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.

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. 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 $\operatorname{Re}\sqrt{\xi^2+\mu^2}\geq c\sqrt{1+\xi^2}$ for $|\arg\mu|\leq\pi/4$. 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

$$Q(z)=\sum_{j\geq1}j^{-1}\operatorname{Tr}[(A_\mu^{-1}BA_\mu^{-1}B)^j].$$

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

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

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 $|e^{-\mu s}|\leq e^{-s/\sqrt{2}}$. Terms with $j\geq2$ 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 $|\arg\mu|\leq\pi/4$, 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

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

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 uf_μ gives $(u+1/(4\mu))f_\mu/\sqrt{2\mu}$, first for positive real μ. Consequently the pairing of uf_μ 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 $u=t^2v$. 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 $C(K)=2\log\operatorname{cap}(K)$. 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

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

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,

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

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

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

Equivalently $W(x) = 1 - 2(4\pi x)^{-1/2}\sum_{n\geq 1} e^{-n^2/(4x)}$. 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 $\lambda > 0$

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

Proof. For $t = g^2 T$, 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 $J^c_h(T) = J^{ch}_1(T/h^2)$ and substitute $T = h^2 u$. 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 $\mathrm{Tr}(R_{-,g}B_gR_{+,g}B_g^*)$. 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 $g^{\gamma_*}c_g^2q_g(\kappa)$ 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 $g^{\gamma_*}c_g^2q_g$ 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

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

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*

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

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 $\operatorname{sech}(\pi n W/H_0)$. 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*

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

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 $P(s) = \prod_{n\geq 1}(1-e^{-sn})$. 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 $\mathrm{Tr}(R_{-,g} C_g)$. The difference from $\mathrm{Tr}\, C_g$ is at most $\mathrm{Tr}[(P_{-,g} - R_{-,g}) C_{\kappa,0}]$, 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 $2\,\mathrm{Re}\langle f_{g,Y}, v\rangle$ 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 $C\|v\|_{\dot{H}^{1/2}}^2$ 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 $\min(1, \operatorname{dist}(Y, K_{-,g}^c)/\delta)$. 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 $I - R_{-,g} \leq A_{-,g}/c_{-,g}$ 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 $W_{1,0}(\sqrt{\kappa^2 + |k|^2}, 1) \leq W_{1,0}(0, 1)$. 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 $d \geq 2$.

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 $\kappa \geq 0$ 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 $1-e^{-aL^- -bL^+} \leq m(L^- + L^+)$ 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 $d \geq 2$ 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

$$C_* = \lim_{L\to\infty} \left[\int_0^{L^2} J(T)\frac{dT}{T} - \tfrac{1}{4}\log L + \log\log L \right],$$

$$C_{\ell_-,\ell_+} = \log\pi - \tfrac{1}{4}\log(\ell_-^{-1} + \ell_+^{-1}),$$

$$N_\lambda = 2\sum_{n\geq 1} \int_0^\infty e^{-(2\pi n/\lambda)^2 T} J(T)\frac{dT}{T}.$$

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 $q \geq 0, \ell > 0$, 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* $\kappa \geq 0$ *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 $\int_0^\infty |v(x)|^2 dx/x \le C\mathfrak{a}_0[v]$ 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 $h_R(x) \le C/x$ 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 $\mathrm{Tr}(R_g C_g)$ 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 $M_g^{-1}\operatorname{Tr}(R_gC_g)$. 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 $CM_g^{-1}g^{-\gamma_*}$ 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 $x, x' \geq 0$ 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

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

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

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

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 $x \geq 0$ 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 $x_0 \geq 0$. 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 $\varepsilon_M \to 0$, $\varepsilon_M \geq 0$, and take the compressed form

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

with $\kappa_M \to \kappa \geq 0$. 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

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

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 $|\xi| \le r$ 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 $\|f\|_{\text{inner}}^2 = O(\rho_M)$ 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 $b \ge 0$ 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

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

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 $\ell \ge h$,

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

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 $0 \le \chi \le 1$ 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 $2|\xi| \le 1 + |\xi|^2$. Finally

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

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 $\|Q_b\| \le C_h/M$, 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 $a_g \sum_{0<ja_g<d} F(ja_g)$ 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.

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