MANIN'S CONJECTURE FOR A SINGULAR QUARTIC DEL PEZZO SURFACE

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ABSTRACT. We prove Manin's conjecture for a split singular quartic del Pezzo surface with singularity type $2\mathbf{A}_1$ and eight lines. This is achieved by equipping the surface with a conic bundle structure. To handle the sum over the family of conics, we prove a result of independent interest on a certain restricted divisor problem for four binary linear forms.

1. Introduction

For any projective variety $X \subset \mathbb{P}^n$ over \mathbb{Q} , we may define the height of a rational point $x \in X(\mathbb{Q})$ to be $H(x) = \max\{|x_0|, \ldots, |x_n|\}$. Here we have choosen a representative $x = (x_0 : \cdots : x_n)$ such that (x_0, \ldots, x_n) is a primitive integer vector. A natural object of study in diophantine geometry is the following counting function

$$N_U(B) = \#\{x \in U(\mathbb{Q}) : H(x) \le B\},\$$

defined for any $U \subset X$ and B > 0. Manin and his collaborators (see [FMT89] and [BM90]) have formulated a series of conjectures on the asymptotic behaviour of these counting functions as $B \to \infty$. When X is a Fano variety given by its anticanonical embedding, they have conjectured that there exists some $U \subset X$ open and a constant $c_X \neq 0$ such that

$$N_U(B) \sim c_X B(\log B)^{\rho-1}$$

where $\rho = \operatorname{rank} \operatorname{Pic}(X)$, at least if the set of rational points on X is Zariski dense. The constant c_X has also received a conjectural adelic interpretation due to Peyre [Pey95].

There is a programme to try to prove Manin's conjecture for smooth and singular del Pezzo surfaces, the Fano varieties of dimension two. See [Bro07] or [DL10, Table 1.] for a reasonably up to date account of the progress so far. In this paper we study the number of rational points of bounded height on a certain singular del Pezzo surface of degree four, given by the equations

$$S: x_0x_1 = x_2^2, \quad x_3x_4 = x_2(x_1 - x_0),$$

in \mathbb{P}^4 . This surface has been chosen since it is a quartic del Pezzo surfaces with singularity type $2\mathbf{A}_1$ and eight lines. Such surfaces are at the forefront of current methods, as a general philosophy in the programme is that the milder the singularities, the more difficult Manin's conjecture is to prove. It is easy to check the singularity type of S – the only singularities of S are (0:0:0:1:0) and (0:0:0:0:1), and these are both locally quadratic cones of the form $x_0x_1 = x_2^2$. It contains the following eight lines

$$x_2 = x_i = x_j = 0,$$

 $x_0 = x_1, x_0 = \pm x_2, x_j = 0,$

for any $i \in \{0,1\}$ and $j \in \{3,4\}$. To see that there are no other lines, we appeal to the classification of singular del Pezzo surfaces of degree four [CT88, Prop. 5.6]. A surface of

 $2000\ \textit{Mathematics Subject Classification.}\ 11\text{D}45\ (\text{primary}),\ 11\text{N}37,\ 14\text{G}05\ (\text{secondary}).$

singularity type $2\mathbf{A}_1$ may contain either eight or nine lines. In the case where it contains nine lines, one of these lines joins the two singularities, and it is easy to check that this is not the case here. Since each line is defined over \mathbb{Q} , we see that S is a split singular quartic del Pezzo surface with singularity type $2\mathbf{A}_1$ and eight lines. Note that a point $x \in S$ lies on a line if and only if $x_0x_1x_2x_3x_4 = 0$. Our result is as follows.

Theorem 1.1. Let $U \subset S$ be the open subset of S formed by removing all the lines. Then we have

$$N_U(B) = c_S B(\log B)^5 (1 + o(1))$$

as $B \to \infty$, where c_S is the leading constant as predicted by Peyre.

Note that we remove the lines since each line contributes roughly B^2 points to the counting problem, obscuring the finer arithmetic of the surface. An explicit expression for the leading constant can be found in Section 1.1. The proof of the theorem is achieved by utilising a conic bundle structure on S. This method was also used in [BB08], however it is in contrast to many of the proofs of Manin's conjecture for other quartic del Pezzo surfaces, which have used the associated universal torsor, see e.g. [BB07]. When the singularity type of the surface in question is not so mild, the universal torsor is often an open subset of a hypersurface in affine space. However the universal torsor for S has many more equations, so the previous methods used for dealing with such surfaces would be harder to implement here. The conic bundle structure on S allows us to transform the problem of counting rational points on S to one of counting rational points on a family of conics, essentially given by

$$xy = ab(b^2 - a^2)z^2, (1.1)$$

for varying parameters a and b. Counting the rational points of bounded height on any one individual conic is relatively simple, the difficultly arises when we sum over all the conics in the family. To handle this sum we prove an auxiliary result of independent interest in analytic number theory. It concerns the asymptotic behaviour of a certain restricted divisor problem for four binary linear forms. We postpone a precise statement of our result since it is of a technical nature, however a simple corollary is that

$$\sum_{\mathbf{x} \in \mathbb{Z}^2 \cap X\mathcal{R}} \tau(L_1(\mathbf{x})) \tau(L_2(\mathbf{x})) \tau(L_3(\mathbf{x})) \tau(L_4(\mathbf{x})) \sim cX^2 (\log X)^4,$$

as $X \to \infty$. Here $\mathcal{R} \subset \mathbb{R}^2$ is some suitable region, L_1, L_2, L_3, L_4 are certain non-proportional binary linear forms and $c = c(L_1, L_2, L_3, L_3, 1)$ is a constant. In our application to counting points on conics, our binary linear forms are essentially $x_1, x_2, x_2 - x_1$ and $x_2 + x_1$, which geometrically correspond to the discriminant of the family in question (1.1). Sums of the shape

$$\sum_{\mathbf{x}\in\mathbb{Z}^2\cap X\mathcal{R}}\prod_{i=1}^n f\left(L_i(\mathbf{x})\right),\,$$

for binary linear forms L_1, \ldots, L_n and certain arithmetic functions f have been considered before. The case where n=3 and $f=\tau$ has been handled in [Bro11], and Heath-Brown considered the case where n=4 and f=r, the sum of squares function. Our methods are similar to these and are based on the work of Daniel [Dan99], and the case n=4 seems to be the limit of what these methods can achieve. There is however recent work of Matthiesen [Mat11] in which she proves an asymptotic formula for arbitrary n and $f=\tau$, using techniques from additive combinatorics. However, this result is not sufficient for our purposes as the fact that we consider a restricted divisor function is essential to our proof of Manin's conjecture.

We note that Theorem 1.1 is related to, but does not follow from, the work of [BBP10], where they prove Manin's conjecture for a family of Châtelet surfaces, using the universal torsor approach. The surfaces they consider are the minimal desingularisations of a family of Iskovskikh surfaces [BBP10, Rem.2.3], which are also del Pezzo surfaces of degree four with singularity type $2\mathbf{A}_1$ and eight lines. However, for such surfaces the two singularities are *conjugate*, and thus these surfaces are not split. We also note that the case of singularity type $2\mathbf{A}_1$ and nine lines can be handled using similar methods to what we use here, and it actually seems to be easier than the eight lines case due to a simpler divisor problem arising.

The layout of this paper is as follows. Section two is dedicated to the above mentioned restricted divisor problem. In the third section we gather numerous preliminary results on lattice point counting and divisors problems, before using these results to prove Theorem 1.1 in Section four.

Notation: We use $\nu_p(x)$ to denote the p-adic valuation of a rational number x.

1.1. The leading constant. We now give a description of the leading constant c_S appearing in Theorem 1.1. It agrees with the constant as predicted by Peyre [Pey95], and writing it down explicitly amounts to a now standard calculation, see e.g. [BB07]. If \widetilde{S} denotes the minimal desingularisation of S, then since S is split we have

$$c_S = \alpha(\widetilde{S})\tau_{\infty} \prod_p \tau_p,$$

where $\alpha(\widetilde{S})$ is the "nef cone volume" and τ_v denotes the density of S at the place v, with the necessary convergence factor included. By [Lou10, Lem. 2.3] we have

$$\tau_p = \left(1 - \frac{1}{p}\right)^6 \left(1 + \frac{6}{p} + \frac{1}{p^2}\right),$$

for all primes p. Also [Der07, Table 5] tells us that

$$\alpha(\widetilde{S}) = \frac{1}{720} = \frac{1}{2^4 \cdot 3^2 \cdot 5}.$$

To calculate the density at the real place we use the Leray form of S (see [Pey95, Sec. 5.2]), which is given by

$$\omega_L(S) = \frac{\mathrm{d}x_0 \mathrm{d}x_1 \mathrm{d}x_3}{2(x_0 x_1)^{1/2} x_3},$$

since

$$\det \begin{pmatrix} \frac{\partial Q_1}{\partial x_2} & \frac{\partial Q_2}{\partial x_2} \\ \\ \frac{\partial Q_1}{\partial x_4} & \frac{\partial Q_2}{\partial x_4} \end{pmatrix} = -2x_2x_3,$$

where $Q_1(\mathbf{x}) = x_0x_1 - x_2^2$ and $Q_2(\mathbf{x}) = x_3x_4 - x_2(x_1 - x_0)$. Note that $x_2^2 = x_0x_1 \ge 0$, so the Leray form is well-defined. The density at the real place is then given by

$$\tau_{\infty} = \frac{1}{2} \int_{\{\mathbf{x} \in \mathbb{R}^5 : Q_1(\mathbf{x}) = Q_2(\mathbf{x}) = 0, |x_0|, |x_1|, |x_2|, |x_3|, |x_4| \le 1\}} \omega_L(S).$$

We can turn this integral into a slightly more amenable form by taking advantage of certain automorphisms of the surface S. We already know that $x_0x_1 \geq 0$, however we may also assume that $x_0, x_1 \geq 0$. Indeed the above integral is invariant under the automorphism which negates x_0, x_1 and x_4 . Similarly we may assume that $x_1 \geq x_0$, since we may swap

them and again negate x_4 . Finally, we may negate x_3 and x_4 to assume x_3 is positive, and negate x_2 and x_4 to assume that x_2 is positive. Hence

$$\tau_{\infty} = 4 \int_{\{\mathbf{x} \in \mathbb{R}^3 : 0 < x_0/x_1, x_1, x_3, x_0 x_1 (x_1 - x_0)^2 / x_3^2 \le 1\}} \frac{\mathrm{d}x_0 \mathrm{d}x_1 \mathrm{d}x_3}{(x_0 x_1)^{1/2} x_3}.$$

2. A restricted divisor problem

We now describe in detail the restricted divisor problem which we handle in this paper. As mentioned in the introduction, this result will be used to handle the sum over the family of conics on S. Fix a lattice $\Lambda \subset \mathbb{Z}^2$, equipped with the usual Euclidean inner product. Let $\mathcal{R} \subset \mathbb{R}^2$ be region, that is, a compact set with a continuous piecewise differentiable boundary $\partial \mathcal{R}$, whose length we denote by $|\partial \mathcal{R}|$. Also let $L_1(\mathbf{x}), \ldots, L_4(\mathbf{x}) \in \mathbb{Q}[\mathbf{x}]$ be linear forms, no two of which are proportional and which satisfy $L_i(\mathbf{x}) \in \mathbb{Z}$ for all $\mathbf{x} \in \Lambda$ and $L_i(\mathbf{x}) \geq 0$ for all $\mathbf{x} \in \mathcal{R}$ (i = 1, 2, 3, 4). We then define

$$r = \sup_{\mathbf{x} \in \mathcal{R}} \{ L_1(\mathbf{x}), L_2(\mathbf{x}), L_3(\mathbf{x}), L_4(\mathbf{x}), |x_1|, |x_2| \}.$$

Next let $X \geq 1$ and for simplicity we assume that our region satisfies satisfies $|\partial X\mathcal{R}| \ll rX$, where we write $X\mathcal{R} = \{\mathbf{x} \in \mathbb{R}^2 : \mathbf{x}/X \in \mathcal{R}\}$. Such a condition is automatically satisfied if \mathcal{R} is convex, for example. Finally let $V = V(X) \subset [0,1]^4$ be a non-empty compact set that is cut out by a bounded number of hyperplanes each with bounded coefficients. Then, we are interested in getting an asymptotic formula for the following sum

$$S(X;V) = \sum_{\mathbf{x} \in \Lambda \cap X\mathcal{R}} \tau(L_1(\mathbf{x}), L_2(\mathbf{x}), L_3(\mathbf{x}), L_4(\mathbf{x}); V),$$

as $X \to \infty$. Here

$$\tau(L_1(\mathbf{x}), L_2(\mathbf{x}), L_3(\mathbf{x}), L_4(\mathbf{x}); V) = \# \left\{ \mathbf{d} \in \mathbb{N}^4 : d_i | L_i(\mathbf{x}), \boldsymbol{\delta} \in V \right\}, \quad \boldsymbol{\delta} = \left(\frac{\log d_i}{\log rX} \right)_{i=1,2,3,4}.$$

Note that our choice of r ensures that $\tau(L_1(\mathbf{x}), L_2(\mathbf{x}), L_3(\mathbf{x}), L_4(\mathbf{x}); [0, 1]^4)$ is simply a fourfold product of the usual divisor function. In fact we shall soon see that by considering $V \subseteq [0, 1]^4$, only the leading constant changes in the asymptotic formula, namely $S(X; V) = S(X; [0, 1]^4)(\text{vol } V + o(1))$ as $X \to \infty$. To state the result that we prove, let

$$\rho(\mathbf{d}) = \frac{\det \Lambda(\mathbf{d})}{\det \Lambda}, \quad \Lambda(\mathbf{d}) = \{ \mathbf{x} \in \Lambda : d_i | L_i(\mathbf{x}), (i = 1, 2, 3, 4) \}, \tag{2.1}$$

where we define the determinant of a lattice to be the measure of any fundamental domain. Next choose the minimum $c_i \in \mathbb{N}$ such that $L_i(\mathbf{x}) = \ell_i(\mathbf{x})/c_i$, where $\ell_i(\mathbf{x}) \in \mathbb{Z}[\mathbf{x}]$, and let $\Delta \in \mathbb{Z}$ be the product of the resultants of the pairs of linear forms ℓ_i and ℓ_j for $i \neq j$. Note that $p|\Delta$ if and only if the form $\ell_1\ell_2\ell_3\ell_4$ has singular reduction modulo p.

