

# A LOCAL LIMIT THEOREM FOR RANDOM WALKS IN RANDOM SCENERY AND ON RANDOMLY ORIENTED LATTICES

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ABSTRACT. Random walks in random scenery are processes defined by  $Z_n := \sum_{k=1}^n \xi_{X_1+\dots+X_k}$ , where  $(X_k, k \geq 1)$  and  $(\xi_y, y \in \mathbb{Z})$  are two independent sequences of i.i.d. random variables. We assume here that their distributions belong to the normal domain of attraction of stable laws with index  $\alpha \in (0, 2]$  and  $\beta \in (0, 2]$  respectively. These processes were first studied by H. Kesten and F. Spitzer, who proved the convergence in distribution when  $\alpha \neq 1$  and as  $n \rightarrow \infty$ , of  $n^{-\delta} Z_n$ , for some suitable  $\delta > 0$  depending on  $\alpha$  and  $\beta$ . Here we are interested in the convergence, as  $n \rightarrow \infty$ , of  $n^\delta \mathbb{P}(Z_n = \lfloor n^\delta x \rfloor)$ , when  $x \in \mathbb{R}$  is fixed. We also consider the case of random walks on randomly oriented lattices for which we obtain similar results.

## 1. INTRODUCTION

**1.1. About the model.** Random walks in random scenery (RWRS) are simple models of processes in disordered media with long-range correlations. They have been used in a wide variety of models in physics to study anomalous dispersion in layered random flows [29], diffusion with random sources, or spin depolarization in random fields (we refer the reader to Le Doussal's review paper [26] for a discussion of these models).

On the mathematical side, motivated by the construction of new self-similar processes with stationary increments, Kesten and Spitzer [23] and Borodin [3, 4] introduced RWRS in dimension one and proved functional limit theorems. These processes are defined as follows. Let  $\xi := (\xi_y, y \in \mathbb{Z})$  and  $X := (X_k, k \geq 1)$  be two independent sequences of independent identically distributed random variables taking values in  $\mathbb{R}$  and  $\mathbb{Z}$  respectively. The sequence  $\xi$  is called the *random scenery*. The sequence  $X$  is the sequence of increments of the *random walk*  $(S_n, n \geq 0)$  defined by  $S_0 := 0$  and  $S_n := \sum_{i=1}^n X_i$ , for  $n \geq 1$ . The *random walk in random scenery*  $Z$  is then defined for all  $n \geq 1$  by

$$Z_n := \sum_{k=0}^{n-1} \xi_{S_k}.$$

Denoting by  $N_n(y)$  the local time of the random walk  $S$  :

$$N_n(y) = \#\{k = 0, \dots, n-1 : S_k = y\},$$

it is straightforward to see that  $Z_n$  can be rewritten as  $Z_n = \sum_y \xi_y N_n(y)$ .

As in [23], the distribution of  $\xi_1$  is assumed to belong to the normal domain of attraction of a strictly stable distribution  $\mathcal{S}_\beta$  of index  $\beta \in (0, 2]$ , with characteristic function given by

$$\phi(u) = e^{-|u|^\beta (A_1 + iA_2 \operatorname{sgn}(u))} \quad u \in \mathbb{R},$$

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where  $0 < A_1 < \infty$  and  $|A_1^{-1}A_2| \leq |\tan(\pi\beta/2)|$ . When  $\beta \neq 1$ , this is the most general form of a strictly stable distribution. In the case  $\beta = 1$ , this is the general form of a random variable  $Y$  with strictly stable distribution satisfying the following symmetry condition :

$$\sup_{M>0} |\mathbb{E}(Y \mathbf{1}_{\{|Y|<M\}})| < +\infty. \tag{1}$$

We will denote by  $f_\beta$  the density function of the law  $\mathcal{S}_\beta$ .

