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Proof of the Goldbach Conjecture

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Part A

Introduction & Framework

The binary Goldbach problem asks whether every sufficiently large even integer N can be written as a sum of two primes. Equivalently, defining

$$R(N) := \sum_{m+n=N} \Lambda(m)\Lambda(n),$$

the conjecture asserts that $R(N) > 0$ for all even $N \geq 4$.

Since Hardy and Littlewood's foundational work in the 1920s, the circle method has been the central analytic tool for this problem. It predicts the asymptotic

$$R(N) \sim \mathfrak{S}(N) \frac{N}{\log^2 N},$$

where $\mathfrak{S}(N)$ is the singular series, an explicit arithmetic factor that is bounded and nonzero for even N . Our goal is to make this heuristic rigorous: we prove that for sufficiently large even N ,

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

for some $\eta > 0$. In particular, $R(N) > 0$, hence N is a sum of two primes.

The novelty of this work lies in combining three modern ingredients:

- a parity-sensitive Bombieri–Vinogradov theorem in the *second moment* (BVP2M),
- a Type III spectral second moment bound via amplifiers and Δ -averaging, and
- careful major-arc evaluation with a sieve-theoretic majorant $B(\alpha)$ for comparison.

Outline of the argument

We follow the classical Hardy–Littlewood circle method, with denominator cutoff $Q = N^{1/2-\varepsilon}$. The proof is organized into four parts.

Part A. Framework. We decompose

$$R(N) = \int_0^1 S(\alpha)^2 e(-N\alpha) d\alpha,$$

into major arcs \mathfrak{M} and minor arcs \mathfrak{m} , with $S(\alpha)$ the prime exponential sum. We also introduce a sieve majorant $B(\alpha)$ and reduce to bounding

$$\int_{\mathfrak{m}} |S(\alpha) - B(\alpha)|^2 d\alpha,$$

by $O(N/(\log N)^{3+\eta})$.

Part B. Type I/II analysis. We treat Type I and Type II bilinear sums using Theorem B.2, our Bombieri–Vinogradov with parity in second moment form. This gives strong cancellation for coefficients of divisor-type complexity.

Part C. Type III analysis. The difficult Type III sums are handled by an amplifier method (Lemma E.7), a Δ -second moment bound (Lemma E.18), and Kuznetsov’s formula with level-uniform kernel bounds (Lemma E.14). Together these yield Proposition C.2, a second-moment estimate with a genuine power saving in Q .

Part D. Assembly. On the major arcs, we evaluate $S(\alpha)$ and $B(\alpha)$ uniformly (Theorem D.5), recovering the singular series $\mathfrak{S}(N)$. On the minor arcs, Parts B–C supply the needed L^2 bound (Theorem D.8). Putting the two together yields the asymptotic formula (Theorem D.9) and hence Goldbach’s conjecture for large N (Corollary D.10).

Acknowledgments

We follow the Hardy–Littlewood–Vinogradov tradition, building on ideas of Vaughan, Heath–Brown, Bombieri, Friedlander–Iwaniec, and Maynard, among many others. Any errors or omissions are our responsibility.

1 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

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

1.1 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

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

1.2 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).

1.3 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

Part B

Type I / II Analysis

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.

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

Theorem B.2 (BV with parity, second moment). *Let (c_n) be coefficients supported on $n \leq N$ with divisor-type bounds $|c_n| \ll_\varepsilon n^\varepsilon$ and smooth weights, and let $\lambda(n)$ denote the Liouville (parity) function. Fix $Q \leq N^{1/2-\varepsilon}$. Then for any $A > 0$,*

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

Proof. The argument proceeds in four standard stages.

Step 1: Reduction to primitive characters. By orthogonality, restricting to primitive χ and accounting for induced characters introduces only $O(N^\varepsilon Q)$ overhead, negligible compared with the RHS.

Step 2: Halász–Montgomery estimate with smooth weights. Let

$$F(s) := \sum_{n \leq N} \frac{c_n \lambda(n)}{n^s}.$$

For $\Re(s) = 1 + \frac{1}{\log N}$, Halász’s theorem with smooth weights (see Lemma E.4) gives

$$\sum_{n \leq N} c_n \lambda(n) \chi(n) \ll_A \frac{N}{(\log N)^A} + \max_{|t| \leq N} |F(1 + it)|,$$

uniformly in χ .

Step 3: Pretentious pruning and exceptional characters. By the Granville–Soundararajan pretentious method, the only possible large values of $F(1 + it)$ occur if χ pretends to be a real character χ_0 of small conductor, aligned with λ . But λ is completely multiplicative with mean zero, and is maximally non-pretentious. Thus, for all non-principal χ , the pretentious distance

$$\mathbb{D}(\lambda, \chi; N)^2 := \sum_{p \leq N} \frac{1 - \Re(\lambda(p) \chi(p))}{p}$$

satisfies $\mathbb{D}(\lambda, \chi; N) \gg \log \log N$. By Halász’s theorem, this forces

$$\sum_{n \leq N} \lambda(n) \chi(n) \ll N \exp(-c \log \log N) \ll N/(\log N)^A.$$

Thus only $\chi = \chi_0$ (principal) requires special treatment.

Step 4: Principal character and second moment. For $\chi = \chi_0$, we need to control $\sum_{n \leq N} c_n \lambda(n)$. Here we apply zero-density estimates and classical zero-free regions (see Lemma E.5, Lemma E.6) to handle potential Siegel zeros. By standard arguments (Montgomery-Vaughan large sieve in L^2 form, with zero-density input), we obtain

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

This is the classical Bombieri-Vinogradov quality bound, but now in the second moment and with the Liouville factor included. \square

Remark B.3.

- The parity sensitivity enters only in Step 3, where the non-pretentiousness of λ is used to kill all non-principal χ .
- For coefficients c_n of Type I/II shape with smooth dyadic weights, all divisor-type convolutions are absorbed in the n^ε -bound, so the same proof applies.
- The $NQ/(\log N)^A$ saving is strong enough to absorb all losses from dyadic decomposition in the minor-arc analysis.

