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ONE-LEVEL DENSITY ESTIMATES FOR DIRICHLET L-FUNCTIONS WITH EXTENDED SUPPORT

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ABSTRACT. We estimate the 1-level density of low-lying zeros of $L(s,\chi)$ with χ ranging over primitive Dirichlet characters of conductor $\in [Q/2, Q]$ and for test functions whose Fourier transform is supported in $[-2-\frac{50}{1093}, 2+\frac{50}{1093}]$. Previously any extension of the support past the range $[-2,2]$ was only known conditionally on deep conjectures about the distribution of primes in arithmetic progressions, beyond the reach of the Generalized Riemann Hypothesis (e.g Montgomery's conjecture). Our work provides the first example of a family of L-functions in which the support is unconditionally extended past the "trivial range" that follows from a simple application of the underlying trace formula (in this case orthogonality of characters). We also highlight consequences for non-vanishing of $L(s,\chi)$.

1. INTRODUCTION

Motivated by the problem of establishing the non-existence of Siegel zeros (see [CI02] for details), Montgomery [Mon73] investigated in 1972 the *vertical* distribution of the zeros of the Riemann zeta-function. He showed that under the assumption of the Riemann Hypothesis for any smooth function f with supp $\widehat{f} \subset [-1,1]$,

$$\lim_{T\to\infty} \frac{1}{N(T)} \sum_{T\leq \gamma,\gamma'\leq 2T} f\Big(\frac{\log T}{2\pi}\cdot(\gamma-\gamma')\Big) = \int_{\mathbb{R}} f(u)\cdot\Big(\delta(u)+1-\Big(\frac{\sin 2\pi u}{2\pi u}\Big)^2\Big)du \tag{1}$$

where $N(T)$ denotes the number of zeros of the Riemann zeta-function up to height T and γ,γ' are ordinates of the zeros of the Riemann zeta-function, and $\delta(u)$ is a Dirac mass at 0. Dyson famously observed that the right-hand side coincides with the pair correlation function of eigenvalues of a random Hermitian matrix.

Dyson's observation leads one to conjecture that the spacings between the zeros of the Riemann zeta-function are distributed in the same way as spacings between eigenvalues of a large random Hermitian matrix. Subsequent work of Rudnick-Sarnak [RS94] provided strong evidence towards this conjecture by computing (under increasingly restrictive conditions) the n-correlations of the zeros of any given automorphic L-function. Importantly the work of Rudnick-Sarnak suggested that the distribution of the zeros of an automorphic L-function is universal and independent of the distribution of its coefficients.

For number theoretic applications of particular interest is the distribution of the so-called "low-lying zeros", that is zeros close to the central point (see e.g [HB04, You06] for various applications). Following the work of Katz-Sarnak [KS99] and Iwaniec-Luo-Sarnak [ILS00] we believe that the distribution of these low-lying is also universal and predicted by only a few random matrix ensembles (which are either symplectic, orthogonal or unitary).

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Specifically the work of Katz-Sarnak suggests that for any smooth function ϕ and any natural "family" of automorphic objects $\mathcal{F}$,

$$\frac{1}{\#\mathcal{F}}\sum_{\pi\in\mathcal{F}}\sum_{\gamma_\pi}\phi\Big(\frac{\log \mathfrak{c}_\pi}{2\pi}\cdot\gamma_\pi\Big) \underset{\#\mathcal{F}\to\infty}{\longrightarrow} \int_{\mathbb{R}}\phi(x)K_{\mathcal{F}}(x)dx \tag{2}$$

where γ_π are ordinates of the zeros of the L-function attached to π, $\mathfrak{c}_\pi$ is the analytic conductor of π and $K_{\mathcal{F}}(x)$ is a function depending only on the "symmetry type" of $\mathcal{F}$ (see [ILS00] for a more detailed discussion).

There is a vast literature providing evidence for (4) (see [MMR$^+$16]). Similarly to Montgomery's result (1) all of the results in the literature place a restriction on the support of the Fourier transform of ϕ. This restriction arises from the limitations of the relevant trace formula. In practice an application of the trace formula gives rise to so-called "diagonal" and "off-diagonal" terms. Trivially bounding the off-diagonal terms corresponds to what we call a "trivial" application of the trace formula

A central yet extremely difficult problem is to extend the support of $\widehat{\phi}$ beyond what a "trivial" application of the trace formula gives. In fact most works in which the support of $\widehat{\phi}$ has been extended further rely on the assumption of various deep hypothesis about primes that sometimes lie beyond the reach of the Generalized Riemann Hypothesis (GRH).

For example Iwaniec-Luo-Sarnak show that in the case of holomorhic forms of weight $\leq K$ one obtains unconditionally a result for $\widehat{\phi}$ supported in $[-1,1]$ and that under the assumption of the Generalized Riemann Hypothesis this can be enlarged to $[-2,2]$ (it is observed in [LDS] that assuming GRH only for Dirichlet L-functions is sufficient). Iwaniec-Luo-Sarnak also show that this range can be pushed further to $\operatorname{supp}\widehat{\phi}\subset(-22/9,22/9)$ under the additional assumption that, for any $c\geq 1$, $(a,c)=1$ and $\varepsilon>0$,

$$\sum_{\substack{p\leq x\\ p\equiv a \pmod c}} e(2\sqrt{p}/c)\ll_\varepsilon x^{1/2+\varepsilon}.$$

A similar behaviour is observed on low-lying zeroes of dihedral L-functions associated to an imaginary quadratic field [FI03], where an extension of the support is shown to be equivalent to an asymptotic formula on primes with a certain splitting behaviour.

As another example, it follows for instance from minor modifications of [HR03, CLLR14] that in the family of primitive Dirichlet characters of modulus $\leq Q$ one can estimate 1-level densities unconditionally for ϕ with $\widehat{\phi}$ supported in $[-2,2]$[1]. Fiorilli-Miller [FM15] have shown that for any $\delta\in(0,2)$, this support can be enlarged to $[-2-\delta,2+\delta]$ under the following "de-averaging hypothesis"

$$\sum_{Q/2\leq q\leq Q}\Big|\sum_{\substack{p\leq x\\ p\equiv 1 \pmod q}}\log p-\frac{x}{\varphi(q)}\Big|^2\ll Q^{-\delta/2}\sum_{Q/2\leq q\leq Q}\sum_{(a,q)=1}\Big|\sum_{\substack{p\leq x\\ p\equiv a \pmod q}}\log p-\frac{x}{\varphi(q)}\Big|^2. \tag{3}$$

In this paper we give a first example of a family of L-functions in which we can *unconditionally* enlarge the support past the "trivial" range that follows from a simple application of the trace formula (in this case orthogonality of characters).

[1]This is in fact the $GL(1)$ analogue of the result of Iwaniec-Luo-Sarnak for holomorphic forms

Theorem 1. *Let Φ be a smooth function compactly supported in $[3/4, 9/4]$, and ϕ be a smooth function such that supp $\widehat{\phi} \subset [-2 - \frac{50}{1093}, 2 + \frac{50}{1093}]$. Then, as $Q \to \infty$,*

$$\sum_q \Phi\Big(\frac{q}{Q}\Big) \sum_{\substack{\chi \pmod q \\ \text{primitive}}} \sum_{\gamma_\chi} \phi\Big(\frac{\log Q}{2\pi}\gamma_\chi\Big) = \widehat{\phi}(0) \sum_q \Phi\Big(\frac{q}{Q}\Big) \sum_{\substack{\chi \pmod q \\ \text{primitive}}} 1 + o(Q^2) \tag{4}$$

Here $\frac{1}{2} + i\gamma_\chi$ correspond to zeros of $L(s, \chi)$ and since we do not assume the Generalized Riemann Hypothesis we allow the γ_χ to be complex.

Note that ϕ, initially defined on $\mathbb{R}$, is analytically continued to $\mathbb{C}$ by compactness of supp $\widehat{\phi}$. Our arguments can be adapted to show that if supp $\widehat{\phi} \subset [-2 - \frac{50}{1093} + \varepsilon, 2 + \frac{50}{1093} - \varepsilon]$ for some $\varepsilon > 0$, then the error term in (4) is $O(Q^{2-\delta})$ with $\delta = \delta(\varepsilon)$, up to altering slightly the main terms.

We remark that we make no progress on the "de-averaging hypothesis" (3) of Fiorilli-Miller, which remains a difficult open problem. We estimate the original sum over primes in arithmetic progressions, on average over moduli, by a variant of an argument of Fouvry [Fou85] and Bombieri-Friedlander-Iwaniec [BFI86] which is based on Linnik's dispersion method. The GRH will be dispensed with by working throughout, as in [Dra15], with characters of large conductors.

The asymptotic formula (4) is expected to hold true without the extra averaging over q. This extra averaging over q, and the fact that the summands are summed in relative values, play an important role in our arguments.

If the GRH is true for Dirichlet L-functions, then choosing any $0 < \kappa < \frac{50}{1093}$

$$\phi(x) = \Big(\frac{\sin \pi(2+\kappa)x}{\pi(2+\kappa)x}\Big)^2$$

and using the inequality

$$1 - \sum_{\gamma_\chi} \phi\Big(\frac{\log Q}{2\pi}\gamma_\chi\Big) \leq \mathbf{1}\Big(L(\tfrac{1}{2}, \chi) \neq 0\Big)$$

we deduce from Theorem 1 that the proportion of non-vanishing $L(\frac{1}{2}, \chi)$ with χ ranging over primitive characters of conductor in $[Q/2, Q]$ is at least $1 - (2+\kappa)^{-1}$ for any $\kappa < \frac{50}{1093}$. We record this consequence in the Corollary below.

Corollary 2. *Let $\varepsilon \in (0, 10^{-6})$. Assume the Generalized Riemann Hypothesis for Dirichlet L-functions. Then for all Q large enough, the proportion of primitive characters χ with modulus $\in [Q/2, Q]$ for which*

$$L(\tfrac{1}{2}, \chi) \neq 0$$

is at least

$$\frac{1}{2} + \frac{25}{2235} - \varepsilon > 0.51118.$$

Corollary 2 is related to a recent result of Pratt [Pra19] who showed unconditionally that the proportion of non-vanishing in this family is at least 0.50073. We note that both the arguments of [Pra19] and those presented here eventually rely on bounds of Deshouillers-Iwaniec [DI82] on cancellation in sums of Kloosterman sums.

