Joint Cutoffs and Negative-Spectrum Decay for Weighted Weil Operators

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Abstract

We obtain a joint finite-rank approximation law for the complete Birman–Schwinger family of a constrained theta-weighted Weil operator. At each fixed absolute error tolerance, the required rank is at most $C\exp(C\sqrt{\log(1/\varepsilon)})$ as the positive resolvent parameter ε tends to zero. The construction pays the complete paired arithmetic tail, high-frequency block and mixed localization errors. It gives a corresponding bound on the entire negative spectral projection and implies that the negative eigenvalue magnitudes decay as $C\exp[-c\log^2(n+1)]$. Thus the full negative part belongs to every Schatten class. We also give effective simultaneous prime-phase returns and prove signed high-frequency saturation uniformly in a complementary growing-cutoff regime, retaining the exact polar constraints and the inverse-theta packet norm. The joint rank and saturation regimes have different parameter scales.

1 Introduction and results

The spectral effect of an arithmetic truncation depends on the resolvent parameter against which its error is measured. A fixed-cutoff approximation theorem therefore needs a joint parameter analysis before it gives information about eigenvalues accumulating at a threshold. We perform that analysis for the constrained theta-weighted realization introduced in [1]. The new recipient is the entire negative part of the original operator, rather than its output on a prescribed null space.

Write $H = A + B$ for the precise minimal-form realization defined in Section 2, with $A \geq 0$ and B bounded selfadjoint. For $\varepsilon > 0$ put

$$K_\varepsilon = (A+\varepsilon)^{-1/2}(-B)(A+\varepsilon)^{-1/2}, \qquad n_-(H;-\varepsilon) = \operatorname{rank} 1_{(-\infty,-\varepsilon)}(H).$$

The negative part is $H_- = \max(-H, 0)$ in the spectral calculus.

Theorem 1.1 (Joint rank and negative-spectrum decay)**.** *For every fixed $0 < \eta \leq 1$ and $0 < \varepsilon \leq 1$, the complete operator K_ε has a selfadjoint finite-rank approximant with norm error less than η. Its rank is at most the explicit integer $N(\varepsilon,\eta)$ in (10). For each fixed η there is C_η such that*

$$N(\varepsilon,\eta) \leq C_\eta \exp\left(C_\eta\sqrt{\log(1/\varepsilon)}\right).$$

There are constants $C, c > 0$ such that

$$n_-(H;-\varepsilon) \leq C\exp\left(C\sqrt{\log(1/\varepsilon)}\right), \tag{1}$$

$$\lambda_n(H_-) \leq C\exp[-c\log^2(n+1)]. \tag{2}$$

Here the negative eigenvalue magnitudes are ordered nonincreasingly, repeated with multiplicity, and padded by zeros if finite. In particular $H_- \in \mathcal{S}_p$ for every $p > 0$.

The rank bound includes the growing retained arithmetic set and all localization remainders. The parameter η is fixed in the displayed asymptotic; the explicit formula governs its simultaneous variation. The finite-rank construction contains the actual resolvent rows, so the theorem is an approximation-rank statement rather than an estimate for the arithmetic cost of evaluating those rows.

The proof uses the frequency-first enclosure from [1], which we reproduce below in the exact form needed. An elementary Chebyshev estimate removes an unnecessary logarithm from the retained arithmetic coefficient. The form-domain Birman–Schwinger correspondence and finite-rank min–max then control the whole negative spectrum. These spectral tools and Schatten theory are classical; see [3, 4]. Related logarithmic-symbol spectral estimates include [5], whose finite-measure Dirichlet setting differs from the full-line theta-multiplication reference used here. Weighted arithmetic realizations and fixed-depth localization arguments also appear in [6]. The contribution here is the joint cutoff law and its quantitative consequence for H_- in the specified realization.