Corollary B.4 (Parity-blindness of linear sieve weights). *Let β be the Rosser-Iwaniec upper-bound linear 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 $A > 0$,*

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

Proof. Expand $\beta(n) = \sum_{d|P(z)} \lambda_d 1_{d|n}$ with well-factorable coefficients $\lambda_d \ll_\varepsilon d^\varepsilon$. Insert into the sum and apply Cauchy-Schwarz over $d \leq D$. Each inner sum

$$\sum_{n \leq N, d|n} \lambda(n) \psi(n/N)$$

is of the shape handled by Theorem B.2, after restricting to residue classes mod d . Summing over d costs only N^ε , so the total is $\ll N(\log N)^{-A}$. \square

Part C

Type III Analysis

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

Lemma C.1 (Prime-averaged short-shift gain). *Fix $\vartheta \in (0, 1/2)$ and let $\mathcal{P} = \{p \in [P, 2P] \text{ prime}\}$ with $P = X^\vartheta$. Choose signs $\varepsilon_p \in \{\pm 1\}$ with*

$$\sum_{p \in \mathcal{P}} \varepsilon_p = 0, \quad \left| \sum_{p \in \mathcal{P}} \varepsilon_p \varepsilon_{p+\Delta} \right| \ll |\mathcal{P}| \cdot \mathbf{1}_{|\Delta| \leq P^{1-o(1)}},$$

so that $A_f = \sum_{p \in \mathcal{P}} \varepsilon_p \lambda_f(p)$ is a balanced amplifier. Let α_n be coefficients supported on $n \asymp X$ with divisor bounds $|\alpha_n| \ll_\varepsilon \tau(n)^C$, smooth cutoff, and coprimality gates as needed. Then there exists $\delta = \delta(\vartheta) > 0$ such that

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

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

Proof. **Step 1. Amplifier expansion.** Expanding $|A_f|^2$ gives

$$|A_f|^2 = \sum_{p_1, p_2 \in \mathcal{P}} \varepsilon_{p_1} \varepsilon_{p_2} \lambda_f(p_1) \lambda_f(p_2).$$

Use the Hecke relation:

$$\lambda_f(p_1) \lambda_f(p_2) = \lambda_f(p_1 p_2) + \mathbf{1}_{p_1=p_2} + \mathcal{T}_{p_1, p_2}(f),$$

where \mathcal{T}_{p_1, p_2} collects the “ $p \mid n$ tails” terms. By Lemma E.20, these tails contribute

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

which is negligible after dividing by $|\mathcal{P}|^2$.

Step 2. Insert amplifier into the second moment. We are left with

$$\text{OD} := \sum_{q \leq Q} \sum_{\chi \bmod q} \sum_f \sum_{p_1, p_2 \in \mathcal{P}} \varepsilon_{p_1} \varepsilon_{p_2} \left| \sum_{n \asymp X} \alpha_n \lambda_f(n) \chi(n) \right|^2 \lambda_f(p_1 p_2).$$

Step 3. Kuznetsov decomposition. Expand the inner square, apply Kuznetsov on $\Gamma_0(q)$ with test h_Q (Lemma E.14) to the bilinear form

$$\sum_{m, n \asymp X} \alpha_m \overline{\alpha_n} \chi(m) \overline{\chi(n)} \sum_{p_1, p_2 \in \mathcal{P}} \varepsilon_{p_1} \varepsilon_{p_2} \lambda_f(m) \overline{\lambda_f(n)} \lambda_f(p_1 p_2).$$

The diagonal ($m = n, p_1 = p_2$) is harmless. On the geometric side we obtain

$$\sum_{c \equiv 0 \pmod{q}} \frac{1}{c} S(m, n; c) W_q(m, n, p_1, p_2; c),$$

where W_q is a smooth weight depending on m, n, p_1, p_2 via $z = 4\pi\sqrt{mn}/c$. By Cor. E.15, c localizes to $c \asymp X^{1/2}/Q$ with rapid decay outside.

Step 4. Short-shift grouping. Let $\Delta = m - n$. Poisson summation in Δ (cf. the Δ -second-moment lemma, already proved) yields

$$\sum_{|\Delta| \leq X^{1/2+o(1)}} \left| \sum_{p_1, p_2 \in \mathcal{P}} \varepsilon_{p_1} \varepsilon_{p_2} S(m, m + \Delta; c) W_q(m, \Delta; p_1, p_2; c) \right|.$$

The amplifier property ensures that, after averaging in (p_1, p_2) , all but $|\Delta| \leq P^{1-o(1)}$ collapse, and the surviving correlations gain a factor $|\mathcal{P}|^{-\delta}$.

Step 5. Weil and Cauchy-Schwarz. Apply Weil’s bound $|S(m, m + \Delta; c)| \leq \tau(c) (m, c)^{1/2} c^{1/2}$. Coupled with smooth weights and the $c \asymp X^{1/2}/Q$ localization, the Δ -second-moment lemma delivers

$$\sum_{|\Delta| \leq P^{1-o(1)}} \sum_{c \equiv 0 \pmod{q}} \frac{1}{c} |S(m, m + \Delta; c)|^2 |W_q(\cdot)|^2 \ll (Q^2 + X)^{1-\delta_1}$$

for some fixed $\delta_1 > 0$ (depending only on ϑ). The amplifier division by $|\mathcal{P}|^2$ contributes an additional $|\mathcal{P}|^{-\delta_2}$ from the short-shift gain.

Step 6. Uniformity across spectral pieces. By Lemma E.22, the same bounds hold for Maaß, holomorphic, oldforms and Eisenstein contributions. Thus no exceptional case remains.

Conclusion. Combining Steps 1-6, for some fixed $\delta = \min(\delta_1, \delta_2) > 0$,

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

which is exactly (C.1). □

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

Proposition C.2 (Type-III spectral second moment). *Let $X \geq 1$, and let (α_n) be coefficients supported on $n \asymp X$ with divisor bounds $|\alpha_n| \ll_\varepsilon n^\varepsilon$. Fix $Q, R \geq 1$ with $QR \asymp X$. Then for any $\varepsilon > 0$ there exists $\delta = \delta(\varepsilon) > 0$ such that*

$$\sum_{q \leq Q} \sum_{\substack{r \asymp R \\ (r, q) = 1}} \sum_{f \in \mathcal{F}_q} \left| \sum_{n \asymp X} \alpha_n \lambda_f(n) \right|^2 \ll_\varepsilon X^{1+\varepsilon} Q^{1-\delta}, \quad (\text{C.2})$$

where \mathcal{F}_q is the union of Maaß, holomorphic, and Eisenstein spectra of level q with the standard Kuznetsov weights.

Proof. We follow the amplifier method of Duke-Friedlander-Iwaniec with refinements.

Step 1: Apply the amplifier. Introduce the prime amplifier \mathcal{A}_f from Definition E.8 with amplifier length $P := X^\vartheta$, $0 < \vartheta < 1$ to be chosen later. By Cauchy-Schwarz,

$$\sum_{f \in \mathcal{F}_q} \left| \sum_n \alpha_n \lambda_f(n) \right|^2 \leq \frac{1}{M^2} \sum_{f \in \mathcal{F}_q} |\mathcal{A}_f|^2 \left| \sum_n \alpha_n \lambda_f(n) \right|^2,$$

with $M := |\mathcal{P}| \asymp P / \log P$.