Notations. We call a map $f : \mathbb{R}_+ \to \mathbb{C}$ a *test function* if f is smooth and supported inside $[\frac{1}{2}, 3]$.

For $w \in \mathbb{N}$, $n \in \mathbb{Z}$ and $R \geq 1$, we let

$$\mathfrak{u}_R(n, w) := \mathbf{1}_{n \equiv 1 \pmod{w}} - \frac{1}{\varphi(w)} \sum_{\substack{\chi \pmod{w} \\ \mathrm{cond}(\chi) \leq R}} \chi(n).$$

Note the trivial bound

$$|\mathfrak{u}_R(n, w)| \ll \mathbf{1}_{n \equiv 1 \pmod{w}} + \frac{R\tau(w)}{\varphi(w)}. \tag{5}$$

The symbol $n \sim N$ in a summation means $n \in [N, 2N) \cap \mathbb{Z}$. We say that a sequence $(\alpha_n)_n$ is *supported at scale* N if $\alpha_n = 0$ unless $n \sim N$.

The letter ε will denote an arbitrarily small number, whose value may differ at each occurence. The implied constants will be allowed to depend on ε.

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2. Proof of Theorem 1

2.1. **Lemmas on primes in arithmetic progressions.** We will require two results about primes in arithmetic progressions. The first is a standard estimate, obtained from an application of the large sieve.

Lemma 3. *Let $A > 0$, $X, Q, R \geq 2$ satisfy $1 \leq R \leq Q$ and $X \geq Q^2/(\log Q)^A$, and f be a test function with $\|f^{(j)}\|_\infty \ll_j 1$. Then*

$$\sum_{q \leq Q} \left| \sum_{n \in \mathbb{N}} f\Big(\frac{n}{X}\Big) \Lambda(n) \mathfrak{u}_R(n, q) \right| \ll Q(\log Q)^{O(1)} \sqrt{X} \Big(1 + \frac{\sqrt{X}}{RQ} + \frac{X^{3/8}}{Q}\Big). \tag{6}$$

The implied constant depends at most on A and the implied constants in the hypothesis.

Proof. By a combinatorial formula for primes, for instance [IK04, Proposition 13.4], we restrict to proving the bound with $\Lambda(n)$ replaced by convolutions of type I and II, say

$$\sum \sum_{\substack{n = m\ell \\ m \sim M}} \alpha_m \qquad (M \ll X^{1/4}),$$

$$\sum \sum_{\substack{n = m\ell \\ m \sim M}} \alpha_m \beta_\ell \qquad (X^{1/4} \ll M \ll X^{3/4}).$$

We treat the type I case by the Polyá-Vinogradov inequality [IK04, Theorem 12.5], getting a bound $O(MR^{3/2}(\log Q)^{O(1)})$. We treat the type II case by the large sieve [IK04, Theorem 17.4], getting a contribution $O(\sqrt{X}(\log Q)^{O(1)}(Q + \sqrt{M} + \sqrt{X/M} + \sqrt{X}R^{-1}))$. □

The second estimate is substantially deeper and we defer its proof to Section 4.

Proposition 4. *Let $\kappa \in (0, \frac{50}{1093})$ and $\varepsilon > 0$. Let Ψ and f be test functions, $A > 0$, $X, Q, W, R \geq 1$, and $b \in \mathbb{N}$. Assume that*

$$\frac{Q^2}{(\log Q)^A} \ll X \ll Q^{2+\kappa}, \qquad X^{1/2}Q^{-1} \leq R \leq Q^{2/3}X^{-2/9},$$
$$b \leq Q^{\varepsilon} \qquad Q^{1-\varepsilon} \ll W \ll Q,$$

and that $\|f^{(j)}\|_\infty, \|\Psi^{(j)}\|_\infty \ll_j 1$. Then if $\varepsilon > 0$ is small enough in terms of κ, we have

$$\sum_{w\in\mathbb{N}} \Psi\Big(\frac{w}{W}\Big) \sum_{n\in\mathbb{N}} \Lambda(n) f\Big(\frac{n}{X}\Big) \mathfrak{u}_R(n, bw) \ll Q^{1-\varepsilon}\sqrt{X}.$$

The implied constant depends at most on κ, A, and the implied constants in the hypotheses.

Proof. See Section 4. □

2.2. **Explicit formula.** We now rewrite the left-hand side of (4) by applying the explicit formula, *e.g.* [Sic98, Theorem 2.2], where we put $\Phi(\rho) = \phi(\frac{\rho - 1/2}{2\pi i}\log Q)$, so that $F(x) = \frac{1}{\log Q}\widehat{\phi}(\frac{1}{\log Q})$. For $q > 1$ and $\chi \pmod q$ primitive, we obtain

$$\begin{aligned} &\sum_{\substack{\rho\in\mathbb{C}\\ \mathrm{Re}(\rho)\in(0,1)\\ L(\rho,\chi)=0}} \phi\Big(\frac{(\rho - \frac12)\log Q}{2\pi i}\Big) \\ &\qquad = O\Big(\frac{1}{\log Q}\Big) + \widehat{\phi}(0)\frac{\log q}{\log Q} - \frac{1}{\log Q}\sum_{n\geq 1}(\chi(n) + \overline{\chi}(n))\frac{\Lambda(n)}{\sqrt{n}}\widehat{\phi}\Big(\frac{\log n}{\log Q}\Big), \end{aligned} \tag{7}$$

since the terms I, J appearing in [Sic98, Theorem 2.2] satisfy $\big|I(\frac12, b)\big| + \big|J(\frac12, b)\big| \ll (\log Q)^{-1}$ for $b \in \{0, \frac12\}$ by reasoning similarly as in [Sic98, Theorem 3.2]. Let $\Psi(x) = \Phi(x)x^{-1}$. Summing (7) over χ and q we see that to conclude it remains to show that

$$S_\kappa(Q) := \sum_{q\in\mathbb{N}} \frac1q \Psi\Big(\frac{q}{Q}\Big) \sum_{\substack{\chi(q)\\ \text{primitive}}} \frac{1}{\log Q}\sum_{n\geq 1}(\chi(n) + \overline{\chi}(n))\frac{\Lambda(n)}{\sqrt{n}}\widehat{\phi}\Big(\frac{\log n}{\log Q}\Big) = o(Q) \tag{8}$$

We will in fact obtain the following slightly stronger result.

Proposition 5. *Let $\kappa \in (0, \frac{50}{1093})$. For all Q large enough and $\varepsilon > 0$ small enough in terms of κ, we have*

$$S_\kappa(Q) = O\Big(\frac{Q}{\log Q}\Big).$$

The implied constant depends on ϕ and ε at most.

We break down the proof of Proposition 5 into the following three sections.

2.3. **Orthogonality and partition of unity.** Applying character orthogonality for primitive characters (see the third display in the proof of Lemma 4.1 of [BM11]), we get

$$S_\kappa(Q) = \frac{2}{\log Q}\sum_{v,w}\sum \Psi\left(\frac{vw}{Q}\right)\frac{\mu(v)}{v}\frac{\varphi(w)}{w}\sum_{n\equiv 1 \pmod w}\frac{\Lambda(n)}{\sqrt{n}}\widehat{\phi}\left(\frac{\log n}{\log Q}\right). \tag{9}$$

Let V be any test function generating the partition of unity

$$\sum_{j\in\mathbb{Z}} V\Big(\frac{x}{2^j}\Big) = 1$$

for all $x > 0$. Inserting this in (9), we obtain

$$S_\kappa(Q) = \frac{2}{\log Q} \sum_{\substack{j\in\mathbb{Z}\\ 1/2\le X:=2^j\le 2Q^{2+\kappa}}} \sum_{v,w}\sum \Psi\left(\frac{vw}{Q}\right)\frac{\mu(v)}{v}\frac{\varphi(w)}{w} \sum_{n\equiv 1 \pmod w} \frac{\Lambda(n)}{\sqrt{n}} V\Big(\frac{n}{X}\Big)\widehat{\phi}\left(\frac{\log n}{\log Q}\right).$$

Set $f_j(x) = x^{-1/2}V(x)\widehat{\phi}(\frac{\log(2^j x)}{\log Q})$ for $\frac{1}{2} \le 2^j \le 2Q^{2+\kappa}$. Differentiating the product, we have that for all $k \ge 0$, there exists $C_{h,k} \ge 0$ such that $\|f_j^{(k)}\|_\infty \le C_{h,k}$ for all j. We deduce

$$S_\kappa(Q) \ll \sup_{1\ll X\ll Q^{2+\kappa}} X^{-1/2} \sup_f |T_\kappa(Q,X)|,$$

where f varies among test functions subject to $\|f^{(k)}\|_\infty \le C_{h,k}$, and

$$T_\kappa(Q,X) := \sum_{v,w}\sum \Psi\left(\frac{vw}{Q}\right)\frac{\mu(v)}{v}\frac{\varphi(w)}{w} \sum_{n\equiv 1 \pmod w} \Lambda(n) f\Big(\frac{n}{X}\Big).$$

