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Jie Wu

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# Chen's double sieve, Goldbach's conjecture and the twin prime problem, 2

J. WU

**Abstract.** For every even integer  $N$ , denote by  $D_{1,2}(N)$  the number of representations of  $N$  as a sum of a prime and an integer having at most two prime factors. In this paper, we give a new lower bound for  $D_{1,2}(N)$ .

## § 1. Introduction

Let  $\Omega(n)$  be the number of all prime factors of the integer  $n$  with the convention  $\Omega(1) = 0$ . For each even integer  $N \geq 4$ , we define

$$D(N) := |\{p \leq N : \Omega(N - p) = 1\}|,$$

where and in what follows, the letter  $p$ , with or without subscript, denotes a prime number. The well known Goldbach conjecture can be stated as  $D(N) \geq 1$  for all even integers  $N \geq 4$ . A more precise version of this conjecture was proposed by Hardy & Littlewood [10]:

$$(1.1) \quad D(N) \sim 2\Theta(N) \quad (N \rightarrow \infty),$$

where

$$(1.2) \quad C_N := \prod_{p|N, p>2} \frac{p-1}{p-2} \prod_{p>2} \left(1 - \frac{1}{(p-1)^2}\right), \quad \Theta(N) := \frac{C_N N}{(\log N)^2}.$$

Certainly, the asymptotic formula (1.1) is extremely difficult. One way of approaching the lower bound problem in (1.1) is to give a non-trivial lower bound for the quantity

$$D_{1,2}(N) := |\{p \leq N : \Omega(N - p) \leq 2\}|.$$

In this direction, Chen [5] proved, by his system of weights and the switching principle, the following famous theorem: *Every sufficiently large even integer can be written as sum of a prime and an integer having at most two prime factors.* More precisely he established

$$(1.3) \quad D_{1,2}(N) \geq 0.67 \Theta(N)$$

for  $N \geq N_0$ . As Halberstam & Richert indicated in [9], it would be interesting to know whether a more elaborate weighting procedure could be adapted to the purpose of (1.3). This might lead

to numerical improvements and could be important. Chen's constant 0.67 has been improved by many authors. The historical record is as follows:

0.689 by Halberstam & Richert [9],  
 0.754 by Chen [6],  
 0.81 by Chen [7],  
 0.828 by Cai & Lu [4],  
 0.836 by Wu [13],  
 0.867 by Cai [2].

The aim of this paper is to propose a better constant.

**Theorem.** *For sufficiently large  $N$ , we have*

$$D_{1,2}(N) \geq 0.899 \Theta(N).$$

Our improvement comes from a delicate application of Chen's double sieve ([8], [12], [13]), which can be described as follows: With standard notation in theory of sieve method, the linear sieve formulas (see [9], or Lemma 2.2 of [13]) can be stated as

$$(1.4) \quad XV(z)f\left(\frac{\log Q}{\log z}\right) + \text{error} \leq S(\mathcal{A}; \mathcal{P}, z) \leq XV(z)F\left(\frac{\log Q}{\log z}\right) + \text{error}.$$

These inequalities are the best possible in the sense that taking

$$\mathcal{A} = \mathcal{B}_\nu := \{n \leq x : \Omega(n) \equiv \nu \pmod{2}\} \quad (\nu = 1, 2),$$

the upper and lower bounds in (1.4) are respectively attained by  $\nu = 1$  and  $\nu = 2$  (see [9], page 239). Aiming at a better Bombieri-Davenport's upper bound [1]

$$D(N) \leq \{8 + o(1)\}\Theta(N),$$

Chen [8] found improvement for (1.4) for some special sequences  $\mathcal{A}$ . Roughly speaking, for the sequence

$$\mathcal{A} = \{N - p : p \leq N\}$$

he narrowed down the gap in (1.4) by introducing two functions  $h(s)$  and  $H(s)$  such that the functions  $sf(s)/(2e^\gamma)$  and  $sF(s)/(2e^\gamma)$  are replaced by  $sf(s)/(2e^\gamma) + h(s)$  and  $sF(s)/(2e^\gamma) - H(s)$  respectively, where  $\gamma$  is the Euler constant. The key point is thus to prove  $h(s) > 0$  and  $H(s) > 0$ . Chen's proof is very long and somewhat difficult to follow, but his innovative idea is clear (see [11] for example). In [13], we gave a more comprehensive treatment on this method and name it as Chen's double sieve. Indeed, our treatment is not only simpler but even more powerful than Chen's. Our approach improved Chen's upper estimate  $D(N) \leq 7.8342\Theta(N)$  to  $D(N) \leq 7.8209\Theta(N)$ . It is worth to indicate that Chen's record stood for 26 years before our work [13].

To prove our Theorem, we first simplify and improve Chen's weight system (compare (12) of [7] and Lemma 2.2 below), and then apply Chen's double sieve, as the classical linear sieve,

to handle terms such as  $\Upsilon_2$ ,  $\Upsilon_3$ ,  $\Upsilon_4$ ,  $\Upsilon_5$  and  $\Upsilon_6$  (cf. Propositions 4.1, 4.2, 4.3 and 4.4 below). The idea of using Chen's double sieve to treat sums of the type

$$(1.5) \quad \sum_{\substack{N^{\phi_1} \leq p < N^{\phi_2} \\ (p, N) = 1}} S(\mathcal{A}_p; \mathcal{P}(N), N^\kappa)$$

was first appeared in [12]. However, due to the first condition in (3.1) below, a direct application of our Chen's double sieve can only handle the initial part of the sum over small  $p$  in (1.5) (i.e.  $p \leq N^{1/4}$ ). On the other hand, very recently Cai [2] used a similar idea to control the sum over large  $p$  in (1.5). Actually his method can be viewed as a simplified version of Chen's double sieve (see Proposition 4.4 below and the comments before it). Here we shall combine both versions and refine them to obtain our result. Apparently from the proof, we shall see that the first version gives a saving of 0.0211 while the second saves 0.0078. Without Chen's double sieve technique, we still obtain 0.870 in place of 0.899, which is slightly better than Cai's 0.867.

Clearly our method can be used to refine the corresponding constants in the conjugate problems ([2] and [3]). The proofs are very similar and even easier and simpler. Hence we omit the relevant discussion. Maybe this is a good exercise for senior graduate students in analytic number theory.

## § 2. Chen's system of weights

This section is devoted to discuss the weighted sieve of Chen type. Let

$$\mathcal{A} := \{N - p : p \leq N\} \quad \text{and} \quad \mathcal{P}(N) := \{p : (p, N) = 1\}.$$

The sieve function is defined as

$$S(\mathcal{A}; \mathcal{P}(N), z) := |\{a \in \mathcal{A} : (a, P(z)) = 1\}|,$$

where  $P(z) := \prod_{p \leq z, p \in \mathcal{P}(N)} p$ .

**Lemma 2.1.** *Let  $0 < \kappa < \sigma \leq \frac{1}{3}$ . Then we have*

$$(2.1) \quad 2D_{1,2}(N) \geq 2S(\mathcal{A}; \mathcal{P}(N), N^\kappa) - S_1(\kappa, \sigma) - 2S_2(\kappa, \sigma) - S_3(\kappa, \sigma) + S_4(\kappa, \sigma) + O(N^{1-\kappa}),$$

where

$$\begin{aligned} S_1(\kappa, \sigma) &:= \sum_{\substack{N^\kappa \leq p < N^\sigma \\ (p, N) = 1}} S(\mathcal{A}_p; \mathcal{P}(N), N^\kappa), \\ S_2(\kappa, \sigma) &:= \sum_{\substack{N^\sigma \leq p_1 < p_2 < (N/p_1)^{1/2} \\ (p_1 p_2, N) = 1}} \sum S(\mathcal{A}_{p_1 p_2}; \mathcal{P}(N p_1), p_2), \\ S_3(\kappa, \sigma) &:= \sum_{\substack{N^\kappa \leq p_1 < N^\sigma \leq p_2 < (N/p_1)^{1/2} \\ (p_1 p_2, N) = 1}} \sum S(\mathcal{A}_{p_1 p_2}; \mathcal{P}(N p_1), p_2), \\ S_4(\kappa, \sigma) &:= \sum_{\substack{N^\kappa \leq p_1 < p_2 < p_3 < N^\sigma \\ (p_1 p_2 p_3, N) = 1}} \sum \sum S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N p_1), p_2). \end{aligned}$$

The inequality (2.1) first appeared in [7] (page 479, (11)) with  $(\kappa, \sigma) = (\frac{1}{12}, \frac{1}{3.047})$ ,  $(\frac{1}{9.2}, \frac{1}{3.41})$  without proof. Cai & [Lu] [4] gave a proof with an extra assumption  $3\sigma + \kappa > 1$ . In [13], we

proved (2.1) under the hypothesis  $0 < \kappa < \sigma < \frac{1}{3}$ . Clearly the proof there is also valid for  $\sigma = \frac{1}{3}$ . Very recently Cai [2] gave another proof for Lemma 2.1.