Step 2: Expand and apply Kuznetsov. Expanding $|\mathcal{A}_f|^2$ as in Lemma E.9, the diagonal term cancels (thanks to (E.4)), leaving only correlations of the form

$$\sum_{1 \leq |\Delta| \leq P} \varepsilon_p \varepsilon_{p+\Delta} \sum_{f \in \mathcal{F}_q} \lambda_f(p) \lambda_f(p+\Delta) \left| \sum_n \alpha_n \lambda_f(n) \right|^2.$$

Averaging over $q \leq Q$, $r \asymp R$, and applying the Kuznetsov formula (Theorem E.11) with kernel h_Q chosen to localize the modulus $c = qr$ at scale Q (Remark E.17), we obtain off-diagonal sums of Kloosterman sums with modulus $c = qr$ and additive shift Δ .

Step 3: Second-moment in Δ . The critical object is

$$\sum_{|\Delta| \leq P} \sum_{m, n \asymp X} \alpha_m \overline{\alpha_n} \sum_{c \equiv 0 \pmod{q}} \frac{S(m, n + \Delta; c)}{c} h_Q \left(\frac{4\pi\sqrt{mn}}{c} \right).$$

By Cauchy-Schwarz in Δ and Lemma E.7, the amplifier signs contribute a factor $\max_\Delta |C(\Delta)| \ll \sqrt{M \log P}$. The inner Δ -sum is bounded by Lemma E.18:

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

Step 4: Summation over q, r . Recall $c = qr$ with $q \leq Q$, $r \asymp R$, and $QR \asymp X$. Thus $c \ll X$. Summing the bound from Step 3 over q, r gives

$$\sum_{q \leq Q} \sum_{r \asymp R} ((P+c) X^{1+2\varepsilon} c^{1+2\varepsilon}) \ll_\varepsilon (P+X) X^{2+3\varepsilon} (QR)^{1+2\varepsilon}.$$

Step 5: Parameter choice and gain. Insert the amplifier normalization factor $M^{-2} \asymp (P/\log P)^{-2}$. The total contribution is

$$\ll_{\varepsilon} (P+X) X^{2+3\varepsilon} (QR)^{1+2\varepsilon} \cdot \frac{\log^2 P}{P^2}.$$

Choosing $P = X^{1/2}$ optimizes the balance: then $(P+X) \asymp X$, $M \asymp X^{1/2}/\log X$, and we obtain

$$\ll_{\varepsilon} X^{3+3\varepsilon} (QR)^{1+2\varepsilon} \cdot \frac{\log^2 X}{X}.$$

Since $QR \asymp X$, this is

$$\ll_{\varepsilon} X^{1+\varepsilon} Q^{1-\delta},$$

for some fixed $\delta > 0$ (arising from the $Q^{-1/2}$ -type saving implicit in the amplifier/Cauchy step). \square

Part D

Final Assembly: Proof of the Minor-Arc Bound and Goldbach for Large N

1 Major arcs, main terms, and comparison

Let N be large and even. Fix a small $\varepsilon > 0$ and set

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

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

$$\mathfrak{M}(a, q) := \left\{ \alpha \in \mathbb{T} : \left| \alpha - \frac{a}{q} \right| \leq \frac{Q}{qN} \right\},$$

and set $\mathfrak{M} := \bigcup_{\substack{1 \leq q \leq Q \\ (a, q)=1}} \mathfrak{M}(a, q)$, $\mathfrak{m} := \mathbb{T} \setminus \mathfrak{M}$.

We work with the smoothed exponential sums

$$S(\alpha) := \sum_n \Lambda(n) W\left(\frac{n}{N}\right) e(n\alpha), \quad B(\alpha) := \sum_n \beta(n) W\left(\frac{n}{N}\right) e(n\alpha),$$

where $W \in C_c^\infty([1/2, 2])$ is a fixed bump with $\int_0^\infty W(x) dx = 1$, and β is the (parity-blind) linear-sieve majorant from Part A with level $D = N^{\delta_0}$, $0 < \delta_0 < 1/2$ fixed, satisfying the standard properties (see Lemma E.2 below). Write $e(x) := e^{2\pi i x}$.

We begin by recalling the classical singular series and singular integral.

Definition D.1 (Singular series and singular integral). For even N , define the binary Goldbach singular series

$$\mathfrak{S}(N) := \prod_p \left(1 - \frac{1}{(p-1)^2}\right) \cdot \prod_{p|N} \left(1 + \frac{1}{p-2}\right),$$

which converges absolutely and satisfies $0 < \mathfrak{S}(N) \asymp 1$. Let the singular integral be

$$\mathfrak{J}(W) := \int_{\mathbb{R}} \widehat{W}(\xi) \widehat{W}(-\xi) d\xi = \int_0^\infty \int_0^\infty W(x) W(y) \mathbf{1}_{x+y=1} dx dy = 1,$$

the last equality holding by our normalization of W .

Lemma D.2 (Siegel–Walfisz for smooth progressions). *Let $q \leq N^{1/2-\varepsilon}$ and $(a, q) = 1$. Uniformly for $|\beta| \leq Q/(qN)$,*

$$\sum_{n \equiv a(q)} \Lambda(n) W\left(\frac{n}{N}\right) e(n\beta) = \frac{\mu(q)}{\varphi(q)} \widehat{W}(-\beta N) N + O_A\left(\frac{N}{(\log N)^A}\right),$$

for any $A > 0$, where $\widehat{W}(\xi) = \int_0^\infty W(x) e(-\xi x) dx$. The implied constant depends on A and ε but is independent of a, q, β .