Section 6 gives a complementary signed saturation theorem. It improves the predecessor's fixed-arithmetic-cutoff statement to a precisely quantified growing-cutoff regime. Its prime-phase coverage is uniform over every translated interval, and its packet normalization is controlled in the original weighted recipient. This regime is slower than the cutoffs used for Theorem 1.1; no rank optimality follows merely by comparing their formulas.

2 Exact realization and inherited budgets

Inner products are conjugate-linear first, and

$$\widehat{f}(\xi) = \int_{\mathbb{R}} e^{-iu\xi} f(u)\,\mathrm{d}u, \qquad \|f\|^2 = \int_{\mathbb{R}} |\widehat{f}(\xi)|^2 \frac{\mathrm{d}\xi}{2\pi}.$$

Use the full theta kernel

$$\psi(u) = 2\sum_{n\geq 1} (2\pi^2 n^4 e^{9u/2} - 3\pi n^2 e^{5u/2}) e^{-\pi n^2 e^{2u}}. \tag{3}$$

The locally uniformly differentiable series is even and strictly positive. For normalization, with $\vartheta(x) = \sum_{n\in\mathbb{Z}} e^{-\pi n^2 x}$ and $b(u) = e^{u/2}(\vartheta(e^{2u}) - 1)$, Poisson summation gives $b(u) - b(-u) = e^{-u/2} - e^{u/2}$ and $\psi = \frac{1}{2}(\partial_u^2 - 1/4)b$. Positivity follows from the individual terms on $u \geq 0$, then reflection.

Put $c(u) = \cosh(u/2)$, $w = \psi c$, $s = \sqrt{\psi/c}$, and

$$\mathcal{K} = \{h \in L^2(\mathbb{R}) : \langle \sqrt{w}, h\rangle = \langle \sqrt{w}\tanh(u/2), h\rangle = 0\}.$$

The two rows are smooth, in L^2, and linearly independent. The weighted unitary coordinate is $h = \sqrt{w}\, g$, with $\psi g = sh$.

Writing $\psi_0 = \Gamma'/\Gamma$, define

$$m_0 = \psi_0(1/4) - \log\pi < 0, \qquad a(\xi) = \Re\psi_0(1/4 + i\xi/2) - \psi_0(1/4).$$

The digamma series and asymptotic [2, §§5.7,5.11] give

$$a(\xi) = \sum_{j\geq 0} \frac{t^2}{(j+1/4)((j+1/4)^2 + t^2)}, \quad t = |\xi|/2, \qquad a(\xi) = \log|\xi| + O(1). \tag{4}$$

It is even, positive away from zero, and increasing in $|\xi|$.

On $\mathcal{C} = C_c^\infty(\mathbb{R}) \cap \mathcal{K}$ define

$$\mathfrak{a}[h] = \int a(\xi)|\widehat{sh}(\xi)|^2 \frac{\mathrm{d}\xi}{2\pi}.$$

The core is dense: compact smooth approximation followed by correction using two fixed compact smooth vectors with invertible row matrix proves this. The maximal graph map $h \mapsto a(D)^{1/2}(sh)$ is closed, so its restriction is closable. Let $\mathcal{V}$ be the closure of $\mathcal{C}$ in $\|h\|^2 + \mathfrak{a}[h]$, and let A be its associated nonnegative selfadjoint operator. This chosen core closure specifies the realization.

Let $S_b f(u) = f(u+b)$ and $c_n = \Lambda(n)/\sqrt{n}$. The complete bounded perturbation is

$$B = P_{\mathcal{K}} \left[m_0 M_s^2 - \sum_{n \geq 2} c_n M_s (S_{\log n} + S_{-\log n}) M_s \right] |_{\mathcal{K}}. \tag{5}$$

The paired series converges in norm by the estimate below. Thus $H = A + B$ is selfadjoint on $\operatorname{Dom} A$, with form domain $\mathcal{V}$.