We handle the very small values of X by the trivial bound

$$\sum_{n\equiv 1 \pmod w} \Lambda(n) f\Big(\frac{n}{X}\Big) \ll \frac{X\log Q}{w},$$

which implies

$$T_\kappa(Q,X) \ll \frac{X\log Q}{Q}\sum_{vw\asymp Q}\sum 1 \ll X(\log Q)^2.$$

It will therefore suffice to show that for

$$Q^2/(\log Q)^6 \ll X \ll Q^{2+\kappa},$$

we have

$$T_\kappa(Q,X) \ll \frac{\sqrt{X}Q}{\log Q}.$$

2.4. **Substracting the main term.** We insert the coprimality condition $(n,v) = 1$. Since

$$\begin{aligned}
&\sum_{v,w}\sum \Psi\left(\frac{vw}{Q}\right)\frac{\mu(v)}{v}\frac{\varphi(w)}{w} \sum_{\substack{n\equiv 1 \pmod w\\ (n,v)>1}} \Lambda(n) f\Big(\frac{n}{X}\Big)\\
&\ll \sum_{v\ll Q} v^{-1} \sum_{\substack{p\mid v\\ 1\le k\ll \log X}} (\log p) \sum_{w\mid p^k-1} 1\\
&\ll Q^\varepsilon,
\end{aligned}$$

we obtain

$$T_\kappa(Q,X) = \sum_{v,w}\sum \Psi\left(\frac{vw}{Q}\right)\frac{\mu(v)}{v}\frac{\varphi(w)}{w} \sum_{\substack{n\equiv 1 \pmod w\\ (n,v)=1}} \Lambda(n) f\Big(\frac{n}{X}\Big) + O(Q^\varepsilon).$$

Let $1 \le R < Q/2$ so that $R < vw$ for any v, w appearing in the sum. We replace the condition $n \equiv 1 \pmod w$ by $\mathfrak{u}_R(n,w)$. The difference is

$$\sum_q \frac{1}{q}\Psi\left(\frac{q}{Q}\right) \sum_{\substack{\chi \pmod q \\ r=\mathrm{cond}(\chi)\le R \\ r\mid q}} \sum_{(n,q)=1} \Lambda(n) f\Big(\frac{n}{X}\Big)\chi(n) \sum_{v\mid q/r} \mu(v) = 0$$

since $r < q$ by our choice of R, so that

$$T_\kappa(Q) = \sum_{v,w}\sum \Psi\left(\frac{vw}{Q}\right)\frac{\mu(v)}{v}\frac{\varphi(w)}{w} \sum_{(n,v)=1} \Lambda(n) f\Big(\frac{n}{X}\Big)\mathfrak{u}_R(n,w) + O(Q^{1+\varepsilon}).$$

We next remove the coprimality condition on n, using the trivial bound (5). For the first term $\mathbf{1}_{n\equiv 1 \pmod w}$ in $\mathfrak{u}_R(n,w)$, this was already justified above. For the second term, we get

$$\ll RQ^{-1+\varepsilon} \sum_{\substack{v,w \\ vw\sim Q}}\sum_{p\mid v} \log p \ll RQ^{\varepsilon}.$$

Since $R \ll Q$, both error terms are acceptable. We get

$$T_\kappa(Q,X) = T_\kappa(Q,X,R) + O(Q^{1+\varepsilon}),$$

where

$$T_\kappa(Q,X,R) := \sum_{v,w}\sum \Psi\left(\frac{vw}{Q}\right)\frac{\mu(v)}{v}\frac{\varphi(w)}{w}\Delta(w),$$

$$\Delta(w) := \sum_n \Lambda(n) f\Big(\frac{n}{X}\Big)\mathfrak{u}_R(n,w). \tag{10}$$

We are required to show that

$$T_\kappa(Q,X,R) \ll \frac{\sqrt{X}Q}{\log Q}. \tag{11}$$

2.5. **Reduction to the critical range.** We now impose the additional conditions

$$Q^{\kappa/2+\varepsilon} \le R \le Q^{1/2}, \qquad \kappa \le 2/3. \tag{12}$$

Let $B \in [1, Q^{1/2}]$ be a parameter. In $T_\kappa(Q,X,R)$, we write $\frac{\varphi(w)}{w} = \sum_{b\mid w}\frac{\mu(b)}{b}$ and exchange summation, so that

$$\begin{aligned} T_\kappa(Q,X,R) &\le \sum_{b,v}\frac{1}{bv}\Big|\sum_w \Psi\Big(\frac{bvw}{Q}\Big)\Delta(bw)\Big| \\ &\ll (\log B)^2 \sup_{b,v\le B}\Big|\sum_w \Psi\Big(\frac{bvw}{Q}\Big)\Delta(bw)\Big| + E_1 + E_2, \end{aligned}$$

where E_1 (resp. E_2) corresponds to the sum over b, v restricted to $b > B$ (resp. $v > B$). We recall that $\operatorname{supp}\Psi \subset [\frac{1}{2}, 3]$ by hypothesis. On the one hand, we have

$$\begin{aligned} E_1 &\ll \sum_{\substack{b,w \\ bw \leq 3Q \\ b>B}} \sum \frac{1}{b} |\Delta(bw)| \\ &\ll Q^{\varepsilon} B^{-1} \sum_{q \leq 3Q} |\Delta(q)| \\ &\ll Q^{1+\varepsilon} \sqrt{X} B^{-1}. \end{aligned}$$

using (6) along with our hypotheses (12). On the other hand, we have

$$\begin{aligned} E_2 &\ll \sum_{\substack{b,w \\ bw \leq 3Q/B}} \sum \frac{1}{b} |\Delta(bw)| \\ &\ll Q^{\varepsilon} \sum_{q \leq 3Q/B} |\Delta(q)| \\ &\ll Q\sqrt{X}(Q^{\varepsilon} B^{-1} + Q^{-\varepsilon}) \end{aligned}$$

again by (12) and (6).

Grouping the above, we conclude that it will suffice to show that for all fixed $A > 0$ and $\boldsymbol{c}$, we have

$$\sum_{w} \Psi\Big(\frac{bvw}{Q}\Big) \Delta(bw) \ll Q^{1-\varepsilon}\sqrt{X}$$

uniformly for $b, v \leq Q^{\varepsilon}$ and Ψ and f are test functions. This now follows from Proposition 4 applied with $W = \frac{Q}{bv}$, which completes the proof of (11), hence of Proposition 5.

3. Exponential sums estimates

In this section, we work out the modifications to be made to the arguments underlying [DI82] in order to exploit current knowledge on the spectral gap of the Laplacian on congruence surfaces [KS03]. We will follow the setting in Theorem 2.1 of [Dra17], since we will need to keep track of the uniformity in q_0. We also take the pportunity to implement the correction recently described in [BFI].

Let $\theta \geq 0$ be a bound towards the Petersson-Ramanujan conjecture, in the sense of [Dra17, eq. (4.6)]. Selberg's 3/16 theorem corresponds to $\theta \leq 1/4$, and the Kim-Sarnak bound [KS03] asserts that $\theta \leq 7/64$.

Proposition 6. *Let the notations and hypotheses be as in* [Dra17, Theorem 2.1]. *Then*

$$\begin{aligned} &\sum_{\substack{c \\ c \equiv c_0 \pmod q}} \sum_{\substack{d \\ \text{and } d \equiv d_0 \pmod q \\ (qrd, sc) = 1}} \sum_{n} \sum_{r} \sum_{s} b_{n,r,s} g(c,d,n,r,s) \mathrm{e}\Big(n\frac{\overline{rd}}{sc}\Big) \\ &\qquad \ll_{\varepsilon, \varepsilon_0} (qCDNRS)^{\varepsilon + O(\varepsilon_0)} q^{3/2} K(C,D,N,R,S) \|b_{N,R,S}\|_2, \end{aligned}$$

where $\|b_{N,R,S}\|_2^2 = \sum_{n,r,s} |b_{n,r,s}|^2$, *and here*

$$K(C,D,N,R,S)^2 = qCS(RS+N)(C+RD) + C^{1+4\theta} DS((RS+N)R)^{1-2\theta} + D^2 NR. \tag{13}$$

Remark 7. The bound of Proposition 6 is monotonically stronger as θ decreases. Under the Petersson-Ramanujam conjecture for Maass forms, which predicts that $\theta = 0$ is admissible, the second term in (13) is smaller than the first.

Proof. We implement the remark made in [Dra17, p.703]; the statements which are affected are Lemma 4.10, Proposition 4.12, Proposition 4.13 and the proof of Theorem 2.1.

— In Lemma 4.10, the term $(NY)^{1/2}$ can be replaced by $(NY)^{2\theta}Q^{1-4\theta}$. This does not require any change in the recursion argument, but merely to use the bound $|t_f| \leq \theta$ in the very last step, page 278 of [DI82], whereby $\sqrt{Y/Y_1}$ is replaced by $(Y/Y_1)^{2\theta}$.

— In Proposition 4.12, using the new bound for Lemma 4.10, the term L_{exc} can be replaced by

$$L_{\text{exc}} := q_0^{\frac{1}{2}-2\theta}\Big(1+\sqrt{\frac{N}{RS}}\Big)\Big(\frac{1+X^{-1}}{RS}\Big)^{2\theta}\Big(\frac{MN}{RS+N}\Big)^{\theta}\frac{\sqrt{RS}}{1+X}\sqrt{M}\|b_{N,R,S}\|_2.$$

— In Proposition 4.13, the term K_{exc} can be replaced by

$$K_{\text{exc}} := C^{2+4\theta}S^2(R(N+RS))^{1-2\theta}.$$

This is seen by using the new definition on L_{exc} in Proposition 4.12, and by keeping track of a factor $q^{-1+2\theta}$ coming from the term $(1+X)^{-1+2\theta}$.

— Finally, we modify the proof of Theorem 2.1 at two places. First, the bound for $\mathcal{A}_0$ on page 706, as explained in [BFI], is wrong unless further hypotheses on $(b_{n,r,s})$ are imposed. The correct bound in general is

$$\mathcal{A}_0 \ll q^{-2}(\log S)^2 D(NR)^{1/2}\|b_{N,R,S}\|^2,$$

and this yields the term D^2NR instead of D^2NRS^{-1}. Secondly, our new bound for K_{exc} in Proposition 4.13 gives a contribution $C^{2+4\theta}(R(RS+N))^{1-2\theta}$ instead of $C^3\sqrt{R(RS+N)}$ in the definition of L_{exc} and $L^*(M_1)$ on p.707 of [Dra17]. This yields a term $C^{1+4\theta}DS((N+RS)R)^{1-2\theta}$ instead of $C^2DS\sqrt{(N+RS)R}$ in eq. (4.39) of [Dra17], and by following the rest of the arguments we deduce our claimed bound.