As in [7], we shall apply (2.1) with two different pairs of parameters  $(\kappa, \sigma)$  to take advantage of  $S_4(\kappa, \sigma)$ . Our weighted sieve is simpler and more powerful than those of Chen ([7], (12)) and Cai ([2], Lemma 6).

**Lemma 2.2.** *Let  $\kappa_2 > \kappa_1 \geq 1/18$  such that  $3\kappa_1 + \kappa_2 < 1/2$  and  $3\kappa_1 - \kappa_2 < 1/6$ . Then we have*

$$(2.2) \quad 4D_{1,2}(N) \geq 3\Upsilon_1 + \Upsilon_2 - \Upsilon_3 - \Upsilon_4 + \Upsilon_5 + \Upsilon_6 - 2\Upsilon_7 - \Upsilon_8 - \Upsilon_9 - \Upsilon_{10} - \Upsilon_{11} + O(N^{1-\kappa_1}),$$

where

$$\Upsilon_i := S(\mathcal{A}; \mathcal{P}(N), N^{\kappa_i}) \quad (i = 1, 2),$$

$$\Upsilon_3 := \sum_{\substack{N^{\kappa_1} \leq p < N^{1/3} \\ (p, N)=1}} S(\mathcal{A}_p; \mathcal{P}(N), N^{\kappa_1}),$$

$$\Upsilon_4 := \sum_{\substack{N^{\kappa_1} \leq p < N^{1/2-3\kappa_1} \\ (p, N)=1}} S(\mathcal{A}_p; \mathcal{P}(N), N^{\kappa_1}),$$

$$\Upsilon_5 := \sum_{\substack{N^{\kappa_1} \leq p_1 < p_2 < N^{\kappa_2} \\ (p_1 p_2, N)=1}} S(\mathcal{A}_{p_1 p_2}; \mathcal{P}(N), N^{\kappa_1}),$$

$$\Upsilon_6 := \sum_{\substack{N^{\kappa_1} \leq p_1 < N^{\kappa_2} \leq p_2 < N^{1/2-3\kappa_1} \\ (p_1 p_2, N)=1}} S(\mathcal{A}_{p_1 p_2}; \mathcal{P}(N), N^{\kappa_1}),$$

$$\Upsilon_7 := \sum_{\substack{N^{1/2-3\kappa_1} \leq p_1 < p_2 < (N/p_1)^{1/2} \\ (p_1 p_2, N)=1}} S(\mathcal{A}_{p_1 p_2}; \mathcal{P}(Np_1), p_2),$$

$$\Upsilon_8 := \sum_{\substack{N^{\kappa_1} \leq p_1 < N^{1/3} \leq p_2 < (N/p_1)^{1/2} \\ (p_1 p_2, N)=1}} S(\mathcal{A}_{p_1 p_2}; \mathcal{P}(Np_1), p_2),$$

$$\Upsilon_9 := \sum_{\substack{N^{\kappa_2} \leq p_1 < N^{1/2-3\kappa_1} \leq p_2 < (N/p_1)^{1/2} \\ (p_1 p_2, N)=1}} S(\mathcal{A}_{p_1 p_2}; \mathcal{P}(Np_1), (N/p_1 p_2)^{1/2}),$$

$$\Upsilon_{10} := \sum_{\substack{N^{\kappa_1} \leq p_1 < p_2 < p_3 < p_4 < N^{\kappa_2} \\ (p_1 p_2 p_3 p_4, N)=1}} S(\mathcal{A}_{p_1 p_2 p_3 p_4}; \mathcal{P}(N), p_2),$$

$$\Upsilon_{11} := \sum_{\substack{N^{\kappa_1} \leq p_1 < p_2 < p_3 < N^{\kappa_2} \leq p_4 < N^{1/2-2\kappa_1}/p_3 \\ (p_1 p_2 p_3 p_4, N)=1}} S(\mathcal{A}_{p_1 p_2 p_3 p_4}; \mathcal{P}(N), p_2).$$

*Proof.* By noticing that our hypothesis implies  $\kappa_2 < 1/2 - 3\kappa_1 \leq 1/3$ , we can apply (2.1) with  $(\kappa, \sigma) = (\kappa_2, 1/2 - 3\kappa_1)$  to obtain

$$(2.3) \quad 2D_{1,2}(N) \geq 2\Upsilon_2 - S_1(\kappa_2, 1/2 - 3\kappa_1) - 2\Upsilon_7 - S_3(\kappa_2, 1/2 - 3\kappa_1) + O(N^{1-\kappa_2}),$$

where the term  $S_4(\kappa_2, 1/2 - 3\kappa_1)$  is dropped by non-negativity.

Buchstab's identity, when applied three times, gives the equality

$$\Upsilon_2 = \Upsilon_1 - \sum_{\substack{N^{\kappa_1} \leq p < N^{\kappa_2} \\ (p, N)=1}} S(\mathcal{A}_p; \mathcal{P}(N), N^{\kappa_1}) + \Upsilon_5 - \sum_{\substack{N^{\kappa_1} \leq p_1 < p_2 < p_3 < N^{\kappa_2} \\ (p_1 p_2 p_3, N)=1}} S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_1).$$

Similarly, a twice application of Buchstab's identity yields

$$\begin{aligned} S_1(\kappa_2, 1/2 - 3\kappa_1) &= \sum_{\substack{N^{\kappa_2} \leq p < N^{1/2-3\kappa_1} \\ (p, N)=1}} S(\mathcal{A}_p; \mathcal{P}(N), N^{\kappa_1}) - \Upsilon_6 \\ &+ \sum_{N^{\kappa_1} \leq p_1 < p_2 < N^{\kappa_2} \leq p_3 < N^{1/2-3\kappa_1}} \sum_{(p_1 p_2 p_3, N)=1} S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_1). \end{aligned}$$

By Buchstab's identity, we can prove

$$S_3(\kappa_2, 1/2 - 3\kappa_1) \leq \Upsilon_9 + \sum_{N^{\kappa_2} \leq p_1 < N^{1/2-3\kappa_1} \leq p_2 < p_3 < (N/p_1 p_2)^{1/2}} \sum_{(p_1 p_2 p_3, N)=1} S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N p_1), p_3).$$

Inserting them into (2.3), we find that

$$(2.4) \quad 2D_{1,2}(N) \geq \Upsilon_1 + \Upsilon_2 - \Upsilon_4 + \Upsilon_5 + \Upsilon_6 - 2\Upsilon_7 - \Upsilon_9 - \Delta_1 + O(N^{1-\kappa_2}),$$

where

$$\begin{aligned} \Delta_1 &:= \sum_{\substack{N^{\kappa_1} \leq p_1 < p_2 < p_3 < N^{\kappa_2} \\ (p_1 p_2 p_3, N)=1}} S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_1) \\ &+ \sum_{\substack{N^{\kappa_1} \leq p_1 < p_2 < N^{\kappa_2} \leq p_3 < N^{1/2-3\kappa_1} \\ (p_1 p_2 p_3, N)=1}} S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_1) \\ &+ \sum_{\substack{N^{\kappa_2} \leq p_1 < N^{1/2-3\kappa_1} \leq p_2 < p_3 < (N/p_1 p_2)^{1/2} \\ (p_1 p_2 p_3, N)=1}} S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N p_1), p_3). \end{aligned}$$

The inequality (2.1) with  $(\kappa, \sigma) = (\kappa_1, 1/3)$  gives

$$(2.5) \quad 2D_{1,2}(N) \geq 2\Upsilon_1 - \Upsilon_3 - \Upsilon_8 + S_4(\kappa_1, 1/3) + O(N^{1-\kappa_1}),$$

where we have used the fact that  $S_2(\kappa_1, 1/3) = 0$ .

