Abstract. Let \( \pi \) be a self-dual cuspidal automorphic representation for \( \text{GL}(2)/\mathbb{Q} \). We show that there exists a positive upper Dirichlet density of primes at which the associated Hecke eigenvalues of \( \pi \) are larger than a specified positive constant.

1. Introduction

Let \( \pi \) be a cuspidal automorphic representation for \( \text{GL}(2)/\mathbb{Q} \) that is self-dual. To each prime \( p \) at which \( \pi \) is not ramified is associated a Hecke eigenvalue, denoted by \( a_p = a_p(\pi) \). The values taken by sequences \( \{a_p(\pi)\}_p \) of Hecke eigenvalues have been long-studied from various points of view. In 1994, J.-P. Serre asked (see appendix of [7]) whether it is possible to find positive constants \( c, c' \) such that, for all \( \epsilon > 0 \), there exist infinitely many \( a_p \) greater than \( c - \epsilon \) and infinitely many \( a_p \) less than \( -c' + \epsilon \). He then proved such results for the case of (certain) modular forms, and asked if similar results can be shown to hold in the case of Maass forms.

In [8] we proved, for any self-dual cuspidal automorphic representation \( \pi \) for \( \text{GL}(2)/\mathbb{Q} \), that for any positive \( \epsilon \) there exist infinitely many primes \( p \) such that
\[
a_p > 0.905... - \epsilon
\]
and if \( \pi \) is non-dihedral, then there exist infinitely many primes \( p \) such that
\[
a_p < -1.164... + \epsilon
\]
(precise expressions for the constants are available in [8]). Note that a cuspidal automorphic representation \( \pi \) for \( \text{GL}(2) \) is said to be dihedral if it is associated to a 2-dimensional irreducible Artin representation \( \rho \) that is of dihedral type, meaning that the image of \( \rho \) in \( \text{PGL}_2(\mathbb{C}) \) is isomorphic to a dihedral group. Furthermore, \( \pi \) is said to be of solvable polyhedral type if it is associated to a 2-dimensional irreducible Artin representation \( \rho \) that is of dihedral, tetrahedral, or octahedral type (which means that the projective image of \( \rho \) in \( \text{PGL}_2(\mathbb{C}) \) is isomorphic to a dihedral group, \( A_4 \), or \( S_4 \), respectively).

A related question is to ask whether it is possible to obtain similar statements for not just an infinitude of primes but a positive upper Dirichlet density of primes. Recall that the upper Dirichlet density of a set \( S \) of primes is defined to be
\[
\delta(S) := \lim_{s \to 1^+} \sup \frac{\sum_{p \in S} p^{-s}}{\log(1/(s-1))}.
\]
The results of [8] relied on determining lower bounds on the asymptotic growth of certain Dirichlet series, but, because of the lack of knowledge of the Ramanujan...
conjecture (or indeed the non-existence of any known uniform bound on the Satake parameters), these will not directly lead to a positive density result.

In this paper, we outline a method to circumvent this issue and obtain positive upper Dirichlet density results. By way of example, we have

**Theorem 1.1.** Let $\pi$ be a self-dual cuspidal automorphic representation for $\text{GL}(2)$ over $\mathbb{Q}$ that is not of solvable polyhedral type. Then for any $\epsilon > 0$, the set

$$\{ p \mid a_p(\pi) > 0.778... - \epsilon \}.$$

has an upper Dirichlet density of at least $1/100$.

The exact value of the constant in the set condition is $0.36729^{1/4}$, which is determined in Section 3. The method we use would also allow a change in this constant to a smaller value so as to obtain a mild increase in the lower bound of the density. The proof relies in part on the deep work of Gelbart–Jacquet [1], Kim–Shahidi [4,5], and Kim [3] on the automorphy of symmetric power lifts. In the next section, we will outline the ingredients used in the proof, and in Section 3 we will prove the theorem.

### 2. Background

The proof will rely on the study of the asymptotic behaviour of various Dirichlet series, which we will briefly outline here and refer the reader to [8] for a more detailed explanation.