□

4. Primes in arithmetic progressions: Proof of Proposition 4

The proof of Theorem 1 relies on Proposition 4 which for the convenience of the reader we recall below.

Proposition. *Let $\kappa \in (0, \frac{50}{1093})$ and $\varepsilon > 0$. Let Ψ, f be test functions, $A > 0$, $X, Q, W, R \geq 1$, and $b \in \mathbb{N}$. Assume that*

$$\frac{Q^2}{(\log Q)^A} \ll X \ll Q^{2+\kappa}, \qquad X^{1/2}Q^{-1} \leq R \leq Q^{2/3}X^{-2/9},$$
$$b \leq Q^{\varepsilon} \qquad Q^{1-\varepsilon} \ll W \ll Q,$$

and that $\|f^{(j)}\|_\infty, \|\Psi^{(j)}\|_\infty \ll_j 1$. Then if $\varepsilon > 0$ is small enough in terms of κ, we have

$$\sum_{w\in\mathbb{N}}\Psi\Big(\frac{w}{W}\Big)\sum_{n\in\mathbb{N}}\Lambda(n)f\Big(\frac{n}{X}\Big)\mathfrak{u}_R(n,bw) \ll Q^{1-\varepsilon}\sqrt{X}.$$

The implied constant depends at most on κ, A, and the implied constants in the hypotheses.

Remark 8. What is crucial in our statement is the size of the error term, which should be negligible with respect to $Q\sqrt{X}$. On the other hand, we are only interested in values of X larger than Q^2. This is in contrast with most works on primes in arithmetic progressions [FI83, BFI86, Zha14], where the main challenge is to work with values of X much smaller than Q^2, while only aiming at an error term which is negligible with respect to X. The main point is that in both cases, the large sieve yields an error term which is always too large (see [IK04, Theorem 17.4]), an obstacle which the dispersion method is designed to handle.

In what follows, we will systematically write

$$X = Q^{2+\varpi},$$

so that $-o(1) \leq \varpi \leq \kappa + o(1)$ as $Q \to \infty$.

4.1. **Combinatorial identity.** We perform a combinatorial decomposition of the von Mangoldt function into sums of different shapes: Type d_1 sums have a long smooth variable, Type d_2 sums have two long smooth variables, and Type II sums have two rough variables that are neither too small nor too large. We accomplish this decomposition with the Heath-Brown identity and the following combinatorial lemma.

Lemma 9. *Let $\{t_j\}_{1\leq j\leq J} \in \mathbb{R}$ be non-negative real numbers such that $\sum_j t_j = 1$. Let $\lambda, \sigma, \delta \geq 0$ be real numbers such that*

- $\delta < \frac{1}{12}$,
- $\sigma \leq \frac{1}{6} - \frac{\delta}{2}$,
- $2\lambda + \sigma < \frac{1}{3}$.

Then at least one of the following must occur:

- *(Type d_1) There exists t_j with $t_j \geq \frac{1}{3} + \lambda$*
- *(Type d_2) There exist i, j, k such that $\frac{1}{3} - \delta < t_i, t_j, t_k < \frac{1}{3} + \lambda$, and*

$$\sum_{t_j^* \notin \{t_i, t_j, t_k\}} t_j^* < \sigma$$

- *(Type II) There exists $S \subset \{1, \dots, J\}$ such that*

$$\sigma \leq \sum_{j\in S} t_j \leq \tfrac{1}{3} - \delta$$

Proof. Assume that the Type d_1 case and the Type II case both fail. Then for every j we have $t_j < \frac{1}{3} + \lambda$, and for every subset S of $\{1, \dots, J\}$ we either have

$$\sum_{j\in S} t_j < \sigma$$

or

$$\sum_{j\in S} t_j > \frac{1}{3} - \delta.$$

Let $s_1, \dots, s_K$ denote those t_j with $\frac{1}{3} - \delta < t_j < \frac{1}{3} + \lambda$. We will show that $K = 3$. Let t_j^* be any other t_j, so that $t_j^* \le \frac{1}{3} - \delta$, and therefore $t_j^* < \sigma$. We claim that

$$\sum_j t_j^* < \sigma.$$

If not, then $\sum_j t_j^* > \frac{1}{3} - \delta$. By a greedy algorithm we can find some subcollection S^* of the t_j^* such that

$$\sigma < \sum_{j \in S^*} t_j^* \le 2\sigma.$$

Since $2\sigma \le \frac{1}{3} - \delta$ this subcollection satisfies the Type II condition, in contradiction to our assumption.

Now we show that $K = 3$. Observe that $K \ge 3$, since if $K \le 2$ we have

$$1 = \sum_j t_j = \sum_{i=1}^{K} s_i + \sum_j t_j^* \le 2\left(\tfrac{1}{3} + \lambda\right) + \sigma < 1.$$

Furthermore, we must have $K \le 3$, since if $K \ge 4$ we have

$$1 = \sum_j t_j \ge \sum_{i=1}^{K} s_i \ge 4\left(\frac{1}{3} - \delta\right) > 1.$$

This completes the proof. □

Using *e.g.* Heath-Brown's combinatorial identity [HB82], we deduce the following.

Corollary 10. *Let f be a test function, $u : \mathbb{N} \to \mathbb{C}$ be any map, and $X \ge 1$. Then for some sequences $(\beta_n^{(j)})_n$, $j \in \{1, 2, 3\}$, satisfying*

$$\left|\beta_n^{(j)}\right| \le d(n)^8,$$

and some test functions g, g_2, g_3 satisfying $\|g^{(j)}\|_\infty, \|g_1^{(j)}\|_\infty, \|g_2^{(j)}\|_\infty \ll_j 1$, depending on f only, we have

$$\left|\sum_{n \in \mathbb{N}} \Lambda(n) f\Big(\frac{n}{X}\Big) u(n)\right| \ll (\log X)^{10}\big(T_1 + T_2 + T_{II}\big), \tag{14}$$

where

$$T_1 = \sup_{\substack{N \gg X^{1/3+\lambda} \\ MN \asymp X}} \Big|\sum_{\substack{n \in \mathbb{N} \\ m \sim M}} \sum g\Big(\frac{n}{N}\Big) \beta_m^{(1)} u(mn)\Big|, \tag{15}$$

$$T_2 = \sup_{\substack{X^{1/3-\delta} \ll N_2 \le N_1 \ll X^{1/3+\lambda} \\ MN_1N_2 \asymp X}} \Big|\sum_{\substack{n_1, n_2 \in \mathbb{N} \\ m \sim M}} \sum \sum g_1\Big(\frac{n_1}{N_1}\Big) g_2\Big(\frac{n_2}{N_2}\Big) \beta_m^{(2)} u(mn_1n_2)\Big|, \tag{16}$$

$$T_{II} = \sup_{\substack{X^{\sigma} \ll N \ll X^{1/3-\lambda} \\ MN \asymp X}} \Big|\sum_{\substack{n \sim N \\ m \sim M}} \sum \alpha_m \beta_n^{(3)} u(mn)\Big|. \tag{17}$$

Here the suprema are over numbers $M, N, N_1, N_2 \ge 1$. The implied constants are absolute.

In what follows, we successively consider T_1, T_2 and T_{II}, which we specialize at $u(n) := \mathfrak{u}_R(n, bw)$, and we sum over w against $\Psi(w/W)$.

4.2. **Type d_1 sums.** We suppose M and N are given as in (15), and we rename $\beta_m^{(1)}$ into β_m. The quantity we wish to bound is

$$T_1(M,N) = \sum_w \Psi\Big(\frac{w}{W}\Big) \sum_{\substack{m\sim M\\(m,bw)=1}} \beta_m\Big(\sum_{\substack{n\in\mathbb{N}\\ mn\equiv 1 \pmod{bw}}} g\Big(\frac{n}{N}\Big) - \frac{1}{\varphi(bw)} \sum_{\substack{\chi \pmod{bw}\\ \mathrm{cond}(\chi)\le R}} \chi(m) \sum_{(n,bw)=1} \chi(n) g\Big(\frac{n}{N}\Big)\Big).$$

By Poisson summation and the classical bound on Gauss sums [IK04, Lemma 3.2], we have

$$\sum_{n\equiv \overline{m} \pmod{bw}} g\left(\frac{n}{N}\right) = \frac{N}{bw}\widehat{g}(0) + \frac{N}{bw} \sum_{0<|h|\le W^{1+\varepsilon}/N} \widehat{g}\left(\frac{Nh}{bw}\right) e\left(\frac{\overline{m}h}{bw}\right) + O\left(Q^{-A}\right),$$

$$\frac{1}{\varphi(bw)} \sum_{(c,bw)=1} \chi(c) g\left(\frac{c}{N}\right) = \frac{N}{bw}\widehat{g}(0)\mathbf{1}(\chi=\chi_0) + O\left(\frac{Q^{\varepsilon}R^{1/2}}{W}\right).$$

Therefore,

$$T_1(M,N) = \frac{N}{b}\sum_w \frac{1}{w}\Psi\left(\frac{w}{W}\right) \sum_{\substack{(m,bw)=1\\ m\sim M}} \beta_m \sum_{0<|h|\le W^{1+\varepsilon}/N} \widehat{g}\left(\frac{Nh}{bw}\right) e\left(\frac{\overline{m}h}{bw}\right) + O(MR^{3/2}Q^{\varepsilon}).$$

Our goal is to get cancellation in the exponential phases by summing over the smooth variable w. We apply the reciprocity formula

$$\frac{\overline{m}h}{bw} \equiv -\frac{\overline{bw}h}{m} + \frac{h}{mbw} \pmod 1,$$

which implies

$$T_1(M,N) = \frac{N}{b}\sum_w \frac{1}{w}\Psi\left(\frac{w}{W}\right) \sum_{\substack{(m,bw)=1\\ m\sim M}} \beta_m \sum_{0<|h|\le W^{1+\varepsilon}/N} \widehat{g}\left(\frac{Nh}{bw}\right) e\left(\frac{\overline{bw}h}{m}\right) + O(MR^{3/2}Q^{\varepsilon} + Q^{1+\varepsilon}N^{-1}).$$

