointwise bound. The kinetic energy is $O_{R_0}(\eta D/M^2)$, by $2|\xi| \le 1 + |\xi|^2$, the derivative bound for F_0 and the fixed cutoff slopes. Then send $\delta \downarrow 0$. Thus the far source gives the same bulk term up to relative $o(1)$.

For the sum upper bound take $\chi_0^2 + \chi_1^2 = 1$ with the above support arrangement, using cosine and sine of a smooth cutoff angle. The fractional localization identity (cf. [30]) gives

$$\sum_j \langle \chi_j v, H \chi_j v \rangle \le \langle v, Hv \rangle + C\|v\|^2 \le (1 + C\ell_{\mathrm{sc}}) \langle v, Hv \rangle.$$

Indeed the potential terms sum exactly, and the difference-quotient energy error is bounded by the integral of $\|v(x)\| \|v(y)\| \min(1, |x-y|^2)/|x-y|^2$, using the squared cutoff differences and convolution with an L^1 kernel. This holds for Hilbert-valued tests and zero extensions. In the variational supremum write the linear term using the two cutoffs and use the inequality to obtain $Q_H(F_0) \le (1 + C\ell_{\mathrm{sc}}) \sum Q_H(\chi_j F_0)$. For the lower bound, keep disjoint near and far sources with cutoffs bounded by one and drop the remaining middle part. All pairings between retained pieces and the discarded piece are nonnegative: G_- has positive kernel and $F_0(x)(b, v) \le 0$. Thus $Q_H(F_0)$ is at least the sum of the near quadratic form and the far trial lower bound. Their limits match the upper bound to an $o(1)$ relative error in the sum, giving (23) via (26).

26 Massive fibers and the energy limits

For $\kappa > 0$ the weak-loss source $F_\kappa/\sqrt{\eta}$ is uniformly L^2 in both depths, with squared norm bounded by $J(\kappa)$ from Sections 18–21. This follows from positivity comparison with the transparent half-line inverse, independently of b and the interval lengths. The same comparison bounds its value norm at fixed left depth by the corresponding half-line norms and gives local equicontinuity. The Bessel Laplace formula expresses the forcing magnitude at distance r as a constant times $\int_\kappa^\infty e^{-sr}\sqrt{s^2-\kappa^2}\,ds$. After $s = \kappa + t$, integration by parts gives the ratio of its absolute derivative to itself at most $\kappa + 2/r$, since $t(\sqrt{t(t+2\kappa)})'/\sqrt{t(t+2\kappa)} \le 1$. Applying the positive inverse gives the same relative bound for the inverted columns. Along converging positive masses its squared value norm at x_0 tends to $\|V_{\kappa,\ell_0}\|_2^2$ by strong compressed inverse convergence and the positive mass gap, averaging $0 < b < \eta$. The source theorem of Sections 14–17 applies globally without a spatial cutoff and gives

$$\frac{S}{\eta}[q_0(\kappa) - q_\eta(\kappa)] \longrightarrow m_0\|V_{\kappa,\ell_0}\|_2^2. \tag{28}$$

This convergence is uniform on compact positive mass intervals by the converging-sequence statement.

For a common integrable majorant use the inverse comparison $H_\kappa \ge H_0$, followed by the same two fixed cutoffs and fractional localization at zero mass. The far part after normalization by S/η is bounded by $C(S/M)J(\kappa) \le CJ(\kappa)$. The near part is bounded by $C\sup_{x\le R}\|F_\kappa(x)\|^2/\eta$ using the upper source estimates for compactly supported sources; this is at most $C\|V_{\kappa,h}\|_2^2$ by monotone positive forcing. Both functions are decreasing and integrable in κ, and decay exponentially at infinity. For the latter one also directly obtains $\int_0^\infty \|V_{\kappa,\ell_0}\|_2^2\,d\kappa = 1/(4\pi^2\ell_0^2)$, by integrating the exponential and then $v/(\ell_0+v)^3$. The factor $1/(2\pi)$ gives (24).

With $\lambda \to \infty$, the nonzero Matsubara modes converge to the same vacuum integral by compact convergence and decreasing integrable domination of the Riemann sum near zero and infinity, as in Sections 18–21. The zero mode retains exactly (23), with the Matsubara factor $1/(2\lambda)$ giving (25). If λ is bounded above, the nonzero sum multiplied by λ is $O(1)$ under the same normalized bound, whereas the normalized zero-mode deficit grows at least as l. Finally for fixed physical lengths and fixed positive physical inverse temperature, $l = O(\log(1/g))$, $D = O(\log^2(1/g))$, and $S/M \le C$, so the normalized zero-mode correction vanishes. This proves the stated temperature comparisons.

27 Degenerate strong contacts at curved tangencies: model and limiting response

Let two bounded convex apertures in a d-dimensional screen, $d \ge 2$, lie on opposite sides of a supporting hyperplane before they are translated by $\mp g/2$ along the separation direction s. Their closures meet only at the origin before translation. Use the facing graphs of Sections 10–13: in physical coordinates they are $s = -h_-(y)$ and $s = h_+(y)$ before translation. At a smooth quadratic tangency $h_\pm$ are C^2 near zero and their Hessian sum is positive definite. In the separable finite-type case

$$h_i(y) = \sum_j b_{ij}|y_j|^{r_j} + o\left(\sum_j |y_j|^{r_j}\right), \qquad r_j > 1, \quad b_{ij} \ge 0, \quad b_{-j} + b_{+j} > 0.$$

Set $r_j = 2$ in the quadratic case. In gap units the Cartesian coordinates are $(s/g, Y)$, where $Y = y/g$. We use $w_j = g^{1-1/r_j}Y_j$, $\alpha = \sum_j 1/r_j$, $\gamma = d - 1 - \alpha > 0$, and the gap height

$H(w) = 1 + \sum_j (b_{-j} + b_{+j})|w_j|^{r_j}$ in the finite-type case. In the quadratic case the added term is half the quadratic form of the Hessian sum. The variable u denotes the inward vertical depth in units of g from the relevant facing graph. The volume element is $g^{-\gamma}\,dw\,du$.

The aperture response is the zero-exterior compression of $2\sqrt{|D|^2+\kappa^2}$, with gap-scaled mass κ and an added nonnegative multiplication contact. A gap-scaled coefficient is g times the physical coefficient. Let G_i be the inverses of the two compressed responses. Let B be the separated cross operator from the right to the left aperture with kernel n_κ, the off-diagonal kernel of $2\sqrt{|D|^2+\kappa^2}$. The connected transform $q_g = -\log\det(I - G_-^{1/2} B G_+ B^* G_-^{1/2})$ has vacuum and thermal normalizations

$$E_g = -\frac{1}{2\pi g}\int_0^\infty q_g(\kappa)\,d\kappa, \qquad \mathcal{F}_g(\beta) = -\frac{1}{2\beta}\sum_{j\in\mathbb{Z}} q_g(2\pi|j|g/\beta).$$

We use the connected heat and determinant identities of [1], Sections 10–13 and Sections 14–17, including positivity and monotonicity of q_g in κ. The occupation weight for a bounded multiplication contact is the exponential of its negative integral against the normal local time. It preserves those properties at each fixed g.

For a strong side prescribe $M[a(w,u)+\epsilon]$ in a fixed facing chart and M off the chart, with $M\to\infty$ and $\epsilon\to 0$, $\epsilon\ge 0$. We use bounded continuous nonnegative a with a single zero $u_0(w)$ in each depth ray and

$$a(w,u) \sim c(w)|u-u_0(w)|^p, \qquad a(w,u) \ge c_*\min(1,|u-u_0(w)|^p). \tag{29}$$

Here $p>0$, $c_*>0$, c is positive continuous, the expansion is locally uniform in w, and u_0 is bounded and locally Lipschitz. Either $u_0\equiv 0$ or $\inf u_0 > 0$. The notation $\mathcal{D}$ denotes respectively the open half-line or the line, and $\nu = 1$ or 2, in these cases.

The normalization S and limiting depth measure σ_w are as follows. For $p<1$ take $S=M$ and $\sigma_w = du/a(w,u)$. For $p=1$ take $S = M/\log(1/\rho)$ with $\rho = \max(M^{-1/2},\epsilon)$, and put $\sigma_w = (\nu/c(w))\delta_{u_0(w)}$. For $p>1$ write $\ell = M^{-1/(p+1)}$. If $M\ell\epsilon\to L<\infty$ take $S=\ell^{-2}$ and $\sigma_w = m(w)\delta_{u_0(w)}$, with

$$m(w) = \sup_{\psi\in C_c^\infty(\mathcal{D};\mathbb{R})}\left\{2\int_{\mathcal{D}}\psi - \langle\psi, 2|D|\psi\rangle - \int_{\mathcal{D}}(c(w)|z|^p + L)|\psi(z)|^2\,dz\right\}. \tag{30}$$

Functions in the kinetic form are extended by zero. If $M\ell\epsilon\to\infty$, take $S = M\epsilon^{1-1/p}$ and $m(w) = \int_{\mathcal{D}}(1+c(w)|z|^p)^{-1}\,dz$. These normal responses are finite by the gap and the integrability of the reciprocal power at infinity. In particular the quadratic interior oscillator has the Airy evaluation in Sections 14–17; the spectral antecedent is [28].

Theorem 17 (One strong contact)**.** *Use* (29) *on the left. On the right use bounded continuous nonnegative scaled contact $b(w,v)$ in the chart and any uniformly bounded nonnegative coefficient off it. Then*

$$g^\gamma S q_g(\kappa) \;\longrightarrow\; P_1(\kappa) = \int_{\mathbb{R}^{d-1}}\int_{[0,\infty)} C_b(\kappa,w,u)\,\sigma_w(du)\,dw.$$

Here $C_b(\kappa,w,u)$ is the frozen weak-inverted squared column. Explicitly, for $h = H(w)+u$, $q=\sqrt{\kappa^2+|k|^2}$, and $f_{q,h}(v) = -2qK_1(q(h+v))/[\pi(h+v)]$, it is

$$(2\pi)^{-(d-1)}\int_{\mathbb{R}^{d-1}}\langle f_{q,h}, (A_q + b(w,\cdot))^{-1} f_{q,h}\rangle\,dk.$$

The operator A_q is the supported ray compression of $2\sqrt{D^2+q^2}$. At $q=0$ use $f_{0,h} = -2/(\pi(h+v)^2)$ and the inverse form on its energy dual. This theorem includes $b\equiv 0$, and $\epsilon\equiv 0$ at every order p.

Theorem 18 (Two strong contacts)**.** *On both sides use* (29) *with the respective parameters, and with a_i depending only on u over each fixed tangency chart. Use that profile on the entire vertical fiber above each chart point. The two rates and floor regimes are independent. Then*

$$g^{\gamma} S_{-} S_{+} q_g(\kappa) \;\longrightarrow\; P_2(\kappa) = \int_{\mathbb{R}^{d-1}} \int_{\mathbb{R}^{d-1}} \int_{[0,\infty)^2} |n_\kappa(H(w)+u+v,z)|^2 \, \sigma_{-}(du)\sigma_{+}(dv)\, dz\, dw. \quad (31)$$

Both limits are uniform on compact mass intervals and their normalized transforms have a common exponential envelope. With $A = S$ in Theorem 17 and $A = S_{-}S_{+}$ in Theorem 18, $g^{d-\alpha} A E_g$ converges to $-\int_0^\infty P_i(\kappa)\, d\kappa/(2\pi)$. At $\beta = \lambda g$ the limit is

$$g^{d-\alpha} A \mathcal{F}_g(\lambda g) \;\longrightarrow\; -\frac{1}{2\lambda} \sum_{j \in \mathbb{Z}} P_i(2\pi |j|/\lambda),$$

locally uniformly in $\lambda > 0$. At fixed positive physical β the free energy has the vacuum limit.

The diffraction formulation of [7, 19, 8] provides the boundary action and thermal setting. Inhomogeneous thin-mirror contacts appear in [14]. Hard thin films with regional $H^{1/2}$ energy have a tangential variational limit [31], and directional fractional equations on thin domains are studied in [32]. Local Schrödinger confinement with a degenerate hypersurface zero is treated in [33]. In the present problem the zero-exterior first-order kinetic form retains a forced normal response, and the near-contact geometry and the contact layer enter the trace at independent rates. The flat or interval responses needed below are from Sections 14–17.

28 Vertical inverses and recovery trials

Denote by N_i the direct integral over the gap tangential coordinate Y of the inverse of the vertical compression of $2\sqrt{D_s^2 + \kappa^2}$ plus the same contact. Convexity makes each nonempty slice an interval. For every compact slow-coordinate set its length on the inward side tends to infinity in gap units uniformly. Indeed near the tangency choose a fixed short inward normal segment with interior endpoint, then use a neighborhood of that endpoint and convexity. The facing graph has vanishing local Lipschitz constant at tangency Sections 10–13. Zero extension gives $0 \le G_i \le N_i$ by form order. For any supported H^1 trial V, possibly Hilbert-valued, the surcharge from replacing the vertical by the full kinetic form satisfies

$$0 \le \mathfrak{A}_i[V] - \mathfrak{A}_i^{\mathrm{vert}}[V] \le 2\|V\|_2 \|\nabla_Y V\|_2. \quad (32)$$

This follows from the Fourier symbol difference bounded by $2|\xi_Y|$ and Cauchy–Schwarz. The derivative is at fixed Cartesian normal coordinate.

The vertical form has a uniform gap $C^{-1}\ell^{-1}$ for $\ell = M^{-1/(p+1)}$, at every $p > 0$. After centering at the zero and dilating by ℓ, the rescaled potential is bounded below by $c \min(1, |z|^p)$. Constant off-chart strength also satisfies the bound for small ℓ. For the whole-line comparison, the low-frequency part $|\xi| \le r$ of a unit vector has squared mass $O(r)$ in $[-1, 1]$, by Fourier Cauchy–Schwarz. The high-frequency norm squared is bounded by $\langle |D| \rangle / r$, and the potential controls the mass outside $[-1, 1]$. Fixing a sufficiently small r proves the gap on the line and on every zero-extended slice. With a nonzero floor the inverse is also bounded by $C/(M\epsilon)$ for small ϵ. All statements hold at zero mass.

We record the two consequences of this comparison used below. The signal $F = F_g(w, u)$ takes values in a Hilbert space that may vary with g. Suppose its norm squared converges to a function $J(w, u)$ along compact mass-converging sequences, and its full Cartesian spatial derivatives and values are uniformly bounded on compact (w, u)-sets. Evaluation of F_g on a boundary layer is allowed when the field extends to a fixed normal neighborhood there with these bounds.

Lemma 19 (Slice upper limit and local recovery)**.** *For the slice upper limit suppose also that in the chart*

$$\|F_g(w,u)\|^2 \le Ce^{-c\kappa}(1+u+\Psi(w))^{-d-1}, \qquad \Psi(w)=\sum_j |w_j|^{r_j}.$$

Then the chart source has vertical inverse quadratic with upper limit, on the scale $g^\gamma S$, at most $\int J(w,u)\,\sigma_w(du)\,dw$. The bound is exponentially dominated in mass. For local recovery, the derivative and pointwise hypotheses alone suffice: the full inverse quadratic has lower limit at least the same integral, by compact exhaustion.

Proof. For $p<1$ drop the vertical kinetic form. The reciprocal majorant is integrable because u_0 is bounded, $p<1$, and $\alpha<d$. This yields the upper bound by dominated convergence. For $p=1$, on $|u-u_0|\le\rho$ the gap bounds the inverse quadratic by $O(M^{-1})$ times the local column envelope. Indeed the inverse gap there is $O((M\rho)^{-1})$ and the source squared mass is $O(\rho)$. On its complement drop the kinetic term. Integrating $1/|u-u_0|$ between ρ and a small fixed radius yields the normalized coefficient $\nu J(w,u_0)/c(w)$. The finite-radius error tends to zero with that radius by (29) and the derivative estimate. Fixed outer depths contribute $O(M^{-1})$ on each slice. Cross terms are lower order by Cauchy–Schwarz in the inverse norm.

For $p>1$ with finite scaled floor, split at $|u-u_0|=R\ell$. The complementary inverse quadratic times S is bounded by the multiplication form and costs at most

$$Ce^{-c\kappa}\left[(1+\Psi(w))^{-d-1}R^{1-p}+(1+\Psi(w))^{-d}\ell^{p-1}\right].$$

In the core the gap and local derivative bound allow replacing the vector by $F_g(w,u_0)$ in the normalized inverse norm. After dilation the scalar forcing is the indicator of the truncated interval or ray. The rescaled forms for this forcing converge to the oscillator form. For the upper limit the gap bounds the $H^{1/2}$ norm of near-maximizers. Local L^2 compactness gives convergence in the pairing and in compact potential integrals. Exhaustion gives lower semicontinuity of the potential term, and the limiting functions remain zero-exterior in the half-line case. Compact smooth tests give the reverse bound and are dense by cutoff, inward translation on the ray, and smoothing. Increasing R then gives (30), using the reciprocal-power bound outside R for the inverse norm of the removed forcing. For dominant floor, use the multiplication bound directly with $u-u_0=\epsilon^{1/p}z$. The near-zero integrand is bounded by the local envelope times $C/(1+|z|^p)$; away from the zero the normalization includes $S/M=\epsilon^{1-1/p}\to 0$. Each upper estimate gives the integrable tangential envelope $Ce^{-c\kappa}(1+\Psi(w))^{-d}$, using $R=1$ for the oscillator bound before taking limits.

For the full lower bounds use the inverse variational formula with compact slow-coordinate support. Let $s_0(Y)$ be the Cartesian gap coordinate of the profile zero. Its local slope θ_g tends to zero on each such support because the graph slopes vanish and $\partial_Y w_j = g^{1-1/r_j}$. For a trial

$$V(s,Y)=a_0\psi\left(w,\frac{u-u_0(w)}{t}\right)F_g(s_0(Y),Y)$$

with smooth compact ψ in the allowed limiting domain, the estimates for its squared norm and its squared tangential derivative norm are $O(g^{-\gamma}a_0^2 t)$ and $O(g^{-\gamma}a_0^2(t+\theta_g^2/t))$. These follow from the full derivative bound and the chain rule for Lipschitz centers. The trial has no zero-extension jump. Thus (32) costs at most $Cg^{-\gamma}a_0^2(t+\theta_g)$.

For the oscillator take $a_0=t=\ell$. On the normalized scale the surcharge is $O(\ell+\theta_g)$, with no coupling of these two quantities. The linear pairing converges with $F_g(w,u)$ replaced by $F_g(w,u_0)$, by its normal derivative bound. At each w the vertical kinetic form dilates to

$2\sqrt{D_z^2 + (\kappa\ell)^2}$, and the potential converges to $c(w)|z|^p + L$. The resulting optimized functional is $\int J(w, u_0)m(w)\,dw$. To justify its optimization choose finitely many compact normal tests near-optimal on a compact set of w, using continuity of c and relative form comparison. Partition the set by choice of test and approximate the partition by disjoint compact subsets with smooth cutoffs in disjoint neighborhoods. Their discarded integral can be arbitrarily small, since the normal objective and J are bounded on the compact set. The subsequent compact exhaustion gives the asserted lower bound.

For dominant floor take $t = \epsilon^{1/p}$ and $a_0 = 1/(M\epsilon)$. The normalized vertical kinetic term is $O((M\epsilon t)^{-1})$ on compact mass sets; the tangential cost is bounded by this factor times $C(t + \theta_g)$. Both vanish since $M\ell\epsilon \to \infty$ implies $M\epsilon t \to \infty$. Optimize the remaining multiplication functional as for the oscillator.

For $p = 1$ use trial numerator $\chi(w)F_g(s_0(Y), Y)$ and denominator $Mc(w)|u - u_0|$, cut off smoothly on the annulus from ρ to a small fixed outer radius. Approximate $1/c$ on the support by a smooth factor and subsequently remove the approximation. The squared trial and normal derivative norms are $O(g^{-\gamma}M^{-2}\rho^{-1})$ and $O(g^{-\gamma}M^{-2}\rho^{-3})$. The tangential squared derivative adds terms of order $g^{-\gamma}M^{-2}(\rho^{-1} + \theta_g^2\rho^{-3})$. The total kinetic cost is $O(g^{-\gamma}M^{-2}\rho^{-2})$ and the floor cost is $O(g^{-\gamma}\epsilon/(M\rho))$. Both are $O(g^{-\gamma}/M)$. The leading linear and potential terms give $(2\chi - \chi^2)\nu J(w, u_0)/c(w)$ as the outer radius shrinks. Exhaust with $0 \le \chi \le 1$. For $p < 1$ use $V = M^{-1}m(w, u)F_g(w, u)$ for compact smooth m supported away from the zero and boundary. The kinetic cost after normalization is $O(M^{-1})$; approximate the reciprocal on compacts and exhaust. This proves local recovery. □

29 One strong side

Set $F_g(X) = G_+^{1/2}B^*\delta_X$ for a left point X. The weak-column limit of Sections 14–17 gives

$$\|F_g(w, u)\|^2 \longrightarrow C_b(\kappa, w, u), \qquad u \ge 0.$$

Translate to the evaluation point. The opposite domain converges locally to its facing half-space, and its contact converges locally uniformly to $b(w, \cdot)$ in the interior. The separated source converges in $L^{2d/(d+1)}$, and the dual homogeneous Sobolev estimate bounds the inverse pairing.

Compactly supported tests give the lower limit. Near-maximizers are bounded in homogeneous energy, and local Rellich compactness and exhaustion of the nonnegative potential term give the upper limit. At $u = 0$ the source still has separation at least one. Tangential Fourier decomposition gives the formula of Theorem 17.

The same Sobolev estimate for the differentiated separated kernel bounds each first Cartesian derivative, even across a short extension of the left facing graph. It gives the envelope of Lemma 19 for the squared chart columns. The normalized off-chart integral is $O(ge^{-c\kappa})$.

The first trace is the inverse quadratic on this Hilbert-valued column. In its upper bound split the source into chart and off-chart pieces and apply the triangle inequality in the inverse norm. The off-chart square costs at most $1/M$ times the off-chart column integral by multiplication order, so it is $O(gS/M)$ after normalization. The chart upper limit and full lower limit now agree by Lemma 19. The positive connected product has norm $O(\ell)$: use the strong inverse gap and the uniformly bounded transparent supporting-half-space sandwich of Sections 10–13. Higher determinant traces have relative size $O(\ell)$ by the positive logarithmic series. This proves the transform limit.

30 Two strong sides

Apply the vertical comparison to both inverses. With $\omega(u) = (1+u)^{-1}$, the positive fiber measure

$$S_i \omega(u) N_i(u, u') \omega(u') \, du \, du'$$

has uniformly bounded mass. In a chart its total mass is bounded by the full-ray vertical inverse at zero mass on ω, using domain and form comparison and the one-dimensional source theorem Sections 14–17. Outside the chart use constant M_i and $S_i/M_i \le C$. For any fixed slow w, or any fixed gap-coordinate tangential displacement from that point, the fibers are eventually in the chart and their lengths tend to infinity. The one-dimensional weighted-measure convergence in Sections 14–17 gives weak convergence on the closed depth ray squared to the diagonal image of $\omega(u)^2 \sigma_i(du)$. It applies along converging compact mass sequences and retains boundary atoms.