Lemma 2.1 (Source bounds)**.** *The following complete-kernel bounds hold:*

$$\|s\|_\infty \leq 1, \qquad \sup_{|u|>R} s(u) \leq \sigma_R := \min\{1, 13e^{2R-(3/2)e^{2R}}\}, \tag{6}$$

$$\|B - B_M\| \leq \delta_M := 640(M+1)^2/20^{M+1}, \tag{7}$$

$$|m_0| < 6, \qquad a(L) \geq \tfrac{1}{2}\log(2L) \quad (L \geq 1/2), \qquad a(\xi) \leq 5 + \log(1+|\xi|). \tag{8}$$

Here B_M retains the same diagonal term and all $n \leq M$.

Proof. The elementary full-series proof of the unit bound in [1, Lemma 2.1] gives the stronger explicit value $\psi(u) < 11161963/11500000 < 1$. We use this published estimate with exactly the normalization (3). Its companion envelope is

$$\psi(u) \leq 8\pi^2 e^{9u/2 - \pi e^{2u}}, \qquad s(u)^2 \leq 16\pi^2 e^{4u - \pi e^{2u}} \quad (u \geq 0).$$

For completeness, the first follows by bounding the theta sum after its first exponential using

$$\sum_{n \geq 1} n^4 q^{n-1} < 2, \qquad q = e^{-3\pi} < 1/100.$$

Division by $c(u) \geq e^{u/2}/2$ gives the second. Its square root, reflection and $\pi > 3$, $4\pi < 13$ give (6). For a shift $b \geq 0$, write $v = |u| + |u+b| \geq b$. The envelopes and arithmetic–geometric mean give

$$\begin{aligned} \|M_s S_b M_s\| &= \sup_u s(u)s(u+b) \\ &\leq 16\pi^2 e^{2b - \pi e^b}. \end{aligned}$$

Indeed the intermediate exponent is at most $2v - \pi e^v$, decreasing for $v \geq 0$. Since $c_n \leq 1$, both directions beyond M cost at most $32\pi^2 \sum_{n>M} n^2 e^{-\pi n}$. For $k = M+1 \geq 2$, use $e^{-\pi} < 1/20$ and

$$\sum_{n \geq k} n^2 e^{-\pi n} \leq k^2 20^{-k} \sum_{j \geq 0} (j+1)^2 20^{-j} < 2k^2 20^{-k}.$$

This proves (7) with $\pi^2 < 10$. The classical quarter-argument digamma value gives $|m_0| < 6$. Retaining the terms $0 \leq j \leq \lfloor L/2 - 1/4 \rfloor$ in (4) gives the lower bound in (8) by comparison with the reciprocal integral. For the upper bound, the summand decreases in its denominator variable. Its first term is at most4 and its remaining integral is $\frac{1}{2}\log(1+4\xi^2)$. Hence $a(\xi) \leq 4 + \frac{1}{2}\log(1+4\xi^2) \leq 5 + \log(1+|\xi|)$. □

3 A complete finite-rank enclosure

For $\varepsilon > 0$ put $R_\varepsilon = (A + \varepsilon)^{-1/2}$ and $J = M_s R_\varepsilon$. For unit $h \in \mathcal{K}$,

$$\|Jh\| \le \varepsilon^{-1/2}, \qquad \int a(\xi)|\widehat{Jh}(\xi)|^2 \frac{\mathrm{d}\xi}{2\pi} \le 1.$$

Define

$$V_M = -m_0 I + \sum_{2 \le n \le M} c_n (S_{\log n} + S_{-\log n}), \quad d_M = |m_0| + 2 \sum_{2 \le n \le M} c_n.$$

Its Fourier multiplier is $v_M(\xi) = -m_0 + 2\sum c_n \cos(\xi \log n)$, and $\|V_M\| \le d_M$. Let Q_L denote the band projection and P_R the spatial projection. For $d \ge 0$ define

$$\widehat{E_d f}(\xi) = 1_{[-L,L]}(\xi) \sum_{k=0}^{d} \frac{(-i\xi)^k}{k!} \int_{-R}^{R} u^k f(u)\,\mathrm{d}u, \quad F_d = E_d J, \quad \mathcal{F} = F_d^* V_M F_d.$$

It is selfadjoint of rank at most $d + 1$.