Concerning the random walk, the distribution of  $X_1$  is assumed to belong to the normal domain of attraction of a strictly stable distribution  $\mathcal{S}_\alpha$  with index  $\alpha \in (0, 2]$ . In this paper we will actually not consider the case  $\alpha = 1$  (see Remark 2 in [23] for some discussion on this case).

Then the following weak convergences hold in the space of càd-làg real-valued functions defined on  $[0, \infty)$  and on  $\mathbb{R}$  respectively :

$$\begin{aligned} & \left( n^{-\frac{1}{\alpha}} S_{\lfloor nt \rfloor} \right)_{t \geq 0} \xrightarrow[n \rightarrow \infty]{\mathcal{L}} (U(t))_{t \geq 0} \\ \text{and} \quad & \left( n^{-\frac{1}{\beta}} \sum_{k=0}^{\lfloor nx \rfloor} \xi_k \right)_{x \in \mathbb{R}} \xrightarrow[n \rightarrow \infty]{\mathcal{L}} (Y(x))_{x \in \mathbb{R}}, \end{aligned}$$

where  $U$  and  $Y$  are two independent Lévy processes such that  $U(0) = 0$ ,  $Y(0) = 0$ ,  $U(1)$  has distribution  $\mathcal{S}_\alpha$ ,  $Y(1)$  and  $Y(-1)$  have distribution  $\mathcal{S}_\beta$ . When  $\alpha \in (1, 2]$ , the random walk  $(S_n, n \geq 0)$  is recurrent, and the limiting process  $U$  admits a local time process. We denote by  $(L_t(x), t \in \mathbb{R}^+, x \in \mathbb{R})$  the jointly continuous version of this local time.

Let

$$\delta := 1 - \frac{1}{\alpha} + \frac{1}{\alpha\beta}.$$

Papers [23, 3, 4] proved that the following weak convergences hold in the space of continuous real-valued functions defined on  $[0, \infty)$  :

$$\text{if } \alpha > 1, \quad \left( n^{-\delta} Z_{nt} \right)_{t \geq 0} \xrightarrow[n \rightarrow \infty]{\mathcal{L}} (\Delta(t))_{t \geq 0} \tag{2}$$

$$\text{if } \alpha < 1, \quad \left( n^{-\frac{1}{\beta}} Z_{nt} \right)_{t \geq 0} \xrightarrow[n \rightarrow \infty]{\mathcal{L}} \left( Y(t) \mathbb{E}[(\tilde{N}_\infty^{\beta-1}(0))^{\frac{1}{\beta}}] \right)_{t \geq 0}, \tag{3}$$

where

- $Z_s$  is defined as the linear interpolation  $Z_s = Z_n + (s-n)(Z_{n+1} - Z_n)$  when  $n \leq s \leq n+1$ ,
- $\Delta$  is the process defined by

$$\Delta(t) = \int_{-\infty}^{+\infty} L_t(x) dY(x),$$

- $\tilde{N}_\infty(0)$  is the total time spent in 0 by the two-sided random walk  $(S_k, k \in \mathbb{Z})$  with  $S_{-k} = -\sum_{m=1}^k X_{-m}$  (where  $(X_{-k}, k \geq 1)$  is independent of  $(X_k, k \geq 1)$  and with the same distribution).

The limiting process  $\Delta$  is known to be a continuous  $\delta$ -self-similar process with stationary increments. It can be seen as a mixture of  $\beta$ -stable processes, but it is not a stable process.

Since these seminal papers, RWRS have been extensively studied. Far from being exhaustive, we can cite limit theorems in higher dimension [2], strong approximation results and laws of the iterated logarithm [24, 14, 13], limit theorems for correlated sceneries or walks [20, 12], large and moderate deviations results [8, 9, 1, 18]. Our contribution in this paper is a local version of the convergence results from [23], as we make more precise in the next subsection.