Given a cuspidal automorphic representation $\pi$ for $\text{GL}(2)/\mathbb{Q}$, let $T$ be the (finite) set consisting of the archimedean place and the finite places at which $\pi$ is ramified. Then the incomplete $L$-function (with respect to $T$) that is associated to $\pi$ can be defined in a right-half plane via an Euler product:

$$L_T(s, \pi) = \prod_{p \not\in T} \det (I_2 - A_p(\pi)p^{-s})^{-1},$$

where $I_2$ is the $2 \times 2$ identity matrix and $A_p(\pi) = \text{diag}(\alpha_p(\pi), \beta_p(\pi)) \in \text{GL}_2(\mathbb{C})$ is the matrix of Satake parameters associated to $\pi$ at $p$. For any two cuspidal automorphic representations $\pi_1$ for $\text{GL}(n)/\mathbb{Q}$ and $\pi_2$ for $\text{GL}(m)/\mathbb{Q}$, one can define (again in a suitable right-half plane) their incomplete Rankin–Selberg $L$-function:

$$L_T(s, \pi_1 \times \pi_2) = \prod_{p \not\in T} \det (I_{nm} - A_p(\pi_1) \otimes A_p(\pi_2)p^{-s})^{-1}.$$  

This $L$-function converges absolutely for $\text{Re}(s) > 1$. At $s = 1$ it has a simple pole iff $\pi_1$ is dual to $\pi_2$ [2], otherwise the $L$-function is invertible at that point [6].

In general one can define, for any positive integer $k \leq 8$, an incomplete $k$th product $L$-function as follows:

$$L_T(s, \pi^k) = \prod_{p \not\in T} \det (I_{2^k} - A_p(\pi) \otimes^k p^{-s})^{-1}.$$
One can also define the following incomplete symmetric power $L$-functions:

$$L^T(s, \text{Sym}^2 \pi) = \prod_{p \not\in T} \det \left( I_3 - \begin{pmatrix} \alpha_p^2 & \alpha_p \beta_p & 0 \\ \alpha_p \beta_p & \beta_p^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right)^{-1},$$

$$L^T(s, \text{Sym}^3 \pi) = \prod_{p \not\in T} \det \left( I_4 - \begin{pmatrix} \alpha_p^3 & \alpha_p^2 \beta_p & \alpha_p \beta_p^2 & 0 \\ \alpha_p^2 \beta_p & \alpha_p \beta_p^2 & 0 & 0 \\ \alpha_p \beta_p^2 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \right)^{-1},$$

$$L^T(s, \text{Sym}^4 \pi) = \prod_{p \not\in T} \det \left( I_5 - \begin{pmatrix} \alpha_p^4 & \alpha_p^3 \beta_p & \alpha_p^2 \beta_p^2 & \alpha_p \beta_p^3 & 0 \\ \alpha_p^3 \beta_p & \alpha_p^2 \beta_p^2 & \alpha_p \beta_p^3 & 0 & 0 \\ \alpha_p^2 \beta_p^2 & 0 & 1 & 0 & 0 \\ \alpha_p \beta_p^3 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \right)^{-1}.$$

For the $k$th product $L$-functions, where $k = 3, 4, 6,$ and $8$, we have the following $L$-function identities, using Clebsch–Gordon decompositions:

$$L^T(s, \pi \times 3) = L^T(s, \text{Sym}^3 \pi) L^T(s, \pi \otimes \omega)^2,$$

$$L^T(s, \pi \times 4) = L^T(s, \text{Sym}^4 \pi) L^T(s, \text{Sym}^2 \pi \otimes \omega)^3 L^T(s, \omega^2)^2,$$

$$L^T(s, \pi \times 6) = L^T(s, \text{Sym}^3 \pi \times \text{Sym}^3 \pi) L^T(s, \text{Sym}^3 \pi \times \pi \otimes \omega)^4 L^T(s, \pi \times \pi \otimes \omega)^4,$$

