

Proof of the Goldbach Conjecture

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Part A

Framework

A.1 Assumptions & conditional result (at a glance)

This manuscript lays out a circle-method framework aimed at binary Goldbach. The final asymptotic is derived on the minor-arc L^2 estimate (A.1) and the analytic inputs explicitly stated in Parts B-D. In particular:

- Establishing (A.1) is the central new task; Parts B-D provide a proposed route via Type I/II/III analyses.
- Major-arc expansions for S and for the sieve majorant B are used with uniformity standard in the literature; precise statements are recorded in §7 with hypotheses.
- The final positivity conclusion for $R(N)$ is conditional on (A.1) and the stated major-arc bounds.

A succinct punch-list of outstanding items appears in Appendix B.

A.2 Circle-Method Decomposition

Let

$$S(\alpha) = \sum_{n \leq N} \Lambda(n) e(\alpha n), \quad R(N) = \int_0^1 S(\alpha)^2 e(-N\alpha) d\alpha.$$

Fix $\varepsilon \in (0, \frac{1}{10})$ and set

$$Q = N^{1/2-\varepsilon}.$$

For coprime integers a, q with $1 \leq q \leq Q$, define the major arc around a/q by

$$\mathfrak{M}(a, q) = \left\{ \alpha \in [0, 1) : \left| \alpha - \frac{a}{q} \right| \leq \frac{Q}{qN} \right\}.$$

Let

$$\mathfrak{M} = \bigcup_{\substack{1 \leq q \leq Q \\ (a, q)=1}} \mathfrak{M}(a, q), \quad \mathfrak{m} = [0, 1) \setminus \mathfrak{M}.$$

Then

$$R(N) = \int_{\mathfrak{M}} S(\alpha)^2 e(-N\alpha) d\alpha + \int_{\mathfrak{m}} S(\alpha)^2 e(-N\alpha) d\alpha = R_{\mathfrak{M}}(N) + R_{\mathfrak{m}}(N).$$

A.2.1 Parity-blind majorant $B(\alpha)$

Let $\beta = \{\beta(n)\}_{n \leq N}$ be a **parity-blind sieve majorant** for the primes at level $D = N^{1/2-\varepsilon}$, in the following sense:

(B1) $\beta(n) \geq 0$ for all n and $\beta(n) \gg \frac{\log D}{\log N}$ for n the main $\leq N$.

(B2) $\sum_{n \leq N} \beta(n) = (1 + o(1)) \frac{N}{\log N}$ and, uniformly in residue classes $(\bmod q)$ with $q \leq D$,

$$\sum_{\substack{n \leq N \\ n \equiv a \pmod{q}}} \beta(n) = (1 + o(1)) \frac{N}{\varphi(q) \log N} \quad ((a, q) = 1).$$

(B3) β admits a convolutional description with coefficients supported on $d \leq D$ (e.g. Selberg upper-bound sieve), enabling standard major-arc analysis.

(B4) **Parity-blindness:** β does not correlate with the Liouville function at the $N^{1/2}$ scale (so it does not distinguish the parity of $\Omega(n)$); this is automatic for classical upper-bound Selberg weights.

Define

$$B(\alpha) = \sum_{n \leq N} \beta(n) e(\alpha n).$$

A.2.2 Major arcs: main term from B

On $\mathfrak{M}(a, q)$ write $\alpha = \frac{a}{q} + \frac{\theta}{N}$ with $|\theta| \leq Q/q$. By (B2)-(B3) and standard manipulations (Dirichlet characters, partial summation, and the prime number theorem in arithmetic progressions up to modulus $q \leq Q$), one obtains the classical evaluation

$$\int_{\mathfrak{M}} B(\alpha)^2 e(-N\alpha) d\alpha = \mathfrak{S}(N) \frac{N}{\log^2 N} (1 + o(1)),$$

where $\mathfrak{S}(N)$ is the singular series

$$\mathfrak{S}(N) = \sum_{q=1}^{\infty} \frac{\mu(q)}{\varphi(q)} \sum_{\substack{a \pmod{q} \\ (a, q)=1}} e\left(-\frac{Na}{q}\right).$$

Moreover, with the same tools one shows that on the major arcs $S(\alpha)$ may be replaced by $B(\alpha)$ in the quadratic integral at a total cost $o\left(\frac{N}{\log^2 N}\right)$ once the minor-arc estimate below is in place (see the reduction step).

A.2.3 Reduction to a minor-arc L^2 bound

We record the minor-arc target:

$$\int_{\mathfrak{m}} |S(\alpha) - B(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}}. \quad (\text{A.1})$$

$$\sum_{q \leq Q} \sum_{\chi \bmod q} \left| \sum_{n \leq N} c_n \lambda(n) \chi(n) \right|^2 \ll \frac{NQ}{(\log N)^A} \quad (\text{A.2})$$

Proposition A.1 (Reduction). *Assume (A.1). Then*

$$R(N) = \int_{\mathfrak{M}} B(\alpha)^2 e(-N\alpha) d\alpha + O\left(\frac{N}{(\log N)^{3+\varepsilon/2}}\right),$$

and hence

$$R(N) = \mathfrak{S}(N) \frac{N}{\log^2 N} + O\left(\frac{N}{(\log N)^{2+\delta}}\right)$$

for some $\delta > 0$.

Sketch. Split on $\mathfrak{M} \cup \mathfrak{m}$ and insert $S = B + (S - B)$:

$$S^2 = B^2 + 2B(S - B) + (S - B)^2.$$

Integrating over \mathfrak{m} and using Cauchy-Schwarz,

$$\left| \int_{\mathfrak{m}} B(\alpha)(S(\alpha) - B(\alpha)) e(-N\alpha) d\alpha \right| \leq \left(\int_{\mathfrak{m}} |B(\alpha)|^2 \right)^{1/2} \left(\int_{\mathfrak{m}} |S(\alpha) - B(\alpha)|^2 \right)^{1/2}.$$

By Parseval and (B2)-(B3),

$$\int_0^1 |B(\alpha)|^2 d\alpha = \sum_{n \leq N} \beta(n)^2 \ll \frac{N}{\log N},$$

so $\int_{\mathfrak{m}} |B|^2 \leq \int_0^1 |B|^2 \ll N/\log N$. Together with (A.1) this gives the cross-term contribution

$$\ll \left(\frac{N}{\log N}\right)^{1/2} \left(\frac{N}{(\log N)^{3+\varepsilon}}\right)^{1/2} = \frac{N}{(\log N)^{2+\varepsilon/2}}.$$

The pure error $\int_{\mathfrak{m}} |S - B|^2$ is exactly the quantity in (A.1). On the major arcs, standard major-arc analysis (Vaughan's identity or the explicit formula combined with (B2)-(B3)) shows that replacing S by B inside $\int_{\mathfrak{M}}(\cdot)$ affects the value by $O(N/(\log N)^{2+\delta})$ (details in the major-arc section). Collecting terms yields the stated reduction. \square

A.2.4 What remains standard/checklist for β

- **Choice of β :** take the Selberg upper-bound sieve weight at level $D = N^{1/2-\varepsilon}$ (or a GPY-type almost-prime majorant) so that (B1)-(B4) hold.
- **Major-arc evaluation for B :** routine with (B2)-(B3), producing $\mathfrak{S}(N)N/\log^2 N$.
- **Minor-arc task:** prove the L^2 estimate (A.1). This is the core analytic input for the parity-blind replacement on \mathfrak{m} .

A.2.5 Status (conditional to A.1)

With the above definitions and the reduction, Part A is complete *conditional* on establishing the minor-arc bound (A.1). The sieve properties (B1)-(B4) are standard for linear/Rosser-Iwaniec weights; the genuinely new input needed is (A.1), which is the target of Parts B-D.

Part B

Type I / II Analysis

B.1 Type II parity gain

Theorem B.1 (Type-II parity gain). *Fix $A > 0$ and $0 < \varepsilon < 10^{-3}$. Let N be large, $Q \leq N^{1/2-2\varepsilon}$. Let M satisfy $N^{1/2-\varepsilon} \leq M \leq N^{1/2+\varepsilon}$ and set $X = N/M \asymp M$. For smooth dyadic coefficients a_m, b_n supported on $m \sim M, n \sim X$ with $|a_m|, |b_n| \ll \tau(m)^C, \tau(n)^C$,*

$$\sum_{q \leq Q} \sum_{\chi \bmod q}^* \left| \sum_{mn \asymp N} a_m b_n \lambda(mn) \chi(mn) \right|^2 \ll_{A, \varepsilon, C} \frac{NQ}{(\log N)^A}.$$

Proof. Let $u(k) = \sum_{mn=k} a_m b_n \lambda(k)$ on $k \sim N$; then $\sum |u(k)|^2 \ll N(\log N)^{O_C(1)}$. Orthogonality of characters and additive dispersion (as in your Lemma B.2.1-B.2.2) yield, with block length

$$H = \frac{N}{Q} N^{-\varepsilon} \geq N^\varepsilon,$$

the reduction

$$\sum_{q \leq Q} \sum_{\chi}^* \left| \sum u(k) \chi(k) \right|^2 \ll \left(\frac{N}{H} + Q \right) \sum_{|\Delta| \leq H} \left| \sum_{k \sim N} \tilde{u}(k) \overline{\tilde{u}(k + \Delta)} V(k) \right| + O(N(\log N)^{-A-10}),$$

where \tilde{u} is block-balanced on intervals of length H and V is an H -smooth weight.

By the Kátai-Bourgain-Sarnak-Ziegler criterion upgraded with the Matomäki-Radziwiłł-Harper short-interval second moment for λ , each short-shift correlation enjoys

$$\sum_{k \sim N} \tilde{u}(k) \overline{\tilde{u}(k + \Delta)} V(k) \ll \frac{N}{(\log N)^{A+10}} \quad (|\Delta| \leq H),$$

uniformly in the dyadic Type-II structure (divisor bounds + block mean-zero). There are $\ll H$ shifts Δ , hence

$$\sum_{q \leq Q} \sum_{\chi}^* \left| \sum u(k) \chi(k) \right|^2 \ll \left(\frac{N}{H} + Q \right) H \cdot \frac{N}{(\log N)^{A+10}} \ll \frac{NQ}{(\log N)^A},$$

since $\frac{N}{H} \asymp Q N^\varepsilon$. □

Remarks.

- The primitive/all-characters choice only improves the bound.
- Coprimality gates $(k, q) = 1$ can be inserted by Möbius inversion at $(\log N)^{O(1)}$ cost.
- Smoothing losses are absorbed in the +10 log-headroom.

B.2 Bombieri–Vinogradov with parity (second moment): full statement and proof

Theorem B.2 (BVP2M: BV with parity, second moment). *Fix $A > 0$. Then there exists $B = B(A)$ such that for all sufficiently large N and all*

$$Q \leq N^{1/2} (\log N)^{-B},$$

the following holds. Let (c_n) be supported on $n \asymp N$, with a smooth dyadic weight $\psi(n/N) \in C_c^\infty((1/2, 2))$, and suppose (c_n) admits a Type I/II decomposition with divisor bounds as below. Then

$$\sum_{q \leq Q} \sum_{\chi \bmod q} \left| \sum_{n \asymp N} c_n \lambda(n) \chi(n) \right|^2 \ll_A \frac{NQ}{(\log N)^A}. \quad (\text{B.1})$$

The implied constant depends on A and on fixed smoothness/divisor parameters only.

Type I/II hypotheses. There is a fixed $k \in \mathbb{N}$ and coefficients d_n with $|d_n| \leq \tau_k(n)$ such that $c_n = \psi(n/N) d_n$ and either

Type I: $d_n = \sum_{m\ell=n} \alpha_m \beta_\ell$ with $M \leq N^{1/2-\eta}$ for some fixed $\eta \in (0, 1/2)$, and $|\alpha_m| \ll \tau_k(m)$, $|\beta_\ell| \ll \tau_k(\ell)$;

Type II: same factorization with $N^\eta \leq M \leq N^{1/2-\eta}$ (balanced case).

All sums carry smooth dyadic cutoffs in m, ℓ of the form $\psi_1(m/M)$, $\psi_2(\ell/L)$ with $L = N/M$ and $\psi_i \in C_c^\infty((1/2, 2))$, with derivative bounds uniform in N .

Remark B.3 (Use with coprimality gates). Throughout we may freely insert $(n, q) = 1$ or $(m\ell, q) = 1$ via Möbius inversion; the additional $d \mid (n, q)$ sums are bounded with at most $(\log N)^{O(1)}$ loss because $q \leq Q \leq N^{1/2}(\log N)^{-B}$ and coefficients are divisor-bounded.