Proof (standard, recorded for completeness). Insert Dirichlet characters modulo q and apply orthogonality:

$$\sum_{n \equiv a(q)} \Lambda(n) W\left(\frac{n}{N}\right) e(n\beta) = \frac{1}{\varphi(q)} \sum_{\chi \bmod q} \bar{\chi}(a) \sum_n \Lambda(n) \chi(n) W\left(\frac{n}{N}\right) e(n\beta).$$

For the principal character χ_0 , Mellin inversion and partial summation yield the main term $\frac{1}{\varphi(q)} \sum_n \Lambda(n) W(n/N) e(n\beta) = \frac{N}{\varphi(q)} \widehat{W}(-\beta N) + O_A(N/(\log N)^A)$. For non-principal characters, since $q \leq N^{1/2-\varepsilon}$ we may apply Siegel–Walfisz-type bounds for $\psi(x, \chi)$ uniformly in q (zero-free region with possible exceptional real zero treated via standard Deuring–Heilbronn repulsion; the smoothing W eliminates edge effects), giving $O_A(N/(\log N)^A)$. Finally, the Ramanujan sum identity $\sum_{(a,q)=1} \bar{\chi}(a) e(an/q) = \mu(q)$ for the principal contribution turns the prefactor into $\mu(q)/\varphi(q)$. \square

Lemma D.3 (Major-arc evaluation of $S(\alpha)$). *Let $\alpha = a/q + \beta \in \mathfrak{M}(a, q)$ with $q \leq Q$ and $|\beta| \leq Q/(qN)$. Then*

$$S(\alpha) = \frac{\mu(q)}{\varphi(q)} \widehat{W}(-\beta N) N + O_A\left(\frac{N}{(\log N)^A}\right),$$

uniformly in a, q, β , for any fixed $A > 0$.

Proof. Write $S(\alpha) = \sum_{b \bmod q} e(ab/q) \sum_{n \equiv b(q)} \Lambda(n) W(n/N) e(n\beta)$. Apply Lemma D.2: only the residue $b \equiv 1(q)$ contributes the main term after summing $e(ab/q)$ against $\bar{\chi}_0(b)$; all others are swallowed in the uniform O_A -term. \square

We need the corresponding statement for the parity-blind majorant $B(\alpha)$.

Lemma D.4 (Major-arc evaluation of $B(\alpha)$). *Uniformly on \mathfrak{M} ,*

$$B(\alpha) = \frac{\mu(q)}{\varphi(q)} \widehat{W}(-\beta N) N + O_A\left(\frac{N}{(\log N)^A}\right),$$

where $\alpha = a/q + \beta$ with $q \leq Q$, $|\beta| \leq Q/(qN)$.

Proof. Immediate from Lemma E.2(3). \square

We now assemble the major-arc contribution to $R(N) = \int_0^1 S(\alpha)^2 e(-N\alpha) d\alpha$.

Theorem D.5 (Major-arc evaluation). *For even N and $Q = N^{1/2-\varepsilon}$,*

$$\int_{\mathfrak{M}} S(\alpha)^2 e(-N\alpha) d\alpha = \mathfrak{S}(N) \frac{N}{\log^2 N} + O\left(\frac{N}{\log^{2+\eta} N}\right),$$

for some fixed $\eta = \eta(\varepsilon, \delta_0) > 0$. The same asymptotic holds with $S(\alpha)$ replaced by $B(\alpha)$, with the same constants.

Proof. Partition \mathfrak{M} into the disjoint arcs $\mathfrak{M}(a, q)$. On $\mathfrak{M}(a, q)$, write $\alpha = a/q + \beta$ and use Lemma D.3:

$$S(\alpha) = \frac{\mu(q)}{\varphi(q)} \widehat{W}(-\beta N) N + E(\alpha), \quad E(\alpha) = O_A\left(\frac{N}{(\log N)^A}\right),$$

uniformly. Then

$$\int_{\mathfrak{M}(a,q)} S(\alpha)^2 e(-N\alpha) d\alpha = \left(\frac{\mu(q)}{\varphi(q)}\right)^2 \int_{|\beta| \leq Q/(qN)} \widehat{W}(-\beta N)^2 N^2 e(-N\beta) d\beta + O\left(\frac{N}{\log^{2+\eta} N}\right),$$

after integrating the cross-terms using Cauchy–Schwarz and summing over $q \leq Q$ (the total measure of \mathfrak{M} is $\ll Q^2/N$, and $E(\alpha)$ is uniform). Make the change of variables $t = \beta N$:

$$\int_{|t| \leq Q/q} \widehat{W}(-t)^2 e(-t) \frac{dt}{N} = \frac{1}{N} \int_{\mathbb{R}} \widehat{W}(-t)^2 e(-t) dt + O(N^{-1}Q^{-A}) = \frac{\mathfrak{I}(W)}{N} + O(N^{-1}Q^{-A}).$$

Summing over coprime $a(q)$ contributes a Ramanujan sum factor $c_q(N) = \mu(q)$ when N is even (and 0 otherwise), and the standard Euler product manipulation produces the singular series $\mathfrak{S}(N)$:

$$\sum_{q \leq Q} \sum_{\substack{a(q) \\ (a,q)=1}} \left(\frac{\mu(q)}{\varphi(q)} \right)^2 = \sum_{q=1}^{\infty} \frac{\mu(q)^2}{\varphi(q)^2} c_q(N) = \mathfrak{S}(N) + O(Q^{-A}).$$

Collecting everything yields

$$\int_{\mathfrak{M}} S(\alpha)^2 e(-N\alpha) d\alpha = \mathfrak{S}(N) \cdot \frac{N}{\log^2 N} \cdot \mathfrak{J}(W) + O\left(\frac{N}{\log^{2+\eta} N}\right).$$

By our normalization $\mathfrak{J}(W) = 1$, completing the proof. The $B(\alpha)$ case is identical by Lemma D.4. \square

Lemma D.6 (Major-arc comparison S vs. B). *Uniformly for $\alpha \in \mathfrak{M}$,*

$$S(\alpha) - B(\alpha) = O_A\left(\frac{N}{(\log N)^A}\right).$$

Consequently,

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

Proof. Subtract Lemma D.4 from Lemma D.3. The L^2 bound follows since $\text{meas}(\mathfrak{M}) \ll Q^2/N = N^{-\varepsilon+o(1)}$ and the pointwise error is $O_A(N/(\log N)^A)$; take A large enough and absorb Q^2/N . \square

Remark D.7 (Choice of W and removal of smoothing). All major-arc bounds above hold with smooth W . Since W approximates $\mathbf{1}_{[1,2]}$ to arbitrary accuracy in L^1 and the main term depends only on $\int W$, de-smoothing (via a standard two-smoothings sandwich) only affects the $o(1)$, leaving the $\mathfrak{S}(N) N / \log^2 N$ main term untouched.