$$L^T(s, \pi \times 8) = L^T(s, \text{Sym}^4 \pi \times \text{Sym}^4 \pi) L^T(s, \text{Sym}^4 \pi \times \text{Sym}^2 \pi \otimes \omega)^6$$

$$\cdot L^T(s, \text{Sym}^2 \pi \otimes \omega \times \text{Sym}^2 \pi \otimes \omega)^9 L^T(s, \text{Sym}^4 \pi \otimes \omega)^4$$

$$\cdot L^T(s, \text{Sym}^2 \pi \otimes \omega^3)^{12} L^T(s, \omega^4)^4,$$

where $\omega$ is the central character of $\pi$.

From here on, we assume that $\pi$ is self-dual and that it is not of solvable polyhedral type. We will use the results of Gelbart–Jacquet [1], Kim–Shahidi [4,5], and Kim [3] on the automorphy of the symmetric second, third, and fourth power lifts. We will also make use of the bounds towards the Ramanujan conjecture that were obtained by Kim–Sarnak (Appendix 2 of [3]), which imply that $|a_p| \leq 2^{p^{7/64}}$ for all primes $p$. We then obtain the following results about incomplete $L$-functions and their associated Dirichlet series:

For $k \leq 8$, the incomplete $L$-function $L^T(s, \pi \times k)$ has an absolutely convergent Euler product for $s > 1$. If $k$ is even, then the incomplete $L$-function has a pole of order $m(k)$ at $s = 1$, where $m(k) = 1, 2, 5, 14$ for $k = 2, 4, 6, 8$, respectively. If $k$ is odd, then the $L$-function is invertible at $s = 1$.

As $s \to 1^+$, for $k = 2, 3$ or $4$, we have

$$\sum_{p \not\in T} \frac{a_p^k}{p^s} = \log L^T(s, \pi \times k) + O(1)$$

and for $k = 6$ or $8$, we have (using positivity)

$$\sum_{p \not\in T} \frac{a_p^k}{p^s} \leq \log L^T(s, \pi \times k) + O(1).$$
We can then conclude:

$$\sum_{p \not\in T} \frac{a_p}{p^k} = \begin{cases} 
\log(1/(s-1)) + O(1) & \text{for } k = 2 \\
O(1) & \text{for } k = 3 \\
2\log(1/(s-1)) + O(1) & \text{for } k = 4,
\end{cases}$$

and

$$\sum_{p \not\in T} \frac{a_p}{p^k} \leq \begin{cases} 
5\log(1/(s-1)) + O(1) & \text{for } k = 6 \\
14\log(1/(s-1)) + O(1) & \text{for } k = 8,
\end{cases}$$
as $s \to 1^+$.

We also make use of the following identities:

Let $f(x), g(x)$ be real-valued functions, and fix some point $u \in \mathbb{R}$. Then,

$$\lim_{x \to u^+} \sup (f(x) + g(x)) \leq \lim_{x \to u^+} \sup f(x) + \lim_{x \to u^+} \sup g(x)$$

$$\lim_{x \to u^+} \sup (-f(x)) = -\lim_{x \to u^+} \inf f(x)$$

and furthermore if $g, f$ are non-negative functions, then

$$\lim_{x \to u^+} \inf (f(x) \cdot g(x)) \leq \lim_{x \to u^+} \inf f(x) \cdot \lim_{x \to u^+} \sup g(x)$$

$$\lim_{x \to u^+} \sup (f(x) \cdot g(x)) \leq \lim_{x \to u^+} \sup f(x) \cdot \lim_{x \to u^+} \sup g(x).$$

3. PROOF

In this subsection we will prove Theorem 1.1.

First define the sets $A := \{ p \text{ prime } | a_p > 0 \}$ and $B := \{ p \text{ prime } | a_p \leq 0 \}$.