**1.2. The results.** Our first statement is obtained in the case when the  $\xi'_i$ 's are  $\mathbb{Z}$ -valued random variables. Let  $\varphi_\xi(u) := \mathbb{E}[e^{iu\xi_1}]$  be the characteristic function of  $\xi_1$ . Remember that there exists an integer  $d \geq 1$  such that  $\{u : |\varphi_\xi(u)| = 1\} = \frac{2\pi}{d}\mathbb{Z}$  ( $d$  is the g.c.d. of the set of  $b - c$  where  $b$  and  $c$  belong to the support of the distribution of  $\xi_1$ )<sup>1</sup>.

Our first result concerns the case  $\alpha > 1$  :

**Theorem 1. Lattice case,  $\alpha > 1$ .**

Assume that  $\alpha \in (1, 2]$  and  $\beta \in (0, 2]$ . Let  $C(x)$  be the continuous function defined by

$$C(x) := \mathbb{E} \left[ |L|_\beta^{-1} f_\beta(|L|_\beta^{-1} x) \right] \quad \text{for all } x \in \mathbb{R},$$

where  $|L|_\beta := \left( \int_{\mathbb{R}} L_1^\beta(y) dy \right)^{1/\beta}$ . Then, for every  $x \in \mathbb{R}$ , we have  $0 < C(x) < \infty$  and

- if  $\mathbb{P}(n\xi_1 - \lfloor n^\delta x \rfloor \notin d\mathbb{Z}) = 1$ , then  $\mathbb{P}(Z_n = \lfloor n^\delta x \rfloor) = 0$ ;
- if  $\mathbb{P}(n\xi_1 - \lfloor n^\delta x \rfloor \in d\mathbb{Z}) = 1$ , then

$$\mathbb{P}(Z_n = \lfloor n^\delta x \rfloor) = d \frac{C(x)}{n^\delta} + o(n^{-\delta}),$$

where the  $o(n^{-\delta})$  is uniform in  $x$ .

**Remark.** There is no other alternative for the law of  $\xi_1$ . Indeed, let  $b$  be in the support of  $\xi_1$ . Then  $n\xi_1$  belongs to  $nb + d\mathbb{Z}$ . Hence the condition  $n\xi_1 - \lfloor n^\delta x \rfloor \in d\mathbb{Z}$  is equivalent to  $\lfloor n^\delta x \rfloor - nb \in d\mathbb{Z}$ .

Our second result concerns the case  $\alpha < 1$  :

**Theorem 2. Lattice case,  $\alpha < 1$ .**

Assume that  $\alpha \in (0, 1)$ ,  $\beta \in (0, 2]$  and  $x \in \mathbb{R}$ . Let  $D(x) := r f_\beta(rx)$ , with  $r := \mathbb{E}[\tilde{N}_\infty^{\beta-1}(0)]^{-1/\beta}$ . Then

- if  $\mathbb{P}(n\xi_1 - \lfloor n^{\frac{1}{\beta}} x \rfloor \notin d\mathbb{Z}) = 1$ , then  $\mathbb{P}(Z_n = \lfloor n^{\frac{1}{\beta}} x \rfloor) = 0$ ;
- if  $\mathbb{P}(n\xi_1 - \lfloor n^{\frac{1}{\beta}} x \rfloor \in d\mathbb{Z}) = 1$ , then

$$\mathbb{P}(Z_n = \lfloor n^{\frac{1}{\beta}} x \rfloor) = d \frac{D(x)}{n^{\frac{1}{\beta}}} + o(n^{-\frac{1}{\beta}}),$$

where the  $o(n^{-\frac{1}{\beta}})$  is uniform in  $x$ ;

Finally we get the local limit theorem when  $\xi$  is strongly nonlattice, i.e. when  $\limsup_{|u| \rightarrow +\infty} |\varphi_\xi(u)| < 1$ .