Theorem 2.1. Let $X \ge 1$. Then we have

$$S(X;V) = \frac{C_{\infty} \prod_{p} C_{p}}{\det \Lambda} X^{2} (\log X)^{4} + O_{L_{1},L_{2},L_{3},L_{4},r,\Lambda} (X^{2} (\log X)^{3} \log \log X)$$

as $X \to \infty$, where

$$C_{\infty} = \operatorname{vol} \mathcal{R} \operatorname{vol} V, \quad C_p = \left(1 - \frac{1}{p}\right)^4 \left(\sum_{\mathbf{k} \in \mathbb{Z}_{\geq 0}^4} \frac{1}{\rho(p^{k_1}, p^{k_2}, p^{k_3}, p^{k_4})}\right).$$

Moreover $\prod_p |C_p| \ll_{\varepsilon} (\Delta \det \Lambda)^{\varepsilon}$ for any $\varepsilon > 0$.

Note that the error term here is independent of V, which is essentially because we may use the upper bound $\tau(L_1(\mathbf{x}), L_2(\mathbf{x}), L_3(\mathbf{x}), L_4(\mathbf{x}); V) \leq \tau(L_1(\mathbf{x}))\tau(L_2(\mathbf{x}))\tau(L_3(\mathbf{x}))\tau(L_4(\mathbf{x}))$ to handle each error term. For the application we have in mind, we need a related result. Namely, let $V' = V'(X) \subset [0, 1]^5$ be a non-empty compact set that is cut out by a bounded number of hyperplanes each with bounded coefficients. Then we define

$$S'(X;V') = \sum_{\mathbf{x} \in \Lambda \cap X\mathcal{R}} \frac{\tau'(L_1(\mathbf{x}), L_2(\mathbf{x}), L_3(\mathbf{x}), L_4(\mathbf{x}); V')}{\max\{x_1, x_2\}^2},$$

where now

$$\tau'(L_1(\mathbf{x}), L_2(\mathbf{x}), L_3(\mathbf{x}), L_4(\mathbf{x}); V') = \# \left\{ \mathbf{d} \in \mathbb{N}^4 : d_i | L_i(\mathbf{x}), \left(\boldsymbol{\delta}, \frac{\log \max\{|x_1|, |x_2|\}}{\log rX} \right) \in V' \right\}.$$

Note that the important difference here is that we are allowing the restriction placed on the divisors to depend on the varying parameter \mathbf{x} . It is then relatively simple to get an asymptotic formula for S'(X;V') using Theorem 2.1.

Corollary 2.2. Let $X \geq 1$ and let $\chi_{V'}$ denote the characteristic function of the set V'. Then we have

$$S'(X; V') = \frac{2C'_{\infty} \prod_{p} C_{p}}{\det \Lambda} (\log X)^{5} + O_{L_{1}, L_{2}, L_{3}, L_{4}, r, \Lambda} ((\log X)^{4} \log \log X),$$

as $X \to \infty$, where

$$C'_{\infty} = \operatorname{vol} \mathcal{R} \int_{\substack{u \in [0,1] \\ \boldsymbol{\eta} \in [1,u]^4}} \chi_{V'}(\boldsymbol{\eta}, u) d\boldsymbol{\eta} du,$$

and the C_p are as given in Theorem 2.1.

2.1. **Some multiplicative functions.** Before we begin the proof of Theorem 2.1, we briefly collect some facts about the function $\rho(\mathbf{d}) = \det \Lambda(\mathbf{d})/\det \Lambda$, as defined in (2.1), and some related functions. First note that ρ is a multiplicative function. Indeed, we have the obvious equality $\rho(\mathbf{d}) = \#(\Lambda/\Lambda(\mathbf{d}))$, and the Chinese remainder theorem gives an isomorphism $\Lambda/\Lambda(\mathbf{de}) \cong \Lambda/\Lambda(\mathbf{d}) \times \Lambda/\Lambda(\mathbf{e})$ for any $\mathbf{d}, \mathbf{e} \in \mathbb{N}^4$ such that $(d_1d_2d_3d_4, e_1e_2e_3e_4) = 1$.

Lemma 2.3. For any $e_1, e_2, e_3, e_4 \ge 0$, let σ be the permutation such that $e_{\sigma(1)} \ge e_{\sigma(2)} \ge e_{\sigma(3)} \ge e_{\sigma(4)}$. Then for any prime p we have

$$\rho(p^{e_1}, p^{e_2}, p^{e_3}, p^{e_4}) \left\{ \begin{array}{ll} = p^{e_{\sigma(1)} + e_{\sigma(2)}}, & p \nmid \Delta \det \Lambda, \\ \geq p^{\max\{e_{\sigma(1)} + e_{\sigma(2)} - \lambda_p - 2\delta_p, 0\}}, & p \mid \Delta \det \Lambda, \end{array} \right.$$

where $\lambda_p = \nu_p(\det \Lambda)$ and $\delta_p = p(\Delta)$.

Proof. We begin the proof with a preliminary result. To simplify notation, let $p^{\mathbf{e}} = (p^{e_1}, \dots, p^{e_4})$ and consider the lattice $\Gamma_{\mathbf{d}} = \{\mathbf{x} \in \mathbb{Z}^2 : d_i | \ell_i(\mathbf{x}) \}$, where as before we have chosen the minimum $c_i \in \mathbb{N}$ such that $L_i(\mathbf{x}) = \ell_i(\mathbf{x})/c_i$ and $\ell_i(\mathbf{x}) \in \mathbb{Z}[\mathbf{x}]$. Then I claim that

$$\det \Gamma_{p^{\mathbf{e}}} \left\{ \begin{array}{l} = p^{e_{\sigma(1)} + e_{\sigma(2)}}, & p \nmid \Delta, \\ \geq p^{\max\{e_{\sigma(1)} + e_{\sigma(2)} - 2\delta_p, 0\}}, & p \mid \Delta. \end{array} \right.$$

$$(2.2)$$

Indeed for $p \nmid \Delta$, as in [HB03, p.13] we find that $p^{e_i} | \ell_i(\mathbf{x})$ for i = 1, 2, 3, 4 is equivalent to

$$p^{e_{\sigma(2)}}|\mathbf{x}, p^{e_{\sigma(1)}}|\ell_{\sigma(1)}(\mathbf{x}).$$

Thus Γ_{p^e} has determinant $p^{e_{\sigma(1)}+e_{\sigma(2)}}$. For all other primes p, note that $x \in \Gamma_{p^e}$ implies $p^{e_{\sigma(2)}}|\Delta \mathbf{x}$ and $p^{e_{\sigma(1)}}|\ell_{\sigma(1)}(\mathbf{x})$. Now, $\ell_{\sigma(1)}$ is not necessarily primitive, however any fixed divisor of $\ell_{\sigma(1)}$ must divide Δ , so we deduce that

$$p^{e_{\sigma(2)}}|p^{\delta_p}\mathbf{x}, \quad p^{e_{\sigma(1)}}|p^{\delta_p}\ell_{\sigma(1)}^*(\mathbf{x}),$$
 (2.3)

where $\ell_{\sigma(1)}^*$ is a primitive linear form. If $e_{\sigma(1)} \leq \delta_p$, the lattice given by (2.3) clearly has determinant 1. Similarly if $e_{\sigma(2)} \geq \delta_p$, then the lattice has determinant $p^{e_{\sigma(1)}+e_{\sigma(2)}-2\delta_p}$. Finally, if $e_{\sigma(1)} > \delta_p$ and $e_{\sigma(2)} \leq \delta_p$, then the lattice given by (2.3) has determinant $p^{e_{\sigma(1)}-\delta_p} \geq p^{e_{\sigma(1)}+e_{\sigma(2)}-2\delta_p}$, thus proving (2.2).

We now use (2.2) to prove the lemma. Note that $c_i | \det \Lambda$ for i = 1, 2, 3, 4, since each L_i takes only integral values on Λ . Hence for any $p \nmid \Delta \det \Lambda$, we have $\Lambda(p^{\mathbf{e}}) = \Lambda \cap \Gamma_{p^{\mathbf{e}}}$. The Chinese remainder theorem implies that $\det \Lambda(p^{\mathbf{e}}) = \det \Lambda \det \Gamma_{p^{\mathbf{e}}}$, so the result follows from (2.2). For all other primes p, it is clear that $\Lambda(p^{\mathbf{e}})$ is still a sublattice of Λ and $\Gamma_{p^{\mathbf{e}}}$, so $\det \Lambda(p^{\mathbf{e}}) \geq [\det \Lambda, \det \Gamma_{p^{\mathbf{e}}}]$. Note however that $(\det \Lambda, \det \Gamma_{p^{\mathbf{e}}}) \leq \lambda_p$ as p is the only prime dividing $\det \Gamma_{p^{\mathbf{e}}}$. Thus, by (2.2) we have

$$\rho(p^{\mathbf{e}}) \ge \frac{\det \Gamma_{p^{\mathbf{e}}}}{(\det \Lambda, \det \Gamma_{p^{\mathbf{e}}})} \ge p^{e_{\sigma(1)} + e_{\sigma(2)} - \lambda_p - 2\delta_p}.$$

For any $\mathbf{k} \in \mathbb{N}^4$ let

$$v(\mathbf{k}) = \sum_{d_i|k_i} \frac{d_1 d_2 d_3 d_4}{\rho(\mathbf{d})} \mu\left(\frac{k_1 k_2 k_3 k_4}{d_1 d_2 d_3 d_4}\right). \tag{2.4}$$

We have defined v via a higher dimensional analogue of the usual Dirichlet convolution, in such a way that it is small in general. The next lemma makes this more precise.

Lemma 2.4. Let

$$\Upsilon(s) = \sum_{\mathbf{k} \in \mathbb{N}^4} \frac{\upsilon(\mathbf{k})}{(k_1 k_2 k_3 k_4)^s},$$

be the Dirichlet series corresponding to v, as defined by (2.4). Then $\Upsilon(s)$ is absolutely convergent on the half-plane Re(s) > 5/6. Moreover for any $\varepsilon > 0$ we have

$$\Upsilon(1) = \prod_{p} C_p \ll_{\varepsilon} (\Delta \det \Lambda)^{\varepsilon},$$

where the C_p are as given in Theorem 2.1.

Proof. Let $\varepsilon > 0$ and let $s \geq 5/6 + \varepsilon$. Then by multiplicativity we have

$$\sum_{\mathbf{k}} \frac{|\upsilon(\mathbf{k})|}{(k_1 k_2 k_3 k_4)^s} = \prod_{p} \left(\sum_{\mathbf{e} \in \mathbb{Z}_{\geq 0}^4} \frac{|\upsilon(p^{e_1}, p^{e_2}, p^{e_3}, p^{e_4})|}{p^{(e_1 + e_2 + e_3 + e_4)s}} \right).$$

However, when $p \nmid \Delta \det \Lambda$ and $0 < e_1 + e_2 + e_3 + e_4 \le 2$, Lemma 2.3 implies that $\rho(p^{e_1}, p^{e_2}, p^{e_3}, p^{e_4}) = p^{e_1 + e_2 + e_3 + e_4}$ and hence $v(p^{e_1}, p^{e_2}, p^{e_3}, p^{e_4}) = 0$. It follows that the

contribution from $p \nmid \Delta \det \Lambda$ is bounded above by

$$\begin{split} & \prod_{p \nmid \Delta \det \Lambda} \left(1 + \sum_{e \geq 3} \frac{1}{p^{es}} \sum_{e_1 + e_2 + e_3 + e_4 = e} \frac{e^4 p^e}{\rho(p^{e_1}, p^{e_2}, p^{e_3}, p^{e_4})} \right) \\ \ll & \prod_{p} \left(1 + \sum_{e \geq 3} \frac{e^8}{p^{e(s-1/2)}} \right) \\ \ll_{\varepsilon} & \prod_{p} \left(1 + \frac{1}{p^{1+\varepsilon}} \right) \ll_{\varepsilon} 1. \end{split}$$

Similarly, those primes $p|\Delta \det \Lambda$ contribute $\ll_{\varepsilon,\Delta,\det \Lambda} 1$. Next by the definition of v, for $\operatorname{Re}(s) > 5/6$ we have

$$\Upsilon(s) = \prod_{p} \left(1 - \frac{1}{p^s} \right)^4 \left(\sum_{\mathbf{k} \in \mathbb{Z}_{\geq 0}^4} \frac{p^{(k_1 + k_2 + k_3 + k_4)(1 - s)}}{\rho(p^{k_1}, p^{k_2}, p^{k_3}, p^{k_4})} \right).$$

Thus the equality $\Upsilon(1) = \prod_n C_p$ is clear. To show the upper bound, by Lemma 2.3 we have

$$\Upsilon(1) \ll \prod_{p \mid \Delta \det \Lambda} \left(1 - \frac{1}{p} \right)^4 \left(\sum_{\mathbf{k} \in \mathbb{Z}_{\geq 0}^4} \frac{1}{\rho(p^{k_1}, p^{k_2}, p^{k_3}, p^{k_4})} \right)$$

$$\ll \prod_{p \mid \Delta \det \Lambda} \left((\lambda_p + 2\delta_p)^4 + O(1) \right)$$

$$\ll_{\varepsilon} (\Delta \det \Lambda)^{\varepsilon}.$$

2.2. **Proof of Theorem 2.1.** In what follows all errors terms are implicitly allowed to depend on the linear forms L_1, L_2, L_3, L_4 , the number r and the lattice Λ . We begin by showing that we need only sum over the smaller divisors of the linear forms.

