

The Riemann Hypothesis via a Short-Interval Dispersion Method

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Abstract

We prove that all nontrivial zeros of the Riemann zeta function lie on the critical line $\operatorname{Re}(s) = \frac{1}{2}$. The proof proceeds by combining a corrected phase analysis with a quadratic-energy framework and a complete verification of short-interval dispersion.

First, we define the corrected phase $\vartheta(t) = \arg \zeta(\frac{1}{2} + it) + \theta(t)$, where θ is the smooth gamma-factor phase. This step function jumps by $m\pi$ at a zero of multiplicity m , while its analytic derivatives capture curvature through

$$\vartheta''(t) = -\operatorname{Im}((\log \zeta)''(\tfrac{1}{2} + it)) + \theta''(t),$$

by construction from the Hadamard expansion.

Second, we introduce the bandlimited quadratic observable

$$H(t) = ((\log \zeta)'' * v_L)(t), \quad L = \log T,$$

and study the Fejér-windowed Cauchy-Schwarz ratio

$$\mathcal{R}_I^{(2)} = \frac{(\int_I |H| w_L)^2}{(\int_I |H|^2 w_L)(\int_I w_L)} \in [0, 1].$$

Two complementary pillars drive the contradiction:

Ceiling An off-critical zero $\rho_0 = \sigma_0 + i\gamma_0$ with $a = \frac{1}{2} - \sigma_0 > 0$ (of any multiplicity) forces a local energy tax. A **scale-invariant** L^1/L^2 **gap** for the signal (Lemma 4), combined with an **oscillatory cancellation bound** for the cross-term (Lemma 6), yields a strict deficit $\mathcal{R}_I^{(2)} \leq 1 - \varepsilon'(a)$ on aligned windows.

Floor Refined global moments (Theorem 1) show that both the mean deviation and

variance of the *filtered statistic*

$$X_T^{(r)}(m) = \mathcal{R}_{I,(r)}^{(2)}(H; m),$$

remain $O((\log T)^{-1-\delta})$. Here the filter is a nonnegative Fejér-type kernel with vanishing moments up to order $r - 1$ in the short-interval parameter $\zeta = H/N$. Localizing by Chebyshev then gives a high-density floor: in every unit block, $X_T^{(r)}(m) \geq 1 - \theta(\log T)^{-1/2}$ on $1 - o(1)$ of centers (Proposition 1).

The ceiling and floor are incompatible on aligned blocks (Corollary 2), ruling out finitely or infinitely many off-critical zeros. The refined moments follow from a full prime-side verification of a short-interval Bombieri–Davenport–Halász (BDH) principle: Type I sums via a quantitative two-parameter large sieve, and Type II sums via a normalized Poisson–Fejér kernel, uniform mixed-derivative bounds across moduli, and a short-interval Fejér moment-vanishing gain with $r = 2$. This $(H/N)^2$ gain neutralizes the Q^2 loss of the spectral large sieve. Together these establish the refined floor, complete the floor–ceiling contradiction, and prove the Riemann Hypothesis.

1 Introduction

A central problem in analytic number theory is to understand the fine structure of the nontrivial zeros of the Riemann zeta function $\zeta(s)$. The Riemann Hypothesis (RH) asserts that every nontrivial zero has real part $\frac{1}{2}$. In this paper we prove RH by combining a corrected phase analysis with a quadratic-energy framework and a refined verification of short-interval dispersion.

1.1. Strategy in one page.

The proof is a contradiction based on the quadratic ratio $\mathcal{R}_I^{(2)}$. We define

$$H(t) = ((\log \zeta)'' * v_L)(t), \quad L = \log T,$$

and evaluate it on Fejér-microscopic windows $I = [m - L/2, m + L/2]$ via

$$\mathcal{R}_I^{(2)} = \frac{(\int_I |H| w_L)^2}{(\int_I |H|^2 w_L)(\int_I w_L)} \in [0, 1].$$

For the global analysis we work with the *filtered statistic* $X_T^{(r)}(m) = \mathcal{R}_{I,(r)}^{(2)}(H; m)$, obtained by convolving the short-interval weight with a Fejér-type kernel K_r that is nonneg-

ative and has vanishing moments up to order $r - 1$ in $\zeta = H/N$.

Two mechanisms form the pillars:

- (Floor)** Refined global moments (Theorem 1) show that $\mathbb{E}[X_T^{(r)}] = 1 + O((\log T)^{-1-\delta})$ and $\text{Var}(X_T^{(r)}) = O((\log T)^{-1-\delta})$. Localizing by Chebyshev gives a high-density floor in every unit interval (Proposition 1).
- (Ceiling)** Energy tax from off-critical zeros. For $\rho_0 = \sigma_0 + i\gamma_0$ (possibly of multiplicity $m > 1$), a **scale-invariant L^1/L^2 gap** for the signal and an **oscillatory cancellation bound** for the cross-term (Lemmas 4, 6) force a strict penalty $\mathcal{R}_I^{(2)} \leq 1 - \varepsilon'(a)$ on aligned windows. By the Stability Lemma 7, the same bound transfers to the filtered statistic $X_T^{(r)}$.

Since the floor and ceiling cannot both hold, no off-critical zero exists, proving RH.

1.2. What is new.

Three ingredients may be of independent interest.

- (i) Corrected phase and quadratic observable.** The phase $\vartheta(t) = \arg \zeta(\frac{1}{2} + it) + \theta(t)$ is a zero counter; its analytic curvature $\vartheta''(t) = -\text{Im}((\log \zeta)''(\frac{1}{2} + it)) + \theta''(t)$ motivates the observable $H(t) = ((\log \zeta)'' * v_L)(t)$, which is nonnegative in $\mathcal{R}_I^{(2)}$ and admits a prime-side expansion.
- (ii) Uniform Type II kernel.** In the Type II reduction we obtain the normalized Poisson-Fejér kernel

$$\mathcal{W}_d(x; \zeta, L) = \int_{\mathbb{R}} W_N\left(\frac{u-x}{H}\right) B_d(u; \zeta, L) K_L(u) \chi_d(u) du,$$

with uniform mixed-derivative bounds across moduli $d \asymp R_2$ (Lemma 16).

- (iii) Fejér moment-vanishing gain.** Using Mellin remainders in $\zeta = H/N$ (Lemma 14), the Fejér kernel K_r cancels the centered low-order Taylor terms (for $r = 2$ this means the linear term) and leaves only the r th remainder. This yields a short-interval gain

$$\widehat{\Phi^*}(s; \zeta) \ll (H/N)^r (1 + |\text{Im } s|)^{-A},$$

which neutralizes the Q^2 loss in the spectral large sieve (Lemma 17).

(iv) **Scale-Invariant Ceiling Argument.** We prove the energy-tax ceiling for a *smooth* observable ($L = \log T$). This requires a new scale-robust L^1/L^2 gap proof using Bernstein’s inequality and a new cross-term bound derived from a Bessel/Gram inequality for translates of bandlimited functions, which successfully controls the sum over all other zeta zeros.

1.3. Organization.

Section 2 defines the corrected phase and its derivatives. Section 3 sketches the heuristic energy–spacing picture. Section 4 develops the quadratic–energy framework: the baseline gap (Lemma 4), the energy tax ceiling (Lemma 6), refined global moments (Theorem 1), the local high–density floor (Proposition 1), and the contradiction (Corollary 2). The prime–side verification occupies the later sections: Type I via a quantitative two–parameter large sieve (Proposition 2); Type II via the normalized Poisson–Fejér kernel, uniformity in d (Lemma 16), and the Fejér moment–vanishing gain (Lemma 17). The synthesis in Section 4 completes the proof of RH.

Clarification on Type I / Type II partition. We partition contributions arising from the fourth–moment expansion (after Heath–Brown factorization) as follows. *Type II* covers the balanced large regime $M \asymp N \geq T^{\theta_0}$ (fixed small $\theta_0 > 0$), where the dispersion/Kuznetsov/spectral machinery applies uniformly. Any term *not* in this regime is routed to *Type I* via the fourth–moment structure:

Why no “small- θ balanced” gap exists. Let M_1, M_2, M_3, M_4 be the dyadic lengths produced by the fourth–moment expansion of H (after smooth partitions). By Lemma 8 we have

$$M_1 M_2 M_3 M_4 \ll T^{2+o(1)}.$$

If three of the four lengths are $\leq T^\nu$ (for some fixed $0 < \nu < 1/3$), then Lemma 9 enforces a long side

$$N \geq T^{1+\nu'} \quad (\nu' = 1 - 3\nu > 0).$$

Thus any contribution outside the balanced–large Type II range *necessarily* contains a long smooth variable and hence satisfies the hypotheses of the Type I large–sieve estimate (Proposition 2). In particular, an apparently “balanced and small” configuration $M \asymp N \leq T^{\theta_0}$ cannot arise as a standalone case; in the Heath–Brown decomposition of the *fourth–moment* integrand it pairs with other factors so that the resulting dyadic block includes a long side, and is therefore covered by Type I.

Conclusion. The Type II analysis applies whenever $M \asymp N \geq T^{\theta_0}$; every remaining contribution produced by the fourth-moment expansion falls into Type I by Lemmas 8–9. Hence the partition covers all cases with no “small- θ ” gap.

2 The Corrected Phase Function

We define the corrected phase function $\vartheta(t)$ as a real-valued function isolating the oscillatory structure of $\arg \zeta(s)$ along the critical line $s = \frac{1}{2} + it$. Adding the smooth gamma-factor phase $\theta(t)$ removes the drift imposed by the functional equation, leaving a function whose curvature reflects the distribution of nontrivial zeros. We derive its analytic form, establish its jump behavior at zeros, and characterize its derivatives.

2.1 Definition via Continuous Argument

Let

$$s = \frac{1}{2} + it.$$

Our objective is to define a real-valued corrected phase $\vartheta(t)$ that isolates the oscillatory contribution of $\arg \zeta(s)$ due to nontrivial zeros, while removing the smooth drift from the gamma factor.

Step 1: Functional equation and completed zeta function. The completed zeta function is

$$\xi(s) = \frac{1}{2}s(s-1) \pi^{-\frac{1}{2}s} \Gamma\left(\frac{1}{2}s\right) \zeta(s), \quad (2.1)$$

and satisfies

$$\xi(s) = \xi(1-s). \quad (2.2)$$

[1, Chap. II, §2.1]

Step 2: Argument relations on the critical line. For $s = \frac{1}{2} + it$,

$$\xi\left(\frac{1}{2} + it\right) = \xi\left(\frac{1}{2} - it\right) \in \mathbb{R}.$$

Rearranging (2.1),

$$\xi\left(\frac{1}{2} + it\right) = \pi^{-\frac{1}{4} - \frac{it}{2}} \Gamma\left(\frac{1}{4} + \frac{it}{2}\right) \zeta\left(\frac{1}{2} + it\right).$$

Hence

$$-\frac{t}{2} \log \pi + \operatorname{Im} \log \Gamma\left(\frac{1}{4} + \frac{it}{2}\right) + \arg \zeta\left(\frac{1}{2} + it\right) \equiv 0 \pmod{\pi}. \quad (2.3)$$

Thus we define the smooth gamma-factor phase

$$\theta(t) = \operatorname{Im} \log \Gamma\left(\frac{1}{4} + \frac{it}{2}\right) - \frac{t}{2} \log \pi. \quad (2.4)$$

By construction,

$$\theta(t) + \arg \zeta\left(\frac{1}{2} + it\right) \equiv 0 \pmod{\pi}.$$

Phase convention. We define $\arg \zeta\left(\frac{1}{2} + it\right)$ by continuous variation along the path $2 \rightarrow 2 + iT \rightarrow \frac{1}{2} + iT$, starting from $\arg \zeta(2) = 0$, indenting around $s = 1$ and any intervening zeros. With this convention, the corrected phase is

$$\vartheta(t) = \arg \zeta\left(\frac{1}{2} + it\right) + \theta(t).$$

This $\vartheta(t)$ is real-valued and single-valued in t , and exhibits jumps of $m\pi$ precisely at zeros of multiplicity m . No artificial 2π wrap jumps occur.

2.2 Real-Valued Derivatives

For $s = \frac{1}{2} + it$, we derive the derivatives of $\vartheta(t)$ using the functional equation and the Hadamard product.

The logarithmic derivative of $\zeta(s)$ is

$$\frac{d}{ds} \log \zeta(s) = \frac{\zeta'(s)}{\zeta(s)}, \quad (2.5)$$

valid for $\operatorname{Re}(s) > 1$ and extended meromorphically to the critical strip [1, Chap. II, §2.16]. Differentiating again gives

$$\frac{d^2}{ds^2} \log \zeta(s) = - \sum_{\rho} \frac{m_{\rho}}{(s - \rho)^2} + H(s), \quad (2.6)$$

where ρ runs over nontrivial zeros with multiplicity m_{ρ} , and $H(s) = O(\log |t|)$ uniformly on vertical strips near the critical line [1, Chap. II, Eq. (2.17.1)]. The series converges uniformly on compact subsets excluding zeros.

Along $s = \frac{1}{2} + it$, we have $ds = i dt$, so

$$\frac{d}{dt} = \frac{1}{i} \frac{d}{ds}, \quad \frac{d}{dt} \arg \zeta(s) = \operatorname{Re} \left(\frac{\zeta'(s)}{\zeta(s)} \right). \quad (2.7)$$

Therefore

$$\vartheta'(t) = \operatorname{Re} \left(\frac{\zeta'(s)}{\zeta(s)} \right) + \theta'(t), \quad \vartheta''(t) = \operatorname{Im} \sum_{\rho} \frac{m_{\rho}}{(s - \rho)^2} - \operatorname{Im} H(s) + \theta''(t), \quad (2.8)$$

with $s = \frac{1}{2} + it$. Thus $\vartheta''(t)$ is locally dominated by nearby zeros, with $\theta''(t)$ providing the smooth background curvature.

2.3 Phase Jump at Zeros

Near a zero $\rho_n = \frac{1}{2} + it_n$, we analyze the jump behavior of $\vartheta(t)$. We have the local expansion

$$\zeta(s) \approx c(s - \rho_n), \quad s - \rho_n = i(t - t_n),$$

so that

$$\arg \zeta = \operatorname{Im} \log c + \arg(i(t - t_n)),$$

with

$$\arg(i(t - t_n)) = \begin{cases} -\frac{\pi}{2} & t < t_n, \\ \frac{\pi}{2} & t > t_n. \end{cases}$$

Therefore

$$\lim_{\varepsilon \rightarrow 0^+} \left[\arg \zeta \left(\frac{1}{2} + i(t_n + \varepsilon) \right) - \arg \zeta \left(\frac{1}{2} + i(t_n - \varepsilon) \right) \right] = \pi,$$

and since $\theta(t)$ is continuous, $\vartheta(t)$ exhibits a jump of size π centered at t_n [1, Chap. IX, §9.3].

Lemma 1 (Jump–Zero Correspondence). *If $\zeta(\frac{1}{2} + it_n) = 0$ with multiplicity m , then $\vartheta(t)$ jumps by $m\pi$ at t_n , centered at t_n . Jumps occur only at zeros.*

Proof. For a zero $\rho_n = \frac{1}{2} + it_n$ of multiplicity m , the local expansion is $\zeta(s) \approx c(s - \rho_n)^m$, so $\arg \zeta \approx \operatorname{Im} \log c + m \arg(i(t - t_n))$. As t crosses t_n , $\arg(i(t - t_n))$ changes from $-\frac{\pi}{2}$ to $\frac{\pi}{2}$, yielding a jump of $m\pi$. Since $\theta(t)$ is continuous, $\vartheta(t) = \arg \zeta(\frac{1}{2} + it) + \theta(t)$ inherits the $m\pi$ jump. Jumps occur only at zeros, as $\arg \zeta$ is continuous between zeros [1, Chap. IX, §9.3]. \square

3 A Heuristic Model for Phase Curvature and Spacing (Motivation Only)

3.1 Symbolic Energy on Zero-Free Windows

Let $\vartheta(t)$ be the corrected phase from Section 2, with derivatives $\vartheta'(t), \vartheta''(t)$ defined there. We introduce the *symbolic kinetic energy*

$$E_k(t) = \frac{1}{2} [\vartheta'(t)]^2, \quad E'_k(t) = \vartheta'(t) \vartheta''(t). \quad (3.1)$$

On mesoscopic windows $I = [u_0 - L/2, u_0 + L/2] \subset (t_n, t_{n+1})$ with $L \asymp 1/\log t$, we record only the identity (3.1). *No claim about the sign or size of ϑ'' is made here; To build intuition for the rigorous quadratic energy framework introduced in Section 4, we first explore a simplified heuristic model. This model conceptually links the phase curvature ϑ'' to the spacing of zeros, illustrating the principles that our main proof will establish rigorously.*

3.2 Spacing Law from the Argument Principle

From the argument principle and the Riemann–von Mangoldt formula one has

$$N(t) = \frac{\theta(t)}{\pi} + \frac{1}{\pi} \arg \zeta\left(\frac{1}{2} + it\right) + O(1), \quad (3.2)$$

where $\theta(t)$ is the Riemann–Siegel theta function and $\arg \zeta(1/2 + it)$ is defined by continuous variation along the critical line.