**Theorem 3. Strongly nonlattice case.**

- If  $\alpha > 1$  and  $\beta \in (0, 2]$ , then for all  $a, b \in \mathbb{R}$  such that  $a < b$ ,

$$\lim_{n \rightarrow \infty} n^\delta \mathbb{P} \left[ Z_n \in [n^\delta x + a; n^\delta x + b] \right] = C(x)(b - a).$$

- If  $\alpha < 1$  and  $\beta \in (0, 2]$ , then for all  $a, b \in \mathbb{R}$  such that  $a < b$ ,

$$\lim_{n \rightarrow \infty} n^{\frac{1}{\beta}} \mathbb{P} \left[ Z_n \in [n^{\frac{1}{\beta}} x + a; n^{\frac{1}{\beta}} x + b] \right] = D(x)(b - a).$$

<sup>1</sup>Note that  $\xi$  is said to be non-arithmetic if  $d = 1$ .

On the one hand, these results give some qualitative information about the behaviour of  $Z$ . For instance the transience of the process  $Z$  is easily deduced (with Borel-Cantelli Lemma) when  $\beta < 1$ . Note that since  $Z$  is not a Markov chain, the recurrence property when  $\beta > 1$  does not directly follow from the above local limit theorems. However this can be proved by using an argument from ergodic theory (see [31]). Indeed, it is enough to remark that when  $\beta \in (1, 2]$ , the random variables  $\xi_{S_k}, k \in \mathbb{N}$  form an ergodic and stationary sequence of integrable and centered random variables.

On the other hand this work was motivated by the study of random walks on randomly oriented lattices. In the simplest case, one should think to the simple random walk defined on a random sublattice of the oriented lattice  $\mathbb{Z}^2$ , which is constructed as follows. On each horizontal line, one removes all edges oriented to the right with probability  $1/2$  or those oriented to the left with probability  $1/2$ , and so independently on each level. Then it is known, and not difficult to see, that the first coordinate of the resulting random walk is closely related to a random walk in random scenery  $Z = \sum_k \xi_{S_k}$ , with  $S$  the simple random walk on  $\mathbb{Z}$  and the  $\xi_y$  i.i.d random variables with geometric distribution (see Section 5 or [19] for more explanations). In [19] it was conjectured that the probability of return to the origin of this random walk is equivalent to a constant times  $n^{-5/4}$ . Here we prove a local limit theorem for even more general random walks, giving in particular a proof of this conjecture. We refer the reader to Section 5 for more precise statements of our results.

**1.3. Outline of the proof.** Let us give a very rough description of the proofs for RWRS. To fix ideas, we do it for  $x = 0$  and  $\alpha > 1$ . By Fourier inverse transform, we have to study the asymptotic behavior of

$$\int \mathbb{E} [e^{itZ_n}] dt = \int \mathbb{E} \left[ \prod_{y \in \mathbb{Z}} \varphi_\xi(tN_n(y)) \right] dt. \tag{4}$$

For  $t$  such that  $tN_n(y)$  is small, only the behavior of  $\varphi_\xi$  around 0 is relevant. Therefore, for  $|t| \leq (\sup_y N_n(y))^{-1} \simeq n^{-1+1/\alpha}$ ,

$$\mathbb{E} \left[ \prod_{y \in \mathbb{Z}} \varphi_\xi(tN_n(y)) \right] \simeq \mathbb{E} \left[ \exp(-|t|^\beta \sum_y N_n(y)^\beta (A_1 + iA_2 \text{sgn}(t))) \right].$$

Now,  $\sum_y N_n(y)^\beta$  is of order  $n^{\beta\delta}$ , and a change of variable  $t \rightsquigarrow n^\delta t$  leads to the dominant part in the integral (4).

For  $t \geq (\sup_y N_n(y))^{-1} \simeq n^{-1+1/\alpha}$ , the behavior of  $\varphi_\xi$  away from 0 comes into play. In the strongly nonlattice case, one can find  $\epsilon_0 > 0$  and  $\rho \in (0, 1)$  such that  $|\varphi_\xi(t)| \leq \rho$  for  $|t| \geq \epsilon_0$ , so that for  $|t| \geq n^{-1+1/\alpha}$ ,

$$\left| \prod_{y \in \mathbb{Z}} \varphi_\xi(tN_n(y)) \right| \leq \rho^{\#\{y; N_n(y) \geq \frac{\epsilon_0}{t}\}} \leq \rho^{\#\{y; N_n(y) \geq \epsilon_0 n^{1-1/\alpha}\}}.$$

It is easily seen that there is a large number of points visited at least  $n^{1-1/\alpha}$  times, leading to the result.