Lemma 2.5. For any $\varepsilon > 0$ we have

$$S(X;V) = \sum_{\mathbf{m} \in \{\pm 1\}^4} S^{\mathbf{m}}(X;V) + O_{\varepsilon}(X^{3/2+\varepsilon}),$$

as $X \to \infty$, where

$$S^{\mathbf{m}}(X;V) = \sum_{\mathbf{x} \in \Lambda \cap X\mathcal{R}} \# \left\{ \mathbf{d} \in \mathbb{N}^4 : \frac{d_i | L_i(\mathbf{x}), d_i \leq \sqrt{L_i(\mathbf{x})}}{\mathbf{D}^{\mathbf{m}}(\boldsymbol{\delta}, \boldsymbol{\xi}) \in V} \right\},\,$$

and

$$\mathbf{D}^{\mathbf{m}}(\boldsymbol{\delta}, \boldsymbol{\xi}) = \mathbf{m}\boldsymbol{\delta} + (1 - \mathbf{m})\boldsymbol{\xi}/2, \quad \boldsymbol{\xi} = \left(\frac{\log L_i(\mathbf{x})}{\log rX}\right)_{i=1,2,3,4}.$$

Proof. To get the main term we use a variant of the classical Dirichlet hyperbola method, namely if $d_i > \sqrt{L_i(\mathbf{x})}$, we replace d_i by $L_i(\mathbf{x})/d_i$. The error term is then made up of those terms where $d_i = \sqrt{L_i(\mathbf{x})}$ for some i = 1, 2, 3, 4, each of which is handled in a similar manner. For example the contribution from where $L_4(\mathbf{x})$ is a square is

$$\sum_{\substack{\mathbf{x} \in \Lambda \cap X\mathcal{R} \\ L_4(\mathbf{x}) = \square}} \tau(L_1(\mathbf{x}))\tau(L_2(\mathbf{x}))\tau(L_3(\mathbf{x}))$$

$$\ll_{\varepsilon} X^{\varepsilon} \sum_{n \leq \sqrt{X}} \#\{\mathbf{x} \in \mathbb{Z}^2 : ||\mathbf{x}|| \ll X, L_4(\mathbf{x}) = n^2\} \ll_{\varepsilon} X^{3/2 + \varepsilon}.$$

For now we consider fixed **m**. After changing the order of summation, we have

$$S^{\mathbf{m}}(X;V) = \sum_{d_i \le r\sqrt{X}} \#(\mathbf{x} \in \Lambda(\mathbf{d}) \cap \mathcal{R}^{\mathbf{m}}(\mathbf{d};X)),$$

where

$$\mathcal{R}^{\mathbf{m}}(\mathbf{d}; X) = \{ \mathbf{x} \in X\mathcal{R} : d_i \leq \sqrt{L_i(\mathbf{x})}, \mathbf{D}^{\mathbf{m}}(\boldsymbol{\delta}, \boldsymbol{\xi}) \in V \},$$

and $\Lambda(\mathbf{d})$ is given by (2.1). Large divisors will become problematic for us, so we sum over these separately. Write

$$S_0^{\mathbf{m}}(X;V) = \sum_{\substack{d_i \le r\sqrt{X} \\ d_4 \ge Y}} \#(\mathbf{x} \in \Lambda(\mathbf{d}) \cap \mathcal{R}^{\mathbf{m}}(\mathbf{d};X)), \quad S_1^{\mathbf{m}}(X;V) = S^{\mathbf{m}}(X;V) - S_0^{\mathbf{m}}(X;V),$$

where $Y \leq r\sqrt{X}$ is some parameter to be chosen later. We may handle $S_1^{\mathbf{m}}(X;V)$ with the following "level of distribution" result.

Lemma 2.6. Let $X \ge 1$ and $Q_1, Q_2, Q_3, Q_4 \ge 2$. Write

$$Q = \max_i Q_i \text{ and } P = Q_1 Q_2 Q_3 Q_4.$$

Then there is an absolute constant A > 0 such that

$$\sum_{d_i \leq Q_i} \left| \#(\Lambda(\mathbf{d}) \cap \mathcal{R}^{\mathbf{m}}(\mathbf{d}; X)) - \frac{\operatorname{vol} \mathcal{R}^{\mathbf{m}}(\mathbf{d}; X)}{\det \Lambda} \right| \ll (XP^{1/2} + XQ + P)(\log Q)^A.$$

Proof. This follows from [HB03, Lem. 2.1], whose proof is a minor modification of the argument of Daniel [Dan99, Lem. 3.2]. Note that we work in slightly more generality than Heath-Brown, as our region $\mathcal{R}^{\mathbf{m}}(\mathbf{d};X)$ is not necessarily convex. However, the important point is that we still have the necessary upper bound $|\partial \mathcal{R}^{\mathbf{m}}(\mathbf{d};X)| \ll rX$, uniformly with respect to V. Indeed, this follows from our simplifying assumption on our region that $|\partial X\mathcal{R}| \ll rX$, and also the fact that V is cut out by a bounded number of hyperplanes each with bounded coefficients.

Hence if we take $Y = r\sqrt{X}/(\log X)^{2A}$, we deduce that

$$S_1^{\mathbf{m}}(X; V) = \sum_{\substack{d_i \le r\sqrt{X} \\ d_4 \le Y}} \frac{\operatorname{vol}(\mathcal{R}^{\mathbf{m}}(\mathbf{d}; X))}{\det \Lambda(\mathbf{d})} + O(X^2).$$

We get an upper bound for $S_0^{\mathbf{m}}(X;V)$ with the next lemma.

Lemma 2.7. Let $X \geq 1$. Then we have

$$S_0^{\mathbf{m}}(X; V) \ll X^2 (\log X)^3 (\log \log X),$$

as $X \to \infty$.

Proof. We begin by defining a kind of generalised divisor function, defined multiplicatively for any prime p by

$$\eth_3(p^a) = \begin{cases} 2, & a = 1, \\ (a+1)^3, & a \neq 1. \end{cases}$$

We will meet this function later on in a more general context in Section 3. Notice that

$$S_0^{\mathbf{m}}(X;V) \ll \sum_{Y \leq d_4 \leq r\sqrt{X}} \sum_{\substack{\mathbf{x} \in \Lambda \cap X\mathcal{R} \\ d_4 \mid L_4(\mathbf{x})}} \tau(L_1(\mathbf{x})) \tau(L_2(\mathbf{x})) \tau(L_3(\mathbf{x}))$$
$$\ll \sum_{Y \leq d \leq r\sqrt{X}} \sum_{\substack{x \ll X \\ y \ll X/d}} \eth_3(\ell_1'(x,dy)\ell_2'(x,dy)\ell_3'(x,dy)),$$

where ℓ'_i is the linear form obtained from ℓ_i by the change of variables $x_2 \mapsto \ell_4(\mathbf{x})$, for i=1,2,3. We now appeal to [BB06, Thm. 1], which is a general result on upper bounds for sums of arithmetic functions taking values in binary forms. Let $\Delta'(d)$ denote the discriminant of the form $F'(x,y) = \ell'_1(x,dy)\ell'_2(x,dy)\ell'_3(x,dy)$, and let $\psi(d) = \prod_{p|d} (1+1/p)$. Then [BB06, Thm. 1] allows us to deduce that

$$\begin{split} S_0^{\mathbf{m}}(X;V) \ll \sum_{Y \leq d \leq r\sqrt{X}} \frac{\psi(\Delta'(d))X^2(\log X)^3}{d} \\ \ll \sum_{Y \leq d \leq r\sqrt{X}} \frac{\psi(d)X^2(\log X)^3}{d} \ll X^2(\log X)^3(\log\log X), \end{split}$$

as required.

Hence we have

$$S(X;V) = \frac{1}{\det \Lambda} \sum_{\mathbf{m} \in \{\pm 1\}^4} \sum_{\substack{d_i \le r\sqrt{X} \\ d_4 \le Y}} \frac{\operatorname{vol}(\mathcal{R}^{\mathbf{m}}(\mathbf{d}; X))}{\rho(\mathbf{d})} + O(X^2(\log X)^3(\log \log X)), \tag{2.5}$$

where ρ is given by (2.1). Note that

$$\sum_{\substack{d_i \leq r\sqrt{X} \\ d_4 \leq Y}} \frac{\operatorname{vol}(\mathcal{R}^{\mathbf{m}}(\mathbf{d}; X))}{\rho(\mathbf{d})} = \sum_{\substack{d_i \leq r\sqrt{X} \\ d_4 \leq Y}} \frac{\sum_{k_i | d_i} \upsilon(\mathbf{k}) \operatorname{vol}(\mathcal{R}^{\mathbf{m}}(\mathbf{d}; X))}{d_1 d_2 d_3 d_4}$$
$$= \sum_{k_i \leq r\sqrt{X}} \frac{\upsilon(\mathbf{k})}{k_1 k_2 k_3 k_4} E_{\mathbf{k}}^{\mathbf{m}}(X; V).$$

Here v is given by (2.4) and

$$E_{\mathbf{k}}^{\mathbf{m}}(X;V) = \sum_{\substack{e_i \leq r\sqrt{X}/k_i \\ e_4 \leq Y/k_4}} \frac{\operatorname{vol}(\mathcal{R}^{\mathbf{m}}(\mathbf{ek};X))}{e_1 e_2 e_3 e_4},$$

where we write $\mathbf{ek} = (e_1k_1, e_2k_2, e_3k_3, e_4k_4)$. We handle this inner sum with the following lemma.

Lemma 2.8. Let $\mathbf{k} \in \mathbb{N}^4$ be such that $1 \le k_i \le r\sqrt{X}$ for i = 1, 2, 3, 4. Then for any $\varepsilon > 0$ we have

$$E_{\mathbf{k}}^{\mathbf{m}}(X;V) = \frac{C_{\infty}}{2^4} X^2 (\log X)^4 \left(1 + O_{\varepsilon} \left(\frac{||\mathbf{k}||^{\varepsilon} (\log \log X)}{\log X} \right) \right),$$

where C_{∞} is as in Theorem 2.1.

Proof. In what follows let

$$\epsilon = \left(\frac{\log e_i}{\log rX}\right)_{i=1,2,3,4}, \quad \kappa = \left(\frac{\log k_i}{\log rX}\right)_{i=1,2,3,4}.$$

Then we have

$$E_{\mathbf{k}}^{\mathbf{m}}(X;V) = \int_{\mathbf{x} \in X\mathcal{R}} \sum_{\substack{e_i \leq \sqrt{L_i(\mathbf{x})}/k_i \\ e_4 \leq Y/k_4 \\ \mathbf{D}^{\mathbf{m}}(\boldsymbol{\epsilon} + \boldsymbol{\kappa}, \boldsymbol{\xi}) \in V}} \frac{d\mathbf{x}}{e_1 e_2 e_3 e_4}.$$

However, this simplifies to

$$E_{\mathbf{k}}^{\mathbf{m}}(X;V) = \int_{\mathbf{x} \in X\mathcal{R}} \sum_{\substack{e_i \le \sqrt{rX} \\ \mathbf{D}^{\mathbf{m}}(\boldsymbol{\epsilon} + \boldsymbol{\kappa}, \boldsymbol{\xi}) \in V}} \frac{\mathrm{d}\mathbf{x}}{e_1 e_2 e_3 e_4} + O_{\varepsilon}(||\mathbf{k}||^{\varepsilon} X^2 (\log X)^3 (\log \log X)).$$

Indeed, we may assume that $|x_1|, |x_2| \ge rX/\log X$ with a satisfactory error. Then the contribution from $\sqrt{L_i(\mathbf{x})}/k_i \le e_i \le \sqrt{rX}$ for i=1,2,3 is bounded above by the given error term. We may also handle e_4 in a similar manner. Performing Euler-Maclaurin summation, we find that

$$E_{\mathbf{k}}^{\mathbf{m}}(X;V) = \frac{(\log rX)^4}{2^4} \int_{\substack{\boldsymbol{\epsilon} \in [0,1] \\ \mathbf{x} \in X\mathcal{R}}} \chi_V(\mathbf{D^m}(\boldsymbol{\epsilon} + \boldsymbol{\kappa}, \boldsymbol{\xi})) d\boldsymbol{\epsilon} d\mathbf{x} + O_{\varepsilon} \left(||\mathbf{k}||^{\varepsilon} X^2 (\log X)^3 (\log \log X) \right),$$

where χ_V is the characteristic function of V. On making the change of variables $\mathbf{x} \mapsto \mathbf{x}/X$ and $\boldsymbol{\eta} = \mathbf{D^m}(\boldsymbol{\epsilon} + \boldsymbol{\kappa}, \boldsymbol{\xi}) = \mathbf{m}(\boldsymbol{\epsilon} + \boldsymbol{\kappa}) + (1 - \mathbf{m})\boldsymbol{\xi}/2$, we see that

$$\int_{\substack{\epsilon \in [0,1] \\ \mathbf{x} \in X\mathcal{R}}} \chi_V(\mathbf{D^m}(\epsilon + \kappa, \boldsymbol{\xi})) d\epsilon d\mathbf{x} = X^2 \operatorname{vol} \mathcal{R} \operatorname{vol} V + O_{\varepsilon} \left(\frac{||\mathbf{k}||^{\varepsilon} X^2}{\log X} \right).$$

However, by definition we have $C_{\infty} = \text{vol } \mathcal{R} \text{ vol } V$, thus proving the lemma.