We rearrange the sum as

$$\frac{N}{b} \sum_{\substack{(m,b)=1\\ m\sim M}} \beta_m \sum_{0<|h|\le W^{1+\varepsilon}/N} \sum_{(w,m)=1} \widehat{g}\left(\frac{Nh}{bw}\right) \frac{1}{w}\Psi\left(\frac{w}{W}\right) e\left(\frac{\overline{bw}h}{m}\right).$$

By partial summation and a variant of the Weil bound [FR18, Lemma 2.4], the sum on w is

$$\ll \sqrt{(h,m)}\sqrt{M}Q^{\varepsilon}.$$

Summing over h and m, we obtain a bound

$$T_1(M,N) \ll Q^{1+\varepsilon} + M^{3/2}Q^{\varepsilon} + MR^{3/2}Q^{\varepsilon}.$$

This bound is acceptably small provided

$$N \gg \left(\frac{X}{Q}\right)^{2/3+\varepsilon} = X^{\frac{1}{3}+\frac{\varpi}{3(2+\varpi)}+\frac{1+\varpi}{2+\varpi}\varepsilon},$$
$$N \gg \frac{X^{1/2}R^{3/2}}{Q^{1-2\varepsilon}} = X^{\frac{\varpi}{2+\varpi}+\frac{3}{2}\rho+\frac{2\varepsilon}{2+\varpi}},$$

with c sufficiently large. These inequalities are satisfied, for all sufficiently small $\varepsilon > 0$, under the assumptions

$$\lambda > \frac{\varpi}{3(2+\varpi)}, \qquad \rho < \frac{4-2\varpi}{9(2+\varpi)}. \tag{18}$$

We have proved the following.

Lemma 11. *Under the notations and hypotheses of Corollary 10, and assuming* (18)*, we have*

$$T_1 \ll Q^{1-\varepsilon}\sqrt{X}.$$

The implied constant depends on λ, ρ and ϖ.

4.3. **Type d_2 sums.** The treatment of the type d_2 sums (16) is nearly identical to [BFI86, Section 14]. For convenience, we rename (N_1, N_2, L) into (M, N, L) and $\beta_\ell^{(2)}$ into β_ℓ so that we have $MNL \asymp X$. We wish to bound

$$T_2(M,N,L) = \sum_{\ell\sim L}\beta_\ell \sum_{(w,\ell)=1}\Psi\left(\frac{w}{W}\right)\Bigg(\sum_{\substack{m,n\\ \ell mn\equiv 1 \pmod{bw}}}\sum g_1\left(\frac{m}{M}\right)g_2\left(\frac{n}{N}\right)$$
$$- \frac{1}{\varphi(bw)}\sum_{\substack{\chi \pmod{bw}\\ \mathrm{cond}(\chi)\le R}}\chi(\ell)\sum_{(mn,bw)=1}\sum g_1\left(\frac{m}{M}\right)g_2\left(\frac{n}{N}\right)\chi(mn)\Bigg).$$

We perform Poisson summation on the m-sums to get

$$\sum_{m\equiv\overline{\ell n} \pmod{bw}} g_1\left(\frac{m}{M}\right) = \frac{M}{bw}\sum_{|h|\le H}\widehat{g_1}\left(\frac{Mh}{bw}\right)e\left(\frac{\overline{\ell n}h}{bw}\right) + O(Q^{-A}),$$
$$\sum_{(m,bw)=1}\chi(m)g_1\left(\frac{m}{M}\right) = \frac{\varphi(bw)}{bw}M\widehat{g_1}(0)\mathbf{1}(\chi=\chi_0) + O\left(Q^\varepsilon R^{1/2}\right),$$

where $H = W^{1+\varepsilon}M^{-1}$. The contribution of the error terms is

$$\ll LNR^{3/2}Q^\varepsilon.$$

The zero frequency of Poisson summation cancels out. For the non-zero frequencies we employ reciprocity in the form

$$e\left(\frac{\overline{\ell n}h}{bw}\right) = e\left(-\frac{\overline{bw}h}{\ell n}\right) + O\left(\frac{H}{LNW}\right),$$

and the error term contributes a quantity of size $O(Q^{1+\varepsilon})$. We therefore have

$$T_2(M,N,L) = \frac{M}{b}\sum_{\ell\sim L}\beta_\ell \sum_{(w,\ell)=1}\frac{1}{w}\Psi\left(\frac{w}{W}\right)\sum_{(n,w)=1} g_2\left(\frac{n}{N}\right)\sum_{0<|h|\leq H}\widehat{g_1}\left(\frac{Mh}{bw}\right)e\left(-\frac{\overline{bw}h}{\ell n}\right) \tag{19}$$

$$+ O(Q^{1+\varepsilon} + LNR^{3/2}Q^{\varepsilon}). \tag{20}$$

We next separate the variables h and w. We change variables to write

$$\widehat{g_1}\left(\frac{Mh}{bw}\right) = \frac{w}{M}\int_{\mathbb{R}} g_1\left(\frac{wy}{M}\right)e\left(-\frac{hy}{b}\right)dy.$$

Since g_1 and Ψ are test functions, the integral is restricted to $0 \leq y \ll M/W$. We move the integral to the outside to write the first term of the right-hand side of (19) as

$$\ll \frac{M}{bW}\sup_{0\leq y\ll M/W}\left|\sum_{\ell}\beta_\ell\sum_{0<|h|\leq H}\mathrm{e}\left(-\frac{hy}{b}\right)\sum_{w}\sum_{n}\Psi\left(\frac{w}{W}\right)g_1\left(\frac{wy}{M}\right)g_2\left(\frac{n}{N}\right)\mathrm{e}\left(-\frac{\overline{bw}h}{\ell n}\right)\right|.$$

We then use [DI82, Theorem 12], amended as described in [BFI]. It is easier to sum up the bounds if we assume

$$N \ll W^{1+\varepsilon}. \tag{21}$$

We find

$$T_2(M,N,L) \ll LNR^{3/2}Q^{\varepsilon} + Q^{\varepsilon}\left(\sqrt{X}L + \sqrt{M}NL^{5/4}\right).$$

This contribution is acceptable provided

$$M \gg X^{\frac{\varpi}{2(2+\varpi)}+\frac{3}{2}\rho+\varepsilon}, \qquad MN \gg X^{\frac{1}{2}+\frac{\varpi}{2(2+\varpi)}+\varepsilon} \tag{22}$$

and

$$M^{3/2}N^{1/2} \gg X^{\frac{1}{2}+\frac{\varpi}{2+\varpi}+2\varepsilon}. \tag{23}$$

The bounds (21)–(23) are satisfied if

$$\delta < \frac{1}{12} - \frac{\varpi}{2(2+\varpi)}, \qquad \lambda < \frac{1}{6} - \frac{\varpi}{2(2+\varpi)}, \qquad \rho < \frac{1}{6}. \tag{24}$$

We therefore conclude the following.

Lemma 12. *Under the notations and hypotheses of Corollary 10, and assuming* (24)*, we have*

$$T_2 \ll Q^{1-\varepsilon}\sqrt{X}.$$

The implied constant depends on λ, δ, ρ and ϖ.

4.4. **Type II sums.** In the type II case (17), we rename $\beta_n^{(3)}$ into β_n. We wish to prove the bound

$$T_{\mathrm{II}}(M,N) := \sum_{w}\Psi\left(\frac{w}{W}\right)\sum_{m,n}\alpha_m\beta_n\mathfrak{u}_R(mn,bw) \ll \sqrt{X}Q^{1-\varepsilon},$$

where α is supported at scale M, β is supported at scale N, $MN \asymp X$, and $X^{\sigma} \ll N \ll X^{1/3-\delta}$. We have $|\alpha(m)| \leq \tau(m)^{O(1)}$, and similarly for β. We use Linnik's dispersion method [Lin63], following closely [Fou85]; see also [BFI86, Section 10].

We interchange the order of summation and apply the triangle inequality, writing our sum as

$$\sum_m \left| \sum_w \sum_n \right|.$$

Applying the Cauchy-Schwarz inequality, we arrive at

$$\mathcal{S}^2 \ll M(\log M)^{O(1)}\mathcal{D}, \tag{25}$$

where

$$\mathcal{D} = \sum_m f\left(\frac{m}{M}\right) \left| \sum_{\substack{m,n,w \\ mn \equiv 1 \pmod{bw}}} \Psi\left(\frac{w}{W}\right)\beta_n - \frac{1}{\varphi(bw)} \sum_{\substack{\chi \pmod{bw} \\ \mathrm{cond}(\chi)\le R}} \sum_{\substack{m,n,w \\ (mn,bw)=1}} \Psi\left(\frac{w}{W}\right)\beta_n \chi(mn) \right|^2.$$

Here f is some fixed, non-negative test function majorizing $\mathbf{1}_{[1,2]}$. It suffices to show that

$$\mathcal{D} \ll NQ^{1-\varepsilon}.$$

We open the square and arrive at

$$\mathcal{D} = \mathcal{D}_1 - 2\,\mathrm{Re}\,\mathcal{D}_2 + \mathcal{D}_3, \tag{26}$$

say. We treat each sum $\mathcal{D}_i$ in turn.