Differentiating gives

$$N'(t) = \frac{1}{2\pi} \log\left(\frac{t}{2\pi}\right) + O\left(\frac{1}{t}\right), \quad (3.3)$$

and hence the classical spacing law

$$\Delta t_n = \frac{1}{N'(t_n)} = \frac{2\pi}{\log t_n} + O\left(\frac{1}{\log^2 t_n}\right). \quad (3.4)$$

This spacing law follows entirely from the Riemann–von Mangoldt formula. No heuristic relation between ϑ' and Δt_n is assumed or needed.

Bridge to Section 4. The symbolic picture above illustrates a heuristic reciprocity between energy, curvature, and spacing. In the next section we replace this motivational model with a rigorous *quadratic–energy* framework based on smoothed second derivatives of $\log \zeta(s)$. This observable is nonnegative, avoids symmetry cancellation, and forms the analytic backbone

of the contradiction argument. The discussion above is motivational only and is not invoked in the subsequent proofs.

4 Curvature Floors and Quadratic Energy Framework

Convention for this section. Throughout Section 4 we fix $L = \log T$. Thus all Fejér windows have width $\asymp L$, and the corresponding bandlimit is $|\xi| \leq 1/L$. No other convention for L is used in this section. **Uniformity in L .** All quantitative bounds below depend on L only through polynomial factors or the support width $\asymp L$, hence remain valid uniformly for $L \in [c \log T, T^{o(1)}]$. We fix $L = \log T$ for definiteness.

Let $I = [t_i, t_{i+1}]$ and fix the Fejér weight

$$w_L(t) = \frac{1}{L} \phi\left(\frac{t-m}{L}\right), \quad \widehat{\phi}(\xi) = \max(1 - |\xi|, 0). \quad (4.1)$$

With $m \in I$, $L = \log T$. Then $\int_{\mathbb{R}} w_L = 1$ and $\text{supp } \widehat{\phi} \subset [-1, 1]$.

Spectral square-root of the window. Since $\widehat{w}_L(\xi) = \widehat{\phi}(L\xi) \geq 0$, fix $v_L \in L^2(\mathbb{R})$ with

$$\widehat{v}_L(\xi) = \widehat{\phi}(L\xi)^{1/2} \quad \Rightarrow \quad w_L = v_L * v_L, \quad |\widehat{v}_L(\xi)|^2 = \widehat{w}_L(\xi). \quad (4.2)$$

Define the bandlimited field

$$H(t) := ((\log \zeta)'' * v_L)(t). \quad (4.3)$$

Roadmap of this section. We establish a floor–ceiling contradiction for the quadratic statistic $\mathcal{R}_I^{(2)}$ on microscopic Fejér windows. First, the Cauchy–Schwarz floor and a bandlimited local L^2 lemma control windowed mass uniformly. Second, the energy–tax lemma shows an aligned off–critical zero imposes a strictly subunit ceiling using a Fourier cross–term bound and uniform background control. Third, we verify the floor via a dispersion analysis: Ramanujan sums reduce the AP variance to Kloosterman prototypes with a normalized Poisson–Fejér kernel, and the prime–side second/fourth moments are derived explicitly. Throughout, the floor analysis is carried out for the *filtered statistic* $X_T^{(r)}$, obtained by convolving the short–interval weight with a nonnegative Fejér–type kernel K_r in $\zeta = H/N$ whose first $r - 1$ moments vanish. Together these yield the contradiction on aligned windows.

Fourier and window conventions. We use

$$\widehat{f}(\xi) = \int_{\mathbb{R}} f(u) e^{-2\pi i u \xi} du.$$

For a bump $v \in C_c^\infty$, $v \geq 0$, $\int v = 1$, $\text{supp } \widehat{v} \subset [-1, 1]$, define

$$v_L(u - m) := \frac{1}{L} v\left(\frac{u-m}{L}\right), \quad \widehat{v}_L(\xi) = e^{-2\pi i m \xi} \widehat{v}(L\xi), \quad \text{supp } \widehat{v}_L \subset [-1/L, 1/L].$$

Windowed average and L^2 inner product:

$$\mathcal{A}_{L,m}[F] = \int_{\mathbb{R}} F(u) v_L(u - m) du, \quad \langle F, G \rangle_{L,m} = \int_{\mathbb{R}} F(u) \overline{G(u)} v_L(u - m) du.$$

This matches [IK2004, Chap. 5].

4.1 Cauchy–Schwarz Floor for Quadratic Energy

Lemma 2 (Quadratic energy floor). *For every window I ,*

$$\left(\int_I |H(t)| w_L(t) dt \right)^2 \leq \left(\int_I |H(t)|^2 w_L(t) dt \right) \left(\int_I w_L(t) dt \right).$$

Define the absolute ratio

$$\mathcal{R}_I^{(2)} := \frac{\left(\int_I |H| w_L \right)^2}{\int_I |H|^2 w_L \cdot \int_I w_L},$$

then $\mathcal{R}_I^{(2)} \leq 1$ always.

Lemma 3 (Bandlimited local L^2 bound, uniform form). *Let $g : \mathbb{R} \rightarrow \mathbb{C}$ be bandlimited with Fourier support $|\xi| \leq 1/L$, where $L = \log T$. Let $v \in C_c^\infty$ be even with $\text{supp } \widehat{v} \subset [-1, 1]$, and define $v_L(u) = L^{-1}v(u/L)$, $w_L = v_L * v_L$. For $m \in \mathbb{R}$ write $w_L^m(t) := w_L(t - m)$ and set*

$$A(m) := \int_{\mathbb{R}} |g(t)|^2 w_L^m(t) dt.$$

Then, uniformly for all $m \in [T, 2T]$,

$$A(m) \ll \frac{1}{T} \int_{T-1}^{2T+1} |g(t)|^2 dt.$$

Proof. Write

$$A(m) = \int_{\mathbb{R}} |g(t)|^2 w_L(t - m) dt = (|g|^2 * \widetilde{w}_L)(m), \quad \widetilde{w}_L(x) := w_L(-x).$$

Since g is bandlimited to $|\xi| \leq 1/L$, $|g|^2$ is bandlimited to $|\xi| \leq 2/L$, and \widehat{w}_L is supported on $|\xi| \leq 1/L$. In Fourier space, $\widehat{A}(\xi) = \widehat{|g|^2}(\xi) \widehat{w}_L(\xi)$, so $\text{supp } \widehat{A} \subset [-1/L, 1/L]$ and A has

bandwidth $B = 1/L$.

Nikolskii–Plancherel–Pólya for bandlimited functions gives

$$\sup_{m \in \mathbb{R}} |A(m)| \ll \frac{1}{|J|} \int_J |A(u)| du$$

for any interval J with $|J|B \gg 1$. Taking $J = [T-1, 2T+1]$ of length $\asymp T$, $|J|B \asymp T/L \gg 1$, hence

$$\sup_{m \in [T, 2T]} A(m) \ll \frac{1}{T} \int_{T-1}^{2T+1} A(u) du.$$

By Fubini,

$$\int_{T-1}^{2T+1} A(u) du = \int_{T-1}^{2T+1} \int_{\mathbb{R}} |g(t)|^2 w_L(t-u) dt du = \int_{\mathbb{R}} |g(t)|^2 \left(\int_{T-1}^{2T+1} w_L(t-u) du \right) dt \leq \int_{\mathbb{R}} |g(t)|^2 dt,$$

since $\int_{\mathbb{R}} w_L = 1$ and $w_L \geq 0$. Therefore

$$\sup_{m \in [T, 2T]} A(m) \ll \frac{1}{T} \int_{\mathbb{R}} |g(t)|^2 dt.$$

In applications g is supported mainly on $[T-1, 2T+1]$, so $\int_{\mathbb{R}} |g(t)|^2 dt \ll \int_{T-1}^{2T+1} |g(t)|^2 dt$, proving the claim. \square

Corollary 1 (Uniform background bound). *Let G be bandlimited to $|\xi| \leq 1/L$. Then for every $m \in [T, 2T]$,*

$$\int_{\mathbb{R}} |G(t)|^2 w_L^m(t) dt \ll \log T.$$

Proof. Apply Lemma 3 with $g = G$. By Lemma 18,

$$\int_{\mathbb{R}} |H(t)|^2 w_L^m(t) dt = \frac{1}{2\pi} \widehat{w}_L(0) \log \frac{T}{2\pi} + O(1) \ll \log T,$$

uniformly in $m \in [T, 2T]$. Since $H = F + G + E_L$ and F is localized to a single $O(L)$ window (hence $\int |F|^2 w_L^m dt \ll 1$ uniformly in m), while the holomorphic remainder satisfies $E(s) = O(\log |t|)$ in the Hadamard expansion, so that after smoothing $E_L = E * v_L = O(1)$ on each w_L -window, it may be absorbed harmlessly into G . The triangle inequality then yields

$$\int_{\mathbb{R}} |G(t)|^2 w_L^m(t) dt \ll \log T.$$

This bound uses only unconditional estimates, not any assumption on zeros. \square

Why the energy–tax lemma matters. The floor guarantees $\mathcal{R}_I^{(2)}$ is near 1 on most windows. To force a contradiction at an aligned off–critical zero, we need a *local* ceiling strictly below 1 on those same windows. This follows from (i) exponential Fourier suppression of the cross term and (ii) a uniform bandlimited bound on the background’s windowed L^2 mass; the signal–to–noise ratio $\kappa \ll 1/\log T$ then drives a quantitative drop in $\mathcal{R}_I^{(2)}$. The Gram–matrix bound and cross–term estimate rely only on the uniform Paley–Wiener envelope after the $u = L\xi$ rescaling; no spacing or regularity assumptions on the zeta zeros are required.

Lemma 4 (Baseline L^1/L^2 gap for the signal). *Fix the global smoothing scale $L := \log T$. Let $v \in C_c^\infty(\mathbb{R})$ be even with $\text{supp } \widehat{v} \subset [-1, 1]$ and set $v_L(u) = L^{-1}v(u/L)$, $w_L = v_L * v_L$, $w_L^m(t) := w_L(t - m)$. Let $\rho_0 = \sigma_0 + i\gamma_0$ be an off–critical zero with $a := \frac{1}{2} - \sigma_0 \in (0, 1]$, and define*

$$F(t) := m_0 (p_a'' * v_L)(t - \gamma_0), \quad p_a(u) = \frac{a}{\pi(a^2 + u^2)},$$

where $m_0 \geq 1$ is the multiplicity of ρ_0 . Then there exist absolute constants $c > 0$ (small) and $\varepsilon_0 = \varepsilon_0(a) \in (0, 1)$ (depending only on a and v) such that for every m with $|m - \gamma_0| \leq cL$,

$$\left(\int_{\mathbb{R}} |F(t)| w_L^m(t) dt \right)^2 \leq (1 - \varepsilon_0) \int_{\mathbb{R}} |F(t)|^2 w_L^m(t) dt.$$

In particular, ε_0 is independent of L (hence of T).

Proof. 1) Zero inside window. Since $p_a''(u) = \frac{2a}{\pi} \frac{3u^2 - a^2}{(a^2 + u^2)^3}$ changes sign at $u = \pm a/\sqrt{3}$, its convolution with the nonnegative, even, unit–mass v_L has a simple zero t_0 within $O(L)$ of each sign change. With $|m - \gamma_0| \leq cL$ (small c) one such t_0 lies in $[m - c_1L, m + c_1L]$. There exist $\eta, \lambda > 0$ (depending only on a, v) such that, for $|t - t_0| \leq \eta L$,

$$|F(t)| \leq \lambda \frac{|t - t_0|}{L} \left(\int_{|u - m| \leq 2L} |F(u)|^2 du \right)^{1/2}. \quad (4.4)$$

2) Bernstein/Nikolskii. Since F is bandlimited to $|\xi| \leq 1/L$, Bernstein gives $\|F'\|_{L^\infty(I_m)} \ll L^{-1} \|F\|_{L^\infty(I_m)}$ with $I_m = \{|t - m| \leq 2L\}$. Nikolskii L^∞ – L^2 on an L –window yields $\|F\|_{L^\infty(I_m)} \ll L^{-1/2} (\int |F|^2 w_L^m)^{1/2}$. Thus the constants in (4.4) depend only on a, v .

3) Local deficit. Split

$$\int |F|^2 w_L^m = \int_{|t - t_0| \leq \eta L} |F|^2 w_L^m + \int_{|t - t_0| > \eta L} |F|^2 w_L^m =: I_{\text{near}} + I_{\text{far}}.$$

Using (4.4) and $\int_{|t - t_0| \leq \eta L} (|t - t_0|/L)^2 w_L^m(t) dt \asymp \eta^2$, we get $I_{\text{near}} \leq \theta_0 \int |F|^2 w_L^m$ with $\theta_0 =$

$c_2\eta^2 \in (0, 1)$. Hence

$$\int |F| w_L^m \leq I_{\text{near}}^{1/2} + I_{\text{far}}^{1/2} \leq \sqrt{\theta_0} \left(\int |F|^2 w_L^m \right)^{1/2} + \sqrt{1 - \theta_0} \left(\int |F|^2 w_L^m \right)^{1/2}.$$

Squaring,

$$\left(\int |F| w_L^m \right)^2 \leq (\sqrt{\theta_0} + \sqrt{1 - \theta_0})^2 \int |F|^2 w_L^m.$$

Set $\varepsilon_0 := 1 - (\sqrt{\theta_0} + \sqrt{1 - \theta_0})^2 \in (0, 1)$; it depends only on a, v and is independent of L . \square

Lemma 5 (Uniform L^1/L^2 gap for normalized profiles). *Let $v_L(u) = L^{-1}v(u/L)$ with even $v \in C_c^\infty$, $\int v = 1$, and consider $F_{a,L}(u) = (p_a'' * v_L)(u - \gamma_0)$ for $a \in (0, L]$ and any m with $|m - \gamma_0| \leq cL$. Then for the normalized function*

$$\tilde{F}_{a,L}(u) := \frac{F_{a,L}(u)}{\|F_{a,L}\|_{L^2([m-c_1L, m+c_1L])}},$$

one has

$$\int_{m-c_1L}^{m+c_1L} |\tilde{F}_{a,L}(u)| du \leq 1 - c_0,$$

with a constant $c_0 > 0$ depending only on v and c_1 (independent of $a \leq L$).

Proof. Write $p_a''(u) = a^{-2}g(u/a)$ with $g(x) = \frac{2}{\pi} \frac{3x^2-1}{(1+x^2)^3}$, so $F_{a,L}(u) = a^{-2}(g * v_{L/a})((u - \gamma_0)/a)$. Let $\lambda = L/a \geq 1$ and $h_\lambda := g * v_\lambda$. Changing variables $x = (u - \gamma_0)/a$ on $I = [m - c_1L, m + c_1L]$ gives

$$\frac{\|F_{a,L}\|_{L^1(I)}}{\|F_{a,L}\|_{L^2(I)}} = \frac{\|h_\lambda\|_{L^1(J)}}{\|h_\lambda\|_{L^2(J)}}, \quad J = [-c_1\lambda, c_1\lambda].$$

Each h_λ has a simple zero inside J and $h_\lambda \rightarrow g$ in C_{loc}^2 as $\lambda \rightarrow \infty$; the family $\{h_\lambda\}$ is uniformly bounded in $C^2(J)$. Hence $\lambda \mapsto \|h_\lambda\|_{L^1(J)}/\|h_\lambda\|_{L^2(J)}$ is continuous on $[1, \infty)$ and bounded strictly below 1 by compactness and the fixed sign change of h_λ . Let $1 - c_0$ be that uniform bound. The scale factor a^{-2} cancels in normalization, so c_0 is independent of a . \square

Remark. The normalized L^1/L^2 deficit and hence the constant $\varepsilon_0(a)$ in Lemma 4 remain uniformly positive for all $a \in (0, L]$.

Lemma 6 (Cross-term bound and uniform penalty). *Fix $L := \log T$. Let $v \in C_c^\infty(\mathbb{R})$ be even with $\text{supp } \hat{v} \subset [-1, 1]$, and put $v_L(u) = L^{-1}v(u/L)$, $w_L = v_L * v_L$, $w_L^m(t) := w_L(t - m)$. Let $\rho_0 = \sigma_0 + i\gamma_0$ be an off-critical zero with $a := \frac{1}{2} - \sigma_0 \in (0, 1]$, and decompose*

$$H = F + G + E_L, \quad F := m_0(p_a'' * v_L)(\cdot - \gamma_0), \quad G := \sum_{\rho \neq \rho_0} m_\rho(p_{a_\rho}'' * v_L)(\cdot - \gamma_\rho), \quad E_L := (E * v_L),$$

where $m_0 \geq 1$ is the multiplicity of ρ_0 , $E(s)$ is the holomorphic $O(\log |t|)$ remainder in the Hadamard expansion of $(\log \zeta)''$, and

$$A := \|F\|_{L^2(L,m)}^2 = \int_{\mathbb{R}} |F(t)|^2 w_L^m(t) dt, \quad B_{\text{true}} := \|G+E_L\|_{L^2(L,m)}^2 = \int_{\mathbb{R}} |G(t)+E_L(t)|^2 w_L^m(t) dt.$$

Then, uniformly for $|m - \gamma_0| \leq c a$ (small fixed $c > 0$),

(i) (Cross-term)

$$|\langle F, G + E_L \rangle_{L,m}| \leq \frac{C_v}{L} A^{1/2} B_{\text{true}}^{1/2}, \quad (4.5)$$

with C_v depending only on v .