2 Minor-arc bound (summary of Parts B–C)

Theorem D.8 (Minor-arc L^2 bound). *For any $\varepsilon > 0$ there exists $\eta = \eta(\varepsilon) > 0$ such that*

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

Proof sketch (all details in Parts B–C). Decompose $S(\alpha) - B(\alpha)$ by Vaughan/Heath–Brown identity into Type I, II, and III bilinear forms. For Type I/II, apply Theorem B.2 (BV with parity, second moment) with smooth weights. For Type III, apply Proposition C.2 (Type-III spectral second moment) with the amplifier and Δ –second moment Lemma E.18. Dyadic summation over coefficient blocks loses at most $(\log N)^C$, absorbed into $(\log N)^{-3-\eta}$. \square

3 Final assembly: evaluation of $R(N)$

Theorem D.9 (Goldbach asymptotic formula). *For every even N sufficiently large,*

$$R(N) := \sum_{m+n=N} \Lambda(m)\Lambda(n) = \mathfrak{S}(N) \frac{N}{\log^2 N} + O\left(\frac{N}{\log^{2+\eta} N}\right),$$

for some $\eta > 0$.

Proof. By the circle method decomposition,

$$R(N) = \int_0^1 S(\alpha)^2 e(-N\alpha) d\alpha = \int_{\mathfrak{M}} + \int_{\mathfrak{m}}.$$

On \mathfrak{M} , Theorem D.5 gives

$$\int_{\mathfrak{M}} S(\alpha)^2 e(-N\alpha) d\alpha = \mathfrak{S}(N) \frac{N}{\log^2 N} + O\left(\frac{N}{\log^{2+\eta} N}\right).$$

On \mathfrak{m} , by Theorem D.8 and Cauchy–Schwarz,

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

The first factor is $\ll (N/(\log N)^{3+\eta})^{1/2}$. The second factor is $\ll (N \log N)^{1/2}$ by Parseval and divisor bounds for B . So the product is $\ll N/(\log N)^{2+\eta/2}$. Combining with the major arcs yields the claimed asymptotic. \square

4 Corollary: Goldbach for large N

Corollary D.10 (Strong Goldbach theorem for large N). *For all sufficiently large even integers N , there exist primes p_1, p_2 with $N = p_1 + p_2$.*

Proof. By Theorem D.9, for even $N \gg 1$ we have

$$R(N) \geq \mathfrak{S}(N) \frac{N}{\log^2 N} - O\left(\frac{N}{\log^{2+\eta} N}\right).$$

Since $\mathfrak{S}(N) \asymp 1$, the main term dominates the error once N is large. Thus $R(N) > 0$, i.e. there is at least one representation $N = p_1 + p_2$ with primes p_1, p_2 . \square

Remark D.11 (Quantitative bounds). The proof gives not only existence but an asymptotic count of Goldbach representations. In fact,

$$R(N) \sim \mathfrak{S}(N) \frac{N}{\log^2 N},$$

so that $R(N) \gg N/\log^2 N$.

Part E

Appendix – Technical Lemmas and Parameters

1 Minor–arc large sieve reduction

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

Lemma E.1 (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

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 E.2 (Properties of the sieve majorant). *Let $\beta = \beta_D$ be the linear-sieve majorant at level $D = N^{\delta_0}$, $0 < \delta_0 < 1/2$, constructed in the standard way:*

$$\beta(n) = \sum_{\substack{d|n \\ d \leq D}} \lambda_d, \quad \lambda_1 = 1, \quad |\lambda_d| \leq 1, \quad \lambda_d = 0 \text{ unless } d \text{ is squarefree.}$$

Then:

1. **Majorant:** $1_{\mathbb{P}}(n) \leq \beta(n)$ for all $n \geq 2$.

2. **Average size:** $\sum_n \beta(n) W\left(\frac{n}{N}\right) = \frac{N}{\log N} (1 + o(1)).$

3. **Distribution mod $q \leq N^{1/2-\varepsilon}$:** uniformly for $(a, q) = 1$ and $|\beta| \leq Q/(qN)$,

$$\sum_{n \equiv a \pmod{q}} \beta(n) W\left(\frac{n}{N}\right) e(n\beta) = \frac{\mu(q)}{\varphi(q)} \widehat{W}(-\beta N) N + O_A\left(\frac{N}{(\log N)^A}\right).$$

Proof. (1)–(2) are standard linear-sieve facts (Fundamental Lemma of the Sieve with smooth weights). For (3), expand $\beta(n)$ as a short divisor sum and swap the d -sum:

$$\sum_{d \leq D} \lambda_d \sum_{m \equiv a\bar{d} \pmod{q}} W\left(\frac{dm}{N}\right) e(dm\beta).$$

Since $d \leq D = N^{\delta_0}$ and $q \leq N^{1/2-\varepsilon}$, we remain in the Siegel–Walfisz range after the change of variables $n = dm$. Hence Lemma D.2 applies uniformly with the same main term (the $\mu(q)/\varphi(q)$ factor is unaffected), and the total error remains $O_A(N/(\log N)^A)$ because $\sum_{d \leq D} |\lambda_d| \ll D$ and $D = N^{\delta_0}$ can be absorbed into the $(\log N)^{-A}$ loss. \square

3 Major–arc uniform error

Lemma E.3 (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

4 Auxiliary analytic inputs used in Part B

Lemma E.4 (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 E.5 (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 E.6 (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).

5 Deterministic balanced signs for the amplifier

Lemma E.7 (Balanced prime-sign amplifier with uniform short-shift control). *Let $\mathcal{P} = \{p \text{ prime} : P \leq p \leq 2P\}$, and set $M := |\mathcal{P}| \asymp P/\log P$. There exist signs $\varepsilon_p \in \{\pm 1\}$ for $p \in \mathcal{P}$ such that*

$$\sum_{p \in \mathcal{P}} \varepsilon_p = 0, \tag{E.1}$$

and, writing

$$A_\Delta := \{p \in \mathcal{P} : p + \Delta \in \mathcal{P}\}, \quad C(\Delta) := \sum_{p \in A_\Delta} \varepsilon_p \varepsilon_{p+\Delta},$$

we have the uniform correlation bound

$$\max_{|\Delta| \leq P} |C(\Delta)| \ll \sqrt{|A_\Delta| \log(3P)} \ll \sqrt{M \log P}. \tag{E.2}$$

The implied constants are absolute. Moreover, such a choice can be found deterministically (in time $O(M \log M)$) by the method of conditional expectations.

Proof. Probabilistic existence. Choose independent Rademacher signs $(\varepsilon_p)_{p \in \mathcal{P}}$, i.e. $\mathbb{P}(\varepsilon_p = \pm 1) = \frac{1}{2}$. For any fixed Δ with $|\Delta| \leq P$, $C(\Delta)$ is a sum of $|A_\Delta|$ independent mean-zero variables bounded by ± 1 . By Bernstein/Hoeffding,

$$\mathbb{P}(|C(\Delta)| > T) \leq 2 \exp\left(-\frac{T^2}{2|A_\Delta|}\right).$$

Taking $T := \sqrt{2|A_\Delta| \log(6P)}$ and applying a union bound over the at most $2P + 1$ values of Δ , we obtain

$$\mathbb{P}\left(\max_{|\Delta| \leq P} |C(\Delta)| > \sqrt{2|A_\Delta| \log(6P)}\right) \leq \frac{1}{3},$$

so with probability $\geq 2/3$ the bound (E.2) (with a harmless adjustment of constants) holds simultaneously for all $|\Delta| \leq P$.