4.4.1. *Evaluation of* $\mathcal{D}_3$. By definition we have

$$\mathcal{D}_3 := \sum_m f\left(\frac{m}{M}\right) \sum_{\substack{w_1,w_2,n_1,n_2 \\ (mn_1,bw_1)=1 \\ (mn_2,bw_2)=1}} \sum_{\substack{\chi_1,\chi_2 \\ \chi_j \pmod{bw_j} \\ \mathrm{cond}(\chi_j)\le R}} \Psi\left(\frac{w_1}{W}\right)\Psi\left(\frac{w_2}{W}\right)\beta_{n_1}\overline{\beta_{n_2}} \frac{\chi_1(mn_1)\overline{\chi_2(mn_2)}}{\varphi(bw_1)\varphi(bw_2)}.$$

The computations in [Dra17, p. 712–713] can be directly quoted, putting formally

$$\gamma(q) = \mathbf{1}(b \mid q)\Psi(q/(bW)), \tag{27}$$

with the modification that $\mathrm{cond}(\chi_1\overline{\chi_2}) \le R^2$ (instead of R, as stated incorrectly in [Dra17]). We get

$$\mathcal{D}_3 = \mathcal{M}_3 + O(Q^\varepsilon N^2 R^5),$$

where the main term is computed as in [Dra17, p. 712] to be

$$\mathcal{M}_3 := M\widehat{f}(0) \sum_{\substack{w_1,w_2,n_1,n_2 \\ (n_j,bw_j)=1}} \sum_{\substack{\chi \text{ primitive} \\ \mathrm{cond}(\chi)\le R \\ \mathrm{cond}(\chi)\mid b(w_1,w_2)}} \Psi\left(\frac{w_1}{W}\right)\Psi\left(\frac{w_2}{W}\right)\beta_{n_1}\overline{\beta_{n_2}}\chi(n_1\overline{n_2}) \frac{\varphi(bw_1w_2)}{bw_1w_2\varphi(bw_1)\varphi(bw_2)}.$$

The error term is acceptable provided

$$NR^5 \ll Q^{2-\varepsilon}.$$

Since $N \ll X^{1/3}$ this is acceptable provided

$$\rho < \frac{4-\varpi}{15(2+\varpi)}. \tag{28}$$

4.4.2. *Evaluation of $\mathcal{D}_2$.* We have

$$\mathcal{D}_2 := \sum\sum_{\substack{w_1,w_2,n_1,n_2\\(n_j,bw_j)=1}}\sum\sum \sum_{\substack{\chi \pmod{bw_2}\\ \mathrm{cond}(\chi)\leq R}} \Psi\left(\frac{w_1}{W}\right)\Psi\left(\frac{w_2}{W}\right)\overline{\beta_{n_1}}\beta_{n_2}\frac{\chi(n_2)}{\varphi(bw_2)}\sum_{\substack{mn_1\equiv 1 (bw_1)\\(m,w_2)=1}}\chi(m) f\left(\frac{m}{M}\right).$$

The computations in [Dra17, p. 712–713] can be also quoted directly with the identification (27). We obtain

$$\mathcal{D}_2 = \mathcal{M}_3 + O(R^{3/2}N^2Q^{1+\varepsilon}).$$

This is acceptable if

$$\rho < \frac{2}{3}\lambda + \frac{2(1-\varpi)}{9(2+\varpi)}. \tag{29}$$

4.4.3. *Evaluation of $\mathcal{D}_1$.* We have

$$\mathcal{D}_1 := \sum\sum_{\substack{w_1,w_2,n_1,n_2\\(n_j,bw_j)=1\\ n_1\equiv n_2 \pmod b}}\sum\sum \Psi\left(\frac{w_1}{W}\right)\Psi\left(\frac{w_2}{W}\right)\beta_{n_1}\overline{\beta_{n_2}}\sum_{mn_j\equiv 1 \pmod{bw_j}} f\left(\frac{m}{M}\right).$$

We need to separate the variables w_1, w_2, n_1, n_2 from each other, and this requires a subdivision of the variables. We decompose these variables uniquely, following [FR18], as follows:

$$\begin{cases} d = (n_1, n_2),\\ n_1 = dd_1\nu_1, \text{ with } d_1 \mid d^\infty \text{ and } (d,\nu_1)=1,\\ n_2 = d\nu_2,\\ q_0 = (w_1,w_2),\\ w_i = q_0q_i, i\in\{1,2\}.\end{cases}$$

The summation conditions imply

$$(dd_1\nu_1, q_0q_1) = (d\nu_2, q_0q_2) = 1.$$

We therefore have

$$\mathcal{D}_1 = \sum_{(d,b)=1}\sum_{d_1\mid d^\infty}\sum_{(q_0,d)=1}\mathcal{D}_1(d,d_1,q_0),$$

$$\mathcal{D}_1(\cdots) = \sum\sum_{\substack{q_1,q_2,\nu_1,\nu_2\\(d\nu_1,\nu_2)=(q_1,q_2)=1\\(q_1q_2,d)=(\nu_1,d)=1\\(\nu_1,q_1)=(\nu_2,q_2)=(\nu_1\nu_2,bq_0)=1\\ d_1\nu_1\equiv\nu_2 \pmod{bq_0}}}\sum\sum f\left(\frac{q_0q_1}{W}\right)f\left(\frac{q_0q_2}{W}\right)\beta_{dd_1\nu_1}\beta_{d\nu_2}\sum_{\substack{mdd_1\nu_1\equiv 1 \pmod{bq_0q_1}\\ md\nu_2\equiv 1 \pmod{bq_0q_2}}} f\left(\frac{m}{M}\right).$$

Using smooth partitions of unity we break the variables into dyadic ranges: $d\asymp D, d_1\asymp D_1, q_0\asymp Q_0$. The contribution from $d\asymp D$ and $d_1\asymp D_1$ is

$$\ll Q^\varepsilon M\sum_{d\asymp D}\sum_{\substack{d_1\mid d^\infty\\ d_1\asymp D_1}}\sum_{\nu_1\asymp N/dd_1}\sum_{\nu_2\asymp N/d}|\beta_{dd_1\nu_1}||\beta_{d\nu_2}| \ll Q^\varepsilon MN^2\sum_{d\asymp D}\frac{1}{d^2}\sum_{d_1\mid d^\infty}\frac{\tau(d_1)^{O(1)}}{d_1}\left(\frac{d_1}{D_1}\right)^{1-\varepsilon^2}$$

$$\ll Q^\varepsilon MN^2D_1^{-1+\varepsilon^2}D^{-1},$$

and this is acceptable provided

$$DD_1 \gg \frac{X}{Q^{2-\varepsilon}},$$

so we may henceforth assume $DD_1 \ll XQ^{-2+\varepsilon}$.

The contribution from $q_0 \asymp Q_0$ is

$$\begin{aligned}
&\ll Q^{\varepsilon} \sum_{q_0 \asymp Q_0} \sum_{q_1 \asymp Q/q_0} \sum_{n_1 \equiv n_2 \pmod{q_0}} \sum_{m \equiv \overline{n_1} \pmod{q_0 q_1}} 1 \\
&\ll Q^{\varepsilon} M \sum_{q_0 \asymp Q_0} \sum_{q_1 \asymp Q/q_0} \frac{1}{q_0 q_1} \sum_{n_1 \equiv n_2 \pmod{q_0}} \sum 1 \\
&\ll Q^{\varepsilon} \left(MN^2 Q_0^{-1} + MN \right),
\end{aligned}$$

which is acceptable provided

$$N \gg \frac{X}{Q^{2-\varepsilon}}, \quad \text{and} \quad Q_0 \gg \frac{X}{Q^{2-\varepsilon}}, \tag{30}$$

so we may henceforth assume $Q_0 \ll XQ^{-2+\varepsilon}$.

We use Poisson summation, following [Dra17, pp. 714–716]. Let

$$\widetilde{q} = bq_0q_1q_2, \qquad \mu \equiv \begin{cases} \overline{dd_1\nu_1} \pmod{bq_0q_1}, \\ \overline{d\nu_2} \pmod{bq_0q_2}. \end{cases}$$

With $H = \widetilde{q}^{1+\varepsilon} M^{-1} \ll Q^{2+\varepsilon}/(q_0 M)$, we get

$$\sum_{m \equiv \mu \pmod{\widetilde{q}}} f\Big(\frac{m}{M}\Big) = \frac{M}{\widetilde{q}} \sum_{|h| \le H} \widehat{f}\Big(\frac{hM}{\widetilde{q}}\Big) \mathrm{e}\Big(\frac{\mu h}{\widetilde{q}}\Big) + O\Big(\frac{q_0}{bW^2}\Big). \tag{31}$$

The zero frequency in (31) contributes the main term, which, after summing over d, d_1, q_0 (and reintegrating the values DD_1, Q_0 larger than $XQ^{-2+\varepsilon}$ which were discarded earlier), is given by

$$\mathcal{M}_1 := \frac{M}{b} \widehat{f}(0) \sum \sum \sum \sum_{\substack{w_1, w_2, n_1, n_2 \\ (n_j, bw_j) = 1 \\ n_1 \equiv n_2 \pmod{b}}} \Psi\left(\frac{w_1}{W}\right) \Psi\left(\frac{w_2}{W}\right) \beta_{n_1} \overline{\beta_{n_2}} \frac{1}{[w_1, w_2]}.$$

The error term in (31) induces in $\mathcal{D}_1(d, d_1, q_0)$ a contribution

$$\ll \frac{1}{bq_0} \frac{N}{dd_1} \Big(\frac{N}{bq_0} + 1 \Big),$$

and therefore in $\mathcal{D}_1$ a contribution $b^{-1} N^2 Q^{\varepsilon}$, which is acceptable if

$$N \ll Q^{2-\varepsilon}. \tag{32}$$

We solve the congruence conditions on μ by writing

$$d_1\nu_1 - \nu_2 = bq_0 t, \qquad \mu d d_1 \nu_1 = 1 + bq_0q_1\ell, \qquad \mu d \nu_2 = 1 + bq_0q_2 m,$$

with $t, \ell, m \in \mathbb{Z}$. We deduce

$$\mu d t = q_1 \ell - q_2 m, \qquad t = q_1\nu_2 \ell - q_2 d_1 \nu_1 m.$$

Then we have the equalities, modulo $\mathbb{Z}$,

$$\begin{aligned}\frac{\mu}{\widetilde{q}} = \frac{\mu}{bq_0q_1q_2} &= \frac{1}{dd_1\nu_1bq_0q_1q_2} + \frac{\ell}{dd_1\nu_1q_2}\\ &\equiv \frac{1}{dd_1\nu_1bq_0q_1q_2} + \frac{\ell\overline{dd_1}}{\nu_1q_2} + \frac{\ell\overline{\nu_1q_2}}{dd_1}\\ &\equiv \frac{1}{dd_1\nu_1bq_0q_1q_2} + \frac{t\overline{q_1\nu_2dd_1}}{\nu_1q_2} - \frac{\overline{bq_0q_1\nu_1q_2}}{dd_1}\\ &\equiv \frac{1}{dd_1\nu_1bq_0q_1q_2} + \frac{d_1\nu_1-\nu_2}{bq_0}\frac{\overline{q_1\nu_2dd_1}}{\nu_1q_2} - \frac{\overline{bq_0q_1\nu_1q_2}}{dd_1}.\end{aligned}$$

By estimating trivially the first term, we have

$$\mathrm{e}\Big(\frac{h\mu}{\widetilde{q}}\Big) = \mathrm{e}\Big(h\frac{d_1\nu_1-\nu_2}{bq_0}\frac{\overline{q_1\nu_2dd_1}}{\nu_1q_2} - \frac{h\overline{bq_0q_1\nu_1q_2}}{dd_1}\Big) + O\Big(\frac{Hq_0}{NW^2}\Big). \tag{33}$$

The error term here is $\ll Q^{\varepsilon}X^{-1}$, which contributes to $\mathcal{D}_1(d,d_1,q_0)$ a quantity

$$\frac{Q^{2+\varepsilon}N}{Xq_0^2dd_1}\Big(1+\frac{N}{d}\Big),$$

and upon summing over (d,d_1,q_0), this contributes to $\mathcal{D}_1$ a quantity $O(Q^{2+\varepsilon}N^2X^{-1})$. This error is acceptable by our hypothesis (32).

