# PRIMES IN ARITHMETIC PROGRESSIONS TO SMOOTH MODULI: A MINORANT VERSION

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Abstract. The author prove that there exists a function $\rho(n)$ which is a minorant for the prime indicator function $\mathbb{1}_p(n)$ and has distribution level $\frac{65}{123}$ in arithmetic progressions to smooth moduli. This refines the previous results of Baker–Irving and Stadlmann.

Contents



## 1. Introduction

One of the famous topics in number theory is to study the distribution of primes in arithmetic progressions. Given some $\theta > 0$, $A > 0$ and sets $\mathcal{Q}(x) \subseteq \mathbb{N}$, we are looking for results of the type

$$\sum_{\substack{q \leqslant x^{\theta-\varepsilon} \\ q \in \mathcal{Q}(x) \\ (q,a)=1}} \left| \sum_{\substack{n \leqslant x \\ n \equiv a (\bmod q)}} \mathbb{1}_p(n) - \frac{1}{\varphi(q)} \sum_{\substack{n \leqslant x \\ (n,q)=1}} \mathbb{1}_p(n) \right| \ll \frac{x}{(\log x)^A}. \tag{1}$$

When $\mathcal{Q}(x) = \mathbb{N}$, the most famous result is due to Bombieri [2] and Vinogradov [9], who showed in 1965 that (1) holds with $\theta = \frac{1}{2}$. The exponent $\frac{1}{2}$ is also the limit obtained under Generalized Riemann Hypothesis (GRH), Hence improving this result directly is extremely difficult.

Now we are focusing on the case $\mathcal{Q}(x) = \left\{ q : q \in \mathbb{N}, q \mid \prod_{p<x^\delta} p \right\}$ or square-free $x^\delta$-smooth moduli. Then (1) may be written as

$$\sum_{\substack{q \leqslant x^{\theta-\varepsilon} \\ q \mid \prod_{p<x^\delta} p \\ (q,a)=1}} \left| \sum_{\substack{n \leqslant x \\ n \equiv a (\bmod q)}} \mathbb{1}_p(n) - \frac{1}{\varphi(q)} \sum_{\substack{n \leqslant x \\ (n,q)=1}} \mathbb{1}_p(n) \right| \ll \frac{x}{(\log x)^A} \tag{2}$$

in this case. This type of results have played an important role in the study of bounded gaps between primes, see [10] [6]. In [10] Zhang proved (2) holds with $\theta = \frac{1}{2} + \frac{1}{584} \approx 0.5017$, which was later improved by Polymath [6] to $\theta = \frac{1}{2} + \frac{7}{300} \approx 0.5233$ and by Stadlmann to $\theta = \frac{1}{2} + \frac{1}{40} = 0.525$.

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In 2017, Baker and Irving [1] considered a variant of (2). They constructed a minorant $\rho(n)$ for the prime indicator function $\mathbb{1}_p(n)$ and proved corresponding result

$$\sum_{\substack{q \leqslant x^{\theta-\varepsilon} \\ q \mid \prod_{p<x^\delta} p \\ (q,a)=1}} \left| \sum_{\substack{n \leqslant x \\ n \equiv a (\bmod q)}} \rho(n) - \frac{1}{\varphi(q)} \sum_{\substack{n \leqslant x \\ (n,q)=1}} \rho(n) \right| \ll \frac{x}{(\log x)^A} \tag{3}$$

with $\theta = \frac{1}{2} + \frac{7}{300} + \frac{187}{197700} \approx 0.5243$. In their paper Harman's sieve [3] was used to construct a suitable minorant and prove stronger results on the length of bounded intervals containing many primes. Stadlmann [8] further improved this to $\theta = 0.5253$, which is the current best distribution level in this direction.

In this paper, we shall use a delicate sieve decomposition to prove (3) with $\theta = \frac{65}{123} \approx 0.5285$. A defect of our method is that the lower bound of our minorant is much worse than it in [1] and [8]. Both of them use the lower bounds (very close to $\mathbb{1}_p(n)$) to handle the bounded prime gap problem. Our method leads to no new things on that topic.