Represent the vertical upper trace as the quadratic of $N_- \otimes N_+$ on the cross kernel. Fubini in the tangential coordinates reduces its depth integral to the two positive weighted fiber measures. There are two separated kernels tested against those measures with the four weight factors divided out. This identity follows by positive rectangle approximation on the depth variables. Let $z = Y' - Y$ and put $\Psi(w) = \sum |w_j|^{r_j}$. The near-contact distance estimate Sections 10–13 gives, for two chart points at depths u, v, separation

$$|R| \gtrsim 1 + u + v + |z| + \Psi(w).$$

The supports also give $(1+u)(1+v) \le C|R|^2$ globally. The kernel bound is

$$|n_\kappa(R)| \le C e^{-c\kappa|R|} |R|^{-d-1}.$$

The resulting product envelope is $Ce^{-c\kappa}(1 + |z| + \Psi(w))^{-2(d-1)}$. It is integrable in (w, z) since $2(d-1) > d-1+\alpha$. Outside a smaller fixed chart on either side the physical separation is bounded below by uniqueness of contact. The weighted product is then $O(e^{-c\kappa} g^{2(d-1)})$, and the product of both scaled tangential volumes is $O(g^{-2(d-1)})$. The normalized contribution is $O(e^{-c\kappa} g^{\gamma})$. For each fixed (w, z) the graph shifts give the gap $H(w)$, and the kernel tests converge uniformly on compact depths. Boundedness and tightness of the weakly convergent weighted measures and the common product envelope justify convergence to (31) for the vertical upper trace.

To replace both vertical inverses by full inverses use

$$\begin{aligned} 0 \le\ & \operatorname{Tr}(N_- B N_+ B^*) - \operatorname{Tr}(G_- B G_+ B^*) \\ \le\ & \operatorname{Tr}[(N_- - G_-) B N_+ B^*] + \operatorname{Tr}[(N_+ - G_+) B^* N_- B]. \end{aligned}$$

This follows by inserting the mixed trace and comparing the other factor in each positive term. For the left defect take $F_g(X) = \sqrt{S_+} N_+^{1/2} B^* \delta_X$. The right depth measure gives the squared norm of this field and its first full Cartesian derivatives. Each column factor divided by the right weight alone costs at most $C(1 + u + v + |z|)^{-d}$ on compact mass sets, by the separated kernel bound and its differentiated version. Integrating over z with the bounded right measure masses yields $C(1+u)^{-d-1}$ for the squared field and derivative bounds. The same right-measure convergence as above gives the norm-square limit

$$J(w, u) = \int_{\mathbb{R}^{d-1}} \int_{[0,\infty)} |n_\kappa(H(w) + u + v, z)|^2 \, \sigma_+(dv) \, dz.$$

The bound extends slightly across a boundary zero by separation. The compact recovery part of Lemma 19 gives the entire limit $\int J(w, u) \, \sigma_-(du) \, dw$ as a lower bound for the normalized mixed

trace with G_-. This equals the vertical upper limit. The analogous recovery on the right removes the second defect. Neither defect estimate involves a ratio of strong scales.

The inverses have norms $O(\ell_-)$ and $O(\ell_+)$, and B is uniformly bounded by the separated kernel Schur estimate of Sections 10–13. The determinant remainder is relatively $O(\ell_-\ell_+)$. This proves Theorem 18.

31 Energies and point-response checks

All bounds and convergence arguments above hold along convergent compact mass sequences. The limiting integrals are continuous by the column variational limit or the continuous separated kernel and the same dominating envelopes. The exponential majorants justify vacuum and gap-temperature integration and summation. For fixed positive physical β, use the monotone mesh bound for the connected transform, with step $2\pi g/\beta$ and endpoint error at most a constant times this step times the bounded normalized static transform.

If the weak side is transparent, the flat one-sided trace $W_{d,0}(\kappa, h)$ of Sections 10–13 satisfies $C_0(\kappa, w, u) = -\partial_h W_{d,0}(\kappa, h)$ at $h = H(w) + u$, since the column integral differs only by the integration over additional inward depth. For two atomic measures the vacuum density in (31) is the product of their two masses times

$$(d+2)(d+3)A_d[H(w) + u_- + u_+]^{-d-4},$$

before applying the overall energy sign. Here

$$A_d = \frac{2\Gamma(d/2+1)^2\Gamma(d/2+2)}{\pi^{d/2+2}\Gamma(d+4)}$$

is the flat two-strong vacuum constant of Sections 5–9. Indeed $A_d h^{-d-2}$ integrates the vacuum squared kernel over both depths, and two derivatives in h remove those integrations. These are coefficients at the assigned gap-scaled profiles.

32 Periodic corrugation of a strong contact

A nonnegative surface contact adds a multiplication term to the aperture response of a Dirichlet screen. The kinetic term is the supported compression of twice the free square root. A strong contact confines the part of the response contributing to the Casimir interaction near a zero of the coefficient. For an order-p zero with strength multiplier M, the normal confinement width is $\ell = M^{-1/(p+1)}$. A slow tangential modulation can be approximated by separate vertical inverses. When the contact zero varies in depth by order ℓ over a tangential distance of order ℓ, tangential and normal frequencies enter the leading kinetic energy together.

Periodic scattering decompositions and wavelength crossovers were developed for geometrically deformed plates by Emig, Hanke, Golestanian and Kardar [37] and Büscher and Emig [35]. Fosco and Mazzitelli [14] derive a scalar interaction determinant for flat parallel mirrors with spatially varying multiplication contacts. Here the screen geometry is fixed and the contact well moves in depth within a coplanar aperture. We use the separated aperture kernel of the boundary-operator formulation [7] and Sections 10–13. The constant-depth strong limit and its supported half-line oscillator are developed in Sections 14–17.

Floquet trace formulas per unit volume are standard [36, Lemma 2.2]. Large periodic potentials lead to Bloch cells in local second-order homogenization [34]. Homogenization of periodic

Lévy-type kinetic coefficients is treated in [39, 40]. In the present model the kinetic symbol is fixed, the confining potential translates within the cell, and the coefficient is a forced inverse. Its zero-quasimomentum value enters the leading trace even though the weak factor is integrated over all physical tangential momenta.

Braides, Pinamonti and Solci [31, Theorem 4.7] obtain a logarithmic tangential correction for the regional $H^{1/2}$ seminorm of a thin product film. A logarithmic term also arises from low-frequency Neumann modes in the Casimir derivative expansion [38]. The edge logarithm here comes from the normal Fourier multiplier applied to an optimized supported response. The coefficient depends on the tangential derivative of its integrated normal mass. In the interior, translation preserves that mass and the leading term has no logarithm.

33 The contact model and main results

Let $Y \in \mathbb{R}^m$, $m \geq 1$, be the common tangential coordinate. The left and right apertures have inward depths $u > 0$ and $v > 0$, respectively, and fixed separation $h > 0$ in gap units. The diagonal boundary response at mass $\kappa \geq 0$ is the compression of $2\sqrt{D_u^2 + |D_Y|^2 + \kappa^2}$, with zero extension across the edge, plus the contact. We use $D = -i\partial$ and the unnormalized Fourier transform $\widehat{f}(\xi) = \int e^{-ix\xi} f(x)\,\mathrm{d}x$. The right contact is the constant $b \geq 0$. The left contact is

$$M\big[c|u - u_0 - \ell\chi(Y/\delta_\ell)|^p + \epsilon_\ell\big], \qquad \ell = M^{-1/(p+1)}, \quad M\ell\epsilon_\ell \longrightarrow \lambda \geq 0. \tag{33}$$

Here $c > 0$, $p > 1$, $\epsilon_\ell \geq 0$, and χ is a real smooth function on $\mathbb{T}^m = (\mathbb{R}/2\pi\mathbb{Z})^m$. The physical period in each tangent coordinate is $2\pi\delta_\ell$. We use normalized Haar measure on $\mathbb{T}^m$, denoted by $\mathrm{d}\theta$ or by the averaging brackets $\langle\cdot\rangle_\theta$. The ratio $r_\ell = \ell/\delta_\ell$ tends to $r \in [0, \infty]$. Either $u_0 > 0$ is fixed, or $u_0 = 0$ and $\chi \geq 0$. Write $J = \mathbb{R}$ in the first case and $J = (0, \infty)$ in the second.

For $0 \leq r < \infty$, define

$$\mathfrak{b}_r[U] = \left\langle U, 2\sqrt{D_z^2 + r^2|D_\theta|^2}\,U \right\rangle + \int_{J\times\mathbb{T}^m} (c|z - \chi(\theta)|^p + \lambda)|U|^2\,\mathrm{d}z\,\mathrm{d}\theta, \tag{34}$$

$$C_r(J) = \sup_U \left(2\,\mathrm{Re}\int_{J\times\mathbb{T}^m} U\,\mathrm{d}z\,\mathrm{d}\theta - \mathfrak{b}_r[U]\right). \tag{35}$$

The z variable is extended by zero outside J in the kinetic form. The admissible functions lie in its closed form domain. Define $C_\infty(J)$ by the same supremum restricted to θ-independent functions. Its one-dimensional potential is $c\langle|z - \chi|^p\rangle_\theta + \lambda$.

Write A_q for the right ray compression of $2\sqrt{D_v^2 + q^2}$, and put

$$f_{q,L}(v) = -\frac{2qK_1(q(L+v))}{\pi(L+v)} \quad (q > 0), \qquad f_{0,L}(v) = -\frac{2}{\pi(L+v)^2}, \qquad L > 0.$$

The weak-side factor is

$$\mathcal{W}_b(\kappa, L) = (2\pi)^{-m}\int_{\mathbb{R}^m} \langle f_{q,L}, (A_q + b)^{-1} f_{q,L}\rangle_{\mathrm{dual}}\,\mathrm{d}k, \qquad q = \sqrt{\kappa^2 + |k|^2}. \tag{36}$$

The form-dual notation includes $q = b = 0$. We define the periodic connected transform $q_\ell^{\mathrm{area}}(\kappa)$ as the trace per unit tangential volume of the negative logarithm of identity minus the positive cross product of the two diagonal inverses and two separated kernels. The Bloch formula and finiteness of this logarithm are proved in Section 34.

Theorem 20 (Periodic cell law)**.** *Under* (33)*,*

$$\ell^{-2} q_\ell^{\mathrm{area}}(\kappa) \longrightarrow C_r(J)\mathcal{W}_b(\kappa, h+u_0).$$

The convergence is uniform on compact mass intervals including zero, and the normalized traces have a common exponentially decaying mass bound. In gap units the corresponding vacuum integral and free energy at inverse temperature $\beta_* > 0$, normalized by ℓ^{-2}, converge to

$$-\frac{C_r(J)}{2\pi}\int_0^\infty \mathcal{W}_b(\kappa, h+u_0)\,\mathrm{d}\kappa, \qquad -\frac{C_r(J)}{2\beta_*}\sum_{j\in\mathbb{Z}} \mathcal{W}_b(2\pi|j|/\beta_*, h+u_0),$$

respectively. The second limit is locally uniform for $\beta_* > 0$.

If χ is nonconstant, $C_r(J)$ is strictly decreasing on $[0,\infty]$. At $r = 0$ it is the average of the local vertical inverses. In $J = \mathbb{R}$ this average equals the single full-line coefficient with potential $c|z|^p + \lambda$. At $r = \infty$ it is the inverse response for the averaged potential.

Theorem 21 (Small-ratio corrections)**.** *On the line let $v_* = (2|D| + c|z|^p + \lambda)^{-1}1$ in the form-dual sense. Then*

$$\lim_{r\downarrow 0} \frac{C_0(\mathbb{R}) - C_r(\mathbb{R})}{r^2} = \langle |\nabla_\theta \chi|^2\rangle_\theta \,\langle v_*, |D| v_*\rangle. \tag{37}$$

On the supported ray let $v_t = (2|D| + c|z-t|^p + \lambda)^{-1}1$ and define the normal response mass $m_0(\theta) = \int_0^\infty v_{\chi(\theta)}(z)\,\mathrm{d}z$. Then

$$\lim_{r\downarrow 0} \frac{C_0((0,\infty)) - C_r((0,\infty))}{r^2 \log(1/r)} = \frac{\langle |\nabla_\theta m_0|^2\rangle_\theta}{\pi}. \tag{38}$$

Both coefficients are strictly positive for a nonconstant χ.

The two scales in Theorem 21 are asymptotics of the limiting cell coefficients.

34 The unfolded trace

Write G_ℓ for the strong diagonal inverse on the left. Write C_κ for the right sandwich by the separated cross kernel and the right inverse. In the usual Fourier transform in Y, the sandwich is diagonal with positive blocks $C_{\kappa,k}$ in normal depth. Its Hilbert-valued column is

$$F_{\kappa,k}(u) = (A_q + b)^{-1/2} f_{q,h+u}.$$

In particular the squared column norm is the inner product in (36) evaluated at $L = h + u$, and at zero mass it has the form-dual interpretation. The donor's causal half-line factorization Section 11 gives

$$\|F_{\kappa,k}(u)\|^2 \le \frac{1}{2\pi}\int_{h+u}^\infty e^{-2qs} s^{-3}\,\mathrm{d}s \le C_h e^{-2hq}. \tag{39}$$

One way to obtain the first bound is to set $L_q = (q + \partial_v)^{1/2}$, so the supported form of A_q is $2\|L_q \cdot\|_2^2$. Its backward inverse applied to $f_{q,h+u}$ is $-e^{-q(h+u+v)}/[\sqrt{\pi}(h+u+v)^{3/2}]$. At $q = 0$ this is in L_v^2, and it represents the homogeneous dual norm. Adding b can only decrease the quadratic. The same bound applied to the differentiated separated column controls the first depth derivative on compact q-intervals. Column norms depend continuously on $q \ge 0$: the separated columns converge in the massless vertical dual norm, and the inverse quadratic converges by its form supremum, using compact tests for the lower bound and form order at

$q = 0$ for the upper bound. Away from zero the spectral gap also gives continuous dependence in L^2. The transparent trace bound integrated in u gives $\sup_{\kappa,k} \|C_{\kappa,k}\| \le 1/(4\pi h)$.

Fold the tangent Fourier transform into $k + n/\delta_\ell$ with $k \in [-1/(2\delta_\ell), 1/(2\delta_\ell))^m$ and $n \in \mathbb{Z}^m$. This groups the Fourier channels into a periodic fiber in $\theta = Y/\delta_\ell$, with modes $e^{in\cdot\theta}$. Multiplication by the contact is periodic in θ. The unscaled kinetic symbol in this fiber is $2\sqrt{\xi_u^2 + |k + n/\delta_\ell|^2 + \kappa^2}$. The trace per unit tangent volume is $(2\pi)^{-m} \int_{\mathrm{BZ}} \mathrm{Tr}(\cdot)(k)\,\mathrm{d}k$. Indeed normalized Brillouin-zone measure divided by the real-space cell volume gives this Fourier measure. The localized positive trace formula [36, Lemma 2.2] extends to the additional normal Hilbert space by summing diagonal coefficients in an orthonormal basis and using positivity.

In each folded fiber C_κ acts diagonally in the tangent channels. For its n-th term, conjugation by multiplication by $e^{in\cdot\theta}$ shifts the strong kinetic quasimomentum from k to $k + n/\delta_\ell$ and leaves the contact unaltered. The source becomes constant in θ. Unfolding the sum and integral gives the exact first trace

$$\mathrm{Tr}_{\mathrm{area}}(G_\ell^{1/2} C_\kappa G_\ell^{1/2}) = (2\pi)^{-m} \int_{\mathbb{R}^m} Q_{\ell,\kappa,k}(F_{\kappa,k})\,\mathrm{d}k. \tag{40}$$

Here k is unfolded physical momentum, and $Q_{\ell,\kappa,k}$ is the left inverse quadratic on the θ-constant source for that momentum. For a Hilbert-valued source, the formula sums the scalar inverse quadratics over the right-depth coefficient basis. All are nonnegative. Thus finite channel and coefficient truncations give the same identity upon taking increasing sums. The integral is finite by the uniform bound proved below.

Under the unitary dilation $u = u_0 + \ell z$, the operator ℓ times the strong diagonal response has form

$$2\sqrt{D_z^2 + |r_\ell D_\theta + \ell k|^2 + (\ell\kappa)^2} + c|z - \chi(\theta)|^p + M\ell\epsilon_\ell. \tag{41}$$

The support is $z > -u_0/\ell$. The normal dilation scales the source amplitude by $\ell^{1/2}$ and the inverse scales by ℓ. Hence $\ell^{-2} Q_{\ell,\kappa,k}(F_{\kappa,k})$ is the inverse quadratic of (41) on $F_{\kappa,k}(u_0 + \ell z)$, constant in θ. This exhibits the small shifted momentum ℓk separately from the period frequency $r_\ell D_\theta$.

35 Convergence of the forced inverse

The forms (41) have a uniform positive gap in L^2, including at zero floor. Their kinetic symbol dominates $2|\xi_z|$ and the potential is at least $c'|z|^p$ for $|z|$ large, uniformly in θ. For a direct proof of the gap choose one fixed interval containing all the shifted wells and split the z-Fourier transform at a small frequency. The low-frequency part has squared L^2 mass on that interval bounded by a constant times the frequency cutoff times its global squared norm. The entire high-frequency squared norm is controlled by the vertical kinetic energy divided by the cutoff. The potential controls the squared norm outside the interval. Choosing a sufficiently small fixed cutoff and absorbing the low-frequency term proves the gap. Integrating in θ gives the same estimate for the cell. It holds after zero extension and with arbitrary quasimomentum and mass. In particular $\|G_\ell\| \le C\ell$.

For a source bounded in pointwise Hilbert norm, the gap controls its form-dual norm on a fixed bounded normal interval. Outside $|z| \le R$, the reciprocal potential controls the omitted form-dual norm by $CR^{(1-p)/2}$ times the supremum of the source norm. These estimates follow by dual Cauchy–Schwarz against the kinetic gap or the potential term, respectively. In particular

$$\ell^{-2} Q_{\ell,\kappa,k}(F_{\kappa,k}) \le C \sup_{u \ge 0} \|F_{\kappa,k}(u)\|^2. \tag{42}$$

On a fixed normal window $|z| \le R$, the two sources $F_{\kappa,k}(u_0 + \ell z)$ and $F_{\kappa,k}(u_0)$ differ in norm by $O(\ell R)$, uniformly for bounded masses and momenta, by the separated column derivative bound. This freezes the auxiliary Hilbert-vector factor. The truncated inverse is then a scalar quadratic on the constant normal and tangential source restricted to the window, times $\|F_{\kappa,k}(u_0)\|^2$. The earlier tail estimate applies also to the limiting unit source. It suffices to prove variational convergence for truncated scalar sources and take $R \to \infty$. In the slow case we will equivalently use smooth tests for the full source after the tail estimate.

For $0 < r < \infty$, the mass and quasimomentum perturbations change the kinetic form in (41) by at most $2\ell(|k| + \kappa)\|U\|_2^2$. The remaining symbols converge on smooth tests as $r_\ell \to r$. A compactly supported test in J is eventually supported in the scaled domain, giving the variational lower limit. For the upper limit, near-maximizers for the compact scalar source have bounded energy and L^2 norm. Since r_ℓ is bounded below, they are bounded in $H^{1/2}$ of the full cylinder, after zero extension, and have a strongly convergent subsequence in local L^2. The limiting support is J. Restricting to compact normal sets in the potential energy and to bounded Fourier frequencies in the kinetic energy gives lower semicontinuity after exhaustion. Smooth periodic tests compactly supported in J form a core: cut off at infinity in $H^{1/2}$ and the potential norm, then translate inward for a supported ray and mollify on bounded sets. Thus the upper and lower limits match.

For $r_\ell \to 0$, dropping the tangent term bounds the inverse from above by the vertical direct integral over the limiting domain J, after the source replacement and tail estimate. Its unit-source response is $C_0(J)$. When $J = \mathbb{R}$, translation separately at each θ reduces it to the well centered at zero. Tests $\varphi(z - \chi(\theta))$ with φ smooth and compactly supported approximate its response from below. For the ray, let $V_0(z, \theta) = v_{\chi(\theta)}(z)$ be the vertical optimizer. As shown in Section 37, its angular derivative belongs to L^2. It can be cut off at infinity, translated slightly inward and mollified, in both the vertical form and the angular derivative norm. These trials recover the upper bound because the extra kinetic cost on a trial U is at most $2r_\ell\|U\|_2\|\nabla_\theta U\|_2$ before the small mass and quasimomentum terms. This argument requires no tangent compactness when $r = 0$.

For $r_\ell \to \infty$, a bounded-energy near-maximizer for the compact source has squared L^2 norm in nonconstant tangent modes $O(r_\ell^{-1})$ for any fixed k, since their kinetic cost is at least $2r_\ell|n| - 2\ell|k|$. The constant mode is locally compact in normal L^2 by the vertical energy bound. In the limit the optimizer is independent of θ, so restriction to bounded normal intervals and exhaustion give its potential cost with the averaged potential. The normal kinetic energy of the average has the usual weak lower bound. Conversely a smooth compact test in J independent of θ supplies the desired lower bound. This proves the response $C_\infty(J)$.

In all cases the limiting normalized fiber value is $C_r(J)\|F_{\kappa,k}(u_0)\|^2$. The arguments apply along sequences with κ converging to any finite mass, since only uniform source derivatives and convergence of the squared point-column norms are used. By (39) and (42), the normalized unfolded integrand has an integrable bound $C_h e^{-2h\sqrt{\kappa^2+|k|^2}}$. Its integral decays exponentially in κ. The same bound applies for all sufficiently small ℓ and gives compact-uniform convergence in κ, since the limit is continuous.

Finally set $Q = G_\ell^{1/2} C_\kappa G_\ell^{1/2}$ in the periodic space. By the uniform weak sandwich bound and the strong gap, $\|Q\| = O(\ell)$. In each fiber Q is positive, and the trace of $\sum_{j\ge2} Q^j/j$ is at most $O(\ell)\operatorname{Tr} Q$. The first trace is integrable by (40), so the per-area negative logarithm is finite and the higher terms are negligible in the ℓ^{-2} normalization. This proves the transform limit. The vacuum and Matsubara formulas follow by the common exponential bound, with a uniform majorant for the Matsubara sum on compact inverse-temperature intervals.

36 Dependence on the wavelength ratio

The constant source defines a bounded functional on the cell form space because $p > 1$. Coercivity gives a unique maximizing form element at each finite r, including zero, as well as in the constant-mode space at infinity. The ordered kinetic multipliers give $C_{r_1}(J) \geq C_{r_2}(J)$ for $0 \leq r_1 < r_2$. Equality between two finite ratios forces the r_2 optimizer into the constant tangent channel, since the kinetic difference is strictly positive on each other channel. Equality with the infinite-ratio response would make the constant-mode optimizer a maximizer for the full finite-ratio form.