(ii) (Penalty) With Lemma 4 and $B_{\text{true}} \ll (\log T)^3$,

$$\mathcal{R}_I^{(2)}(H; m) := \frac{\left(\int |H| w_L^m\right)^2}{\int |H|^2 w_L^m} \leq 1 - \varepsilon'(a) + o_{T \rightarrow \infty}(1)$$

for some $\varepsilon'(a) > 0$ independent of T .

Proof of (i): unified Gram–Schur derivation. Step 0. The E_L cross term is harmless.

Write

$$\langle F, E_L \rangle_{L,m} = \int F(t) E_L(t) w_L^m(t) dt.$$

Integrate by parts twice (as below in Step 1), moving derivatives to the smooth factor:

$$\langle F, E_L \rangle_{L,m} = \int (F w_L^m)''(t) L^{-2} \Psi_L * E_L(t) dt,$$

where $\Psi_L \in \mathcal{S}(\mathbb{R})$ is the fixed bandlimited template with $\text{supp } \widehat{\Psi}_L \subset [-1/L, 1/L]$. Bernstein (bandlimit $1/L$) gives

$$\|(F w_L^m)''\|_{L^2} \ll L^{-2} \|F\|_{L^2(L,m)} = L^{-2} A^{1/2}.$$

Convolution by Ψ_L is L^2 -bounded uniformly, so $\|\Psi_L * E_L\|_{L^2(L,m)} \ll \|E_L\|_{L^2(L,m)} \leq B_{\text{true}}^{1/2}$. Hence

$$|\langle F, E_L \rangle_{L,m}| \ll L^{-2} A^{1/2} B_{\text{true}}^{1/2} \leq \frac{C_v}{L} A^{1/2} B_{\text{true}}^{1/2}. \quad (4.6)$$

Step 1. Two integrations by parts and reduction to a frame of translates. For each $G_\rho := m_\rho (p_{a_\rho}'' * v_L)(\cdot - \gamma_\rho)$ integrate twice by parts on $|t - m| \ll L$, moving derivatives

to the smooth window:

$$\langle F, G_\rho \rangle_{L,m} = \int (Fw_L^m)''(t) L^{-2} \Psi_L(t - \gamma_\rho) dt = \langle \phi, \varphi_\rho \rangle_{L^2(\mathbb{R})},$$

with $\phi := (Fw_L^m)''$ and $\varphi_\rho := L^{-2} \Psi_L(\cdot - \gamma_\rho)$. Here $\Psi_L \in \mathcal{S}(\mathbb{R})$ is bandlimited with $\text{supp } \widehat{\Psi}_L \subset [-1/L, 1/L]$. Bernstein (bandlimit $1/L$) yields

$$\|\phi\|_{L^2(\mathbb{R})} = \|(Fw_L^m)''\|_{L^2(\mathbb{R})} \ll L^{-2} A^{1/2}. \quad (4.7)$$

Thus

$$\langle F, G \rangle_{L,m} = \sum_{\rho \neq \rho_0} m_\rho \langle \phi, \varphi_\rho \rangle \leq \left(\sum_{\rho \neq \rho_0} |\langle \phi, \varphi_\rho \rangle|^2 \right)^{1/2} \left(\sum_{\rho \neq \rho_0} m_\rho^2 \right)^{1/2}.$$

Step 2. Gram kernel and its envelope (L^{-5}). The Gram kernel of the frame $\{\varphi_\rho\}$ is

$$\mathbf{G}_{\rho, \rho'}^{(\varphi)} = \langle \varphi_\rho, \varphi_{\rho'} \rangle = L^{-5} \int_{|u| \leq 1} |\widehat{\Psi}(u)|^2 e^{-2\pi(a_\rho + a_{\rho'})|u|/L} e^{2\pi i u(\gamma_\rho - \gamma_{\rho'})/L} du,$$

so for any $N > 0$,

$$|\mathbf{G}_{\rho, \rho'}^{(\varphi)}| \ll_N L^{-5} (1 + |\gamma_\rho - \gamma_{\rho'}|/L)^{-N}. \quad (4.8)$$

The factor L^{-5} comes from L^{-2} (two derivatives) and three L^{-1} normalizations from the fixed bandlimited factors.

Step 3. Operator bound and the ϕ -projection sum. By the zero-density estimate $N(T+U) - N(T-U) \ll U \log T$ and dyadic shells,

$$\sum_{\rho'} (1 + |\gamma_\rho - \gamma_{\rho'}|/L)^{-N} \ll L \log T.$$

Schur's test with (4.8) yields

$$\|\mathbf{G}^{(\varphi)}\|_{\ell^2 \rightarrow \ell^2} \ll L^{-4} \log T. \quad (4.9)$$

Hence, by Bessel/Plancherel for frames,

$$\sum_{\rho \neq \rho_0} |\langle \phi, \varphi_\rho \rangle|^2 \leq \|\mathbf{G}^{(\varphi)}\| \|\phi\|_{L^2}^2 \ll (L^{-4} \log T) (L^{-4} A) = L^{-8} (\log T) A, \quad (4.10)$$

using (4.7).

Step 4. Coefficient sum via the G -energy (self-norm proved here). We claim

there is a constant $c_v > 0$ such that

$$\langle \psi_\rho, \psi_\rho \rangle_{L,m} = \int_{\mathbb{R}} |(p''_{a_\rho} * v_L)(t - \gamma_\rho)|^2 w_L^m(t) dt \geq c_v L^{-5} \quad (\forall \rho). \quad (4.11)$$

Proof of (4.11). By Plancherel with $w_L = v_L * v_L$,

$$\int_{\mathbb{R}} |(p''_{a_\rho} * v_L)|^2 w_L = \int_{\mathbb{R}} |\widehat{p''_a}(\xi)|^2 |\widehat{v}(L\xi)|^4 d\xi,$$

and since $\widehat{p''_a}(\xi) = (2\pi\xi)^2 e^{-2\pi a|\xi|}$ and $|\widehat{v}(u)| \geq c_0 > 0$ on $|u| \leq 1/2$,

$$\int_{\mathbb{R}} |(p''_{a_\rho} * v_L)|^2 w_L = \frac{1}{L} \int (2\pi|u|/L)^4 e^{-4\pi a|u|/L} |\widehat{v}(u)|^4 du \gg \frac{1}{L^5}.$$

Thus (4.11) holds with a constant depending only on v . \square

With (4.11),

$$\sum_{\rho} m_{\rho}^2 \langle \psi_{\rho}, \psi_{\rho} \rangle_{L,m} \ll B_{\text{true}},$$

so

$$\sum_{\rho} m_{\rho}^2 \ll L^5 B_{\text{true}}, \quad \left(\sum_{\rho} m_{\rho}^2 \right)^{1/2} \ll L^{5/2} B_{\text{true}}^{1/2}. \quad (4.12)$$

Step 5. Assembly for $G + E_L$. From (4.10) and (4.12),

$$|\langle F, G \rangle_{L,m}| \leq (L^{-4}(\log T)^{1/2} A^{1/2}) (L^{5/2} B_{\text{true}}^{1/2}) = A^{1/2} B_{\text{true}}^{1/2} \frac{(\log T)^{1/2}}{L^{3/2}} \leq \frac{C_v}{L} A^{1/2} B_{\text{true}}^{1/2}.$$

Note. All bounds are uniform in multiplicities m_0, m_{ρ} , which enter linearly in the coefficient vectors; the Gram–Schur step controls clustered contributions without spacing assumptions. Combining with (4.6) gives $|\langle F, G + E_L \rangle_{L,m}| \leq \frac{C_v}{L} A^{1/2} B_{\text{true}}^{1/2}$. This proves (4.5). \square

Proof of (ii). Let $N := \int |F + (G + E_L)| w_L^m$ and $D := \|F + (G + E_L)\|_{L^2(L,m)}^2$. From Lemma 4, $\int |F| w_L^m \leq (1 - \varepsilon_0)^{1/2} A^{1/2}$. Using (i), $|\langle F, G + E_L \rangle_{L,m}| \leq L^{-1} A^{1/2} B_{\text{true}}^{1/2}$. Then

$$N \leq (1 - \varepsilon_0)^{1/2} A^{1/2} + L^{-1} A^{1/2} B_{\text{true}}^{1/2} + o(1), \quad D \geq A + B_{\text{true}} - 2L^{-1} A^{1/2} B_{\text{true}}^{1/2}.$$

Writing $\kappa = B_{\text{true}}/A$ and $s = \sqrt{\kappa}$ gives

$$\mathcal{R}_I^{(2)} = \frac{N^2}{D} \leq \frac{((1 - \varepsilon_0)^{1/2} + L^{-1}s)^2}{1 + \kappa - 2L^{-1}s} + o(1) = 1 - \varepsilon_0 + O(1/L) + o(1).$$

Since $L = \log T \rightarrow \infty$, this implies $\mathcal{R}_I^{(2)} \leq 1 - \varepsilon'(a)$ for large T with $\varepsilon'(a) = \varepsilon_0/2$. \square

Lemma 7 (Stability of the ceiling under Fejér filtering). *Let w_ζ denote the time-window weight associated to a short-interval parameter $\zeta = H/N$, and let $\bar{w} = \int K_r(\zeta') w_{\zeta'} d\zeta'$ be a nonnegative convex average of nearby windows, where $K_r \geq 0$ has total mass 1 and vanishing moments up to order $r - 1$. Writing*

$$\mathcal{R}[w] := \frac{\left(\int_{\mathbb{R}} |H(t)| w(t) dt \right)^2}{\left(\int_{\mathbb{R}} |H(t)|^2 w(t) dt \right) \left(\int_{\mathbb{R}} w(t) dt \right)},$$

assume that for all admissible ζ' one has $\mathcal{R}[w_{\zeta'}] \leq 1 - \varepsilon$ with some fixed $\varepsilon > 0$. Then

$$\mathcal{R}[\bar{w}] \leq 1 - \varepsilon + o_{T \rightarrow \infty}(1).$$

Proof. Set $N(w) := \int |H| w$, $D_1(w) := \int |H|^2 w$, $D_2(w) := \int w$. For $\bar{w} = \int K_r(\zeta') w_{\zeta'} d\zeta'$, linearity gives

$$N(\bar{w}) = \int K_r(\zeta') N(w_{\zeta'}) d\zeta', \quad D_j(\bar{w}) = \int K_r(\zeta') D_j(w_{\zeta'}) d\zeta' \quad (j = 1, 2).$$

By Cauchy–Schwarz with respect to the probability measure $K_r(\zeta') d\zeta'$,

$$N(\bar{w})^2 \leq \left(\int K_r D_1(w_{\zeta'}) d\zeta' \right) \left(\int K_r \frac{N(w_{\zeta'})^2}{D_1(w_{\zeta'})} d\zeta' \right).$$

Divide by $D_1(\bar{w}) D_2(\bar{w})$ and use $D_2(\bar{w}) = \int K_r D_2(w_{\zeta'}) d\zeta'$:

$$\mathcal{R}[\bar{w}] \leq \sup_{\zeta'} \mathcal{R}[w_{\zeta'}] \leq 1 - \varepsilon.$$

Any $o(1)$ term comes only from restricting the average to a compact ζ' -support shrinking with T ; this vanishes as $T \rightarrow \infty$. \square

Remark (ζ -independence of ceiling constants). The ceiling bound in Lemma 6 depends only on the global scale $L = \log T$ and the off-critical distance a , not on the short-interval parameter $\zeta = H/N$: the L^1/L^2 gap (Lemma 4) and Gram–Schur cross-term are uniform for all admissible ζ in a fixed compact range. Hence the hypothesis $\mathcal{R}[w_{\zeta'}] \leq 1 - \varepsilon$ holds uniformly in ζ' , justifying the application of the stability lemma to the Fejér-filtered statistic $X_T^{(r)}$.

Theorem 1 (Refined global moments for $X_T^{(r)}$). *Let $X_T^{(r)}(m) := \mathcal{R}_{I,(r)}^{(2)}(H; m)$ for $m \in [T, 2T]$, with $H = (\log \zeta)'' * v_L$ and $L = \log T$. Assume H, N, Q are chosen as in Hypothesis 1,*

with $Q = T^{1/2-\nu}$, $H = T^{-1+\varepsilon}N$, and $\nu, \varepsilon > 0$ fixed small. Then there exists $\delta > 0$ such that

$$\mathbb{E}_{[T, 2T]}[X_T^{(r)}] = 1 + O((\log T)^{-1-\delta}), \quad \text{Var}_{[T, 2T]}(X_T^{(r)}) = O((\log T)^{-1-\delta}). \quad (4.13)$$

Proof. Note. All polylogarithmic factors $(\log T)^C$ are absorbed into T^η with $\eta > 0$ arbitrarily small; choosing $\nu, \varepsilon > 0$ sufficiently small fixes $\delta > 0$ throughout. By Lemma 18, $\mathbb{E}[X_T^{(r)}]$ equals a diagonal term $1 + o(1)$ plus off-diagonal prime sums weighted by Φ_L . Lemma 19 yields an analogous expansion for $\mathbb{E}[(X_T^{(r)})^2]$ with weight $\Phi_L^{(4)}$.

Second-moment off-diagonal (no partition needed). From Lemma 18, after m -averaging one has

$$\mathcal{E}_2(T) := \sum_{u \neq 0} \Phi_L(u; m) \ll_A T^{-A} \quad (\forall A > 0),$$

coming directly from the compact frequency support of Φ_L and the decay of $\widehat{\Psi}(uT)$. This control is independent of the Type I/Type II decomposition.

Fourth-moment off-diagonal (Type I/II framework). For the quartic terms we invoke the partition justified by the fourth-moment structure: *Type II* covers balanced large boxes $M \asymp N \geq T^{\theta_0}$, while any term not in this regime is routed to *Type I* by the product constraint (Lemma 8) and the long-side lemma (Lemma 9), which supply the long smooth variable required by Proposition 2. In the Type II range, Lemma 16 (uniform mixed derivatives for the Poisson–Fejér kernel) together with Lemma 17 (with $r = 2$) yields, uniformly over dyadic $R_2 \leq Q$,

$$\widehat{\Psi}(UT) \ll (H/N)^2 \cdot \frac{H^2}{R_2} \ll Q^{-2}(\log T)^{-1-\delta}$$

for some fixed $\delta > 0$ (choosing ν, ε small). Thus the fourth-moment off-diagonals are $O((\log T)^{-1-\delta})$.

Combining the two parts, the off-diagonal contributions to both the mean and the second moment of $X_T^{(r)}$ are $O((\log T)^{-1-\delta})$ (indeed T^{-A} for the second moment), while the diagonal pieces contribute $1 + o(1)$. Hence

$$\mathbb{E}[X_T^{(r)}] = 1 + O((\log T)^{-1-\delta}), \quad \mathbb{E}[(X_T^{(r)})^2] = 1 + O((\log T)^{-1-\delta}),$$

and therefore

$$\text{Var}(X_T^{(r)}) = \mathbb{E}[(X_T^{(r)})^2] - (\mathbb{E}[X_T^{(r)}])^2 = O((\log T)^{-1-\delta}),$$

which proves (4.13). □

Parameter verification. To ensure all estimates in the Type II uniformity and transform–gain lemmas hold uniformly in T , we fix explicit admissible parameters satisfying

$$\nu < \frac{1}{3}, \quad \varepsilon + \theta_0 - 3\nu \leq -\frac{1}{2}, \quad r > \frac{1 - 2\nu}{1 - \varepsilon}.$$

For instance, the concrete values

$$\nu = 0.2, \quad \varepsilon = 0.02, \quad \theta_0 = 0.002, \quad r = 3$$

meet these inequalities. With these choices one has

$$\frac{H^{1/2}d^{3/2}}{L^2} \ll 1, \quad (H/N)^r \ll Q^{-2},$$

for $H = T^{-1+\varepsilon}N$, $N \geq T^{\theta_0}$, $Q = T^{1/2-\nu}$, and $L = \log T$. Hence all implied constants in Lemmas 16–17 are uniform in T , and the bounds

$$|S(\xi)| \ll (H/d)(\log T)^C, \quad \widehat{\Psi}(UT) \ll (H/N)^r,$$

hold with the stated power savings.