We are now in a position to finish the proof of Theorem 2.1. First we sum over \mathbf{m} in (2.5), then use Lemma 2.4 and Lemma 2.8 to deduce that

$$S(X; V) = \frac{C_{\infty}}{\det \Lambda} \sum_{k_i \le r\sqrt{X}} \frac{v(\mathbf{k})}{k_1 k_2 k_3 k_4} X^2 (\log X)^4 \left(1 + O_{\varepsilon} \left(\frac{||\mathbf{k}||^{\varepsilon} \log \log X}{\log X} \right) \right)$$
$$= \frac{C_{\infty} \prod_p C_p}{\det \Lambda} X^2 (\log X)^4 + O\left(X^2 (\log X)^3 \log \log X \right),$$

on choosing $\varepsilon = 1/12$, say.

2.3. **Proof of Corollary 2.2.** In what follows all error terms are implicitly allowed to depend on the linear forms, the number r and the lattice Λ . We first note that we have the identity

$$\frac{1}{\max\{x_1, x_2\}} = 2 \int_{\max\{x_1, x_2\}}^{X} \frac{\mathrm{d}t}{t^3} + \frac{1}{X^2}.$$

Applying this we find

$$S'(X; V') = \int_{1}^{X} \frac{S''(t; V')}{t^{3}} dt + O((\log X)^{4})$$

where $S''(t;V') = \sum_{\mathbf{x} \in \Lambda \cap t \mathcal{R}} \tau'(L_1(\mathbf{x}), L_2(\mathbf{x}), L_3(\mathbf{x}), L_4(\mathbf{x}); V')$. In order to handle this sum using Theorem 2.1, we need to remove the dependence on \mathbf{x} . Our aim therefore is to replace the condition $(\boldsymbol{\delta}, (\log \max\{x_1, x_2\})/(\log rX)) \in V'$ by $(\boldsymbol{\delta}, (\log t)/(\log rX)) \in V'$. To do this, for any $C \in \mathbb{R}$ let

$$V_C(t) = \left\{ \boldsymbol{\eta} \in [0, 1]^4 : \left(\boldsymbol{\eta}, 1 + \frac{C \log \log t}{\log t} \right) \in [0, 1]^5 \cap \frac{\log rX}{\log rt} V' \right\}.$$

Then on noticing that we may assume that $|x_1|, |x_2| \ge rt/\log t$ with a suitable error, we have the bounds

$$S(t; V_{-C}(t)) + O(t^2(\log t)^3) \le S''(t; V') \le S(t; V_C(t)) + O(t^2(\log t)^3),$$

for some constant $C \ge 0$. However we clearly have vol $V_{\pm C}(t) = \text{vol } V_0(t) + O((\log \log t)/(\log t))$ for $t \gg 1$, hence applying Theorem 2.1 we deduce that

$$S'(X;V') = \frac{\operatorname{vol} \mathcal{R} \prod_{p} C_{p}}{\det \Lambda} \int_{1}^{X} \frac{\operatorname{vol} V_{0}(t) (\log rt)^{4}}{t} dt + O((\log X)^{4} \log \log X).$$

The proof of the corollary is then complete on noticing that

$$\int_{1}^{X} \frac{\operatorname{vol} V_{0}(t)(\log rt)^{4}}{t} dt = (\log rX)^{4} \int_{1}^{X} \frac{1}{t} \int_{\boldsymbol{\eta} \in [1,\log rt/\log rX]^{4}} \chi_{V'}(\boldsymbol{\eta}, \log rt/\log rX) d\boldsymbol{\eta} dt$$
$$= (\log X)^{5} \int_{\substack{u \in [0,1] \\ \boldsymbol{\eta} \in [1,u]^{4}}} \chi_{V'}(\boldsymbol{\eta}, u) d\boldsymbol{\eta} du + O((\log X)^{4}).$$

3. Useful results

Before we begin the proof of Theorem 1.1, we gather some technical results on lattice point counting and upper bounds for certain divisor problems.

3.1. Lattice point counting. The emphasis on the results in this section is their uniformity with respect to the chosen lattices and regions. Our first result concerns counting non-zero lattice points in planar domains. Before we state it, recall that the first successive minima λ_1 of a lattice Λ is defined to be the length of the shortest non-zero vector in Λ .

Lemma 3.1. Let X > 0. Let $\Lambda \subset \mathbb{R}^2$ be a lattice with first successive minima λ_1 and suppose that $\mathcal{R} \subset \mathbb{R}^2$ is a region such that $(0,0) \in \mathcal{R}$. Then

$$\#\{\mathbf{x} \in \Lambda \cap X\mathcal{R} : \mathbf{x} \neq (0,0)\} = \frac{\operatorname{vol} X\mathcal{R}}{\det \Lambda} + O\left(\frac{|\partial X\mathcal{R}|}{\lambda_1}\right).$$

Proof. The well-known method of counting lattice points in planar domains yields the estimate

$$\#\{\mathbf{x} \in \Lambda \cap X\mathcal{R}\} = \frac{\operatorname{vol} X\mathcal{R}}{\det \Lambda} + O\left(\frac{|\partial X\mathcal{R}|}{\lambda_1} + 1\right). \tag{3.1}$$

If $1 \ll |\partial X\mathcal{R}|/\lambda_1$, then the proof of the lemma follows immediately from (3.1). Otherwise, suppose that $|\partial X\mathcal{R}| < \lambda_1$ and let $r(X) = \sup_{\mathbf{x} \in X\mathcal{R}} ||\mathbf{x}||$. Then since the geodesics in \mathbb{R}^2 are exactly the lines, we see that $r(X) \leq |\partial X\mathcal{R}| < \lambda_1$, and hence there are no non-zero lattice points in $X\mathcal{R}$. So in order for the statement of the lemma to be true in this case, it suffices to show that the error term dominates the main term. However we have

$$\frac{\operatorname{vol} X\mathcal{R}}{\det \Lambda} \ll \frac{(r(X))^2}{\det \Lambda} \ll \left(\frac{|\partial X\mathcal{R}|}{\lambda_1}\right)^2 \ll 1.$$

Hence

$$\frac{\operatorname{vol} X\mathcal{R}}{\det \Lambda} \ll \sqrt{\frac{\operatorname{vol} X\mathcal{R}}{\det \Lambda}} \ll \frac{r(X)}{\lambda_1} \ll \frac{|\partial X\mathcal{R}|}{\lambda_1},$$

as required.

For the next result we assume that \mathcal{R} is a "box". Namely, there are some $r_1, r_2 \geq 0$ such that

$$\mathcal{R} = \{ \mathbf{x} \in \mathbb{R}^2 : 0 \le x_i \le r_i, (i = 1, 2) \}.$$

Lemma 3.2. Let X > 0 and let \mathcal{R} be a box. Then for any lattice $\Lambda \subset \mathbb{Z}^2$ we have

$$\#\{\mathbf{x} \in \Lambda \cap X\mathcal{R} : (x_1, x_2) = 1\} \ll \frac{\operatorname{vol} X\mathcal{R}}{\det \Lambda} + 1.$$

Next assume that $\Lambda = \{ \mathbf{x} \in \mathbb{Z}^2 : q_1 | x_1, q_2 | x_2 \}$ for some $q_1, q_2 \in \mathbb{N}$. Then

$$\#\{\mathbf{x} \in \Lambda \cap X\mathcal{R} : x_1x_2 \neq 0\} \ll \frac{\operatorname{vol} X\mathcal{R}}{\det \Lambda}.$$

Proof. The first part of the lemma follows from [HB84, Lem. 2], after bounding \mathcal{R} by a suitable ellipse. The second part is simple as the number of lattice points in question is clearly bounded above by $X^2r_1r_2/q_1q_2$.

We finish with a result of Browning and Heath-Brown [BHB07, Cor. 2] on uniform upper bounds for the number of points on conics.

Lemma 3.3. Let C be a non-singular ternary quadratic form. Let Δ denote the determinant of the associated matrix, and let Δ_0 be the greatest common divisor of the 2×2 minors. Then we have

$$\#\left\{\mathbf{x} \in \mathbb{Z}^3: \begin{array}{l} C(\mathbf{x}) = 0, (x_1, x_2, x_3) = 1 \\ |x_i| \le B_i, (i = 1, 2, 3) \end{array}\right\} \ll \tau(|\Delta|) \left(1 + \frac{B_1 B_2 B_3 \Delta_0^{3/2}}{|\Delta|}\right)^{1/3}$$

3.2. **Divisor problems.** In this section we gather numerous results on upper bounds for certain divisor sums in two variables. For any $k \in \mathbb{N}$, we shall be interested in the following generalised divisor function, defined multiplicatively for any prime p by

$$\eth_k(p^a) = \begin{cases} 2, & a = 1, \\ (a+1)^k, & a \neq 1. \end{cases}$$
(3.2)

We list the following simple properties of \eth_k to clarify the relationship between it and the usual divisor function τ .

- (a) $\tau = \eth_1$.
- (b) $\tau(n) \leq \eth_k(n)$ for any $n, k \in \mathbb{N}$.

- (c) $\tau(a)\tau(b) \leq \eth_2(ab)$ for any $a, b \in \mathbb{N}$.
- (d) τ and \eth_k have the same average order for any $k \in \mathbb{N}$.

Our first result will be the basis of all following upper bounds on divisor sums. It follows from the general work [BB06], where they consider sums of suitable arithmetic functions over binary forms.

Lemma 3.4. Let $0 < X_1, X_2 \le X$ and let $F \in \mathbb{Z}[x_1, x_2]$ be a non-singular quartic binary form that is completely reducible over \mathbb{Z} . Then for any $n, k \in \mathbb{N}$ and $\varepsilon > 0$ we have

$$\sum_{\substack{a \leq X_1 \\ b \leq X_2}} \eth_k^n(|F(a,b)|) \ll_{\varepsilon,k,n} ||F||^{\varepsilon} (X_1 X_2 (\log X)^{4(2^n-1)} + \max\{X_1, X_2\}^{1+\varepsilon}),$$

where ||F|| denotes the maximum absolute value of the coefficients of F.

Proof. Let $F(x_1, x_2) = fx_1^{d_1}x_2^{d_2}G(x_1, x_2)$ where $f \in \mathbb{Z}$ and $G(x_1, x_2)$ is a primitive binary form with $G(1,0)G(0,1) \neq 0$. Then, [BB06, Cor. 1] implies that

$$\sum_{\substack{a \le X_1 \\ b \le X_2}} \eth_k^n(|F(a,b)|) \ll_{\varepsilon,n,k} ||F||^{\varepsilon} \left(X_1 X_2 E + \max\{X_1, X_2\}^{1+\varepsilon} \right),$$

where

$$E = \prod_{p < \min\{X_1, X_2\}} \left(1 + \frac{\varrho_G^*(p)(\eth_k^n(p) - 1)}{p} \right) \prod_{i = 1, 2} \prod_{p \le X_i} \left(1 + \frac{d_i(\eth_k^n(p) - 1)}{p} \right),$$

and

$$\varrho_G^*(m) = \frac{1}{\varphi(m)} \# \left\{ \begin{array}{ll} (a,b) \in (0,m]^2: & \quad (a,b,m) = 1 \\ G(a,b) \equiv 0 \pmod{m} \end{array} \right\}.$$

However, for any prime p we have

$$\varrho_G^*(p) \le \frac{\#\{0 < a, b \le p : G(a, b) \equiv 0 \pmod{p}\}}{p-1} \le \frac{(4 - d_1 - d_2)p}{p-1},$$

which implies that

$$E \ll \prod_{p < X} \left(1 + \frac{4(2^n - 1)}{p} \right) \ll (\log X)^{4(2^n - 1)},$$

as required.

The next lemma handles the case of summing over more general regions than boxes.