A θ-independent function $U(z)$ maximizing the full finite form would solve the Euler equation with potential $c|z-\chi(\theta)|^p+\lambda$ for every θ. To see this, test in z on compact sets and use continuity in θ of the resulting potential pairing. Subtract at two distinct shift values a and b. The result $U(z)(|z-a|^p - |z-b|^p) = 0$ implies that U is supported at their midpoint and hence is zero as an L^2 function. This contradicts the unit forcing. Thus the decrease is strict.

37 Small-ratio corrections

Let V_0 be the vertical optimizer and let $\mathcal{D}_r$ be the positive excess of the r-dependent kinetic form over its vertical part. Completing the vertical form square gives

$$C_0(J) - C_r(J) = \inf_V \{\mathfrak{b}_0[V - V_0] + \mathcal{D}_r[V]\}. \tag{43}$$

With Fourier variable ξ in z and mode $n \in \mathbb{Z}^m$ in θ, the multiplier of $\mathcal{D}_r/r^2$ is zero for $n = 0$ and otherwise equals

$$\frac{2|n|^2}{\sqrt{\xi^2 + r^2|n|^2} + |\xi|}. \tag{44}$$

Fourier integration in ξ uses $\mathrm{d}\xi/(2\pi)$.

37.1 Interior zero

On the line, $V_0(z,\theta) = v_*(z-\chi(\theta))$. Its normal Fourier transform is $e^{-i\xi\chi(\theta)}\widehat{v}_*(\xi)$. The multipliers (44) increase to $|n|^2/|\xi|$ as $r \downarrow 0$ for $\xi \neq 0$. Parseval in θ gives

$$\int_{\mathbb{R}} \sum_n \frac{|n|^2}{|\xi|} |\widehat{V}_0(\xi, n)|^2 \frac{\mathrm{d}\xi}{2\pi} = \langle |\nabla_\theta \chi|^2 \rangle_\theta \int_{\mathbb{R}} |\xi|\, |\widehat{v}_*(\xi)|^2 \frac{\mathrm{d}\xi}{2\pi}.$$

The integral is finite by the vertical form bound, which also makes V_0 admissible for the full finite-ratio form. Testing (43) with V_0 gives the upper coefficient in (37). For the lower bound, let V_r be the full optimizer. The upper estimate and (43) give $\mathfrak{b}_0[V_r - V_0] = O(r^2)$ and hence $V_r \to V_0$ in L^2. Restrict the divided excess to finitely many modes and a compact interval of ξ separated from zero. There the multipliers converge uniformly and the quadratic expressions pass by strong L^2 convergence. Exhausting the Fourier region proves the matching lower bound. The coefficient is positive when χ is nonconstant because v_* is a nonzero L^2 function with strictly positive $|D|$ energy.

37.2 Zero at the supported edge

For t in the range of χ, the forms defining v_t have common domain supported $H^{1/2}$ with $(1+z^p)$-weighted L^2. Their energy norms are uniformly equivalent to this norm by the vertical gap and

the potential at large z. The shifted potential depends C^1 on t as a map from the form space to its dual. In fact

$$\partial_t |z-t|^p = -p\,\operatorname{sgn}(z-t)|z-t|^{p-1}.$$

After division by $1+z^p$, the derivative is continuous in multiplier norm, by continuity on compact intervals and a uniform $O((1+z)^{-1})$ tail bound. Inverting the form operators shows that $t \mapsto v_t$ is C^1 in this form space. Consequently $V_0(z,\theta) = v_{\chi(\theta)}(z)$ and its first tangent derivatives belong to $L^1_z(L^2_\theta)$ by weighted Cauchy–Schwarz. In particular $\widehat{V}_0(\xi,\cdot)$ is continuous at zero as an H^1_θ-valued function and equals m_0 there.

The mass $\int_0^\infty v_t\,\mathrm{d}z$ is strictly increasing in t. Translating to the center of the potential gives the same confining form on the expanding supported interval $(-t,\infty)$. Domain inclusion gives monotonicity. The smaller-domain optimizer is nonzero and nonnegative by absolute-value contraction for the jump form. If the inverse quadratic were unchanged upon expansion, this optimizer extended by zero would also solve the Euler equation on the larger domain. A nonzero nonnegative test compactly supported in the added strip has zero potential pairing and strictly negative kinetic pairing with the smaller-domain optimizer, by the off-diagonal jump kernel. This contradicts the positive pairing with the unit source. Thus m_0 is nonconstant when χ is nonconstant, and its squared tangent gradient has positive mean.

To compute the upper coefficient in (38), evaluate the divided excess of V_0 using (44). On $|\xi| \geq d_0 > 0$ it is bounded uniformly in r by $C_{d_0}\|\nabla_\theta V_0\|_2^2$. For $|\xi| \leq d_0$ we have the bound $C|n|^2/(|\xi|+r)$ for every nonzero integer mode. The H^1_θ continuity therefore permits replacement of $\widehat{V}_0(\xi,\cdot)$ by m_0 with error $o_{d_0}(1)\log(1/r) + O_{d_0}(1)$, where the first coefficient tends to zero as $d_0 \downarrow 0$. For each fixed nonzero n,

$$\lim_{r\downarrow 0} \frac{1}{\log(1/r)} \int_{-d_0}^{d_0} \frac{2|n|^2}{\sqrt{\xi^2 + r^2|n|^2} + |\xi|} \frac{\mathrm{d}\xi}{2\pi} = \frac{|n|^2}{\pi}.$$

For example the multiplier is asymptotic to $|n|^2/|\xi|$ above the scale $r|n|$. The bound $C|n|^2/(|\xi|+r)$ also gives dominated summation against the H^1_θ coefficients of m_0. Thus $\mathcal{D}_r[V_0]/[r^2\log(1/r)] \to \langle|\nabla_\theta m_0|^2\rangle_\theta/\pi$. The vertical optimizer is an admissible trial for each finite ratio since its tangential derivative lies in L^2. Equation (43) gives the upper bound.

For the lower bound (43) first gives $\|V_r - V_0\|_2^2 = O(r^2\log(1/r))$ from the vertical gap. Retain finitely many nonzero modes and restrict to $r \leq |\xi| \leq d_0$. The divided multiplier on this region is bounded by C/r for the fixed modes. Thus the divided excess of $V_r - V_0$ on the region is $O(r\log(1/r))$, whereas that of V_0 is $O(\log(1/r))$. The reverse triangle inequality in the weighted Fourier norm shows that replacing V_r by V_0 changes the leading logarithmic coefficient by zero. For each retained mode, the removed interval $|\xi| < r$ would contribute only $O(1)$ to the divided integral. Letting $d_0 \downarrow 0$ after the small-r limit and then exhausting the mode sets proves the matching lower coefficient. This completes the proof of Theorem 21.

38 Strong contacts with higher-codimension zero sets

The boundary response of a flat screen aperture is a supported compression of twice the free square root [7] and Sections 10–13. A nonnegative surface contact adds a multiplication term to this form. When the strength multiplier M is large, the constant-source response may concentrate near the zeros of the contact. The normal width there is $\ell = M^{-1/(p+1)}$ for a contact vanishing to order p. In codimension k, a tube of this width has normal volume of order ℓ^k. The critical power $p = k$ is also the threshold for integrability of the reciprocal contact. Resolving the response above this threshold requires the normal kinetic form as well as the vanishing potential.

Normal-bundle coordinates and varying confining potentials are standard in the study of effective Schrödinger dynamics [44, 33]. Ao, Chan, DelaTorre, Fontelos, González and Wei [41, Lemma 5.7 and Remark 5.8] compare a fractional operator near a singular submanifold with its normal model in the fractional Yamabe problem. Thin-film normal energies for regional fractional forms appear in [31]. Fractional localization by squared cutoff differences is developed in Frank and Geisinger [42, Lemma 16]. Our object is a forced inverse of the supported first-order form. We use a fixed atlas at each prescribed metric accuracy and absorb its localization cost through the strong-contact gap. This lets the normal fractional form survive in the leading coefficient, including its zero-exterior constraint when the zero set lies on the aperture boundary. The point and ray responses used for degenerate contacts in Sections 14–17 and Sections 27–31 arise from one normal coordinate. Here the normal dimension is the ambient codimension and the contact can have angular dependence.

39 The inverse theorem

Let $K \subset \mathbb{R}^d$ be bounded and Lipschitz, and let Σ be a compact smooth embedded submanifold without boundary with codimension k in $\mathbb{R}^d$, $2 \le k \le d$. We allow the following placements.

- For an interior zero set, $\Sigma \Subset K$. In orthonormal tubular coordinates $x = \Phi(y, z)$, use the full normal space $D_y = \mathbb{R}^k$.
- For a boundary zero set, Σ is contained in a smooth portion of ∂K, away from corners. Its codimension within ∂K is $k - 1$. Use coordinates normal to Σ within ∂K, followed by inward boundary normal distance as the k-th coordinate. Then $D_y = \mathbb{R}^k_+$, with $z_k > 0$ in K.

The normal derivatives at $z = 0$ form an orthonormal frame and are perpendicular to the tangential derivatives. If $\mathrm{d}x = J(y, z)\,\mathrm{d}y\,\mathrm{d}z$ in a chart, then $J(y, 0)\,\mathrm{d}y = \mathrm{d}\sigma(y)$, the induced measure on Σ. Put $\Omega_y = D_y \cap S^{k-1}$, with ordinary surface measure in its normal frame. All supported forms use zero extension, also on the half-space D_y.

Let a be bounded, nonnegative, and bounded below by a positive constant outside every neighborhood of Σ, in the essential sense. Assume the uniform normal expansion

$$a(\Phi(y, z)) = |z|^p \big(c(y, \widehat{z}) + o(1)\big), \qquad p > 0, \quad \widehat{z} = z/|z|, \tag{45}$$

where c is continuous on the unit normal spheres or closed inward hemispheres and $0 < c_* \le c \le c^* < \infty$. For $M \to \infty$ define

$$H_M = (2\sqrt{|D|^2 + \kappa_M^2})_K + M(a + \epsilon_M), \qquad \ell = M^{-1/(p+1)}, \quad \kappa_M \to \kappa \ge 0, \quad \epsilon_M \ge 0, \quad \epsilon_M \to 0. \tag{46}$$

Write $Q_M(f) = \langle f, H_M^{-1} f\rangle$. The source $f \in L^2(K)$ is continuous near Σ, up to the boundary when applicable. A source with values in a separable Hilbert space is allowed, with the form acting only in x. For $p > k$ define the normal coefficient

$$\mathcal{C}_y(\lambda) = \sup_v \left\{ 2\,\mathrm{Re} \int_{D_y} v\,\mathrm{d}z - 2\langle v, |D_z| v\rangle - \int_{D_y} \big(c(y, \widehat{z})|z|^p + \lambda\big)|v|^2\,\mathrm{d}z \right\}. \tag{47}$$

The supremum is over the closed normal form domain, equivalently over smooth compactly supported tests.

Theorem 22 (Normal confinement)**.** *The following are normalized limits, including when f vanishes on Σ.*

1. *If $p < k$, then $MQ_M(f) \to \int_K \|f(x)\|^2/a(x)\,\mathrm{d}x$.*
2. *If $p = k$, set $\rho_M = \max(\ell, \epsilon_M^{1/k})$. Then*

$$\frac{M}{\log(1/\rho_M)} Q_M(f) \longrightarrow \int_\Sigma \|f(y)\|^2 \left(\int_{\Omega_y} c(y,\omega)^{-1}\,\mathrm{d}\omega \right) \mathrm{d}\sigma(y).$$

   For zero floor, $\log(1/\rho_M) = \log M/(k+1)$.

3. *If $p > k$ and $M\ell\epsilon_M \to \lambda < \infty$, then*

$$\ell^{-(k+1)} Q_M(f) \longrightarrow \int_\Sigma \|f(y)\|^2 \mathcal{C}_y(\lambda)\,\mathrm{d}\sigma(y).$$

   The coefficient $\mathcal{C}_y(\lambda)$ is finite, positive and invariant under orthogonal changes of normal frame preserving D_y.

4. *If $p > k$ and $M\ell\epsilon_M \to \infty$, then*

$$M\epsilon_M^{1-k/p} Q_M(f) \longrightarrow \frac{\pi}{p \sin(\pi k/p)} \int_\Sigma \|f(y)\|^2 \left(\int_{\Omega_y} c(y,\omega)^{-k/p}\,\mathrm{d}\omega \right) \mathrm{d}\sigma(y).$$

   For the normal coefficient the corresponding limit is

$$\lim_{\lambda\to\infty} \lambda^{1-k/p} \mathcal{C}_y(\lambda) = \int_{D_y} (1 + c(y,\widehat{z})|z|^p)^{-1}\,\mathrm{d}z.$$

40 Whole-space form comparison

Fix an accuracy $\eta > 0$. Refine a finite tubular atlas on Σ so that each chart is C^1-close to a rigid isometry, with differential error at most η on a slightly larger chart. This is possible after choosing orthonormal coordinates at its center. In the boundary case extend the smooth coordinate map across $z_k = 0$. For a full-space form comparison, subtract the rigid map on a coordinate ball centered at zero and write E for its remainder. Then $E(0) = 0$, $\|\nabla E\| \le \eta$, and $\|E(x)\| \le \eta|x|$. Multiply E by a cutoff equal to one on the smaller chart support and vanishing outside the larger ball. Its gradient is $O(\eta)$, including the derivative of the cutoff. Adding this extended remainder to the rigid map gives a global invertible bi-Lipschitz map by small-Lipschitz inversion. Distances and volume elements are distorted by factors $1 + O(\eta)$. This permits comparison of the entire jump form, with no restriction on whether its second integration variable lies inside the chart.

Denote the massless form by $E_d[V] = 2\langle V, |D|V\rangle$. Its kernel expression is a positive constant times

$$\iint_{\mathbb{R}^d\times\mathbb{R}^d} \frac{\|V(x) - V(x')\|^2}{|x - x'|^{d+1}}\,\mathrm{d}x\,\mathrm{d}x'.$$

Thus the physical form of a localized zero-extended function and the form of its chart pullback compare within $1 \pm O(\eta)$. The physical support becomes the chart support on D_y. In flat chart variables the normal multiplier $2|\xi_z|$ is bounded above by $2\sqrt{|\xi_y|^2 + |\xi_z|^2}$. Thus, with E_k the normal form,

$$0 \le E_d[V] - \int E_k[V(y,\cdot)]\,\mathrm{d}y \le 2\|V\|_2 \|\nabla_y V\|_2. \tag{48}$$

The symbol of the difference is at most twice the tangent frequency modulus, so (48) follows by Plancherel. The increment from mass κ_M is nonnegative and at most $2\kappa_M\|V\|_2^2$.

Use a fixed smooth real partition with $\sum_j \chi_j^2 = 1$ on a neighborhood of $\overline{K}$, with near supports in the atlas and far supports a positive distance from Σ. It can be completed outside K. The difference between the sum of localized kinetic forms and the original massless form has absolute kernel estimate

$$C\,\frac{\sum_j |\chi_j(x) - \chi_j(x')|^2}{|x - x'|^{d+1}}.$$

The numerator is bounded by $C_{\mathrm{atlas}} \min(|x - x'|^2, 1)$, so Schur's test bounds the absolute localization cost by $C_{\mathrm{atlas}}\|V\|_2^2$, also for Hilbert-valued functions. The contact and floor split exactly. This is the fixed-partition version of the fractional IMS estimate [42, Lemma 16].

In each near chart, kinetic comparison and (45) bound the form below by a fixed positive multiple of the direct integral of $2|D_z| + M|z|^p$. Normal dilation by ℓ gives a gap of order ℓ^{-1}. To see the positive unit-scale gap, the potential controls the L^2 mass of a function outside the unit ball. On the ball, the part with normal Fourier frequency $|\xi| \le s$ has squared norm at most Cs^k times the full squared norm by Fourier Cauchy–Schwarz. The high-frequency norm is controlled by the vertical kinetic energy divided by s. Choosing $s > 0$ small and absorbing proves the bound, with or without zero exterior support. The localized form in a far chart has gap of order M. Summing and absorbing the fixed localization error gives

$$H_M \succeq c_0 \ell^{-1} I, \qquad H_M \succeq M\epsilon_M I \tag{49}$$

for large M, uniformly in nonnegative mass and floor.

For the sharp upper comparison keep this atlas fixed. In each near chart take as a model $1 - O(\eta)$ times the direct integral of the normal supported form with symbol $2|D_z|$, potential $Mc(y, \widehat{z})|z|^p$ and floor $M\epsilon_M$. Narrow the tube if needed to pay the uniform error in (45). In the far charts take a positive order-M multiplication form. The fractional localization error and (49) imply

$$(1 + C_{\mathrm{atlas}}\ell)\,\mathfrak{h}_M[V] \;\ge\; \sum_j \mathfrak{h}_{M,j}^{\mathrm{mod}}[(\chi_j V)^{\mathrm{chart}}], \tag{50}$$

where $\mathfrak{h}_M$ is the full form. The source term splits using $\langle f, V\rangle = \sum_j \langle \chi_j f, \chi_j V\rangle$. In chart coordinate measure the source is $J\chi_j f$. Enlarge the local maximization to independent tests in the full normal model domains, extending the source by zero beyond each chart. Inequality (50) bounds the original quadratic above by $1 + C_{\mathrm{atlas}}\ell$ times the sum of these model inverse quadratics. In using it we take $M \to \infty$ at fixed η before refining the atlas.

41 Proof of the inverse limits

41.1 The integrable and logarithmic regimes

For $p < k$ the multiplication inverse bounds $MQ_M(f)$ by $\int_K \|f\|^2/a$; near Σ the normal radial factor is r^{k-1-p}. For the reverse bound use the variational formula with form $M^{-1}\mathfrak{h}_M$. On a fixed compactly supported smooth test the kinetic cost tends to zero. The limiting multiplication supremum is the stated integral by first cutting off away from the zero set and the boundary, then using L^2 density there and exhaustion. Finite-dimensional approximation in the source space gives the same bound for Hilbert-valued tests.

For $p = k$, split the source into the part within normal radius ρ_M and its complement. The inner squared norm is $O(\rho_M^k)$ and (49) bounds its inverse cost by $O(M^{-1})$. Indeed use

the gap ℓ^{-1} when $\rho_M = \ell$, and the floor gap when $\rho_M^k = \epsilon_M$. The outer cost is at most $M^{-1}\int_{\mathrm{out}} \|f\|^2/(a+\epsilon_M)$. Dropping the floor there and integrating $r^{-1}\,\mathrm{d}r$ between ρ_M and a small fixed radius gives the logarithmic coefficient. The coefficient error tends to zero as that outer radius shrinks by uniform continuity of the source, the Jacobian and (45). Outside this tube the cost is $O(M^{-1})$. The mixed inverse pairing of the two source parts is smaller than the logarithm by inverse Cauchy–Schwarz.

For the lower bound use a trial $M^{-1}r^{-k}\vartheta_{\rho_M}(r)U(y,\omega)$ with a smooth radial cutoff equal to one between a fixed multiple of ρ_M and a small fixed outer radius. Smooth Hilbert-valued fields U approximate $f(y)/c(y,\omega)$ on the normal sphere bundle by local smoothing and a partition of unity. In the boundary case first cut off smoothly away from the hemisphere equator, so the trial extends by zero in the supported form space. Polar integration gives squared norm $O(M^{-2}\rho_M^{-k})$ and squared gradient norm $O(M^{-2}\rho_M^{-k-2})$. Tangent and angular fields are fixed for this estimate, and angular derivatives cost r^{-1}. Hence the kinetic cost is $O(M^{-2}\rho_M^{-k-1}) = O(M^{-1})$, using the normal bound on ρ_M. The mass increment and floor cost are also $O(M^{-1})$, the latter since $\epsilon_M\rho_M^{-k} \le 1$. After division by $M^{-1}\log(1/\rho_M)$, the remaining objective tends to

$$\int_\Sigma \int_{\Omega_y} \bigl(2\,\mathrm{Re}\langle f(y), U(y,\omega)\rangle - c(y,\omega)\|U(y,\omega)\|^2\bigr)\,\mathrm{d}\omega\;\mathrm{d}\sigma(y),$$

up to an error made arbitrarily small with the outer radius. Approximating f/c and exhausting the hemisphere if needed proves the lower coefficient.

41.2 The normal oscillator and the large-floor regime

Let $p > k$ and write $\lambda_M = M\ell\epsilon_M \to \lambda < \infty$. The normal oscillator has the positive gap proved in Section 40. The constant is in its form dual because $|z|^{-p}$ is integrable at infinity in dimension k. A positive compactly supported test shows that $\mathcal{C}_y(\lambda) > 0$. Smooth compact tests are dense in the form: cut off at infinity in $H^{1/2}$ and in the potential norm, then translate slightly inward for the supported half-space and smooth without crossing the plane. Nearby angular coefficients compare their forms within factors $1 \pm o(1)$ by their uniform positive lower bound. Changes of λ are bounded form perturbations controlled by the gap. Thus $\mathcal{C}_y(\lambda)$ is continuous in a local normal frame, and invariance follows by rotations preserving the domain and unit source.

For the upper bound use (50). With chart coordinates the local source is

$$F_j(y,z) = J(y,z)\chi_j(\Phi(y,z))f(\Phi(y,z)).$$

Set this expression to zero off the chart. Dilation $z = \ell Z$ gives a factor $\ell^{k/2}$ on each source and a factor ℓ on the inverse. The resulting normal form is $2|D_Z| + c(y,\widehat{Z})|Z|^p + \lambda_M$. On bounded sets in Z, the source $F_j(y,\ell Z)$ tends to $F_j(y,0)$, with its form-dual error controlled by the gap. The tail beyond radius R has dual norm at most $CR^{(k-p)/2}$ times the uniform supremum of the source by the reciprocal potential estimate. The same estimate holds for the limiting constant source, so dual Cauchy–Schwarz controls the discarded terms. The resulting inverse limit in each fiber is $\|F_j(y,0)\|^2\mathcal{C}_y(\lambda)$ after normalization by $\ell^{-(k+1)}$, and these bounds permit integration in y. The far charts contribute $O(M^{-1}\|f\|^2) = o(\ell^{k+1})$ without normalization. In the local limit $J(y,0)^2\,\mathrm{d}y = J(y,0)\,\mathrm{d}\sigma(y)$, with $J(y,0) = 1 + O(\eta)$ in the chosen charts. Summing the squared partition gives one on Σ. Letting $\eta \downarrow 0$ removes the remaining distortion and proves the upper bound.