Lemma 3.1 (Full error)**.** *For $M \ge 1$, $R, L > 0$, and integer $d \ge 0$,*

$$\|K_\varepsilon - \mathcal{F}\| \le \frac{\delta_M}{\varepsilon} + \frac{d_M}{a(L)} + d_M \tau (2/\sqrt{\varepsilon} + \tau), \tag{9}$$

$$\tau = (\sigma_R + b_d)/\sqrt{\varepsilon}, \qquad b_d = \sqrt{2/\pi} \frac{(RL)^{d+3/2}}{(2d+3)(d+1)!}.$$

Proof. The arithmetic tail costs δ_M/ε. The retained sandwich is $J^* V_M J$. Since V_M commutes with Q_L, it is the sum of $(Q_L J)^* V_M (Q_L J)$ and $((I - Q_L)J)^* V_M ((I - Q_L)J)$, with zero cross-frequency blocks. The high block has norm at most $d_M/a(L)$ by the energy bound. The real-phase Taylor remainder, integrated on the space–frequency rectangle, gives $\|Q_L P_R - E_d\| \le b_d$. Consequently

$$Q_L J - F_d = Q_L (I - P_R) J + (Q_L P_R - E_d) J$$

has norm at most τ, and $\|F_d\| \le \varepsilon^{-1/2} + \tau$. Expanding the difference of the two low-band signed products gives the last term of (9). This proves the bound on the entire receiving space. □

4 Joint cutoff selection

We first sharpen the arithmetic coefficient with an elementary prime-power count.

Lemma 4.1 (Square-root arithmetic bound)**.** *For integer $M \ge 1$, $d_M \le 18\sqrt{M}$.*

Proof. Let $\Psi(x) = \sum_{n \le x} \Lambda(n)$. Every prime power $p^j \in (n, 2n]$ contributes one unit to the corresponding summand $\lfloor 2n/p^j \rfloor - 2\lfloor n/p^j \rfloor$ in the valuation of $\binom{2n}{n}$; all other summands are nonnegative. Thus

$$\Psi(2n) - \Psi(n) \le \log \binom{2n}{n} \le 2n \log 2.$$

Summing along powers of two gives $\Psi(2^r) < 2^{r+1} \log 2$. If $2^{r-1} < x \le 2^r$, then $\Psi(x) < 4x \log 2 < 3x$; at $x = 1$ it is zero. Stieltjes partial summation yields

$$\sum_{n \le M} \frac{\Lambda(n)}{\sqrt{n}} = \frac{\Psi(M)}{\sqrt{M}} + \frac{1}{2} \int_1^M \Psi(t) t^{-3/2}\,\mathrm{d}t \le 6\sqrt{M} - 3 \le 6\sqrt{M}.$$

Together with $|m_0| < 6$, this gives $d_M \le 6 + 12\sqrt{M} \le 18\sqrt{M}$. □

For $0 < \varepsilon, \eta \le 1$ define the following positive quantities:

$$\begin{aligned} k &= \max\left\{4, \left\lceil \frac{\log(1920/(\varepsilon\eta))}{\log 10} \right\rceil\right\}, & M &= k-1, & D &= 18\sqrt{M}, \\ L &= \exp(6D/\eta), & X_0 &= \log\frac{312D}{\varepsilon\eta}, & R &= \tfrac{1}{2}\log(2X_0), \\ z &= RL, & b &= \frac{\varepsilon\eta}{24D}, & & \\ N(\varepsilon,\eta) &= \max\left\{1, \lceil 6z\rceil, \left\lceil \frac{\log(\sqrt{z}/b)}{\log 2} \right\rceil\right\}, & d &= N(\varepsilon,\eta)-1. & & \end{aligned} \tag{10}$$

These formulas, including their integer ceilings, specify the joint approximation.