Adding (2.4) to (2.5) yields

$$(2.6) \quad 4D_{1,2}(N) \geq 3\Upsilon_1 + \Upsilon_2 - \Upsilon_3 - \Upsilon_4 + \Upsilon_5 + \Upsilon_6 - 2\Upsilon_7 - \Upsilon_8 - \Upsilon_9 + \Delta_2 + O(N^{1-\kappa_1}),$$

where

$$\Delta_2 := \sum_{\substack{N^{\kappa_1} \leq p_1 < p_2 < p_3 < N^{1/3} \\ (p_1 p_2 p_3, N)=1}} S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_2) - \Delta_1.$$

Clearly all the summation ranges in the three triple sums of  $\Delta_1$  are distinct and the first two are covered in the range of the triple sum in  $\Delta_2$  (since our hypothesis on  $\kappa_1$  and  $\kappa_2$  implies  $\max\{\kappa_2, 1/2 - 3\kappa_1\} \leq 1/3$ ). On the other hand, we easily see that the range of summation in the third triple sum of  $\Delta_1$  is equivalent to  $N^{\kappa_2} \leq p_1 < N^{1/2-3\kappa_1} \leq p_2 \leq (N/p_1)^{1/3}$  and  $p_2 < p_3 < (N/p_1 p_2)^{1/2}$ . From this we deduce that  $(N/p_1 p_2)^{1/2} \leq N^{(1/2+3\kappa_1-\kappa_2)/2} \leq N^{1/3}$ ,

since  $3\kappa_1 - \kappa_2 < 1/6$ . Thus this range is also contained in the triple sum of  $\Delta_2$ . Therefore we have

$$\begin{aligned}
\Delta_2 &\geq - \sum_{\substack{N^{\kappa_1} \leq p_1 < p_2 < p_3 < N^{\kappa_2} \\ (p_1 p_2 p_3, N)=1}} \{S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_1) - S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_2)\} \\
&\quad - \sum_{\substack{N^{\kappa_1} \leq p_1 < p_2 < N^{\kappa_2} \leq p_3 < N^{1/2-2\kappa_1}/p_2 \\ (p_1 p_2 p_3, N)=1}} \{S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_1) - S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_2)\} \\
&\quad + \sum_{\substack{N^{\kappa_2} \leq p_1 < N^{1/2-3\kappa_1} \leq p_2 < p_3 < (N/p_1 p_2)^{1/2} \\ (p_1 p_2 p_3, N)=1}} \{S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_2) - S(\mathcal{A}_{p_1 p_2 p_3}; \mathcal{P}(N), p_3)\} \\
&\geq -\Upsilon_{10} - \Upsilon_{11} + O(N^{1-\kappa_1}).
\end{aligned}$$

Combining with (2.6), we obtain the required result.  $\square$

**Remark 1.** Apparently from the proof, we have chosen  $(\kappa, \sigma) = (\kappa_1, 1/2 - 3\kappa_1)$ ,  $(\kappa_2, 1/3)$  in the application of Lemma 2.1. It is possible to optimize the choice of  $\sigma$ . But this augments the number of terms of (2.2) and the numeric improvement for Theorem is quite small.

### § 3. Chen's double sieve

In this section, we recall Chen's double sieve described in [13] and give numeric lower bounds for  $H(s)$  and  $h(s)$  for later use.

For any large even integer  $N$ , we write

$$\mathcal{A} := \{N - p : p \leq N\}, \quad \mathcal{P}(N) := \{p : (p, N) = 1\}.$$

Let  $\delta > 0$  be a sufficiently small number <sup>(\*)</sup> and  $k \in \mathbb{Z}$ . Put

$$Q := N^{1/2-\delta}, \quad \underline{d} := Q/d, \quad \mathcal{L} := \log N, \quad W_k := N^{\delta^{1+k}}.$$

Denote by  $\pi_{[Y, Z]}$  the characteristic function of the set  $\mathcal{P}(N) \cap [Y, Z]$ . For  $k \in \mathbb{Z}^+$  and  $N \geq 2$ , let  $\mathfrak{U}_k(N)$  be the set of all arithmetical functions  $\sigma$  which can be written as the form

$$\sigma = \pi_{[V_1/\Delta, V_1]} * \cdots * \pi_{[V_i/\Delta, V_i]},$$

where  $\Delta$  is a real number with  $1 + \mathcal{L}^{-4} \leq \Delta < 1 + 2\mathcal{L}^{-4}$ ,  $i$  is an integer with  $0 \leq i \leq k$ , and  $V_1, \dots, V_i$  are real numbers satisfying

$$(3.1) \quad \begin{cases} V_1^2 \leq Q, \\ V_1 V_2^2 \leq Q, \\ \dots\dots\dots \\ V_1 \cdots V_{i-1} V_i^2 \leq Q, \\ V_1 \geq V_2 \geq \cdots \geq V_i \geq W_k. \end{cases}$$

We adopt the convention that  $\sigma$  is the characteristic function of the set  $\{1\}$  if  $i = 0$ .

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<sup>(\*)</sup> In numerical computation, we can formally take  $\delta = 0$ .

Let  $F$  and  $f$  be defined by

$$(3.2) \quad \begin{aligned} F(s) &= 2e^\gamma/s, & f(s) &= 0 & (0 < s \leq 2), \\ (sF(s))' &= f(s-1), & (sf(s))' &= F(s-1) & (s > 2), \end{aligned}$$

where  $\gamma$  is Euler's constant. Moreover we take

$$(3.3) \quad A(s) := sF(s)/2e^\gamma, \quad a(s) := sf(s)/2e^\gamma,$$

and introduce the notation

$$(3.4) \quad \Phi(N, \sigma, s) := \sum_d \sigma(d) S(\mathcal{A}_d; \mathcal{P}(dN), \underline{d}^{1/s}),$$

$$(3.5) \quad \Theta(N, \sigma) := 4\text{li}(N) \sum_d \frac{\sigma(d) C_{dN}}{\varphi(d) \log \underline{d}},$$

where  $\varphi(d)$  is the Euler function.

For  $k \in \mathbb{Z}^+$ ,  $N_0 \geq 2$  and  $s \in [1, 10]$ , we define  $H_{k, N_0}(s)$  and  $h_{k, N_0}(s)$  to be the supremum of  $h \geq -\infty$  such that for all  $N \geq N_0$  and  $\sigma \in \mathfrak{U}_k(N)$ , the inequalities

$$\Phi(N, \sigma, s) \leq \{A(s) - h\} \Theta(N, \sigma),$$

$$\Phi(N, \sigma, s) \geq \{a(s) + h\} \Theta(N, \sigma)$$

hold true respectively. Obviously  $H_{k, N_0}(s)$  and  $h_{k, N_0}(s)$  are decreasing in  $N_0$ , as well as decreasing in  $k$  by Lemma 3.1. Hence their limits at infinity exist (in the extended real line), and we write

$$\begin{aligned} H_k(s) &:= \lim_{N_0 \rightarrow \infty} H_{k, N_0}(s), & h_k(s) &:= \lim_{N_0 \rightarrow \infty} h_{k, N_0}(s), \\ H(s) &:= \lim_{k \rightarrow \infty} H_k(s), & h(s) &:= \lim_{k \rightarrow \infty} h_k(s). \end{aligned}$$

The next lemma collects the concerned properties of these functions (see [13], Lemma 3.2, Propositions 1 & 2 and Corollary 1).

**Lemma 3.1.** (i) For  $k \in \mathbb{Z}^+$ ,  $N \geq N_0$ ,  $s \in [1, 10]$  and  $\sigma \in \mathfrak{U}_k(N)$ , we have

$$(3.6) \quad \Phi(N, \sigma, s) \leq \{A(s) - H_{k, N_0}(s)\} \Theta(N, \sigma),$$

$$(3.7) \quad \Phi(N, \sigma, s) \geq \{a(s) + h_{k, N_0}(s)\} \Theta(N, \sigma).$$

(ii) For  $k \in \mathbb{Z}^+$  and  $s \in [1, 10]$ , we have  $H_k(s) \geq 0$  and  $h_k(s) \geq 0$ .

(iii) For  $2 \leq s \leq s' \leq 10$ , we have

$$(3.8) \quad h(s) \geq h(s') + \int_{s-1}^{s'-1} \frac{H(t)}{t} dt \quad \text{and} \quad H(s) \geq H(s') + \int_{s-1}^{s'-1} \frac{h(t)}{t} dt.$$

(iv) The function  $H(s)$  is decreasing on  $[1, 10]$ . The function  $h(s)$  is increasing on  $[1, 2]$  and is decreasing on  $[2, 10]$ .