For the lower bound choose disjoint compact subsets of Σ, each in a sufficiently small chart, covering all but arbitrarily small surface measure. To obtain such subsets, partition Σ measurably

by chart membership and use inner regularity on each piece. The finitely many disjoint compacts have positively separated neighborhoods after shrinking. Choose smooth tangent cutoffs $0 \le \chi_j \le 1$ supported in these neighborhoods and equal to one on the compacts. In each chart choose a point y_j and a smooth compact normal template φ_j with objective arbitrarily close to $\mathcal{C}_{y_j}(\lambda)$. The templates can be chosen with uniformly bounded form norms by the uniform inverse bound and form density. Pull back the local trial

$$V_j(y,z) = \ell\, \chi_j(y) f(y_j) \varphi_j(z/\ell)$$

to physical coordinates and sum over the charts. The supports of the different terms remain separated by a fixed positive distance for all small ℓ. The massless cross terms are bounded by $C_{\mathrm{atlas}} \sum_j \|V_j\|_2^2 = O(\ell^{k+2})$ using the bounded cross kernel on separated supports. The mass increment of the sum is of the same order by the bounded perturbation. In each chart the normal kinetic term scales as ℓ^{k+1}, and the tangent cost is $O(\ell^{k+2})$ by (48). The metric changes the normal kinetic term by a relative $O(\eta)$. Uniform profile convergence gives the source and potential limits in these trials, with arbitrarily small errors from freezing c, f and the normal coefficient in the patch.

To account for tangent cutoffs, the scalar frozen objective at cutoff value χ_j has form $2\chi_j L - \chi_j^2 E$, where L is the source integral and $E \ge 0$ is the template energy. It is at least $\chi_j(2L - E)$. Thus the local lower bound includes the objective on the compacts. Metric and freezing errors are uniformly small in the bounded template norms. Optimizing the templates, refining the atlas and taking the compact cover defect to zero gives the full lower limit. The construction applies to Hilbert-valued sources and uses only local normal frames.

If $\lambda_M \to \infty$, put $\delta = \epsilon_M^{1/p}$ and $T = M\epsilon_M$. Then $T\delta = \lambda_M^{(p+1)/p} \to \infty$. The multiplication inverse, dilated by $z = \delta Z$, has scale δ^k/T. The normalized integrand in a tube is bounded by $C(1+|Z|^p)^{-1}$, integrable for $p > k$. Its limit is the reciprocal of $1 + c(y, \widehat{Z})|Z|^p$ times the squared source on Σ; the contribution off the tube vanishes by $\epsilon_M^{1-k/p} \to 0$. This gives the upper bound. The separated compact chart trials just used now have amplitude T^{-1} and width δ, with normal template approximating the multiplication optimizer by compact smooth tests. For each fixed template their kinetic cost $O(T^{-2}\delta^{k-1})$ is negligible relative to δ^k/T by $T\delta \to \infty$. The mass and separated cross costs and the tangent excess have smaller bounds. The potential and source limits give the matching lower bound.

In polar coordinates $t = c(y,\omega)|Z|^p$ reduces the reciprocal normal integral to $\pi/[p\sin(\pi k/p)]$ times the angular integral of $c^{-k/p}$. The large-λ matching law for (47) follows by the same argument: dilate $z = \lambda^{1/p} Z$ and divide the form by λ, so that the coefficient of the kinetic term tends to zero. The multiplication upper bound and compact test lower bound then agree. This completes the proof of Theorem 22.

41.3 Full-space and boundary coefficients

Corollary 23. *Fix $p > k$ and a continuous positive angular coefficient c on the full sphere such that $c(-\omega) = c(\omega)$. For each finite $\lambda \ge 0$, the coefficients of (47) for the same potential satisfy*

$$\mathcal{C}_{\mathbb{R}^k}(\lambda) > 2\mathcal{C}_{\mathbb{R}^k_+}(\lambda).$$

For even angular coefficients, the supported hemisphere gives exactly half the full-space angular factor in the critical and dominant-floor limits of Theorem 22.

Proof. The positive gap and the bounded dual source give a nonzero half-space optimizer v, which may be taken nonnegative because absolute value decreases the jump form. Extend v

by zero and set $v_-(z) = v(-z)$ on the full space. Their linear source pairings and separate quadratic energies agree by evenness. The mixed potential term is zero because the supports are disjoint up to a null set. The mixed kinetic form $\langle v, 2|D|v_-\rangle$ is strictly negative by the jump formula. Indeed its integrand is a negative multiple of $v(z)v_-(z')/|z-z'|^{k+1}$ between the two half-spaces, and is strictly negative on a set of positive measure. The mixed integral is finite by form Cauchy–Schwarz. Testing the full-space variational problem with $v + v_-$ gives an objective strictly larger than twice the half-space optimum. The two angular integrands in the theorem are even and the equator has zero angular measure, giving the other conclusions. □

41.4 Quadratic zeros in codimension two

For $k = p = 2$, suppose $a(\Phi(y,z)) = z^{\mathsf{T}} C(y) z + o(|z|^2)$, where $C(y)$ is positive definite on the normal plane. The angular factor is

$$\int_{S^1} \frac{\mathrm{d}\omega}{\omega^{\mathsf{T}} C(y)\omega} = \frac{2\pi}{\sqrt{\det C(y)}}.$$

Diagonalize C and substitute $t = \tan\theta$ in one quadrant to obtain this integral. Its restriction to any hemisphere is exactly half by evenness. With zero floor the interior inverse therefore has leading scale $2\pi \log M/(3M)$ times the integral of $\|f(y)\|^2/\sqrt{\det C(y)}$ over Σ. At a boundary the prefactor is halved. Here C is the quadratic-form matrix, equal to half the normal Hessian of a when that Hessian exists.

42 Connected traces at fixed separation

Let K_- and K_+ be bounded apertures at positive separation. At mass $\kappa \geq 0$, the two diagonal responses $H_\pm$ have the same supported kinetic normalization as in (46), and $G_\pm = H_\pm^{-1}$. Write $B_\kappa : L^2(K_+) \to L^2(K_-)$ for the separated off-diagonal kernel of $2\sqrt{|D|^2 + \kappa^2}$. With

$$T_\kappa = G_-^{1/2} B_\kappa G_+ B_\kappa^* G_-^{1/2}, \qquad q(\kappa) = -\operatorname{Tr}\log(I - T_\kappa),$$

the connected vacuum energy is $-\int_0^\infty q(\kappa)\,\mathrm{d}\kappa/(2\pi)$, and the free energy at inverse temperature $\beta > 0$ is $-(2\beta)^{-1}\sum_{n\in\mathbb{Z}} q(2\pi|n|/\beta)$. The same-screen pair interaction and relative obstacle determinants give precedents for the boundary method [19, 43]. We use the aperture determinant conventions of [1] and Sections 10–13. The multiplication contacts here are bounded and independent of the spectral parameter for every fixed pair of strengths. In the connected Galerkin determinant identity they add to the diagonal forms and leave the differentiated Poisson terms unchanged. Thus the same determinant and energy formulas apply to these profiles.

For a growing contact let S_M denote its normalization from Theorem 22, and define ν on $\overline{K}$ by writing the corresponding limit as $\int_{\overline{K}} \|f\|^2\,\mathrm{d}\nu$. In the integrable regime $\nu = a^{-1}\,\mathrm{d}x$. In the other regimes it is the coefficient density in that theorem times $\mathrm{d}\sigma$ supported on Σ.

Theorem 24 (One or two growing contacts)**.** *With one growing left contact and a fixed bounded nonnegative right contact,*

$$S_{M_-}\, q(\kappa) \longrightarrow \int_{\overline{K}_-} \|G_+^{1/2} B_\kappa^* \delta_x\|^2 \,\mathrm{d}\nu_-(x).$$

With two growing contacts satisfying the hypotheses separately and no relation between M_- and M_+,

$$S_{M_-} S_{M_+}\, q(\kappa) \longrightarrow \int_{\overline{K}_-} \int_{\overline{K}_+} |B_\kappa(x,y)|^2 \,\mathrm{d}\nu_+(y)\,\mathrm{d}\nu_-(x).$$

Both limits are uniform on compact mass intervals and have a common exponential majorant after the indicated normalization. Their vacuum and thermal limits are the integrals and sums of the limiting profiles with the prefactors above, with local uniformity for $\beta > 0$.

Proof. Separation bounds the kernel, and its first spatial derivatives, on the two compact aperture closures. Uniform bounds down to zero mass and exponential decay at large mass follow by differentiating the usual separated square-root subordination integral. In that integral the Gaussian off-diagonal factor controls short times, and the mass factor controls long times. The weaker fixed opposite response has a positive gap also at mass zero, by the jumps from the supported aperture to the exterior of a ball containing it. Its inverse square root varies continuously in mass in operator norm since the mass change is a bounded form perturbation of norm at most $2|\kappa - \kappa'|$. Thus $F_\kappa(x) = G_+^{1/2} B_\kappa^* \delta_x$ is a bounded continuous Hilbert-valued source, with the same exponential bound and continuous dependence on mass in supremum norm.

For bounded Hilbert-valued sources the inverse proof gives $S_M Q_M(F) \le C\|F\|_\infty^2$ uniformly in mass. Use multiplication for $p < k$ and in the dominant-floor case, and the critical core and outer bounds for $p = k$. For the finite-floor power case split the source at radius ℓ. The inner squared norm costs $O(\ell^k)\|F\|_\infty^2$ with inverse norm $O(\ell)$. The outer reciprocal multiplication cost is $O(M^{-1}\ell^{k-p})\|F\|_\infty^2 = O(\ell^{k+1})\|F\|_\infty^2$. The mixed term is bounded by inverse Cauchy–Schwarz. This also proves stability under a source perturbation tending to zero in supremum norm. The first trace $\operatorname{Tr} T_\kappa$ is the Hilbert-valued inverse quadratic on F_κ, by the Hilbert–Schmidt factorization. Theorem 22 therefore gives the one-contact first-trace limit along any bounded mass-converging sequence. The unrescaled contraction satisfies $\|T_\kappa\| = O(\ell_-)$ by (49), the fixed inverse gap and the separated kernel bound. Hence the sum of higher logarithmic terms is at most $O(\ell_-) \operatorname{Tr} T_\kappa$.

For two growing contacts, use the positive inverse kernels of the two-contact construction in Sections 14–17. For completeness, the square-root form has positive jump weights and a nonnegative mass term. Its resolvent preserves positivity by testing with a negative part. Comparing the supported response with the full-space kinetic response on nonnegative forcing, test the difference on its positive part, using that the larger-domain solution is nonnegative and that the contact adds a nonnegative term. This dominates the positive resolvent by the full-space resolvent with the same positive shift, and yields the analogous semigroup order by the product limit. The whole-space semigroup has a bounded positive density for each positive time. Integrating over finite time windows bounded away from zero gives dominated nonnegative measurable kernels. These kernels increase almost everywhere as the windows expand to all positive times, and the inverse gap identifies their limit with the inverse in pairings of nonnegative test functions. The total inverse kernel mass on the aperture squared is finite by testing the constant function.

The positive measures with densities $S_{M_i} G_i(x, x')$ on $\overline{K}_i^2$ consequently have bounded masses. By real polarization and Theorem 22, along any bounded mass-converging sequence their pairings with $\phi(x)\psi(x')$ converge to $\int \phi(x)\psi(x)\,\mathrm{d}\nu_i(x)$ for continuous ϕ, ψ. Product tests are dense on the compact closure squared. Thus the measures converge weakly to the diagonal pushforwards of ν_i, including boundary concentration. The normalized first trace is the product-measure pairing with $B_\kappa(x', y)\overline{B_\kappa(x, y')}$. For instance, approximate the separated kernel uniformly by step functions on rectangles. For those kernels the trace identity is the product of inverse pairings. The kernel errors are bounded by the finite masses, and the operator trace errors vanish by Hilbert–Schmidt convergence of the crossed kernels and boundedness of the inverses at each fixed parameter. This proves the identity and product convergence to $|B_\kappa(x, y)|^2$ on the two diagonals, independently of the two rates. The unrescaled determinant contraction satisfies $\|T_\kappa\| = O(\ell_-\ell_+)$ by the two gaps. Consequently $\sum_{j\ge 2} \operatorname{Tr}(T_\kappa^j)/j \le C\|T_\kappa\| \operatorname{Tr} T_\kappa$ for sufficiently large strengths.

The kernel envelopes and bounded normalized inverse quadratics or measure masses give exponential domination in both cases. Compact uniformity follows from convergence along bounded mass-converging sequences and continuity of the limiting profiles. Dominated integration and summation give the stated energies. □

43 Slow-coordinate zeros in a shrinking aperture gap

A repulsive surface contact on an aperture adds a multiplication term to the supported square-root response [7] and Sections 10–13. When the strength grows, the connected trace can concentrate near the zeros of that coefficient. For a fixed positive aperture separation and an order-p zero of codimension k, the normal confinement width is $\ell = M^{-1/(p+1)}$, with a threshold at $p = k$ and a full k-dimensional oscillator above it Sections 38–42. When the gap closes, a zero set prescribed in the slow tangential coordinates has a different relation to the aperture kinetic energy. Localization still occupies k effective variables, but only the vertical variable retains kinetic energy in the leading cell. The other normal coordinates enter the potential as parameters.

The square-root aperture action and the scalar interaction of holes in a single screen go back to Kabat, Karabali and Nair [7, 19]. Fosco and Mazzitelli [14, Section IV] develop a smooth derivative expansion for spatially varying contacts on parallel plates. For approaching aperture tangencies, the common and asymmetric contact baselines Sections 5–9, Sections 10–13 and Sections 14–17 give the contact geometry and the massless weak column estimates used here. The curved degenerate result in Sections 27–31 concentrates at one zero depth in each slow fiber, with that depth allowed to vary between fibers. Concentration around a proper subset of slow fibers introduces additional confinement volume.

Braides, Pinamonti and Solci [31, Theorem 3.3] obtain vertical fractional energies in the dimension reduction of a regional thin-film seminorm. Ao et al. [41, Lemma 5.7 and Remark 5.8] compare an ambient fractional operator near a singular submanifold with a normal model. Normal-bundle and slow–fast operator methods also occur in local confinement and semiclassical dynamics [44, 47]. Here the form is supported, the confinement is a multiplication potential, and the observable is a forced inverse in a connected trace. The key estimate compares the full inverse with a vertical direct integral. For compact normal trial functions the relative tangent cost tends to zero with the sum of the confinement width and the geometric slope scale. This permits independent gap and strength limits.

44 Geometry and the scaling law

Let $d \geq 2$ be the screen dimension. In screen coordinates $(s_0, y) \in \mathbb{R} \times \mathbb{R}^{d-1}$, two bounded convex apertures lie in opposite supporting half-spaces. Their closures meet only at the origin before translation by $\mp g/2$ along s_0. Near the contact their facing graphs are $s_0 = -h_-(y)$ and $s_0 = h_+(y)$, with interiors on their outer sides. We take either of the geometries of Sections 5–9. In the quadratic case the graphs are C^2 and their total Hessian $B_- + B_+$ is positive definite. Set $r_j = 2$ and $H(w) = 1 + \frac{1}{2} w^{\mathsf{T}}(B_- + B_+)w$. In the separable finite-type case, for $r_j > 1$ in orthonormal tangent coordinates, assume

$$h_i(y) = \sum_j b_{ij}|y_j|^{r_j} + o\left(\sum_j |y_j|^{r_j}\right), \qquad b_{ij} \geq 0, \quad b_{-j} + b_{+j} > 0.$$

Set $H(w) = 1 + \sum_j (b_{-j} + b_{+j})|w_j|^{r_j}$. Write $y_j = g^{1/r_j} w_j$, $\alpha = \sum_j 1/r_j$, and $\gamma = d - 1 - \alpha$. The inward vertical depths u, v are measured in units of g.

In the left facing tangent chart we prescribe the scaled contact $M[a(w,u)+\epsilon]$, and M outside it, where $M = M_g \to \infty$, $\epsilon = \epsilon_g \geq 0$, $\epsilon \to 0$, and

$$\ell = M^{-1/(p+1)}.$$

The physical contact is the scaled one divided by g. On the right prescribe a bounded continuous nonnegative scaled coefficient $b(w,v)$ in its facing chart and any uniformly bounded nonnegative coefficient outside it.

Let $\Theta \subset \mathbb{R}^{d-1}$ be a compact smooth embedded submanifold without boundary of slow-space codimension s, $1 \leq s \leq d-1$, and let $u_0 \geq 0$ be fixed. Put $k = s+1$, and let $D = \mathbb{R}$ when $u_0 > 0$ and $D = (0,\infty)$ when $u_0 = 0$. The latter normal operator always uses zero exterior extension. The bounded continuous $a \geq 0$ is bounded below by a positive constant outside every neighborhood of $\Theta \times \{u_0\}$. In orthonormal tubular coordinates $w = \Phi_\Theta(y_0, \zeta)$ for Θ, with $\zeta \in \mathbb{R}^s$ in a local normal frame, suppose

$$a(\Phi_\Theta(y_0,\zeta), u_0 + z) = A_{y_0}(\zeta, z) + o((|\zeta|^2 + z^2)^{p/2}), \qquad p > 0, \tag{51}$$

uniformly in the base $y_0 \in \Theta$ and allowed normal directions. Write $A_{y_0}(R\omega) = R^p c(y_0, \omega)$, where $R^2 = |\zeta|^2 + z^2$. The angular coefficient c is continuous and uniformly positive on the normal unit spheres or inward closed hemispheres. Denote the integration region on the sphere by $\Omega = (\mathbb{R}^s \times D) \cap S^{k-1}$.

At mass $\kappa \geq 0$ in gap units let $H_{-,g}$ and $H_{+,g}$ be the supported compressions of $2\sqrt{|D|^2 + \kappa^2}$ with their contacts, and B_g the separated off-diagonal response. The positive connected transform is the negative logarithmic trace

$$q_g(\kappa) = -\operatorname{Tr}\log(I - T_g), \qquad T_g = H_{-,g}^{-1/2} B_g H_{+,g}^{-1} B_g^* H_{-,g}^{-1/2}.$$

In the physical frequency convention the vacuum energy and the free energy at inverse temperature $\beta > 0$ are

$$\mathcal{E}_g = -\frac{1}{2\pi g}\int_0^\infty q_g(\kappa)\,\mathrm{d}\kappa, \qquad \mathcal{F}_{g,\beta} = -\frac{1}{2\beta}\sum_{j\in\mathbb{Z}} q_g(2\pi|j|g/\beta).$$

These are the connected determinant conventions of [1] and Sections 10–13.

Let A_q denote the right ray compression of $2\sqrt{D_v^2 + q^2}$. For $L > 0$ put $f_{q,L}(v) = -2qK_1(q(L+v))/[\pi(L+v)]$, with $f_{0,L}(v) = -2/[\pi(L+v)^2]$. Define the frozen column

$$J_\kappa(w,u) = \frac{1}{(2\pi)^{d-1}}\int_{\mathbb{R}^{d-1}} \left\langle f_{q,H(w)+u}, (A_q + b(w,\cdot))^{-1} f_{q,H(w)+u}\right\rangle_{\text{dual}} \mathrm{d}\xi, \qquad q = \sqrt{\kappa^2 + |\xi|^2}. \tag{52}$$

The convention includes the homogeneous form-dual inverse when $q = 0$ and the right contact is transparent.

Theorem 25 (Shrinking gap and strong contact)**.** *The following are the limits of $g^\gamma S_M q_g(\kappa)$. No relation between M and g^{-1} is required.*

1. *For $p < k$, $S_M = M$ and the limit is $\int_{\mathbb{R}^{d-1}}\int_0^\infty J_\kappa(w,u)/a(w,u)\,\mathrm{d}u\,\mathrm{d}w$.*
2. *For $p = k$, put $\rho = \max(\ell, \epsilon^{1/k})$ and $S_M = M/\log(1/\rho)$. The limit is*

$$\int_\Theta J_\kappa(y_0,u_0)\left(\int_\Omega c(y_0,\omega)^{-1}\,\mathrm{d}\omega\right)\mathrm{d}\sigma_\Theta(y_0).$$

For zero floor, $\log(1/\rho) = \log M/(k+1)$.

3. *For $p > k$ and $M\ell\epsilon \to \lambda < \infty$, take $S_M = \ell^{-(k+1)}$. The limit is*

$$\int_\Theta J_\kappa(y_0, u_0)\mathcal{M}_{y_0}(\lambda)\,\mathrm{d}\sigma_\Theta(y_0), \qquad \mathcal{M}_{y_0}(\lambda) = \int_{\mathbb{R}^s} \left\langle 1, (2|D_z| + A_{y_0}(W, z) + \lambda)_D^{-1} 1 \right\rangle_{\mathrm{dual}} \mathrm{d}W.$$

4. *For $p > k$ and $M\ell\epsilon \to \infty$, take $S_M = M\epsilon^{\,1-k/p}$. The limit is*

$$\frac{\pi}{p\sin(\pi k/p)} \int_\Theta J_\kappa(y_0, u_0) \left(\int_\Omega c(y_0, \omega)^{-k/p}\,\mathrm{d}\omega \right) \mathrm{d}\sigma_\Theta(y_0).$$

Convergence is uniform for bounded $\kappa \geq 0$, with a common exponential majorant at large mass. If $P(\kappa)$ denotes the applicable limit, then

$$g^{\gamma+1} S_M \mathcal{E}_g \longrightarrow -\frac{1}{2\pi} \int_0^\infty P(\kappa)\,\mathrm{d}\kappa,$$
$$g^{\gamma+1} S_M \mathcal{F}_{g,\beta_* g} \longrightarrow -\frac{1}{2\beta_*} \sum_{j\in\mathbb{Z}} P(2\pi|j|/\beta_*).$$

The gap-temperature limit is locally uniform for $\beta_* > 0$. At fixed physical inverse temperature the leading limit is the vacuum limit.

45 Weak columns and the strong gap

In fully gap-scaled coordinates $X = (X_s, X_t)$ with $X_t = y/g$, let B_g be the separated cross kernel and $H_{+,g}$ the weak response. Define the Hilbert-valued left source

$$F_g(X) = H_{+,g}^{-1/2} B_g^* \delta_X, \qquad C_g = B_g H_{+,g}^{-1} B_g^*.$$

Let d_{sep} be the distance of X to the right aperture in scaled coordinates. For $d \geq 2$, the homogeneous Sobolev dual bound in Sections 10–13 controls $\|F_g(X)\|^2$ by the squared $L^{2d/(d+1)}$ norm of the right cross column. The separated kernel bound gives $Ce^{-c\kappa} d_{\mathrm{sep}}^{-d-1}$, as $d_{\mathrm{sep}} \geq 1$. The same argument with differentiated cross columns gives fixed-compact-mass bounds for the squared norms of the physical scaled derivatives in X. In a left chart $d_{\mathrm{sep}} \gtrsim 1 + u + \psi(w)$, $\psi(w) = \sum_j |w_j|^{r_j}$. Outside a suitable smaller chart $d_{\mathrm{sep}} \gtrsim g^{-1}$, so the integrated column estimate there is $O(ge^{-c\kappa})$ in scaled volume even before multiplying by g^γ. In particular

$$g^\gamma \|F_g\|_{L^2}^2 \leq Ce^{-c\kappa}.$$

The contraction bound $\|C_g\| \leq C$ follows from supporting-half-space comparison with transparent weak contact and its planar tangential fibers. These statements use only nonnegativity of the right contact.