Proposition 4.2. *The cutoffs* (10) *make the full error* (9) *strictly less than* η. *For fixed* η, $\log N(\varepsilon,\eta) = O_\eta(\sqrt{\log(1/\varepsilon)})$ *as* $\varepsilon \downarrow 0$.

Proof. For integers $k \ge 4$, $k^2 \le 2^k$ by induction, starting at4. Thus $\delta_M \le 640\,10^{-k} \le \varepsilon\eta/3$, which pays the arithmetic term. Next, $a(L) \ge \frac{1}{2}\log(2L) > 3D/\eta$ pays the high-frequency term by less than $\eta/3$. Since $e^{2R} = 2X_0$,

$$\sigma_R \le 26 X_0 e^{-3X_0} \le 13 e^{-X_0} = b,$$

using $2X_0 \le e^{2X_0}$. Write $n = d+1 = N(\varepsilon,\eta)$. Stirling's elementary factorial lower bound $n! \ge (n/e)^n$ and $n \ge 6z$, $e < 3$ give

$$b_{n-1} \le \sqrt{z}(ez/n)^n \le \sqrt{z}\,2^{-n} \le b.$$

The last inequality is precisely the logarithmic ceiling in (10). Hence $\tau \le \eta\sqrt{\varepsilon}/(12D)$, and the last error term is at most

$$D\frac{\eta\sqrt{\varepsilon}}{12D}\left(\frac{2}{\sqrt{\varepsilon}} + \frac{\eta\sqrt{\varepsilon}}{12D}\right) = \frac{\eta}{6} + \frac{\eta^2\varepsilon}{144D} < \frac{\eta}{3}.$$

This proves the strict total error. All quantities in the formulas are finite, with $M \ge 3$, $X_0 > 1$, $R > 0$ and $z > 1$.

For the rank asymptotic put $u = \log(1/\varepsilon)$. At fixed η, M is comparable to u for large u, $D = O_\eta(\sqrt{u})$, $\log L = O_\eta(\sqrt{u})$ and $R = O_\eta(\log u)$. The third cutoff for n is $O_\eta(u + \log z)$, whereas $z = R\exp(6D/\eta)$ eventually dominates every fixed power of u. Thus $\log n = O_\eta(\sqrt{u})$. Enlarging the multiplicative constant on a remaining compact interval of ε proves the rank assertion in Theorem 1.1. □

5 The entire negative part

Proof of the spectral conclusions. The preceding norm approximations, with arbitrary positive accuracy, imply that K_ε is compact selfadjoint. Fix $\eta = 1/2$ and a rank-N approximant $\mathcal{F}$ with error less than η. If the spectral subspace of K_ε for $(1,\infty)$ had dimension greater than N, it would intersect $\ker\mathcal{F}$ nontrivially. On that intersection its Rayleigh quotient is strictly greater than1, but $\mathcal{F}u = 0$ and the norm error bound make it at most η. This contradiction bounds that dimension by $N(\varepsilon, 1/2)$.

The map $h = (A+\varepsilon)^{-1/2}u$ is a bijection from $\mathcal{K}$ onto the chosen form domain $\mathcal{V}$, with its form topology, and

$$\langle h, (H+\varepsilon)h\rangle_{\text{form}} = \|u\|^2 - \langle u, K_\varepsilon u\rangle.$$

Transporting finite-dimensional strictly negative form subspaces in both directions proves equality of the two negative indices. The spectral theorem identifies the form index of $H + \varepsilon$ with $\operatorname{rank} 1_{(-\infty,-\varepsilon)}(H)$. This proves (1) from Proposition 4.2, without replacing a form-domain statement by a finite compression.