**Theorem 1.1.** *There exists a function $\rho(n)$ which satisfies the following properties:*

*(Minorant) $\rho(n)$ is a minorant for the prime indicator function $\mathbb{1}_p(n)$. That is, we have*

$$\rho(n) \leqslant \begin{cases} 1, & n \text{ is prime}, \\ 0, & \text{otherwise}. \end{cases}$$

*(Size of prime factors) If $n$ has a prime factor less than some fixed $\xi > 0$, then $\rho(n) = 0$.*

*(Lower bound) We have*

$$\sum_{n \sim x} \rho(n) \geqslant 0.02(1+o(1)) \frac{x}{\log x}.$$

*(Distribution in AP to smooth moduli) For any integer $a$ that coprime to $\prod_{p<x^\delta} p$ and any $A > 0$, we have*

$$\sum_{\substack{q \leqslant x^{\frac{65}{123}-\varepsilon} \\ q \mid \prod_{p<x^\delta} p \\ (q,a)=1}} \left| \sum_{\substack{n \leqslant x \\ n \equiv a (\bmod q)}} \rho(n) - \frac{1}{\varphi(q)} \sum_{\substack{n \leqslant x \\ (n,q)=1}} \rho(n) \right| \ll \frac{x}{(\log x)^A}.$$

Throughout this paper, we always suppose that $\delta = 10^{-10}$ and $x$ is sufficiently large. The letter $p$, with or without subscript, is reserved for prime numbers. We define the sieve function $\psi(n, z)$ as

$$\psi(n, z) = \begin{cases} 1, & \left(n, \prod_{p<z} p\right) = 1, \\ 0, & \text{otherwise}. \end{cases}$$

## 2. Asymptotic formulas

**Lemma 2.1.** *Suppose that a function $f : \mathbb{N} \to \mathbb{C}$ satisfies one of the following conditions:*

*(Type-I) $f = \alpha * \beta$ where $\alpha$ and $\beta$ are coefficient sequences at scales $M$ and $N$. Moreover, assume that $\alpha$ satisfies the Siegel–Walfisz theorem, $\beta$ is smooth, $MN \asymp x$ and*

$$N \geqslant x^{\frac{43}{123}};$$

*(Type-II) $f = \alpha * \beta$ where $\alpha$ and $\beta$ are coefficient sequences at scales $M$ and $N$. Moreover, assume that $\alpha$ and $\beta$ satisfy the Siegel–Walfisz theorem, $MN \asymp x$ and*

$$x^{\frac{56}{123}} \leqslant N \leqslant x^{\frac{67}{123}}.$$

*Then for any integer $a$ that coprime to $\prod_{p<x^\delta} p$ and any $A>0$, we have*

$$\sum_{\substack{q\leqslant x^{\frac{65}{123}-\varepsilon}\\ q\mid\prod_{p<x^\delta} p\\ (q,a)=1}} \left| \sum_{\substack{n\leqslant x\\ n\equiv a(\bmod q)}} f(n) - \frac{1}{\varphi(q)} \sum_{\substack{n\leqslant x\\ (n,q)=1}} f(n) \right| \ll \frac{x}{(\log x)^A}.$$

*Proof.* The proof is very similar to that of [[7], Lemma 3.20 (I)(II)]. We remark that we use the arithmetical information of Polymath [[6], Theorem 2.8] instead of the newer information of Stadlmann [[8], Proposition 3.1]. This is because Stadlmann's information has a restriction $\theta < \frac{1}{2}+\frac{1}{36} \approx 0.5278$, while in [6] this restriction becomes $\theta < \frac{1}{2}+\frac{1}{34} \approx 0.5294$. □

By Lemma 2.1, we can easily deduce the following two lemmas.