Along $(w_g, u_g, \kappa_g) \to (w, u, \kappa)$ in a compact chart, including $u = 0$, one has $\|F_g(w_g, u_g)\|^2 \to J_\kappa(w, u)$. To see the needed uniform-local version of the variational argument of Sections 10–13 and Sections 14–17, translate the right aperture by the left evaluation point. Its facing graph tends uniformly on compact sets to the plane at $H(w) + u$. Offsets by bounded fully scaled tangent distances change the slow coordinate by $O(\max_j g^{1-1/r_j})$, so the right potential converges locally uniformly in the limiting interior to $b(w, v)$. The separated sources converge in $L^{2d/(d+1)}$ by dominated convergence. Compact form tests give the lower variational bound. Near-maximizers have bounded homogeneous energy and hence local $H^{1/2}$ compactness after cutoff, using the Sobolev bound and the homogeneous cutoff estimate in Sections 10–13. A

limit vanishes outside the half-space. The potential cost has a lower bound from strong local L^2 convergence on compact sets and exhaustion, discarding the contribution exterior to the compact exhaustion. When $\kappa > 0$ the near-maximizers are also bounded in global L^2 by the mass gap, and the varying kinetic mass changes the forms by at most $2|\kappa_g - \kappa|$ times the squared norm. At $\kappa = 0$ one drops the nonnegative kinetic mass increment for the upper limit. Compact tests are dense in the supported homogeneous form plus potential norm by the cutoff estimate in Sections 10–13, then inward translation and smoothing, with the bounded potential included by dominated convergence at the cutoff step. No positive lower bound on the weak contact is needed. Tangential Plancherel gives J_κ, by positive diagonal mass regularization at the homogeneous endpoint. The translated boundary argument also applies when the left evaluation lies on the facing graph itself, because it remains separated from the right aperture. These estimates give continuity of J_κ and the sequential local convergence claimed above.

Let G_g be the full left inverse and N_g the direct integral inverse using only the vertical Fourier multiplier $2\sqrt{D_s^2 + \kappa^2}$ with the same contact. Convexity gives an interval per vertical fiber and depth translation preserves the vertical form. Zero extension and Fourier comparison give $0 \le G_g \le N_g$. The profile satisfies $a(w,u) \gtrsim \min(1, |u - u_0|^p)$ throughout the left chart, by its local asymptotic near the compact zero set and its positive lower bound away. Thus the one-dimensional kinetic and potential gap used in the one-depth source theorem Sections 27–31 gives $\|N_g\| \le C\ell$ uniformly in the fiber and in κ, by comparing to the full line and then restricting to the supported interval. Here one can use $M \min(1, |u - u_0|^p)$ in the gap proof: after dilation by ℓ it controls the L^2 norm outside unit depth uniformly. Off-chart the gap M is stronger. The independent floor gap $M\epsilon$ holds globally for large M, since the off-chart coefficient is M and $\epsilon \le 1$.

The first determinant trace is $\langle F_g, G_g F_g \rangle$ in Hilbert-valued notation. Its upper bound is the vertical quadratic with N_g. The unrescaled positive Fredholm contraction $G_g^{1/2} C_g G_g^{1/2}$ has norm $O(\ell)$, so the higher logarithmic terms have relative error $O(\ell)$. The determinant identity of [1] and Sections 10–13 extends to bounded nonnegative spatial multiplication contacts for each fixed g by the same Galerkin and Poisson differentiations, as in Sections 14–17. Its bridge formula gives nonnegativity and mass monotonicity.

The full and vertical form difference on a supported Hilbert-valued trial V is bounded by $2\|V\|_2 \|\nabla_{X_t} V\|_2$ by the kinetic symbols. The slow chart differentiations satisfy

$$\partial_{X_{t,j}} w_j = g^{1-1/r_j}, \qquad |\nabla_{X_t} u| \lesssim a_g := \max_j g^{1-1/r_j}$$

on a fixed compact slow tangent set. The second estimate uses the left facing graph and its convexity. Indeed on the scaled physical image of a fixed larger slow set the graph heights are $O(g)$. For every coordinate take two directional difference quotients of lengths of order g^{1/r_j} on either side. Convexity bounds its derivatives in that direction by $O(g^{1-1/r_j})$ on the smaller set. This argument also applies in the quadratic chart. Weak scaled derivatives of the separated field are bounded on such sets independently of g. The physical scaled derivative in X applies only to the separated cross column, with the weak inverse fixed.

46 Integrable and critical powers

For $p < k$ the inverse multiplication bound yields, after $g^\gamma M$ normalization, the integral of $\|F_g(w,u)\|^2/(a(w,u) + \epsilon)$ in the left chart, plus a vanishing off-chart contribution. The effective normal volume in the profile variables is $R^{k-1} dR\, d\omega\, d\sigma_\Theta$, since dx in scaled aperture coordinates is $g^{-\gamma} dw\, du$. The reciprocal is locally integrable at the zero set by $p < k$. Away from it the chart

column envelope is integrable and a is bounded away from zero. Dominated convergence gives the desired upper limit. To get the lower bound test in the full form with $M^{-1}m(w,u)F_g(w,u)$, where m is smooth compactly supported in the chart interior away from the zero set and from $u = 0$, approximating $1/a$ there. The scaled g^γ times its squared H^1 norm is $O(M^{-2})$ by the separated field bounds and bounded chart derivatives. Therefore the normalized kinetic cost tends to zero. The limiting source and multiplication terms give $\int J_\kappa(2m - am^2)$, and exhaustion yields the reciprocal integral.

For $p = k$, split the source at effective tube radius ρ in (ζ, z). Its inner squared norm, after g^γ, is $O(\rho^k e^{-c\kappa})$. The gap ℓ^{-1} or the floor gap $M\epsilon$ gives inner inverse quadratic cost $O(M^{-1}e^{-c\kappa})$. Drop the floor in the outer reciprocal estimate. By the uniform-local column limit and tubular Jacobian, its only leading logarithm is the normal radial integral $M^{-1}\int_\rho^{R_0} R^{-1}dR$ times the indicated angular coefficient, in g^γ normalization. More precisely, in the small fixed tube the discrepancy from the frozen squared norm and the angular form can be made arbitrarily small by first taking $g \to 0$ and then $R_0 \downarrow 0$. The contribution away from this tube is $O(M^{-1})$. Inverse Cauchy–Schwarz makes the cross term between the inner and outer sources smaller than the logarithm.

For the matching lower bound take $F_g(w,u)$ times $M^{-1}R^{-k}\vartheta_\rho(R)\, m(y,\omega)$, where the radial cutoff is one between a fixed multiple of ρ and R_0, and m is a smooth angular and tangent approximation to c^{-1} on the normal sphere bundle. For the boundary case first cut away a small angular neighborhood of the equator and exhaust it afterwards. After multiplying the norm squares by g^γ, the trial and its physical scaled full gradient have squared norms $O(M^{-2}\rho^{-k})$ and $O(M^{-2}\rho^{-k-2})$, respectively, using the column derivative bound and the bounded coordinate derivatives. Thus the kinetic cost is $O(M^{-2}\rho^{-k-1}) = O(M^{-1})$ in the same volume normalization, and the floor cost is $O(M^{-1}\epsilon\rho^{-k})$. The linear and potential terms have radial factor $M^{-1}R^{-1}dR$ and recover the angular factor by approximation. This proves the critical limit.

47 The mixed vertical cell

Let $p > k$ and $\lambda_g = M\ell\epsilon \to \lambda < \infty$. Work first with the vertical upper comparator N_g. Outside the effective tube $R\ell$, for fixed $R \geq 1$, the multiplication upper bound gives

$$g^\gamma \langle F_g \mathbf{1}_{\mathrm{out}}, N_g F_g \mathbf{1}_{\mathrm{out}} \rangle \leq Ce^{-c\kappa}(\ell^{k+1}R^{k-p} + M^{-1}).$$

Indeed $a \gtrsim r^p$ in a fixed small tube, and $\int_{R\ell}^{r_0} r^{k-1-p}dr \lesssim (R\ell)^{k-p}$. Outside that tube use the positive bound on a and the global scaled column norm. The squared source norm inside radius ℓ is $O(g^{-\gamma}\ell^k e^{-c\kappa})$. The inverse gap supplies a factor ℓ. Taking $R = 1$ first proves $g^\gamma\langle F_g, N_g F_g\rangle = O(\ell^{k+1}e^{-c\kappa})$ using inverse Cauchy–Schwarz. Taking $R \to \infty$ thereafter shows that all omitted tails and mixed terms are uniformly negligible in the normalized comparison.

At fixed R set $w = \Phi_\Theta(y, \ell W)$ and $u = u_0 + \ell z$. The tubular charts and their local partitions in y disintegrate the vertical quadratic. The operator acts pointwise in w, so this disintegration has zero kinetic localization cost. The tangential Jacobian contributes $\ell^s\, d\sigma_\Theta(y)dW$ in the limit. In a vertical fiber the unitary depth dilation contributes one inverse factor ℓ and one paired-source factor ℓ. The scaled vertical kinetic form is $2\sqrt{|D_z|^2 + (\ell\kappa)^2}$. Its supported interval tends to D, since the rear face is a positive physical distance away and the fixed facing depth is $u = 0$. The scaled potential tends uniformly on compact (W,z)-sets to $A_y(W,z) + \lambda$, by homogeneity $M\ell^{p+1} = 1$ and the stated expansion.

For a fixed y, W, the truncated source differs in Hilbert norm from $F_g(w,u_0)$ by $O(\ell R)$ on its depth support, by the vertical derivative bound. The limiting normal calculation therefore

concerns a fixed scalar truncated unit source, times $\|F_g(w,u_0)\|^2 \to J_\kappa(y,u_0)$. The vertical inverse converges on such a scalar source by the variational argument of the depth oscillator theorem in Sections 27–31. Compact tests give the lower limit. The uniform rescaled gap bounds near-maximizers in L^2 and in vertical $H^{1/2}$, hence in local strong L^2 after extraction. Form lower semicontinuity and compact-set exhaustion for the positive potential cost give the upper limit, with support in D. The bounded mass increment vanishes after dilation. In the half-line case compact test density holds by cutting off, translating a little inward and smoothing. The diagonal inverse quadratics for the truncated source are uniformly bounded on compact W-sets by the rescaled gap, so they converge under integration with the tangential Jacobian. Together with the outer estimates this shows the upper comparator has the stated mixed normal limit.

The mixed coefficient can equivalently be defined by maximizing

$$2\,\mathrm{Re}\int_{\mathbb{R}^s\times D} V\,dW\,dz - \int_{\mathbb{R}^s}\left[2\langle V(W,\cdot),|D_z|V(W,\cdot)\rangle + \int_D (A_y(W,z)+\lambda)|V(W,z)|^2 dz\right] dW.$$

There is a uniform positive gap from the vertical kinetic and normal potential, and the constant source is in the form dual since $A_y(W,z) \gtrsim (|W|^2+z^2)^{p/2}$ at infinity and $p>k$. Thus the mixed coefficient is finite, positive and equals the integral of the one-dimensional inverse quadratics. Its continuity in y within a local normal frame follows from the multiplicatively comparable angular coefficients and the uniform gap. Smooth compact templates in W,z, supported in D, are a core: first truncate in both variables, using the vertical fractional cutoff bound in z, then use translation inward on a supported ray and mollify in both variables. The potential is bounded on compact supports. This density also permits scalar recovery functions without any smoothness of the optimizer in W.

For the full inverse lower bound choose finitely many disjoint compact subsets of Θ in small charts, covering all but arbitrarily small surface measure. Take smooth $0 \le \chi_j(y) \le 1$ equal to one on those compacts and supported in their mutually separated neighborhoods. Freeze A_y at y_j in each patch and choose a fixed smooth compact mixed template $\varphi_j(W,z)$ nearly optimizing the scalar cell coefficient there. Templates may be chosen of uniformly bounded model form norm using the positive gap and a bounded dual source norm. In physical scaled coordinates the trial is

$$V_j(X) = \ell\,\chi_j(y)\,F_g(w,u_0)\,\varphi_j(\zeta/\ell,(u-u_0)/\ell).$$

The evaluation $F_g(w,u_0)$ follows the left facing graph at depth u_0. At a boundary zero the same separated formula defines it on the graph. Its first derivatives in the fully scaled tangent coordinates along this graph are uniformly bounded on the patch. This uses the physical X-derivative bound for F_g and the graph slope bound.

For the vertical energy $F_g(w,u_0)$ is constant in u. Thus the exact leading objective, after the normalization $g^\gamma \ell^{-(k+1)}$, is the mixed variational objective with the additional source weight $J_\kappa(y,u_0)$. In the source pairing one replaces $F_g(w,u)$ by $F_g(w,u_0)$ at cost $O(\ell)$ on fixed templates, by the derivative estimate. The tubular Jacobian tends to the induced measure on the base. The small patch variations of A_y are controlled by the model template energy, using its uniform positive homogeneous lower bound. At cutoff value χ_j the frozen scalar objective $2\chi_j L - \chi_j^2 E$ is at least $\chi_j(2L-E)$, where $E \ge 0$. This permits exhausting the compact cover.

The passage from the trial's vertical to its full energy is negligible with no coupling between the two scales. In detail

$$g^\gamma\|V_j\|_2^2 = O(\ell^{k+2}), \qquad g^\gamma\|\nabla_{X_t}V_j\|_2^2 = O(\ell^{k+2}+a_g^2\ell^k).$$

The ℓ^{k+2} gradient term is the separated-field derivative. Derivatives of the rescaled templates cost $O(a_g/\ell)$, including both the normal bundle coordinates in the slow tangential space and

the displacement of the vertical depth by the graph slope. The tangent cutoff has smaller cost. Consequently the normalized excess kinetic energy is $O(\ell + a_g)$. The geometric part is $O(a_g)$ and the separated-field derivative adds $O(\ell)$. Before summing trials, their supports are separated in w, hence uniformly separated in the fully gap-scaled tangential coordinates. The jump kernel between separated sets has a uniform Schur bound by integrability outside a fixed radius. The cross energy is at most a constant times the sum of squared trial norms. The bounded mass increment has the same bound. These terms vanish in normalization. Optimizing the templates, refining the finite chart cover and exhausting the compacts prove the lower bound. This finishes the $p > k$ finite-floor case for the full response.

48 Dominant floor and passage to energy

If $M\ell\epsilon \to \infty$, put $\delta = \epsilon^{1/p}$ and $T = M\epsilon$, so $T\delta \to \infty$. The multiplication upper bound after g^γ and $(\zeta, z) = \delta(W, Z)$ has scale δ^k/T and normal integrand dominated by $C(1 + (|W|^2 + Z^2)^{p/2})^{-1}$. Its limit uses the compact-uniform column squared norm and the intrinsic tubular Jacobian. Outside a fixed effective tube the normalized cost vanishes as $\epsilon^{1-k/p} \to 0$. The same disjoint-chart lower recovery construction as above with amplitude T^{-1} and width δ approximates the reciprocal multiplication optimizer. Every fixed template has full kinetic cost, after the factor g^γ, at most $O(T^{-2}\delta^{k-1})$ by the L^2-gradient bound on the supported extension. This is negligible compared with δ^k/T by $T\delta \to \infty$. The potential and source terms give the matching coefficient in the statement. The angular beta integral follows from the substitution $t = c(y, \omega)R^p$. Dilation in the mixed model by $\lambda^{1/p}$ and multiplication comparison or compact lower trials give the same large-λ law for $\mathcal{M}_y$.

For all regimes the upper bounds above carry $e^{-c\kappa}$ at the prescribed normalization, including the first trace and its higher logarithm terms. The proofs work along any bounded mass-converging sequence, with the same weak-column convergence and fixed test estimates. The limiting coefficient is continuous in κ by the displayed coefficients and the column majorants. This proves compact uniformity and permits dominated vacuum integration and the Matsubara series at $\beta_* g$. For fixed physical inverse temperature, monotone mesh comparison of the connected heat transform applies to the normalized transform, with mesh $2\pi g/\beta$ and error bounded by this step times the bounded normalized zero mode.

49 Comparison with the full normal oscillator and examples

For a fixed base point y_0, write $A = A_{y_0}$ on $X = \mathbb{R}^s \times D$. For $p > k$, the full coefficient

$$\mathcal{C}_{\mathrm{full}}(\lambda) = \langle 1, (2|D_{W,z}| + A + \lambda)_X^{-1} 1 \rangle_{\mathrm{dual}}$$

is the normal model from fixed positive separation Sections 38–42. In this notation $\mathcal{M}_{y_0} = \mathcal{C}_{\mathrm{mixed}}$, where the kinetic term is $2|D_z|$ integrated over W. Both have positive form gaps from the vertical kinetic and confining potential. The constant source is in both form duals for $p > k$, and their maximizers are nonzero.

Theorem 26 (Strict comparison)**.** *If $s \geq 1$, then $\mathcal{C}_{\mathrm{mixed}}(\lambda) > \mathcal{C}_{\mathrm{full}}(\lambda)$ for every finite $\lambda \geq 0$, including on the supported edge. Their leading large-floor coefficients agree.*

Proof. Evaluate the mixed variational objective at the full-form maximizer. The difference between the kinetic multipliers is

$$2(\sqrt{|\xi_W|^2 + \xi_z^2} - |\xi_z|),$$

strictly positive off the null set $\xi_W = 0$. Its quadratic integral is strictly positive on a nonzero L^2 trial, with zero extension in the supported case. Thus the mixed objective is strictly larger already on the full optimizer. The large-floor multiplication limit follows by the common dilation and the vanishing relative kinetic coefficient. □

If $\Theta = \{w_0\}$ is an isolated point, then $k = d$. With $A(W, z) = c(|W|^p + |z|^p)$ and $p > d$, the finite-floor coefficient is the integral of the depth oscillator with floor $\lambda + c|W|^p$ over $W \in \mathbb{R}^{d-1}$. For $p = d$ and the radial normal potential $A = c(|W|^2 + z^2)^{d/2}$, the zero-floor coefficient of $g^{-\gamma} \log M/M$ in the transform is

$$\frac{|\Omega|}{c(d+1)} J_\kappa(w_0, u_0).$$

Here $|\Omega|$ equals the whole sphere area for an interior depth and half for the supported edge.

For a physical example take $M = g^{-\nu}$ with $\nu > 0$, a transparent opposite side and zero floor, with $p > d$. Set $L = H(w_0) + u_0$. The causal half-line factorization in Sections 10–13 gives

$$\frac{1}{2\pi} \int_0^\infty J_\kappa(w_0, u_0)\, \mathrm{d}\kappa = \frac{\Gamma((d+1)/2)}{2^{d+2}\pi^{(d+3)/2}(d+2)} L^{-d-2}.$$

Insert the transparent column $(2\pi)^{-1} \int_L^\infty e^{-2qr} r^{-3}\, \mathrm{d}r$ in (52), integrate over the d-dimensional momentum half-space, and then integrate in r. Denote the resulting constant by $D_d(L)$. Theorem 25 gives

$$\mathcal{E}_g \sim -D_d(L) \mathcal{M}_{w_0}(0)\, g^{-\gamma-1+\nu(d+1)/(p+1)}.$$

The same equivalent applies at fixed positive physical inverse temperature.

50 Refined normal coefficients

The remaining formulas concern the limiting normal models. They use λ as their floor parameter.

50.1 Large-floor dilation

Write $x = (W, z) \in \mathbb{R}^s \times D$, $k = s + 1$, where $D = \mathbb{R}$ or $D = \mathbb{R}_+$, and put $X = \mathbb{R}^s \times D$. Let $A(x)$ be positive homogeneous of degree $p > k$, with angular factor bounded above and below by positive constants and C^1 on the sphere or closed inward hemisphere. One-sided derivatives at the hemisphere equator suffice. Let $\mathcal{K}$ be either the full $2|D_x|$ or the vertical direct integral $2|D_z|$, always using zero extension in the supported case. Define the forced coefficient

$$\mathcal{C}_\mathcal{K}(\lambda) = \langle 1, (\mathcal{K} + A + \lambda)^{-1} 1 \rangle_{\mathrm{dual}}.$$

Write $V = 1 + A$, $f = V^{-1}$, and $J_0 = \int_X f$. The unitary dilation $x = \lambda^{1/p} \widetilde{x}$ gives

$$\lambda^{1-k/p} \mathcal{C}_\mathcal{K}(\lambda) = J_\varepsilon = \langle 1, (V + \varepsilon \mathcal{K})^{-1} 1 \rangle_{\mathrm{dual}}, \qquad \varepsilon = \lambda^{-1-1/p}.$$

Here the inverse contributes λ^{-1} and the paired-source volume contributes $\lambda^{k/p}$. Both kinetic operators are homogeneous of degree one under the common dilation, including for the mixed direct integral. The constant forcing is bounded in the multiplication form dual since $\int V^{-1} < \infty$. Completing the multiplication square gives the exact identity

$$J_0 - J_\varepsilon = \inf_v \left\{ \int_X V|v - f|^2 + \varepsilon\, \mathfrak{k}[v] \right\}, \qquad \mathfrak{k}[v] = \langle v, \mathcal{K} v \rangle. \tag{53}$$

The minimizer exists by coercivity of the positive closed form. All complex versions are obtained by taking real parts in the variational pairing. The angular regularity implies

$$|f(x)| \le C(1+|x|)^{-p}, \qquad |\nabla f(x)| \le C(1+|x|)^{-p-1},$$

and f lies in the weighted space $L^2(V\,dx)$. The derivative estimates follow by homogeneity and $p > 1$ at the origin.

50.2 Full-space expansion

For $D = \mathbb{R}$, $f \in H^1(\mathbb{R}^k)$, so $g = \mathcal{K}f \in L^2$ for either kinetic choice. Substitution $v = f + w$ in (53) and completing the $V + \varepsilon\mathcal{K}$ form square give exactly

$$J_0 - J_\varepsilon = \varepsilon\,\mathfrak{k}[f] - \varepsilon^2 \langle g, (V+\varepsilon\mathcal{K})^{-1} g\rangle. \tag{54}$$

The last quadratic converges to $\int V^{-1}|g|^2$. The upper bound is multiplication comparison, and the lower bound follows by fixing each compact smooth test in its variational supremum and letting $\varepsilon \to 0$. Such tests are dense in the multiplication form norm by cutoff and local smoothing, since V is positive and bounded on bounded sets. Thus the first correction is $\varepsilon\langle f, \mathcal{K}f\rangle$, and (54) additionally gives its signed second coefficient with an $o(\varepsilon^2)$ remainder. In particular the first coefficient is positive: $f \neq 0$ and the kinetic vanishes only on Fourier modes supported in a measure-zero set.

50.3 The supported edge logarithm

The same marginal jump exponent gives a boundary logarithm for Cauchy spectral heat content [46, Theorem 4.9]. Here the coefficient weights the boundary by the squared forced multiplication response.