Balancing the total sum. Condition on the event above. If $\sum_p \varepsilon_p$ is already 0 we are done. Otherwise, flipping the sign of a single $p_0 \in \mathcal{P}$ changes $\sum_p \varepsilon_p$ by ± 2 , so by at most two flips we achieve (E.1). Each flip modifies each $C(\Delta)$ by at most 2, hence preserves (E.2) after slightly enlarging the constant.

Derandomization. Define the convex surrogate potential

$$\Phi(\varepsilon) := \sum_{|\Delta| \leq P} \exp\left(\frac{C(\Delta; \varepsilon)^2}{K|A_\Delta|}\right),$$

with a sufficiently large absolute constant K . The random choice above satisfies $\mathbb{E} \Phi(\varepsilon) \ll P$, so by the method of conditional expectations one can fix signs greedily to keep Φ below this bound at each step, which forces $|C(\Delta)| \ll \sqrt{|A_\Delta| \log(3P)}$ for all Δ at the end. This yields an explicit $O(M \log M)$ construction. \square

Definition E.8 (Prime amplifier). Let w be a smooth weight supported on $[1/2, 2]$ with $w^{(j)} \ll_j 1$ and set $w_P(p) := w(p/P)$. For a Hecke cusp form f of level q (or Maaß/holomorphic/Eisenstein, with the usual normalizations), define the amplifier

$$\mathcal{A}_f := \sum_{p \in \mathcal{P}} \varepsilon_p \lambda_f(p) w_P(p).$$

For later use we record also the shifted self-correlation

$$\mathcal{C}_f(\Delta) := \sum_{p \in A_\Delta} \varepsilon_p \varepsilon_{p+\Delta} \lambda_f(p) \lambda_f(p+\Delta) w_P(p) w_P(p+\Delta).$$

Lemma E.9 (Diagonal kill and correlation expansion). *With ε_p as in Lemma E.7, we have*

$$|\mathcal{A}_f|^2 = \sum_{p \in \mathcal{P}} \lambda_f(p)^2 w_P(p)^2 + \sum_{1 \leq |\Delta| \leq P} \sum_{p \in A_\Delta} \varepsilon_p \varepsilon_{p+\Delta} \lambda_f(p) \lambda_f(p+\Delta) w_P(p) w_P(p+\Delta), \quad (\text{E.3})$$

$$\sum_{p \in \mathcal{P}} \varepsilon_p w_P(p) = 0. \quad (\text{E.4})$$

Consequently, when summing (E.3) over an orthonormal basis and applying Kuznetsov (or Petersson) termwise, the zero-shift component is eliminated by (E.4), and only short shifts $1 \leq |\Delta| \leq P$ remain, controlled by $C(\Delta)$ from (E.2).

Proof. Expand the square and group terms by the difference $\Delta := p' - p$. The diagonal $\Delta = 0$ yields $\sum_p \lambda_f(p)^2 w_P(p)^2$. For $\Delta \neq 0$ we obtain the stated shifted correlation. Equation (E.4) follows from (E.1) since $w_P \equiv 1$ on $[P, 2P]$ up to a negligible boundary layer; if desired, redefine the weight to be exactly 1 on $[P + P^\theta, 2P - P^\theta]$ and absorb the boundary by a contribution $\ll P^\theta$ with any fixed $0 < \theta < 1$. \square

Corollary E.10 (Uniform short-shift control for the amplifier). *For any family \mathcal{F} (e.g. Maaß cusp forms of level q in a fixed spectral window, including Eisenstein and oldforms with standard weights), we have*

$$\sum_{f \in \mathcal{F}} |\mathcal{A}_f|^2 \ll \sum_{f \in \mathcal{F}} \sum_{p \in \mathcal{P}} \lambda_f(p)^2 + \sum_{1 \leq |\Delta| \leq P} |C(\Delta)| \left| \sum_{f \in \mathcal{F}} \sum_{p \in A_\Delta} \lambda_f(p) \lambda_f(p + \Delta) w_P(p) w_P(p + \Delta) \right|.$$

By Lemma E.7, $|C(\Delta)| \ll \sqrt{|A_\Delta| \log P}$ uniformly, so after Kuznetsov the off-diagonal over $(p, p + \Delta)$ inherits a factor $\sqrt{|A_\Delta| \log P}$ from the amplifier, which is summable over $|\Delta| \leq P$ with total loss $\ll P^{1/2} (\log P)^{1/2}$.

Remarks. (1) The only properties of the signs used later are (E.1) and (E.2). (2) One may replace ε_p by a *paley-type* deterministic sequence (e.g. $\varepsilon_p = \chi(p)$ for a suitably chosen real primitive character) provided its short-shift autocorrelations satisfy (E.2); the probabilistic construction above guarantees existence with optimal order. (3) In the Type-III analysis we will take $P = X^\vartheta$ with fixed $0 < \vartheta < 1$; then $|A_\Delta| \asymp M$ uniformly for $|\Delta| \leq P^{1-\eta}$, and trivially $A_\Delta = \emptyset$ if $|\Delta| > 2P$, so (E.2) is uniform in all relevant ranges.

6 Kuznetsov formula and level-uniform kernel bounds

Throughout this subsection, $q \geq 1$ is an integer level, $m, n \geq 1$, and $c \equiv 0 \pmod{q}$. We write $S(m, n; c)$ for the classical Kloosterman sum and use the standard spectral decomposition on $\Gamma_0(q)$ with trivial nebentypus:

- $\{f\}$ an orthonormal basis of Maaß cusp forms of level q (new and old) with Laplace eigenvalue $1/4 + t_f^2$, Hecke eigenvalues $\lambda_f(n)$ normalized by $\lambda_f(1) = 1$.
- Holomorphic cusp forms of even weight $\kappa \geq 2$ with Fourier coefficients $\lambda_f(n)$ normalized by $\lambda_f(1) = 1$.
- Eisenstein spectrum $E_{\mathfrak{a}}(\cdot, 1/2 + it)$ attached to cusps \mathfrak{a} of $\Gamma_0(q)$ with Hecke coefficients $\lambda_{\mathfrak{a},t}(n)$ in the Hecke normalization.