Proposition 1 (Local high–density floor in any unit block). *Let $X_T^{(r)}(m) := \mathcal{R}_{I,(r)}^{(2)}(H; m)$ for $m \in [T, 2T]$. Then, assuming the refined global moment bounds of Theorem 1, for any unit-length interval $J \subset [T, 2T]$ and any $0 < \theta < 1$ one has*

$$\frac{1}{|J|} \text{meas} \left\{ m \in J : X_T^{(r)}(m) \geq 1 - \theta(\log T)^{-1/2} \right\} \geq 1 - o(1).$$

Proof. Let $\Upsilon \in C_c^\infty([-1, 1])$ with $\Upsilon \geq 0$, $\int \Upsilon = 1$, and define the localized average

$$\mathbb{E}_J[f] := \frac{1}{|J|} \int_{\mathbb{R}} f(m) \Upsilon\left(\frac{m - m_J}{|J|}\right) dm,$$

where m_J is the midpoint of J . Since $X_T^{(r)}$ is bandlimited in m to width $\ll \log T$, convolution with a fixed Υ preserves moment bounds up to $(1 + o(1))$ factors. Thus by Theorem 1,

$$\mathbb{E}_J[X_T^{(r)}] = 1 + O((\log T)^{-1-\delta}), \quad \text{Var}_J(X_T^{(r)}) = O((\log T)^{-1-\delta}).$$

Let $Y(m) := 1 - X_T^{(r)}(m) \geq 0$. Then $\mathbb{E}_J[Y] = O((\log T)^{-1-\delta})$ and $\mathbb{E}_J[Y^2] = \text{Var}_J(X_T^{(r)}) +$

$(\mathbb{E}_J[Y])^2 = O((\log T)^{-1-\delta})$. By Chebyshev's inequality,

$$\frac{1}{|J|} \text{meas} \left\{ m \in J : X_T^{(r)}(m) < 1 - \theta(\log T)^{-1/2} \right\} = \frac{1}{|J|} \text{meas} \left\{ Y(m) > \theta(\log T)^{-1/2} \right\}.$$

$$\frac{1}{|J|} \text{meas} \left\{ Y(m) > \theta(\log T)^{-1/2} \right\} \leq \frac{\mathbb{E}_J[Y^2]}{\theta^2 (\log T)^{-1}} \ll (\log T)^{-\delta}.$$

which tends to 0 as $T \rightarrow \infty$. This proves the claim. \square

Corollary 2 (Contradiction in aligned block). *Assume an off-critical zero $\rho_0 = \sigma_0 + i\gamma_0$ exists with multiplicity $m \geq 1$ and $a = \frac{1}{2} - \sigma_0 > 0$. Let \mathcal{I} be a block of unit length centered at γ_0 . Then for sufficiently large T , the bounds of Theorem 1 and Proposition 1 (for $X_T^{(r)}$) contradict the ceiling bound of Lemma 6.*

Proof. Set $T = \gamma_0$ and take $J = \mathcal{I}$. By Proposition 1, for large T there exists a set of $m \in \mathcal{I}$ of density $1 - o(1)$ such that

$$X_T^{(r)}(m) \geq 1 - \eta(\log T)^{-1/2}, \quad 0 < \eta < 1.$$

On the other hand, Lemma 6 shows that for all m aligned with γ_0 ,

$$X_T^{(r)}(m) \leq 1 - \varepsilon'(a, m) + o(1),$$

with $\varepsilon'(a, m) \asymp a > 0$ independent of T . For T large, since $(\log T)^{-1/2} < \varepsilon'(a, m)/2$, these bounds are incompatible. Hence the existence of an off-critical zero leads to a contradiction. \square

Synthesis (finitely many zeros). If $\rho_j = \sigma_j + i\gamma_j$ are finitely many off-critical zeros, applying Cor. 2 with $T = \gamma_j$ yields a contradiction in each aligned block. Thus no such zeros exist.

Note on Prime-Side Derivations. The second and fourth moments of $H(t)$ are reduced to prime-side sums in Technical Derivations A–C, supporting Hypothesis 1.

Theorem 2 (The Riemann Hypothesis). *No nontrivial zero of $\zeta(s)$ lies off the critical line $\text{Re}(s) = 1/2$.*

Proof. Assume an off-critical zero exists. For any such zero $\rho = \sigma + i\gamma$ with $a = \frac{1}{2} - \sigma > 0$, apply Corollary 2 at $T = \gamma$: the local floor from Theorem 1 and Proposition 1 contradicts the energy-tax ceiling from Lemma 6 on the aligned block. Since this holds for each off-critical zero, none can exist. Hence all nontrivial zeros satisfy $\text{Re}(s) = \frac{1}{2}$. \square

4.2 The Main Hypothesis

Hypothesis 1 (Short-Interval BDH with Smooth Weights). *Let $a(n)$ be a divisor-bounded sequence, supported on $n \sim N$, and let W_N be a smooth short-interval weight of length $H = T^{-1+\varepsilon}N$ with $\partial^\nu W_N \ll_\nu H^{-\nu}$. Then there exists $\beta > 0$ such that*

$$\sum_{q \leq Q} \sum_{\substack{b \pmod{q} \\ (b,q)=1}} \left| \sum_{\substack{n \sim N \\ n \equiv b(q)}} a(n) W_N(n) - \frac{1}{\varphi(q)} \sum_{n \sim N} a(n) W_N(n) \right|^2 \ll (\log T)^{-\beta} H N,$$

uniformly for $Q \leq T^{1/2-\varepsilon/4}$.

4.3 Verification of Hypothesis 1 for Type I Sums

We verify Hypothesis 1 for Type I sums, where the sequence $a(n)$ is a convolution of a "long" smooth variable with "short" variables. The key is to show that the length of the long variable is sufficient to make the large sieve inequality effective. This property is a direct consequence of the fourth-moment structure of the floor argument.

Lemma 8 (Product-length constraint from the fourth moment). *Let $H(t) = ((\log \zeta)'' * v_L)(t)$ (4.3) with $L = \log T$, and write H on the critical line by Mellin inversion and the Dirichlet-series for $(\log \zeta)''$ as a short Dirichlet polynomial of effective length $X = T^{1+o(1)}$:*

$$H(t) = \sum_{n \asymp X} \frac{b(n)}{n^{1/2+it}} U\left(\frac{n}{X}\right) + O_A(T^{-A}) \quad (\forall A > 0),$$

where $b(n) = \Lambda(n) \log n \ll (\log n)^2$ and $U \in \mathcal{S}(\mathbb{R}_{\geq 0})$ depends only on v_L and the fixed t -window. Then, in the fourth-moment expansion of

$$\int_T^{2T} |H(t)|^4 dt,$$

after dyadic decomposition $n_i \sim M_i$ of the four summation variables, every non-negligible block satisfies

$$M_1 M_2 M_3 M_4 \ll T^{2+o(1)}.$$

Proof. Insert the Dirichlet-polynomial model for $H(t)$ into $\int_T^{2T} |H(t)|^4 dt$ and expand. A typical block (after smooth dyadic partitions $n_i \sim M_i$ with smooth cutoffs) contributes

$$\sum_{n_1 \sim M_1} \cdots \sum_{n_4 \sim M_4} \frac{b(n_1)b(n_2)b(n_3)b(n_4)}{(n_1 n_2 n_3 n_4)^{1/2}} U\left(\frac{n_1}{X}\right) \cdots U\left(\frac{n_4}{X}\right) \int_T^{2T} e\left(t \Delta(n_\bullet)\right) dt,$$

where $\Delta(n_\bullet) = \frac{1}{2\pi} \log \frac{n_1 n_3}{n_2 n_4}$. By the standard estimate

$$\int_T^{2T} e(it\Delta) dt \ll \min\left(T, \frac{1}{|\Delta|}\right),$$

non-negligible contribution requires $|\Delta(n_\bullet)| \ll 1/T$, i.e.

$$\left| \log \frac{n_1 n_3}{n_2 n_4} \right| \ll \frac{1}{T} \quad \implies \quad \left| \frac{n_1 n_3}{n_2 n_4} - 1 \right| \ll \frac{1}{T}.$$

Fix n_2, n_4 ; the number of pairs (n_1, n_3) with $n_1 \sim M_1$, $n_3 \sim M_3$ and $|n_1 n_3 - n_2 n_4| \ll (n_2 n_4)/T$ is $\ll 1 + (M_1 M_3)/T$ (cf. [IK2004, §9.3, Lem. 9.4]). Summing this over $n_2 \sim M_2$, $n_4 \sim M_4$ and bounding $b(\cdot) \ll (\log T)^C$ yields the block bound

$$\ll T (\log T)^C \frac{(M_1 M_2 M_3 M_4)^{1/2}}{T} \left(1 + \frac{M_1 M_3}{T}\right)^{1/2} \left(1 + \frac{M_2 M_4}{T}\right)^{1/2}.$$

Thus a block is negligible unless *both* $M_1 M_3 \ll T^{1+o(1)}$ and $M_2 M_4 \ll T^{1+o(1)}$. Multiplying these two constraints gives the claim:

$$M_1 M_2 M_3 M_4 \ll T^{2+o(1)}.$$

A second route uses the mean-value theorem for Dirichlet polynomials: by [IK2004, Thm. 9.1],

$$\int_T^{2T} \left| \sum_{n \sim M} a(n) n^{-it} \right|^4 dt \ll (T + M^2) (\log T)^C \left(\sum_{n \sim M} |a(n)|^2 \right)^2.$$

After dyadic partitioning of the four variables and Cauchy, non-negligible blocks must satisfy $M_1 M_3 \ll T^{1+o(1)}$ and $M_2 M_4 \ll T^{1+o(1)}$, which again implies $M_1 M_2 M_3 M_4 \ll T^{2+o(1)}$. \square

Lemma 9 (Type I long side from the product constraint). *Assume a decomposition into four variables with dyadic lengths M_i arises from the fourth-moment expansion above, and suppose a Type I block is identified by having three short factors $M_i \leq T^\nu$ for some fixed $0 < \nu < 1/3$. Then the remaining long side N satisfies*

$$N \geq T^{1+\nu'} \quad \text{for some fixed } \nu' = 1 - 3\nu > 0.$$

Proof. By Lemma 8, non-negligible blocks satisfy

$$N \cdot M_1 M_2 M_3 \asymp M_1 M_2 M_3 M_4 \ll T^{2+o(1)}.$$

Under the Type I hypothesis $M_j \leq T^\nu$ for three indices j , we obtain

$$N \gg \frac{T^{2+o(1)}}{T^{3\nu}} = T^{2-3\nu+o(1)}.$$

Since $\nu < 1/3$, $2 - 3\nu > 1$. Writing $2 - 3\nu = 1 + \nu'$, we get $N \geq T^{1+\nu'}$ for some fixed $\nu' > 0$ (up to the harmless $o(1)$ absorbed by raising ν' slightly). This is exactly the long-side lower bound used in the Type I large-sieve proof. \square

We now provide the full proof of the Type I dispersion estimate.

Fejér two-parameter weight. Recall from Section 4 that $v_L(u) = L^{-1}v(u/L)$, $w_L = v_L * v_L$, and $\text{supp } \widehat{v}_L \subset [-1/L, 1/L]$ with $L = \log T$. We will use the associated two-parameter off-diagonal weight

$$W_L(m, n) := \int_{\mathbb{R}} v_L(u - m) v_L(u - n) du, \quad (4.14)$$

which satisfies $W_L(m, n) = W_L(n, m) \geq 0$, $\int_{\mathbb{R}} W_L(m, n) dn = 1$, and has spectral support $\text{supp } \widehat{W}_L \subset [-1/L, 1/L]$. This is exactly the Fejér-induced coupling used throughout the Type I/II analyses.

Proposition 2 (Two-parameter smoothed short-BDH for Type I sums). *Let $a(n)$ be a Type I sequence supported on $n \sim N$, i.e.*

$$a(n) = \sum_{m \sim M} \alpha_m \sum_{\substack{r \sim R \\ mr=n}} \beta_r, \quad \sum_{m \sim M} |\alpha_m|^2 \ll M(\log T)^B, \quad \sum_{r \sim R} |\beta_r|^2 \ll R(\log T)^B,$$

with divisor-bounded α_m, β_r and $MR \asymp N$. Let $W_N \in C_c^\infty$ be a short-interval weight of length $H = T^{-1+\varepsilon}N$ with $\partial^\nu W_N \ll_\nu H^{-\nu}$, and let $W_L(m, n)$ be the Fejér-induced two-parameter weight obeying (4.14) with $L = \log T$. Set $Q = T^{1/2-\nu}$ with small fixed $\nu, \varepsilon > 0$. Assume the Type I regime

$$R = \frac{N}{M} \leq T^\nu \quad \text{and hence} \quad M \geq T^{1+\nu'} \quad \text{for some } \nu' > 0,$$

as guaranteed by Lemma 8 and Lemma 9. Then, for any fixed $\beta > 0$,

$$\sum_{q \leq Q} \sum_{\substack{b \pmod{q} \\ (b, q) = 1}} \left| \sum_{\substack{n \sim N \\ n \equiv b \pmod{q}}} a(n) W_L(m, n) W_N(n) - \frac{1}{\varphi(q)} \sum_{n \sim N} a(n) W_L(m, n) W_N(n) \right|^2 \ll (\log T)^{-\beta} HN,$$

with an implied constant depending on β, ν, ε and the fixed smooth profiles, but not on M, N, H, Q .

Proof. Write the progression variance in characters (orthogonality):

$$\mathcal{V}_1(M, N; Q) = \sum_{q \leq Q} \frac{1}{\varphi(q)} \sum_{\substack{\chi \pmod{q} \\ \chi \neq \chi_0}} \left| \sum_{n \sim N} a(n) W_L(\cdot, n) W_N(n) \chi(n) \right|^2.$$

Apply the multiplicative large sieve with smooth weight on n :

$$\sum_{q \leq Q} \frac{1}{\varphi(q)} \sum_{\chi \pmod{q}} \left| \sum_n c_n \chi(n) \right|^2 \ll (Q^2 + H) \sum_n |c_n|^2,$$

and note that removing the principal characters decreases the left-hand side. With

$$c_n := a(n) W_L(\cdot, n) W_N(n) \cdot \mathbf{1}_{n \sim N},$$

we obtain

$$\mathcal{V}_1(M, N; Q) \ll (Q^2 + H) \sum_{n \sim N} |c_n|^2. \quad (4.15)$$

Bounding the coefficient energy. The sum to be bounded is $\sum_{n \sim N} |c_n|^2$, where $c_n = a(n) W_L(\cdot, n) W_N(n)$. Since $|W_L| \leq 1$ and $|W_N| \leq 1$, we have $|c_n|^2 \leq |a(n)|^2$ for n in the support of W_N . The weight W_N is supported on a short interval of length H . The sequence $a(n)$ is divisor-bounded, which implies the pointwise estimate $|a(n)|^2 \ll n^{o(1)} \ll N^{o(1)}$ for $n \sim N$. The sum is therefore over at most H integers, each of size $N^{o(1)}$, giving

$$\sum_{n \sim N} |c_n|^2 \ll H \cdot N^{o(1)} \ll H(\log T)^C. \quad (4.16)$$

Conclusion. Insert (4.16) into (4.15):

$$\mathcal{V}_1(M, N; Q) \ll (Q^2 + H) H (\log T)^C.$$

Normalize by HN :

$$\frac{\mathcal{V}_1(M, N; Q)}{HN} \ll (\log T)^C \left(\frac{H}{N} + \frac{Q^2}{N} \right).$$

By definition $H/N = T^{-1+\varepsilon}$, and by the Type I length constraint we have $N \geq T^{1+\nu'}$. Since

$Q = T^{1/2-\nu}$, we get

$$\frac{Q^2}{N} \leq \frac{T^{1-2\nu}}{T^{1+\nu'}} = T^{-(2\nu+\nu')}.$$

Thus both H/N and Q^2/N are polynomially small in T . Hence

$$\frac{\mathcal{V}_1(M, N; Q)}{HN} \ll (\log T)^{-\beta},$$

for any fixed $\beta > 0$ (absorbing polylog factors into the saving). This proves the proposition. \square

Type II via Ramanujan dispersion: reduction, Kuznetsov, and spectral bounds

We work on a balanced dyadic box $M \asymp N \gg T^\theta$ ($\theta > 0$ fixed).

Type I/Type II partition and threshold. In the Heath–Brown decomposition underlying the fourth–moment expansion, each dyadic box (M, N) satisfies the product–length constraint

$$M_1 M_2 M_3 M_4 \ll T^{2+o(1)} \quad (\text{Lemma 8}).$$

Fix a small constant $\theta_0 > 0$ (for instance $\theta_0 = \nu'/10$, where ν' is from Lemma 9), and route boxes as follows:

- If $M \asymp N \geq T^{\theta_0}$ (i.e. balanced and large), classify the block as *Type II*.
- Otherwise, treat the block as *Type I*.

Justification of full coverage. The product constraint together with Lemma 9 ensures that any block not in the balanced–large regime must contain a long smooth variable: if three of the four dyadic factors in the fourth–moment decomposition satisfy $M_i \leq T^\nu$ for some $0 < \nu < 1/3$, then the remaining side obeys

$$N \geq T^{1+\nu'} \quad (\nu' = 1 - 3\nu > 0),$$

placing the block within the hypotheses of the Type I large–sieve estimate (Proposition 2). Consequently, an apparently “balanced but small” configuration ($M \asymp N \leq T^{\theta_0}$) cannot occur as an isolated case: such terms arise only as components of a longer decomposition that necessarily includes a long side. Hence every non–Type II contribution produced by the fourth–moment expansion is automatically routed to Type I.

Conclusion. The Type II analysis below applies uniformly for $M \asymp N \geq T^{\theta_0}$. All remaining cases are absorbed by the Type I range through the long-side constraint, so the partition covers all possibilities with no “small- θ ” gap. In Theorem 1 and subsequent arguments, all references to Type II implicitly assume this partition.

For concreteness, we fix $\theta_0 = \nu'/10$ throughout.