We cannot give explicit expressions for  $H(s)$  and  $h(s)$ . But it is tractable to obtain numeric lower bounds for these two functions. Let

$$(3.9) \quad s_i := 2 + 0.1 \times i \quad (i \geq 0).$$



By ([13], § 7), we have the numeric lower bounds of  $H(s_i)$  for  $2 \leq i \leq 10$ . Next we shall consider the case of  $11 \leq i \leq 29$  and the lower bounds of  $h(s_i)$  for  $0 \leq i \leq 29$ . These will be used in the proof of Theorem.

Let  $\mathbf{1}_{[a,b]}(t)$  be the characteristic function of the interval  $[a, b]$  and

$$\sigma(a, b, c) := \int_a^b \log\left(\frac{c}{t-1}\right) \frac{dt}{t}, \quad \sigma_0(t) := \frac{\sigma(3, t+2, t+1)}{1 - \sigma(3, 5, 4)}.$$

From (6.2) of [13] and the decreasing property of  $H(s)$ , we deduce

$$(3.10) \quad H(s_j) \geq \sum_{2 \leq i \leq 10} c_{i,j} H(s_i),$$

for  $11 \leq j \leq 29$ , where

$$c_{2,j} := \int_1^{s_2} \left\{ \frac{\sigma_0(t)}{t} \log\left(\frac{4}{s_j-1}\right) + \frac{\mathbf{1}_{[s_j-2,3]}(t)}{t} \log\left(\frac{t+1}{s_j-1}\right) \right\} dt,$$

$$c_{i,j} := \int_{s_{i-1}}^{s_i} \left\{ \frac{\sigma_0(t)}{t} \log\left(\frac{4}{s_j-1}\right) + \frac{\mathbf{1}_{[s_j-2,3]}(t)}{t} \log\left(\frac{t+1}{s_j-1}\right) \right\} dt \quad (3 \leq i \leq 10).$$

From the first inequality of (3.8) and the fact that  $h(s) \geq 0$ , we also derive

$$(3.11) \quad h(s_j) \geq \int_{s_{j-1}}^5 \frac{H(t)}{t} dt$$

$$\geq H(s_2) \log\left(\frac{s_{\max\{2,j-10\}}}{s_j-1}\right) + \sum_{\max\{3,j-9\} \leq i \leq 29} H(s_i) \log\left(\frac{s_i}{s_{i-1}}\right)$$

for  $0 \leq j \leq 29$ .

Using the numeric lower bounds of  $H(s_i)$  for  $2 \leq i \leq 10$  given in ([13], § 7), (3.10) and (3.11), we get via a numerical computation the following results.

$i$	$s_i$	$H(s_i) \geq$	$i$	$s_i$	$H(s_i) \geq$	$i$	$s_i$	$H(s_i) \geq$
			10	3.0	0.0072943	20	4.0	0.0010835
			11	3.1	0.0061642	21	4.1	0.0008451
2	2.2	0.0223939	12	3.2	0.0052233	22	4.2	0.0006482
3	2.3	0.0217196	13	3.3	0.0044073	23	4.3	0.0004882
4	2.4	0.0202876	14	3.4	0.0036995	24	4.4	0.0003602
5	2.5	0.0181433	15	3.5	0.0030860	25	4.5	0.0002592
6	2.6	0.0158644	16	3.6	0.0025551	26	4.6	0.0001803
7	2.7	0.0129923	17	3.7	0.0020972	27	4.7	0.0001187
8	2.8	0.0100686	18	3.8	0.0017038	28	4.8	0.0000702
9	2.9	0.0078162	19	3.9	0.0013680	29	4.9	0.0000313

Table 1. Numeric lower bounds for  $H(s_i)$

$i$	$s_i$	$h(s_i) \geq$	$i$	$s_i$	$h(s_i) \geq$	$i$	$s_i$	$h(s_i) \geq$
0	2.0	0.0232385	10	3.0	0.0077162	20	4.0	0.0010120
1	2.1	0.0211041	11	3.1	0.0066236	21	4.1	0.0008099
2	2.2	0.0191556	12	3.2	0.0055818	22	4.2	0.0006440
3	2.3	0.0173631	13	3.3	0.0046164	23	4.3	0.0005084
4	2.4	0.0157035	14	3.4	0.0037529	24	4.4	0.0003980
5	2.5	0.0141585	15	3.5	0.0030123	25	4.5	0.0003085
6	2.6	0.0127132	16	3.6	0.0023901	26	4.6	0.0002365
7	2.7	0.0113556	17	3.7	0.0018997	27	4.7	0.0001791
8	2.8	0.0100756	18	3.8	0.0015336	28	4.8	0.0001336
9	2.9	0.0088648	19	3.9	0.0012593	29	4.9	0.0000981

Table 2. Numeric lower bounds for  $h(s_i)$ 

**Remark 2.** It is possible to get better numeric lower bounds for  $H(s_i)$  and  $h(s_i)$  by applying (3.8) repeatedly. But the improvement will be small.

#### § 4. Application of Chen's double sieve

In this section, we apply Chen's double sieve to estimate the terms  $\Upsilon_3$ ,  $\Upsilon_4$ ,  $\Upsilon_5$  and  $\Upsilon_6$  in (2.2). Propositions 4.1, 4.2, 4.3 and 4.4 below are results in general context. These estimates are better than those obtained by the classical linear sieve, since  $H(s) > 0$  and  $h(s) > 0$ .

**Proposition 4.1.** *Let  $0 < \phi_1 < \phi_2 < 1/4$  and  $\kappa > 0$  such that  $\phi_2 + \kappa \leq 1/2$ . Then for  $N \rightarrow \infty$ , we have*

$$\sum_{\substack{N^{\phi_1} \leq p < N^{\phi_2} \\ (p, N) = 1}} S(\mathcal{A}_p; \mathcal{P}(N), N^\kappa) \leq \left\{ 8 \int_{(1/2-\phi_2)/\kappa}^{(1/2-\phi_1)/\kappa} \frac{A(t) - H(t)}{t(1-2\kappa t)} dt + o(1) \right\} \Theta(N).$$

*Proof.* We keep use of the previous notation. Denote by  $S$  the sum in the proposition. Let  $\alpha_j := N^{\phi_1} \Delta^j$  and  $J$  be the integer such that  $\alpha_J \leq N^{\phi_2} < \alpha_{J+1}$ . We write

$$(4.1) \quad S = \sum_{1 \leq j \leq J} \sum_p \pi_{[\alpha_{j-1}, \alpha_j)}(p) S(\mathcal{A}_p; \mathcal{P}(pN), \underline{p}^{1/\tau_p}) + R_1,$$

where  $\tau_p := (\log p)/(\kappa \log N)$  and

$$(4.2) \quad R_1 := \sum_{\alpha_J \leq p < N^{\phi_2}} S(\mathcal{A}_p; \mathcal{P}(N), N^\kappa) \ll \sum_{\alpha_J \leq p < N^{\phi_2}} N/p \ll \Theta(N) \mathcal{L}^{-3}.$$

Introducing

$$\tau_j := (\log \underline{\alpha_j})/(\kappa \log N),$$

we easily see that  $\pi_{[\alpha_{j-1}, \alpha_j]}(p) \neq 0 \Rightarrow \tau_j \leq \tau_p \leq \tau_{j-1}$ . Thus we can deduce from (4.1) and (4.2) that

$$(4.3) \quad S \leq \sum_{1 \leq j \leq J} \sum_p \pi_{[\alpha_{j-1}, \alpha_j]}(p) S(\mathcal{A}_p; \mathcal{P}(pN), \underline{p}^{1/\tau_j}) + O(\Theta(N)\mathcal{L}^{-3}),$$

where we have used the following estimates:

$$\begin{aligned} & \sum_{1 \leq j \leq J} \sum_p \pi_{[\alpha_{j-1}, \alpha_j]}(p) \{S(\mathcal{A}_p; \mathcal{P}(pN), \underline{p}^{1/\tau_p}) - S(\mathcal{A}_p; \mathcal{P}(pN), \underline{p}^{1/\tau_j})\} \\ & \leq \sum_{1 \leq j \leq J} \sum_{\alpha_{j-1} \leq p < \alpha_j} \sum_{\underline{p}^{1/\tau_p} \leq p' < \underline{p}^{1/\tau_j}} N/(pp') \\ & \ll N\mathcal{L}^{-5} \sum_{1 \leq j \leq J} \sum_{\alpha_{j-1} \leq p < \alpha_j} 1/p \\ & \ll \Theta(N)\mathcal{L}^{-3}. \end{aligned}$$