**Lemma 2.2.** *Let*

$$f(x) = \sum_{p_1,\ldots,p_n} \psi\left(\frac{n}{p_1\cdots p_n}, x^{\frac{11}{123}}\right).$$

*Then Lemma 2.1 holds for $f(n)$ if we can group $\{1,\cdots,n\}$ into $I$ and $J$ such that*

$$\prod_{i\in I} p_i \leqslant x^{\frac{56}{123}} \qquad \text{and} \qquad \prod_{j\in J} p_j \leqslant x^{\frac{8}{41}}.$$

**Lemma 2.3.** *Let*

$$f(x) = \sum_{p_1,\ldots,p_n} \psi\left(\frac{n}{p_1\cdots p_n}, p_n\right).$$

*Then Lemma 2.1 holds for $f(n)$ if we can group $\{1,\cdots,n\}$ into $I$ and $J$ such that*

$$x^{\frac{56}{123}} \leqslant \prod_{i\in I} p_i \leqslant x^{\frac{67}{123}}.$$

Our aim is to decompose the prime indicator function $\mathbb{1}_p(n)$ into sieve functions of the above forms and show that the total loss from the dropped parts (which don't satisfy the conditions in Lemma 2.2 or Lemma 2.3 and must be non-negative) is less than $1-0.02=0.98$ in order to get a positive lower bound with same order of magnitude.

## 3. The final decomposition

In this section we will decompose the prime indicator function $\mathbb{1}_p(n)$ using Buchstab's identity. Let $\omega(u)$ denotes the Buchstab function determined by the following differential-difference equation

$$\begin{cases} \omega(u) = \frac{1}{u}, & 1\leqslant u\leqslant 2,\\ (u\omega(u))' = \omega(u-1), & u\geqslant 2.\end{cases}$$

Moreover, we have the upper and lower bounds for $\omega(u)$:

$$\omega(u) \geqslant \omega_0(u) = \begin{cases} \frac{1}{u}, & 1\leqslant u<2,\\ \frac{1+\log(u-1)}{u}, & 2\leqslant u<3,\\ \frac{1+\log(u-1)}{u} + \frac{1}{u}\int_2^{u-1} \frac{\log(t-1)}{t} dt \geqslant 0.5607, & 3\leqslant u<4,\\ 0.5612, & u\geqslant 4,\end{cases}$$

$$\omega(u) \leqslant \omega_1(u) = \begin{cases} \frac{1}{u}, & 1\leqslant u<2,\\ \frac{1+\log(u-1)}{u}, & 2\leqslant u<3,\\ \frac{1+\log(u-1)}{u} + \frac{1}{u}\int_2^{u-1} \frac{\log(t-1)}{t} dt \leqslant 0.5644, & 3\leqslant u<4,\\ 0.5617, & u\geqslant 4.\end{cases}$$

We shall use $\omega_0(u)$ and $\omega_1(u)$ to give numerical bounds for some sieve functions discussed below. Let $p_j = (2x)^{t_j}$ and by Buchstab's identity, we have

$$\begin{aligned}
\mathbb{1}_p(n) &= \psi\left(n,(2x)^{\frac{1}{2}}\right) \\
&= \psi\left(n,x^{\frac{11}{123}}\right) - \sum_{\frac{11}{123}\leqslant t_1<\frac{56}{123}} \psi\left(\frac{n}{p_1},x^{\frac{11}{123}}\right) - \sum_{\frac{56}{123}\leqslant t_1<\frac{1}{2}} \psi\left(\frac{n}{p_1},p_1\right) \\
&\quad + \sum_{\substack{\frac{11}{123}\leqslant t_1<\frac{56}{123} \\ \frac{11}{123}\leqslant t_2<\min\left(t_1,\frac{1}{2}(1-t_1)\right)}} \psi\left(\frac{n}{p_1p_2},p_2\right) \\
&= S_1 - S_2 - S_3 + S_4. \qquad (4)
\end{aligned}$$

By Lemmas 2.2–2.3 we know that Lemma 2.1 holds for $S_1$–$S_3$, hence we only need to consider $S_4$. Before further decomposing, we define non-overlapping polygons $A$, $B$, $C$, $D$, whose union is

$$\left\{(t_1,t_2): \frac{11}{123}\leqslant t_1<\frac{56}{123},\ \frac{11}{123}\leqslant t_2<\min\left(t_1,\frac{1}{2}(1-t_1)\right),\ t_1+t_2\notin\left[\frac{56}{123},\frac{67}{123}\right]\right\}.$$