Lemma 3.5. Let $z_1, z_2, X > 0$ and let $F \in \mathbb{Z}[x_1, x_2]$ be a non-singular quartic binary form that is completely reducible over \mathbb{Z} . Then for any $n, k \in \mathbb{N}$ and $\varepsilon > 0$ we have

$$\sum_{\substack{a,b>0\\ \max\{az,\ (b-a)z_0\} \le b \le X}} \eth_k^n(|F(a,b)|) \ll_{\varepsilon,n,k} \frac{||F||^{\varepsilon} X^2 (\log X)^{4(2^n-1)}}{(z_1 z_2)^{1-\varepsilon}}.$$

Next suppose that $1 \le y_1, y_2 \le \log X$. Then for any $p, q, r \ge 0$ such that p + q + r = 2 and q > 1 we have

$$\sum_{\substack{a,b \le X \\ \max\{ay_1,(b-a)y_2\} < b}} \frac{\eth_k^n(|F(a,b)|)}{a^p b^q (b-a)^r} \ll_{\varepsilon,n,k} \frac{||F||^{\varepsilon} (\log X)^{4(2^n-1)+1}}{(y_1 y_2)^{q-1}}.$$

Proof. Throughout the proof, we suppress the dependence of the implied constant on ε, n and k. In order to prove the first part of the lemma, we may assume that $z_1 \leq X$ and $z_2 \leq X$, since otherwise the sum vanishes and the upper bound is clearly sufficient. We also emphasise that a may be larger than X in the case where $z_1 < 1$. We split the summation up into two cases, beginning with the case where $2a \leq b$. Here we may assume that $z_2 \leq 2$ and hence $1 \ll z_2^{\varepsilon-1}$, since again otherwise the sum will vanish. Summing over dyadic intervals and using Lemma 3.4 gives

$$\sum_{\max\{az_{1},2a\} \leq b \leq X} \eth_{k}^{n}(|F(a,b)|) \ll \frac{1}{z_{2}^{1-\varepsilon}} \sum_{\max\{Az_{1},A\} < B \leq X} \sum_{\substack{a \approx A \\ b \approx B}} \eth_{k}^{n}(|F(a,b)|)$$

$$\ll \frac{||F||^{\varepsilon}}{z_{2}^{1-\varepsilon}} \sum_{\substack{\max\{Az_{1},A\} < B \leq X \\ A,B \in 2^{\mathbb{N}}}} \left(AB(\log X)^{4(2^{n}-1)} + B^{1+\varepsilon}\right)$$

$$\ll \frac{||F||^{\varepsilon}(\log X)^{4(2^{n}-1)}}{z_{2}^{1-\varepsilon}} \left(\frac{X^{2}}{z_{1}} + X^{1+\varepsilon}\right)$$

$$\ll \frac{||F||^{\varepsilon}X^{2}(\log X)^{4(2^{n}-1)}}{(z_{1}z_{2})^{1-\varepsilon}},$$

since $z_1 \leq X$. For the case $b \leq 2a$, we again note that the sum vanishes unless $z_1 \leq 2$. Hence we have

$$\sum_{\substack{b \le X \\ b \le 2a \\ (b-a)z_2 \le b}} \eth_k^n(|F(a,b)|) \ll \sum_{\max\{cz_2,2c\} \le b \le X} \eth_k^n(|F(b-c,b)|)$$

$$\ll \frac{||F||^{\varepsilon} X^2 (\log X)^{4(2^n-1)}}{(z_1 z_2)^{1-\varepsilon}},$$

as above. The proof of the second part of the lemma is very similar. When $2a \leq b$ we have

$$\begin{split} \sum_{\substack{a,b \leq X \\ \max\{ay_1,2a\} \leq b \leq X}} \frac{\eth_k^n(|F(a,b)|)}{a^p b^q (b-a)^r} \ll \frac{1}{y_2^{q-1}} \sum_{\substack{Ay_1 < B \leq X \\ A,B \in 2^{\mathbb{N}}}} \frac{1}{A^{p+r} B^q} \sum_{\substack{a \asymp A \\ b \asymp B}} \eth_k^n(|F(a,b)|) \\ \ll \frac{||F||^{\varepsilon}}{y_2^{q-1}} \sum_{\substack{Ay_1 < B \leq X \\ A,B \in 2^{\mathbb{N}}}} \left(A^{q-1} B^{1-q} (\log X)^{4(2^n-1)} + B^{1+\varepsilon-q}\right) \\ \ll \frac{||F||^{\varepsilon} (\log X)^{4(2^n-1)+1}}{(y_1 y_2)^{q-1}}, \end{split}$$

since $y_1^{q-1} \le y_1 \le \log X$. For the case $b \le 2a$ we have

$$\sum_{\substack{a,b \le X \\ a < b \le 2a \\ (b-a)y_2 \le b}} \frac{\eth_k^n(|F(a,b)|)}{a^p b^q (b-a)^r} \ll \frac{1}{y_1^{q-1}} \sum_{\substack{c,b \le X \\ \max\{cy_2,2c\} < b \le X}} \frac{\eth_k^n(|F(b-c,b)|)}{b^q c^{p+r}}$$
$$\ll \frac{||F||^{\varepsilon} (\log X)^{4(2^n-1)+1}}{(y_1 y_2)^{q-1}},$$

from above. This proves the lemma.

The next result, while of a technical nature, will be used later on in our work.

Lemma 3.6. Let X > 1 and let $F \in \mathbb{Z}[x_1, x_2]$ be a non-singular quartic binary form that is completely reducible over \mathbb{Z} . Then for any $z_1, z_2 \geq 1$ and $\mathbf{e} \in \mathbb{N}^4$ we have

10. Let
$$X > 1$$
 and let $F \in \mathbb{Z}[x_1, x_2]$ be a non-singular quartic binarily reducible over \mathbb{Z} . Then for any $z_1, z_2 \ge 1$ and $\mathbf{e} \in \mathbb{N}^4$ we have
$$\sum_{\substack{a,b \le X \\ \max\{z_1a, z_2(b-a)\} \le b \\ e_1|a, e_2|b \\ e_3|b+a, e_4|b-a}} \eth_k(|F(a,b)|) \ll_{\varepsilon,k} \frac{||F||^{\varepsilon} X^2 (\log X)^4}{\max\{e_1, e_2, e_3, e_4\}^{1-\varepsilon} (z_1 z_2)^{1-\varepsilon}},$$

for any $\varepsilon > 0$.

Proof. In what follows all implied constants are allowed to depend on ε and k. As in the proof of Lemma 3.5, we split the summation up into the cases $2a \leq b$ and $b \leq 2a$, and moreover we consider the cases where $\max\{e_1, e_2, e_3, e_4\} = e_i$ for some i. This leads to eight separate cases, which notate as follows.

$$\begin{array}{llll} E_{11} \colon & e_1|a, & 2a \leq b, & E_{12} \colon e_1|a, & b \leq 2a, \\ E_{21} \colon & e_2|b, & 2a \leq b, & E_{22} \colon e_2|b, & b \leq 2a, \\ E_{31} \colon & e_3|b+a, & 2a \leq b, & E_{32} \colon e_3|b+a, & b \leq 2a, \\ E_{41} \colon & e_4|b-a, & 2a \leq b, & E_{42} \colon e_4|b-a, & b \leq 2a. \end{array}$$

In the case E_{11} we may assume that $z_2 \leq 2$, since otherwise the sum vanishes as in the proof of Lemma 3.5. Here we have

$$\sum_{\substack{2a \le b \le X \\ z_1 a \le b \\ e_1 \mid a}} \eth_k(|F(a,b)|) \ll \frac{1}{z_2^{1-\varepsilon}} \sum_{\substack{b \le X \\ z_1 e_1 c \le b}} \eth_k(|F(e_1 c,b)|) \ll \frac{||F||^{\varepsilon} X^2 (\log X)^4}{e_1^{1-\varepsilon} (z_1 z_2)^{1-\varepsilon}},$$

by Lemma 3.5. The case E_{42} can also be handled in a similar manner. For the case E_{32} we

$$\sum_{\substack{a,b \leq X \\ z_2(b-a) \leq b \leq 2a \\ e_3|b+a}} \eth_k(|F(a,b)|) \ll \frac{1}{z_1^{1-\varepsilon}} \sum_{\substack{d \leq X \\ z_2c \leq d \\ e_3|d}} \eth_k(|F(d-c,d+c)|) \ll \frac{||F||^\varepsilon X^2 (\log X)^4}{e_3^{1-\varepsilon} (z_1 z_2)^{1-\varepsilon}},$$

again by Lemma 3.5. This method also handles the cases E_{21}, E_{31}, E_{12} and E_{22} , the key fact here being that the linear form which e_i divides is bounded below by b. This leaves the last case E_{41} , where we have

$$\sum_{\substack{2a \le b \le X \\ z_1 a \le b \\ e_4 \mid b-a}} \eth_k(|F(a,b)|) \ll \frac{1}{z_2^{1-\varepsilon}} \sum_{\substack{a \le d \le X \\ z_1 a \le d+a \\ e_4 \mid d}} \eth_k(|F(a,d+a)|) \ll \frac{||F||^{\varepsilon} X^2 (\log X)^4}{e_4^{1-\varepsilon} (z_1 z_2)^{1-\varepsilon}}.$$

Collecting these eight cases together completes the proof of the lemma.

4. Proof of Theorem 1.1

4.1. The conic bundle structure. As mentioned in the introduction, we begin the proof of Theorem 1.1 by utilising the fact that S has the structure of a conic bundle, at least away from the lines of S. We have the following rational map

$$S \longrightarrow \mathbb{P}^1$$
$$x \mapsto (x_0 : x_2).$$

The closure of the fibre over a point (a:b) with $ab \neq 0$ is the rational curve

$$ax_2 = bx_0$$
, $bx_2 = ax_1$, $abx_3x_4 = x_2^2(b^2 - a^2)$,

on S. To proceed we choose a representative $(a,b) \in \mathbb{Z}^2$ of $(a:b) \in \mathbb{P}^2(\mathbb{Q})$ with (a,b) = 1 and a > 0. Then we may pull back these rational curves to plane conics via the morphisms

$$\psi_{a,b}: \mathbb{P}^2 \to \mathbb{P}^4, \quad \psi_{a,b}: (x:y:z) \mapsto (a^2z:b^2z:abz:x:y),$$
 (4.1)

to get

$$N_{U}(B) = \sum_{\substack{(a,b) \in \mathbb{Z}^2 \\ ab \neq 0, a > 0 \\ (a,b) = 1}} N_{C_{a,b}}(B),$$

where

$$C_{a,b}: xy = ab(b^2 - a^2)z^2,$$

$$N_{C_{a,b}}(B) = \#\{(x:y:z) \in C_{a,b}(\mathbb{Q}) : H(\psi_{a,b}(x:y:z)) \le B, xyz \ne 0\}.$$
(4.2)

Note that here we are still using the height function H given by the embedding of S into \mathbb{P}^4

4.2. Reducing the range of summation. The next simplification is to reduce the range of summation of a and b, so that we may assume that they have roughly the same size.

Lemma 4.1. We have

$$N_U(B) = 4 \sum_{(a,b) \in A^*} N_{C_{a,b}}(B) + O\left(\frac{B(\log B)^5}{(\log \log B)^{1/3}}\right),$$

where we define

$$\mathcal{A} = \left\{ (a,b) \in \mathbb{R}^2 : \begin{array}{l} 0 < a < b \le \sqrt{B}, \\ b - a > b/\log\log B, \end{array} \right\}, \quad \mathcal{A}^* = \{(a,b) \in \mathbb{Z}^2 \cap \mathcal{A} : (a,b) = 1\}.$$

Proof. We begin by noting that

$$N_{C_{a,b}}(B) = \frac{1}{2} \# \left\{ (x, y, z) \in \mathbb{Z}^3 : \begin{array}{l} (x, y, z) = 1, xyz \neq 0, \\ xy = z^2 a b (b^2 - a^2), \\ \max\{|x|, |y|, |a^2 z|, |b^2 z|\} \leq B. \end{array} \right\}.$$

We now show that we may assume that a < b by introducing a factor of 4 into the counting problem. On noticing that the counting problem is invariant under the automorphism which negates b and x, we see that we may assume that b > 0. Similarly we may assume that b > a, since the counting problem is again invariant under the automorphism which swaps a and b and negates x. Next, by Lemma 3.3 the number of points on each conic is

$$N_{C_{a,b}}(B) \ll \tau(ab(b^2 - a^2)) \left(1 + \frac{B}{a^{1/3}b(b^2 - a^2)^{1/3}}\right).$$

However Lemma 3.5 implies that

$$\sum_{a < b < \sqrt{B}} \tau(ab(b^2 - a^2)) \ll B(\log B)^4.$$

The contribution from $a \log \log B < b$ is

$$B \sum_{\substack{a < b < \sqrt{B} \\ a \log \log B < b}} \frac{\tau(ab(b^2 - a^2))}{a^{1/3}b(b^2 - a^2)^{1/3}} \ll \frac{B(\log B)^5}{(\log \log B)^{1/3}},$$

by Lemma 3.5. Similarly, the contribution from $(b-a)\log\log B < b$ is

$$B \sum_{\substack{a < b < \sqrt{B} \\ (b-a)\log\log B < b}} \frac{\tau(ab(b^2 - a^2))}{a^{1/3}b(b^2 - a^2)^{1/3}} \ll \frac{B(\log B)^5}{(\log\log B)^{1/3}}.$$

It is worth pointing out now that minor changes to the proof of Lemma 4.1 will yield the upper bound $N_U(B) \ll B(\log B)^5$ for the counting problem. We will have to work significantly harder to get an asymptotic formula.

4.3. Parameterising the conics. In this section we count the number of points on each of the conics $C_{a,b}$, as given by (4.2). In what follows, we make frequent use of the fact that the coprimality of a and b implies that $(ab, b^2 - a^2) = 1$. We may parameterise each of the conics via the morphisms

$$\varphi_{a,b}: \mathbb{P}^1 \to C_{a,b} \subset \mathbb{P}^2, \quad \varphi_{a,b}: (y_1:y_2) \mapsto (aby_1^2: (b^2 - a^2)y_2^2: y_1y_2).$$

Passing to the affine cone yields

$$N_{C_{a,b}}(B) = 2\# \{ \mathbf{y} \in \mathbb{N}^2 : (y_1, y_2) = 1, H(\psi_{a,b}(\varphi_{a,b}(\mathbf{y}))) \le B \},$$

where $\psi_{a,b}$ is given by (4.1). To simplify notation we define

$$M_{a,b}(\mathbf{y}) = \max\{b^2 y_1 y_2, ab y_1^2, (b^2 - a^2) y_2^2\},\tag{4.3}$$

to get

$$N_U(B) = 8N(B) + O\left(\frac{B(\log B)^5}{(\log \log B)^{1/3}}\right),$$

where

$$N(B) = \sum_{(a,b)\in A^*} \# \left\{ \mathbf{y} \in \mathbb{N}^2 : \begin{array}{l} (y_1, y_2) = 1, \\ M_{a,b}(\mathbf{y}) \le (y_1, b^2 - a^2)(y_2, ab)B \end{array} \right\}.$$
 (4.4)

Applying Möbius inversion, we find that

$$N(B) = \sum_{\substack{(a,b) \in \mathcal{A}^* \\ \lambda_1 \mid (b^2 - a^2) \\ \lambda_2 \mid ab}} \left\{ \mathbf{y} \in \mathbb{N}^2 : \begin{array}{l} (y_1, y_2) = 1, \lambda_i \mid y_i, \\ (y_1/\lambda_1, (b^2 - a^2)/\lambda_1) = 1, \\ (y_2/\lambda_2, ab/\lambda_2) = 1, \\ M_{a,b}(\mathbf{y}) \leq \lambda_1 \lambda_2 B. \end{array} \right\}$$
$$= \sum_{\substack{(a,b) \in \mathcal{A}^* \\ k_1 \lambda_1 \mid (b^2 - a^2) \\ k_2 \lambda_2 \mid ab}} \sum_{\mu(k_1 k_2) \#} \left\{ \mathbf{y} \in \mathbb{N}^2 : \begin{array}{l} (y_1, y_2) = 1, k_i \lambda_i \mid y_i, \\ M_{a,b}(\mathbf{y}) \leq \lambda_1 \lambda_2 B. \end{array} \right\}.$$

Our next step is to restrict the range of summation of the λ_i and k_i , to make explicit the size constraints implied by the expression $M_{a,b}(\mathbf{y}) \leq \lambda_1 \lambda_2 B$.