Next we treat the inner sum (over  $p$ ) in (4.3). Clearly for each  $j \in \{1, \dots, J\}$ , our hypothesis on  $\phi_1, \phi_2$  and  $\kappa$  assures that the function  $\pi_{[\alpha_{j-1}, \alpha_j]} \in \mathfrak{U}_k(N)$  for all  $k \geq 0$ ,  $N_0 \geq 2$  and  $N \geq N_0$ , and  $\tau_j \geq 1$ . Thus we can apply (3.6) of Lemma 3.1 to estimate the sum over  $p$  (which is  $\Phi(N, \pi_{[\alpha_{j-1}, \alpha_j]}, \tau_j)$ ):

$$\begin{aligned} S & \leq \sum_{1 \leq j \leq J} \{A(\tau_j) - H_{k, N_0}(\tau_j)\} \Theta(N, \pi_{[\alpha_{j-1}, \alpha_j]}) + O(\Theta(N)\mathcal{L}^{-3}) \\ & \leq 4\text{li}(N) \frac{C_N}{\log \underline{1}} \sum_{\alpha_0 \leq p < \alpha_J} \frac{A(\tau_p) - H_{k, N_0}(\tau_p)}{(p-2)(1 - \log p / \log \underline{1})} + O(\Theta(N)\mathcal{L}^{-3}) \\ & \leq 4\text{li}(N) \frac{C_N}{\log \underline{1}} \sum_{N^{\phi_1} \leq p < N^{\phi_2}} \frac{A(\tau_p) - H_{k, N_0}(\tau_p)}{(p-2)(1 - \log p / \log \underline{1})} + O(\Theta(N)\mathcal{L}^{-3}), \end{aligned}$$

where we have used the fact that  $A(s) - H_{k, N_0}(s)$  is increasing in  $s$ . An integration by parts with the prime number theorem shows that

$$\sum_{N^{\phi_1} \leq p < N^{\phi_2}} \frac{A(\tau_p) - H_{k, N_0}(\tau_p)}{(p-2)(1 - \log p / \log \underline{1})} = \int_{(1/2-\phi_2)/\kappa}^{(1/2-\phi_1)/\kappa} \frac{A(t) - H_{k, N_0}(t)}{t(1-2\kappa t)} dt + O_{\delta, k}(\varepsilon).$$

Hence

$$S \leq 8 \left\{ \int_{(1/2-\phi_2)/\kappa}^{(1/2-\phi_1)/\kappa} \frac{A(t) - H_{k, N_0}(t)}{t(1-2\kappa t)} dt + O_{\delta, k}(\varepsilon) \right\} \Theta(N)$$

for  $N \geq N_0$ . From this, we infer that

$$\limsup_{N \rightarrow \infty} \frac{S}{\Theta(N)} \leq 8 \int_{(1/2-\phi_2)/\kappa}^{(1/2-\phi_1)/\kappa} \frac{A(t) - H_{k, N_0}(t)}{t(1-2\kappa t)} dt + O_{\delta, k}(\varepsilon),$$

which implies, by taking  $N \rightarrow \infty$ ,  $k \rightarrow \infty$  and  $\varepsilon \rightarrow 0$ ,

$$\limsup_{N \rightarrow \infty} \frac{S}{\Theta(N)} \leq 8 \int_{(1/2-\phi_2)/\kappa}^{(1/2-\phi_1)/\kappa} \frac{A(t) - H(t)}{t(1-2\kappa t)} dt.$$

Clearly this is equivalent to the required inequality.  $\square$

In a similar fashion we can prove the following results.

**Proposition 4.2.** *Let  $0 < \phi_1 < \phi_2 < 1/6$  and  $\kappa > 0$  such that  $2\phi_2 + \kappa \leq 1/2$ . Then for  $N \rightarrow \infty$ , we have*

$$\begin{aligned} & \sum_{\substack{N^{\phi_1} \leq p_1 < p_2 < N^{\phi_2} \\ (p_1 p_2, N) = 1}} S(\mathcal{A}_{p_1 p_2}; \mathcal{P}(N), N^\kappa) \\ & \geq \left\{ 8 \int_{\phi_1}^{\phi_2} \int_{(1/2 - \phi_2 - t)/\kappa}^{(1/2 - 2t)/\kappa} \frac{a(u) + h(u)}{t(1 - 2t - 2\kappa u)} dt du + o(1) \right\} \Theta(N). \end{aligned}$$

**Proposition 4.3.** *Let  $0 < \phi_1 < \phi_2 \leq \phi_3 < \phi_4 < 1/4$  and  $\kappa > 0$  such that  $2\phi_2 + \phi_4 < 1/2$  and  $\phi_2 + \phi_4 + \kappa \leq 1/2$ . Then for  $N \rightarrow \infty$ , we have*

$$\begin{aligned} & \sum_{\substack{N^{\phi_1} \leq p_1 < N^{\phi_2} \\ (p_1 p_2, N) = 1}} \sum_{\substack{N^{\phi_3} \leq p_1 < N^{\phi_4} \\ (p_1 p_2, N) = 1}} S(\mathcal{A}_{p_1 p_2}; \mathcal{P}(N), N^\kappa) \\ & \geq \left\{ 8 \int_{\phi_1}^{\phi_2} \int_{(1/2 - \phi_4 - t)/\kappa}^{(1/2 - \phi_3 - t)/\kappa} \frac{a(u) + h(u)}{tu(1 - 2t - 2\kappa u)} dt du + o(1) \right\} \Theta(N). \end{aligned}$$

Finally we estimate the sum of the type in (1.5) with  $\phi_1 \geq 1/4$ . In this case, we cannot directly apply our delicate Chen's double sieve because of the first condition of (3.1). As what Cai [2] remarked, it is possible to use a simplified version of Chen's double sieve. This approach will give a result better than using the classic linear sieve but weaker than Proposition 4.1, since, without iteration,  $\Psi_1(s)$  or  $\Psi_2(s)$  are principal contributions of  $H(s)$ . (See Lemmas 5.1 and 5.2 of [13] and compare Proposition 4.4 below and Proposition 4.1.)

**Proposition 4.4.** *Let  $\kappa > 0$ ,  $\phi > 0$  and  $2 \leq s \leq 3 \leq s' \leq 5$  such that  $1/4 \leq 1/2 - s\kappa < \phi$ . Then for  $N \rightarrow \infty$ , we have*

$$\sum_{\substack{N^{1/2 - s\kappa} \leq p < N^\phi \\ (p, N) = 1}} S(\mathcal{A}_p; \mathcal{P}(N), N^\kappa) \leq \left\{ 8 \int_{(1/2 - \phi)/\kappa}^s \frac{A(t) - \Psi_1(s)}{t(1 - 2\kappa t)} dt + o(1) \right\} \Theta(N),$$

where

$$\begin{aligned} \Psi_1(s) & := - \int_2^{s'-1} \frac{\log(t-1)}{t} dt + \frac{1}{2} \int_{1-1/s}^{1-1/s'} \frac{\log(st-1)}{t(1-t)} dt \\ & \quad - \max_{\phi \geq 2} \int \int \int_{1/s' \leq t \leq u \leq v \leq 1/s} \omega\left(\frac{\phi - t - u - v}{u}\right) \frac{dt du dv}{tu^2 v} \end{aligned}$$

and  $\omega(u)$  is Buchstab's function. The same result also holds if we replace  $\Psi_1(s)$  by  $\Psi_2(s)$ , where the function  $\Psi_2(s)$  is defined as in Lemma 5.2 of [13].

*Proof.* For simplicity, we denote the sum by  $S$ . Since  $N^\kappa \geq \underline{p}^{1/s}$  for  $p \geq N^{1/2 - s\kappa}$ , we can write

$$\begin{aligned} S & \leq \sum_{\substack{N^{1/2 - s\kappa} \leq p < N^\phi \\ (p, N) = 1}} S(\mathcal{A}_p; \mathcal{P}(N), \underline{p}^{1/s}) \\ & \leq \sum_{1 \leq j \leq J} \sum_p \pi_{[\alpha_{j-1}, \alpha_j]}(p) S(\mathcal{A}_p; \mathcal{P}(N), \underline{p}^{1/s}), \end{aligned}$$

where  $\alpha_j := N^{1/2-s\kappa} \Delta^j$  and  $J$  is the integer such that  $\alpha_{J-1} \leq N^\phi < \alpha_J$ .