These regions are defined as

$$\begin{aligned}
A &= \left\{(t_1,t_2): \frac{11}{123}\leqslant t_1<\frac{56}{123},\ \frac{11}{123}\leqslant t_2<\min\left(t_1,\frac{1}{2}(1-t_1)\right),\ t_1+t_2<\frac{56}{123},\ t_2<\frac{8}{41}\right\}, \\
B &= \left\{(t_1,t_2): \frac{11}{123}\leqslant t_1<\frac{56}{123},\ \frac{11}{123}\leqslant t_2<\min\left(t_1,\frac{1}{2}(1-t_1)\right),\ t_1+t_2>\frac{67}{123},\ t_2<\frac{8}{41}\right\}, \\
C &= \left\{(t_1,t_2): \frac{11}{123}\leqslant t_1<\frac{56}{123},\ \frac{11}{123}\leqslant t_2<\min\left(t_1,\frac{1}{2}(1-t_1)\right),\ t_1+t_2>\frac{67}{123},\ t_2>\frac{8}{41}\right\}, \\
D &= \left\{(t_1,t_2): \frac{11}{123}\leqslant t_1<\frac{56}{123},\ \frac{11}{123}\leqslant t_2<\min\left(t_1,\frac{1}{2}(1-t_1)\right),\ t_1+t_2<\frac{56}{123},\ t_2>\frac{8}{41}\right\}.
\end{aligned}$$

Now we have

$$\begin{aligned}
S_4 &= \sum_{(t_1,t_2)\in A} \psi\left(\frac{n}{p_1p_2},p_2\right) + \sum_{(t_1,t_2)\in B} \psi\left(\frac{n}{p_1p_2},p_2\right) + \sum_{(t_1,t_2)\in C} \psi\left(\frac{n}{p_1p_2},p_2\right) + \sum_{(t_1,t_2)\in D} \psi\left(\frac{n}{p_1p_2},p_2\right) \\
&= S_A + S_B + S_C + S_D. \qquad (5)
\end{aligned}$$

We first decompose $S_A$. By Buchstab's identity, we have

$$\begin{aligned}
S_A &= \sum_{(t_1,t_2)\in A} \psi\left(\frac{n}{p_1p_2},p_2\right) \\
&= \sum_{(t_1,t_2)\in A} \psi\left(\frac{n}{p_1p_2},x^{\frac{11}{123}}\right) - \sum_{\substack{(t_1,t_2)\in A \\ \frac{11}{123}\leqslant t_3<\min\left(t_2,\frac{1}{2}(1-t_1-t_2)\right)}} \psi\left(\frac{n}{p_1p_2p_3},x^{\frac{11}{123}}\right) \\
&\quad + \sum_{\substack{(t_1,t_2)\in A \\ \frac{11}{123}\leqslant t_3<\min\left(t_2,\frac{1}{2}(1-t_1-t_2)\right) \\ \frac{11}{123}\leqslant t_4<\min\left(t_3,\frac{1}{2}(1-t_1-t_2-t_3)\right)}} \psi\left(\frac{n}{p_1p_2p_3p_4},p_4\right) \\
&= S_{A1} - S_{A2} + S_{A3}. \qquad (6)
\end{aligned}$$

We know that Lemma 2.1 holds for $S_{A1}$. Since $t_3 < t_2 < \frac{8}{41}$ and $t_1 + t_2 < \frac{56}{123}$, Lemma 2.1 also holds for $S_{A2}$. For $S_{A3}$, we can use Buchstab's identity twice more to reach a six-dimensional sum if we can group $\{1, 2, 3, 4, 4\}$ into $I$ and $J$ satisfy the conditions in Lemma 2.2. We can also use Lemma 2.3 to handle part of $S_{A3}$ if we can group $\{1, 2, 3, 4\}$ into $I$ and $J$ satisfy the corresponding conditions. For the remaining part, we cannot sure that it has a distribution level of $\frac{65}{123}$, hence we need to discard it. We do the same thing for the six-dimensional sum we just mentioned. In this way we obtain a loss from $S_A$ of