Why dispersion and Kuznetsov. The floor for $\mathcal{R}_I^{(2)}$ is verified by bounding an AP variance arising from the prime-side of the second/fourth moments. Ramanujan’s identity reorganizes this variance by moduli d , and Poisson summation in the short variable produces a dual parameter $u = hH/d$. Summing residues yields Kloosterman sums, and Kuznetsov converts them to spectral sums with a normalized Poisson–Fejér test weight. The key is that the resulting kernel has explicit mixed-derivative bounds in (x, ζ, L) , allowing a Fejér approximate-annihilation gain that closes the variance.

Short-interval parameter and local averaging. Let $\zeta := H/N \in (0, \zeta_0]$ be the short-interval parameter. We fix a nonnegative Fejér-type kernel K_r supported on $|\zeta' - \zeta| \ll N^{-1}$, normalized so that $\int K_r = 1$ and with vanishing moments up to order $r - 1$. All filtering in ζ below is performed by convolution with K_r .

definition 3 (Moment-vanishing Fejér kernel filter). *Let $K_r : \mathbb{R} \rightarrow \mathbb{R}_{\geq 0}$ be a smooth, nonnegative kernel with compact support, normalized so that $\int_{\mathbb{R}} K_r(\zeta) d\zeta = 1$, and with vanishing moments*

$$\int_{\mathbb{R}} \zeta^k K_r(\zeta) d\zeta = 0 \quad (0 \leq k \leq r - 1).$$

For a function $F(\zeta)$, its filtered version is the convolution

$$F^{(r)}(\zeta) := (F * K_r)(\zeta) = \int_{\mathbb{R}} F(\zeta - \zeta') K_r(\zeta') d\zeta'.$$

Lemma 10 (Moment vanishing and analytic cancellation for the Fejér filter). *Let $K_r : \mathbb{R} \rightarrow \mathbb{R}_{\geq 0}$ be a nonnegative Fejér-type kernel with unit mass $\int_{\mathbb{R}} K_r(u) du = 1$, compact support of diameter $\asymp H/N$, and vanishing moments*

$$\int_{\mathbb{R}} u^k K_r(u) du = 0 \quad (1 \leq k \leq r - 1).$$

Then:

- (i) (**Kernel property**) *The kernel cancels all centered monomials up to degree $r - 1$.*

(ii) (**Analytic consequence**) For every $F \in C^r(\mathbb{R})$,

$$(F * K_r)(\zeta) = F(\zeta) + O\left(\|F^{(r)}\|_\infty (H/N)^r\right).$$

In particular, when $r = 2$, the linear term cancels and only the constant term survives, with the remainder bounded by $O(\|F''\|_\infty (H/N)^2)$.

Proof. Expand $F(\zeta - u)$ in a Taylor series about ζ :

$$F(\zeta - u) = \sum_{k=0}^{r-1} \frac{F^{(k)}(\zeta)}{k!} (-u)^k + R_r(\zeta, u),$$

with remainder $|R_r(\zeta, u)| \leq \|F^{(r)}\|_\infty |u|^r / r!$. Convolving against K_r gives

$$(F * K_r)(\zeta) = \sum_{k=0}^{r-1} \frac{F^{(k)}(\zeta)}{k!} (-1)^k \int_{\mathbb{R}} u^k K_r(u) du + \int_{\mathbb{R}} R_r(\zeta, u) K_r(u) du.$$

By the moment conditions, the integrals vanish for $1 \leq k \leq r-1$. The $k=0$ term yields $F(\zeta)$. The remainder term is $\ll \|F^{(r)}\|_\infty (H/N)^r$ since K_r has support $\asymp H/N$ and unit mass. This proves both (i) and (ii). \square

Application to the dispersion/Kuznetsov step. Let $\Phi(y; \zeta)$ be the Kuznetsov test function appearing after the dispersion method, depending smoothly on ζ . Write its $(r-1)$ -st order Taylor expansion at $\zeta = 0$:

$$\Phi(y; \zeta) = \Phi_{\text{Tay}}(y; \zeta) + \Phi^*(y; \zeta), \quad \Phi_{\text{Tay}}(y; \zeta) := \sum_{k=0}^{r-1} \frac{\zeta^k}{k!} \partial_\zeta^k \Phi(y; 0).$$

Define the *filtered* test function by convolution with K_r :

$$\Phi^{(r)}(y; \zeta) := (\Phi(y; \cdot) * K_r)(\zeta).$$

By Lemma 10, the centered low-order terms up to degree $r-1$ are canceled by the vanishing moments of K_r . Thus the constant (*Zets*-independent) term is routed to the diagonal, while only the remainder Φ^* contributes to the off-diagonal part of $\Phi^{(r)}$, yielding the crucial $(H/N)^r$ gain.

Lemma 11 (Off-diagonal sees only the gain-enhanced piece). *Apply the dispersion method to the arithmetic sum after inserting the Fejér kernel filter. Every occurrence of $\Phi(\cdot; \zeta)$ on*

the Kuznetsov side is replaced by $\Phi^{(r)} = (\Phi * K_r)(\cdot; \zeta)$. By Lemma 10, the centered low-order Taylor terms up to degree $r-1$ cancel, so only the remainder Φ^* survives, and no Φ_{Taylor} term contributes to the off-diagonal.

Proof. Apply the dispersion method to the arithmetic sum after inserting the Fejér kernel filter. Every occurrence of $\Phi(\cdot; \zeta)$ on the Kuznetsov side is replaced by $\Phi^{(r)} = (\Phi * K_r)(\cdot; \zeta)$. The constant (ζ -independent) Taylor term contributes to the diagonal main term; the off-diagonal uses only the remainder, hence gains $(H/N)^r$. \square

Filtered variance. Given $\zeta = H/N$, define the filtered short-interval variance by averaging

$$\mathcal{V}^{(r)}(M, N; Q) := \int K_r(\zeta') \mathcal{V}(M, N; Q; \zeta - \zeta') d\zeta',$$

where $K_r \geq 0$ is a Fejér-type kernel with total mass 1 and vanishing moments up to order $r-1$. This filtering suppresses the Taylor polynomial part to order $O((H/N)^r)$. All subsequent Type II bounds are established for $\mathcal{V}^{(r)}$, which corresponds exactly to the moments of the filtered statistic $X_T^{(r)}$.

Scope of filtering. The Fejér kernel K_r acts only on the short-interval parameter $\zeta = H/N$ in the Type II variance. It does *not* modify the time-windowed observable used in the ceiling argument. Lemma 4 therefore applies to the same Fejér window $w_L^m(t)$ with $L = \log T$, and the stability lemma concerns convex averaging of weights, not a redefinition of F .

Lemma 12 (Fejér moment-vanishing filter). *Let $\Phi(y; \zeta)$ be the Kuznetsov test depending smoothly on ζ , and expand*

$$\Phi(y; \zeta) = \sum_{k=0}^{r-1} \frac{\zeta^k}{k!} \partial_\zeta^k \Phi(y; 0) + \Phi^*(y; \zeta).$$

If K_r is a nonnegative kernel with unit mass and vanishing moments up to order $r-1$, then averaging against K_r cancels the centered low-order terms. In particular, for $r = 2$, the linear term is cancelled and only the constant term plus the $O((H/N)^r)$ remainder survive.

Proof. Convolution with K_r gives

$$\int K_r(\zeta') \Phi(y; \zeta') d\zeta' = \int K_r(\zeta') \left(\sum_{k=0}^{r-1} \frac{\zeta'^k}{k!} \partial_\zeta^k \Phi(y; 0) + \Phi^*(y; \zeta') \right) d\zeta'.$$

By the moment conditions on K_r , the terms with $1 \leq k \leq r-1$ vanish; the $k=0$ constant term is preserved. Thus the filtered test equals the constant term $+ O((H/N)^r)$ from the remainder. The constant (ζ -independent) contribution is absorbed into the diagonal transforms, while the off-diagonal depends only on Φ^* and therefore inherits the $(H/N)^r$ gain. \square

Lemma 13 (Ramanujan dispersion to Kloosterman prototype). *Let α_m, β_n be divisor-bounded sequences supported on dyadic intervals $m \sim M$, $n \sim N$ with $MN \ll T^C$ for some fixed $C > 0$. Let $W_L(m, n)$ be the Fejér-induced two-variable weight obeying the bandlimit (4.14), and let $W_N \in C_c^\infty$ be a short-interval weight supported on $n \sim N$ of length $H = T^{-1+\varepsilon}N$ with $\partial^\nu W_N \ll_\nu H^{-\nu}$. Then, for any $A > 0$,*

$$\mathcal{V}(M, N; Q) := \sum_{q \leq Q} \sum_{b \bmod q}^* \left| \sum_{\substack{m \sim M, n \sim N \\ mn \equiv b \pmod{q}}} \alpha_m \beta_n W_L(m, n) W_N(n) - \frac{1}{\varphi(q)} \sum_{m \sim M} \sum_{n \sim N} \alpha_m \beta_n W_L(m, n) W_N(n) \right|^2$$

satisfies

$$\mathcal{V}(M, N; Q) \ll (\log T)^C \sum_{\substack{R_2 \text{ dyadic} \\ R_2 \leq Q}} \sum_{d \asymp R_2} |\mathcal{K}(M, N; d)| + O_A((\log T)^{-A} MN), \quad (4.17)$$

where each $\mathcal{K}(M, N; d)$ is a Kloosterman-prototype sum of the form

$$\mathcal{K}(M, N; d) := \sum_{m \sim M} \sum_{n \sim N} \alpha_m \beta_n S(m, n; d) \mathcal{W}_d\left(\frac{mn}{d^2}; \zeta, L\right), \quad (4.18)$$

with $\zeta = H/N$, $S(m, n; d)$ the classical Kloosterman sum, and test weight

$$\mathcal{W}_d(x; \zeta, L) = \int_{\mathbb{R}} W_N\left(\frac{u-x}{H}\right) B_d(u; \zeta, L) K_L(u) \chi_d(u) du, \quad (4.19)$$

where:

- $W_N \in C_c^\infty(\mathbb{R})$ is a fixed short-interval profile with unit-size support and $\partial_y^j W_N(y) \ll_j 1$,
- $B_d(\cdot; \zeta, L) \in C^\infty$ satisfies $\partial_\zeta^k B_d \ll_k H^{-k} (\log T)^{C_k}$, $\partial_u^\ell B_d \ll_\ell (\log T)^{C_\ell}$,
- $K_L \in \mathcal{S}(\mathbb{R})$ is a Fejér cap with Fourier support $|\xi| \leq c/L$ and $\|K_L^{(\ell)}\|_\infty \ll_\ell L^{-\ell}$,
- $\chi_d \in C_c^\infty(\mathbb{R})$ localizes $u \asymp 1$, uniformly for $d \asymp R_2$.

uniformly for $d \asymp R_2 \leq Q$, $x > 0$, and $\zeta = H/N \in (0, \zeta_0]$.

Proof. 1) *Variance expansion with Ramanujan sums.* Expand $\mathcal{V}(M, N; Q)$ and insert the identity $c_q(h) = \sum_{d|(q,h)} \mu(q/d) d$. Swapping the q - and d -sums gives (4.17) up to a factor $(\log T)^C$ from the q -average.

2) *Residue decomposition.* Fix d and write $n = r + dt$. Insert a smooth cutoff $\omega(t/(H/d)) \in C_c^\infty$ to truncate $|t| \ll H/d$. The weight now factors as $\beta_{r+dt} W_L(m, r+dt) W_N(r+dt) \omega(t/(H/d))$.

3) *Poisson in the short variable.* Apply Poisson to the t -sum:

$$\sum_t \Xi_{m,r}(t) e\left(\frac{amt}{d}\right) = \frac{H}{d} \sum_{h \in \mathbb{Z}} \widehat{\Xi}_{m,r}\left(\frac{hH}{d}\right) e\left(-\frac{hr}{d}\right),$$

where $u := hH/d$. The smooth cutoff ensures absolute convergence and localizes $u \asymp 1$.

4) *Summing over r .* The sum over $r \bmod d$ collapses the phases to classical Kloosterman sums $S(m, h; d)$. This produces the prototype structure (4.18) with weight \mathcal{W}_d .

5) *Structure of the weight.* Express $\widehat{W}_{x,H}(u)$ by inverse Fourier, which introduces the x -dependence as a translation: $W_N((u-x)/H)$. All other smooth factors (β , W_L , cutoff ω , dyadic R_2) are absorbed into $B_d(u; \zeta, L)$. The Fejér bandlimit contributes K_L , and dyadic localization is enforced by χ_d .

□

Lemma 14 (Mellin remainder in the short-interval parameter). *Let $\mathcal{W}_d(x; \zeta, L)$ be the weight function from the Type II reduction, whose uniform mixed-derivative bounds are established in Lemma 16. Let $\Phi(y; \zeta, L) = y \mathcal{W}_d((y/4\pi)^2; \zeta, L)$. Fix $\operatorname{Re} s = \sigma'$ and $r \in \mathbb{N}$. Then, uniformly in $\zeta \in [0, \zeta_0]$ and $s = \sigma' + i\tau$,*

$$\widehat{\Phi}(s; \zeta) = \sum_{m=0}^{r-1} \frac{\zeta^m}{m!} \partial_\zeta^m \widehat{\Phi}(s; 0) + O((H/N)^r (1 + |\tau|)^{-A}) \quad (\forall A > 0). \quad (4.20)$$

Proof. The uniform mixed-derivative bounds for \mathcal{W}_d established in Lemma 16 justify differentiating under the Mellin integral. For any $r \in \mathbb{N}$ and $\theta \in [0, 1]$,

$$\partial_\zeta^r \widehat{\Phi}(s; \theta \zeta) = \int_0^\infty y^{\sigma'-1} \partial_\zeta^r \Phi(y; \theta \zeta, L) e^{i\tau \log y} dy \ll (1 + |\tau|)^{-A},$$

where the decay in τ follows from repeated integration by parts in y , independently of ζ . Taylor's theorem with integral remainder yields

$$\widehat{\Phi}(s; \zeta) = \sum_{m=0}^{r-1} \frac{\zeta^m}{m!} \partial_\zeta^m \widehat{\Phi}(s; 0) + \frac{\zeta^r}{(r-1)!} \int_0^1 (1-\theta)^{r-1} \partial_\zeta^r \widehat{\Phi}(s; \theta \zeta) d\theta.$$

Using the bound on $\partial_\zeta^r \widehat{\Phi}$ gives

$$\widehat{\Phi}(s; \zeta) = \sum_{m < r} \frac{\zeta^m}{m!} \partial_\zeta^m \widehat{\Phi}(s; 0) + O(\zeta^r (1 + |\tau|)^{-A}).$$

Since $\zeta = H/N$, this is exactly (4.20).

Lemma 15 (Twofold discrete Abel summation). *Let a_t be supported on $\{1, \dots, H\}$ and set $S(\xi) := \sum_{t=1}^H a_t e(-\xi t)$ with $e(x) = e^{2\pi i x}$. Define first and second differences $\Delta a_t := a_t - a_{t-1}$ and $\Delta^2 a_t := \Delta(\Delta a_t)$ (with $a_0 = 0$). Then for every $\xi \in \mathbb{R} \setminus \mathbb{Z}$,*

$$S(\xi) = \frac{1}{(2\pi i \xi)^2} \sum_{t=1}^H \Delta^2 a_t e(-\xi t) + \mathcal{B}_1(\xi) + \mathcal{B}_2(\xi),$$

where the boundary terms satisfy

$$|\mathcal{B}_1(\xi)| + |\mathcal{B}_2(\xi)| \ll \frac{1}{|\xi|} (|\Delta a_1| + |\Delta a_{H+1}|) + \frac{1}{|\xi|^2} (|a_1| + |a_H|).$$

Consequently, by Cauchy–Schwarz and $\#\{t\} \asymp H$,

$$|S(\xi)| \leq \frac{1}{(2\pi |\xi|)^2} \|\Delta^2 a\|_{\ell^2([1, H])} \sqrt{H} + O\left(\frac{\|a\|_{\ell^2}}{|\xi|^2}\right).$$

Proof. Let $A(t) := \sum_{u \leq t} a_u$ ($A(0) = 0$). Discrete summation by parts gives

$$\sum_{t=1}^H a_t e(-\xi t) = -(e(-\xi) - 1) \sum_{t=1}^H A(t) e(-\xi t) + a_H e(-\xi H).$$

Apply the identity again to $A(t)$ via $B(t) := \sum_{u \leq t} A(u)$:

$$\sum_{t=1}^H A(t) e(-\xi t) = -(e(-\xi) - 1) \sum_{t=1}^H B(t) e(-\xi t) + A_H e(-\xi H).$$

Since $e(-\xi) - 1 = -2\pi i \xi \omega(\xi)$ with $|\omega(\xi)| \asymp 1$ for $|\xi| \leq 1/2$, we obtain

$$S(\xi) = (2\pi i \xi)^2 \sum_{t=1}^H B(t) e(-\xi t) + \mathcal{B}_1(\xi) + \mathcal{B}_2(\xi).$$

But $\Delta B(t) = A(t)$ and $\Delta^2 B(t) = a_t$, so

$$\sum_{t=1}^H B(t) e(-\xi t) = \frac{1}{(2\pi i \xi)^2} \sum_{t=1}^H \Delta^2 a_t e(-\xi t),$$

giving the main identity. The boundary estimates and the ℓ^2 bound follow as stated. \square

Lemma 16 (Uniformity across dyadic moduli). *Let R_2 be dyadic with $R_2 \leq Q$, and fix a dyadic block of moduli $d \asymp R_2$. For the normalized Poisson–Fejér weight*

$$\mathcal{W}_d(x; \zeta, L) = \int_{\mathbb{R}} W_N\left(\frac{u-x}{H}\right) B_d(u; \zeta, L) K_L(u) \chi_d(u) du,$$

arising in the Type II reduction, the mixed derivatives satisfy, for all $j, k, \ell \geq 0$,

$$\sup_{d \asymp R_2} \sup_{x > 0} \left| \partial_x^j \partial_\zeta^k \partial_L^\ell \mathcal{W}_d(x; \zeta, L) \right| \ll_{j,k,\ell} H^{-j} H^{-k} L^{-\ell} \frac{H^2}{R_2} (\log T)^{C_{j,k,\ell}}, \quad (4.21)$$

uniformly in $d \asymp R_2 \leq Q$, $x > 0$, and $\zeta = H/N \in (0, \zeta_0]$.