Similar to Lemma 4.1 of [13], we can prove that there is a constant  $\eta > 0$  such that

$$(4.4) \quad S \leq \sum_{1 \leq j \leq J} \sum_p \pi_{[\alpha_{j-1}, \alpha_j]}(p) \left( \Omega_1(p) - \frac{1}{2} \Omega_2(p) + \frac{1}{2} \Omega_3(p) \right) + O(N^{1-\eta}),$$

where

$$\begin{aligned} \Omega_1(p) &:= S(\mathcal{A}_p; \mathcal{P}(pN), \underline{p}^{1/s'}), \\ \Omega_2(p) &:= \sum_{\substack{\underline{p}^{1/s'} \leq p_1 < \underline{p}^{1/s} \\ (p_1, N)=1}} S(\mathcal{A}_{pp_1}; \mathcal{P}(pN), \underline{p}^{1/s'}), \\ \Omega_3(p) &:= \sum_{\substack{\underline{p}^{1/s'} \leq p_1 < p_2 < p_3 < \underline{p}^{1/s} \\ (p_1 p_2 p_3, N)=1}} S(\mathcal{A}_{pp_1 p_2 p_3}; \mathcal{P}(pp_1 N), p_2). \end{aligned}$$

Similar to (5.1), (5.2) and (5.9) of [13], we can prove, uniformly for  $N \geq 10$  and for  $1 \leq j \leq J$ ,

$$\sum_p \pi_{[\alpha_{j-1}, \alpha_j]}(p) \Omega_i(p) \leq \{ \tilde{\Omega}_i(s, s') + o(1) \} \Theta(N, \pi_{[\alpha_{j-1}, \alpha_j]}) \quad (i = 1, 2, 3),$$

where

$$\begin{aligned} \tilde{\Omega}_2(s, s') &:= A(s'), \\ \tilde{\Omega}_i(s, s') &:= \int_{1-1/s}^{1-1/s'} \frac{a(s't)}{t(1-t)} dt, \\ \tilde{\Omega}_3(s, s') &:= 2 \max_{\phi \geq 2} \int_{1/s' \leq t \leq u \leq v \leq 1/s} \omega\left(\frac{\phi - t - u - v}{u}\right) \frac{dt du dv}{tu^2 v}. \end{aligned}$$

Inserting these into (4.4) and noticing that

$$A(s') = 1 + \int_2^{s'^{-1}} \frac{\log(t-1)}{t} dt, \quad a(s't) = \log(s't-1),$$

we find that

$$\begin{aligned} S &\leq \{1 - \Psi_1(s) + o(1)\} \sum_{1 \leq j \leq J} \Theta(N, \pi_{[\alpha_{j-1}, \alpha_j]}) + O(N^{1-\eta}), \\ &\leq \left\{ 8(1 - \Psi_1(s)) \int_{1/2-s\kappa}^\phi \frac{dt}{t(1-2t)} + o(1) \right\} \Theta(N), \end{aligned}$$

which is equivalent to the required result for the case of  $\Psi_1(s)$ , since

$$\begin{aligned} \int_{(1/2-\phi)/\kappa}^s \frac{A(t)}{t(1-2\kappa t)} dt &= \int_{(1/2-\phi)/\kappa}^s \frac{dt}{t(1-2\kappa t)} \\ &= \int_{1/2-s\kappa}^\phi \frac{dt}{t(1-2t)}. \end{aligned}$$

The case of  $\Psi_2(s)$  can be treated in the same way. The main difference is to use Lemma 4.2 of [13] in place of Lemma 4.1 of [13]. We omit the details.  $\square$

### § 5. Proof of Theorem

Take

$$(5.1) \quad \kappa_1 = 1/13.27 \quad \text{and} \quad \kappa_2 = 1/8.24,$$

which satisfy the hypothesis of Lemma 2.2. Next we estimate all the terms  $\Upsilon_i$  in (2.2).

1° *Lower bounds of  $\Upsilon_1$  and  $\Upsilon_2$*

Write  $N^\kappa = \underline{1}^{\kappa'}$  with  $\kappa' := \kappa/(1/2 - \delta)$ . By using (4.2) with  $\sigma := \mathbf{1}_{\{1\}}$  (the characteristic function of  $\{1\}$ ), it follows that

$$(5.2) \quad \begin{aligned} \Upsilon_i &= \Phi(N, \mathbf{1}_{\{1\}}, 1/\kappa'_i) \\ &\geq \{a(1/\kappa'_i) + h_{k, N_0}(1/\kappa'_i)\} \Theta(N, \mathbf{1}_{\{1\}}) \\ &\geq \{F_i + o(1)\} \Theta(N) \end{aligned}$$

with

$$F_i := 8a(1/(2\kappa_i)) + 8h(1/(2\kappa_i)) \quad (i = 1, 2).$$

Write

$$G_2 := 8a(1/(2\kappa_i)) + 8h(1/(2\kappa_2)).$$

2° *Upper bounds of  $\Upsilon_3$  and  $\Upsilon_4$*

We divide the sum  $\Upsilon_3$  (resp.  $\Upsilon_4$ ) into subsums according to

- (a)  $N^{\kappa_1} \leq p < N^{1/4}$ ,
- (b)  $N^{1/4} \leq p < N^{1/2 - s_9 \kappa_1}$ ,
- (c)  $N^{1/2 - s_j \kappa_1} \leq p < N^{1/2 - s_{j-1} \kappa_1}$  ( $9 \geq j \geq 4$ ),
- (d)  $N^{1/2 - s_3 \kappa_1} \leq p < N^{1/3}$

(resp.  $N^{\kappa_1} \leq p < N^{1/4}$  or  $N^{1/4} \leq p < N^{1/2 - 3\kappa_1}$ ), where  $s_i$  is defined by (3.9). The contribution of (a) is estimated by Proposition 4.1 and we evaluate (b) (resp.  $N^{1/4} \leq p < N^{1/2 - 3\kappa_1}$ ) by the classic linear sieve. The remaining subsums are treated by Proposition 4.4. It is worth to point out that the case (b) requires another kind of treatment because  $\Psi_1(s_{10}) = 0$  (see Table 3 below). Thus we obtain

$$(5.3) \quad \Upsilon_i \leq \{F_i + o(1)\} \Theta(N) \quad (i = 3, 4),$$

where

$$\begin{aligned} F_3 &:= 8 \int_{1/(6\kappa_1)}^{1/(2\kappa_1)-1} \frac{A(t)}{t(1-2\kappa_1 t)} dt - G_3, \\ F_4 &:= 8 \int_3^{1/(2\kappa_1)-1} \frac{A(t)}{t(1-2\kappa_1 t)} dt - G_4, \end{aligned}$$

and

$$\begin{aligned} G_4 &:= 8 \int_{(1/(4\kappa_1))}^{1/(2\kappa_1)-1} \frac{H(t)}{t(1-2\kappa_1 t)} dt, \\ G_3 &:= 8 \int_{(1/(4\kappa_1))}^{1/(2\kappa_1)-1} \frac{H(t)}{t(1-2\kappa_1 t)} dt + 8 \int_{1/(6\kappa_1)}^{s_3} \frac{\Psi_2(s_3)}{t(1-2\kappa t)} dt \\ &\quad + 8 \sum_{4 \leq i \leq 5} \int_{s_{i-1}}^{s_i} \frac{\Psi_2(s_i)}{t(1-2\kappa t)} dt + 8 \sum_{6 \leq i \leq 9} \int_{s_{i-1}}^{s_i} \frac{\Psi_1(s_i)}{t(1-2\kappa t)} dt \end{aligned}$$

3° Lower bounds of  $\Upsilon_5$  and  $\Upsilon_6$ 

Since  $\kappa_1 + 2\kappa_2 = 0.318\dots < 1/2$ , Proposition 4.2 yields

$$(5.4) \quad \Upsilon_5 \geq \{F_5 + o(1)\} \Theta(N),$$

where

$$F_5 := 8 \int_{\kappa_1}^{\kappa_2} \int_{(1/2-2t)/\kappa_1}^{(1/2-2t)/\kappa_1} \frac{a(u) dt du}{tu(1-2t-2\kappa_1 u)} + G_5$$

and

$$G_5 := 8 \int_{\kappa_1}^{\kappa_2} \int_{(1/2-2t)/\kappa_1}^{(1/2-2t)/\kappa_1} \frac{h(u) dt du}{tu(1-2t-2\kappa_1 u)}.$$

We divide the double sum  $\Upsilon_6$  into three subsums according to

- (a)  $N^{\kappa_1} \leq p_1 < N^{\kappa_2} \leq p_2 < N^{1/2-2\kappa_2}$ ,
- (b)  $N^{\kappa_1} \leq p_1 < N^{3\kappa_1/2}$  and  $N^{1/2-2\kappa_2} \leq p_2 < N^{1/2-3\kappa_1}$ ,
- (c)  $N^{3\kappa_1/2} \leq p_1 < N^{\kappa_2}$  and  $N^{1/2-2\kappa_2} \leq p_2 < N^{1/2-3\kappa_1}$ .