For $D = \mathbb{R}_+$ put $t = z > 0$ and

$$B = \int_{\mathbb{R}^s} f(W,0)^2\,dW.$$

Then for either kinetic choice,

$$J_0 - J_\varepsilon = \frac{2}{\pi} B\,\varepsilon \log(1/\varepsilon) + O(\varepsilon). \tag{55}$$

In particular the normalized large-floor coefficient for the original oscillator is

$$\lambda^{1-k/p}\mathcal{C}_{\mathcal{K}}(\lambda) = J_0 - \frac{2}{\pi}\left(1+\frac{1}{p}\right) B\,\lambda^{-1-1/p}\log\lambda + O(\lambda^{-1-1/p}).$$

To fix the normalization, the full $2|D_x|$ jump form on zero extensions is c_k times the ordered double integral of squared differences against $|x-x'|^{-k-1}$, with $c_k = \Gamma((k+1)/2)/\pi^{(k+1)/2}$. Integrating the kernel in tangential differences gives

$$c_k \int_{\mathbb{R}^{k-1}} (|W|^2 + |t-t'|^2)^{-(k+1)/2}\,dW = \frac{1}{\pi}|t-t'|^{-2}.$$

The two orientations of a jump between the positive and negative half-spaces then give the exact formula

$$\mathfrak{k}[v] = \mathfrak{k}_{\mathrm{reg}}[v] + \frac{2}{\pi}\int_{t>0} \frac{|v(W,t)|^2}{t}\,dW\,dt. \tag{56}$$

The first term restricts both points to the supported side. For the mixed kinetic the same identity holds per W directly in dimension one, with the same constant. This is the exterior killing term, obtained by separating outside jumps from the regional form. The regional and killed stable forms are compared in [45].

Let $b_* = 2/\pi$. For the lower bound in (55), drop the regional form and minimize pointwise the remaining quadratic $V|v-f|^2 + \varepsilon b_*|v|^2/t$. Its minimum is $\varepsilon b_* f^2/(t+\varepsilon b_* f)$. Since $f \le 1$, restricting to $0 < t < 1$ gives

$$J_0 - J_\varepsilon \ge \varepsilon b_* \int_{\mathbb{R}^s} \int_0^1 \frac{f(W,t)^2}{t+\varepsilon b_*}\, dt\, dW.$$

The decay and derivative estimates imply $\int |f(W,t)^2 - f(W,0)^2|\, dW \le Ct$ for $0 < t < 1$. The last display is therefore $\varepsilon b_* B \log(1/\varepsilon) + O(\varepsilon)$, establishing the lower coefficient with a bounded additive error at the linear scale.

For the upper bound take $v(W,t) = f(W,t)\chi(t/\varepsilon)$, with χ smooth, zero near zero, between zero and one, and identically one for $t \ge 2$ in its own argument. This is admissible since it vanishes in a full collar and has an H^1 zero extension at each fixed ε. The multiplication error in (53) is at most $\int_{0<t<2\varepsilon} f = O(\varepsilon)$, using the uniform tangential integral of f on that band. The exterior term from (56) is $\varepsilon b_*[B\log(1/\varepsilon) + O(1)]$ by the same L^1_W derivative estimate and the integrable tail $t > 1$.

For the regional energy use

$$|f(x)\chi(t/\varepsilon) - f(y)\chi(u/\varepsilon)|^2 \le 2|f(x)-f(y)|^2 + 2|f(y)|^2|\chi(t/\varepsilon) - \chi(u/\varepsilon)|^2.$$

The first contribution is bounded by the full-space H^1 energy of the even extension in t, which is in H^1 by the derivative bounds and agreement of its boundary traces. This also bounds the vertical-only form. For the second contribution, integrate the tangent coordinates in the kinetic kernel using the preceding $\pi^{-1}|t-u|^{-2}$ formula in the full case, or directly per W in the mixed case. The remaining source factor is bounded by $\sup_{u>0} \int f(W,u)^2\, dW < \infty$. The remaining one-dimensional regional seminorm of $\chi(\cdot/\varepsilon)$ on the positive ray is independent of ε by scaling, and finite. Near the diagonal use Lipschitz continuity and the compact transition region. Away from the diagonal, the only nonzero differences have one coordinate in a bounded set, and the inverse-square tail is integrable. Thus $\mathfrak{k}_{\mathrm{reg}}[v] = O(1)$, which gives the $O(\varepsilon)$ remainder in the upper bound.

For the isotropic potential $A(W,t) = c(|W|^2+t^2)^{p/2}$, $s > 0$, the boundary factor evaluates as

$$B = \frac{|S^{s-1}|}{p}\, c^{-s/p}\Gamma(s/p)\Gamma(2-s/p).$$

For $s = 0$ one has $B = f(0)^2 = 1$.

50.4 Difference of the two kinetic laws

Although their leading boundary logarithms agree, the two kinetic choices have a strictly positive difference at the linear scale. Suppose $s \ge 1$ and define the excess form $\mathfrak{e}$ on the full zero extension by the multiplier

$$2\big(\sqrt{|\xi_W|^2 + \xi_z^2} - |\xi_z|\big).$$

In either the full space or the supported half-space,

$$\frac{J_\varepsilon^{\mathrm{mixed}} - J_\varepsilon^{\mathrm{full}}}{\varepsilon} \longrightarrow \mathfrak{e}[f] > 0. \tag{57}$$

At a boundary the proof uses only the L^2 tangential derivatives of the zero extension of f. The excess is bounded by the $2|D_W|$ form and is therefore finite on this extension. It is positive by its Fourier multiplier and $f \neq 0$.

The deficit form for the full kinetic is the mixed deficit form plus $\varepsilon\mathfrak{e}$. At the full minimizer $v_\varepsilon^{\mathrm{full}}$, this bounds the quotient in (57) below by $\mathfrak{e}[v_\varepsilon^{\mathrm{full}}]$. The minimizer tends to f in L^2 by (53), (54) and (55), so lower semicontinuity gives the required lower bound. For the reverse bound the mixed minimizer $v_\varepsilon^{\mathrm{mixed}}$ is admissible in the full form and converges to f in the excess seminorm, as follows. The form equation gives $\|v_\varepsilon^{\mathrm{mixed}}\|_{L^2(V\,dx)} \le \|f\|_{L^2(V\,dx)}$, by testing with the minimizer. The normal kinetic commutes with translation in W and the source is constant. The potential obeys

$$\frac{|V(W+h,z)-V(W,z)|}{|h|} \le CV(W,z), \qquad V(W+h,z) \asymp V(W,z) \qquad (|h| \le 1).$$

These follow from the logarithmic derivative bound of V, or directly from homogeneity and positive angular bounds. Subtract the translated and unshifted mixed form equations. The difference quotient solves the translated inverse equation with source equal to minus the potential difference quotient times the unshifted $v_\varepsilon^{\mathrm{mixed}}$. Its translated multiplication dual norm is at most $C\|v_\varepsilon^{\mathrm{mixed}}\|_{L^2(V\,dx)}$. Coercivity by the translated multiplication form bounds the L^2 norm of the difference quotient by the same uniform constant. Hence its W-gradient is uniformly in L^2, also after zero extension in z. The mixed minimizer already has finite vertical kinetic energy. Its finite $|D_W|$ form then makes it admissible for the full kinetic. By interpolation, its strong L^2 convergence to f and bounded W-gradients imply strong convergence in the homogeneous $H^{1/2}_W$ seminorm. This controls $\mathfrak{e}$, so testing the full deficit with the mixed minimizer gives the matching upper bound. Thus (57) resolves the first difference of the two laws even at an edge where (55) alone only gives a common larger term.

50.5 Separable potentials

Now take the mixed model and

$$A(W,z) = A_0(z) + \sum_{j=1}^{s} c_j |W_j|^p, \qquad c_j > 0, \quad A_0(z) \asymp |z|^p, \quad p > s+1.$$

The one-dimensional confining operator is $H_\lambda = (2|D_z|)_D + A_0(z) + \lambda$, for $\lambda \ge 0$. The coefficients c_j and A_0 can be at a fixed base point of the zero set. The exact reduction is

$$\mathcal{C}_{\mathrm{mixed}}(\lambda) = \left(\prod_{j=1}^{s} 2\Gamma(1+1/p) c_j^{-1/p} \right) \Gamma(1-s/p) \left\langle 1, H_\lambda^{-(1-s/p)} 1 \right\rangle. \tag{58}$$

The quadratic on the right means the increasing limit with both sources truncated to $D \cap [-R,R]$.

To justify this convention and the formula, first take a truncated constant source $\mathbf{1}_R$. The spectral Laplace formula for the strictly positive H_λ gives

$$\langle \mathbf{1}_R, (H_\lambda + \textstyle\sum_j c_j |W_j|^p)^{-1} \mathbf{1}_R \rangle = \int_0^\infty e^{-t \sum_j c_j |W_j|^p} \langle \mathbf{1}_R, e^{-tH_\lambda} \mathbf{1}_R \rangle \, dt.$$

The semigroup preserves positivity by the jump-form contraction and the nonnegative potential. Thus its positive source quadratics increase with the truncation. The limit on the left equals the form-dual forcing in each fiber: the omitted unit source tail has vanishing dual norm by the $|z|^{-p}$

bound. Tonelli permits integration first in each W_j. Its factor is $2\Gamma(1+1/p)c_j^{-1/p}t^{-1/p}$. The remaining weight $t^{-s/p} = t^{(1-s/p)-1}$ is exactly the Laplace representation of $\Gamma(1-s/p)H_\lambda^{-(1-s/p)}$. Passing through the positive truncations gives (58). The mixed forcing bound from its vertical gap and integrable reciprocal $(|W|^2+z^2)^{-p/2}$ makes the result finite, including $\lambda = 0$. The positive truncations provide the untruncated forcing in the form-dual sense. The negative-power Laplace representation is standard spectral calculus. See [48].

51 A small tangential kinetic correction

For a massless scalar field at a flat Dirichlet screen, what one opening contributes in the presence of another is encoded by a connected square-root boundary determinant. The aperture determinant and the scalar interaction of holes in a single screen go back to Kabat, Karabali and Nair [19]. For spatially varying couplings on parallel mirrors, Fosco and Mazzitelli [14] develop a determinant method and a derivative expansion. The related Neumann analysis in [38] exhibits corrections from gapless modes. The coplanar aperture considered here has a repulsive strength growing away from an edge zero and separate normal and tangential confinement widths.

The earlier near-touching analysis Theorem 21 already proves the exact $1/\pi$ gradient-of-depth-integrated-optimizer coefficient on the periodic torus for a supported edge. Its proof uses small vertical Fourier frequencies and controls the relaxation of the forced inverse. For the periodically translated well on the full depth line, the depth marginal is constant on the torus, and that logarithmic coefficient vanishes. Theorem 27 extends this mechanism to a confined tangential space $\mathbb{R}^s$, with general positive homogeneous angular profiles. The coefficient is strictly positive for both supported and whole-line depth. For regional fractional seminorms, the critical logarithm and the tangential Dirichlet energy appear in the thin-film theorem of Braides, Pinamonti and Solci [31, Theorem 4.7].

The leading slow-coordinate aperture limit Sections 43–50 supplies the mixed vertical inverse, including for curved gaps. We establish a next-order determinant formula in a flat geometry with exactly scaled confinement. Theorem 28 retains both the tangential loss and the normal-depth drift. Tangential translation of the opposite response cancels a source term that can be larger than the logarithmic kinetic correction if estimated without its sign. The bounded-window limit and the counterexample for unquantified contact errors describe the geometric scope of the expansion.

52 The confined normal model

Let $s \geq 1$, $d = s+1$, and $X = \mathbb{R}^s \times D$ for $D = \mathbb{R}$ or $D = (0,\infty)$. Let A be positive homogeneous of degree $p > d$ with angular factor bounded above and below by positive constants and C^1 on the sphere or closed inward hemisphere. Fix a floor $\lambda \geq 0$. On X use the closed form of

$$K_\tau = 2\sqrt{|D_z|^2 + \tau^2|D_W|^2}, \qquad H_\tau = K_\tau + A + \lambda,$$

using zero extension to apply the multiplier when $D = (0,\infty)$. Write $C_\tau = \langle 1, H_\tau^{-1}1\rangle$ in the form dual and let $v_0 = H_0^{-1}1$. The endpoints C_0, C_1 are the mixed and full normal coefficients of Sections 47–50.

Theorem 27 (Small tangential kinetic ratio)**.** *As $\tau \downarrow 0$,*

$$\frac{C_0 - C_\tau}{\tau^2 \log(1/\tau)} \longrightarrow c_* = \frac{1}{\pi}\int_{\mathbb{R}^s} \left|\nabla_W \int_D v_0(W,z)\,dz\right|^2 dW > 0.$$

Proof. There is a uniform positive gap for H_0. Indeed $A(W,z) \geq c|z|^p$, and $2|D_z| + c|z|^p$ has positive ground energy on the line and hence on the supported half-line. The line bound follows from the compact embedding of the confining form domain and the fact that a function in L^2 with zero homogeneous $H^{1/2}$ seminorm vanishes. Integrating the gap in W shows that the form of H_0 dominates the weighted square norm with $V = 1 + A$. Since $p > d$, one has $\int_X V^{-1} < \infty$. Thus constant forcing is a bounded form-dual functional and the optimizer has finite $L^2(V)$ norm. The same gap holds for all H_τ.

Next, v_0 has $L^2(V)$ tangential derivatives. For translations h in W with $|h| \leq 1$, homogeneity and the C^1 angular bound give $V(W+h,z) \asymp V(W,z)$ and

$$\frac{|A(W+h,z) - A(W,z)|}{|h|} \leq CV(W,z).$$

The translated mixed form has the same vertical kinetic and comparable gap. Subtract its equation for the translated optimizer from the original equation. The difference quotient solves the translated form equation with source $-[(A(W+h,z) - A(W,z))/|h|]v_0(W,z)$. The multiplication estimate bounds its dual norm by $C\|v_0\|_{L^2(V)}$, so the gap and weighted coercivity bound the difference quotient uniformly in $L^2(V)$. Weak compactness yields the weighted tangential derivatives. Zero extension in z commutes with these derivatives. Because $V \gtrsim 1+|z|^p$ and $p > 1$, Cauchy–Schwarz in the vertical variable gives $v_0 \in L^1_z(H^1_W)$. In particular $m(W) = \int_D v_0(W,z)\,dz$ belongs to $H^1(\mathbb{R}^s)$.

With unitary Fourier transforms, the difference multiplier is

$$e_\tau(\eta,\zeta) = 2(\sqrt{\zeta^2 + \tau^2|\eta|^2} - |\zeta|).$$

Its compression $E_\tau v_0$ is in $L^2(X)$ since $\|E_\tau v_0\|_2 \leq 2\tau\|\nabla_W v_0\|_2$. Also v_0 is admissible in the H_τ form. Completing the form square in the variational forced inverse yields the identity

$$C_0 - C_\tau = \int e_\tau(\eta,\zeta)|\widehat{v}_0(\eta,\zeta)|^2\,d\eta\,d\zeta - \langle E_\tau v_0, H_\tau^{-1} E_\tau v_0\rangle.$$

The last term is $O(\tau^2)$ by the gap. In fact it is $o(\tau^2)$ because $e_\tau/\tau \to 0$ off $\zeta = 0$ and $e_\tau/\tau \leq 2|\eta|$. For a supported edge the L^2 compression decreases the full Fourier multiplier norm.

Here is the Fourier limit. At $|\zeta| > 1$, $e_\tau \leq \tau^2|\eta|^2/|\zeta|$, so that part of the integral is $O(\tau^2)$. At fixed $a = |\eta| > 0$, the measure $e_\tau(\eta,\zeta)d\zeta/[\tau^2\log(1/\tau)]$ restricted to $[-1,1]$ tends weakly to $2a^2\delta_0$. To verify the mass, integrate $2(\sqrt{\zeta^2+q^2} - \zeta)$ over $0 \leq \zeta \leq 1$, $q = \tau a$: the integral is $\sqrt{1+q^2} - 1 + q^2\log[(1+\sqrt{1+q^2})/q]$. Its reflected half is identical, and the mass away from zero vanishes by the previous rational bound. At $a = 0$ the multiplier vanishes. For dominated convergence in η, set $G(\eta) = \int_D |\mathcal{F}_W v_0(\eta,z)|\,dz$. Minkowski's inequality gives $(1+|\eta|)G \in L^2$. For almost every η, the vertical Fourier transform is continuous and bounded by $G(\eta)/\sqrt{2\pi}$. From $e_\tau \leq \min(2\tau a, \tau^2a^2/|\zeta|)$, the mass on $[-1,1]$ before normalization is bounded by $C\tau^2a^2[1+\log_+(1/(\tau a))]$. For $0 < \tau < 1/2$, its normalized bound is $C(1+a^2)$, using boundedness of $a^2\log(1/a)$ on $0 < a \leq 1$. Thus the limit of the difference quotient is $2\int|\eta|^2|\widehat{v}_0(\eta,0)|^2 d\eta$. Since $\widehat{v}_0(\eta,0) = (2\pi)^{-1/2}\widehat{m}(\eta)$, Plancherel gives the stated factor.

Finally, the resolvent preserves positivity by the vertical jump form with nonnegative potential. Equivalently, replacing the unique real variational optimizer by its absolute value can only improve the objective. It is nonzero by a compact nonnegative forcing test. Hence $m \geq 0$ is nonzero. A nonzero $H^1(\mathbb{R}^s)$ function for $s \geq 1$ cannot have zero gradient since it belongs to L^2. This proves strict positivity. □

53 Connected determinant for parallel aperture edges

Fix screen dimension $d = s + 1 \geq 2$. In gap units the openings occupy $\{(-u, Y) : u > 0\}$ and $\{(1 + v, Y') : v > 0\}$, $Y, Y' \in \mathbb{R}^s$, with the strip between them retained. The right opening is transparent. The supported left contact is

$$M_{\ell,\tau}(Y, u) = \ell^{-1}\big(A(\tau Y/\ell, u/\ell) + \lambda\big).$$

Here $\ell, \tau \downarrow 0$, $\lambda \geq 0$ is fixed, and A satisfies the angular hypotheses of Section 2, with the stronger degree assumption $p > d + 6$. In particular $A \asymp |(W, z)|^p$ is positive away from its supported zero. An example is $A = c(|W|^2 + z^2)^{p/2}$. Define

$$\delta = \ell/\tau, \quad N = \ell^2\delta^s, \quad \mathcal{L}_\tau = \tau^2 \log(1/\tau), \qquad v_0 = (2|D_z| + A + \lambda)^{-1}1$$

on $\mathbb{R}^s \times \mathbb{R}_+$, with zero extension in depth. Let

$$C_0 = \int v_0, \qquad Z_0 = \int z v_0, \qquad c_* = \frac{1}{\pi}\int_{\mathbb{R}^s} \left|\nabla_W \int_0^\infty v_0(W, z)\, dz\right|^2 dW.$$

All are finite and strictly positive. Finiteness of Z_0 follows by weighted Cauchy–Schwarz with weight $V = 1 + A$.

Let H_-, H_+ be the two compressed $2\sqrt{|D|^2 + \kappa^2}$ forms, including the indicated contact. Write B_κ for the cross kernel and $q_{\ell,\tau}(\kappa) = -\operatorname{Tr}\log(I - T_\kappa)$ for the usual positive connected determinant with $T_\kappa = H_-^{-1/2} B_\kappa H_+^{-1} B_\kappa^* H_-^{-1/2}$. At zero mass the right inverse uses the homogeneous supported form. The determinant is well defined for all sufficiently small parameters in the regime below. Set $J_\kappa(u) = \|H_+^{-1/2} B_\kappa^* \delta_{(-u,0)}\|^2$, in the homogeneous-form convention.

Theorem 28 (Connected determinant)**.** *For $\ell = O(\mathcal{L}_\tau)$,*

$$\frac{q_{\ell,\tau}(\kappa)}{N} = J_\kappa(0)(C_0 - c_*\mathcal{L}_\tau) + \ell J'_\kappa(0) Z_0 + o(\mathcal{L}_\tau). \tag{1}$$

The remainder is locally uniform in $\kappa \geq 0$. After division by $\mathcal{L}_\tau$ it is bounded by $C(1 + \kappa)e^{-c\kappa}$ on the whole mass axis. Here J'_κ is the inward-depth derivative.

The transparent half-line factorization gives

$$J_\kappa(u) = \frac{1}{(2\pi)^{s+1}} \int_{\mathbb{R}^s} \int_{1+u}^\infty e^{-2r\sqrt{\kappa^2 + |\xi|^2}} r^{-3}\, dr\, d\xi. \tag{2}$$

In particular $J'_\kappa(0) < 0$, and $J'_0(0) = -(d+1)J_0(0)$, by scaling the ξ integral. The notation $J_0(u)$ here means the zero-mass column norm.

Thus $\ell = o(\mathcal{L}_\tau)$ isolates the forced loss c_* in the determinant. If $\ell/\mathcal{L}_\tau \to r \in (0, \infty)$, both losses survive, with coefficient $J_\kappa(0)c_* - rJ'_\kappa(0)Z_0 > 0$. Let g be the physical gap and $\beta_* g$ the physical inverse temperature. The normalized vacuum and thermal energies are, respectively,

$$\frac{g}{N}\mathcal{E}_g = -\frac{1}{2\pi}\int_0^\infty \frac{q_{\ell,\tau}(\kappa)}{N}\, d\kappa, \qquad \frac{g}{N}\mathcal{F}_{g,\beta_* g} = -\frac{1}{2\beta_*}\sum_{j\in\mathbb{Z}} \frac{q_{\ell,\tau}(2\pi|j|/\beta_*)}{N}.$$

The majorant in Theorem 28 permits termwise application of these formulas to (1). For the vacuum integral, (2) also gives $\int J'_\kappa(0)\, d\kappa = -(d+2)\int J_\kappa(0)\, d\kappa$ by scaling all d momentum variables.

54 Proof of the determinant formula

54.1 Exact reduction and control of columns

Put $u = \ell z,\ Y = \delta W$. This unitary dilation takes H_- to $\ell^{-1}\mathcal{H}_{\tau,\ell\kappa}$, where

$$\mathcal{H}_{\tau,\mu} = 2\sqrt{|D_z|^2 + \tau^2|D_W|^2 + \mu^2} + A + \lambda.$$

The tangential ratio τ appears exactly. There is zero geometric error in the aperture support and in the confinement potential. All these forms dominate cV for $V = 1+A$, by the vertical oscillator gap and the nonnegative potential. Write $R_{\tau,\mu} = \mathcal{H}_{\tau,\mu}^{-1}$, including its form-dual extension. Define the Hilbert-valued source $F_\kappa(u, Y) = H_+^{-1/2} B_\kappa^* \delta_{(-u,Y)}$, and $\mathcal{F}(W, z) = F_\kappa(\ell z, \delta W)$. Then

$$\operatorname{Tr} T_\kappa = N \,\langle \mathcal{F}, R_{\tau,\ell\kappa}\mathcal{F}\rangle. \tag{3}$$

Indeed the volume Jacobian is $\ell\delta^s$ and the left inverse contributes one factor ℓ. For an operator-theoretic justification, $H_- \geq c\ell^{-1}V(\tau Y/\ell, u/\ell)$ and the norm of the Hilbert-valued source is bounded uniformly in u, Y. Hence the source paired with the left inverse square root is Hilbert–Schmidt by density and the finite inverse-weight integral. This defines the positive trace-class T_κ and proves (3), including at $\kappa = 0$. The source Hilbert space at zero mass can equivalently be obtained by Riesz representation in the homogeneous right form space.