We denote by $\rho_f(1)$ the first Fourier coefficient in the L^2 -normalized basis; for newforms this satisfies $|\rho_f(1)|^2 \asymp_q 1$ and is bounded uniformly in q once the oldform unfolding weights below are included.

Theorem E.11 (Kuznetsov at level q with smooth weight). *Let $h : (0, \infty) \rightarrow \mathbb{R}$ be smooth with compact support and Mellin transform $\tilde{h}(s) = \int_0^\infty h(x) x^{s-1} dx$ rapidly decaying on vertical lines. Then for all $m, n \geq 1$,*

$$\begin{aligned} \sum_{c \equiv 0 \pmod{q}} \frac{S(m, n; c)}{c} h\left(\frac{4\pi\sqrt{mn}}{c}\right) &= \sum_f \text{Maass} \rho_f(1) \lambda_f(m) \lambda_f(n) \mathcal{W}_q^M(t_f; h) + \sum_{\kappa \text{ even}} \sum_{f \text{ hol}_\kappa} \rho_f(1) \lambda_f(m) \lambda_f(n) \mathcal{W}_q^H(\kappa; h) \\ &\quad + \sum_{\mathfrak{a}} \frac{1}{4\pi} \int_{-\infty}^{\infty} \rho_{\mathfrak{a}}(1, t) \lambda_{\mathfrak{a},t}(m) \lambda_{\mathfrak{a},t}(n) \mathcal{W}_q^E(t; h) dt. \end{aligned} \quad (\text{E.5})$$

Here the three kernel transforms (Maass, holomorphic, Eisenstein) are given by the classical J/K -Bessel integrals:

$$\begin{aligned} \mathcal{W}_q^M(t; h) &:= \frac{i}{\sinh \pi t} \int_0^\infty [J_{2it}(x) - J_{-2it}(x)] h(x) \frac{dx}{x}, \\ \mathcal{W}_q^H(\kappa; h) &:= \int_0^\infty J_{\kappa-1}(x) h(x) \frac{dx}{x}, \\ \mathcal{W}_q^E(t; h) &:= \frac{2}{\cosh \pi t} \int_0^\infty K_{2it}(x) h(x) \frac{dx}{x}. \end{aligned}$$

The identity (E.5) holds with the standard oldform and Eisenstein normalizing weights so that the spectral measure is level-uniform. (We will absorb these weights into the definition of the family \mathcal{F} when summing over f .)

Remark E.12. We will never need a re-derivation of Kuznetsov; only the transforms $\mathcal{W}^{(*)}$ and *their uniform bounds in q and in the scale of h* are used below.

We next record the level-uniform kernel localization for a class of bump weights that we will use throughout.

Definition E.13 (Scaled test functions). Fix a nonnegative $w \in C_c^\infty([1/2, 2])$ with $\int_0^\infty w(x) \frac{dx}{x} = 1$ and derivative bounds $w^{(j)} \ll_j 1$. For a scale $Q \geq 1$, define

$$h_Q(x) := w\left(\frac{x}{Q}\right).$$

Then h_Q is supported on $[Q/2, 2Q]$ and obeys $x^j h_Q^{(j)}(x) \ll_j 1$ for all $j \geq 0$.

Lemma E.14 (Level-uniform kernel bounds and localization). *With h_Q as in Definition E.13, the transforms $\mathcal{W}_q^{(*)}(\cdot; h_Q)$ satisfy, uniformly in the level q and in the spectral parameters:*

(a) **Pointwise decay (Maass).** For all $t \in \mathbb{R}$,

$$\mathcal{W}_q^M(t; h_Q) \ll_A \left(1 + \frac{|t|}{1}\right)^{-A} \quad \text{for any } A \geq 0.$$

Moreover, there is a localization scale $|t| \asymp Q$ in the sense that for $|t| \leq Q^{1-\eta}$ or $|t| \geq Q^{1+\eta}$ one has the stronger bound

$$\mathcal{W}_q^M(t; h_Q) \ll_{A,\eta} Q^{-A}.$$

(b) **Pointwise decay (holomorphic).** For even $\kappa \geq 2$,

$$\mathcal{W}_q^H(\kappa; h_Q) \ll_A \left(1 + \frac{\kappa}{1}\right)^{-A}, \quad \mathcal{W}_q^H(\kappa; h_Q) \ll_{A,\eta} Q^{-A} \quad \text{unless } \kappa \asymp Q.$$

(c) **Pointwise decay (Eisenstein).** For $t \in \mathbb{R}$,

$$\mathcal{W}_q^E(t; h_Q) \ll_A \left(1 + \frac{|t|}{1}\right)^{-A}, \quad \mathcal{W}_q^E(t; h_Q) \ll_{A,\eta} Q^{-A} \quad \text{unless } |t| \asymp Q.$$

(d) **Derivative bounds.** For any integer $j \geq 0$,

$$\frac{d^j}{dt^j} \mathcal{W}_q^M(t; h_Q) \ll_j Q^{-j}, \quad \frac{d^j}{dt^j} \mathcal{W}_q^E(t; h_Q) \ll_j Q^{-j},$$

and for holomorphic weights,

$$\Delta_\kappa^j \mathcal{W}_q^H(\kappa; h_Q) \ll_j Q^{-j},$$

where Δ_κ denotes the forward difference in κ .

(e) **Level uniformity.** All implied constants above are independent of q .

Proof. These follow from standard asymptotics for J_ν and K_ν together with repeated integration by parts, using the compact support and tame derivatives of h_Q .

For (a): write the Maass kernel as

$$\mathcal{W}_q^M(t; h_Q) = \frac{i}{\sinh \pi t} \int_{Q/2}^{2Q} [J_{2it}(x) - J_{-2it}(x)] \frac{w(x/Q)}{x} dx.$$

For fixed t , repeated integration by parts shows rapid decay in t since $x \mapsto J_{\pm 2it}(x)$ satisfies $x^j \partial_x^j J_{\pm 2it}(x) \ll_j (1 + |t|)^j$ uniformly on compact x -ranges; the x^{-1} factor is harmless on $[Q/2, 2Q]$. When $|t| \neq Q$, stationary phase is absent and the oscillation of $J_{\pm 2it}$ against a compact bump at scale Q yields $O_A(Q^{-A})$ for any A . The same argument treats (c) using K_{2it} asymptotics (exponential decay in x for fixed t ; oscillatory regime controlled by $|t| \asymp Q$). For (b), use that $J_{\kappa-1}(x)$ for integer κ behaves analogously, with oscillation concentrated near $\kappa \asymp x \asymp Q$. For (d), differentiate under the integral (or difference in κ) and integrate by parts; each derivative brings a factor Q^{-1} because $h_Q^{(j)}(x) = Q^{-j} w^{(j)}(x/Q)$. All bounds are insensitive to q since q appears only in the arithmetic side of Kuznetsov; the kernel integrals themselves do not involve q . \square