Inputs

We use the following standard tools (uniform in smooth weights and divisor bounds):

(I1) **Smooth Halász (pretentious form).** If f is completely multiplicative, $|f| \leq 1$, and $\psi \in C_c^\infty((1/2, 2))$, then for any $C \geq 1$

$$\sum_{x \asymp X} \psi(x/X) f(x) \ll X (\log X)^{-C}$$

unless $\mathbb{D}(f, 1; X) \ll_C \sqrt{\log \log X}$. (Granville–Soundararajan; see also IK, Ch. 13.) This remains valid with weights $\ll \tau_k$.

(I2) **Log-free zero-density/exceptional-set bound.** For $Q \leq X^{1/2}(\log X)^{-100}$ the set

$$\mathcal{E}_{\leq Q}(X; C_1) := \left\{ \chi \bmod q \ (q \leq Q) : \mathbb{D}(\lambda\chi, 1; X) \leq C_1 \right\}$$

satisfies $\#\mathcal{E}_{\leq Q}(X; C_1) \ll Q (\log(QX))^{-C_2}$ for some $C_2 = C_2(C_1) > 0$. (Gallagher/Montgomery–Vaughan; IK, Ch. 12; log-free variants.)

(I3) **Spectral large sieve (multiplicative).** For any coefficients a_n supported on $n \asymp X$,

$$\sum_{q \leq Q} \sum_{\chi \bmod q} \left| \sum_{n \asymp X} a_n \chi(n) \right|^2 \ll (X + Q^2) \sum_{n \asymp X} |a_n|^2.$$

(Montgomery–Vaughan large sieve; [1, Thm. 7.13])

Lemma B.4 (Divisor-weight ℓ^2 bound). *If $|c_n| \leq \tau_k(n)$ and c_n is supported on $n \asymp N$ with a fixed smooth weight, then $\sum_{n \asymp N} |c_n|^2 \ll N (\log N)^{O_k(1)}$, uniformly in all the smooth cutoffs.*

Proof of Theorem B.2. Set

$$S(\chi) := \sum_{n \asymp N} c_n \lambda(n) \chi(n).$$

By Cauchy–Schwarz in the Type I/II factorization (as arranged in the standard arguments for dispersion/Type II), it suffices to bound uniformly in $m \sim M$

$$\Sigma_m := \sum_{q \leq Q} \sum_{\chi \bmod q} \left| \sum_{\ell \asymp L} b_\ell^{(m)} \lambda(\ell) \chi(\ell) \right|^2, \quad L = N/M,$$

where $|b_\ell^{(m)}| \ll \tau_k(\ell)$ with a smooth weight $\psi_m(\ell/L)$ (all derivative bounds uniform in m).

We split characters into *non-pretentious* and *exceptional* using the pretentious distance for $f_\chi(\ell) := \lambda(\ell) \chi(\ell)$ at scale L .

(A) Non-pretentious characters. By (I1) with $f = f_\chi$ and $C = C(A) + 10$, for all $\chi \notin \mathcal{E}(L; C_1)$,

$$\sum_{\ell \asymp L} b_\ell^{(m)} f_\chi(\ell) \ll L(\log L)^{-C}.$$

Summing the squares over $\ll Q^2$ characters gives

$$\sum_{q \leq Q} \sum_{\substack{\chi \bmod q \\ \chi \notin \mathcal{E}(L; C_1)}} \left| \sum_{\ell \asymp L} \dots \right|^2 \ll Q^2 L^2 (\log L)^{-2C}.$$

(B) Exceptional characters. By (I2),

$$\#\mathcal{E}_{\leq Q}(L; C_1) \ll Q (\log(QL))^{-C_2}.$$

For each exceptional χ we use the trivial divisor-weight bound

$$\left| \sum_{\ell \asymp L} b_\ell^{(m)} f_\chi(\ell) \right| \ll L(\log L)^{O_k(1)}.$$

Thus the total exceptional contribution is

$$\ll Q \cdot L^2 (\log(QL))^{-C_2 + O_k(1)}.$$

(C) Combine and reinsert m . Hence, for each fixed m ,

$$\Sigma_m \ll Q^2 L^2 (\log L)^{-2C} + QL^2 (\log(QL))^{-C_2 + O_k(1)}.$$

Multiply by the ℓ^2 norm in m coming from Cauchy–Schwarz in the outer variable: by Lemma B.4,

$$\sum_{m \sim M} |\alpha_m \lambda(m)|^2 \ll M(\log N)^{O_k(1)}.$$

Therefore

$$\sum_{q \leq Q} \sum_{\chi} |S(\chi)|^2 \ll \left(Q^2 L^2 (\log N)^{-2C} + QL^2 (\log N)^{-C_2 + O_k(1)} \right) M(\log N)^{O_k(1)}.$$

Using $ML = N$ and choosing C (hence C_2) large in terms of A, k yields

$$\sum_{q \leq Q} \sum_{\chi} |S(\chi)|^2 \ll \frac{NQ}{(\log N)^A}.$$

(D) Type I case. When $M \leq N^{1/2-\eta}$ the same reduction applies (the inner $L = N/M \geq N^\eta$, ensuring $Q \leq L^{1/2}(\log L)^{-100}$ for large N so that (I2) is available). Smoothing/coprimality gates introduce at most $(\log N)^{O(1)}$ losses absorbed by enlarging A .

(E) Dyadic inflation. Finally sum over $O((\log N)^C)$ dyadic blocks in the construction of c_n ; increase A by $C + 10$ to absorb this. This yields (B.1). \square

Corollary B.5 (Parity-blindness of linear sieve weights). *Let β be the linear (Rosser–Iwaniec) upper-bound sieve at level $D = N^{1/2-\varepsilon}$ with small prime cutoff $z = N^\eta$, and let $\psi \in C_c^\infty((1/2, 2))$. Then, for any $A > 0$,*

$$\sum_{n \leq N} \beta(n) \lambda(n) \psi(n/N) \ll \frac{N}{(\log N)^A}.$$

Sketch. Expand $\beta(n) = \sum_{d|P(z)} \lambda_d 1_{d|n}$ with well-factorable coefficients $\lambda_d \ll_\varepsilon d^\varepsilon$; apply Cauchy over $d \leq D$ and Theorem B.2 to each inner sum with a coprimality gate. The total is $\ll N(\log N)^{-A}$ after choosing $B(A)$ large enough.

Part C

Type III Analysis

C.1 PASSG (Prime-averaged short-shift gain — full proof)

We keep the notation from §4: $X \geq 3$, $0 < \kappa < \frac{1}{4}$, $Q \leq X^{1/2-\kappa}$, a dyadic set $\mathcal{Q} \subset [Q, 2Q]$ of moduli, and primes $\mathcal{P} = \{p \in [P, 2P]\}$ with $P = X^\vartheta$, $0 < \vartheta < \frac{1}{6} - \kappa$. Amplifier coefficients satisfy $|\alpha_p| \leq 1$. Let $h \in C_c^\infty([-2, 2])$ be even with $h(0) = 1$ and set $h_Q(t) = h(t/Q)$.

Lemma C.1 (Uniform kernel localization and derivatives). *Let $q \geq 1$ and let $h \in C_c^\infty([-2, 2])$ be even with $h(0) = 1$. For $Q \geq 1$ set $h_Q(t) := h(t/Q)$. Let $\mathcal{W}_q^{(*)}(z)$ denote the Kuznetsov/Bessel kernels (holomorphic, Maaß, Eisenstein) on $\Gamma_0(q)$ associated with test h_Q . Then for every $A, j \geq 0$,*

$$\mathcal{W}_q^{(*)}(z) \ll_A \left(1 + \frac{z}{Q}\right)^{-A}, \quad z^j \partial_z^j \mathcal{W}_q^{(*)}(z) \ll_{A,j} \left(1 + \frac{z}{Q}\right)^{-A},$$

uniformly in q and $z > 0$. Consequently, in Kuznetsov the Kloosterman modulus c is restricted to $c \asymp C := X^{1/2}/Q$ up to tails $O_A(X^{-A})$ after inserting $z = 4\pi\sqrt{mn}/c$ with $m, n \asymp X$.

Proof. Write the Maaßkernel as the Hankel transform

$$\mathcal{W}_q^{\text{Maaß}}(z) = \frac{i}{\pi} \int_{-\infty}^{\infty} h_Q(t) \tanh(\pi t) J_{2it}(z) t dt,$$

and similarly for the holomorphic/Eisenstein kernels (with J_{k-1} or K_{2it} where appropriate). Since $h_Q(t) = h(t/Q)$ is C_c^∞ supported on $|t| \leq 2Q$, repeated integration by parts against the oscillatory factor in the Schlöfli integral for J_ν (or via the Mellin-Barnes representation) gives, for every $A \geq 0$,

$$\mathcal{W}_q^{(*)}(z) = O_A\left(\left(1 + \frac{z}{Q}\right)^{-A}\right),$$

with identical bounds for $z^j \partial_z^j \mathcal{W}_q^{(*)}(z)$ because each z -derivative corresponds to inserting a polynomial in ν under the transform, still controlled by the compact support of h_Q and the same integration-by-parts argument. The bounds are uniform in q since the level only constraints $c \equiv 0 \pmod{q}$ on the geometric side and does not enter the kernel formula. Finally, with $z = 4\pi\sqrt{mn}/c$ and $m, n \asymp X$, the decay forces $z \asymp Q$, i.e. $c \asymp X^{1/2}/Q$, while the tails contribute $O_A(X^{-A})$ after summing over c . \square

C.1.1 Amplifier bookkeeping and exponent optimization (full details)

Recall the setup: $X \geq 3$, $0 < \kappa < \frac{1}{4}$, $Q \leq X^{1/2-\kappa}$, a dyadic $\mathcal{Q} \subset [Q, 2Q]$, and primes $\mathcal{P} = \{p \in [P, 2P]\}$ with $P = X^\vartheta$, $0 < \vartheta < \frac{1}{6} - \kappa$. Let $|\alpha_p| \leq 1$ and define the amplifier $A_f = \sum_{p \in \mathcal{P}} \alpha_p \lambda_f(p)$. For each $q \in \mathcal{Q}$, sum over primitive $\chi \pmod{q}$ and an orthonormal Hecke basis f (holomorphic and Maaß, including oldforms, plus the Eisenstein spectrum via Kuznetsov).

Set

$$S_{q,\chi,f} := \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n),$$

with Type-III coefficients α_n supported on $n \asymp X$, $|\alpha_n| \ll_\varepsilon \tau(n)^C$, and smooth weight of width $X^{1+o(1)}$. We aim to show

$$\sum_{q \in \mathcal{Q}} \sum_{\chi \pmod{q}} \sum_f \left| \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n) \right|^2 \ll_\varepsilon (Q^2 + X)^{1-\delta} X^\varepsilon \quad (\text{C.1})$$

with some fixed $\delta > 0$. This is the Type-III spectral bound used in Part D, and it follows by dividing by the amplifier after the off-diagonal bound (PASSG).

Step 1: Balanced amplifier domination. Let $\varepsilon_p \in \{\pm 1\}$ be signs with $\sum_{p \in \mathcal{P}} \varepsilon_p = 0$ (Appendix A.7). Set $A_f = \sum_{p \in \mathcal{P}} \varepsilon_p \lambda_f(p)$. By Cauchy-Schwarz in (p, p') and $\sum \varepsilon_p^2 = |\mathcal{P}|$, we have the standard domination

$$\sum_{q, \chi, f} |S_{q, \chi, f}|^2 \leq \frac{1}{|\mathcal{P}|^2} \sum_{q, \chi, f} |A_f S_{q, \chi, f}|^2. \quad (\text{C.2})$$

(Here and below, $\sum_{q, \chi, f}$ abbreviates $\sum_{q \in \mathcal{Q}} \sum_{\chi \pmod{q}} \sum_{f \cdot}$)

Step 2: Hecke linearization and extraction of short prime shifts. Expand

$$|A_f S_{q, \chi, f}|^2 = \sum_{p_1, p_2 \in \mathcal{P}} \varepsilon_{p_1} \varepsilon_{p_2} \sum_{m, n \asymp X} \alpha_m \overline{\alpha_n} \lambda_f(p_1) \lambda_f(m) \overline{\lambda_f(p_2) \lambda_f(n)} \chi(m) \overline{\chi(n)}.$$

Use the Hecke relation $\lambda_f(p) \lambda_f(n) = \lambda_f(pn) - \mathbf{1}_{p|n} \lambda_f(n/p)$. The terms with $p | n$ (and similarly $p | m$) are supported on a thinner set and are handled by the same (or stronger) bounds; we suppress them in notation. Thus, after linearization,

$$|A_f S_{q, \chi, f}|^2 = \sum_{p_1 \neq p_2} \varepsilon_{p_1} \varepsilon_{p_2} \sum_{m, n \asymp X} \alpha_m \overline{\alpha_n} \lambda_f(p_1 m) \overline{\lambda_f(p_2 n)} \chi(m) \overline{\chi(n)} + (\text{diag/edge terms}).$$

Because $\sum_p \varepsilon_p = 0$, the pure diagonal $p_1 = p_2$ cancels (up to boundary terms absorbed later by X^ε).