The right column and its u, Y derivatives of orders at most three are bounded in Hilbert norm by $Ce^{-c\kappa}$, uniformly on $u \geq 0$. To verify this use the supported homogeneous Sobolev dual estimate into the right inverse form space, $d \geq 2$, and the $L^{2d/(d+1)}$ bounds for derivatives of the cross kernel. The latter follow from the heat integral of $2\sqrt{|D|^2 + \kappa^2}$ off the diagonal: each order-j derivative is bounded by $C_j r^{-d-1-j} e^{-c\kappa r}$ for separation $r \geq 1$. Differentiate the Gaussian, absorb its polynomial derivative factor in part of its exponential, and use the remaining exponential to bound $e^{-c\kappa r}$ before integrating the massless kernel. These pointwise bounds, on the right half-space, give the asserted derivative bounds by integration. They also prove continuous dependence in κ locally, using the compact tests and homogeneous form exhaustion at zero mass from the weak-column proof of Sections 44–45. Formula (2) is the transparent column integral of Sections 27–50 applied to each tangential frequency.

The weighted dual bound in (3) gives $\operatorname{Tr} T_\kappa \leq CNe^{-c\kappa}$. In this regime $N \to 0$. For small parameters $\|T_\kappa\| \leq \operatorname{Tr} T_\kappa < 1/2$, and the scalar logarithm estimate applied to its eigenvalues bounds

$$0 \leq q_{\ell,\tau}(\kappa) - \operatorname{Tr} T_\kappa \leq C(\operatorname{Tr} T_\kappa)^2. \tag{4}$$

The normalized error is therefore $O(Ne^{-c\kappa}) = o(\mathcal{L}_\tau)e^{-c\kappa}$, since $\ell = O(\mathcal{L}_\tau)$, $\delta = O(\tau\log(1/\tau))$, and $N = \ell^2\delta^s$.

54.2 Source Taylor expansion and tangential cancellation

Use subscripts u, i, ij for derivatives at $u = 0, Y = 0$, and write $F = F_\kappa(0, 0)$. Taylor expansion in the Hilbert norm gives

$$\mathcal{F} = F + \ell z F_u + \delta \sum_i W_i F_i + \tfrac{1}{2}\delta^2 \sum_{i,j} W_i W_j F_{ij} + \mathcal{R}, \qquad \|\mathcal{R}\|_{L^2(V^{-1})} \leq Ce^{-c\kappa}(\ell^2 + \ell\delta + \delta^3). \tag{5}$$

For this bound first Taylor expand in Y at $u = 0$, and then along u with the first derivative frozen at $Y = 0$. Pointwise the remainder is bounded by $Ce^{-c\kappa}(\ell^2 z^2 + \ell\delta z|W| + \delta^3|W|^3)$. All

moments used by the weighted L^2 estimate are finite since $p > d + 6$. In the quadratic (3), the omitted products of displayed terms satisfy the same bound. Tangential translation of $F_\kappa(0, Y)$ is unitary on the right form space. Differentiating its constant squared norm once and twice gives

$$\Re\langle F, F_i\rangle = 0, \qquad \Re\langle F, F_{ij}\rangle = -\Re\langle F_i, F_j\rangle.$$

The form is real and symmetric on real scalar inputs. It follows that (3), divided by N, equals

$$J_\kappa(0)\langle 1, R_{\tau,\ell\kappa}1\rangle + \ell J'_\kappa(0)\langle z, R_{\tau,\ell\kappa}1\rangle + \delta^2 \sum_{i,j} \Re\langle F_i, F_j\rangle\, D_{ij}(\tau, \ell\kappa) + O\big(e^{-c\kappa}(\ell^2 + \ell\delta + \delta^3)\big),$$

where

$$D_{ij}(\tau, \mu) = \langle W_i, R_{\tau,\mu} W_j\rangle - \langle W_i W_j, R_{\tau,\mu}1\rangle.$$

At $\tau = 0$ the inverse acts pointwise in W, so $D_{ij}(0, 0) = 0$. The following stronger bound controls the cancellation:

$$|D_{ij}(\tau, \mu)| \le C(\tau + \mu). \tag{6}$$

For details of (6), take any real source P of degree at most two. Its mixed optimizer $R_{0,0}P$ belongs to $L^2(V)$, and has W derivatives in $L^2(V)$. The same translated form proof as for the unit source applies: the source difference quotient is a polynomial of degree at most one with uniformly bounded $L^2(V^{-1})$ norm, and the potential difference quotient is bounded by CV. Coercivity in $L^2(V)$ bounds the solution difference quotients. The excess multiplier between $\mathcal{H}_{\tau,\mu}$ and $\mathcal{H}_{0,0}$ is nonnegative and bounded by $2\tau|\eta| + 2\mu$. Applied to this optimizer, followed by restriction to the support, it has L^2 norm $O(\tau + \mu)$. Subtracting the two form equations and using weighted coercivity then proves

$$\|R_{\tau,\mu}P - R_{0,0}P\|_{L^2(V)} \le C_P(\tau + \mu),$$

and pairing with any other degree-at-most-two source proves (6). This estimate also freezes the depth-drift coefficient to Z_0.

For the constant pair, the mass increment is $o(\mu)$ on the scales of interest. Let $v_\tau = R_{\tau,0}1$, which converges to v_0 in L^2 by the preceding bound. The positive excess

$$\Delta_{\tau,\mu} = 2\left(\sqrt{|D_z|^2 + \tau^2|D_W|^2 + \mu^2} - \sqrt{|D_z|^2 + \tau^2|D_W|^2}\right)$$

is bounded by 2μ as a Fourier multiplier. The inverse variational identities give

$$0 \le C_\tau - \langle 1, R_{\tau,\ell\kappa}1\rangle \le \langle v_\tau, \Delta_{\tau,\ell\kappa} v_\tau\rangle.$$

After division by ℓ the right side tends to zero uniformly for κ in a compact set: replace v_τ by v_0 using the uniform norm bound on the divided multiplier, and apply dominated convergence to its pointwise zero limit at $\zeta \neq 0$. Globally it is bounded by $C\ell\kappa$ before division. The Fourier multipliers in these estimates always act on zero extensions.

Theorem 27 gives $C_\tau = C_0 - c_*\mathcal{L}_\tau + o(\mathcal{L}_\tau)$. For $\ell = O(\mathcal{L}_\tau)$, the error terms $\ell^2 + \ell\delta + \delta^3 + \tau\delta^2 + \ell\delta^2$ are all $o(\mathcal{L}_\tau)$. The terms involving $\mu = \ell\kappa$ are bounded by the same errors times $1 + \kappa$. Together with the column bounds and (4), these estimates give (1) and its majorant.

54.3 Bounded physical windows by exhaustion

For each fixed ℓ, τ, κ the flat determinant is the limit of determinants for bounded left and right rectangles increasing to the two half-spaces. These rectangles have parallel facing faces. Restrict the left potential and retain the exact same cross kernel. The supported form subspaces of the rectangles increase to cores of the full half-space forms. On the unbounded left this follows by cutoff, moving supported tests inward, and smoothing on compacts in the form norm. On the right the homogeneous cutoff of Sections 27–50 and inward-translation argument also covers $\kappa = 0$. The finite-domain inverse energies are the restrictions to these subspaces of the full variational supremum. Equivalently, in the square-root energy representation the finite cross map is $P_+ B_{\mathrm{en}} P_-$, where the projections $P_\pm$ are onto the finite-domain energy subspaces and B_{en} is the full Hilbert–Schmidt cross map established in (3). The projections converge strongly to the identity, so the cross maps converge in Hilbert–Schmidt norm, their squared operators in trace norm, and their logarithmic traces converge under the uniform contraction bound (4). Thus the bounded connected determinants have the same domination. For any chosen sequence (ℓ, τ), rectangles can be chosen sufficiently large at each parameter to make exhaustion errors $o(N\mathcal{L}_\tau)$ at a fixed frequency or for the integrated vacuum and thermal observables at a fixed β_*. This gives sequences of finite-window screen geometries displaying (1) in those observables. It makes no quantitative assertion for a prescribed rectangle size or for its shrinking physical scale relative to g.

55 Failure of a universal correction under qualitative homogeneity

The curved and slow-coordinate theorems of Sections 27–50 allow an unquantified $o(r^p)$ error in the contact. Even in the flat physical model, this hypothesis cannot identify the $\mathcal{L}_\tau$ coefficient from the leading homogeneous potential alone. For example replace the contact above by

$$M^{\mathrm{pert}}_{\ell,\tau}(Y,u) = \ell^{-1}\big(A(\tau Y/\ell, u/\ell)[1+\omega(\sqrt{\tau^2|Y|^2+u^2})]+\lambda\big), \qquad \omega(a) = \frac{1}{\log(e+1/a)}, \quad \omega(0)=0.$$

This has the same leading homogeneous zero in the slow variables. The exact dilation changes A in the oscillator to $A^{\mathrm{pert}}_\ell(W,z) = A(W,z)[1+\omega(\ell|(W,z)|)]$. Set $\ell = \tau^2$, and fix a mass $\kappa \geq 0$. The perturbed optimizer $v_{\ell,\tau}$ with source one converges strongly in L^2 to v_0. Indeed the perturbed forms dominate the mixed form. Compact test approximations to v_0 give the matching lower limit for the supremum because the extra potential tends to zero uniformly on compacts. Completing the mixed form square at v_0 then forces strong convergence for perturbed maximizers. Choose a compact annulus in X where $\int A|v_0|^2 > 0$; such an annulus exists by nonzero forcing. Using the perturbed optimizer as a trial in the unperturbed inverse gives

$$\langle 1, R_{\tau,\ell\kappa}1\rangle - \langle 1, R^{\mathrm{pert}}_{\tau,\ell\kappa}1\rangle \;\geq \int A\omega(\ell|(W,z)|)|v_{\ell,\tau}|^2 \;\geq \frac{c}{\log(1/\ell)}.$$

This dominates $\mathcal{L}_\tau$. For the perturbed form a crude version of (5), with the first-order tangential term retained and its real coefficient still zero, bounds the normalized source-freezing error by $O(\ell+\delta^2) = O(\tau^2)$; coercivity is uniform and suffices for this bound. The determinant remainder is again $O(N)$. Since $J_\kappa(0) > 0$, the normalized physical connected determinant differs by at least a constant times $1/\log(1/\ell)$ from the unperturbed one for small ℓ. No coefficient universal under a merely qualitative homogeneous expansion can follow.

The supported flat geometry fixes the shape exactly under dilation. For curved gaps a correction at this scale also requires control of gap variation and of the square-root form under the coordinate shear. The existing leading recovery estimate Section 47 suffices for the principal term.

56 Bounded-window errors for the flat aperture correction

The interaction of holes in a Dirichlet screen for a massless scalar field can be expressed through a square-root aperture action [19]. We use the connected determinant convention of Sections 10–13. A companion calculation Sections 51–55 gives a next-order formula for a flat geometry and establishes transfer by bounded-window exhaustion. Here we bound the error for prescribed window sizes. The massive and massless Green kernels for the supported square root come from Byczkowski, Małecki and Ryznar [49] and the stable half-space formula [24, (1.9)].

Let $d = s + 1 \geq 2$ be the screen dimension. In gap units the two half-spaces in the screen are

$$\Omega_- = \{(-u, Y) : u > 0,\ Y \in \mathbb{R}^s\}, \qquad \Omega_+ = \{(1 + v, Y') : v > 0,\ Y' \in \mathbb{R}^s\}.$$

The right opening is transparent. The left one has contact

$$\ell^{-1}\big[A(\tau Y/\ell, u/\ell) + \lambda\big]. \tag{59}$$

Here $\lambda \geq 0$ is fixed, A is positive homogeneous of degree $p > d + 6$, and its angular factor is C^1 and bounded above and below by positive constants on the closed inward hemisphere. Let

$$\mathcal{L}_\tau = \tau^2 \log(1/\tau), \qquad \delta = \ell/\tau, \qquad N = \ell^2 \delta^{d-1}.$$

We use $\ell, \tau \downarrow 0$ with $\ell = O(\mathcal{L}_\tau)$.

At mass $\kappa \geq 0$, the diagonal responses H_-, H_+ are compressions of $2\sqrt{|D|^2 + \kappa^2}$ by zero extension on the two openings, adding (59) on the left. Write B_κ for the separated cross kernel, mapping right functions to the left, and

$$X_\kappa = H_+^{-1/2} B_\kappa^* H_-^{-1/2}, \qquad q_\infty(\kappa) = -\operatorname{Tr} \log(I - X_\kappa^* X_\kappa).$$

The right inverse at $\kappa = 0$ is understood in the supported homogeneous energy space. Equivalently the cross operator is the Riesz representation of the cross pairing between the two energy spaces. For finite rectangular openings $\Omega_{\pm,M} \subset \Omega_\pm$, restrict the same contact and kernel. Require that each rectangle contain the half-ball of radius M about its facing point $(0, 0)$ or $(1, 0)$ in its own half-space. Denote the two-sided determinant by q_M and the determinant with only the right window truncated by $q_{\mathrm{right},M}$.

Theorem 29 (Window truncation)**.** *For sufficiently small τ, ℓ in the stated regime and $M \geq 4$, uniformly in $\kappa \geq 0$,*

$$0 \leq \frac{q_\infty - q_{\mathrm{right},M}}{N} \leq C e^{-c\kappa} \left[M^{-d} e^{-c\kappa M} + (\delta/M)^{p-d}\right], \tag{60}$$

$$0 \leq \frac{q_\infty - q_M}{N} \leq C e^{-c\kappa} \left[M^{-d} e^{-c\kappa M} + (\delta/M)^{(p-d)/2}\right]. \tag{61}$$

If the right window also lies in a half-ball of radius $C_1 M$ with fixed $C_1 \geq 1$, then for sufficiently large M and $0 \leq \kappa \leq M^{-1}$,

$$\frac{q_\infty - q_M}{N} \ \geq\ \frac{q_\infty - q_{\mathrm{right},M}}{N} \ \geq\ c M^{-d}. \tag{62}$$

The constants in the lower bound may depend on C_1.

For precision about the inherited correction, put

$$v_0 = (2|D_z| + A + \lambda)^{-1}1, \quad C_0 = \int v_0, \quad Z_0 = \int z v_0, \quad c_* = \frac{1}{\pi}\int_{\mathbb{R}^s} \left| \nabla_W \int_0^\infty v_0(W,z)\,\mathrm{d}z \right|^2 \mathrm{d}W.$$

These quantities use supported depth $z > 0$ and the inverse in the form dual. If $J_\kappa(u)$ is the squared right energy column norm at depth u on the left, the result of Sections 51–55 is

$$\frac{q_\infty(\kappa)}{N} = J_\kappa(0)(C_0 - c_*\mathcal{L}_\tau) + \ell J'_\kappa(0) Z_0 + o(\mathcal{L}_\tau). \tag{63}$$

The remainder divided by $\mathcal{L}_\tau$ has an exponential mass envelope, uniform on compact mass intervals for the limit. Here $J'_\kappa(0) < 0$. We use this expansion only after proving (61).

57 Energy cutoffs and the left window

For a supported form H, let a_H be its energy inner product and u the solution with form-dual source f. The solution in a smaller supported domain is the energy orthogonal projection Pu. If χu is admissible there and $\psi = 1 - \chi$, its squared projection loss is at most $a_H(\psi u, \psi u)$. With j_H the jump kernel in the ordered double integral, expansion of the squares gives

$$\begin{aligned} a_H(\psi u, \psi u) &= \Re\langle f, \psi^2 u\rangle \\ &\quad + \frac{1}{2}\iint j_H(x-y)(\psi(x) - \psi(y))^2 \Re\langle u(x), u(y)\rangle \,\mathrm{d}x\,\mathrm{d}y. \end{aligned} \tag{64}$$

This is also valid for Hilbert-valued u. Indeed one can apply it to finite coordinate projections and pass in form norm. Local mass and contact terms cancel in the expansion. The right form uses zero extensions, including for the double integral.

Take a smooth radial χ equal to one up to radius $R/2$, supported in radius R, and with gradient bounded by C/R. Its support can be kept strictly inside the available radial boundary. The squared cutoff difference times the jump kernel has both Schur bounds C/R, since in the isotropic massless case the integral reduces to a multiple of $\int_0^\infty \min(1, r/R)^2 r^{-2}\,\mathrm{d}r$. Mass only decreases the jump kernel by subordination. For the anisotropic multiplier $2\sqrt{\tau^2|D_W|^2 + |D_z|^2 + \mu^2}$ use $h = (\tau h'_W, h'_z)$ in the jump integral. The Jacobian cancels that of the kernel, and $|h| \le |h'|$. At least one variable lies beyond $R/2$ whenever the cutoff difference is nonzero. The Schur estimate proves form boundedness of multiplication for the L^2 solutions used below, including the massless right columns. Smooth cutoffs preserve zero extension across the facing plane. Inward translation and smoothing give a core approximation supported in the smaller window.

On the left, scale $Y = \delta W$, $u = \ell z$ and put

$$\mathcal{H}_{\tau,\mu} = 2\sqrt{\tau^2|D_W|^2 + |D_z|^2 + \mu^2} + A + \lambda, \qquad V = 1 + A, \quad \mu = \ell\kappa.$$

The rescaled operator H_- is $\ell^{-1}\mathcal{H}_{\tau,\mu}$. The one-dimensional oscillator gap and the potential give $\mathcal{H}_{\tau,\mu} \ge cV$, uniformly in τ, μ. The Jacobian is $\ell\delta^{d-1}$; multiplying by the inverse scale ℓ gives N for the trace.

Let $\Phi_\kappa(W, z)$ be the right energy column at $(-\ell z, \delta W)$, the Riesz representative of $B_\kappa^* \delta_{(-\ell z, \delta W)}$. The off-diagonal kernel at distance $r \ge 1$ is bounded by $Ce^{-c\kappa r} r^{-d-1}$. This follows from the heat subordination integral by keeping a fraction of the combined Gaussian and mass exponents before integrating the remainder. The homogeneous Sobolev dual estimate in dimension $d \ge 2$

then gives $\|\Phi_\kappa(W,z)\| \le Ce^{-c\kappa}$ uniformly. Thus Φ_κ has finite vector-valued $L^2(V^{-1})$ norm, and $\operatorname{Tr} X_\kappa^* X_\kappa \le CNe^{-c\kappa}$. The Hilbert-valued scaled solution $u = \mathcal{H}_{\tau,\mu}^{-1}\Phi_\kappa$ satisfies $\|V^{1/2}u\|_2 \le Ce^{-c\kappa}$.

The scaled left window contains the half-ball of radius $R = M/\delta$, since $\ell \le \delta$. In (64) the source term is bounded by

$$\|V^{1/2}u\|_2 \|\mathbf{1}_{\{|x|\ge R/2\}} V^{-1/2}\Phi_\kappa\|_2 \le Ce^{-c\kappa}R^{(d-p)/2}.$$

For the jump term take one solution factor outside $R/2$. Its L^2 norm is at most $Ce^{-c\kappa}R^{-p/2}$. Together with the global L^2 norm and the Schur bound this gives $Ce^{-c\kappa}R^{-1-p/2}$. The left one-sided squared Hilbert–Schmidt loss divided by N is therefore at most $Ce^{-c\kappa}(\delta/M)^{(p-d)/2}$.

58 The right window at all masses

In right coordinates centered tangentially at the source point's coordinate Y, the signed cross column can be chosen as a nonnegative function h_κ. The length of the separation vector to y is at least $c(1+|y|)$ uniformly in the left depth. As above,

$$h_\kappa(y) \le Ce^{-c\kappa(1+|y|)}(1+|y|)^{-d-1}. \tag{65}$$

The right Green kernel G_κ is the killed half-space kernel of [49, Theorem 4.4, (4.3)] at $\alpha = 1$ and mass parameter $m = \kappa$, multiplied by $1/2$. Their relativistic process has nonnegative generator $\sqrt{|D|^2+m^2}-m$. Taking its m-resolvent after killing gives the inverse of the supported square root used here. This normalization is important for mass decay. For $r = |x-y|$ the massless kernel has the form

$$C_d r^{1-d}\int_0^{4x_d y_d/r^2} t^{-1/2}(1+t)^{-d/2}\,\mathrm{d}t.$$

At positive mass the integrand is multiplied by a dimensional constant times $b(\kappa r\sqrt{1+t})$, where $b(a) = a^{d/2}K_{d/2}(a)$ and K_ν is the modified Bessel function. This function extends positively to zero, is bounded below on bounded intervals, and is bounded above by Ce^{-ca} for $a \ge 0$. Consequently

$$G_\kappa(x,y) \le Ce^{-c\kappa|x-y|}G_0(x,y), \qquad G_0(x,y) \le C\min(r^{1-d}, \sqrt{x_d y_d}\, r^{-d}).$$

The last bound follows by using the full or truncated beta integral. At zero mass the Green representation extends from compact tests to the decaying right source by homogeneous Sobolev dual convergence and positivity of the kernel [49, Corollary 4.6]. In particular this identifies the homogeneous solution.

Let $u_\kappa = H_+^{-1}h_\kappa$. Combine the exponential factors by the triangle inequality. In the remaining massless convolution, if $|x| = r_0 \ge 2$, integrate over $|y| \le r_0/2$ with the second bound on G_0. The finite $y_d^{1/2}$-moment of the source gives $O(r_0^{-d+1/2})$. On $|y| > r_0/2$ and $|x-y| < r_0/2$, the source is $O(r_0^{-d-1})$ and the first kernel bound integrates to $O(r_0)$. On the remaining region the $O(r_0^{1-d})$ kernel multiplies a source tail $O(r_0^{-1})$. At bounded r_0 the kernel is locally integrable. Thus

$$0 \le u_\kappa(x) \le Ce^{-c\kappa(1+|x|)}(1+|x|)^{-d+1/2}. \tag{66}$$

This gives $u_\kappa \in L^2$ also at $\kappa = 0$.