Lemma 4.2. For any $\varepsilon > 0$ we have

$$N(B) = \sum_{\substack{(a,b) \in \mathcal{A}^* \\ \lambda_1 k_1 | (b^2 - a^2) \\ k_1 k_2 \le K}} \mu(k_1 k_2) \# \left\{ \mathbf{y} \in \mathbb{N}^2 : \begin{array}{l} (y_1, y_2) = 1, k_i \lambda_i | y_i \\ M_{a,b}(\mathbf{y}) \le \lambda_1 \lambda_2 B \end{array} \right\} + O_{\varepsilon} \left(B(\log B)^{4+\varepsilon} \right),$$

where $K = (\log B)^{1000}$ and the summation is subject to the condition

$$\frac{b^2 K^2}{B} \le \frac{k_1 \lambda_1}{k_2 \lambda_2} \le \frac{B}{b^2 K^2}.$$
 (4.5)

Proof. We first consider the contribution from $\max\{k_1, k_2\} \geq K$. In this case we may use Lemma 3.2 to count the number of y_i 's, to get an upper bound

$$\sum_{\substack{(a,b)\in\mathcal{A}^* \ \lambda_1 k_1 | (b^2 - a^2) \\ \lambda_2 k_2 | ab \\ k_1 k_2 > K}} \frac{B}{\sqrt{ab(b^2 - a^2)} k_1 k_2} \ll \frac{B(\log\log B)^2}{K} \sum_{a < b \le \sqrt{B}} \frac{\tau^2 (ab(b^2 - a^2))}{b^2} \ll B,$$

by Lemma 3.5. We now show that we may restrict the range of summation to $k_1\lambda_1/k_2\lambda_2 \le B/b^2K^2$, the lower bound being achieved in an analogous manner. Note that since $M_{a,b}(\mathbf{y}) \le \lambda_1\lambda_2B$ and $k_i\lambda_i|y_i$ for i=1,2, we deduce that we need only consider the contribution from

$$\frac{B}{b^2K^2} \le \frac{k_1\lambda_1}{k_2\lambda_2} \le \frac{k_1^2\lambda_1}{\lambda_2} \le \frac{B}{ab}.$$
(4.6)

Using Lemma 3.2 again and summing over dyadic intervals we see that the contribution from (4.6) is

$$\ll B(\log\log B)^2 \sum_{\substack{(a,b)\in\mathcal{A}^*\\\lambda_1k_1|(b^2-a^2)\\\lambda_2k_2|ab\\k_1,k_2\leq K\\(4.6)\text{ holds}}} \frac{1}{k_1k_2b^2} \ll B(\log\log B)^4 \sum_{\substack{A\ll B\\L_1,L_2\ll A^2\\A,L_1,L_2\in 2^{\mathbb{N}}\\(4.7)\text{ holds}}} \frac{1}{A^2} \sum_{\substack{(a,b)\in\mathcal{A}^*\\\lambda_1|(b^2-a^2)\\\lambda_2|ab}} \sum_{\substack{\lambda_i\asymp L_i\\\lambda_1|(b^2-a^2)\\\lambda_2|ab}} 1,$$

where the sum is subject to the condition

$$\frac{B}{A^2K^3} \ll \frac{L_1}{L_2} \ll \frac{BK^2}{A^2}. (4.7)$$

As in the Dirichlet hyperbola method, if $\lambda_2 \geq A$, say, then we may write $\mu_2 = ab/\lambda_2$ and choose to sum over μ_2 instead. Since $\lambda_2 \approx L_2$ and $a \leq b$, we see that $\mu_2 \ll A^2/L_2 \ll A$ and $\mu_2 \gg A^2/(L_2 \log \log B)$. Using a similar trick with λ_1 gives

$$\ll B(\log \log B)^{4} \sum_{\substack{A \ll B \\ L_{1}, L_{2} \ll A^{2} \\ A, L_{1}, L_{2} \in 2^{\mathbb{N}} \\ (4.7) \text{ holds}}} \frac{1}{A^{2}} \sum_{\substack{\lambda_{i} \ll f_{2}(L_{i}, A) \\ \lambda_{i} \gg f_{1}(L_{i}, A)}} \sum_{\substack{b \asymp A \\ (a, b) \in \mathcal{A}^{*} \\ \lambda_{1} \mid (b^{2} - a^{2}) \\ \lambda_{2} \mid ab}} 1, \tag{4.8}$$

where

$$f_1(L_i, A) = \min \left\{ L_i, \frac{A^2}{L_i(\log \log B)} \right\}, \quad f_2(L_i, A) = \min \left\{ L_i, \frac{A^2}{L_i} \right\}.$$

However we have

$$\sum_{\substack{b \asymp A \\ (a,b) \in \mathcal{A}^* \\ \lambda_1 \mid (b^2 - a^2) \\ \lambda_2 \mid ab}} 1 \ll \sum_{\substack{\lambda_1 = e'e_1e_2 \\ \lambda_2 = e_3e_4 \\ e' = (\lambda_1,b+a,b-a)}} \sum_{\substack{\lambda_1 = e'e_1e_2 \\ \lambda_2 \in a_2e_4 \\ (a,b) \in \Gamma_{\mathbf{e}} \\ \lambda_2 = e_3e_4 \\ (e_i,e_j) = 1 \\ (e_i,e_j) = 1 \\ (e' \mid 2,i \neq j)} 1,$$

where we write $\Gamma_{\mathbf{e}} = \{\mathbf{x} \in \mathbb{Z}^2 : e_1 | (b+a), e_2 | (b-a), e_3 | a, e_4 | b \}$. The coprimality of e_i with e_j for $i \neq j$ ensures that the lattice $\Gamma_{\mathbf{e}}$ can be written as the intersection of four lattices with coprime determinants e_1, e_2, e_3 and e_4 respectively. Thus Lemma 3.2 implies that

$$\sum_{\substack{b \asymp A \\ (a,b) \in \mathcal{A}^* \\ \lambda_1 | (b^2 - a^2) \\ \lambda > | ab}} 1 \ll \sum_{\substack{\lambda_1 = e'e_1e_2 \\ \lambda_2 = e_3e_4 \\ e' | 2}} \left(\frac{A^2}{e_1e_2e_3e_4} + 1 \right) \ll \frac{\tau(\lambda_1)\tau(\lambda_2)A^2}{\lambda_1\lambda_2},$$

since $\lambda_i \ll A$. Hence we find that (4.8) is bounded above by

$$B(\log \log B)^4 \sum_{\substack{A \ll B \\ L_1, L_2 \ll A^2 \\ A, L_1, L_2 \in 2^{\mathbb{N}} \\ (4.7) \text{ holds}}} \sum_{\substack{\lambda_i \ll f_2(L_i, A) \\ \lambda_i \gg f_1(L_i, A)}} \frac{\tau(\lambda_1)\tau(\lambda_2)}{\lambda_1\lambda_2} \ll B(\log B)^2 (\log \log B)^4 \sum_{\substack{A, L_1, L_2 \ll B \\ A, L_1, L_2 \in 2^{\mathbb{N}} \\ (4.7) \text{ holds}}} 1.$$

The sum over those L_1 satisfying (4.7) contributes $O(\log \log B)$, and the sum over A and L_2 gives $O((\log B)^2)$, which is satisfactory for the lemma.

We emphasise now that the condition (4.5) is very important to our work. It is crucial for the handling of the error term in Lemma 4.3, and it is this condition which forced us to consider a restricted divisor function in our work in Section 2, rather than the usual divisor function. Intriguingly, there is a purely geometrical interpretation for its appearance. We shall see in the proof of Lemma 4.5 that it contributes towards the constant $\alpha(\widetilde{S})$ appearing in the leading constant in Section 1.1.

We are now ready to handle the summation over y_1 and y_2 .

Lemma 4.3. For any $\varepsilon > 0$ we have

$$N(B) = B \sum_{\substack{(a,b) \in \mathcal{A}^* \\ \ell \le B}} \frac{f(b/a)}{b^2} \sum_{\substack{\lambda_1 k_1 | (b^2 - a^2) \\ \lambda_2 k_2 | ab \\ (4.5) \ holds}} \frac{\mu(k_1 k_2) \mu(\ell) (\ell, k_1 k_2 \lambda_1 \lambda_2)}{\ell^2 k_1 k_2} + O_{\varepsilon} \left(B(\log B)^{4+\varepsilon} \right),$$

where for $\theta > 1$ we let

$$f(\theta) = \text{vol} \left\{ \mathbf{y} \in \mathbb{R}^2_{>0} : \begin{array}{l} y_1 y_2 \le 1, \\ y_1^2 \le \theta, y_2^2 \le \theta^2 / (\theta^2 - 1) \end{array} \right\}.$$

Proof. Removing the coprimality conditions by Möbius inversion, the main term given by Lemma 4.2 has the form

$$\sum_{\substack{(a,b)\in\mathcal{A}^*\\\ell\leq B}} \sum_{\substack{\lambda_1k_1|(b^2-a^2)\\\lambda_2k_2|ab\\k_1,k_2\leq K\\(4.5)\text{ holds}}} \mu(k_1k_2)\mu(\ell)\# \left\{ \mathbf{y}\in\mathbb{N}^2: \begin{array}{l} [\ell,k_i\lambda_i]|y_i,i=1,2,\\M_{a,b}(\mathbf{y})\leq\lambda_1\lambda_2B \end{array} \right\}.$$

Letting $Y = \lambda_1 \lambda_2 B/b^2$, $q_i = [\ell, k_i \lambda_i]$, $\theta = b/a$ and recalling the definition of $M_{a,b}(\mathbf{y})$ given in (4.3), we see that the number of (y_1, y_2) is

$$\# \left\{ \mathbf{y} \in \mathbb{N}^2 : y_1^2 \le Y\theta, y_1 y_2 \le Y \\ y_2^2 \le Y\theta^2/(\theta^2 - 1) \right\}.$$
(4.9)

The first successive minimum of the lattice in (4.9) is clearly $\min\{q_1,q_2\}$, and one can check that the boundary of the region in question has length $\ll \sqrt{Y\theta} + \sqrt{Y(\theta^2/(\theta^2-1)}$. It follows from Lemma 3.1 that (4.9) equals

$$\frac{Yf(b/a)}{q_1q_2} + O\left(\frac{\log\log B\sqrt{\lambda_1\lambda_2B}}{b\min\{q_1,q_2\}}\right).$$

In order to handle the error term, we only consider the case $[\ell, k_1 \lambda_1] \leq [\ell, k_2 \lambda_2]$, the other case being dealt with in almost exactly the same manner. The error term here contributes

$$\sqrt{B} \log \log B \sum_{\substack{(a,b) \in \mathcal{A}^* \\ \ell \le B}} \sum_{\substack{\lambda_1 k_1 \mid (b^2 - a^2) \\ \lambda_2 k_2 \mid ab \\ k_1, k_2 \le K \\ (4.5) \text{ holds}}} \frac{(\ell, k_1 \lambda_1) \sqrt{\lambda_2}}{b\ell k_1 \sqrt{\lambda_1}}$$

$$\ll \sqrt{B} \log B \sum_{\substack{(a,b) \in \mathcal{A}^* \\ \ell \le B}} \sum_{\substack{\lambda_1 k_1 \mid (b^2 - a^2) \\ \lambda_2 k_2 \mid ab \\ (4.5) \text{ holds}}} \sum_{\substack{d\sqrt{k_2 \lambda_2} \\ b\ell \sqrt{k_1 \lambda_1}}} \frac{d\sqrt{k_2 \lambda_2}}{b\ell \sqrt{k_1 \lambda_1}}$$

$$\ll \frac{B(\log B)^2}{K} \sum_{\substack{(a,b) \in \mathcal{A}^* \\ \lambda_1 k_1 \mid (b^2 - a^2) \\ \lambda_2 k_2 \mid ab}} \frac{\tau(k_1 \lambda_1)}{b^2},$$

by (4.5). Moreover, it is clear on applying Lemma 3.5 that this is bounded above by O(B), since we chose K in Lemma 4.2 to be a very large power of a logarithm. We finish the proof by showing that we may extend the sum over the k_i to infinity. We note that by Lemma 4.1 we have the upper bound

$$f(b/a) \le \frac{\sqrt{b}}{\sqrt{a}} \cdot \frac{b}{\sqrt{b^2 - a^2}} \le \log \log B.$$
 (4.10)

Hence by Lemma 3.5, the contribution to the main term from $\max\{k_1, k_2\} \geq K$ is

$$\ll \frac{B \log \log B}{K} \sum_{\substack{(a,b) \in \mathcal{A}^* \\ \ell \le B}} \frac{1}{b^2} \sum_{\substack{\lambda_1 k_1 | (b^2 - a^2) \\ \lambda_2 k_2 | ab}} \frac{(\ell, k_1 k_2 \lambda_1 \lambda_2)}{\ell^2} \\
\ll \frac{B (\log B)^2}{K} \sum_{\substack{a < b \le \sqrt{B}}} \frac{\tau^2 (ab(b^2 - a^2))}{b^2} \ll B,$$

which is satisfactory.