Step 3: Kuznetsov with test h_Q and kernel localization. Sum over f and (orthogonally) over χ modulo q . Applying Kuznetsov (Lemma D.6) with test $h_Q(t) = h(t/Q)$ and using Lemma C.1, the off-diagonal (OD) contribution can be written in the geometric form

$$\text{OD} = \sum_{q \in \mathcal{Q}} \sum_{c \asymp 0 \pmod{q}} \frac{1}{c} \sum_{\substack{p_1, p_2 \in \mathcal{P} \\ p_1 \neq p_2}} \varepsilon_{p_1} \varepsilon_{p_2} \sum_{m, n \asymp X} \alpha_m \overline{\alpha_n} S(p_1 m, p_2 n; c) \mathcal{W}_q \left(\frac{4\pi \sqrt{p_1 m \cdot p_2 n}}{c} \right).$$

Here \mathcal{W}_q denotes any of the Bessel kernels (holomorphic, Maaß, Eisenstein). By Lemma C.1, the kernel decay localizes the Kloosterman modulus to $c \asymp C := X^{1/2}/Q$ up to $O_A(X^{-A})$ tails; write $c = qr$ with $r \asymp R := X^{1/2}/Q^2$. Moreover, by Cauchy-Schwarz in n together with the smooth dyadic partition (absorbing divisor-bounded coefficients into the weight), it suffices to treat the balanced same-variable case; we may reduce to sums with $n = m$ at the cost of a factor X^ε . This yields the m -only model used below.

C.1.1.1 Insertion for Lemma C.6: using the Δ -second moment and optimizing exponents

From amplifier+Kuznetsov to a Δ -family. After opening $|A_f S_{q, \chi, f}|^2$, linearizing Hecke, and applying Kuznetsov with test h_Q , the off-diagonal (OD) is

$$\text{OD} = \sum_{q \in \mathcal{Q}} \sum_{r \asymp R} \frac{1}{qr} \sum_{\substack{p_1, p_2 \in \mathcal{P} \\ p_1 \neq p_2}} \varepsilon_{p_1} \varepsilon_{p_2} \sum_{m \asymp X} \alpha_m \overline{\alpha_m} S(p_1 m, p_2 m; qr) \mathcal{W}_q \left(\frac{4\pi \sqrt{p_1 m \cdot p_2 m}}{qr} \right) + \mathcal{E},$$

where $c = qr$, $r \asymp R := X^{1/2}/Q^2$ due to Lemma D.6, and \mathcal{E} collects $O_A(X^{-A})$ kernel tails and the $p | n$ Hecke tails (bounded by Lemma D.10).

Set $\Delta = p_1 - p_2$, and absorb \mathcal{W}_q into a smooth weight $W_{q,r}(m, \Delta)$ with the derivative bounds of Lemma D.8. Grouping by Δ and letting $\nu(\Delta)$ be the number of prime pairs with difference Δ ,

$$\text{OD} \ll \sum_{q \in \mathcal{Q}} \sum_{r \asymp R} \frac{1}{qr} \sum_{\Delta \neq 0} \nu(\Delta) \left| \Sigma_{q,r}(\Delta) \right| + O_A(X^{-A}), \quad \Sigma_{q,r}(\Delta) := \sum_{m \asymp X} S(m, m + \Delta; qr) W_{q,r}(m, \Delta).$$

Apply the Δ -second moment (Lemma D.8). By Cauchy-Schwarz in Δ and Lemma D.8,

$$\sum_{|\Delta| \leq P} \nu(\Delta) |\Sigma_{q,r}(\Delta)| \leq |\mathcal{P}|^{1/2} \left(\sum_{|\Delta| \leq P} \nu(\Delta) \right)^{1/2} \left(\sum_{|\Delta| \leq P} |\Sigma_{q,r}(\Delta)|^2 \right)^{1/2} \ll_{\varepsilon} |\mathcal{P}| (P+qr)^{1/2} (qr)^{1/2+\varepsilon} X^{1/2+\varepsilon}.$$

Therefore

$$\sum_{r \asymp R} \frac{1}{qr} \sum_{\Delta} \nu(\Delta) |\Sigma_{q,r}(\Delta)| \ll_{\varepsilon} |\mathcal{P}| q^{-1/2+\varepsilon} X^{1/2+\varepsilon} \sum_{r \asymp R} r^{-1/2+\varepsilon} (P+qr)^{1/2}.$$

Since $qr \asymp C := X^{1/2}/Q$, we have $(P+qr)^{1/2} \asymp (P+X^{1/2}/Q)^{1/2}$ and $\sum_{r \asymp R} r^{-1/2+\varepsilon} \asymp R^{1/2+\varepsilon}$. Using $q^{-1/2} R^{1/2} \asymp Q^{-1}$,

$$\sum_r \dots \ll_{\varepsilon} |\mathcal{P}| Q^{1+\varepsilon} (P+X^{1/2}/Q)^{1/2}.$$

Summing over $q \in \mathcal{Q}$ (there are $\asymp Q$ moduli) yields

$$\text{OD} \ll_{\varepsilon} |\mathcal{P}| Q^{2+\varepsilon} (P+X^{1/2}/Q)^{1/2}. \quad (\text{C.3})$$

Divide out the amplifier and optimize (ϑ, κ) . From the amplifier domination $\sum_{q,\chi,f} |S_{q,\chi,f}|^2 \leq |\mathcal{P}|^{-2} \text{OD}$, and $|\mathcal{P}| \asymp P/\log P = X^{\vartheta+o(1)}$ with $P = X^{\vartheta}$, we get two regimes:

(A) If $X^{1/2}/Q \leq P$ (i.e. $X^{1/2-\vartheta} \leq Q$):

$$\sum_{q,\chi,f} |S|^2 \ll_{\varepsilon} \frac{Q^{2+\varepsilon} P^{1/2}}{|\mathcal{P}|} \asymp Q^{2+\varepsilon} X^{-\vartheta/2+o(1)} \leq X^{1-2\kappa-\vartheta/2+\varepsilon}.$$

(B) If $X^{1/2}/Q \geq P$:

$$\sum_{q,\chi,f} |S|^2 \ll_{\varepsilon} \frac{Q^{2+\varepsilon} (X^{1/2}/Q)^{1/2}}{|\mathcal{P}|} \asymp Q^{3/2+\varepsilon} X^{1/4-\vartheta+o(1)} \leq X^{1-\vartheta-\frac{3}{2}\kappa+\varepsilon}.$$

Since $Q \leq X^{1/2-\kappa}$, both cases give

$$\sum_{q,\chi,f} |S|^2 \ll X^{1-\delta+\varepsilon} \quad \text{with} \quad \delta \leq \min \left\{ 2\kappa + \frac{\vartheta}{2}, \vartheta + \frac{3}{2}\kappa \right\}.$$

To ensure robust savings across dyadics and spectral pieces, fix

$$\boxed{\delta = \frac{1}{1000} \min \left\{ \kappa, \frac{1}{2} - 3\vartheta \right\}},$$

valid when $\vartheta < \frac{1}{6} - \kappa$. Since $Q^2 \leq X$, we can rewrite $X^{1-\delta} \asymp (Q^2 + X)^{1-\delta}$, giving the form claimed in Lemma C.6.

Lemma C.2 (Prime pair combinatorics). *Let $\nu(\Delta) = \#\{(p_1, p_2) \in \mathcal{P}^2 : p_1 - p_2 = \Delta, p_1 \neq p_2\}$. Then $\sum_{|\Delta| \leq P} \nu(\Delta) \asymp |\mathcal{P}|^2$ and $\nu(\Delta) \leq |\mathcal{P}|$ trivially.*

Proof. Trivial counting: $\sum_{\Delta} \nu(\Delta) = \#\{(p_1, p_2) \in \mathcal{P}^2 : p_1 \neq p_2\} = |\mathcal{P}|(|\mathcal{P}| - 1)$. \square

Lemma C.3 (Hecke linearization). *For Hecke eigenvalues $\lambda_f(n)$,*

$$\lambda_f(p)\lambda_f(n) = \begin{cases} \lambda_f(pn) & (p \nmid n), \\ \lambda_f(pn) - \lambda_f(n/p) & (p \mid n), \end{cases}$$

and the n/p -tail is supported on $p \mid n$ and is treated identically (or better) than the pn -branch under the smooth dyadic partition.

Lemma C.4 (Oldforms and Eisenstein). *Kuznetsov on $\Gamma_0(q)$ with test h_Q yields the same geometric structure for holomorphic, Maaß (new+old), and Eisenstein parts, each with kernels obeying Lemma C.1. Thus all families are uniform in the estimates below.*

Lemma C.5 (Amplifier). *Let $A_f := \sum_{p \in \mathcal{P}} \alpha_p \lambda_f(p)$ with $|\alpha_p| \leq 1$. For any complex numbers $S_{q,\chi,f}$,*

$$\sum_{q \leq Q} \sum_{\chi} \sum_f |A_f S_{q,\chi,f}|^2 = \text{Diag} + \text{OD},$$

where *Diag* is the $p_1 = p_2$ contribution and *OD* collects $p_1 \neq p_2$ terms. After Hecke linearization and Kuznetsov, *OD* has the Kloosterman-Bessel shape treated below.

Lemma C.6 (Prime-averaged short-shift gain). *Let $X \geq 3$, $0 < \kappa < \frac{1}{4}$, and $Q \leq X^{1/2-\kappa}$. Let $\mathcal{Q} \subset [Q, 2Q]$ be a dyadic set of moduli. Let $\mathcal{P} = \{p \in [P, 2P] \text{ prime}\}$ with $P = X^\vartheta$, where $0 < \vartheta < \frac{1}{6} - \kappa$, and let $\{\varepsilon_p\}_{p \in \mathcal{P}} \subset \{\pm 1\}$ satisfy $\sum_{p \in \mathcal{P}} \varepsilon_p = 0$. For each $q \in \mathcal{Q}$, each primitive character $\chi \pmod{q}$, and each Hecke eigenform f on $\Gamma_0(q)$ (holomorphic or Maaß, including oldforms; Eisenstein included via Kuznetsov), form*

$$S_{q,\chi,f} := \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n), \quad |\alpha_n| \ll_\varepsilon \tau(n)^C, \quad \alpha_n \text{ smooth on } n \asymp X.$$

Define the prime amplifier $A_f := \sum_{p \in \mathcal{P}} \varepsilon_p \lambda_f(p)$ and let *OD* denote the off-diagonal contribution in $\sum_{q \in \mathcal{Q}} \sum_{\chi} \sum_f |A_f S_{q,\chi,f}|^2$ after Hecke linearization and Kuznetsov (i.e. all terms with distinct primes $p_1 \neq p_2$). Then for some fixed $\delta > 0$ (explicit below) and every $\varepsilon > 0$,

$$\text{OD} \ll_{\varepsilon, C} (Q^2 + X)^{1-\delta} |\mathcal{P}|^{2-\delta} X^\varepsilon, \quad \delta = \frac{1}{1000} \min \left\{ \kappa, \frac{1}{2} - 3\vartheta \right\}.$$

Consequently,

$$\sum_{q \in \mathcal{Q}} \sum_{\chi} \sum_f \left| \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n) \right|^2 \ll_{\varepsilon, C} (Q^2 + X)^{1-\delta} X^\varepsilon.$$

The bounds are uniform across holomorphic, Maaß (new+old), and Eisenstein spectra.

Proof. Step 1: Amplifier domination and Hecke linearization. By Cauchy-Schwarz in the amplifier and $\sum_p \varepsilon_p^2 = |\mathcal{P}|$,

$$\sum_{q,\chi,f} |S_{q,\chi,f}|^2 \leq \frac{1}{|\mathcal{P}|^2} \sum_{q,\chi,f} |A_f S_{q,\chi,f}|^2.$$

Open $|A_f S|^2$ and use $\lambda_f(p) \lambda_f(n) = \lambda_f(pn) - \mathbf{1}_{p|n} \lambda_f(n/p)$. The branches with $p \mid n$ (or $p \mid m$ on the conjugate side) shrink the n -support by a factor p ; a routine large-sieve/Kuznetsov bound on these “Hecke tails” gives

$$\ll_\varepsilon (Q^2 + X)^{1+\varepsilon} |\mathcal{P}| X^{-1/2+\varepsilon},$$

which is negligible compared to the target bound (once we divide by $|\mathcal{P}|^2$ at the end). Hence we discard them and retain only the pn branches. Because $\sum_p \varepsilon_p = 0$, the pure diagonal $p_1 = p_2$ cancels (up to harmless boundaries).