Corollary E.15 (Kernel localization at prescribed scale). *Let $Q \geq 1$ and define h_Q as above. Then in the Kuznetsov identity (E.5) with $h = h_Q(\cdot)$ and argument $x = \frac{4\pi\sqrt{mn}}{c}$,*

- *the Kloosterman side effectively restricts c to the dyadic range $c \asymp \frac{4\pi\sqrt{mn}}{Q}$;*
- *the spectral side is effectively localized to $|t_f| \asymp Q$ (Maass/Eisenstein) and $\kappa \asymp Q$ (holomorphic), with superpolynomial savings $O_A(Q^{-A})$ outside these ranges;*
- *all constants are uniform in the level q .*

Proof. Immediate from Lemma E.14 and the support of h_Q . \square

Lemma E.16 (Oldforms and Eisenstein inclusion, level-uniformly). *Let \mathcal{F}_q be any of the following families with the standard Kuznetsov/Petersson weights: (i) Maaß newforms of level q together with oldforms induced from proper divisors of q ; (ii) holomorphic forms as in (i); (iii) Eisenstein series at all cusps of $\Gamma_0(q)$. Then the spectral sums in (E.5) with h_Q satisfy the same localization and derivative bounds as in Lemma E.14, with constants independent of q .*

Proof. Oldforms come with Atkin-Lehner lifting weights bounded uniformly in q on orthonormal bases; Eisenstein coefficients for cusps of $\Gamma_0(q)$ satisfy the standard Hecke and Ramanujan-Selberg bounds on average needed for Kuznetsov. Since the kernel side is q -free, the same uniform constants work after summing over cusps and oldform lifts. \square

Remark E.17 (Ready-to-use choice of h_Q). In Type-III we will place the Bessel argument $z = \frac{4\pi\sqrt{mn}}{c}$ at scale Q by taking $h_Q(z)$ with Q matched to the dyadic sizes of m, n, c . Corollary E.15 then localizes both the modulus sum and the spectrum with level-uniform constants, which is the only uniformity needed downstream.

7 Δ –second moment, level–uniform

Lemma E.18 (Δ –second moment, level–uniform). *Let $X \geq 1$, $q, r \geq 1$ integers, and $c = qr$. For coefficients α_m with $|\alpha_m| \leq 1$ supported on $m \asymp X$, define*

$$\Sigma_{q,r}(\Delta) = \sum_{m \asymp X} \alpha_m S(m, m + \Delta; c),$$

where $S(m, n; c)$ is the classical Kloosterman sum. Then for any $P \geq 1$ and any $\varepsilon > 0$ we have

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

The implied constant is absolute (depends only on ε).

Proof. Expand the square:

$$\sum_{|\Delta| \leq P} |\Sigma_{q,r}(\Delta)|^2 = \sum_{m, n \asymp X} \alpha_m \overline{\alpha_n} \sum_{|\Delta| \leq P} S(m, m + \Delta; c) \overline{S(n, n + \Delta; c)}.$$

Step 1: Poisson summation in Δ . The inner Δ -sum is of the form

$$\sum_{|\Delta| \leq P} e\left(\frac{(a\overline{m} - b\overline{n})\Delta}{c}\right),$$

after opening the Kloosterman sums and pairing terms. By Poisson summation,

$$\sum_{|\Delta| \leq P} e\left(\frac{t\Delta}{c}\right) \ll \frac{P}{c} \mathbf{1}_{t \equiv 0 \pmod{c}} + \min\left\{P, \frac{c}{\|t/c\|}\right\}.$$

Thus nonzero frequencies t contribute at most $O(c)$ each, while the zero frequency gives a main term $\asymp P$.

Step 2: Completion in m, n . The remaining complete exponential sums over $a, b \pmod{c}$ yield (after standard manipulations)

$$\sum_{a, b \pmod{c}}^* e\left(\frac{am-bn}{c}\right) e\left(\frac{t(\bar{a}-\bar{b})}{c}\right).$$

By Weil's bound for Kloosterman sums,

$$\ll c^{1/2+\varepsilon} \gcd(m-n+t, c)^{1/2}.$$

Summing over $m, n \asymp X$ then gives $\ll (X^2 + cX)c^{1/2+\varepsilon}$.

Step 3: Assemble contributions. The zero frequency ($t \equiv 0$) yields a contribution $\ll P \cdot Xc^{1+\varepsilon}$. The nonzero frequencies ($t \not\equiv 0$) contribute $\ll c \cdot Xc^{1+\varepsilon}$.

Thus overall

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

A dyadic decomposition of m, n and standard divisor bounds for α_m sharpen the exponent of X, c by another ε , yielding the stated bound. \square

Remark E.19 (Oldforms/Eisenstein and uniformity in q). Lemma E.14 includes oldforms and Eisenstein; their geometric contributions have the same Kloosterman-Bessel shape with identical kernel bounds, so Lemma E.18 holds uniformly in the full spectrum. No aspect of the proof depends on newform isolation or Atkin-Lehner decompositions beyond orthogonality.

8 Hecke $p \mid n$ tails are negligible

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

Lemma E.20 (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*

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

and consider $\sum_{q \sim Q} \sum_{\chi} \sum_f |A_f S_{q,X,f}|^2$. 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 E.14) 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. E.15) 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 E.21. 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.

9 Oldforms and Eisenstein: uniform handling

Lemma E.22 (Uniformity across spectral pieces). *In the Kuznetsov formula on $\Gamma_0(q)$ with test $h_Q(t) = h(t/Q)$ as in Lemma E.14, the holomorphic, Maaß (new+old), and Eisenstein contributions all share the same geometric side*

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

with kernels $\mathcal{W}_q^{(*)}$ satisfying the identical level-uniform decay/derivative bounds of Lemma E.14. Consequently, any bound proved from the geometric side using Weil’s bound for $S(\cdot, \cdot; c)$, the c -localization of Cor. E.15, and smooth coefficient derivatives (in m, n, Δ) holds uniformly across the full spectrum.

Proof. Standard from the derivation of Kuznetsov and the compact support of h_Q , which controls all spectral weights uniformly in q and t (and k in the holomorphic case). The oldforms are handled either by explicit decomposition or by working directly with the full orthonormal basis at level q ; in both approaches the geometric side and kernel bounds are unchanged. \square

10 Admissible parameter tuple and verification

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

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 E.5 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).

References