$$\begin{aligned}
&\left(\int_{(t_1,t_2,t_3,t_4)\in U_{A3}} \frac{\omega_1\left(\frac{1-t_1-t_2-t_3-t_4}{t_4}\right)}{t_1t_2t_3t_4^2} dt_4dt_3dt_2dt_1\right)\\
&+\left(\int_{(t_1,t_2,t_3,t_4,t_5,t_6)\in U_{A31}} \frac{\omega_1\left(\frac{1-t_1-t_2-t_3-t_4-t_5-t_6}{t_6}\right)}{t_1t_2t_3t_4t_5t_6^2} dt_6dt_5dt_4dt_3dt_2dt_1\right)\\
&< 0.071778, \qquad (7)
\end{aligned}$$

where

$$\begin{aligned}
U_{A3}(t_1,t_2,t_3,t_4) := \{ &(t_1,t_2)\in A,\\
&\frac{11}{123} \leqslant t_3 < \min\left(t_2, \frac{1}{2}(1-t_1-t_2)\right),\\
&\{1,2,3\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.3},\\
&\frac{11}{123} \leqslant t_4 < \min\left(t_3, \frac{1}{2}(1-t_1-t_2-t_3)\right),\\
&\{1,2,3,4\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.3},\\
&\{1,2,3,4,4\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.2},\\
&\frac{11}{123} \leqslant t_1 < \frac{1}{2},\ \frac{11}{123} \leqslant t_2 < \min\left(t_1, \frac{1}{2}(1-t_1)\right)\right\},\\
U_{A31}(t_1,t_2,t_3,t_4,t_5,t_6) := \{ &(t_1,t_2)\in A,\\
&\frac{11}{123} \leqslant t_3 < \min\left(t_2, \frac{1}{2}(1-t_1-t_2)\right),\\
&\{1,2,3\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.3},\\
&\frac{11}{123} \leqslant t_4 < \min\left(t_3, \frac{1}{2}(1-t_1-t_2-t_3)\right),\\
&\{1,2,3,4\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.3},\\
&\{1,2,3,4,4\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.2},\\
&\frac{11}{123} \leqslant t_5 < \min\left(t_4, \frac{1}{2}(1-t_1-t_2-t_3-t_4)\right),\\
&\{1,2,3,4,5\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.3},\\
&\frac{11}{123} \leqslant t_6 < \min\left(t_5, \frac{1}{2}(1-t_1-t_2-t_3-t_4-t_5)\right),\\
&\{1,2,3,4,5,6\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.3},\\
&\frac{11}{123} \leqslant t_1 < \frac{1}{2},\ \frac{11}{123} \leqslant t_2 < \min\left(t_1, \frac{1}{2}(1-t_1)\right)\right\}.
\end{aligned}$$

For $S_B$ we cannot perform a straightforward decomposition as in $S_A$. Nonetheless, we can perform a variable role-reversal since we have $t_1 < \frac{56}{123}$, $1-t_1-t_2 < \frac{56}{123}$ and $t_2 < \frac{8}{41}$. We refer the readers to [4], [5] and for more applications of role-reversals. By similar process as in [5], we have

$$\begin{aligned}
S_B &= \sum_{(t_1,t_2)\in B} \psi\left(\frac{n}{p_1p_2}, p_2\right)\\
&= \sum_{(t_1,t_2)\in B} \psi\left(\frac{n}{p_1p_2}, x^{\frac{11}{123}}\right) - \sum_{\substack{(t_1,t_2)\in B\\ \frac{11}{123}\leqslant t_3<\min\left(t_2,\frac{1}{2}(1-t_1-t_2)\right)}} \psi\left(\frac{n}{p_1p_2p_3}, p_3\right)
\end{aligned}$$