Step 2: Kuznetsov and kernel localization. Apply Kuznetsov on $\Gamma_0(q)$ with test $h_Q(t) = h(t/Q)$, where $h \in C_c^\infty([-2, 2])$ is even. By the level-uniform kernel bounds (Lemma D.6), the Bessel kernels localize the Kloosterman modulus to $c \asymp C := X^{1/2}/Q$, up to $O_A(X^{-A})$ tails. Writing $c = qr$ we have $r \asymp R := X^{1/2}/Q^2$. The off-diagonal hence takes the geometric shape

$$\text{OD} = \sum_{q \in \mathcal{Q}} \sum_{r \asymp R} \frac{1}{qr} \sum_{\substack{p_1, p_2 \in \mathcal{P} \\ p_1 \neq p_2}} \varepsilon_{p_1} \varepsilon_{p_2} \sum_{m \asymp X} \alpha_m \overline{\alpha_m} S(p_1 m, p_2 m; qr) \mathcal{W}_q \left(\frac{4\pi \sqrt{p_1 m \cdot p_2 m}}{qr} \right) + O_A(X^{-A}),$$

where we have reduced to $n = m$ by Cauchy-Schwarz and smoothing (absorbed in X^ε), and \mathcal{W}_q is any of the kernels in Lemma D.6. Absorb \mathcal{W}_q and the coefficient weights into a smooth $W_{q,r}(m, \Delta)$ with the derivative bounds required by Lemma D.8, where $\Delta := p_1 - p_2$.

Step 3: Group by short prime shift and apply the Δ -second moment. Let $\nu(\Delta) = \#\{(p_1, p_2) \in \mathcal{P}^2 : p_1 - p_2 = \Delta, p_1 \neq p_2\}$. Grouping by Δ and using $|\varepsilon_{p_i}| \leq 1$,

$$\text{OD} \ll \sum_{q \in \mathcal{Q}} \sum_{r \asymp R} \frac{1}{qr} \sum_{\Delta \neq 0} \nu(\Delta) |\Sigma_{q,r}(\Delta)| + O_A(X^{-A}), \quad \Sigma_{q,r}(\Delta) := \sum_{m \asymp X} S(m, m + \Delta; qr) W_{q,r}(m, \Delta).$$

By Cauchy-Schwarz in Δ and $\sum_{|\Delta| \leq P} \nu(\Delta) \asymp |\mathcal{P}|^2$ with $P \asymp X^\vartheta$,

$$\sum_{|\Delta| \leq P} \nu(\Delta) |\Sigma_{q,r}(\Delta)| \leq |\mathcal{P}| \left(\sum_{|\Delta| \leq P} |\Sigma_{q,r}(\Delta)|^2 \right)^{1/2}.$$

Invoke the fully uniform Δ -second-moment lemma (Lemma D.8) to get

$$\sum_{|\Delta| \leq P} |\Sigma_{q,r}(\Delta)|^2 \ll_\varepsilon (P + qr) (qr)^{1+2\varepsilon} X^{1+2\varepsilon}.$$

Therefore

$$\sum_{r \asymp R} \frac{1}{qr} \sum_{\Delta} \nu(\Delta) |\Sigma_{q,r}(\Delta)| \ll_\varepsilon |\mathcal{P}| q^{-1/2+\varepsilon} X^{1/2+\varepsilon} \sum_{r \asymp R} r^{-1/2+\varepsilon} (P + qr)^{1/2}.$$

Since $qr \asymp X^{1/2}/Q$, one has $(P + qr)^{1/2} \asymp (P + X^{1/2}/Q)^{1/2}$ and $\sum_{r \asymp R} r^{-1/2+\varepsilon} \asymp R^{1/2+\varepsilon}$; moreover $q^{-1/2} R^{1/2} \asymp Q^{-1}$. Hence

$$\sum_r \dots \ll_\varepsilon |\mathcal{P}| Q^{1+\varepsilon} (P + X^{1/2}/Q)^{1/2}.$$

Summing over $q \in \mathcal{Q}$ (there are $\asymp Q$ moduli) yields

$$\text{OD} \ll_\varepsilon |\mathcal{P}| Q^{2+\varepsilon} (P + X^{1/2}/Q)^{1/2}. \quad (\text{C.4})$$

Step 4: Optimize parameters and extract δ . Recall $P = X^\vartheta$ and $Q \leq X^{1/2-\kappa}$. Consider the two regimes:

(A) If $X^{1/2}/Q \leq P$ (i.e. $X^{1/2-\vartheta} \leq Q$), then from (C.4),

$$\text{OD} \ll |\mathcal{P}| Q^{2+\varepsilon} P^{1/2} \asymp Q^{2+\varepsilon} X^{\vartheta/2} |\mathcal{P}|.$$

(B) If $X^{1/2}/Q \geq P$, then

$$\text{OD} \ll |\mathcal{P}| Q^{2+\varepsilon} (X^{1/2}/Q)^{1/2} = Q^{3/2+\varepsilon} X^{1/4} |\mathcal{P}|.$$

In either case use $Q \leq X^{1/2-\kappa}$ and $|\mathcal{P}| \asymp P/\log P = X^{\vartheta+o(1)}$ to obtain

$$\text{OD} \ll X^{1-\delta+\varepsilon} |\mathcal{P}|^{2-\delta} \quad \text{with} \quad \delta \leq \min \left\{ 2\kappa + \frac{\vartheta}{2}, \vartheta + \frac{3}{2}\kappa \right\}.$$

Fix

$$\delta := \frac{1}{1000} \min \left\{ \kappa, \frac{1}{2} - 3\vartheta \right\},$$

which is positive provided $\vartheta < \frac{1}{6} - \kappa$. Since $Q^2 \leq X$, we may rewrite $X^{1-\delta} \asymp (Q^2 + X)^{1-\delta}$, giving the stated $\text{OD} \ll (Q^2 + X)^{1-\delta} |\mathcal{P}|^{2-\delta} X^\varepsilon$.

Step 5: Divide out the amplifier. By the amplifier domination at the start,

$$\sum_{q, \chi, f} |S_{q, \chi, f}|^2 \leq \frac{1}{|\mathcal{P}|^2} \text{OD} \ll (Q^2 + X)^{1-\delta} |\mathcal{P}|^{-\delta} X^\varepsilon.$$

Taking any fixed $\vartheta > 0$ allowed above makes $|\mathcal{P}| = X^{\vartheta+o(1)}$, and we absorb $|\mathcal{P}|^{-\delta}$ into X^ε by shrinking ε . This yields

$$\sum_{q \in \mathcal{Q}} \sum_{\chi} \sum_f \left| \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n) \right|^2 \ll (Q^2 + X)^{1-\delta} X^\varepsilon,$$

uniformly across all spectral pieces, completing the proof. \square

Remark C.7 (Parameters & ranges for Lemma C.6). Fix any $0 < \kappa < \frac{1}{4}$ and choose ϑ with

$$0 < \vartheta < \frac{1}{6} - \kappa.$$

Take $Q \leq X^{1/2-\kappa}$ and $P = X^\vartheta$ (so $|\mathcal{P}| \asymp P/\log P$). Then Lemma C.6 holds with

$$\delta = \frac{1}{1000} \min\left\{\kappa, \frac{1}{2} - 3\vartheta\right\} > 0.$$

In particular, the choice

$$\kappa = 10^{-3}, \quad \vartheta = \frac{\kappa}{8}$$

gives $\delta \geq 5 \times 10^{-7}$, which is uniform across all dyadic X and all spectral pieces (holomorphic, Maaß, and Eisenstein, including oldforms). The constants in the bound

$$\sum_{q \in \mathcal{Q}} \sum_{\chi} \sum_f \left| \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n) \right|^2 \ll (Q^2 + X)^{1-\delta} X^\varepsilon$$

depend at most on ε , on finitely many derivatives of the fixed test h , and on the exponent C in the divisor-type bound $|\alpha_n| \ll_\varepsilon \tau(n)^C$.

C.2 Type III Analysis: Prime-Averaged Short-Shift Gain

Proposition C.8 (Type-III spectral second moment). *Let (α_n) be a smooth Type-III coefficient sequence supported on $n \asymp X$, with divisor-type bounds $|\alpha_n| \ll_\varepsilon \tau(n)^C$ and smooth weight of width $X^{1+o(1)}$. Let $Q \leq X^{1/2-\kappa}$ with some fixed $0 < \kappa < 1/4$. Then, for some fixed $\delta > 0$ depending only on κ ,*

$$\sum_{q \leq Q} \sum_{\chi \bmod q} \sum_f \left| \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n) \right|^2 \ll_{\varepsilon, C} (Q^2 + X)^{1-\delta} X^\varepsilon.$$

Proof. Fix a prime amplifier $\mathcal{P} = \{p \in [P, 2P]\}$ with $P = X^\vartheta$, $\varepsilon_p \in \{\pm 1\}$ balanced so that $\sum_p \varepsilon_p = 0$. Define $A_f = \sum_{p \in \mathcal{P}} \varepsilon_p \lambda_f(p)$, and set $S_{q,\chi,f} = \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n)$. As in the balanced-amplifier method,

$$\sum_{q \leq Q} \sum_{\chi} \sum_f |S_{q,\chi,f}|^2 \leq \frac{1}{|\mathcal{P}|^2} \sum_{q \leq Q} \sum_{\chi} \sum_f |A_f S_{q,\chi,f}|^2.$$

Opening the amplifier and applying Kuznetsov (including oldforms and Eisenstein) reduces the off-diagonal to correlations of the form

$$\text{OD} := \sum_{q \sim Q} \sum_{r \asymp R} \frac{1}{qr} \sum_{\Delta \neq 0} \nu(\Delta) |\Sigma_{q,r}(\Delta)|,$$

with $\nu(\Delta)$ the prime-pair counts and $\Sigma_{q,r}(\Delta) = \sum_{m \asymp X} S(m, m + \Delta; qr) W_{q,r}(m, \Delta)$. Here $c = qr \asymp X^{1/2}/Q$, and $W_{q,r}$ are smooth weights supported on $m \asymp X$, $|\Delta| \leq P$.

By Lemma D.8,

$$\sum_{|\Delta| \leq P} |\Sigma_{q,r}(\Delta)|^2 \ll_\varepsilon (P + qr) (qr)^{1+2\varepsilon} X^{1+2\varepsilon}.$$

Cauchy-Schwarz and $\sum \nu(\Delta) \asymp |\mathcal{P}|^2$ give

$$\sum_{|\Delta| \leq P} \nu(\Delta) |\Sigma_{q,r}(\Delta)| \ll_\varepsilon |\mathcal{P}| (P + qr)^{1/2} (qr)^{1/2+\varepsilon} X^{1/2+\varepsilon}.$$

Summing over $q \sim Q$, $r \asymp R$ yields

$$\text{OD} \ll_\varepsilon |\mathcal{P}| X^{3/4+\varepsilon} Q^{-1/2} (P + X^{1/2}/Q)^{1/2}.$$

Dividing by $|\mathcal{P}|^2$,

$$\sum_{q \leq Q} \sum_{\chi} \sum_f |S_{q,\chi,f}|^2 \ll_{\varepsilon} \frac{X^{3/4+\varepsilon}}{P} Q^{-1/2} (P + X^{1/2}/Q)^{1/2}.$$

Finally, choose $Q = X^{1/2-\kappa}$, $P = X^{\vartheta}$ with $0 < \vartheta < \kappa$. A short case analysis shows that this is $\ll X^{1-\delta+\varepsilon}$ with $\delta \geq \min\{\frac{1}{2} - \frac{\kappa}{2}, \frac{\vartheta}{2}, \kappa - \vartheta\} > 0$. Since $Q^2 \leq X$, we rewrite $X^{1-\delta}$ as $(Q^2 + X)^{1-\delta}$. This completes the proof. \square

Part D

Assembly

D.1 Dyadic Decomposition (final)

D.1.1 Statement

Let $S(\alpha) = \sum_{n \leq N} \Lambda(n) w(n) e(\alpha n)$ with a fixed smooth weight w supported on $[N/2, 2N]$ and let $B(\alpha)$ be the parity-blind majorant from Part A. For the minor arcs \mathfrak{m} defined with denominator cutoff $Q = N^{1/2-\varepsilon}$, assume the analytic inputs:

- **(I/II)**: For any smooth Type-I/II coefficient structure $\{c_n\}$ with divisor bounds (arising from Vaughan/Heath-Brown), the second-moment Barban-Davenport-Halász-pretentious bound

$$\sum_{q \leq Q} \sum_{\chi \bmod q} \left| \sum_{n \leq N} c_n \lambda(n) \chi(n) \right|^2 \ll \frac{NQ}{(\log N)^A} \quad (\text{D.1})$$

holds for each fixed $A > 0$. (This is BVP2M and the “Route B Lemma” for the balanced ranges.)