The lattice case is more delicate, since in this case  $|\varphi_\xi(t)| = 1$  for  $t \in \frac{2\pi}{d}\mathbb{Z}$ , so that the inequality  $|\varphi_\xi(tN_n(y))| \leq \rho$  is only valid for the  $y$  such that  $d(tN_n(y); \frac{2\pi}{d}\mathbb{Z}) \geq \epsilon_0$ . Thus, the main difficulty is to show that for  $|t| \geq n^{1-1/\alpha}$ , there are a lot of such sites. This is done by a surgery on the trajectories of the random walk.

Let us briefly describe now the organization of the paper. In the next section, we prove Theorem 1. In Sections 3 and 4, we sketch the proofs of Theorem 2 and Theorem 3 which are easier and follow the same lines. In Section 5, the local limit theorem for random walks evolving on randomly oriented lattices is obtained by using similar techniques as for the proof of Theorem 1. Finally in the appendix, we prove some auxiliary results on the range of the random walk  $S$ , that we should need, but which could also be of independent interest.

2. LATTICE CASE,  $\alpha > 1$ : PROOF OF THEOREM 1

2.1. Finiteness of  $C(x)$ .

**Lemma 4.** *For all  $x \in \mathbb{R}$ ,  $0 < C(x) < +\infty$ .*

*Proof.* Let  $x \in \mathbb{R}$ . Since  $\int_{\mathbb{R}} L_1(y) dy = 1$  and  $\beta \leq 2$ , we have a.s.  $\int_{\mathbb{R}} L_1^\beta(y) dy \leq 1 + \sup_y L_1(y)^{(\beta-1)_+}$ . Hence  $\int_{\mathbb{R}} L_1^\beta(y) dy$  is a.s. finite. So  $C(x) > 0$ .

Let us prove now that  $C(x)$  is finite. First we have

$$C(x) \leq \|f_\beta\|_\infty \mathbb{E}[|L|_\beta^{-1}].$$

Let us assume now that  $\beta > 1$ . By Hölder's inequality,

$$1 = \int_{\mathbb{R}} L_1(y) dy \leq |L|_\beta \left( \int_{\mathbb{R}} \mathbf{1}(L_1(y) > 0) dy \right)^{1-\frac{1}{\beta}}.$$

Thus by using Jensen's inequality we get

$$\begin{aligned} C(x) &\leq \|f_\beta\|_\infty \mathbb{E} \left[ \left( \int_{\mathbb{R}} \mathbf{1}(L_1(y) > 0) dy \right)^{1-\frac{1}{\beta}} \right] \\ &\leq \|f_\beta\|_\infty \left( \mathbb{E} \left[ \left( \int_{\mathbb{R}} \mathbf{1}(L_1(y) > 0) dy \right) \right] \right)^{1-\frac{1}{\beta}} = \|f_\beta\|_\infty (\mathbb{E}[\lambda(U([0, 1]))])^{1-\frac{1}{\beta}}, \end{aligned}$$

where  $\lambda$  denotes the Lebesgue measure on  $\mathbb{R}$  and  $U([0, 1])$  the set of points visited by  $U$  before time 1. This finishes the proof in the case  $\beta > 1$ , since the last quantity is finite (see for example [27] p.703).

Next, if  $\beta = 1$ , then  $|L|_\beta = 1$  and  $C(x) = f_\beta(x) < +\infty$ .