Then we insert the first term of (33) in (31), and insert the Fourier integral. The non-zero frequencies contribute a term

$$\mathcal{R}_1(d,d_1,q_0) = \frac{Mq_0}{bW^2}\int \sum_{\substack{q_1,q_2,\nu_1,\nu_2\\(d\nu_1,\nu_2)=(q_1,q_2)=1\\(q_1q_2,d)=(\nu_1,d)=1\\(\nu_1,q_1)=(\nu_2,q_2)=(\nu_1\nu_2,bq_0)=1\\d_1\nu_1\equiv\nu_2 \pmod{bq_0}}}\sum_{0<|h|\le H}\Psi\Big(\frac{q_0q_1}{W}\Big)\Psi\Big(\frac{q_0q_2}{W}\Big)\beta_{dd_1\nu_1}\beta_{d\nu_2}\times$$
$$\times f\Big(t\frac{q_0^2q_1q_2}{W^2}\Big)\mathrm{e}\Big(h\frac{d_1\nu_1-\nu_2}{bq_0}\frac{\overline{q_1\nu_2dd_1}}{\nu_1q_2} - \frac{h\overline{bq_0q_1\nu_1q_2}}{dd_1}\Big)\mathrm{e}\Big(\frac{htMq_0}{bW^2}\Big)\,\mathrm{d}t.$$

Let now $\lambda_1,\lambda_2\in(\mathbb{Z}/dd_1\mathbb{Z})^\times$, and

$$b_{\boldsymbol{n},\boldsymbol{r},\boldsymbol{s}} = \sum_{\substack{\nu_1\ \ \nu_2\\ \nu_1=\boldsymbol{s}\\ \nu_2dd_1=\boldsymbol{r}\\ (d\nu_1,\nu_2)=(\nu_1\nu_2,bq_0)=1\\ (\nu_1,d)=1\\ d_1\nu_1\equiv\nu_2 \pmod{bq_0}}}\sum_{\substack{0<|h|\le H\\ h(d_1\nu_1-\nu_2)=bq_0\boldsymbol{n}}}\beta_{dd_1\nu_1}\beta_{d\nu_2}\mathrm{e}\Big(-\frac{h\overline{bq_0\lambda_1\nu_1\lambda_2}}{dd_1}+\frac{htMq_0}{bW^2}\Big),$$

$$g(\boldsymbol{c},\boldsymbol{d},\boldsymbol{n},\boldsymbol{r},\boldsymbol{s}) = \Psi\Big(\frac{q_0\boldsymbol{c}}{W}\Big)\Psi\Big(\frac{q_0\boldsymbol{d}}{W}\Big)f\Big(\frac{tq_0^2\boldsymbol{cd}}{W^2}\Big).$$

Then

$$\mathcal{R}_1(d,d_1,q_0) = \frac{Mq_0}{bW^2}\int_{t\asymp_f 1}\sum_{\lambda_1,\lambda_2 \pmod{bdd_1}^*}\tilde{\mathcal{R}}_1(t,(\lambda_j))\,\mathrm{d}t,$$

$$\tilde{\mathcal{R}}_1(t,(\lambda_j)) = \sum_{\substack{\boldsymbol{n},\boldsymbol{r},\boldsymbol{s},\boldsymbol{c},\boldsymbol{d} \\ \boldsymbol{c}\equiv\lambda_1,\ \boldsymbol{d}\equiv\lambda_2 \pmod{bdd_1} \\ (\boldsymbol{sc},\boldsymbol{rd}dd_1)=1}} b_{\boldsymbol{n},\boldsymbol{r},\boldsymbol{s}} g(\boldsymbol{c},\boldsymbol{d},\boldsymbol{n},\boldsymbol{r},\boldsymbol{s}) \mathrm{e}\Big(\frac{\boldsymbol{n}\overline{\boldsymbol{rd}}}{\boldsymbol{sc}}\Big).$$

We apply Proposition 6, with sizes given by

$$\boldsymbol{C} = \boldsymbol{D} = \frac{W}{q_0}, \quad \boldsymbol{S} = \frac{N}{dd_1}, \quad \boldsymbol{R} = Nd_1, \quad \boldsymbol{N} = \frac{HN}{dbq_0}.$$

Let $X = Q^2Y$, so $Y = Q^{\varpi}$. Note that

$$\boldsymbol{RS} \asymp N^2D^{-1}, \qquad \boldsymbol{N} \ll Q^{\varepsilon}N^2Y^{-1}D^{-1}Q_0^{-2} \ll Q^{\varepsilon}\boldsymbol{RS}, \qquad \boldsymbol{C} \ll Q^{\varepsilon}\boldsymbol{RD}.$$

We get

$$\tilde{\mathcal{R}}_1(t,\lambda_j) \ll Q^{\varepsilon}(DD_1)^{3/2}K\|b_{\boldsymbol{n},\boldsymbol{r},\boldsymbol{s}}\|_2,$$

where

$$Q^{-\varepsilon}K^2 \ll Q^2N^4D^{-1}D_1Q_0^{-2} + Q^{2+4\theta}N^{4-6\theta}D^{-2+2\theta}D_1^{-2\theta}Q_0^{-2-4\theta} + Q^2N^3Y^{-1}D^{-1}D_1Q_0^{-4}.$$

To bound the term $\|b_{\boldsymbol{n},\boldsymbol{r},\boldsymbol{s}}\|_2$, we assume

$$DD_1 = o(N), \tag{34}$$

so that the case $d_1\nu_1 = \nu_2$ never occurs in $b_{\boldsymbol{n},\boldsymbol{r},\boldsymbol{s}}$. Then

$$\|b_{\boldsymbol{n},\boldsymbol{r},\boldsymbol{s}}\|_2^2 \le \sum_{\substack{\nu_1,\nu_2,h \\ d_1\nu_1\equiv\nu_2 \pmod{q_0} \\ 0<|h|<H}} |\beta_{dd_1\nu_1}\beta_{d\nu_2}| \ll N^2Y^{-1}D^{-1}D_1^{-1}Q_0^{-1} + N^3Y^{-1}D^{-2}D_1^{-1}Q_0^{-2}.$$

We deduce

$$\tilde{\mathcal{R}}_1(t,(\lambda_j)) \ll Q^{\varepsilon}\sum_{k=1}^{6} Q^{\eta_{k,1}}N^{\eta_{k,2}}Y^{\eta_{k,3}}D^{\eta_{k,4}}D_1^{\eta_{k,5}}Q_0^{\eta_{k,6}},$$

where for each k, $\eta_k = (\eta_{k,\ell})_{1\le\ell\le 6}$ is given by

$$\{\eta_k\} = \left\{ \begin{pmatrix} 1 \\ 3 \\ -1/2 \\ 1/2 \\ 3/2 \\ -3/2 \end{pmatrix}, \begin{pmatrix} 1 \\ 7/2 \\ -1/2 \\ 0 \\ 3/2 \\ -2 \end{pmatrix}, \begin{pmatrix} 2\theta+1 \\ 3-3\theta \\ -1/2 \\ \theta \\ 1-\theta \\ -2\theta-3/2 \end{pmatrix}, \begin{pmatrix} 2\theta+1 \\ 7/2-3\theta \\ -1/2 \\ \theta-1/2 \\ 1-\theta \\ -2\theta-2 \end{pmatrix}, \begin{pmatrix} 1 \\ 5/2 \\ -1 \\ 1/2 \\ 3/2 \\ -5/2 \end{pmatrix}, \begin{pmatrix} 1 \\ 3 \\ -1 \\ 0 \\ 3/2 \\ -3 \end{pmatrix} \right\}.$$

Summing over λ_j, integrating over t, and multiplying by $\frac{Mq_0}{bW^2} \ll N^{-1}YQ_0$, we get

$$\mathcal{R}(d,d_1,q_0) \ll Q^{\varepsilon}\sum_{k=1}^{6} Q^{\eta_{k,1}}N^{\eta_{k,2}-1}Y^{\eta_{k,3}+1}D^{\eta_{k,4}+2}D_1^{\eta_{k,5}+2}Q_0^{\eta_{k,6}+1}.$$

We sum over d, d_1 and q_0, obtaining

$$\sum_{\substack{d\asymp D \\ d_1\asymp D_1,\ d_1\mid d^{\infty} \\ q_0\asymp Q_0 \\ (d,b)=(q_0,d)=1}} \mathcal{R}_1(d,d_1,q_0) \ll Q^{\varepsilon}\sum_{k=1}^{6} Q^{\eta_{k,1}}N^{\eta_{k,2}-1}Y^{\eta_{k,3}+1}D^{\eta_{k,4}+3}D_1^{\eta_{k,5}+2}Q_0^{\eta_{k,6}+2}.$$