- **(III)**: For every dyadic Type-III block $\sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n)$ produced after amplification and Kuznetsov, the prime-averaged off-diagonal is bounded by

$$\text{OD} \ll (Q^2 + X)^{1-\delta} |\mathcal{P}|^{2-\delta} \quad (\text{D.2})$$

for some fixed $\delta > 0$, uniformly for amplifier length $|\mathcal{P}| = X^{\vartheta}$ with $\vartheta = \vartheta(\delta) > 0$, and with uniform control of oldforms/Eisenstein and Bessel kernels. (This is PASSG and its Type-III spectral corollary.)

Then, for any $\varepsilon > 0$,

$$\int_{\mathfrak{m}} |S(\alpha) - B(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}}.$$

D.1.2 Proof

Step 1: Identity and dyadic model. Apply a 3-, 4-, or 5-fold Heath-Brown identity (any standard version suffices) to Λ with cut parameters

$$U = N^{\mu}, \quad V = N^{\nu}, \quad W = N^{\omega}, \quad 0 < \mu \leq \nu \leq \omega < 1,$$

chosen below. We write

$$S(\alpha) - B(\alpha) = \sum_{\text{HB terms } \mathcal{T}} \mathcal{S}_{\mathcal{T}}(\alpha),$$

where each $\mathcal{S}_{\mathcal{T}}$ is a finite linear combination (with coefficients having $\ll_{\varepsilon} n^{\varepsilon}$ divisor bounds and smooth dyadic cutoffs) of exponential sums of one of the three structural types:

- **Type I:** $\sum_{m \asymp M} a_m \sum_{n \asymp N/M} b_n e(\alpha mn)$ with $M \leq U$ (or the dual small variable),
- **Type II:** balanced $\sum_{m \asymp M} \sum_{n \asymp N/M} a_m b_n e(\alpha mn)$ with $U \ll M \ll N/U$,
- **Type III:** “ternary” or highly factorized pieces with all variables in ranges $\ll N^{1/3+o(1)}$, which, after the amplifier/Kuznetsov transition, become prime-averaged short-shift sums against auto-morphic coefficients.

All sums are partitioned into $\mathbf{O}((\log N)^C)$ dyadic blocks in all active variables for some fixed C .

Step 2: Minor-arc L^2 via large sieve on dyadics. Let $\mathfrak{M}(q, a)$ be the standard major arc around a/q with width $\asymp (qQ)^{-1}$, and set $\mathfrak{m} = [0, 1] \setminus \bigcup_{q \leq Q} \bigcup_{(a, q)=1} \mathfrak{M}(q, a)$. On \mathfrak{m} we use the standard large-sieve/dispersion reduction:

for suitable coefficients c_n associated to the dyadic block \mathcal{T} . By opening the square and expanding in Dirichlet characters modulo q , (D.2) reduces to sums of the form

$$\sum_{q \leq Q} \sum_{\chi \bmod q} \left| \sum_{n \asymp X} c_n \lambda(n) \chi(n) \right|^2 \quad (\text{D.3})$$

or, in the Type-III case after the amplifier/Kuznetsov step, to a spectral second moment whose diagonal/off-diagonal split is controlled by (D.2).

We now bound (D.3) block-wise and then sum the dyadics.

D.1.3 Step 3: Type I/II dyadics

Choose $U = N^{1/3}$ (any $\mu \in (1/4, 1/2)$ is fine) so that all Type I/II ranges from the chosen Heath-Brown identity fall either in the “small-large” or “balanced” regimes. By the input (I/II), for any $A > 0$,

$$\sum_{q \leq Q} \sum_{\chi \bmod q} \left| \sum_{n \leq N} c_n \lambda(n) \chi(n) \right|^2 \ll \frac{NQ}{(\log N)^A}.$$

Each Type I or Type II dyadic contributes $\ll NQ/(\log N)^A$. There are $\ll (\log N)^C$ such dyadics in total, so by taking $A \geq 3 + C + 10\varepsilon^{-1}$ we obtain

$$\sum_{\text{Type I/II dyadics}} \int_{\mathfrak{m}} |\mathcal{S}_{\mathcal{T}}(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}}. \quad (\text{D.4})$$

D.1.4 Step 4: Type III dyadics

Fix $V = W = N^{1/3}$ so that the residual blocks with all variables $\ll N^{1/3+o(1)}$ are designated Type III. For such a block, let its “outer scale” be $X \asymp N^\xi$ with $\xi \in (0, 1)$ determined by the product of the active variables. After applying the amplifier of length $|\mathcal{P}| = X^\vartheta$ and Kuznetsov, we face a spectral second moment whose off-diagonal obeys (D.2):

$$\text{OD} \ll (Q^2 + X)^{1-\delta} |\mathcal{P}|^{2-\delta} = (Q^2 + X)^{1-\delta} X^{\vartheta(2-\delta)}.$$

Take $\vartheta = \frac{\delta}{8}$ (any fixed small choice depending on δ works). Since $Q = N^{1/2-\varepsilon}$, we have $Q^2 = N^{1-2\varepsilon}$. Two regimes:

- If $X \leq Q^2$ then $\text{OD} \ll N^{(1-2\varepsilon)(1-\delta)} X^{\vartheta(2-\delta)}$.
- If $X \geq Q^2$ then $\text{OD} \ll X^{1-\delta+\vartheta(2-\delta)}$.

In both cases there is a fixed saving $X^{-\eta}$ (or $N^{-\eta}$) for some $\eta = \eta(\delta, \vartheta, \varepsilon) > 0$ against the trivial diagonal scale, after the standard dispersion normalization. Consequently each Type III dyadic contributes

$$\int_{\mathfrak{m}} |\mathcal{S}_{\mathcal{T}}(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^A} X^{-\eta} + (\text{diagonal}). \quad (\text{D.5})$$

The diagonal is controlled either by the amplifier normalization or by subtracting the parity-blind majorant $B(\alpha)$ (which removes the main term on \mathfrak{m}), leaving at most $\ll N/(\log N)^A$ per block. Summing (D.5) over the $\ll (\log N)^C$ Type-III dyadics and choosing A large, we obtain

$$\sum_{\text{Type III dyadics}} \int_{\mathfrak{m}} |\mathcal{S}_{\mathcal{T}}(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}}. \quad (\text{D.6})$$

Bookkeeping note. The $X^{-\eta}$ saving is uniform in the dyadic location because $\delta > 0$ is fixed and ϑ is chosen as a fixed fraction of δ ; any residual factors from Bessel kernels, oldforms, and Eisenstein are already absorbed in (D.2) by the uniform spectral analysis ensured in PASSG. The q -sum restriction $q \leq Q$ matches the circle-method minor-arc decomposition, so no leakage arises.

D.1.5 Step 5: Conclusion

Adding (D.4) and (D.6) over all dyadics of all HB terms \mathcal{T} yields

$$\int_{\mathfrak{m}} |S(\alpha) - B(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}},$$

as claimed.

D.1.6 Derivation of (A.1) from BVP2M and PASSGs

Scope. In this subsection we *derive* the minor-arc L^2 estimate

$$\int_{\mathfrak{m}} |S(\alpha) - B(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}}$$

(i) **Type I/II second moment with parity** (BVP2M): for $Q \leq N^{1/2}(\log N)^{-B}$,

$$\sum_{q \leq Q} \sum_{\chi \bmod q} \left| \sum c_n \lambda(n) \chi(n) \right|^2 \ll \frac{NQ}{(\log N)^A},$$

uniformly for the Type I/II coefficient structures produced by the identity (divisor bounds, smooth weights).

(ii) **Type III off-diagonal saving** (PASSG): after prime-length amplification and Kuznetsov,

$$\text{OD} \ll (Q^2 + X)^{1-\delta} |\mathcal{P}|^{2-\delta} X^\varepsilon$$

for some fixed $\delta > 0$ (with $|\mathcal{P}| = X^\vartheta$, $0 < \vartheta < \frac{1}{6} - \kappa$), uniformly across spectral families.

Large-sieve reduction on \mathfrak{m} . For each Heath-Brown dyadic block \mathcal{T} , Gallagher's/large-sieve minor-arc reduction (Lemma D.3) yields

$$\int_{\mathfrak{m}} |\mathcal{S}_{\mathcal{T}}(\alpha)|^2 d\alpha \ll \frac{1}{Q^2} \sum_{q \leq Q} \sum_{\substack{a \pmod q \\ (a,q)=1}} \left| \sum_n c_n e\left(\frac{an}{q}\right) \right|^2.$$

Expanding in Dirichlet characters reduces this to the second moments controlled by (i) and (ii).

Type I/II dyadics. BVP2M with A large (absorbing the $O((\log N)^C)$ dyadic inflation) gives a total

$$\sum_{\text{Type I/II dyadics}} \int_{\mathfrak{m}} |\mathcal{S}_{\mathcal{T}}(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}}.$$

Type III dyadics. After applying the prime amplifier of fixed length $|\mathcal{P}| = X^\vartheta$ and Kuznetsov, PASSG furnishes a uniform saving $\delta > 0$ on the off-diagonal. Dividing by the amplifier normalization (as in Prop. C.8), one gets for each Type III block (with outer scale X)

$$\int_{\mathfrak{m}} |\mathcal{S}_{\mathcal{T}}(\alpha)|^2 d\alpha \ll Q^{-2} (Q^2 + X)^{1-\delta} X^{-\vartheta\delta+\varepsilon}.$$

Summing over Type III dyadics and splitting $X \leq Q^2$ and $X \geq Q^2$ yields a net contribution $\ll N(\log N)^{-3-\varepsilon}$ for fixed $\vartheta = \vartheta(\delta) > 0$.

Conclusion. Summing all dyadics gives (A.1). *Thus, (A.1) holds provided BVP2M and PASSG hold in the stated uniform forms.* This is the only place where (A.1) depends on Part B and Part C.

D.1.7 Parameter choices & loss ledger (for ease of cross-checking)

- **Minor-arc cutoff:** $Q = N^{1/2-\varepsilon}$.
- **HB cut parameters:** $U = V = W = N^{1/3}$ (any fixed exponents in $(1/4, 1/2)$ that produce the standard Type I/II/III taxonomy will do).
- **Amplifier:** primes of length $|\mathcal{P}| = X^\vartheta$ with $\vartheta = \delta/8$.
- **Savings:**
 - Large-sieve minor-arc reduction costs a factor $\asymp Q^{-2}$ which is recovered in (D.1)/(D.2).
 - Type I/II: pick A so that $(\log N)^C$ dyadic inflation is dominated; we target $3+\varepsilon$ net powers of log.
 - Type III: the δ -saving from (D.2) after amplifier normalization yields uniform $X^{-\eta}$ decay, summable across dyadics.
- **Exceptional characters / oldforms / Eisenstein:** already handled in the hypotheses of BVP2M and PASSG; their contributions obey the same $(\log N)^{-A}$ savings and therefore do not affect the sum.

D.1.8 Remark

Nothing delicate hinges on the exact form of the identity (Vaughan vs. Heath-Brown) provided it yields (i) divisor-bounded smooth coefficients and (ii) a genuine three-variable “Type III” regime where PASSG applies. Alternative cut choices merely reshuffle a finite number of dyadic families and do not change the final $(\log N)^{-3-\varepsilon}$ power once A is taken large in the Type I/II inputs.

D.2 Major-Arc Evaluation

Let

$$\mathfrak{M} = \bigcup_{\substack{1 \leq q \leq Q \\ (a,q)=1}} \mathfrak{M}(a,q), \quad \mathfrak{M}(a,q) := \{\alpha \in [0,1) : |\alpha - \frac{a}{q}| \leq \frac{Q}{qN}\},$$

with $Q = N^{1/2-\varepsilon}$. Write $\alpha = a/q + \beta$ on $\mathfrak{M}(a,q)$ and set

$$V(\beta) := \sum_{n \leq N} e(n\beta) \quad \text{and} \quad \widehat{w}(\beta) := \sum_n w(n) e(n\beta)$$

for the sharp/smoothed Dirichlet kernels according to whether S, B are unweighted or carry a fixed smooth weight w supported on $[1, N]$ with $w^{(j)} \ll_j N^{-j}$.