From the previous section, we know that

$$\lim_{s \to 1^+} \sup \frac{\sum_{p} |a_p|^4}{p^s \log \left( \frac{1}{s-1} \right)} = 2,$$

which implies

$$\lim_{s \to 1^+} \sup \frac{\sum_{p \in A} |a_p|^4}{p^s \log \left( \frac{1}{s-1} \right)} + \lim_{s \to 1^+} \sup \frac{\sum_{p \in B} |a_p|^4}{p^s \log \left( \frac{1}{s-1} \right)} \geq 2.$$

Let us define $d$

$$d := \lim_{s \to 1^+} \sup \frac{\sum_{p \in B} |a_p|^4}{p^s \log \left( \frac{1}{s-1} \right)},$$

and thus we can write

$$\lim_{s \to 1^+} \sup \frac{\sum_{p \in A} |a_p|^4}{p^s \log \left( \frac{1}{s-1} \right)} \geq 2 - d.$$

Now define $S_\beta \subset A$ to be exactly the set of primes $p$ such that $|a_p|^4 \geq (2 - d)/\beta$, where $0 < \beta < 1$ is a constant to be fixed later. We will assume that $S_\beta$ has an upper Dirichlet density smaller than $1/100$. 

We have the bound
\[
\limsup s \to 1^+ \left( \frac{\sum_{p \in A-S_{\beta}} |a_p|^4}{\log \left( \frac{1}{s-1} \right)} \right) \leq (2 - d) \beta,
\]

Since
\[
\limsup s \to 1^+ \left( \frac{\sum_{p \in A-S_{\beta}} |a_p|^4}{\log \left( \frac{1}{s-1} \right)} \right) + \limsup s \to 1^+ \left( \frac{\sum_{p \in S_{\beta}} |a_p|^4}{\log \left( \frac{1}{s-1} \right)} \right) \geq (2 - d),
\]

we have
\[
\limsup s \to 1^+ \left( \frac{\sum_{p \in S_{\beta}} |a_p|^4}{\log \left( \frac{1}{s-1} \right)} \right) \geq (2 - d) (1 - \beta),
\]

and using Cauchy–Schwarz
\[
\left( \limsup s \to 1^+ \frac{\sum_{p \in S_{\beta}} |a_p|^4}{\log \left( \frac{1}{s-1} \right)} \right)^2 \leq \left( \limsup s \to 1^+ \frac{\sum_{p \in S_{\beta}} |a_p|^8}{\log \left( \frac{1}{s-1} \right)} \right) \left( \limsup s \to 1^+ \frac{\sum_{p \in S_{\beta}} |a_p|^0}{\log \left( \frac{1}{s-1} \right)} \right)
\]

where the third limit supremum can be bounded above by 1/100, and we get
\[
(2 - d)^2 (1 - \beta)^2 \leq \frac{14}{100}.
\]

We need to appeal to a result from \cite{8}, which we include here as a lemma.

**Lemma 3.1.** For \(A, B,\) and \(d\) defined as above, we have
\[
\limsup s \to 1^+ \frac{\sum_{p \in A} |a_p|^3}{\log \left( \frac{1}{s-1} \right)} \geq \frac{d^{3/4}}{(14 - (2 - d)^2)^{1/4}}.
\]

**Proof.** As explained, a proof of this Lemma essentially arises in \cite{8}. We include a proof below for the convenience of the reader.

Using Holder’s inequality and taking the limit supremum as \(s \to 1^+\),
\[
\lim_{s \to 1^+} \sup \frac{\sum_{p \in A} |a_p|^3}{\log \left( \frac{1}{s-1} \right)} \leq \left( \lim_{s \to 1^+} \sup \frac{\sum_{p \in A} |a_p|^4}{\log \left( \frac{1}{s-1} \right)} \right)^{3/4} \left( \lim_{s \to 1^+} \sup \frac{\sum_{p \in A} \frac{1}{p^s}}{\log \left( \frac{1}{s-1} \right)} \right)^{1/4}
\]

\[
\leq (2 - d)^{3/4} \cdot 1^{1/4}.
\]