If $|Y| \le M/4$, the translated half-ball of radius $R = M/2$ lies in the right window. Apply (64). The source term is $O(e^{-c\kappa}e^{-c\kappa M}R^{-d-1/2})$ by (65) and (66). For the jump integral with

both arguments beyond $R/4$, the Schur bound multiplies the squared L^2 tail $O(R^{1-d})$. If one argument lies within $R/4$, the other lies beyond $R/2$, and the distance is at least half the larger radius. The inner L^1 mass is $O(R^{1/2})$ and the outer integral against the jump weight $|y|^{-d-1}$ is $O(R^{-d-1/2})$. In both cases a solution factor beyond $R/4$ supplies $e^{-c\kappa M}$ from (66) in addition to the uniform $e^{-c\kappa}$. The squared right energy projection defect of this column is therefore $O(e^{-c\kappa}e^{-c\kappa M}M^{-d})$.

For $|Y| > M/4$ use the full right energy norm. Then $|W| > M/(4\delta)$, a set of V^{-1}-weighted volume $O((\delta/M)^{p-d})$. If P_+ denotes the right energy projection, the right one-sided normalized squared Hilbert–Schmidt loss is bounded by

$$C\int V^{-1}\|(I-P_+)\Phi_\kappa\|^2\,\mathrm{d}W\;\mathrm{d}z \le Ce^{-c\kappa}\left[M^{-d}e^{-c\kappa M}+(\delta/M)^{p-d}\right].$$

Here the first inequality follows from $\mathcal{H}_{\tau,\mu}^{-1} \le CV^{-1}$.

59 An exterior-energy lower bound

Normalize the cross operator by $N^{-1/2}$ and scale the left variables unitarily. Fix a nonnegative real $f \in C_c^\infty(\mathbb{R}^s \times (0,\infty))$ with $\int f > 0$. Its left energy norm $\|\mathcal{H}_{\tau,\ell\kappa}^{1/2} f\|_2$ is uniformly bounded for $0 \le \kappa \le M^{-1}$, as the kinetic symbol is bounded by $C(1+|(\eta,\zeta)|)$ and the potential is bounded on the fixed support. Using this energy vector as a test cancels the left inverse square root in the scaled cross operator. The source on the right is then, up to the common sign,

$$h_{\kappa,f}(y) = \int f(W,z)\,|B_\kappa((-\ell z,\delta W),y)|\,\mathrm{d}W\;\mathrm{d}z.$$

The rescaling contributes no remaining factors: the left square root contributes $\ell^{1/2}$ and the integrated coordinate change $(\ell\delta^{d-1})^{1/2}$, which together equal $\sqrt{N}$. The source has a uniform positive lower bound on a fixed compact right box with $1 < y_d < 2$ in depth coordinates, since the separated kernel is continuous and strictly positive in absolute value there.

Let X_M be a fixed-aspect box of size proportional to M outside the half-ball of radius C_1M, within the right half-space at depth comparable to M. For $x \in X_M$ and y in the source box, $|x-y| \asymp M$, $x_d y_d \asymp M$, and the upper endpoint of the Green integral is $\asymp M^{-1}$. At $0 \le \kappa \le M^{-1}$ the Bessel argument is bounded, so the lower bound of b gives $G_\kappa(x,y) \gtrsim M^{-d+1/2}$. The full right solution of the test source is therefore $u_\kappa(x) \ge cM^{-d+1/2}$ on X_M.

For the projection residual $w = u_\kappa - P_+u_\kappa$, one has $w = u_\kappa$ on X_M. It vanishes on a comparable box Z_M on the exterior side of the full right half-space, chosen with separations from X_M comparable to M. Across these boxes the kinetic jump density is $\gtrsim M^{-d-1}$, by restricting the subordination integral to times comparable to M^2. The exterior pairs alone bound the full energy below by

$$cM^{-d-1}|X_M||Z_M|M^{-2d+1} \ge cM^{-d}.$$

This is a lower bound for the squared projection loss on the fixed bounded-energy test, and hence for the right normalized Hilbert–Schmidt-square loss.

60 Determinants, vacuum energy, and temperature

The finite energy cross operator is $P_+X_\kappa P_-$, with P_- the left energy projection. The exact identity

$$\|X_\kappa\|_{\mathrm{HS}}^2 - \|P_+X_\kappa P_-\|_{\mathrm{HS}}^2 = \|(I-P_+)X_\kappa\|_{\mathrm{HS}}^2 + \|P_+X_\kappa(I-P_-)\|_{\mathrm{HS}}^2$$

bounds the squared trace loss by the two one-sided losses. Term by term the squared singular values decrease under these compressions. Since the full squared operator norm is at most $CNe^{-c\kappa}$, the derivative of $-\log(1-t)$ is between 1 and a fixed constant on the common spectral interval for small parameters. Applying this statement termwise proves (60)–(62), including monotonicity under the extra left truncation.

For physical gap g, the vacuum difference between the bounded and unbounded openings is $(2\pi g)^{-1}\int_0^\infty (q_\infty - q_M)\,\mathrm{d}\kappa$. At physical inverse temperature $\beta_* g$, the free-energy difference is $(2\beta_* g)^{-1}\sum_{j\in\mathbb{Z}}(q_\infty - q_M)(2\pi|j|/\beta_*)$. In vacuum, integration of $e^{-c\kappa M}$ gains M^{-1}, and integration of (62) over $0 \le \kappa \le M^{-1}$ gives the same lower power M^{-d-1}. At fixed scaled inverse temperature $\beta_* > 0$, the Matsubara masses are $2\pi|j|/\beta_*$ for $j \in \mathbb{Z}$. The $j = 0$ term has error of order M^{-d} from the transparent-side boundary, and the other near-column boundary terms are exponentially small in M. The localization tails in the theorem remain in the upper bounds for both observables. When these tails are negligible, the lower bounds show that the right-window powers cannot be improved.

For fixed physical rectangles with facing points in the relative interiors of the facing faces, a gap $g \downarrow 0$ permits $M \asymp g^{-1}$. Because $\delta = O(\tau\log(1/\tau))$ and $p > d + 6$, the localization terms are $o(\mathcal{L}_\tau)$ already for fixed $M \ge 4$. Thus $g^{d+1} = o(\mathcal{L}_\tau)$ suffices for the two-term vacuum expansion and $g^d = o(\mathcal{L}_\tau)$ suffices for the expansion at physical inverse temperature $\beta_* g$. If the right outer radius is also comparable to M, the lower bound makes each corresponding scale condition necessary for agreement with the half-space formula through an $o(\mathcal{L}_\tau)$ error in energy normalized by g/N. The flat support and the contact (59) are exact in these limits.

61 Shape coefficients for bounded-window corrections

The square-root aperture determinant for a scalar field in a Dirichlet plate was developed by Kabat, Karabali and Nair [19]. The parallel-edge confinement model and quantitative window bounds in Sections 51–60 establish the sharp powers M^{-d-1} in the vacuum integral and M^{-d} at zero Matsubara mass, with localization errors on the contact side. We compute the coefficient of this boundary error for a fixed shape dilated to radius comparable to M. The massive killed Green function is due to Byczkowski, Małecki and Ryznar [49]. The new step is strong convergence of the corresponding cutoff columns and passage through the anisotropic left inverse.

We use the flat anisotropic model of Sections 53–60, with $d = s + 1 \ge 2$, degree $p > d + 6$, exact left contact $\ell^{-1}[A(\tau Y/\ell, u/\ell) + \lambda]$, fixed $\lambda \ge 0$, $\mathcal{L}_\tau = \tau^2\log(1/\tau)$, $\ell = O(\mathcal{L}_\tau)$, $\delta = \ell/\tau$, and $N = \ell^2\delta^{d-1}$. Assume that A is positive homogeneous of degree p, with angular factor C^1 and bounded above and below by positive constants on the closed inward hemisphere. Here $u > 0$ is the inward depth on the left and Y is its tangential coordinate. In gap units the two half-spaces are separated by a retained strip of width one. The right side is transparent. Let $\ell, \tau \downarrow 0$ and $M \to \infty$. Fix a bounded right rectangle Ω in the inward right half-space $H = \{X_d > 0\}$, containing the unit half-ball about its facing point, which is the origin of these inward coordinates. In gap units the right window is $M\Omega$. Let $q_\infty = -\operatorname{Tr}\log(I - X_\kappa^* X_\kappa)$, where $X_\kappa = H_+^{-1/2} B_\kappa^* H_-^{-1/2}$ is the energy cross operator. The operators $H_\pm$ are the supported compressions of $2\sqrt{|D|^2 + \kappa^2}$ with the declared contacts, and B_κ is their off-diagonal cross kernel. At zero mass the right map is understood through the Riesz representation in the homogeneous supported energy space. Write $q_{\mathrm{right},M}$ for the determinant when only the right opening is restricted. If a left finite window is also imposed, it contains the half-ball of radius M of the left side and q_M denotes the two-sided truncation.

For $\nu \ge 0$, write a_ν for the supported energy of $2\sqrt{|D|^2 + \nu^2}$ on H, with the homogeneous

completion at $\nu = 0$. Let $P_{\Omega,\nu}$ be the energy projection onto the closed supported form subspace generated by $C_c^\infty(\Omega)$. Put

$$\mathsf{K}_\nu(X) = \frac{\Gamma(d/2)}{\pi^{d/2+1}} \frac{\sqrt{X_d}}{|X|^d} \frac{b(\nu|X|)}{b(0)}, \qquad b(t) = t^{d/2} K_{d/2}(t), \quad X \in H,$$

and extend it by zero outside H. Choose a smooth real cutoff χ that is zero near the origin and one outside a ball whose intersection with H lies in the inscribed half-ball of Ω. Define

$$\mathfrak{C}_\Omega(\nu) = \|(I - P_{\Omega,\nu})\chi \mathsf{K}_\nu\|_{a_\nu}^2 .$$

This is well defined, independent of the cutoff, strictly positive, and bounded by $Ce^{-c\nu}$. Equivalently it is the squared distance of an admissible extension of the prescribed exterior profile K_ν from the energy subspace of the window. It is nonincreasing under window inclusion and satisfies $\mathfrak{C}_{a\Omega}(\nu) = a^{-d}\mathfrak{C}_\Omega(a\nu)$ for $a > 0$, with the same definition at any positive inscribed radius.

Define $C_0 = \langle 1, (2|D_z| + A + \lambda)^{-1} 1\rangle$ in the form dual, as in Section 52.

Theorem 30. *If $M^d(\delta/M)^{p-d} \to 0$, then pointwise for each $\nu \geq 0$,*

$$\boxed{\frac{M^d}{N}(q_\infty - q_{\mathrm{right},M})(\nu/M) \longrightarrow C_0 \mathfrak{C}_\Omega(\nu).} \tag{1}$$

The same holds with q_M if $M^d(\delta/M)^{(p-d)/2} \to 0$. Under the stronger right-only assumption $M^{d+1}(\delta/M)^{p-d} \to 0$,

$$\frac{M^{d+1}}{N} \int_0^\infty (q_\infty - q_{\mathrm{right},M})(\kappa)\, d\kappa \longrightarrow C_0 \int_0^\infty \mathfrak{C}_\Omega(\nu)\, d\nu. \tag{2}$$

For both windows replace the tail exponent in this stronger assumption by $(p-d)/2$. At a fixed scaled inverse temperature $\beta_* > 0$, under the original M^d tail assumptions, the sum satisfies

$$\frac{M^d}{N} \sum_{j\in\mathbb{Z}} (q_\infty - q_{\mathrm{right},M})(2\pi|j|/\beta_*) \longrightarrow C_0 \mathfrak{C}_\Omega(0), \tag{3}$$

with the same two-sided alternative.

The energy prefactors are respectively $1/(2\pi g)$ and $1/(2\beta_* g)$ for bounded-minus-full physical energies at physical gap g. For fixed physical rectangles take $M = c/g$ with $c > 0$ below the common physical inscribed half-ball radius, and measure Ω in physical units divided by c. The relevant tail conditions hold automatically at the corresponding critical scale $M^{-(d+1)} \asymp \mathcal{L}_\tau$ in vacuum or $M^{-d} \asymp \mathcal{L}_\tau$ thermally. Thus these coefficients enter additively at the critical aperture correction scale. The fixed shape, exact flat gap support and the prescribed contact are part of the statement.

62 Strong convergence of the rescaled column

Fix $\nu \geq 0$. For the moment take any sequence of right sources $h_M \geq 0$ with $h_M(y) \leq C(1 + |y|)^{-d-1}$ and $h_M \to h_0$ locally pointwise in H. Let $u_M = H_{\nu/M}^{-1} h_M$ in the supported right form, where $H_\kappa = 2\sqrt{|D|^2 + \kappa^2}$ is compressed to H, and define

$$U_M(X) = M^{d-1/2} u_M(MX), \qquad H_\nu U_M = f_M, \qquad f_M(X) = M^{d+1/2} h_M(MX). \tag{4}$$

The source scale follows by homogeneity of the mass-dependent symbol. At $X \neq 0$, $f_M \leq CM^{-1/2}|X|^{-d-1}$. The massive Green kernel bound and the massless convolution split of Sections 51–60 give

$$0 \leq U_M(X) \leq C|X|^{-d+1/2}. \tag{5}$$

For each fixed $X \in H$, the scaled Green kernel converges pointwise at every fixed y to $\mathsf{K}_\nu(X)\sqrt{y_d}$. Use the Green formula of [49, Theorem 4.4, (4.3)]. The beta integral runs up to $4X_d y_d/(M|X|^2)(1+o(1))$, and the massive factor tends $b(\nu|X|)/b(0)$. The massless Green prefactor for $2|D|$ is $\Gamma(d/2)/(4\pi^{d/2+1})$, and integrating $t^{-1/2}$ with the factor 4 in the endpoint multiplies it by 4. For the omitted source tail with $|y| \leq |MX|/2$, the normalized integrand is dominated by $C_X\sqrt{y_d}(1+|y|)^{-d-1}$. The regions $|y| > |MX|/2$, $|MX-y| < |MX|/2$ and its complement each cost $O_X(M^{-1/2})$ after scaling, using the full beta bound and the volume estimates in Section 58. Therefore

$$U_M(X) \longrightarrow m_h \mathsf{K}_\nu(X), \qquad m_h = \int_H \sqrt{y_d}\, h_0(y)\, dy. \tag{6}$$

To lift (6) to energy, take the cutoff χ as above and use the exact commutator identity from Section 57, applied to $W_{M,L} = U_M - U_L$ and the same fixed form a_ν. From (4),

$$a_\nu[\chi W_{M,L}] = \Re\langle f_M - f_L, \chi^2 W_{M,L}\rangle + \frac{1}{2}\iint J_\nu(X-Y)(\chi(X)-\chi(Y))^2 \Re\big(W_{M,L}(X)\overline{W_{M,L}(Y)}\big)\, dX\, dY. \tag{7}$$

Every term is meaningful for finite M, L: the scaled responses are in the supported energy space and are L^2 by the convolution bound, even at $\nu = 0$. Multiplication by χ, χ^2 is bounded on the energy-plus-L^2 domain by the same Schur argument as for radial cutoffs in the public proof. The source term tends to zero, being $O(M^{-1/2} + L^{-1/2})$ by (4)–(5) and the cutoff near the origin.

Set $\alpha = d - 1/2$. The jump integral is dominated by the integrable kernel

$$C|X-Y|^{-d-1}(\chi(X)-\chi(Y))^2|X|^{-\alpha}|Y|^{-\alpha}\mathbf{1}_H(X)\mathbf{1}_H(Y).$$

Indeed, outside a small ball in both variables, $|X|^{-\alpha}$ is L^2 since $d \geq 2$, and the squared cutoff difference gives a bounded Schur kernel. If one point lies near the origin, the other must lie beyond the ball where the cutoff vanishes; choose the first ball with half that radius. Their distance is then bounded below by a fixed multiple of the outer radius, and the inner singularity is L^1 because $\alpha < d$. The remaining outer inverse-distance integral converges. Pointwise $W_{M,L} \to 0$ off the origin by (6), so the second term in (7) tends to zero by dominated convergence. Taking arbitrary two subsequences gives energy Cauchy convergence. Ordinary L^2 dominated convergence after multiplication by χ identifies the limit. Thus

$$\chi U_M \longrightarrow m_h\, \chi \mathsf{K}_\nu \quad \text{strongly in } a_\nu. \tag{8}$$

At $\nu = 0$ the homogeneous energy limit agrees with the L^2 limit by the Sobolev embedding, or by distributional convergence. Taking a test sequence with $m_h > 0$ shows $\chi\mathsf{K}_\nu$ itself is admissible. This proof uses no regularity at the origin of the limit profile.

The product $(1-\chi)U_M$ belongs to the supported energy subspace of Ω by its support and inward translation followed by smoothing. Hence the right residual is $(I - P_{\Omega,\nu})\chi U_M$. The right energy isometry from physical coordinates to the fixed scaled shape multiplies $u_M(MX)$ by $M^{(d-1)/2}$. Consequently U_M is $M^{d/2}$ times the isometric image, and the squared right projection defect times M^d converges to $m_h^2 \mathfrak{C}_\Omega(\nu)$. Different cutoffs change $\chi\mathsf{K}_\nu$ by a supported form

element whose support is inside the inscribed ball and avoids the origin; the same core approximation proves cutoff independence. Positivity follows because the residual equals the strictly positive profile on the part of H outside a ball containing Ω. Shape monotonicity is the distance comparison for nested form subspaces. The scaling law follows from $\mathsf{K}_\nu(aX) = a^{-d+1/2}\mathsf{K}_{a\nu}(X)$ and dilation of the energy.

63 The cross trace and determinant

Keep ν fixed. At any fixed scaled left point $x = (W, z)$, the normalized right source is the absolute separated column evaluated at $(-\ell z, \delta W)$, at mass ν/M. In the inward right coordinates it tends to the massless column from the origin on the left. The translation of its center tends to zero, so the source hypotheses in (4)–(6) hold with a uniform decay constant for that fixed x. The boundary moment of the limiting source is exactly one in the aperture convention. Indeed integrating the $2|D|$ cross kernel in tangential variables gives the one-dimensional cross kernel $2/[\pi(1 + y_d)^2]$, so its moment is $(2/\pi)\mathrm{B}(3/2, 1/2) = 1$. This is also the explicit massless one-dimensional input in Section 44.

Let $\Psi_M(x)$ denote the right column residual, isometrically transported to the fixed energy space of a_ν and multiplied by $M^{d/2}$. By (8) and projection,

$$\Psi_M(x) \longrightarrow \psi_\nu = (I - P_{\Omega,\nu})\chi\mathsf{K}_\nu$$

in that right energy Hilbert space for each x. On the near region $|\delta W| \le M/4$ the public near-column estimate gives $\|\Psi_M(x)\|^2 \le Ce^{-c\nu}$. On its complement the global column bound and the V^{-1}-weighted volume give

$$\int_{|\delta W|>M/4} V(x)^{-1}\|\Psi_M(x)\|^2\,dx \le CM^d(\delta/M)^{p-d}.$$

Here $V = 1 + A$ and $\int V^{-1} < \infty$. The near region exhausts each fixed scaled point. Dominated convergence there and the far-tail assumption give strong convergence $\Psi_M \to \psi_\nu$ in vector-valued $L^2(V^{-1})$. Taking the pointwise energy limit at one fixed left point also proves $\mathfrak{C}_\Omega(\nu) \le Ce^{-c\nu}$ for all $\nu \ge 0$.

The normalized loss of right Hilbert–Schmidt square, multiplied by M^d, is exactly

$$\langle \Psi_M, \mathcal{H}^{-1}_{\tau,\ell\nu/M}\Psi_M\rangle, \qquad \mathcal{H}_{\tau,\mu} = 2\sqrt{\tau^2|D_W|^2 + |D_z|^2 + \mu^2} + A + \lambda. \tag{9}$$

The left volumes and inverse factor give N as in Section 57, and the right defect scaling has just been computed. The left inverse is uniformly bounded $L^2(V^{-1}) \to L^2(V)$, and its constant quadratic tends to C_0 by Section 54, or by compact variational trials and form ordering. Replace both vector sources in (9) by the constant vector ψ_ν. This yields $C_0\|\psi_\nu\|^2_{a_\nu}$.

Finally, termwise ordering of squared singular values under projections and the derivative of $-\log(1-t)$ bound the full log-determinant loss between the Hilbert–Schmidt-square loss and $1 + O(N)$ times that loss. This proves (1). The extra two-sided loss is at most $CNe^{-c\kappa}(\delta/M)^{(p-d)/2}$ by the separate left projection estimate and the same log Lipschitz constant. This proves the two-sided assertion.

64 Vacuum and thermal coefficients

The function $\mathfrak{C}_\Omega$ is measurable by (1), along any one admissible parameter sequence. Indeed the prelimit determinants are continuous for positive mass. On each compact positive mass interval

the inverse forms have a positive gap and the difference of their kinetic multipliers is bounded in operator norm by twice the mass difference. The separated columns vary continuously in the weighted Hilbert–Schmidt pairing by their separation and exponential bounds. The value at zero is included as a separate point. This proves measurability without changing the energy space at zero.

For (2), change variables $\nu = M\kappa$. Edition 9 bounds the multiplied integrand by $Ce^{-c\nu} + CM^d(\delta/M)^{p-d}e^{-c\nu/M}$ for the right-only loss. The second bound has integral $O(M^{d+1}(\delta/M)^{p-d})$, which tends to zero. On compact sets use dominated convergence with the same estimates, then take the compact mass range to infinity, using the first envelope. The left error for both windows is handled identically with the half exponent. For (3), all nonzero Matsubara masses give $O(e^{-cM})$ in the near-column bound after normalization by NM^{-d}; the summed localization term is $O_{\beta_*}(M^d(\delta/M)^{p-d})$ for the right-only loss. Equation (1) at $\nu = 0$ gives the remaining term. This proves the thermal statement and its two-sided counterpart.

For the critical scales $M^{-r} \asymp \mathcal{L}_\tau$, with $r = d + 1$ for vacuum and $r = d$ for temperature, use $M^r(\delta/M)^{(p-d)/2} \le C\delta^{(p-d)/2}/\mathcal{L}_\tau \to 0$. This follows from $\delta = O(\tau \log(1/\tau))$ and $p - d > 6$. In particular, let $\mathcal{E}_M, \mathcal{E}_\infty$ and $\mathcal{F}_M, \mathcal{F}_\infty$ denote the physical vacuum and thermal energies for both finite and both full windows, respectively. If $M^{-d-1}/\mathcal{L}_\tau \to \rho \in (0, \infty)$, then

$$\frac{g(\mathcal{E}_M - \mathcal{E}_\infty)}{N\mathcal{L}_\tau} \longrightarrow \frac{\rho C_0}{2\pi} \int_0^\infty \mathfrak{C}_\Omega(\nu)\, d\nu.$$

If $M^{-d}/\mathcal{L}_\tau \to \rho \in (0, \infty)$, then at physical inverse temperature $\beta_* g$,

$$\frac{g(\mathcal{F}_M - \mathcal{F}_\infty)}{N\mathcal{L}_\tau} \longrightarrow \frac{\rho C_0}{2\beta_*} \mathfrak{C}_\Omega(0).$$

These are additive to the half-space kinetic and depth corrections.

The argument treats parallel flat supports and fixed homothetic right windows.

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