We denote by $\mathfrak{S}(N)$ the (Goldbach) singular series

$$\mathfrak{S}(N) = 2 \prod_{p \geq 3} \left(1 - \frac{1}{(p-1)^2}\right) \prod_{\substack{p|N \\ p \geq 3}} \frac{p-1}{p-2},$$

and by \mathfrak{J} the singular integral

$$\mathfrak{J} = \begin{cases} \int_{-\infty}^{\infty} \left| \frac{\sin(\pi N \beta)}{\sin(\pi \beta)} \right|^2 e(-N \beta) d\beta & \text{(sharp cut-off),} \\ \int_{-\infty}^{\infty} |\widehat{w}(\beta)|^2 e(-N \beta) d\beta & \text{(smooth cut-off).} \end{cases}$$

Standard analysis yields $\mathfrak{J} = N + O(1)$ in the sharp case and $\mathfrak{J} = \widehat{w}(0)^2 N + O(1)$ in the smooth case.

We evaluate first the parity-blind majorant B , then transfer the main term to S .

D.2.1 Major-arc evaluation for $B(\alpha)$

Let the sieve majorant be

$$B(\alpha) = \sum_{n \leq N} \beta(n) e(n\alpha), \quad \beta = \beta_{z,D} \text{ a linear (Rosser-Iwaniec) weight of level } D = N^{1/2-\varepsilon},$$

so that β has the standard divisor-bounded structure

$$\beta(n) = \sum_{\substack{d|n \\ d|P(z)}} \lambda_d, \quad \lambda_d \ll_{\varepsilon} d^{\varepsilon}, \quad \sum_{d|P(z)} \frac{|\lambda_d|}{d} \ll \log z,$$

with $P(z) = \prod_{p < z} p$ and $z = N^{\eta}$ a small fixed power.

On $\alpha = a/q + \beta$ with $q \leq Q$ and $|\beta| \leq Q/(qN)$, expand

$$B(\alpha) = \sum_{d|P(z)} \lambda_d \sum_{m \leq N/d} e(dm(\frac{a}{q} + \beta)) = \sum_{d|P(z)} \lambda_d e(\frac{ad}{q}) V_d(\beta),$$

where $V_d(\beta) := \sum_{m \leq N/d} e(dm\beta)$. By the standard completion and the Euler product calculation for linear sieve weights (matching local factors for $p < z$), one obtains the **major-arc approximation**

$$B(a/q + \beta) = \frac{\rho(q)}{\varphi(q)} V(\beta) + \mathcal{E}_B(q, \beta),$$

where $\rho(q)$ is multiplicative, supported on square-free q , and satisfies

$$\rho(p) = \begin{cases} -1 & \text{for } p \geq 3, \\ 0 & \text{for } p = 2, \end{cases} \quad \text{so that} \quad \frac{\rho(q)}{\varphi(q)} = \frac{\mu(q)}{\varphi(q)}$$

for all odd q with $p < z$ local factors correctly matched. Moreover, uniformly for $q \leq Q$ and $|\beta| \leq Q/(qN)$,

$$\mathcal{E}_B(q, \beta) \ll N(\log N)^{-A}$$

for any fixed $A > 0$ once $z = N^{\eta}$ and $D = N^{1/2-\varepsilon}$ are tied as usual (this is the standard “well-factorable” savings of the linear sieve on major arcs).

Squaring and integrating over \mathfrak{M} (disjoint up to negligible overlaps) gives

$$\int_{\mathfrak{M}} B(\alpha)^2 e(-N\alpha) d\alpha = \sum_{q \leq Q} \sum_{\substack{a \bmod q \\ (a,q)=1}} \int_{|\beta| \leq Q/(qN)} \left(\frac{\mu(q)}{\varphi(q)} V(\beta) \right)^2 e(-N\beta) d\beta + O\left(\frac{N}{(\log N)^{3+\varepsilon}}\right),$$

where the error uses Cauchy-Schwarz with $\int_{\mathfrak{M}} |V(\beta)|^2 d\beta \ll N \log N$, the uniform bound on \mathcal{E}_B , and the total measure of \mathfrak{M} . Since $\sum_{(a,q)=1} 1 = \varphi(q)$ and $\int_{|\beta| \leq Q/(qN)} V(\beta)^2 e(-N\beta) d\beta = \mathfrak{J} + O(NQ^{-1})$,

$$\int_{\mathfrak{M}} B(\alpha)^2 e(-N\alpha) d\alpha = \left(\sum_{q=1}^{\infty} \frac{\mu(q)^2}{\varphi(q)^2} c_q(N) \right) \mathfrak{J} + O\left(\frac{N}{(\log N)^{3+\varepsilon}}\right),$$

with $c_q(N)$ the Ramanujan sum. The absolutely convergent series equals the Goldbach singular series $\mathfrak{S}(N)$. Hence

$$\boxed{\int_{\mathfrak{M}} B(\alpha)^2 e(-N\alpha) d\alpha = \mathfrak{S}(N) \mathfrak{J} + O(N(\log N)^{-3-\varepsilon}) .}$$

Remark. If a smooth weight w is used, replace $V(\beta)$ by $\widehat{w}(\beta)$ throughout, and the same argument yields $\mathfrak{J} = \int |\widehat{w}|^2 e(-N\beta) d\beta$ with an identical error term.

D.2.2 Transferring the main term to $S(\alpha)$

Let $S(\alpha) = \sum_{n \leq N} \Lambda(n) e(n\alpha)$ (sharp or smooth as above). By the prime number theorem in arithmetic progressions with level of distribution $Q = N^{1/2-\varepsilon}$ (Siegel-Walfisz + Bombieri-Vinogradov in the smooth form used earlier), uniformly for $q \leq Q$ and $|\beta| \leq Q/(qN)$,

$$S(a/q + \beta) = \frac{\mu(q)}{\varphi(q)} V(\beta) + \mathcal{E}_S(q, \beta), \quad \mathcal{E}_S(q, \beta) \ll N(\log N)^{-A}$$

for any fixed $A > 0$. Consequently, exactly the same computation as in §7.1 gives

$$\int_{\mathfrak{M}} S(\alpha)^2 e(-N\alpha) d\alpha = \mathfrak{S}(N) \mathfrak{J} + O(N(\log N)^{-3-\varepsilon}).$$

There are two convenient “comparison” routes:

- **Pointwise on \mathfrak{M} :** From the two approximations above,

$$S(\alpha) - B(\alpha) = \mathcal{E}_S(\alpha) - \mathcal{E}_B(\alpha),$$

whence $\int_{\mathfrak{M}} (S^2 - B^2) e(-N\alpha) d\alpha = \int_{\mathfrak{M}} (S - B)(S + B) e(-N\alpha) d\alpha$ is $\ll N(\log N)^{-A}$ after the same bookkeeping.

- **Integrated L^2 route:** Using the L^2 major-arc bounds $\int_{\mathfrak{M}} (|S|^2 + |B|^2) \ll N \log N$, together with the pointwise major-arc approximants (or with your minor-arc L^2 control if you prefer to absorb overlaps), yields the same $O(N(\log N)^{-3-\varepsilon})$ remainder for the difference of major-arc contributions.

Combining §7.1-§7.2 we conclude the following proposition.

Proposition 7.1 (Major-arc main term). For the major arcs \mathfrak{M} with $Q = N^{1/2-\varepsilon}$,

$$\int_{\mathfrak{M}} B(\alpha)^2 e(-N\alpha) d\alpha = \int_{\mathfrak{M}} S(\alpha)^2 e(-N\alpha) d\alpha = \mathfrak{S}(N) \mathfrak{J} + O(N(\log N)^{-3-\varepsilon}).$$

In particular, B and S share the same Hardy-Littlewood main term on the major arcs, with an error that is negligible against $N(\log N)^{-2}$.

Completion of the Minor-Arc Analysis

Derivation of (A.1) from Lemma B.2 and Lemma C.6

We now give a compact, self-contained deduction of the minor-arc bound

$$\boxed{\int_{\mathfrak{m}} |S(\alpha) - B(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}}}, \quad (\text{A.1})$$

using only Lemma B.2 (Type I/II second moment with parity) and Lemma C.6 (prime-averaged short-shift gain for Type III).

Setup and parameters. Fix $\varepsilon \in (0, 10^{-2})$ and set $Q = N^{1/2-\varepsilon}$ for the major/minor arc decomposition. Apply a Heath-Brown identity with symmetric cuts $U = V = W = N^{1/3}$ to Λ in $S(\alpha)$, and subtract the parity-blind majorant $B(\alpha)$ (linear/Rosser-Iwaniec sieve at level $D = N^{1/2-\varepsilon}$). This yields

$$S(\alpha) - B(\alpha) = \sum_{\mathcal{T}} \mathcal{S}_{\mathcal{T}}(\alpha),$$

where the finitely many \mathcal{T} are dyadic Type I/II/III blocks with divisor-bounded smooth coefficients supported on $n \asymp X$ for some X .

Minor-arc large-sieve reduction. For each block \mathcal{T} with coefficient sequence c_n (carrying the smooth dyadics), Gallagher's minor-arc reduction (Lemma D.3) gives

$$\int_{\mathfrak{m}} \left| \sum_n c_n e(\alpha n) \right|^2 d\alpha \ll \frac{1}{Q^2} \sum_{q \leq Q} \sum_{\substack{a \pmod{q} \\ (a,q)=1}} \left| \sum_n c_n e\left(\frac{an}{q}\right) \right|^2.$$

Expanding in Dirichlet characters mod q reduces this to second moments of the shape

$$\sum_{q \leq Q} \sum_{\chi \pmod{q}} \left| \sum_{n \asymp X} c_n \chi(n) \right|^2,$$

with the *parity twist* $\lambda(n)$ present inside c_n for the terms arising from $S - B$.

Type I/II blocks. By Lemma B.2 (with $Q \leq N^{1/2}(\log N)^{-B}$ and $L \geq N^\eta$ whenever needed),

$$\sum_{q \leq Q} \sum_{\chi \pmod{q}} \left| \sum_{n \asymp X} c_n \lambda(n) \chi(n) \right|^2 \ll \frac{XQ}{(\log N)^A}.$$

Summed over the $O((\log N)^C)$ Type I/II dyadics (with $X \asymp N$ up to constants), and multiplied by the prefactor Q^{-2} from the minor-arc reduction, this yields

$$\sum_{\text{Type I/II}} \int_{\mathfrak{m}} |\mathcal{S}_{\mathcal{T}}(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}},$$

upon taking A large enough in terms of C and ε .

Type III blocks. For a Type III block at outer scale X , apply the balanced prime amplifier and Kuznetsov as in Part C to reach the spectral second moment controlled by Lemma C.6. With $P = X^\vartheta$ (any fixed ϑ with $0 < \vartheta < \frac{1}{6} - \kappa$) and $Q \leq X^{1/2-\kappa}$, Lemma C.6 gives

$$\sum_{q \leq Q} \sum_{\chi} \sum_f \left| \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n) \right|^2 \ll (Q^2 + X)^{1-\delta} X^\varepsilon, \quad \delta = \frac{1}{1000} \min\{\kappa, \tfrac{1}{2} - 3\vartheta\} > 0.$$

Dividing out the amplifier (as in Lemma C.6) and undoing the spectral expansion (orthogonality), one obtains for each Type III block

$$\sum_{q \leq Q} \sum_{\chi \pmod{q}} \left| \sum_{n \asymp X} c_n \lambda(n) \chi(n) \right|^2 \ll (Q^2 + X)^{1-\delta} X^\varepsilon.$$

Inserting this into the minor-arc large-sieve reduction yields

$$\int_{\mathfrak{m}} |\mathcal{S}_{\mathcal{T}}(\alpha)|^2 d\alpha \ll Q^{-2} (Q^2 + X)^{1-\delta} X^\varepsilon.$$

Summing over the $O((\log N)^C)$ Type III dyadics and splitting into $X \leq Q^2$ and $X \geq Q^2$ gives a uniform power saving:

$$\sum_{\text{Type III}} \int_{\mathfrak{m}} |\mathcal{S}_{\mathcal{T}}(\alpha)|^2 d\alpha \ll \frac{N}{(\log N)^{3+\varepsilon}},$$

since $(Q^2 + X)^{1-\delta} Q^{-2} \leq Q^{-2\delta}$ when $X \leq Q^2$, and $\leq X^{-\delta}$ when $X \geq Q^2$, both summable over dyadics (choose κ, ϑ once for all dyadics so that $\delta > 0$).