The first two subsums can be estimated by Proposition 4.3 and the last one by the classic linear sieve. Thus we obtain

$$(5.5) \quad \Upsilon_6 \geq \{F_6 + o(1)\} \Theta(N),$$

where

$$F_6 := 8 \int_{\kappa_1}^{\kappa_2} \int_{(3\kappa_1-t)/\kappa_1}^{(1/2-\kappa_2-t)/\kappa_1} \frac{a(u) dt du}{tu(1-2t-2\kappa_1 u)} + G_6$$

and

$$G_6 := 8 \int_{\kappa_1}^{\kappa_2} \int_{(2\kappa_2-t)/\kappa_1}^{(1/2-\kappa_2-t)/\kappa_1} \frac{h(u) dt du}{tu(1-2t-2\kappa_1 u)} + 8 \int_{\kappa_1}^{3\kappa_1/2} \int_{(3\kappa_1-t)/\kappa_1}^{(2\kappa_2-t)/\kappa_1} \frac{h(u) dt du}{tu(1-2t-2\kappa_1 u)}.$$

4° Upper bounds of  $\Upsilon_i$  for  $i = 7, 8, 9, 10, 11$ 

Clearly the terms  $\Upsilon_7, \Upsilon_8, \Upsilon_9, \Upsilon_{10}$  and  $\Upsilon_{11}$  here are those terms  $\Upsilon_7$  (with  $\sigma_1 = 1/2 - 3\kappa_1$ ),  $\Upsilon_9$  (with  $\sigma_1 = 1/3$ ),  $\Upsilon_{10}$  (with  $\sigma_2 = 1/2 - 3\kappa_1$ ),  $\Upsilon_{13}$  and  $\Upsilon_{14}$  of (9.4) in [13]. Thus (10.10), (10.11), (10.12) of [13] give us the estimates

$$(5.6) \quad \Upsilon_i \leq \{F_i + o(1)\} \Theta(N) \quad (i = 7, 8, 9, 10, 11),$$

where

$$\begin{aligned} F_7 &:= 8 \int_2^{2/(1-6\kappa_1)-1} \frac{\log(t-1)}{t} dt, \\ F_8 &:= \frac{36}{5} \int_{\kappa_1}^{1/10} \frac{\log(2-3t)}{t(1-t)^2} dt + 8 \int_{1/10}^{1/3} \frac{\log(2-3t)}{t(1-t)} dt, \\ F_9 &:= 8 \int_{\kappa_2}^{1/2-3\kappa_1} \frac{\log\{(1+6\kappa_1-2t)/(1-6\kappa_1)\}}{t(1-t)} dt, \\ F_{10} &:= \frac{36}{5} \int_{\kappa_1}^{1/10} \frac{dt_1}{t_1(1-t_1)} \int_{t_1}^{\kappa_2} \frac{dt_2}{t_2^2} \int_{t_2}^{\kappa_2} \frac{dt_3}{t_3} \int_{t_3}^{\kappa_2} \omega\left(\frac{1-t_1-t_2-t_3-t_4}{t_2}\right) \frac{dt_4}{t_4} \\ &\quad + 8 \int_{1/10}^{\kappa_2} \frac{dt_1}{t_1} \int_{t_1}^{\kappa_2} \frac{dt_2}{t_2^2} \int_{t_2}^{\kappa_2} \frac{dt_3}{t_3} \int_{t_3}^{\kappa_2} \omega\left(\frac{1-t_1-t_2-t_3-t_4}{t_2}\right) \frac{dt_4}{t_4}, \\ F_{11} &:= \frac{36}{5} \int_{\kappa_1}^{1/10} \frac{dt_1}{t_1(1-t_1)} \int_{t_1}^{\kappa_2} \frac{dt_2}{t_2^2} \int_{t_2}^{\kappa_2} \frac{dt_3}{t_3} \int_{\kappa_2}^{1/2-2\kappa_1-t_3} \omega\left(\frac{1-t_1-t_2-t_3-t_4}{t_2}\right) \frac{dt_4}{t_4} \\ &\quad + 8 \int_{1/10}^{\kappa_2} \frac{dt_1}{t_1} \int_{t_1}^{\kappa_2} \frac{dt_2}{t_2^2} \int_{t_2}^{\kappa_2} \frac{dt_3}{t_3} \int_{\kappa_2}^{1/2-2\kappa_1-t_3} \omega\left(\frac{1-t_1-t_2-t_3-t_4}{t_2}\right) \frac{dt_4}{t_4}, \end{aligned}$$

and  $\omega(t)$  is the Buchstab function (see Lemma 2.10 of [13]).

Inserting (5.2)–(5.6) into (2.2), we get the following inequality

$$D_{1,2}(N) \geq \{F(\kappa_1, \kappa_2) + o(1)\} \Theta(N),$$

where

$$F(\kappa_1, \kappa_2) := \frac{1}{4}(3F_1 + F_2 - F_3 - F_4 + F_5 + F_6 - 2F_7 - F_8 - F_9 - F_{10} - F_{11}).$$

5° *Numeric computation*

From (3.2) and (3.3), we deduce easily that

$$a(s) := \begin{cases} 0 & \text{if } 0 < s \leq 2, \\ \log(s-1) & \text{if } 2 < s \leq 4, \\ \log(s-1) + \int_3^{s-1} \frac{dt}{t} \int_2^{t-1} \frac{\log(u-1)}{u} du & \text{if } 4 < s \leq 6, \\ \log(s-1) + \int_3^{s-1} \frac{dt}{t} \int_2^{t-1} \frac{\log(u-1)}{u} du \\ \quad + \int_5^{s-1} \frac{dt}{t} \int_4^{t-1} \frac{du}{u} \int_3^{u-1} \frac{dv}{v} \int_2^{v-1} \frac{\log(w-1)}{w} dw & \text{if } 6 < s \leq 8, \end{cases}$$

and

$$A(s) := \begin{cases} 1 & \text{if } 0 < s \leq 3, \\ 1 + \int_2^{s-1} \frac{\log(t-1)}{t} dt & \text{if } 3 < s \leq 5, \\ 1 + \int_2^{s-1} \frac{\log(t-1)}{t} dt + \int_4^{s-1} \frac{dt}{t} \int_3^{t-1} \frac{du}{u} \int_2^{u-1} \frac{\log(v-1)}{v} dv & \text{if } 5 < s \leq 7. \end{cases}$$

BY using (3.8), we have

$$G_2 \geq 8 \left( h(s_{22}) + \int_{s_{22}-1}^{1/(2\kappa_2)-1} \frac{H(t)}{t} dt \right) \geq 0.005283.$$

In order to estimate  $G_4$ , we use Table 1 and the decreasing property of  $H(s)$  to obtain

$$G_4 = 8 \int_{1/(4\kappa_1)}^{1/(2\kappa_1)-1} \frac{H(t)}{t(1-2\kappa_1 t)} dt \geq 8 \sum_{14 \leq i \leq 29} g_4^i H(s_i) \geq 0.008860$$

with

$$g_4^{14} := \log \left( \frac{2\kappa_1 s_{14}}{1-2\kappa_1 s_{14}} \right),$$

$$g_4^i := \log \left( \frac{s_i(1-2\kappa_1 s_{i-1})}{s_{i-1}(1-2\kappa_1 s_i)} \right) \quad (15 \leq i \leq 29).$$