Since B is bounded and $A \geq 0$, H is bounded below. Finiteness of every negative-depth projection makes its negative spectrum discrete with finite multiplicities and possible accumulation only at zero. If the count is bounded by $A_0 \exp(B_0\sqrt{\log(1/\varepsilon)})$, take, for large n,

$$\varepsilon_n = \exp\left[-\left(\frac{\log(n/(2A_0))}{B_0}\right)^2\right].$$

The number of eigenvalue magnitudes strictly larger than ε_n is at most $n/2$, so the nth magnitude is at most ε_n. Adjusting constants for finitely many remaining indices proves (2), including finite or empty spectra by zero padding. Every positive power of this bound is summable: for fixed $p > 0$, eventually $cp\log^2(n+1) > 2\log(n+1)$. Hence $\sum_n \lambda_n(H_-)^p < \infty$, proving the stated Schatten conclusion. □

6 Effective phase returns and growing-cutoff sharpness

For the retained operator define

$$K_{\mathrm{hi}}(M,\varepsilon,L) = J^*(I-Q_L)V_M(I-Q_L)J, \qquad b_M(L) = \max\left\{0, \sup_{|\xi|>L}\frac{v_M(\xi)}{a(\xi)}\right\}.$$

The energy estimate gives $\|K_{\mathrm{hi}}\| \leq d_M/a(L)$ and $b_M(L) \leq d_M/a(L)$.

Theorem 6.1 (Uniform growing-cutoff saturation)**.** *Let $X = \log\log\log L$ for sufficiently large L, and let $\omega(L) \geq \log 2$ be any specified envelope satisfying $\omega(L) = o(X)$. Uniformly over integers $2 \leq M \leq e^{\omega(L)}$ and $0 < \varepsilon \leq 1$,*

$$\frac{a(L)\sup\sigma(K_{\mathrm{hi}}(M,\varepsilon,L))}{d_M} \longrightarrow 1, \qquad \frac{a(L)\|K_{\mathrm{hi}}(M,\varepsilon,L)\|}{d_M} \longrightarrow 1.$$

The scalar caps also satisfy $a(L)b_M(L)/d_M \to 1$ uniformly in that range.

6.1 Explicit every-interval prime-phase coverage

Lemma 6.2. *Let $p_1,\dots,p_m$ be the primes at most $M \geq 2$, and put $P = \prod p_j$. For $0 < \rho < 1$ define*

$$h = \lceil 256(m+1)^2\rho^{-4}\rceil, \qquad T = 8P^h(2h+1)^m.$$

Every real interval of length T contains N such that $\max_{p\leq M}|e^{iN\log p} - 1| < \rho$.

Proof. The nonnegative trigonometric polynomial

$$F(t) = \prod_{p\leq M}\left(\frac{1+\cos(t\log p)}{2}\right)^h$$

has nonnegative Fourier coefficients summing to1. Its constant coefficient is $A_h = [\binom{2h}{h}/4^h]^m \geq (2h+1)^{-m}$. Every other frequency is $\sum k_p \log p$, with $|k_p| \leq h$. Unique factorization makes it

nonzero. Write it as $\log(A/B)$, where A, B are distinct positive integers at most P^h. The inequality $\log(A/B) \geq (A-B)/A$ for $A > B$ gives absolute frequency at least P^{-h}. Thus the average of F on any interval of length T differs from A_h by at most $2P^h/T = 1/[4(2h+1)^m]$.

If one prime phase has distance at least ρ from1, then $F(t) \leq (1-\rho^2/4)^h$. This is less than $1/[2(2h+1)^m]$. To check the constants put $B_0 = (m+1)^2\rho^{-4} \geq 1$. Then $h \leq 257B_0$, $2h+1 \leq 515B_0$, and

$$h\rho^2/4 \geq 64(m+1)^2\rho^{-2} > \log 2 + m\log(2h+1).$$

For the last comparison use $\log 515 < 7$, $\log(m+1) \leq m+1$ and $\log(1/\rho) \leq 1/\rho$ to bound its right side by $(1+13m+2m^2)\rho^{-2}$. The exponential inequality $1-x \leq e^{-x}$ now proves the claim. The average lower bound $3/[4(2h+1)^m]$ exceeds the proposed pointwise failure ceiling, so some point of every interval has all phases within ρ. □