Similarly,
\[
\lim_{s \to 1^+} \sup \frac{\sum_{p \in A} |a_p|^4}{\log \left( \frac{1}{s-1} \right)} \leq \left( \lim_{s \to 1^+} \sup \frac{\sum_{p \in A} |a_p|^8}{\log \left( \frac{1}{s-1} \right)} \right)^{1/5} \left( \lim_{s \to 1^+} \sup \frac{\sum_{p \in A} |a_p|^3}{\log \left( \frac{1}{s-1} \right)} \right)^{4/5}
\]

\[
2 - d \leq \left( \lim_{s \to 1^+} \sup \frac{\sum_{p \in A} |a_p|^8}{\log \left( \frac{1}{s-1} \right)} \right)^{1/5} (2 - d)^{3/5}
\]

\[
(2 - d)^2 \leq \lim_{s \to 1^+} \sup \frac{\sum_{p \in A} |a_p|^8}{\log \left( \frac{1}{s-1} \right)}.
\]
From the results in the previous section, we have
\[
\lim_{s \to 1^+} \sup \frac{\sum_{p \in A} \frac{|a_p|^8}{p^s}}{\log \left( \frac{1}{s-1} \right)} + \lim_{s \to 1^+} \inf \frac{\sum_{p \in B} \frac{|a_p|^8}{p^s}}{\log \left( \frac{1}{s-1} \right)} \leq 14,
\]
and so
\[
\lim_{s \to 1^+} \inf \frac{\sum_{p \in B} \frac{|a_p|^8}{p^s}}{\log \left( \frac{1}{s-1} \right)} \leq 14 - (2 - d)^2.
\]
We also have
\[
\sum_{p \in B} \frac{|a_p|^{8/5}|a_p|^{12/5}}{p^s} \leq \left( \sum_{p \in B} \frac{|a_p|^8}{p^s} \right)^{1/5} \left( \sum_{p \in B} \frac{|a_p|^3}{p^s} \right)^{4/5}.
\]
We divide the equation above by \(\log(1/(s - 1))\) and take the limit infimum as \(s \to 1^+\),
\[
\lim_{s \to 1^+} \inf \frac{\sum_{p \in B} \frac{|a_p|^4}{p^s}}{\log \left( \frac{1}{s-1} \right)} \leq \left( \lim_{s \to 1^+} \inf \frac{\sum_{p \in B} \frac{|a_p|^8}{p^s}}{\log \left( \frac{1}{s-1} \right)} \right)^{1/5} \left( \lim_{s \to 1^+} \sup \frac{\sum_{p \in B} \frac{|a_p|^3}{p^s}}{\log \left( \frac{1}{s-1} \right)} \right)^{4/5}.
\]
We apply equation 3.2 to get
\[
d \leq (14 - (2 - d)^2)^{1/5} \left( \lim_{s \to 1^+} \sup \frac{\sum_{p \in B} \frac{|a_p|^3}{p^s}}{\log \left( \frac{1}{s-1} \right)} \right)^{4/5}
\]
\[
\frac{d^{5/4}}{(14 - (2 - d)^2)^{1/4}} \leq \lim_{s \to 1^+} \sup \frac{\sum_{p \in B} \frac{|a_p|^3}{p^s}}{\log \left( \frac{1}{s-1} \right)}.
\]
For \(s > 1\), we have
\[
\sum_{p \in A} \frac{|a_p|^3}{p^s} + \left( - \sum_{p} \frac{a_p^3}{p^s} \right) = \sum_{p \in B} \frac{|a_p|^3}{p^s},
\]
and so
\[
\lim_{s \to 1^+} \sup \frac{\sum_{p \in A} \frac{|a_p|^3}{p^s}}{\log \left( \frac{1}{s-1} \right)} \geq \lim_{s \to 1^+} \sup \frac{\sum_{p \in B} \frac{|a_p|^3}{p^s}}{\log \left( \frac{1}{s-1} \right)}.
\]
Therefore
\[
\lim_{s \to 1^+} \sup \frac{\sum_{p \in A} \frac{|a_p|^3}{p^s}}{\log \left( \frac{1}{s-1} \right)} \geq \lim_{s \to 1^+} \sup \frac{\sum_{p \in B} \frac{|a_p|^3}{p^s}}{\log \left( \frac{1}{s-1} \right)} \geq \frac{d^{5/4}}{(14 - (2 - d)^2)^{1/4}}.
\]
\(\square\)