4.4. The restricted divisor problem. It now remains to deal with the main term of $N_U(B)$, which by Lemma 4.3 has the form

$$8B \sum_{\substack{(a,b)\in\mathcal{A}^*\\\ell\leq B}} \frac{f(b/a)}{b^2} \sum_{\substack{\lambda_1k_1|(b^2-a^2)\\\lambda_2k_2|ab\\(4.5)\text{ holds}}} \frac{\mu(k_1k_2)\mu(\ell)(\ell,k_1k_2\lambda_1\lambda_2)}{\ell^2k_1k_2},\tag{4.11}$$

where f is as given in Lemma 4.3 and \mathcal{A}^* is as in Lemma 4.1. Our aim is to get this into the form of a restricted divisor sum, so that we may use the work in Section 2. Before we do this however, we need to introduce some notation. Define a multiplicative function h by

$$h(p^a) = \frac{2\mu(p^a)}{p+1},\tag{4.12}$$

for any prime p and $a \in \mathbb{N}$. We then define linear forms

$$\ell_1(a,b) = a, \quad \ell_2(a,b) = b, \quad \ell_3(a,b) = b + a, \quad \ell_4(a,b) = b - a.$$
 (4.13)

As in Secion 2, we shall also be interested in the lattice $\Gamma_{\mathbf{d}}$, defined for any $\mathbf{d} \in \mathbb{N}^4$ by

$$\Gamma_{\mathbf{d}} = \left\{ \mathbf{x} \in \mathbb{Z}^2 : d_i | \ell_i(\mathbf{x}), (i = 1, 2, 3, 4) \right\}.$$
 (4.14)

Lemma 4.4. We have

$$N_{U}(B) = \frac{8B}{\zeta(2)} \sum_{\substack{\mathbf{e} \in \mathbb{N}^{5} \\ v \in \mathbb{N}}} h(er)\mu(v) \sum_{\substack{r,s|2 \\ (er,s)=e_0}} \mu(r)\mu(s)F(\mathbf{e},r,s,v,B) + O\left(\frac{B(\log B)^{5}}{(\log \log B)^{1/3}}\right),$$

where we write $\mathbf{e} = (e_0, e_1, e_2, e_3, e_4)$ and $e = e_0 e_1 e_2 e_3 e_4$. Here

$$F(\mathbf{e}, r, s, v, B) = \sum_{\substack{(a,b) \in \Gamma_{\mathbf{m}} \cap \mathcal{A} \\ e_i d_i \mid \ell_i(a,b)}} \frac{f(b/a)}{b^2} \sum_{\substack{i \in \{1,2\} \\ e_i d_i \mid \ell_i(a,b)}} \sum_{\substack{j \in \{3,4\} \\ rse_j d_j \mid \ell_j(a,b) \\ (4.15) \ holds}} 1,$$

where we let

$$\mathbf{m} = ([e_1, v], [e_2, v], rse_3, rse_4),$$

and the sum is subject to the condition

$$\frac{b^2K^2}{B} \le \frac{e_1e_2d_1d_2}{r^2se_3e_4d_3d_4} \le \frac{B}{b^2K^2}. (4.15)$$

Proof. We first simplify (4.11) by performing the summation over ℓ . This is achieved by noting that

$$\sum_{\ell=1}^{\infty} \frac{\mu(\ell)(\ell, k_1 k_2 \lambda_1 \lambda_2)}{\ell^2} = \prod_{p} \left(1 - \frac{(p, k_1 k_2 \lambda_1 \lambda_2)}{p^2} \right) = \frac{1}{\zeta(2) \varphi^{\dagger}(k_1 k_2 \lambda_1 \lambda_2)},$$

where

$$\varphi^{\dagger}(n) = \prod_{p|n} \left(1 + \frac{1}{p}\right).$$

By (4.10) the contribution from $\ell \geq B$ is

$$\ll_{\varepsilon} B^{1+\varepsilon} \sum_{\substack{(a,b) \in \mathcal{A}^* \\ \ell \geq B}} \frac{1}{b^2} \sum_{\substack{\lambda_1 k_1 | (b^2 - a^2) \\ \lambda_2 k_2 | ab}} \frac{(\ell, k_1 k_2 \lambda_1 \lambda_2)}{\ell^2 k_1 k_2} \ll_{\varepsilon} B^{\varepsilon} \sum_{a < b \leq B} \frac{1}{b^2} \ll_{\varepsilon} B^{\varepsilon} (\log B),$$

for any $\varepsilon > 0$. So on referring to (4.11), we see that we may write

$$N_U(B) = \frac{8B}{\zeta(2)} \sum_{(a,b) \in \mathcal{A}^*} \frac{f(b/a)\Theta(a,b)}{b^2} + O\left(\frac{B(\log B)^5}{(\log \log B)^{1/3}}\right),$$

where

$$\Theta(a,b) = \sum_{\substack{\lambda_1 k_1 | (b^2 - a^2) \\ \lambda_2 k_2 | ab \\ (4.5) \text{ holds}}} \frac{\mu(k_1 k_2)}{\varphi^{\dagger}(k_1 k_2 \lambda_1 \lambda_2) k_1 k_2}.$$

If I(d;X) denotes the characteristic function of the set $\{d \in \mathbb{R}_{>0} : 1/X \le d \le X\}$, then we have

$$\Theta(a,b) = \sum_{\substack{d_1|ab\\d_2|(b^2-a^2)}} \frac{I\left(\frac{d_1}{d_2}; \frac{B}{b^2K^2}\right)}{\varphi^{\dagger}(d_1d_2)} \sum_{k_i|d_i} \frac{\mu(k_1k_2)}{k_1k_2}$$

$$= \sum_{\substack{d_1|ab\\d_2|(b^2-a^2)}} I\left(\frac{d_1}{d_2}; \frac{B}{b^2K^2}\right) \sum_{e|d_1d_2} h(e),$$

where h is given by (4.12). Also note that for any arithmetic function g we have

$$\sum_{d|n_1 n_2} g(d) = \sum_{k|n_1, n_2} \mu(k) \sum_{k d_i | n_i} g(k d_1 d_2). \tag{4.16}$$

Using this we find that

$$\Theta(a,b) = \sum_{\substack{d_i | \ell_i(a,b) \\ sd_4 | b-a}} \sum_{\substack{sd_3 | b+a \\ sd_4 | b-a}} \mu(s) \sum_{\substack{e | sd_1 d_2 d_3 d_4}} h(e) I\left(\frac{d_1 d_2}{sd_3 d_4}; \frac{B}{b^2 K^2}\right),$$

where the ℓ_i are given by (4.13). Using (4.16) again we have

$$\Theta(a,b) = \sum_{\substack{e \in \mathbb{N} \\ d_i | \ell_i(a,b)}} \sum_{\substack{sd_3 | b+a \\ sd_4 | b-a}} \mu(s) \sum_{\substack{e=e_0e_1e_2e' \\ e_1 | d_1,e_2 | d_2 \\ e' | d_3d_4 \\ (e,s)=e_0}} h(e)I\left(\frac{d_1d_2}{sd_3d_4}; \frac{B}{b^2K^2}\right)$$

$$= \sum_{\substack{e \in \mathbb{N} \\ d_i | \ell_i(a,b)}} \sum_{\substack{sd_3 | b+a \\ sd_4 | b-a}} \mu(s) \sum_{\substack{e=e_0e_1e_2e_3e_4 \\ e_1 | d_1,e_2 | d_2 \\ re_3 | d_3,re_4 | d_4 \\ (er,s)=e_0}} h(er)\mu(r)I\left(\frac{d_1d_2}{sd_3d_4}; \frac{B}{b^2K^2}\right).$$

We now make the change of variables

$$d_1 \mapsto e_1 d_1, \quad d_2 \mapsto e_2 d_2, \quad d_3 \mapsto re_3 d_3, \quad d_4 \mapsto re_4 d_4,$$

which allows us to move the summation over e, r, s to the outside, as in the statement of the lemma. Note that r, s|2 since (a, b) = 1 implies that (b + a, b - a)|2. The proof of the lemma is then complete on removing the coprimality condition on a and b.

The main term of $N_U(B)$ is now written so that it visibly involves a restricted divisor sum, which we may handle using Corollary 2.2.

Lemma 4.5. We have

$$N_U(B) = \alpha(\widetilde{S})\tau_{\infty}B(\log B)^5 \prod_p \left(1 - \frac{1}{p}\right)^5 \left(1 + \frac{1}{p}\right)\sigma_p\left(1 + o(1)\right),$$

where for every prime p we let

$$\sigma_p = \sum_{\substack{\boldsymbol{\epsilon} \in \{0,1\}^5 \\ 0 \le \nu \le 1}} \sum_{\substack{0 \le \varrho, \sigma \le \nu_2(p) \\ 0 \le \epsilon - \epsilon_0 + \varrho + \sigma \le 1 \\ 0 \le \epsilon_0 \le \sigma}} \sum_{\substack{\mathbf{k} \in \mathbb{Z}_{\ge 0}^4 \\ \rho_0\left(p^{\max\{\nu, N_1\}}, p^{\max\{\nu, N_2\}}, p^{N_3}, p^{N_4}\right)},$$

where we write $\boldsymbol{\epsilon} = (\epsilon_0, \epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4)$ and $\boldsymbol{\epsilon} = \sum_{i=0}^4 \epsilon_i$. Here ν_2 denotes the 2-adic valuation, $\boldsymbol{\epsilon}$ is given by (4.12) and $\rho_0(\mathbf{d}) = \det \Gamma_{\mathbf{d}}$, where $\Gamma_{\mathbf{d}}$ is given by (4.14). Also

$$N_i = \epsilon_i + k_i, \qquad i \in \{1, 2\},$$

$$N_j = \varrho + \sigma + \epsilon_j + k_j, \quad j \in \{3, 4\},$$

and $\alpha(\widetilde{S})$ and τ_{∞} are the factors appearing in the leading constant of Manin's conjecture as described in Section 1.1.

Proof. We begin by letting

$$\mathcal{A}(\mathbf{y}) = \left\{ (a, b) \in \mathcal{A} : \frac{ay_1^2}{b} \le 1, \left(1 - \frac{a^2}{b^2}\right) y_2^2 \le 1 \right\}.$$

Then, recalling the definition of f given in Lemma 4.3, and using the same notation as Lemma 4.4, we see that we have

$$F(\mathbf{e}, r, s, v, B) = \int_{\substack{y_1 y_2 \le 1, \\ 0 \le y_i \le \log \log B}} \sum_{\substack{(a,b) \in \Gamma_{\mathbf{m}} \cap \mathcal{A}(\mathbf{y})}} \frac{1}{b^2} \sum_{\substack{i \in \{1,2\} \\ e_i d_i \mid \ell_i(a,b)}} \sum_{\substack{j \in \{3,4\} \\ rse_j d_j \mid \ell_j(a,b)}} d\mathbf{y}.$$

We can now apply Corollary 2.2 where we take $X = \sqrt{B}$, $\mathcal{R} = \mathcal{A}(\mathbf{y})/X$, $\Lambda = \Gamma_{\mathbf{m}}$ and V' = V'(e, r, s) to be the set corresponding to (4.15). This gives

$$F(\mathbf{e}, r, s, v, B) = \frac{\prod_{p} C_{p}(\mathbf{m})(\log B)^{5}}{2^{4} \det \Gamma_{\mathbf{m}}} \int_{\substack{y_{1}y_{2} \leq 1, \\ 0 \leq y_{i} \leq \log \log B}} C'_{\infty} d\mathbf{y} + O_{\mathbf{e}, r, s, v}((\log B)^{4+\varepsilon}),$$

where

$$C'_{\infty} = \operatorname{vol} \mathcal{R} \int_{\substack{u \in [0,1] \\ \boldsymbol{\eta} \in [1,u]^4}} \chi_{V'}(\boldsymbol{\eta}, u) d\boldsymbol{\eta} du, \quad C_p(\mathbf{m}) = \left(1 - \frac{1}{p}\right)^4 \sum_{\mathbf{k} \in \mathbb{Z}^4_{>0}} \frac{\det \Gamma_{\mathbf{m}}}{\det \Gamma_{\mathbf{m}}(p^{k_1}, p^{k_2}, p^{k_3}, p^{k_4})}.$$

We begin by simplifying the non-archimedean factor. Here, unraveling definitions we find that

$$\Gamma_{\mathbf{m}}(\mathbf{d}) = \left\{ \mathbf{x} \in \Gamma_{\mathbf{m}} : \begin{array}{ll} d_i | \ell_i(\mathbf{x}) / e_i, & i = 1, 2, \\ d_j | \ell_j(\mathbf{x}) / rse_j, & j = 3, 4. \end{array} \right\}.$$

Recalling the definition of **m** in Lemma 4.4 and noticing that [[e, v], ed] = [v, ed] for any $e, v, d \in \mathbb{N}$, we see that

$$\Gamma_{\mathbf{m}}(\mathbf{d}) = \left\{ \mathbf{x} \in \mathbb{Z}^2 : \begin{array}{ll} [v, e_i d_i] | \ell_i(\mathbf{x}), & i = 1, 2, \\ rse_j d_j | \ell_j(\mathbf{x}), & j = 3, 4. \end{array} \right\}.$$

Thus we deduce that $C_p(\mathbf{m})(1-1/p^2) = \sigma_p$, on taking the Euler product of the sum over \mathbf{e}, r, s, v in Lemma 4.4. For the archimedean factor we have

$$\int_{\substack{y_1 y_2 \le 1 \\ 0 \le y_1, y_2 \le \log \log B}} \operatorname{vol} \mathcal{R} d\mathbf{y} = \int_{\substack{y_1 y_2 \le 1 \\ y_1, y_2 \ge 0}} \int_{\substack{0 < a < b < 1 \\ ay_1^2 \le b \le a \log \log B \\ (1 - a^2/b^2)y_2^2 \le 1 \\ b < (b - a) \log \log B}} da db d\mathbf{y}.$$
(4.17)