6.2 Packets with their original weighted norm

Fix once and for all $f_0 \in C_c^\infty(-1,1)$ with $\|f_0\| = 1$, and write $D_0 = \|f_0'\|$. For $R \geq 1$ let $f_R(u) = R^{-1/2}f_0(u/R)$. Then

$$\int_{|\xi|>r} |\widehat{f_R}(\xi)|^2 \frac{\mathrm{d}\xi}{2\pi} \leq D_0^2/(R^2r^2). \tag{11}$$

On $|u| \leq R$ the first positive theta term gives

$$s(u)^2 \geq e^{-4e^{2R}}, \qquad \|f_R/s\| \leq e^{2e^{2R}}. \tag{12}$$

Indeed $4x^2 - 6x \geq 2x^2$ for $x \geq \pi > 3$ implies $\psi(u) \geq 2\pi^2 e^{9u/2-\pi e^{2u}}$ for $u \geq 0$. Divide by $\cosh(u/2) \leq e^{u/2}$, use $\pi < 4$, and reflect.

Choose fixed compact smooth repair vectors χ_0, χ_1 with invertible two-row matrix U. The exact identities

$$\sqrt{w}/s = \cosh(u/2), \qquad \sqrt{w}\tanh(u/2)/s = \sinh(u/2)$$

make the constraint integrals of $e^{iNu}f_R/s$ those of $e^{iNu}f_R$ against cosh and sinh. One integration by parts therefore gives a correction $r_{N,R}$ with $v_{N,R} = e^{iNu}f_R/s - r_{N,R} \in \mathcal{C}$ and

$$\|r_{N,R}\| + \|sr_{N,R}\| + \sqrt{\mathfrak{a}[r_{N,R}]} \leq C_0 e^{R/2}\sqrt{R}/N =: \kappa. \tag{13}$$

For an explicit fixed constant, put $g_j = \|\chi_j\| + \|s\chi_j\| + \sqrt{\mathfrak{a}[\chi_j]}$ and take

$$C_0 = 2(1/2 + D_0)\|U^{-1}\|_{\mathrm{op}}\Big(\sum g_j^2\Big)^{1/2}.$$

The derivative L^1 norms of each row integrand are at most $\sqrt{2}(1/2+D_0)e^{R/2}\sqrt{R}$; multiplication by U^{-1} and Cauchy–Schwarz against the fixed vector norms prove (13). The form expression on a repair vector here denotes the same ambient nonnegative Fourier integral; it is defined for compact smooth functions without imposing the two rows.

The symbol upper bound in Lemma 2.1 and Plancherel give the uniform energy estimate

$$\mathfrak{a}[e^{iNu}f_R/s] \leq \log(1+N) + 6 + D_0^2/R^2.$$

Use $1+|N+\zeta| \leq (1+N)(1+|\zeta|)$ and $\log(1+|\zeta|) \leq 1+\zeta^2$ for this comparison. Form Cauchy–Schwarz then gives

$$\begin{aligned} \mathfrak{a}[v_{N,R}] &\leq [\sqrt{\log(1+N)+6+D_0^2/R^2} + \kappa]^2, \\ \|v_{N,R}\| &\leq e^{2e^{2R}} + \kappa. \end{aligned} \tag{14}$$

The inverse-theta input norm remains in the second bound.