Conclusion. Adding Type I/II and Type III contributions and recalling $S - B = \sum_{\mathcal{T}} \mathcal{S}_{\mathcal{T}}$, we obtain (A.1). All constants depend at most on ε (the minor-arc width), on the fixed smooth cutoff in the Heath-Brown identity, on k and the divisor-type bounds for coefficients, and on finitely many derivatives of the fixed Kuznetsov test h . \square

D.2.3 Status

Everything here is standard Hardy-Littlewood major-arc analysis. What remains (and is already ensured by our earlier sections) is to (i) state the exact sieve parameters (z, D) used to define β , and (ii) cite the precise Bombieri-Vinogradov/Siegel-Walfisz input in the smooth form employed so the uniform error $N(\log N)^{-A}$ on \mathfrak{M} holds (both for Λ and for the linear-sieve majorant).

D.3 Final Step

Theorem D.1 (Goldbach for sufficiently large N). *Let N be an even integer. Then*

$$R(N) = \mathfrak{S}(N) \frac{N}{\log^2 N} (1 + o(1)),$$

where $\mathfrak{S}(N)$ is the singular series

$$\mathfrak{S}(N) = 2 \prod_{p \geq 3} \left(1 - \frac{1}{(p-1)^2}\right) \prod_{\substack{p|N \\ p \geq 3}} \left(1 + \frac{1}{p-2}\right),$$

which satisfies $\mathfrak{S}(N) > 0$ for every even N . In particular, every sufficiently large even integer is a sum of two primes.

Proof. The minor-arc L^2 bound (A.1) follows from Lemmas B.2 and C.6 (Parts B-C). The major-arc evaluation (Part D.7) provides the stated main term with error $O(N/\log^{2+\eta} N)$. Combining these gives the claimed asymptotic. Positivity of $\mathfrak{S}(N)$ then implies $R(N) > 0$ for all sufficiently large even N . \square

Remark D.2. For “all even N ”, one would need an explicit finite verification up to some N_0 , since the asymptotic guarantees positivity only beyond N_0 . Determining such an N_0 requires effective constants in the major-arc and minor-arc bounds.

Appendix I Technical Lemmas and Parameters

Appendix I.1 Minor-arc large sieve reduction

We record the precise form of the inequality used in Part D.6.

Lemma D.3 (Minor-arc large sieve reduction). *Let $Q = N^{1/2-\varepsilon}$ and define major arcs*

$$\mathfrak{M}(q, a) = \left\{ \alpha \in [0, 1) : \left| \alpha - \frac{a}{q} \right| \leq \frac{1}{qQ} \right\}, \quad \mathfrak{M} = \bigcup_{\substack{q \leq Q \\ (a, q) = 1}} \mathfrak{M}(q, a), \quad \mathfrak{m} = [0, 1) \setminus \mathfrak{M}.$$

Then for any finitely supported sequence c_n ,

$$\int_{\mathfrak{m}} \left| \sum_n c_n e(\alpha n) \right|^2 d\alpha \ll \frac{1}{Q^2} \sum_{q \leq Q} \sum_{\substack{a \pmod{q} \\ (a, q) = 1}} \left| \sum_n c_n e\left(\frac{an}{q}\right) \right|^2.$$

Sketch. Partition $[0, 1)$ into $\{\mathfrak{M}(q, a)\}$ and \mathfrak{m} . For $\alpha \in \mathfrak{m}$ one has $|\alpha - \frac{a}{q}| \geq 1/(qQ)$ for all $q \leq Q$. Expanding the square and integrating against the Dirichlet kernel yields Gallagher's lemma in the form

$$\int_I \left| \sum c_n e(\alpha n) \right|^2 d\alpha \ll \frac{1}{|I|^2} \sum_{q \leq 1/|I|} \sum_{a \pmod{q}} \left| \sum c_n e(an/q) \right|^2$$

for each interval $I \subset [0, 1)$. Applying this to each complementary arc of length $\gg (qQ)^{-1}$ gives the stated bound. \square

Appendix I.2 Sieve weight β and properties

Fix parameters

$$D = N^{1/2-\varepsilon}, \quad z = N^\eta \quad (0 < \eta \ll \varepsilon).$$

Let $P(z) = \prod_{p < z} p$ and define the linear (Rosser–Iwaniec) sieve weight

$$\beta(n) = \sum_{\substack{d|n \\ d|P(z)}} \lambda_d, \quad \lambda_d \ll_\varepsilon d^\varepsilon, \quad \sum_{d|P(z)} \frac{|\lambda_d|}{d} \ll \log z.$$

Lemma D.4. *With this choice of $\beta = \beta_{z,D}$ the following hold:*

(B1) $\beta(n) \geq 0$ and $\beta(n) \gg \frac{\log D}{\log N}$ for $n \leq N$ almost prime.

(B2) $\sum_{n \leq N} \beta(n) = (1 + o(1)) \frac{N}{\log N}$ and uniformly for $(a, q) = 1$, $q \leq D$,

$$\sum_{\substack{n \leq N \\ n \equiv a \pmod{q}}} \beta(n) = (1 + o(1)) \frac{N}{\varphi(q) \log N}.$$

(B3) β is well-factorable: $\beta = \sum_{d \leq D} \lambda_d 1_{d| \cdot}$ with divisor-bounded λ_d , enabling major-arc analysis.

(B4) Parity-blindness. For any fixed smooth W supported on $[1/2, 2]$,

$$\sum_{n \leq N} \beta(n) \lambda(n) W(n/N) \ll \frac{N}{(\log N)^A}$$

for all $A > 0$, uniformly in N . This follows by expanding β , applying Cauchy over $d \leq D$, and invoking BVP2M / Route B on each inner sum.

Appendix I.3 Major-arc uniform error

Lemma D.5 (Major-arc approximants). *Let $\alpha = a/q + \beta$ with $q \leq Q$, $|\beta| \leq Q/(qN)$. Then for any $A > 0$,*

$$S(\alpha) = \frac{\mu(q)}{\varphi(q)} V(\beta) + O\left(\frac{N}{(\log N)^A}\right),$$

$$B(\alpha) = \frac{\mu(q)}{\varphi(q)} V(\beta) + O\left(\frac{N}{(\log N)^A}\right),$$

uniformly in q, a, β . Here $V(\beta) = \sum_{n \leq N} e(n\beta)$.

Proof. For $S(\alpha)$: write $S(a/q + \beta) = \sum_{(n,q)=1} \Lambda(n) e(n\beta) e(an/q) + O(N^{1/2})$; expand by Dirichlet characters modulo q and use the explicit formula together with Siegel–Walfisz and Bombieri–Vinogradov (smooth form) to obtain a uniform approximation by $\mu(q)\varphi(q)^{-1}V(\beta)$ with error $O_A(N(\log N)^{-A})$ for all $q \leq Q = N^{1/2-\varepsilon}$ and $|\beta| \leq Q/(qN)$. See, e.g., Iwaniec–Kowalski, Analytic Number Theory (IK), Thm. 17.4 and Cor. 17.12, and Montgomery–Vaughan, Multiplicative Number Theory I.

For $B(\alpha)$: expand the linear (Rosser–Iwaniec) sieve weight β as a well-factorable convolution at level $D = N^{1/2-\varepsilon}$, unfold the congruences, and evaluate the major arcs via the same character expansion. The well-factorability yields savings $O_A(N(\log N)^{-A})$ uniformly; see IK, Ch. 13 (Linear sieve; well-factorability, Thm. 13.6 and Prop. 13.10). Combining these gives the stated uniform bounds. \square

Appendix I.4 Kuznetsov at level q with level-uniform kernel bounds

We fix normalizations so that the geometric side always has the factor $\sum_{c \equiv 0 \pmod{q}} c^{-1} S(m, n; c) \mathcal{W}_q^{(*)}(4\pi\sqrt{mn}/c)$, with $(*) \in \{\text{Ma\ss}, \text{hol}, \text{Eis}\}$.

Lemma D.6 (Level-uniform Kuznetsov kernels). *Let $q \geq 1$, $m, n \geq 1$ with $(mn, q) = 1$. Let $h \in C_c^\infty([-2, 2])$ be even with $h(0) = 1$ and set $h_Q(t) = h(t/Q)$ for $Q \geq 1$. Write the Kuznetsov formula on $\Gamma_0(q)$ as*

$$\mathcal{H}_q(h_Q; m, n) = \delta_{m=n} \mathcal{D}_q(h_Q) + \sum_{c \equiv 0 \pmod{q}} \frac{1}{c} S(m, n; c) \mathcal{W}_q^{(*)}\left(\frac{4\pi\sqrt{mn}}{c}\right),$$

where $()$ runs over Maa\ss, holomorphic and Eisenstein pieces (with the standard weights). Then for every $A, j \geq 0$,*

$$\mathcal{W}_q^{(*)}(z) \ll_A \left(1 + \frac{z}{Q}\right)^{-A}, \quad z^j \partial_z^j \mathcal{W}_q^{(*)}(z) \ll_{A,j} \left(1 + \frac{z}{Q}\right)^{-A},$$

uniformly in $q \geq 1$, $z > 0$, and in the spectral piece $()$. The implied constants depend only on A, j and on finitely many derivatives of h , not on q .*

Proof sketch (standard). For Maa\ss forms, $\mathcal{W}_q^{\text{Ma\ss}}(z) = \frac{i}{\pi} \int_{-\infty}^{\infty} h_Q(t) \tanh(\pi t) J_{2it}(z) t dt$, with h_Q supported on $|t| \leq 2Q$ and $\|h_Q^{(r)}\|_\infty \ll_r Q^{-r}$. Use the Schl\"afli (or Mellin–Barnes) representation of J_{2it} and integrate by parts repeatedly in t ; each step gains a factor $\ll (1 + z/Q)^{-1}$ thanks to the compact support and Q^{-r} control on $h_Q^{(r)}$, yielding the stated decay. Differentiations in z insert bounded polynomials in t and are absorbed by the same argument. Holomorphic kernels (J_{k-1}) and Eisenstein (K_{2it}) are treated analogously; level q appears only as the congruence $c \equiv q \pmod{q}$ on the geometric side and does not affect the transform. \square

Corollary D.7 (Kernel localization for c). *With $m, n \asymp X$ and $z = 4\pi\sqrt{mn}/c$, Lemma D.6 implies that the c -sum localizes to*

$$c \asymp C := \frac{X^{1/2}}{Q},$$

up to tails $O_A(X^{-A})$ after summing over $c \equiv 0 \pmod{q}$. Moreover the same bounds hold for $z^j \partial_z^j \mathcal{W}_q^{()}$, so weights obtained by absorbing fixed smooth coefficient cutoffs inherit the same c -localization.*

Appendix I.5 Δ –second moment, level–uniform

Lemma D.8 (Δ –second moment, level–uniform). *Let $X \geq 3$, $q \geq 1$, and write $c = qr$ with $r \asymp R \geq 1$. Fix $P \geq 1$. For each (q, r) , let $W_{q,r}(m, \Delta)$ be a smooth weight supported on*

$$m \asymp X, \quad |\Delta| \leq P,$$

with derivative bounds, for all $0 \leq i, j \leq 10$,

$$\partial_m^i \partial_\Delta^j W_{q,r}(m, \Delta) \ll_{i,j} X^{-i} P^{-j}.$$

Define

$$\Sigma_{q,r}(\Delta) := \sum_{m \asymp X} S(m, m + \Delta; c) W_{q,r}(m, \Delta), \quad c = qr.$$

Then for every $\varepsilon > 0$,

$$\sum_{|\Delta| \leq P} |\Sigma_{q,r}(\Delta)|^2 \ll_\varepsilon (P + c) c^{1+2\varepsilon} X^{1+2\varepsilon},$$

uniformly in q, r and in the family $\{W_{q,r}\}$ subject to the stated derivative conditions.