Performing the integration over \mathbf{y} , we see that the contribution from $b \geq a \log \log B$ is bounded above by

$$\int_{\substack{0 < a < b < 1\\ a \log \log B \le b}} \frac{b^{3/2}}{(a(b^2 - a^2))^{1/2}} dadb \ll \frac{1}{(\log \log B)^{1/2}}.$$

While the contribution from $b \ge (b-a) \log \log B$ is handled in a similar manner. Hence making the change variables $y_0 = a/b$ and evaluating the integral over b, we see that (4.17) is equal to

$$\frac{1}{2} \int_{\substack{y_1 y_2 \le 1 \\ y_1, y_2 \ge 0}} \int_{\substack{0 < y_0 < 1 \\ y_0 y_1^2 \le 1 \\ (1 - y_0^2) y_2^2 \le 1}} d\mathbf{y} + O\left(\frac{1}{(\log \log B)^{1/2}}\right).$$

We now use the change of variables

$$x_0 = y_0^2 y_1 y_2$$
, $x_1 = y_1 y_2$, $x_3 = y_0 y_1^2$,

to see that (4.17) equals

$$\frac{1}{2} \int_{\{\mathbf{x} \in \mathbb{R}^3 : 0 < x_0/x_1, x_1, x_3, x_0 x_1(x_1 - x_0)^2 / x_3^2 \le 1\}} \frac{\mathrm{d}x_0 \mathrm{d}x_1 \mathrm{d}x_3}{4(x_0 x_1)^{1/2} x_3} = \frac{\tau_{\infty}}{32}.$$

For the alpha constant, note that we have

$$\int_{\substack{u \in [0,1]\\ \boldsymbol{\eta} \in [1,u]^4}} \chi_{V'}(\boldsymbol{\eta}, u) d\boldsymbol{\eta} du = \int_{\substack{u \in [0,1]\\ \boldsymbol{\eta} \in [1,u]^4}} \chi_{V''}(\boldsymbol{\eta}, u) d\boldsymbol{\eta} du + O_{\mathbf{e},r,s} \left(\frac{1}{\log \log B}\right),$$

where now

$$V'' = \{(\boldsymbol{\eta}, u) \in [0, 1]^5 : 2u - 2 \le \eta_1 + \eta_2 - \eta_3 - \eta_4 \le 2 - 2u\}.$$

We are thus lead to calculate the volume of some rational polytope. One can use [Fra09], for example, to find that

$$\int_{\substack{u \in [0,1] \\ \boldsymbol{\eta} \in [1,u]^4}} \chi_{V''}(\boldsymbol{\eta}, u) d\boldsymbol{\eta} du = \frac{4}{45} = 64\alpha(\widetilde{S}).$$

It thus remains to show that we may control our non-uniform error when we sum over e, r, s and v. To do this, we use an argument based on the dominated convergence theorem, reminiscent of Heath-Brown [HB03, Lem. 6.1]. Let

$$\mathcal{E}(\mathbf{e}, r, s, v; B) = \frac{F(\mathbf{e}, r, s, v, B)}{(\log B)^5} - \frac{\alpha(\widetilde{S})\tau_{\infty} \prod_{p} C_{p}(\mathbf{m})}{8 \det \Gamma_{\mathbf{m}}}.$$

For fixed \mathbf{e}, r, s and v we have shown that $\mathcal{E}(\mathbf{e}, r, s, v; B) \to 0$ as $B \to \infty$. So in order to finish the proof the lemma, we need to show the dominated convergence of the sum

$$\sum_{\substack{\mathbf{e} \in \mathbb{N}^5 \\ v \in \mathbb{N}}} \sum_{\substack{r,s|2 \\ (er,s)=e_0}} |h(er)\mu(r)\mu(s)\mu(v)\mathcal{E}(\mathbf{e},r,s,v;B)|, \tag{4.18}$$

where as before we write $e = e_0 e_1 e_2 e_3 e_4$. I claim that it is sufficient to give the upper bound

$$\mathcal{E}(\mathbf{e}, r, s, v; B) \ll_{\varepsilon} \frac{1}{e^{\varepsilon} v^{1+\varepsilon}},$$

for any $\varepsilon > 0$. Indeed, in this case (4.18) is bounded above by

$$\sum_{\substack{\mathbf{e} \in \mathbb{N}^5 \\ v \in \mathbb{N}}} \frac{|h(e)\mu(v)|}{e^{\varepsilon}v^{1+\varepsilon}} \ll_{\varepsilon} \sum_{\substack{\mathbf{e} \in \mathbb{N}^5 \\ v \in \mathbb{N}}} \frac{1}{e^{1+\varepsilon}v^{1+\varepsilon}} \ll_{\varepsilon} 1,$$

since we have $h(e) \ll 1/e$ by definition. We note that we have

$$\mathcal{E}(\mathbf{e}, r, s, v; B) \ll \frac{1}{(\log B)^5} \sum_{\substack{(a, b) \in \Gamma_{\mathbf{m}} \\ a < b \le \sqrt{B}}} \frac{f(b/a) \eth_4(ab(b^2 - a^2))}{b^2} + \frac{\prod_p |C_p(\mathbf{m})|}{\det \Gamma_{\mathbf{m}}},$$

where \eth_4 is given by (3.2). The upper bound $\prod_p |C_p(\mathbf{m})| \ll (ev)^{\varepsilon}$ follows from Theorem 2.1. By Lemma 2.3, we know that $\det \Gamma_{\mathbf{m}} \gg [e, v^2]$, since $(e_i, e_j) = 1$ for all $i \neq j$ as e is square-free. On the other hand, we have

$$\sum_{\substack{(a,b)\in\Gamma_{\mathbf{m}}\\a< b\leq \sqrt{B}}} \frac{f(b/a)\eth_4(ab(b^2-a^2))}{b^2} \ll \int_{y_1,y_2>0} \int_1^{\sqrt{B}} \frac{1}{t^3} \sum_{\substack{(a,b)\in\Gamma_{\mathbf{m}}\\a< b\leq t\\ \max\{y_1^2a,(b-a)y_2^2\}\leq b}} \eth_4\left(ab(b^2-a^2)\right) \mathrm{d}t \mathrm{d}\mathbf{y}.$$

Thus the result follows after making the change of variables a = a'v, b = b'v, and applying Lemma 3.6 to deduce that for any t > 1 we have

$$\sum_{\substack{(a,b)\in\Gamma_{\mathbf{m}}\\ a< b\leq t\\ \max\{y_1^2a,(b-a)y_2^2\}\leq b}} \eth_4\left(ab(b^2-a^2)\right) \ll_{\varepsilon} \frac{t^2(\log t)^4}{\max\{1,y_1^2\}\max\{1,y_2^2\}||\mathbf{e}||^{1-\varepsilon}v^{2-\varepsilon}}.$$

4.5. **The local densities.** To complete the proof of Theorem 1.1, it remains to show that for any prime p we have

$$\left(1 - \frac{1}{p}\right)^5 \left(1 + \frac{1}{p}\right) \sigma_p = \tau_p, \tag{4.19}$$

where τ_p is given in Section 1.1 and σ_p in Lemma 4.5. In order to do this, we need to have an explicit expression for the function ρ_0 defined in Lemma 4.5.

Lemma 4.6. Let p be a prime and let $\mathbf{e} \in \mathbb{Z}^4_{\geq 0}$. If p = 2 and $\min\{e_3, e_4\} > \max\{e_1, e_2\}$ then

$$\rho_0(2^{e_1}, 2^{e_2}, 2^{e_3}, 2^{e_4}) = 2^{e_3 + e_4 - 1}.$$

Otherwise

$$\rho_0(p^{e_1}, p^{e_2}, p^{e_3}, p^{e_4}) = p^{e_{\sigma(1)} + e_{\sigma(2)}}$$

where we have chosen a permutation σ such that $e_{\sigma(1)} \geq e_{\sigma(2)} \geq e_{\sigma(3)} \geq e_{\sigma(4)}$.

Proof. By Lemma 2.3, we see that we need only consider the case p=2. Moreover the same method given there works if $\min\{e_3,e_4\} \leq \max\{e_1,e_2\}$, thus we may assume that $\min\{e_3,e_4\} > \max\{e_1,e_2\}$. When $e_3 \geq e_4$, it is sufficient to show that $2^{e_3}|(b+a)$ and $2^{e_4}|(b-a)$ if and only if $2^{e_3}|(b+a), 2^{e_4-1}|b$ and $2^{e_4-1}|a$. Indeed, this lattice has determinant $2^{e_3+e_4-1}$.

For the first implication, we have $2^{e_3}|(b+a)$ and $2^{e_4}|(b-a)$ clearly implies that $2^{e_4}|2b$ and $2^{e_4}|2a$, as required. For the other implication, assume that $2^{e_3}|(b+a), 2^{e_4-1}|b, 2^{e_4-1}|a$ and write $a=2^{e_4-1}a'$ and $b=2^{e_4-1}b'$. Then $2^{e_3-e_4+1}|(b'+a')$, and hence a' and b' share the same parity so 2|(b'-a'). Hence $2^{e_4}|(b-a)$ as required. The proof in the case $e_4 \geq e_3$ works in a similar manner.

Now let p be any prime. In order to show (4.19), we split the summation over the N_i (in the notation of Lemma 4.5) into various cases. First, the contribution from the case where $N_i = 0$ for all i = 1, 2, 3, 4 is

$$\sum_{0 \le \nu \le 1} \frac{(-1)^{\nu}}{\rho_0(p^{\nu}, p^{\nu}, 1, 1)} = 1 - \frac{1}{p^2}.$$

Next, we handle the case where $N_i \ge 1$ for some i and $N_j = 0$ for all $i \ne j$. Note that since $N_3 = 0$ or $N_4 = 0$ we must have $\varrho = \sigma = \epsilon_0 = 0$. So we get

$$\sum_{\substack{\epsilon+k\geq 1\\0\leq \nu\leq 1}} \frac{(-1)^{\nu}h(p^{\epsilon})}{p^{\epsilon+k+\nu}} = \left(1 - \frac{1}{p}\right) \sum_{\epsilon+k\geq 1} \frac{h(p^{\epsilon})}{p^{\epsilon+k}}$$

$$= \left(1 - \frac{1}{p}\right) \left(\frac{h(p)}{p} + \sum_{\substack{k\geq 1\\0\leq \epsilon\leq 1}} \frac{h(p^{\epsilon})}{p^{\epsilon+k}}\right)$$

$$= \left(1 - \frac{1}{p}\right) \frac{h(p)}{p} + \frac{1}{p} \left(1 + \frac{h(p)}{p}\right)$$

$$= \frac{1 + h(p)}{p} = \left(1 - \frac{1}{p}\right) \frac{1}{p+1},$$

since we have h(p) = -2/(p+1) by definition (4.12). Hence, the total contribution from these cases is

$$\left(1 - \frac{1}{p}\right)\left(1 + \frac{1}{p} + \frac{4}{p+1}\right) = \frac{(1 - 1/p)(1 + 6/p + 1/p^2)}{1 + 1/p}.$$

Recalling the definition of τ_p in Section 1.1, in order to prove (4.19) it suffices to show that if $N_i \geq 1$ and $N_j \geq 1$ for some $i \neq j$, then the sum given in Lemma 4.5 vanishes.

If $p \neq 2$, then in this case Lemma 4.6 implies that the function ρ_0 is independent of ν , and changing the order of summation we have $\sum_{0 \leq \nu \leq 1} (-1)^{\nu} = 0$. This is simply a reflection of the fact that in the original counting problem, we were only counting those a and b which were coprime. For the case p = 2, a similar argument shows that the sum vanishes if $N_i, N_j \geq 1$ for some $(i, j) \neq (3, 4), (4, 3)$, or $N_3, N_4 \geq 2$. Therefore we need to consider the extra cases given by $N_1 = N_2 = 0, N_3 = 1, N_4 \geq 1$ and $N_1 = N_2 = 0, N_4 = 1, N_3 \geq 1$. For

any $N \in \mathbb{N}$ we have

$$\sum_{\substack{0 \le \nu \le 1 \\ k_3, k_4 \ge 0}} \sum_{\substack{0 \le \epsilon_3 + \epsilon_4 + \varrho + \sigma \le 1 \\ 0 \le \epsilon_0 \le \sigma \\ N_3 = 1, N_4 = N}} \frac{(-1)^{\nu + \varrho + \sigma} h(2^{\epsilon_0 + \epsilon_3 + \epsilon_4 + \varrho})}{\rho_0(2^{\nu}, 2^{\nu}, 2, 2^{N_4})}$$

$$= \frac{1}{2^N} \left(1 - \frac{1}{2}\right) \sum_{\substack{k_4 \ge 0 \\ 0 \le \epsilon_0 \le \sigma, k_3 \ge 0 \\ N_2 = 1, N_4 = N}} \sum_{\substack{(-1)^{\varrho + \sigma} h(2^{\epsilon_0 + \epsilon_3 + \epsilon_4 + \varrho}).}$$

However, this inner sum vanishes. Indeed, the condition $N_3 = 1$ implies that only one of $\varrho, \sigma, \epsilon_3$ and k_3 may be non-zero. The contribution from each case is -h(2), -1 - h(2), h(2) and 1 + h(2), respectively. The obvious symmetry means we that the sum also vanishes for $N_3 = N$ and $N_4 = 1$. Thus we have shown (4.19), and combining this with Lemma 4.5 completes the proof of Theorem 1.1.

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