6.3 A joint Rayleigh bound and the uniform limit

Fix $0 < \theta \le 1/8$ and let

$$k_M = \lceil \log_2 M \rceil, \quad \rho = \theta/(2k_M), \quad r = \theta/(2\log M), \quad R = \max\{1, D_0/(r\sqrt{\theta})\}.$$

Choose the return $N \in [L + r + 1, L + r + 1 + T]$ from Lemma 6.2. Each retained nonzero channel is $n = p^k$, $k \le k_M$. Thus $|e^{iN\log n} - 1| \le \theta/2$, and the additional phase on a window $|t| \le r$ is at most $\theta/2$. Consequently $v_M(N + t) \ge (1 - \theta)d_M$ throughout that window. It lies entirely above L, and (11) puts at least $1 - \theta$ of the carrier mass there. On the rest of the high band use $v_M \ge -d_M$. Applying the correction bound yields

$$\langle sv_{N,R}, (I - Q_L)V_M(I - Q_L)sv_{N,R}\rangle \ge d_M(1 - 3\theta - 2\kappa - \kappa^2).$$

No frequency mass outside the central window is assigned an unproved positive sign.

Put

$$\kappa_L = C_0 e^{R/2}\sqrt{R}/L, \quad E_L = \log(1 + L + r + 1 + T) + 6 + D_0^2,$$
$$\mathcal{D}_L = (\sqrt{E_L} + \kappa_L)^2 + \varepsilon(e^{2e^{2R}} + \kappa_L)^2.$$

When $\kappa_L \le 1/8$, the numerator below is positive. Normalizing $v_{N,R}$ by the actual reference form, as $u = (A + \varepsilon)^{1/2}v_{N,R}/\sqrt{\mathfrak{a}[v_{N,R}] + \varepsilon\|v_{N,R}\|^2}$, and using (14) gives

$$\sup \sigma(K_{\mathrm{hi}}) \ge d_M(1 - 3\theta - 2\kappa_L - \kappa_L^2)/\mathcal{D}_L. \tag{15}$$

Proof of Theorem 6.1. Take $\theta = [(1 + \omega(L))/X]^{1/3}$ for large L, so $\theta \to 0$ and eventually $\theta \le 1/8$. The preceding choices give

$$R = O(\sqrt{X(1 + \omega(L))} + 1) = o(X).$$

Since the number of retained primes is at most M, $\log P \le m \log M$, and the explicit phase budget gives

$$\log T \le C(M + 1)^3(\log M + 1)^5\theta^{-4} \le e^{O(\omega(L))}(1 + \omega(L))^5 X^{4/3}.$$

The logarithm of this last bound is $o(X)$, so $\log T = e^{o(X)}$, whereas $\log L = e^{e^X}$. Therefore $T/L \to 0$ and $\kappa_L \to 0$ uniformly over the declared range. The normalization term is also paid uniformly for $0 < \varepsilon \le 1$, because

$$\log\left(\frac{e^{4e^{2R}}}{\log L}\right) = 4e^{2R} - \log\log L = e^{o(X)} - e^X \longrightarrow -\infty.$$

Thus $\mathcal{D}_L/\log L \to 1$ uniformly. Combine (15) with $a(L)/\log L \to 1$ and the universal upper $d_M/a(L)$ to prove both operator limits. For the scalar cap, the same returns give $v_M(N) \ge (1 - \theta)d_M$, $N/L \to 1$ and $a(N)/a(L) \to 1$. This proves its lower limit; its upper bound is again $d_M/a(L)$. □

7 Parameter regimes and further applications

Theorem 1.1 selects M comparable to $\log(1/\varepsilon)$ and $\log L$ comparable to $\sqrt{\log(1/\varepsilon)}$ at fixed approximation tolerance. Theorem 6.1 instead retains the complete packet cost in the slower range $\log M = o(\log\log\log L)$. It gives a genuine uniform extension of fixed-cutoff sharpness, while leaving the optimal joint approximation rank as a separate spectral question. Extending the packet

analysis to the faster cutoff family calls for simultaneous estimates on recurrence length, carrier energy and the weighted input norm.

The new negative-spectrum conclusion concerns H_- itself. It uses no identification of an entire kernel or derivative-null closure. Structured finite signed certificates can address individual lower thresholds through a different reference and computational task. The rank theorem and the joint saturation theorem provide analytic information about the full operator family across parameter ranges.

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