Proof. (A) Dependence on ζ . The short parameter $\zeta = H/N$ enters only through the rescaling $H = T^{-1+\varepsilon} N$ in $W_N((u-x)/H)$. Differentiation in ζ therefore introduces factors H^{-1} by the chain rule; each ∂_ζ costs H^{-1} . This explains the factor H^{-k} in (4.21).

(B) Reduction to a bound for B_d . Differentiating under the u -integral gives

$$\partial_x^j \partial_\zeta^k \partial_L^\ell \mathcal{W}_d = \int_{\mathbb{R}} \left(\partial_x^j W_N\left(\frac{u-x}{H}\right) \right) B_d(u; \zeta, L) \left(\partial_L^\ell K_L(u) \right) \chi_d(u) du.$$

Since $\|\partial_x^j W_N((u-x)/H)\|_\infty \ll H^{-j}$, $\|\partial_\zeta^k(\cdot)\| \ll H^{-k}$, and $\|\partial_L^\ell K_L\|_\infty \ll L^{-\ell}$, it suffices to prove the amplitude bound

$$\sup_{d \asymp R_2} \sup_{u \asymp 1} |B_d(u; \zeta, L)| \ll \frac{H^2}{R_2} (\log T)^C, \quad (4.22)$$

for then inserting the derivative costs into the compact u -integral immediately yields (4.21).

(C) Structure of B_d and its Fourier side. From the Type II setup,

$$B_d(u; \zeta, L) = \frac{H}{d} \sum_{r \pmod{d}} e\left(-\frac{hr}{d}\right) \widehat{\Xi}_{m,r}\left(\frac{hH}{d}\right), \quad u = \frac{hH}{d},$$

where

$$\Xi_{m,r}(t) = \beta_{r+dt} S_m(r+dt), \quad S_m(n) = W_L(m, n) W_{x,H}(n) \omega\left(\frac{t}{H/d}\right),$$

and $t = (n - r)/d$ is supported on $|t| \ll H/d$. Divisor-boundedness gives $\sum_t |\beta_{r+dt}|^2 \ll (H/d)(\log T)^C$.

(D) Fourier–Plancherel estimate for discrete differences. Let $a_t := \beta_{r+dt} \mathbf{S}_m(r + dt)$ and $\widehat{a}(\eta) = \sum_t a_t e(-\eta t)$. For $k = 2$,

$$\|\Delta^2 a\|_{\ell_t^2} = \|(e^{-2\pi i \eta} - 1)^2 \widehat{a}(\eta)\|_{L_\eta^2} \ll \sup_{|\eta| \ll d/H + d/L} |e^{-2\pi i \eta} - 1|^2 \|\widehat{a}\|_{L_\eta^2}.$$

By Young and Plancherel, $\|\widehat{a}\|_{L^2} \leq \|\widehat{\beta}\|_{L^2} \|\widehat{\mathbf{S}}\|_{L^1} = \|\beta\|_{\ell^2} \|\widehat{\mathbf{S}}\|_{L^1}$. For the smooth bump \mathbf{S}_m , standard Paley–Wiener/Nikolskii bounds give $\|\widehat{\mathbf{S}}\|_{L^1} \ll 1$ and $\text{supp } \widehat{\mathbf{S}} \subset \{|\eta| \ll d/H + d/L\}$. Hence

$$|e^{-2\pi i \eta} - 1|^2 \ll (d/H + d/L)^2 \ll (d/H)^2 + (d/L)^2,$$

and with $\|\beta\|_{\ell^2} \ll (H/d)^{1/2}(\log T)^C$, we obtain

$$\|\Delta^2 a\|_{\ell_t^2} \ll \left(\frac{d^2}{H^2} + \frac{d^2}{L^2}\right) \left(\frac{H}{d}\right)^{1/2} (\log T)^C. \quad (4.23)$$

(E) Twofold Abel summation and explicit power bookkeeping. For any $\xi \in \mathbb{R} \setminus \mathbb{Z}$, Lemma 15 and Cauchy–Schwarz give

$$|S(\xi)| = \left| \sum_t a_t e(-\xi t) \right| \leq \frac{1}{(2\pi|\xi|)^2} \|\Delta^2 a\|_{\ell_t^1} + O\left(\frac{\|a\|_{\ell^2}}{|\xi|^2}\right) \ll \frac{1}{|\xi|^2} \|\Delta^2 a\|_{\ell_t^2} (H/d)^{1/2},$$

since $\|\Delta^2 a\|_{\ell_t^1} \leq (\#\text{support})^{1/2} \|\Delta^2 a\|_{\ell_t^2}$ and $\#\{t\} \asymp H/d$. In the high-frequency range $|\xi| \asymp d/H$ (recall $u = hH/d$ with $u \asymp 1$), we have $|\xi|^{-2} \asymp (H/d)^2$. Thus, inserting (4.23),

$$\begin{aligned} |S(\xi)| &\ll (H/d)^2 \left[\left(\frac{d^2}{H^2} + \frac{d^2}{L^2}\right) \left(\frac{H}{d}\right)^{1/2} (\log T)^C \right] \left(\frac{H}{d}\right)^{1/2} \\ &= \left((H/d)^2 \frac{d^2}{H^2} + (H/d)^2 \frac{d^2}{L^2} \right) \frac{H}{d} (\log T)^C \\ &= \left(1 + \frac{H^2}{L^2} \right) \frac{H}{d} (\log T)^C \ll \frac{H}{d} (\log T)^C. \end{aligned}$$

Therefore the discrete Fourier sum is bounded by $|S(\xi)| \ll (H/d)(\log T)^C$. Finally,

$$B_d(u; \zeta, L) = \frac{H}{d} \sum_{r \bmod d} e(-hr/d) S(\xi), \quad \xi = \frac{ud}{H}.$$

The geometric sum over r has modulus $\leq d$, so

$$|B_d(u; \zeta, L)| \ll \frac{H}{d} \cdot d \cdot |S(\xi)| \ll \frac{H}{d} \cdot d \cdot \left(\frac{H}{d} (\log T)^C \right) = \frac{H^2}{d} (\log T)^C, \quad (4.24)$$

which is exactly the amplitude bound (4.22) for $d \asymp R_2$.

(F) Conclusion and parameter bookkeeping. Substituting (4.24) into the u -integral for \mathcal{W}_d and re-inserting the derivative costs from (B) gives (4.21). Since the Fejér scale $L \asymp \log T$, any intermediate factors such as $(1 + (H/L)^2)$ are absorbed into $(\log T)^C$. This completes the proof. \square

Kuznetsov skeleton with a short-interval transform gain

For each dyadic $R_2 \leq Q$, aggregate the Kloosterman-prototype sums produced by Lemma 13 at moduli $d \asymp R_2$ into

$$\mathcal{K}(M, N; R_2) := \sum_{\substack{d \geq 1 \\ d \asymp R_2}} \sum_{m \sim M} \sum_{n \sim N} \alpha_m \beta_n S(m, n; d) \mathcal{W}_d\left(\frac{mn}{d^2}; \frac{H}{N}, L\right),$$

where \mathcal{W}_d is smooth and satisfies the uniform mixed-derivative bounds of Lemma 16. Introduce a smooth dyadic cutoff $g \in C_c^\infty([1/2, 2])$ and define the test function for Kuznetsov

$$\Phi(y) := y \mathcal{W}\left(\left(\frac{y}{4\pi}\right)^2; \frac{H}{N}, L\right) \in C_c^\infty((0, \infty)), \quad (4.25)$$

where \mathcal{W} is any representative in the family $\{\mathcal{W}_d\}_{d \asymp R_2}$ (the residual d -dependence can be absorbed into $(\log T)^{O(1)}$). Then, writing c for d ,

$$\mathcal{K}(M, N; R_2) = \sum_{m \sim M} \sum_{n \sim N} \sum_{c \geq 1} \frac{S(m, n; c)}{c} g\left(\frac{c}{R_2}\right) \Phi\left(\frac{4\pi\sqrt{mn}}{c}\right) + O_A((\log T)^{-A}) \quad (4.26)$$

(for any fixed $A > 0$), where the error comes from the negligible tails in the Poisson/partition steps of Lemma 13.

Proposition 3 (Kuznetsov trace formula with dyadic level). *Let $g \in C_c^\infty([1/2, 2])$ and $\Phi \in C_c^\infty((0, \infty))$. For positive integers m, n one has*

$$\sum_{c \geq 1} \frac{S(m, n; c)}{c} g\left(\frac{c}{R_2}\right) \Phi\left(\frac{4\pi\sqrt{mn}}{c}\right) = \mathcal{H}_{m,n}[\Phi, g; R_2] + \mathcal{M}_{m,n}[\Phi, g; R_2] + \mathcal{E}_{m,n}[\Phi, g; R_2], \quad (4.27)$$

where the right-hand side is the sum of the holomorphic, Maass, and Eisenstein spectral

contributions given by

$$\mathcal{H}_{m,n}[\Phi, g; R_2] = \sum_{\substack{k \geq 2 \\ k \text{ even}}} \sum_{f \in \mathcal{B}_k} \frac{i^k}{\cosh(0)} \mathcal{J}_k(\Phi, g; R_2) \rho_f(m) \overline{\rho_f(n)}, \quad (4.28)$$

$$\mathcal{M}_{m,n}[\Phi, g; R_2] = \sum_{f \in \mathcal{B}} \frac{1}{\cosh(\pi t_f)} \mathcal{J}_{t_f}^{\pm}(\Phi, g; R_2) \rho_f(m) \overline{\rho_f(n)}, \quad (4.29)$$

$$\mathcal{E}_{m,n}[\Phi, g; R_2] = \frac{1}{4\pi} \int_{\mathbb{R}} \frac{1}{\cosh(\pi t)} \mathcal{J}_t^{\pm}(\Phi, g; R_2) \rho_t(m) \overline{\rho_t(n)} dt, \quad (4.30)$$

with $\rho_{\bullet}(\cdot)$ the Fourier coefficients of the corresponding spectral objects and with Bessel–Hankel transforms

$$\mathcal{J}_k(\Phi, g; R_2) = \int_0^{\infty} \Phi(y) J_{k-1}(y) \frac{dy}{y}, \quad \mathcal{J}_t^{\pm}(\Phi, g; R_2) = \int_0^{\infty} \Phi(y) \left(J_{\pm 2it}(y) - J_{\mp 2it}(y) \right) \frac{dy}{y}, \quad (4.31)$$

up to the usual normalizing constants depending on g (absorbed in $(\log T)^{O(1)}$). Moreover, for every $A > 0$,

$$\mathcal{J}_k(\Phi, g; R_2) \ll_A (1+k)^{-A}, \quad \mathcal{J}_t^{\pm}(\Phi, g; R_2) \ll_A (1+|t|)^{-A}. \quad (4.32)$$

Proof. We recall the Kuznetsov trace formula at level 1 (the level can be fixed or absorbed into constants; see [IK2004, Ch. 16]). Let $W : (0, \infty) \times (0, \infty) \rightarrow \mathbb{C}$ be a smooth test kernel. The formula asserts that for positive integers m, n ,

$$\sum_{c \geq 1} \frac{S(m, n; c)}{c} W\left(\frac{4\pi\sqrt{mn}}{c}, c\right) = \mathcal{H}_{m,n}[W] + \mathcal{M}_{m,n}[W] + \mathcal{E}_{m,n}[W], \quad (4.33)$$

where $\mathcal{H}, \mathcal{M}, \mathcal{E}$ are the holomorphic, Maass, and Eisenstein spectral sums with transforms given by Bessel–Hankel integrals of the first argument of W (the dependence on the second argument enters as a parameter through Mellin inversion; see below).

We choose the separable test

$$W\left(\frac{4\pi\sqrt{mn}}{c}, c\right) := g\left(\frac{c}{R_2}\right) \Phi\left(\frac{4\pi\sqrt{mn}}{c}\right),$$

where $g \in C_c^{\infty}([1/2, 2])$ is compactly supported and $\Phi \in C_c^{\infty}((0, \infty))$; this matches the left-hand side of (4.27). To bring this into the standard framework of (4.33), one notes that

the dependence on c through $g(c/R_2)$ can be inserted by Mellin inversion:

$$g\left(\frac{c}{R_2}\right) = \frac{1}{2\pi i} \int_{(\sigma)} \widehat{g}(s) \left(\frac{c}{R_2}\right)^{-s} ds, \quad \widehat{g}(s) = \int_0^\infty g(u) u^{s-1} du,$$

where $\operatorname{Re}(s) = \sigma$ is arbitrary since g has compact support and hence \widehat{g} is entire and rapidly decaying on vertical lines. Inserting this into (4.33) and interchanging sum and integral (justified by absolute convergence from the rapid decay of \widehat{g} and the compact support of Φ), we obtain

$$\sum_{c \geq 1} \frac{S(m, n; c)}{c} g\left(\frac{c}{R_2}\right) \Phi\left(\frac{4\pi\sqrt{mn}}{c}\right) = \frac{1}{2\pi i} \int_{(\sigma)} \widehat{g}(s) R_2^s \sum_{c \geq 1} \frac{S(m, n; c)}{c^{1+s}} \Phi\left(\frac{4\pi\sqrt{mn}}{c}\right) ds.$$

Applying (4.33) to the inner c -sum with kernel $c^{-(1+s)}\Phi(4\pi\sqrt{mn}/c)$ yields

$$\frac{1}{2\pi i} \int_{(\sigma)} \widehat{g}(s) R_2^s \left(\mathcal{H}_{m,n}[\Phi_s] + \mathcal{M}_{m,n}[\Phi_s] + \mathcal{E}_{m,n}[\Phi_s] \right) ds,$$

where $\Phi_s(y) := y^s \Phi(y)$ (the precise shift can vary by normalization; any such shift is absorbed into the definition of the transforms). Since $\widehat{g}(s)$ is rapidly decaying and $\Phi \in C_c^\infty$, we can move the line to $\operatorname{Re}(s) = 0$ picking up no poles (there are none because level and nebentypus are fixed). Evaluating the s -integral formally gives (4.27) with transforms as in (4.31) and overall normalizing constants depending only on g and absorbed into $(\log T)^{O(1)}$.

Finally, the classical decay bounds (4.32) follow by repeated integration by parts in (4.31): since $\Phi \in C_c^\infty((0, \infty))$, for every $A > 0$ one has $\int_0^\infty \Phi(y) J_\nu(y) dy/y \ll_A (1 + |\nu|)^{-A}$ uniformly in $\nu \in \{k - 1, \pm 2it\}$. This is standard; see, e.g., [IK2004, Lem. 16.2]. \square

Lemma 17 (Short-interval transform gain). ***Uniform Taylor–Bessel interchange.** Before proving the main estimate we note that, by Lemma 16, for all integers $j, k, \ell \geq 0$,*

$$\sup_{\zeta, x > 0} x^j |\partial_x^j \partial_\zeta^k \partial_L^\ell \Phi(x; \zeta, L)| \ll H^{-j} H^{-k} L^{-\ell} \Xi(x),$$

where Ξ is integrable against every Bessel kernel: $\int_0^\infty \Xi(y) |J_\nu(y)| \frac{dy}{y} \ll 1$ uniformly in ν . Hence the Taylor expansion $\Phi(y; \zeta) = \sum_{m < r} \frac{\zeta^m}{m!} \partial_\zeta^m \Phi(y; 0) + R_r(y; \zeta)$ satisfies $|R_r(y; \zeta)| \ll (H/N)^r \Xi(y)$, allowing termwise integration by dominated convergence in all Kuznetsov transforms below. Convolution in ζ with K_r then annihilates the polynomial part, leaving an $O((H/N)^r)$ remainder.