$$
\begin{aligned}
&= \sum_{(t_1,t_2)\in B} \psi\left(\frac{n}{p_1p_2}, x^{\frac{11}{123}}\right) - \sum_{\substack{(t_1,t_2)\in B\\ \frac{11}{123}\leqslant t_3<\min\left(t_2,\frac{1}{2}(1-t_1-t_2)\right)}} \psi\left(\frac{n}{\beta p_2p_3}, \left(\frac{2x}{\beta p_2p_3}\right)^{\frac{1}{2}}\right)\\
&= \sum_{(t_1,t_2)\in B} \psi\left(\frac{n}{p_1p_2}, x^{\frac{11}{123}}\right) - \sum_{\substack{(t_1,t_2)\in B\\ \frac{11}{123}\leqslant t_3<\min\left(t_2,\frac{1}{2}(1-t_1-t_2)\right)}} \psi\left(\frac{n}{\beta p_2p_3}, x^{\frac{11}{123}}\right)\\
&\quad + \sum_{\substack{(t_1,t_2)\in B\\ \frac{11}{123}\leqslant t_3<\min\left(t_2,\frac{1}{2}(1-t_1-t_2)\right)\\ \frac{11}{123}\leqslant t_4<\frac{1}{2}t_1}} \psi\left(\frac{n}{\beta p_2p_3p_4}, p_4\right)\\
&= S_{B1} - S_{B2} + S_{B3}, \qquad (8)
\end{aligned}
$$

where $\beta \sim (2x)^{1-t_1-t_2-t_3}$ and $(\beta, P(p_3)) = 1$. We know that Lemma 2.1 holds for $S_{B1}$ since $t_1 < \frac{56}{123}$ and $t_2 < \frac{8}{41}$. By a trivial argument, we know that $\beta$ is the product of at most 4 primes, each of size $> x^{\frac{11}{123}}$. Then by a splitting argument we know that Lemma 2.1 also holds for $S_{B2}$. We can also use the splitting argument to handle $S_{B3}$. If we can group $\{0,2,3,4\}$ (where 0 represents the product of primes that forms $\beta$) into $I$ and $J$ satisfy the conditions in Lemma 2.3, then Lemma 2.1 holds for $S_{B3}$. Working as above, we get a loss from $S_B$ of

$$
\int_{(t_1,t_2,t_3,t_4)\in U_{B3}} \frac{\omega_1\left(\frac{t_1-t_4}{t_4}\right)\omega_1\left(\frac{1-t_1-t_2-t_3}{t_3}\right)}{t_2t_3^2t_4^2} dt_4dt_3dt_2dt_1 < 0.354111, \qquad (9)
$$

where

$$
\begin{aligned}
U_{B3}(t_1,t_2,t_3,t_4) := \{&(t_1,t_2)\in B,\\
&\frac{11}{123}\leqslant t_3 < \min\left(t_2, \frac{1}{2}(1-t_1-t_2)\right),\\
&\{1,2,3\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.3},\\
&\frac{11}{123}\leqslant t_4 < \frac{1}{2}t_1,\\
&\{0,2,3,4\} \text{ cannot be partitioned into } I \text{ and } J \text{ in Lemma 2.3},\\
&\frac{11}{123}\leqslant t_1 < \frac{1}{2},\ \frac{11}{123}\leqslant t_2 < \min\left(t_1, \frac{1}{2}(1-t_1)\right)\bigg\}.
\end{aligned}
$$

For $S_C$ and $S_D$ we can perform neither a straightforward decomposition nor a role-reversal, hence we need to discard the whole regions. We remark that in [1] and [8] Heath-Brown's identity was used to deal with $S_C$, but we can not do that here since the corresponding "Polymath Type-III information" cannot cover all cases after a Heath-Brown decomposition. Discarding the two regions gives the losses of

$$
\int_{\frac{11}{123}}^{\frac{1}{2}} \int_{\frac{11}{123}}^{\min\left(t_1,\frac{1}{2}(1-t_1)\right)} \mathbb{1}_{(t_1,t_2)\in C} \frac{\omega\left(\frac{1-t_1-t_2}{t_2}\right)}{t_1t_2^2} dt_2dt_1 < 0.486844 \qquad (10)
$$

and

$$
\int_{\frac{11}{123}}^{\frac{1}{2}} \int_{\frac{11}{123}}^{\min\left(t_1,\frac{1}{2}(1-t_1)\right)} \mathbb{1}_{(t_1,t_2)\in D} \frac{\omega\left(\frac{1-t_1-t_2}{t_2}\right)}{t_1t_2^2} dt_2dt_1 < 0.062436. \qquad (11)
$$

Finally, by combining (4)–(11), the total loss is less than

$$
0.071778 + 0.354111 + 0.486844 + 0.062436 < 0.98
$$

and the proof of Theorem 1.1 is completed.

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