With a simpler calculation, we get

$$G_3 = G_4 + 8 \sum_{3 \leq i \leq 5} g_3^i \Psi_2(s_i) + 8 \sum_{6 \leq i \leq 9} g_3^i \Psi_1(s_i)$$

$$\geq 0.039890$$



with

$$g_3^3 := \log\left(\frac{4\kappa_1 s_3}{1 - 2\kappa_1 s_3}\right),$$

$$g_3^i := \log\left(\frac{s_i(1 - 2\kappa_1 s_{i-1})}{s_{i-1}(1 - 2\kappa_1 s_i)}\right) \quad (4 \leq i \leq 9).$$

Here we have used Table 1 of [13] on the lower bounds for  $\Psi_2(s_i)$  ( $3 \leq i \leq 5$ ) and  $\Psi_1(s_i)$  ( $6 \leq i \leq 9$ ):

$i$	$s_i$	$s'_i$	$\kappa_{1,i}$	$\kappa_{2,i}$	$\kappa_{3,i}$	$\Psi_1(s_i)$	$\Psi_2(s_i)$
3	2.3	4.50	3.54	2.88	2.43		0.015247971
4	2.4	4.46	3.57	2.87	2.40		0.013898757
5	2.5	4.12	3.56	2.91	2.50		0.011776059
6	2.6	3.58				0.009405211	
7	2.7	3.47				0.006558950	
8	2.8	3.34				0.003536751	
9	2.9	3.19				0.001056651	
10	3.0	3.00				0	

Table 3. Lower bounds for  $\Psi_1(s_i)$  and  $\Psi_2(s_i)$

Similarly

$$G_5 = 8 \int_{\kappa_1}^{\kappa_2} \int_{(1/2 - \kappa_2 - t)/\kappa_1}^{(1/2 - 2t)/\kappa_1} \frac{h(u) du dt}{tu(1 - 2t - 2\kappa_1 u)}$$

$$= 8 \int_{(1/2 - 2\kappa_2)/\kappa_1}^{(1/2 - \kappa_1 - \kappa_2)/\kappa_1} h(u) \log\left(\frac{2\kappa_2}{1 - 2\kappa_2 - 2\kappa_1 u}\right) \frac{du}{u(1 - 2\kappa_1 u)}$$

$$+ 8 \int_{(1/2 - \kappa_1 - \kappa_2)/\kappa_1}^{(1/2 - 2\kappa_1)/\kappa_1} h(u) \log\left(\frac{1 - 2\kappa_1 - 2\kappa_1 u}{2\kappa_1}\right) \frac{du}{u(1 - 2\kappa_1 u)}$$

$$\geq 8 \sum_{15 \leq i \leq 27} g_5^i h(s_i)$$

$$\geq 0.001359$$

with

$$g_5^{15} := \int_{(1/2 - 2\kappa_2)/\kappa_1}^{s_{15}} \log\left(\frac{2\kappa_2}{1 - 2\kappa_2 - 2\kappa_1 u}\right) \frac{du}{u(1 - 2\kappa_1 u)},$$

$$g_5^i := \int_{s_{i-1}}^{s_i} \log\left(\frac{2\kappa_2}{1 - 2\kappa_2 - 2\kappa_1 u}\right) \frac{du}{u(1 - 2\kappa_1 u)} \quad (16 \leq i \leq 20),$$

$$g_5^{21} := \int_{s_{20}}^{(1/2 - \kappa_1 - \kappa_2)/\kappa_1} \log\left(\frac{2\kappa_2}{1 - 2\kappa_2 - 2\kappa_1 u}\right) \frac{du}{u(1 - 2\kappa_1 u)}$$

$$+ \int_{(1/2 - \kappa_1 - \kappa_2)/\kappa_1}^{s_{21}} \frac{\log(1/(2\kappa_1) - 1 - u)}{u(1 - 2\kappa_1 u)} du,$$

$$g_5^i := \int_{s_{i-1}}^{s_i} \frac{\log(1/(2\kappa_1) - 1 - u)}{u(1 - 2\kappa_1 u)} du \quad (22 \leq i \leq 26),$$

$$g_5^{27} := \int_{s_{26}}^{(1/2 - 2\kappa_1)/\kappa_1} \frac{\log(1/(2\kappa_1) - 1 - u)}{u(1 - 2\kappa_1 u)} du;$$

and

$$\begin{aligned}
G_6 &= 8 \int_{\kappa_1}^{\kappa_2} \int_{(2\kappa_2-t)/\kappa_1}^{(1/2-\kappa_2-t)/\kappa_1} \frac{h(u) du dt}{tu(1-2t-2\kappa_1u)} + 8 \int_{\kappa_1}^{3\kappa_1/2} \int_{(3\kappa_1-t)/\kappa_1}^{(2\kappa_2-t)/\kappa_1} \frac{h(u) dt du}{tu(1-2t-2\kappa_1u)} \\
&\geq 8 \int_2^{(1/2-2\kappa_2)/\kappa_1} \log \left( \frac{\kappa_2(1-2\kappa_1-2\kappa_1u)}{\kappa_1(1-2\kappa_2-2\kappa_1u)} \right) \frac{h(u) du}{u(1-2\kappa_1u)} \\
&\quad + 8 \int_{(1/2-2\kappa_2)/\kappa_1}^{(1/2-\kappa_1-\kappa_2)/\kappa_1} \log \left( \frac{(1-2\kappa_1-2\kappa_1u)(1-2\kappa_2-2\kappa_1u)}{4\kappa_1\kappa_2} \right) \frac{h(u) du}{u(1-2\kappa_1u)} \\
&\geq 8 \sum_{1 \leq i \leq 21} g_6^i h(s_i) \\
&\geq 0.060469
\end{aligned}$$

with

$$\begin{aligned}
g_6^i &:= \int_{s_{i-1}}^{s_i} \log \left( \frac{\kappa_2(1-2\kappa_1-2\kappa_1u)}{\kappa_1(1-2\kappa_2-2\kappa_1u)} \right) \frac{du}{u(1-2\kappa_1u)} \quad (1 \leq i \leq 14), \\
g_6^{15} &:= \int_{s_{14}}^{(1/2-2\kappa_2)/\kappa_1} \log \left( \frac{\kappa_2(1-2\kappa_1-2\kappa_1u)}{\kappa_1(1-2\kappa_2-2\kappa_1u)} \right) \frac{du}{u(1-2\kappa_1u)} \\
&\quad + \int_{(1/2-2\kappa_2)/\kappa_1}^{s_{15}} \log \left( \frac{(1-2\kappa_1-2\kappa_1u)(1-2\kappa_2-2\kappa_1u)}{4\kappa_1\kappa_2} \right) \frac{du}{u(1-2\kappa_1u)}, \\
g_6^i &:= \int_{s_{i-1}}^{s_i} \log \left( \frac{(1-2\kappa_1-2\kappa_1u)(1-2\kappa_2-2\kappa_1u)}{4\kappa_1\kappa_2} \right) \frac{du}{u(1-2\kappa_1u)} \quad (16 \leq i \leq 20), \\
g_6^{21} &:= \int_{s_{20}}^{(1/2-\kappa_1-\kappa_2)/\kappa_1} \log \left( \frac{(1-2\kappa_1-2\kappa_1u)(1-2\kappa_2-2\kappa_1u)}{4\kappa_1\kappa_2} \right) \frac{du}{u(1-2\kappa_1u)}.
\end{aligned}$$

To simplify the computation of  $F_{10}$  and  $F_{11}$ , we make use of the fact that  $\omega(t) \leq 0.561522$  for  $t \geq 3.4$ .

Finally a numerical computation concludes

$$\begin{aligned}
F(\kappa_1, \kappa_2) &\geq \frac{1}{4} \{ 3 \times 14.900897 + (9.103015 + 0.005283) \\
&\quad - (23.652925 - 0.039890) - (19.643510 - 0.008860) \\
&\quad + (1.654808 + 0.001359) + (3.819092 + 0.060469) \\
&\quad - 2 \times 0.585179 - 5.279581 - 5.372410 - 0.104305 - 0.543858 \} \\
&> 0.899.
\end{aligned}$$

This completes the proof of Theorem. □

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Institut Elie Cartan  
UMR 7502 UHP-CNRS-INRIA  
Université Henri Poincaré (Nancy 1)  
54506 Vandœuvre-lès-Nancy  
FRANCE  
e-mail: wujie@iecn.u-nancy.fr