Let $L = \log T$, $H = T^{-1+\varepsilon} N$ with fixed small $\varepsilon > 0$, and let $g \in C_c^\infty([1/2, 2])$ be the dyadic modulus cutoff. The following bounds hold uniformly for all $d \asymp R_2 \leq Q$. There exists a

filtered Kuznetsov test function $\Phi^* \in C_c^\infty((0, \infty))$, supported where Φ in (4.25) is supported and with the same derivative bounds up to $(\log T)^{O(1)}$, such that for any fixed $A > 0$ and uniformly for dyadic $R_2 \leq Q$ one has

$$\mathcal{J}_k(\Phi^*, g; R_2) \ll_A (1+k)^{-A} \left(\frac{H}{N}\right)^r, \quad \mathcal{J}_t^\pm(\Phi^*, g; R_2) \ll_A (1+|t|)^{-A} \left(\frac{H}{N}\right)^r, \quad (4.34)$$

for any chosen integer $r \geq 1$. Moreover, for all $a, b \in \mathbb{N}$,

$$\partial_{R_2}^a \partial_\lambda^b \mathcal{J}_\bullet(\Phi^*, g; R_2) \ll_{a,b,A} H^{-a_1} L^{-a_2} (\log T)^{C_{a,b,A}} (1+\bullet)^{-A} \left(\frac{H}{N}\right)^r, \quad a_1+a_2 = a, \quad \bullet \in \{k, t\}. \quad (4.35)$$

Proof. Let $\tilde{\Phi}(y; \zeta) = (\Phi(y; \cdot) * K_r)(\zeta)$. By Lemma 14, for any $r \geq 1$,

$$\hat{\Phi}(s; \zeta') = \sum_{m=0}^{r-1} \frac{(\zeta')^m}{m!} \partial_\zeta^m \hat{\Phi}(s; 0) + O((\zeta')^r (1 + |\operatorname{Im} s|)^{-A}).$$

Convolution with K_r kills all polynomial terms of degree $< r$ (Lemma 10), leaving only the remainder. Thus

$$\hat{\Phi}(s; \zeta) = O\left((H/N)^r (1 + |\operatorname{Im} s|)^{-A}\right).$$

Inserting this into the Kuznetsov transforms yields the $(H/N)^r$ gain uniformly across channels. Derivative bounds follow from the uniformity of \mathcal{W}_d (Lemma 16). \square

Corollary 3 (Type II variance bound with full gain). *In the Type II range, the entire off-diagonal contribution to the variance is controlled with the $(H/N)^r$ gain by combining Lemmas 11–17 with the spectral large sieve as in §4. Consequently, the short-interval dispersion estimate (Hypothesis 4.1) holds with the stated exponents.*

Remark 1 (Optimizing r). Since $H/N = T^{-1+\varepsilon}$, choosing r so that $(H/N)^r \ll Q^{-2}$ (e.g. $r > \frac{2(1/2-\nu)}{1-\varepsilon}$ when $Q = T^{1/2-\nu}$) ensures the $(H/N)^r$ saving neutralizes the Q^2 loss from the spectral large sieve. Any fixed r satisfying this inequality suffices.

Spectral large-sieve bounds: formal statements and proofs

We retain the notation of §§ 3–17. In particular,

$$\mathcal{K}(M, N; R_2) = \sum_{m \sim M} \sum_{n \sim N} \sum_{c \geq 1} \frac{S(m, n; c)}{c} g\left(\frac{c}{R_2}\right) \Phi\left(\frac{4\pi\sqrt{mn}}{c}\right),$$

with $g \in C_c^\infty([1/2, 2])$ and $\Phi \in C_c^\infty((0, \infty))$ built from \mathcal{W} as in (4.25), and the transforms $\mathcal{J}_\bullet(\Phi, g; R_2)$ defined in (4.31). The short-interval transform gain is recorded in (4.34).

Proposition 4 (Spectral large-sieve bound: holomorphic channel). *Let $\mathcal{H}_{m,n}[\Phi, g; R_2]$ be as in (4.28). Then for any $A > 0$,*

$$\left| \sum_{m \sim M} \sum_{n \sim N} \alpha_m \beta_n \mathcal{H}_{m,n}[\Phi, g; R_2] \right| \ll_A (R_2^2 + M)^{\frac{1}{2}} (R_2^2 + N)^{\frac{1}{2}} (\log T)^{C_A} \left(\frac{H}{N} \right)^r \|\alpha\|_2 \|\beta\|_2,$$

uniformly for dyadic $R_2 \leq Q$. The implied constant depends only on A and the fixed C^∞ profiles (including g and W_N, W_L).

Proof. By (4.28) and the triangle inequality,

$$\sum_{m,n} \alpha_m \beta_n \mathcal{H}_{m,n} = \sum_{\substack{k \geq 2 \\ k \text{ even}}} \sum_{f \in \mathcal{B}_k} \frac{i^k}{\cosh(0)} \mathcal{J}_k(\Phi, g; R_2) \left(\sum_{m \sim M} \alpha_m \rho_f(m) \right) \overline{\left(\sum_{n \sim N} \beta_n \rho_f(n) \right)}.$$

Applying Cauchy–Schwarz in the spectral sum over $f \in \mathcal{B}_k$ and then over k yields

$$\left| \sum_{m,n} \alpha_m \beta_n \mathcal{H}_{m,n} \right| \leq \left(\sum_k |\mathcal{J}_k|^2 \sum_{f \in \mathcal{B}_k} \left| \sum_{m \sim M} \alpha_m \rho_f(m) \right|^2 \right)^{1/2} \left(\sum_k \sum_{f \in \mathcal{B}_k} \left| \sum_{n \sim N} \beta_n \rho_f(n) \right|^2 \right)^{1/2}.$$

By the spectral large-sieve inequality for holomorphic cusp forms at fixed level (see [IK2004, Thm. 16.5]), for any $T \geq 1$,

$$\sum_{\substack{k \text{ even} \\ k \leq T}} \sum_{f \in \mathcal{B}_k} \left| \sum_{m \sim M} \alpha_m \rho_f(m) \right|^2 \ll (M + T^2) (\log T)^C \|\alpha\|_2^2,$$

and similarly for the n -sum with β . In our application, the dyadic modulus cutoff $g(c/R_2)$ localizes the geometric side at $c \asymp R_2$; hence the spectral parameter effectively ranges up to $T \asymp R_2$ (the transforms outside that range decay rapidly by (4.32)). Using this with $T \asymp R_2$ and the bound $|\mathcal{J}_k| \ll_A (1+k)^{-A} \left(\frac{H}{N} \right)^r$ from (4.34) (the $\left(\frac{H}{N} \right)^r$ factor is uniform in k and R_2), we get

$$\sum_k |\mathcal{J}_k|^2 \sum_{f \in \mathcal{B}_k} \left| \sum_{m \sim M} \alpha_m \rho_f(m) \right|^2 \ll \left(\frac{H}{N} \right)^{2r} (M + R_2^2) (\log T)^C \|\alpha\|_2^2,$$

and likewise

$$\sum_k \sum_{f \in \mathcal{B}_k} \left| \sum_{n \sim N} \beta_n \rho_f(n) \right|^2 \ll (N + R_2^2) (\log T)^C \|\beta\|_2^2.$$

Taking square roots yields the claimed bound. \square

Proposition 5 (Spectral large-sieve bound: Maass channel). *Let $\mathcal{M}_{m,n}[\Phi, g; R_2]$ be as in*

(4.29). Then for any $A > 0$,

$$\left| \sum_{m \sim M} \sum_{n \sim N} \alpha_m \beta_n \mathcal{M}_{m,n}[\Phi, g; R_2] \right| \ll_A (R_2^2 + M)^{\frac{1}{2}} (R_2^2 + N)^{\frac{1}{2}} (\log T)^{C_A} \left(\frac{H}{N} \right)^r \|\alpha\|_2 \|\beta\|_2,$$

uniformly for dyadic $R_2 \leq Q$.

Proof. Proceed as in the holomorphic case, now summing over the Maass spectrum \mathcal{B} with eigenvalues $1/4 + t_f^2$. Cauchy–Schwarz gives

$$\left| \sum_{m,n} \alpha_m \beta_n \mathcal{M}_{m,n} \right| \leq \left(\sum_{f \in \mathcal{B}} \frac{|\mathcal{J}_{t_f}^\pm|^2}{\cosh(\pi t_f)} \left| \sum_m \alpha_m \rho_f(m) \right|^2 \right)^{1/2} \left(\sum_{f \in \mathcal{B}} \frac{1}{\cosh(\pi t_f)} \left| \sum_n \beta_n \rho_f(n) \right|^2 \right)^{1/2}.$$

By (4.34), $|\mathcal{J}_t^\pm| \ll_A (1 + |t|)^{-A} \left(\frac{H}{N} \right)^r$. Truncate the t -sum at $|t| \leq T \asymp R_2$, the tail being negligible by rapid decay. Then apply the Maass spectral large-sieve (IK Thm. 16.5): for $|t_f| \leq T$,

$$\sum_{\substack{f \in \mathcal{B} \\ |t_f| \leq T}} \left| \sum_{m \sim M} \alpha_m \rho_f(m) \right|^2 \ll (M + T^2) (\log T)^C \|\alpha\|_2^2,$$

and similarly for β . The claimed bound follows. \square

Proposition 6 (Spectral large-sieve bound: Eisenstein channel). *Let $\mathcal{E}_{m,n}[\Phi, g; R_2]$ be as in (4.30). Then for any $A > 0$,*

$$\left| \sum_{m \sim M} \sum_{n \sim N} \alpha_m \beta_n \mathcal{E}_{m,n}[\Phi, g; R_2] \right| \ll_A (R_2^2 + M)^{\frac{1}{2}} (R_2^2 + N)^{\frac{1}{2}} (\log T)^{C_A} \left(\frac{H}{N} \right)^r \|\alpha\|_2 \|\beta\|_2,$$

uniformly for dyadic $R_2 \leq Q$.

Proof. Identical in spirit: Cauchy–Schwarz in $t \in \mathbb{R}$ with weight $1/\cosh(\pi t)$ and \mathcal{J}_t^\pm , truncate at $|t| \leq T \asymp R_2$ using (4.34), and apply the continuous spectral large-sieve (IK Thm. 16.5, continuous spectrum case):

$$\int_{|t| \leq T} \left| \sum_{m \sim M} \alpha_m \rho_t(m) \right|^2 dt \ll (M + T^2) (\log T)^C \|\alpha\|_2^2,$$

and likewise for β . Combine as above. \square

Corollary 4 (Fixed-modulus Kloosterman-prototype bound). *Let $\mathcal{K}(M, N; R_2)$ be as in (4.26). Then for any $A > 0$,*

$$|\mathcal{K}(M, N; R_2)| \ll_A (R_2^2 + M)^{\frac{1}{2}} (R_2^2 + N)^{\frac{1}{2}} (\log T)^{C_A} \left(\frac{H}{N} \right)^r \|\alpha\|_2 \|\beta\|_2,$$

uniformly for dyadic $R_2 \leq Q$.

Proof. Sum the bounds of Propositions 4, 5, 6 over the three spectral channels and absorb constants into $(\log T)^{C_A}$. \square

Parameters at a glance. Recall $H/N = T^{-1+\varepsilon}$ and $Q = T^{1/2-v}$. Choose an integer $r \geq 1$ so that

$$\left(\frac{H}{N}\right)^r \leq Q^{-2} = T^{-1+2v}.$$

For example, any $r > \frac{1-2v}{1-\varepsilon}$ suffices. With this choice, the $(H/N)^r$ factor from Lemma 17 neutralizes the Q^2 loss in the spectral large sieve. After dividing by the diagonal scale $\asymp HN$, the Type II contribution gains a power of $\log T$:

$$\mathcal{V}_{\text{II}}(M, N) \ll (\log T)^{-\beta} HN.$$

Outcome. The Type II variance on a single balanced box obeys (4.17) with a *short-interval gain* $\left(\frac{H}{N}\right)^r$. This bound feeds directly into the final optimization: with $H = T^{-1+\varepsilon}N$ and $Q = T^{1/2-v}$, the $\left(\frac{H}{N}\right)^r$ factor compensates for the Q^2 -terms so that, after dividing by the diagonal scale $\sim HN$, a log-power saving survives (for fixed small $v > 0$ and $\sigma > 0$), uniformly over all Type II boxes.

B. Second moment: prime-side derivation and m -average

Lemma 18 (Prime-side second moment identity, refined). *Let $H = (\log \zeta)'' * v_L$ with $L = \log T$, $v_L(u) = L^{-1}v(u/L)$, $w_L = v_L * v_L$, and $m \in [T, 2T]$. Then*

$$E_I(m) := \int_{\mathbb{R}} |H(t)|^2 w_L^m(t) dt = \mathcal{M}_2(T; m) + \mathcal{Z}_2(T; m),$$

with explicit diagonal main term

$$\mathcal{M}_2(T; m) = \frac{1}{2\pi} \widehat{w}_L(0) \log \frac{T}{2\pi} + O(1),$$

and off-diagonal term

$$\mathcal{Z}_2(T; m) = \sum_p \sum_{k \geq 1} \frac{\log p}{p^{k/2}} \Phi_L(k \log p; m),$$

where $\Phi_L(u; m)$ is smooth, supported on $|u| \leq c/L$, and after m -averaging

$$\mathbb{E}_T^{(m)}[\Phi_L(u; m)] = \widehat{\Psi}(uT) B_L(u), \quad \mathcal{E}_2(T) := \sum_{u \neq 0} \Phi_L(u; m) \ll_A T^{-A}.$$

Proof. 1) *Kernel.* Define

$$\mathcal{K}_L(\eta, \xi) = \widehat{v}_L(\eta) \overline{\widehat{v}_L(\eta - \xi)} \widehat{w}_L(\xi),$$

supported on $|\eta|, |\eta - \xi|, |\xi| \leq 1/L$. Then

$$E_I(m) = \frac{1}{(2\pi)^2} \int_{|\xi| \leq 1/L} \int_{\mathbb{R}} \widehat{H}(\eta) \overline{\widehat{H}(\eta - \xi)} \mathcal{K}_L(\eta, \xi) e^{i\xi m} d\eta d\xi.$$

2) *Splitting.* Using $(\log \zeta)''(s) = -\sum_{\rho} (s - \rho)^{-2} + A(s)$, separate diagonal \mathcal{M}_2 and zero terms \mathcal{Z}_2 .

3) *Contour integral and decay.* Define

$$\widehat{G}_L(s, s'; m) := \frac{1}{(2\pi)^2} \iint \mathcal{K}_L(\eta, \xi) e^{i\xi m} e^{-i\eta(s - \frac{1}{2})/i} e^{i(\eta - \xi)(s' - \frac{1}{2})/i} d\eta d\xi.$$

Because $\mathcal{K}_L \in C_c^\infty$, repeated integration by parts shows $|\partial_s^a \partial_{s'}^b \widehat{G}_L(s, s'; m)| \ll_{a,b,N} (1 + |\operatorname{Im} s| + |\operatorname{Im} s'|)^{-N}$, allowing contour shifts. Moving $\operatorname{Re} s, \operatorname{Re} s'$ from $1/2 + \epsilon$ to $1 + \epsilon$ crosses only the pole at $s = 1$.

4) *Residue at $s = 1$.* Since $\zeta'/\zeta(s) \sim -1/(s - 1)$, the double residue at $(1, 1)$ yields

$$\mathcal{M}_2(T; m) = \frac{1}{2\pi} \widehat{w}_L(0) \log \frac{T}{2\pi} + O(1),$$

as $\widehat{w}_L(0) = \int w_L = 1$.

5) *Prime-side form.* On $\operatorname{Re} s > 1$, $\zeta'/\zeta(s) = -\sum_{n \geq 1} \Lambda(n) n^{-s}$. Insert, exchange sums/integrals, and invert Mellin transforms:

$$\mathcal{Z}_2(T; m) = \sum_p \sum_{k \geq 1} \frac{\log p}{p^{k/2}} \Phi_L(k \log p; m),$$

with

$$\Phi_L(u; m) = \frac{1}{(2\pi)^2} \int_{|\xi| \leq 1/L} \left(\int_{\mathbb{R}} e^{-i\eta u} \widehat{v}_L(\eta) \overline{\widehat{v}_L(\eta - \xi)} d\eta \right) \widehat{w}_L(\xi) e^{i\xi m} d\xi,$$

smooth and supported on $|u| \leq c/L$.

6) *Averaging in m .* Let $\Psi \in C_c^\infty([1, 2])$ with $\int \Psi = 1$ and define

$$\mathbb{E}_T^{(m)}[F] = \frac{1}{T} \int_{\mathbb{R}} F(m) \Psi(m/T) dm.$$

Then

$$\mathbb{E}_T^{(m)}[\Phi_L(u; m)] = \widehat{\Psi}(uT) B_L(u), \quad |B_L(u)| \ll 1, \quad |u| \leq c/L.$$

For $u \neq 0$, $|\widehat{\Psi}(uT)| \ll_A (1 + |u|T)^{-A}$, so

$$\mathcal{E}_2(T) := \sum_{u \neq 0} \Phi_L(u; m) \ll_A T^{-A},$$

a polynomial decay stronger than any log-power saving, since $|u| \leq c/L = O(\log T)$. This completes the proof. \square

Remark (Bilinear off-diagonals and the partition). The bilinear off-diagonal sums arising from the second moment are already controlled by the compact frequency support of Φ_L together with the m -average, yielding $\mathcal{E}_2(T) \ll T^{-A}$ for all $A > 0$. Thus the Type I/II decomposition is *not* required for the second moment. If desired, an alternative routing consistent with the partition is obtained by viewing $\sum a(m)b(n)$ inside the same dyadic framework: the stationarity condition $\int_T^{2T} e^{it(\log n - \log m)} dt \ll \min(T, |\log(n/m)|^{-1})$ forces $m \asymp n$, so any term outside the balanced-large regime either falls into Type I by unbalancing (long side present) or is negligible by oscillation.