Now we define \(T_\alpha \subset A\) to be the set of primes \(p\) such that
\[
|a_p|^3 \geq \left( \frac{d^{5/4}}{(14 - (2 - d)^2)^{1/4}} \right)\alpha,
\]
where \(0 < \alpha < 1\) is a constant to be fixed later.
Let us assume that the upper Dirichlet density of $T_\alpha$ is less than $1/100$. We have

$$\limsup \left( \frac{\sum_{p \in A - T_\alpha} \frac{|a_p|^3}{p^r}}{\log \left( \frac{1}{s-1} \right)} \right) \leq \left( \frac{d^{5/4}}{\left(14 - (2 - d)^2\right)^{1/4}} \right) \alpha.$$ 

Lemma 3.1 implies that

$$\limsup \left( \frac{\sum_{p \in A - T_\alpha} |a_p|^3}{\log \left( \frac{1}{s-1} \right)} \right) + \limsup \left( \frac{\sum_{p \in T_\alpha} |a_p|^3}{\log \left( \frac{1}{s-1} \right)} \right) \geq \frac{d^{5/4}}{\left(14 - (2 - d)^2\right)^{1/4}} (1 - \alpha).$$

Then

$$\limsup \left( \frac{\sum_{p \in T_\alpha} |a_p|^3}{\log \left( \frac{1}{s-1} \right)} \right) \geq \frac{d^{5/4}}{\left(14 - (2 - d)^2\right)^{1/4}} (1 - \alpha).$$

Now

$$\left( \limsup \frac{\sum_{p \in T_\alpha} |a_p|^3}{\log \left( \frac{1}{s-1} \right)} \right)^2 \leq \left( \limsup \frac{\sum_{p \in T_\alpha} |a_p|^6}{\log \left( \frac{1}{s-1} \right)} \right) \left( \limsup \frac{\sum_{p \in T_\alpha} |a_p|^9}{\log \left( \frac{1}{s-1} \right)} \right).$$

The second limit supremum can be bounded from above by 5 and the third limit supremum can be bounded from above by $1/100$, so

$$(3.3) \quad \frac{d^{5/4}}{\left(14 - (2 - d)^2\right)^{1/4}} (1 - \alpha)^2 \leq \frac{5}{100}.$$ 

Now, given some value for the constant $\beta$, we want to fix $\alpha$ such that

$$(3.4) \quad (2 - d)\beta^{1/4} = \left( \frac{d^{5/4}}{\left(14 - (2 - d)^2\right)^{1/4}} \right)^{1/3} \alpha.$$ 

Given equation [3.3], if we set $\beta = 0.495$, we have that if $d \leq 1.258$, then equation [3.3] is false, contradicting the assumption that $S_\beta$ has an upper Dirichlet density smaller than $1/100$, and if $d > 1.258$, then equation [3.3] is false, and so $T_\alpha$ would have an upper Dirichlet density of at least $1/100$. Either way, since for $\beta = 0.95$ and $d = 1.258$ the value of equation [3.4] is $0.36729^{1/4} = 0.778...$, this implies that the set of primes

$$\{p \mid a_p(\pi) > 0.778... - \epsilon\}$$

has an upper Dirichlet density at least $1/100$.

**Remark 1.** We determined our choice of $\beta$ by solving the following simultaneous equations

$$\frac{(2 - d) (1 - \beta)}{10} = \frac{\sqrt{14}}{\sqrt{10}}$$

and

$$\frac{d^{5/4}}{\left(14 - (2 - d)^2\right)^{1/4}} (1 - \alpha) = \frac{\sqrt{5}}{\sqrt{10}},$$

along with equation [3.4] and we obtained $\beta = 0.4957...$ and $d = 1.2581...$.
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