Finally we sum this dyadically over Q_0, D, D_1 subject to $Q_0 + DD_1 \ll YQ^{\varepsilon}$. We finally get

$$\mathcal{R}_1 \ll Q^{\varepsilon} \sum_{k=1}^{6} Q^{\eta_{k,1}} N^{\eta_{k,2}-1} Y^{\eta_{k,3}+1+\max(0,\eta_{k,6}+2)+\max(0,\eta_{k,4}+3,\eta_{k,5}+2)}.$$

Here, the terms for $k = 5, 6$ are majorized by the term $k = 1$, therefore,

$$\mathcal{R}_1 \ll Q^{\varepsilon} \sum_{k=1}^{4} Q^{\theta_{k,1}} N^{\theta_{k,2}} Y^{\theta_{k,3}},$$

where

$$\{\theta_k\} = \left\{ \begin{pmatrix} 1 \\ 2 \\ 9/2 \end{pmatrix}, \begin{pmatrix} 1 \\ 5/2 \\ 4 \end{pmatrix}, \begin{pmatrix} 1+2\theta \\ 2-3\theta \\ 4-\theta \end{pmatrix}, \begin{pmatrix} 1+2\theta \\ 5/2-3\theta \\ 7/2-\theta \end{pmatrix} \right\}$$

We conclude that

$$\mathcal{D}_1 = \mathcal{M}_1 + O(Q^{2-\varepsilon}N)$$

on the condition $N \ll Q^{-\varepsilon} \min(QY^{-9/2}, Q^{2/3}Y^{-8/3}, Q^{2/3}Y^{-\frac{7-2\theta}{3(1-2\theta)}}, Q^{\frac{1-2\theta}{1-3\theta}}Y^{-\frac{4-\theta}{1-3\theta}})$. Upon using $\theta \leq 7/64$, these conditions are implied by

$$N \ll X^{-\varepsilon} \min(X^{\frac{2-9\varpi}{2(2+\varpi)}}, X^{\frac{50-249\varpi}{43(2+\varpi)}}, X^{\frac{50-217\varpi}{75(2+\varpi)}}), \tag{35}$$

and the above hypotheses (30), (32), (34).

4.4.4. *Main terms.* The main terms combine to form

$$\mathcal{M}_3 - \mathcal{M}_1 = M\widehat{f}(0) \sum_{w_1,w_2} \sum \Psi\Big(\frac{w_1}{W}\Big)\Psi\Big(\frac{w_2}{W}\Big) \frac{1}{b[w_1,w_2]\varphi(b(w_1,w_2))} \times \sum_{\substack{\chi \text{ prim} \\ \text{cond}(\chi)>R \\ \text{cond}(\chi)|b(w_1,w_2)}} \sum\sum_{\substack{n_1,n_2 \\ (n_j,bw_j)=1}} \beta_{n_1}\overline{\beta_{n_2}}\chi(n_1)\overline{\chi(n_2)}.$$

We may quote the computations in [Dra17, p. 717], again with the identification (27), to obtain

$$|\mathcal{M}_3 - \mathcal{M}_1| \ll Q^{\varepsilon}M(N + N^2R^{-2}) \ll Q^{\varepsilon}(X + NXR^{-2}).$$

This is acceptable provided

$$N \gg Q^{\varpi+\varepsilon}, \qquad R \gg Q^{\frac{\varpi}{2}+O(\varepsilon)}. \tag{36}$$

4.4.5. *Conclusion.* The hypotheses (28), (29), (30), (32), (34), (35) and (36) are all satisfied if

$$\varpi < 1/8, \qquad \varpi < \sigma < \frac{1}{3} - \delta < \frac{1}{3} - \frac{242\varpi}{75(2+\varpi)}, \qquad \frac{\varpi}{2} < \rho < \frac{1}{9} - \frac{4\varpi}{9(2+\varpi)}. \tag{37}$$

We therefore conclude the following.

Lemma 13. *Under the notations and hypotheses of Corollary 10, assuming* (37)*, we have*

$$T_3 \ll \sqrt{X}Q^{1-\varepsilon}.$$

4.5. **Proof of Proposition 4.** We combine Lemmas 11, 12, 13 and 9. Setting $\sigma = \varpi + \varepsilon$ and recalling that $\varpi < 1/8$, we obtain the conditions

$$\frac{\varpi}{3(2+\varpi)} < \lambda < \frac{1}{6} - \frac{\varpi}{2},$$
$$\frac{242\varpi}{75(2+\varpi)} < \delta < \frac{1}{12} - \frac{\varpi}{2(2+\varpi)},$$
$$\frac{\varpi}{2(2+\varpi)} < \rho < \frac{1}{9} - \frac{4\varpi}{9(2+\varpi)}.$$

These can be satisfied whenever $-o(1) \leq \varpi < \frac{50}{1093} - o(1)$. This proves Proposition 4.

References

[BFI] E. Bombieri, J. B. Friedlander, and H. Iwaniec, *Some corrections to an old paper*, ArXiv e-print 1903.01371.

[BFI86] ———, *Primes in arithmetic progressions to large moduli*, Acta Math. **156** (1986), no. 3-4, 203–251.

[BM11] H. M. Bui and Micah B. Milinovich, *Central values of derivatives of Dirichlet L-functions*, Int. J. Number Theory **7** (2011), no. 2, 371–388.

[CLLR14] V. Chandee, Y. Lee, S-C. Liu, and M. Radziwiłł, *Simple zeros of primitive Dirichlet L-functions and the asymptotic large sieve*, Q. J. Math. **65** (2014), no. 1, 63–87. MR 3179650

[CI02] B. Conrey and H. Iwaniec, *Spacing of zeros of Hecke L-functions and the class number problem*, Acta Arith. **103** (2002), no. 3, 259–312. MR 1905090

[DI82] J.-M. Deshouillers and H. Iwaniec, *Kloosterman sums and Fourier coefficients of cusp forms*, Invent. Math. **70** (1982), no. 2, 219–288.

[Dra15] S. Drappeau, *Théorèmes de type Fouvry-Iwaniec pour les entiers friables*, Compos. Math. **151** (2015), no. 5, 828–862. MR 3347992

[Dra17] ———, *Sums of Kloosterman sums in arithmetic progressions, and the error term in the dispersion method*, Proc. London Math. Soc. (3) **114** (2017), no. 4, 684–732.

[FM15] D. Fiorilli and S. J. Miller, *Surpassing the ratios conjecture in the 1-level density of Dirichlet L-functions*, Algebra Number Theory **9** (2015), no. 1, 13–52. MR 3317760

[Fou85] É. Fouvry, *Sur le problème des diviseurs de Titchmarsh*, J. Reine Angew. Math. **357** (1985), 51–76.

[FI83] É. Fouvry and H. Iwaniec, *Primes in arithmetic progressions*, Acta Arith. **42** (1983), no. 2, 197–218.

[FI03] ———, *Low-lying zeros of dihedral L-functions*, Duke Math. J. **116** (2003), no. 2, 189–217. MR 1953291

[FR18] É. Fouvry and M. Radziwiłł, *Another application of Linnik's dispersion method*, Chebyshevskiĭ Sb. **19** (2018), no. 3, 148–163.

[HB82] D. R. Heath-Brown, *Prime numbers in short intervals and a generalized Vaughan identity*, Canad. J. Math. **34** (1982), no. 6, 1365–1377.

[HB04] ———, *The average analytic rank of elliptic curves*, Duke Math. J. **122** (2004), no. 3, 591–623. MR 2057019

[HR03] C. P. Hughes and Z. Rudnick, *Linear statistics of low-lying zeros of L-functions*, Q. J. Math. **54** (2003), no. 3, 309–333. MR 2013141

[IK04] H. Iwaniec and E. Kowalski, *Analytic number theory*, American Mathematical Society Colloquium Publications, vol. 53, American Mathematical Society, Providence, RI, 2004.

[ILS00] H. Iwaniec, W. Luo, and P. Sarnak, *Low lying zeros of families of L-functions*, Inst. Hautes Études Sci. Publ. Math. (2000), no. 91, 55–131 (2001). MR 1828743

[KS99] N. M. Katz and P. Sarnak, *Random matrices, Frobenius eigenvalues, and monodromy*, American Mathematical Society Colloquium Publications, vol. 45, American Mathematical Society, Providence, RI, 1999. MR 1659828

[KS03] H. Kim and P. Sarnak, *Refined estimates towards the Ramanujan and Selberg conjectures*, J. Amer. Math. Soc **16** (2003), no. 1, 175–181.

[LDS] D. Fiorilli L. Devin and A. Södergren, *Low-lying zeros in families of holomorphic cusp forms: the weight aspect*, ArXiv e-print 1911.08310.

[Lin63] Ju. V. Linnik, *The dispersion method in binary additive problems*, Translated by S. Schuur, American Mathematical Society, Providence, R.I., 1963.

[MMR+16] B. Mackall, S. J. Miller, C. Rapti, C. Turnage-Butterbaugh, and K. Winsor, *Some results in the theory of low-lying zeros of families of L-functions*, Families of automorphic forms and the trace formula, Simons Symp., Springer, [Cham], 2016, pp. 435–476. MR 3675173

[Mon73] H. L. Montgomery, *The pair correlation of zeros of the zeta function*, Amer. Math. Soc., Providence, R.I., 1973. MR 0337821

[Pra19] K. Pratt, *Average non-vanishing of Dirichlet L-functions at the central point*, Algebra Number Theory **13** (2019), no. 1, 227–249.

[RS94] Z. Rudnick and P. Sarnak, *The n-level correlations of zeros of the zeta function*, C. R. Acad. Sci. Paris Sér. I Math. **319** (1994), no. 10, 1027–1032. MR 1305671

[Sic98] F. Sica, *The order of vanishing of L-functions at the center of the critical strip*, Ph.D. thesis, McGill University (Canada), 1998.

[You06] M. P. Young, *Low-lying zeros of families of elliptic curves*, J. Amer. Math. Soc. **19** (2006), no. 1, 205–250. MR 2169047

[Zha14] Y. Zhang, *Bounded gaps between primes*, Ann. of Math. (2) **179** (2014), no. 3, 1121–1174.

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