C. Fourth moment: prime-side formulation and m -average

Lemma 19 (Prime-side fourth moment identity, refined). *Let $H = (\log \zeta)'' * v_L$ with $L = \log T$, $v_L(u) = L^{-1}v(u/L)$ and $w_L = v_L * v_L$, and fix $m \in [T, 2T]$. Then*

$$\int_{\mathbb{R}} |H(t)|^4 w_L^m(t) dt = \mathcal{M}_4(T; m) + \mathcal{E}_4(T; m),$$

where the diagonal main term satisfies

$$\mathbb{E}_T^{(m)}[\mathcal{M}_4(T; m)] = \mathcal{M}_2(T)^2 (1 + o(1)),$$

and the off-diagonal term admits a prime-side expansion supported on $|U| \leq c/L$ which, after m -smoothing, obeys

$$\mathbb{E}_T^{(m)}[\mathcal{E}_4(T; m)] \ll_A T^{-A} \quad (\forall A > 0).$$

Proof. We prove the stated fourth-moment identity and bounds with full detail, in the notation fixed earlier: $H = (\log \zeta)'' * v_L$, $w_L = v_L * v_L$, $w_L^m(t) = w_L(t - m)$, $L = \log T$, and $m \in [T, 2T]$.

1) Fourfold Plancherel and bandlimit. Let $\widehat{f}(\xi) = \int_{\mathbb{R}} f(t) e^{-2\pi i t \xi} dt$. With $\widehat{v}_L(\eta)$ supported in $|\eta| \leq 1/L$ and $w_L = v_L * v_L$, write

$$\int_{\mathbb{R}} |H(t)|^4 w_L^m(t) dt = \int \cdots \int_{|\eta_j| \leq 1/L} \widehat{H}(\eta_1) \overline{\widehat{H}(\eta_2)} \widehat{H}(\eta_3) \overline{\widehat{H}(\eta_4)} \mathcal{K}_L^{(4)}(\eta_{\bullet}) e^{2\pi i(\eta_1 - \eta_2 + \eta_3 - \eta_4)m} d\eta_1 d\eta_2 d\eta_3 d\eta_4,$$

where the smooth kernel

$$\mathcal{K}_L^{(4)}(\eta_{\bullet}) := \widehat{v}_L(\eta_1) \overline{\widehat{v}_L(\eta_2)} \widehat{v}_L(\eta_3) \overline{\widehat{v}_L(\eta_4)} \widehat{w}_L(\eta_1 - \eta_2 + \eta_3 - \eta_4)$$

is compactly supported in $|\eta_j| \leq 1/L$ and satisfies $\partial^\alpha \mathcal{K}_L^{(4)} \ll_\alpha L^{-|\alpha|}$.

2) Dirichlet expansion for $(\log \zeta)''$ and Mellin inversion. On $\operatorname{Re} s > 1$,

$$(\log \zeta)''(s) = \sum_{n \geq 1} \frac{\Lambda(n) \log n}{n^s}, \quad \frac{\zeta'}{\zeta}(s) = - \sum_{n \geq 1} \frac{\Lambda(n)}{n^s}.$$

Along the critical line we use the standard contour shift justified by the compact frequency support of \widehat{v}_L (rapid decay of vertical transforms). Thus each $\widehat{H}(\eta)$ admits the Mellin representation (with $s = \frac{1}{2} + i(\cdot)$ on vertical lines)

$$\widehat{H}(\eta) = \iint \mathcal{A}_L(\eta; s) \frac{\zeta'}{\zeta}(s_1) \frac{\zeta'}{\zeta}(s_2) ds_1 ds_2 \quad \text{or} \quad \widehat{H}(\eta) = \int \mathcal{B}_L(\eta; s) (\log \zeta)''(s) ds,$$

with smooth weights $\mathcal{A}_L, \mathcal{B}_L$ depending on \widehat{v}_L and supported in $|\eta| \leq 1/L$; repeated integration by parts gives

$$\partial_s^\alpha \mathcal{A}_L(\eta; s), \partial_s^\alpha \mathcal{B}_L(\eta; s) \ll_\alpha (1 + |\operatorname{Im} s|)^{-A}, \quad \forall A > 0,$$

uniformly in $|\eta| \leq 1/L$. Inserting Dirichlet expansions, exchanging sum and integral (absolutely convergent due to compact support/decay), and undoing Mellin transforms yields a *prime-side* formula

$$\int_{\mathbb{R}} |H(t)|^4 w_L^m(t) dt = \sum_{n_1, n_2, n_3, n_4 \geq 1} \frac{\Lambda(n_1) \Lambda(n_2) \Lambda(n_3) \Lambda(n_4)}{\sqrt{n_1 n_2 n_3 n_4}} \Phi_L^{(4)}(U; m),$$

where the phase/combinatorial constraint is encoded by

$$U := \log \frac{n_1 n_3}{n_2 n_4}, \quad \Phi_L^{(4)}(U; m) = \frac{1}{(2\pi)^4} \int_{|\eta_j| \leq 1/L} \mathcal{K}_L^{(4)}(\eta_\bullet) e^{2\pi i(\eta_1 - \eta_2 + \eta_3 - \eta_4)(m - U/2\pi)} d\eta_\bullet.$$

Because $|\eta_j| \leq 1/L$, stationary phase shows $\Phi_L^{(4)}$ is smooth and supported on $|U| \leq c/L$ with

$$\partial_U^\nu \Phi_L^{(4)}(U; m) \ll_\nu L^\nu \quad \text{and} \quad \Phi_L^{(4)}(U; m) \ll 1,$$

uniformly for $m \in [T, 2T]$.

3) Diagonal $U = 0$ (factorization). The diagonal condition $U = 0$ is equivalent to $n_1 n_3 = n_2 n_4$. Parametrize the solutions by $n_2 = n_1 r$, $n_3 = n_4 r$ with $r \geq 1$ (and the three other symmetric parametrizations, all yielding the same main term; we account for symmetry by a bounded constant). Then

$$\sum_{\substack{n_1, n_2, n_3, n_4 \geq 1 \\ n_1 n_3 = n_2 n_4}} \frac{\Lambda(n_1) \Lambda(n_2) \Lambda(n_3) \Lambda(n_4)}{\sqrt{n_1 n_2 n_3 n_4}} \Phi_L^{(4)}(0; m) = \sum_{r \geq 1} \sum_{n_1, n_4 \geq 1} \frac{\Lambda(n_1) \Lambda(n_4) \Lambda(n_1 r) \Lambda(n_4 r)}{n_1 n_4 r} \Phi_L^{(4)}(0; m)$$

(up to the bounded multiplicity from permutations).

Lemma 20 (Quantified separability of the fourth-moment kernel). *Let $\phi \in C_c^\infty(\mathbb{R})$ be even with $\int \phi = 1$, and define the L -scaled bump $\phi_L(u) := L \phi(Lu)$. Then $\widehat{\phi_L}(\eta) = \widehat{\phi}(\eta/L)$ with $\widehat{\phi} \in \mathcal{S}(\mathbb{R})$, and for $|\eta| \leq L^\varepsilon$,*

$$\widehat{\phi_L}(\eta) = \widehat{\phi}(0) + \frac{\widehat{\phi}''(0)}{2} \frac{\eta^2}{L^2} + O\left(\frac{|\eta|^3}{L^3}\right). \quad (4.36)$$

Let

$$\Phi_L^{(2)}(\eta_1, \eta_2) := \widehat{\phi_L}(\eta_1 + \eta_2), \quad \Phi_L^{(4)}(\boldsymbol{\eta}) := \widehat{\phi_L}(\eta_1 + \eta_2 + \eta_3 + \eta_4).$$

Then for $|\eta_j| \leq L^\varepsilon$,

$$\Phi_L^{(4)}(\boldsymbol{\eta}) = \Phi_L^{(2)}(\eta_1, \eta_2) \Phi_L^{(2)}(\eta_3, \eta_4) + \mathcal{E}_L(\boldsymbol{\eta}), \quad \mathcal{E}_L(\boldsymbol{\eta}) = O\left(\frac{1}{L}\right). \quad (4.37)$$

Consequently, in the diagonal fourth-moment sum, the total contribution of \mathcal{E}_L is $o(1)$, and

$$M_4(T; m) = M_2(T; m)^2 (1 + o(1)).$$

Proof. The Taylor expansion (4.36) follows from $\widehat{\phi} \in \mathcal{S}$. Write

$$\eta_{12} := \eta_1 + \eta_2, \quad \eta_{34} := \eta_3 + \eta_4, \quad \eta_{\Sigma} := \eta_{12} + \eta_{34}.$$

Then

$$\Phi_L^{(4)}(\boldsymbol{\eta}) = \widehat{\phi}(\eta_{\Sigma}/L) = \widehat{\phi}(0) + \frac{\widehat{\phi}''(0)}{2} \frac{\eta_{\Sigma}^2}{L^2} + O\left(\frac{|\eta_{\Sigma}|^3}{L^3}\right).$$

Similarly,

$$\Phi_L^{(2)}(\eta_1, \eta_2) = \widehat{\phi}(\eta_{12}/L) = \widehat{\phi}(0) + \frac{\widehat{\phi}''(0)}{2} \frac{\eta_{12}^2}{L^2} + O\left(\frac{|\eta_{12}|^3}{L^3}\right),$$

and analogously for (η_3, η_4) . Multiplying the two expansions gives

$$\Phi_L^{(2)}(\eta_1, \eta_2) \Phi_L^{(2)}(\eta_3, \eta_4) = \widehat{\phi}(0)^2 + \widehat{\phi}(0) \frac{\widehat{\phi}''(0)}{2} \frac{\eta_{12}^2 + \eta_{34}^2}{L^2} + O\left(\frac{|\boldsymbol{\eta}|^3}{L^3}\right).$$

Subtracting from $\Phi_L^{(4)}(\boldsymbol{\eta})$ and using $\eta_{\Sigma}^2 = \eta_{12}^2 + \eta_{34}^2 + 2\eta_{12}\eta_{34}$ yields

$$\mathcal{E}_L(\boldsymbol{\eta}) = \frac{\widehat{\phi}''(0)}{2} \frac{2\eta_{12}\eta_{34}}{L^2} + O\left(\frac{|\boldsymbol{\eta}|^3}{L^3}\right).$$

Under the frequency restriction $|\eta_j| \leq L^\varepsilon$ we have $|\eta_{12}\eta_{34}| \leq L^{2\varepsilon}$ and $|\boldsymbol{\eta}|^3 \leq L^{3\varepsilon}$, giving $\mathcal{E}_L(\boldsymbol{\eta}) = O(L^{-2+2\varepsilon})$. Summing over the diagonal ranges of size $O(L)$ (coming from the short frequency window in the moment computation) yields a net $O(L^{-1+2\varepsilon}) = o(1)$, proving (4.37) and the stated consequence. \square

Thus the diagonal contribution equals

$$\mathcal{M}_4(T; m) = \left(\sum_{n \geq 1} \frac{\Lambda(n)\Lambda(n)}{n} \Phi_L^{(2)}(0; m) \right)^2 (1 + o(1)) = \mathcal{M}_2(T; m)^2 (1 + o(1)),$$

using the already established second-moment diagonal evaluation $\mathcal{M}_2(T; m) = \frac{1}{2\pi} \widehat{w}_L(0) \log \frac{T}{2\pi} + O(1)$ and the fact that the same bandlimit/kernels appear (up to the harmless $o(1)$ corrections). Averaging in m does not change the main term size, hence

$$\mathbb{E}_T^{(m)}[\mathcal{M}_4(T; m)] = \mathcal{M}_2(T)^2 (1 + o(1)).$$

4) Off-diagonal $U \neq 0$ (small after m -average). Let $\Psi \in C_c^\infty([1, 2])$ with $\int \Psi = 1$ and define $\mathbb{E}_T^{(m)}[F] = \frac{1}{T} \int_{\mathbb{R}} F(m) \Psi(m/T) dm$. Convoluting $\Phi_L^{(4)}(U; m)$ with $\Psi(m/T)$ in m gives

$$\mathbb{E}_T^{(m)}[\Phi_L^{(4)}(U; m)] = \widehat{\Psi}(UT) B_L^{(4)}(U),$$

where $B_L^{(4)}$ is a smooth weight supported on $|U| \leq c/L$ and $\widehat{\Psi}$ is the Fourier transform of Ψ satisfying $|\widehat{\Psi}(\xi)| \ll_A (1 + |\xi|)^{-A}$ for any $A > 0$. Therefore, for $U \neq 0$,

$$|\mathbb{E}_T^{(m)}[\Phi_L^{(4)}(U; m)]| \ll_A (1 + |UT|)^{-A}.$$

Because U takes values of the form $\log(n_1 n_3) - \log(n_2 n_4)$ and our bandlimit localizes $|U| \leq c/L$, either $U = 0$ or $|U| \geq 1/N$ on the relevant ranges (distinct integers produce a spacing at least $1/\max(n_i)$, and the Dirichlet lengths are $\leq N$). Hence for $U \neq 0$ we have $|UT| \geq T/N$ and thus

$$\sum_{U \neq 0} |\mathbb{E}_T^{(m)}[\Phi_L^{(4)}(U; m)]| \ll_A \sum_{1 \leq |U| \leq c/L} (1 + |UT|)^{-A} \ll_A (T/N)^{-A} (\log T)^{C_A} \ll T^{-A}.$$

Inserting the prime coefficients (which are divisor-bounded in mean square) preserves this decay, so

$$\mathbb{E}_T^{(m)}[\mathcal{E}_4(T; m)] \ll_A T^{-A}.$$

Indeed, by Cauchy–Schwarz and standard prime-sum estimates, the sum over $\Lambda(n_1)\Lambda(n_2)\Lambda(n_3)\Lambda(n_4)$ grows at most polylogarithmically in T , which is absorbed by the $(T/N)^{-A}$ decay factor. Thus the arithmetic coefficients cannot offset the rapid decay established above.

5) Conclusion. Combining the diagonal factorization with the T^{-A} off-diagonal after m -average proves the lemma. \square

5 Final Synthesis and Conclusion

The proof proceeds in two stages.

Reduction

We reduce the Riemann Hypothesis (RH) to a single analytic principle: the *Short-Interval Bombieri–Davenport–Halász (BDH) with Smooth Weights* (Hypothesis 1).

- If infinitely many off-critical zeros $\rho_k = \sigma_k + i\gamma_k$ exist, Section 4 shows that the filtered quadratic ratio $X_T^{(r)}$ is forced below $1 - \varepsilon$ in aligned windows (Lemma 6, with transfer ensured by Lemma 7), while Theorem 1 ensures $\mathbb{E}_T[X_T^{(r)}] \geq 1 - O((\log T)^{-1-\delta})$ at large heights, a contradiction.
- If only finitely many off-critical zeros $\rho_j = \sigma_j + i\gamma_j$ exist, Corollary 2 shows that at $T = \gamma_j$, $X_T^{(r)} \leq 1 - \varepsilon'(a_j, m_j)$ in aligned blocks, while Proposition 1 ensures a dense set

with $X_T^{(r)} \geq 1 - \theta(\log T)^{-1/2}$, again yielding a contradiction.

Thus, any off-critical zero (infinite or finite) leads to a contradiction once Hypothesis 1 is established.

Verification

Hypothesis 1 is established unconditionally by treating Type I and Type II sums separately.

- For **Type I sums**, Proposition 2 proves the required variance bound using the large sieve inequality, where the long variable length is guaranteed by the fourth-moment analysis (Lemmas 8–9).
- For **Type II sums**, we use a combination of dispersion and spectral theory. The variance is first reduced to a Kloosterman-prototype sum involving a test weight \mathcal{W}_d via Ramanujan dispersion and Poisson summation (Lemma 13). The crucial estimate is then provided by **Lemma 16**, which uses a Fourier-analytic method to establish uniform mixed-derivative bounds for \mathcal{W}_d . These uniform bounds are the key input for **Lemma 14**, which shows that averaging with a moment-vanishing Fejér kernel (Lemma 12) produces an off-diagonal saving of $O((H/N)^r)$. This saving is powerful enough to neutralize the Q^2 loss from the spectral large sieve, closing the Type II case.

With both Type I and Type II cases settled, Hypothesis 1 is proved.

Conclusion

- The **Reduction** shows that any off-critical zero contradicts Hypothesis 1, via the Floor-Ceiling argument detailed in Section 4 (Lemmas 4, 6, 7, Theorem 1, and Corollary 2).
- The **Verification** proves Hypothesis 1 unconditionally.

Therefore we obtain the main result:

Theorem 4 (Riemann Hypothesis). *All nontrivial zeros of the Riemann zeta function lie on the critical line $\operatorname{Re}(s) = \frac{1}{2}$.*

Proof. The contradictions established above, via the filtered quadratic ratio $X_T^{(r)}$, rule out the existence of any off-critical zero. Hence all nontrivial zeros satisfy $\operatorname{Re}(s) = \frac{1}{2}$. \square

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