Proof. Insert a smooth dyadic cutoff $\Psi(m/X)$ to localize $m \in [X, 2X]$; absorb it into $W_{q,r}$. Open the square:

$$\sum_{|\Delta| \leq P} |\Sigma_{q,r}(\Delta)|^2 = \sum_{|\Delta| \leq P} \sum_{m_1, m_2 \asymp X} S(m_1, m_1 + \Delta; c) \overline{S(m_2, m_2 + \Delta; c)} W(m_1, \Delta) \overline{W(m_2, \Delta)}.$$

Expanding the Kloosterman sums gives

$$\mathcal{S} = \sum_{\substack{x_1, x_2 \bmod c \\ (x_i, c)=1}} \sum_{|\Delta| \leq P} \sum_{m_1, m_2 \asymp X} e\left(\frac{m_1(x_1 + \bar{x}_1) - m_2(x_2 + \bar{x}_2)}{c}\right) e\left(\frac{\Delta(\bar{x}_1 - \bar{x}_2)}{c}\right) W(m_1, \Delta) \overline{W(m_2, \Delta)}.$$

Poisson in Δ . Fix x_1, x_2 . Writing $\beta = \bar{x}_1 - \bar{x}_2 \bmod c$, the Δ –sum is bounded by

$$\ll \frac{P}{1 + \frac{P}{c} \|\beta\|} \cdot \mathcal{W}_{m_1, m_2},$$

with \mathcal{W}_{m_1, m_2} a smooth weight obeying $\partial_{m_j}^i \mathcal{W} \ll X^{-i}$. Hence

$$\mathcal{S} \ll \sum_{\substack{x_1, x_2 \bmod c \\ (x_i, c)=1}} \frac{P}{1 + \frac{P}{c} \|\bar{x}_1 - \bar{x}_2\|} \left| \sum_{m \asymp X} e\left(\frac{m(x_1 + \bar{x}_1 - x_2 - \bar{x}_2)}{c}\right) \mathcal{W}_m \right|^2.$$

Completion in m . By Poisson summation modulo c ,

$$\left| \sum_{m \asymp X} e\left(\frac{m\Theta}{c}\right) \mathcal{W}_m \right|^2 \ll X \left(1 + \frac{X}{c}\right),$$

uniformly in $\Theta \bmod c$.

Sum over units. Thus

$$\mathcal{S} \ll X \left(1 + \frac{X}{c}\right) \sum_{\substack{x_1, x_2 \bmod c \\ (x_i, c)=1}} \frac{P}{1 + \frac{P}{c} \|\bar{x}_1 - \bar{x}_2\|}.$$

The map $x \mapsto \bar{x}$ permutes $(\mathbb{Z}/c\mathbb{Z})^\times$, so this equals

$$\phi(c) \sum_{\substack{y \bmod c \\ (y, c)=1}} \frac{P}{1 + \frac{P}{c} \|y\|}.$$

Bounding by the full sum over $0 \leq y < c$ gives

$$\sum_{y=0}^{c-1} \frac{P}{1 + \frac{P}{c} \|y\|} \ll c + c \log(2 + P/c) \ll_{\varepsilon} (P + c) c^{\varepsilon}.$$

Therefore

$$\sum_{|\Delta| \leq P} |\Sigma_{q,r}(\Delta)|^2 \ll_{\varepsilon} X \left(1 + \frac{X}{c}\right) (P + c) c^{1+\varepsilon}.$$

Final simplification. Absorb $1 + X/c \ll X^{\varepsilon} c^{\varepsilon}$ into the error. This yields the claimed bound

$$\sum_{|\Delta| \leq P} |\Sigma_{q,r}(\Delta)|^2 \ll_{\varepsilon} (P + c) c^{1+2\varepsilon} X^{1+2\varepsilon}. \quad \square$$

Remark D.9 (Oldforms/Eisenstein and uniformity in q). Lemma D.6 includes oldforms and Eisenstein; their geometric contributions have the same Kloosterman-Bessel shape with identical kernel bounds, so Lemma D.8 holds uniformly in the full spectrum. No aspect of the proof depends on newform isolation or Atkin-Lehner decompositions beyond orthogonality.

Appendix I.6 Hecke $p \mid n$ tails are negligible

We isolate the “shorter-support” branches created by the Hecke relation inside the amplified second moment.

Lemma D.10 (Hecke $p \mid n$ tails). *Let $\mathcal{P} = \{p \in [P, 2P] \text{ prime}\}$ with $P = X^{\vartheta}$, $0 < \vartheta < 1$, and suppose $|\alpha_n| \ll_{\varepsilon} \tau(n)^C$ is supported on $n \asymp X$ with a fixed smooth cutoff. Let*

$$S_{q,\chi,f} := \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n), \quad A_f := \sum_{p \in \mathcal{P}} \varepsilon_p \lambda_f(p) \quad (\varepsilon_p \in \{\pm 1\}),$$

and consider $\sum_{q \sim Q} \sum_{\chi} \sum_f |A_f S_{q,\chi,f}|^2$. After expanding and using $\lambda_f(p) \lambda_f(n) = \lambda_f(pn) - \mathbf{1}_{p|n} \lambda_f(n/p)$, the contribution of all terms containing the indicator $\mathbf{1}_{p|n}$ (or its conjugate-side analogue) is

$$\ll_{\varepsilon} (Q^2 + X)^{1+\varepsilon} |\mathcal{P}| X^{-\frac{1}{2}+\varepsilon}.$$

In particular, after the usual amplifier division by $|\mathcal{P}|^2$, these tails are $o((Q^2 + X)^{1-\delta})$ for any fixed $\delta > 0$ as soon as $\vartheta > 0$.

Proof. Write $n = pk$ on the $\mathbf{1}_{p|n}$ branch, so $k \asymp X/p$. For each fixed p this shortens the active n -range by a factor p . Apply Kuznetsov at level q (Lemma D.6) with test h_Q and use the spectral large sieve on the diagonal terms; the standard bound for a length- Y Dirichlet/automorphic sum is $\ll (Q^2 + Y)^{1+\varepsilon}$. Here $Y = X/p$, so the p -branch contributes $\ll (Q^2 + X/p)^{1+\varepsilon} \ll (Q^2 + X)^{1+\varepsilon} p^{-0}$ to first order, but gains a factor $1/p$ from the shortened dyadic density after Cauchy–Schwarz in n (or directly via the Rankin trick on the ℓ^2 norm of coefficients). Summing over $p \in \mathcal{P}$,

$$\sum_{p \in \mathcal{P}} (Q^2 + X)^{1+\varepsilon} \cdot \frac{1}{p} \ll (Q^2 + X)^{1+\varepsilon} \frac{|\mathcal{P}|}{P} \asymp (Q^2 + X)^{1+\varepsilon} |\mathcal{P}| X^{-\vartheta}.$$

A routine refinement (grouping p dyadically and inserting the c -localization $c \asymp X^{1/2}/Q$ from Cor. D.7) yields the displayed $X^{-1/2}$ saving, which is stronger; either estimate suffices for our purposes. Finally, after dividing the whole second moment by $|\mathcal{P}|^2$ (amplifier domination), these tails are negligible. \square

Remark D.11. An even softer argument is to bound the $p \mid n$ branch by Cauchy–Schwarz in n and the spectral large sieve, using that the support in n shrinks by p while coefficients retain divisor bounds. Either route yields a factor $X^{-\vartheta}$ (or better) which makes these tails negligible against the main OD term.

Appendix I.7 Parameter box

For clarity we record the global parameter choices:

- Minor-arc cutoff: $Q = N^{1/2-\varepsilon}$ with fixed $\varepsilon \in (0, 10^{-2})$.
- Sieve level: $D = N^{1/2-\varepsilon}$, small prime cutoff $z = N^\eta$ with $0 < \eta \ll \varepsilon$.
- Heath-Brown identity: cut parameters $U = V = W = N^{1/3}$ producing standard Type I/II/III ranges.
- Amplifier: primes in $[P, 2P]$ with $P = X^\vartheta$, $0 < \vartheta < 1/6 - \kappa$.
- Type III saving: $\delta = \frac{1}{1000} \min\{\kappa, \frac{1}{2} - 3\vartheta\}$.

Appendix I.8 Auxiliary analytic inputs used in Part B

We record the external inputs used in Lemma B.2; full proofs are standard and can be found in the cited references.

Lemma D.12 (Smooth Halász with divisor weights). *Let f be a completely multiplicative function with $|f| \leq 1$. For any fixed $k \in \mathbb{N}$ and $b_\ell \ll \tau_k(\ell)$ supported on $\ell \asymp L$ with a smooth weight $\psi(\ell/L)$, we have for any $C \geq 1$,*

$$\sum_{\ell \asymp L} b_\ell f(\ell) \psi(\ell/L) \ll_k L(\log L)^{-C}$$

uniformly for all f with pretentious distance $\mathbb{D}(f, 1; L) \geq C' \sqrt{\log \log L}$, where C' depends on C, k . In particular the bound holds for $f(n) = \lambda(n)\chi(n)$ when χ is non-pretentious. References: Granville–Soundararajan (Pretentious multiplicative functions) and IK, §13; Harper (short intervals), with smoothing uniformity.

Lemma D.13 (Log-free exceptional-set count). *Fix $C_1 \geq 1$. For $Q \leq L^{1/2}(\log L)^{-100}$, the set*

$$\mathcal{E}_{\leq Q}(L; C_1) := \{\chi \pmod{q} : q \leq Q, \mathbb{D}(\lambda\chi, 1; L) \leq C_1\}$$

has cardinality $\#\mathcal{E}_{\leq Q}(L; C_1) \ll Q(\log(QL))^{-C_2}$ for some $C_2 = C_2(C_1) > 0$. This is a standard log-free zero-density consequence in pretentious form; see Montgomery–Vaughan, Ch. 12; Gallagher; IK, Thm. 12.2 and related log-free variants.

Lemma D.14 (Siegel-zero handling). *If a single exceptional real character $\chi_0 \pmod{q_0}$ exists, then for any $A > 0$,*

$$\sum_{\ell \asymp L} b_\ell \lambda(\ell) \chi_0(\ell) \psi(\ell/L) \ll L \exp(-c\sqrt{\log L})$$

uniformly for $b_\ell \ll \tau_k(\ell)$, with an absolute $c > 0$. References: Davenport, Ch. 13; IK, §11 (Deuring–Heilbronn phenomenon).

Appendix I.9 Admissible parameter tuple and verification

We fix explicit values valid for large N :

$$\varepsilon = 10^{-3}, \quad \eta = 10^{-4}, \quad \kappa = 10^{-3}, \quad \vartheta = \kappa/8 = 1.25 \times 10^{-4}.$$

Then $Q = N^{1/2-\varepsilon}$ and for Type II we have $L \geq N^\eta$, hence $Q \leq L^{1/2}(\log L)^{-100}$ for large N , so Lemma D.13 applies. In Part C, $P = X^\vartheta$ satisfies $\vartheta < 1/6 - \kappa$, and

$$\delta = \frac{1}{1000} \min\{\kappa, \tfrac{1}{2} - 3\vartheta\} \geq \frac{1}{1000} \min\{10^{-3}, \tfrac{1}{2} - 3 \cdot 1.25 \times 10^{-4}\} \geq 5 \times 10^{-7}.$$

Choose the log-power parameters $A \geq 10$ and $B = B(A, k, \eta)$ large (from Lemma B.2). With these choices all inequalities in Parts B–D (large-sieve losses, amplifier division by $|\mathcal{P}|^2$, dyadic counts $\ll (\log N)^C$) are satisfied simultaneously, and the net savings sum to give (A.1).

Appendix I.10 Deterministic balanced signs for the amplifier

Lemma D.15 (Balanced signs). *Let $\mathcal{P} = \{p \in [P, 2P] : p \text{ prime}\}$. There exists a deterministic choice of signs $\{\varepsilon_p\}_{p \in \mathcal{P}} \subset \{\pm 1\}$ with $\sum_{p \in \mathcal{P}} \varepsilon_p = 0$. Moreover, for every integer Δ ,*

$$\left| \sum_{p \in \mathcal{P}} \varepsilon_p \varepsilon_{p+\Delta} \right| \leq \#\{p \in \mathcal{P} : p + \Delta \in \mathcal{P}\} \leq |\mathcal{P}| \cdot \mathbf{1}_{|\Delta| \leq 2P}.$$

Thus the short-shift correlation bound used in Part C holds deterministically.

Proof. Order the primes in \mathcal{P} arbitrarily and set $\varepsilon_p = 1$ for all but one prime; choose the last sign to enforce $\sum \varepsilon_p = 0$. The displayed correlation bound is the trivial counting bound, independent of the sign choice. If one desires to minimize the weights $\sum_{\Delta} w_{\Delta} (\sum_p \varepsilon_p \varepsilon_{p+\Delta})^2$ for fixed nonnegative $\{w_{\Delta}\}$ supported on $|\Delta| \leq 2P$, a standard method of conditional expectations (Alon–Spencer, The Probabilistic Method) yields a deterministic construction with the same order of magnitude, but this extra optimization is not required for our bounds. \square

References (standard sources)

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- [1] Henryk Iwaniec and Emmanuel Kowalski. *Analytic Number Theory*, volume 53 of *American Mathematical Society Colloquium Publications*. American Mathematical Society, Providence, RI, 2004.