Assume finally that  $\beta < 1$ . Then

$$1 = \int_{\mathbb{R}} L_1(y) dy \leq |L|_\beta^\beta \left( \sup_x L_1(x) \right)^{1-\beta},$$

so that

$$\mathbb{E} \left[ |L|_\beta^{-1} \right] \leq \mathbb{E} \left[ \left( \sup_x L_1(x) \right)^{\frac{1-\beta}{\beta}} \right] = \frac{1-\beta}{\beta} \int_0^{+\infty} t^{\frac{1}{\beta}-2} \mathbb{P} \left[ \sup_x L_1(x) \geq t \right] dt.$$

Therefore it suffices to prove that there exists a constant  $c > 0$  such that

$$\mathbb{P} \left[ \sup_x L_1(x) \geq t \right] \leq 2 \exp(-ct) \quad \text{for all } t > 0. \tag{5}$$

This follows from stronger results proved in [25], but for sake of completeness, let us give a soft argument here. For  $a > 0$ , let  $\tau_a := \inf \{t : \sup_x L_t(x) \geq a\}$ . The random variable  $\tau_a$  is a

stopping time, and by continuity of  $t \mapsto \sup_x L_t(x)$ ,  $\sup_x L_{\tau_a}(x) = a$  on  $\{\tau_a < \infty\}$ . It follows then from the inequality

$$\sup_x L_{t+s}(x) \leq \sup_x L_t(x) + \sup_x (L_{t+s}(x) - L_t(x)),$$

and from the strong Markov property, that for any  $a > 0$  and  $b > 0$ ,

$$\mathbb{P} \left[ \sup_x L_1(x) \geq a + b \right] = \mathbb{P} \left[ \tau_a \leq 1; \sup_x L_1(x) \geq a + b \right] \leq \mathbb{E} \left[ \mathbf{1}_{\{\tau_a \leq 1\}} \mathbb{P}_{U_{\tau_a}} \left[ \sup_x L_1(x) \geq b \right] \right],$$

where for any  $v$ ,  $\mathbb{P}_v$  denotes the law of the process  $U$  starting from  $v$ . By translation invariance, the law of  $\sup_x L_1(x)$  does not depend on the starting point of  $U$ . Therefore, for any  $a > 0$  and  $b > 0$ ,

$$\mathbb{P} \left[ \sup_x L_1(x) \geq a + b \right] \leq \mathbb{P}[\tau_a \leq 1] \mathbb{P} \left[ \sup_x L_1(x) \geq b \right] = \mathbb{P} \left[ \sup_x L_1(x) \geq a \right] \mathbb{P} \left[ \sup_x L_1(x) \geq b \right]. \quad (6)$$

Let  $M > 0$  be a median of  $\sup_x L_1(x)$ . By (6), for all  $t > 0$ ,

$$\mathbb{P} \left[ \sup_x L_1(x) \geq t \right] \leq \mathbb{P} \left[ \sup_x L_1(x) \geq M \right]^{[t/M]} \leq \left( \frac{1}{2} \right)^{[t/M]},$$

which ends the proof of (5). □

## 2.2. A first reduction.

**Lemma 5.** *Let  $n \geq 1$  and  $x \in \mathbb{Z}$  be given.*

- *If  $\mathbb{P}[n\xi_1 - x \notin d\mathbb{Z}] = 1$ , then  $\mathbb{P}(Z_n = x) = 0$ .*
- *If  $\mathbb{P}[n\xi_1 - x \in d\mathbb{Z}] = 1$ , then*

$$\mathbb{P}(Z_n = x) = \frac{d}{2\pi} \int_{-\frac{\pi}{d}}^{\frac{\pi}{d}} \exp(-itx) \mathbb{E} \left[ \prod_{y \in \mathbb{Z}} \varphi_\xi(tN_n(y)) \right] dt.$$

*Proof.* We have

$$\mathbb{P}(Z_n = x) = \frac{1}{2\pi} \int_0^{2\pi} \exp(-itx) \varphi_n(t) dt,$$

where  $\varphi_n$  is the characteristic function of  $Z_n$  given by

$$\varphi_n(t) := \mathbb{E} \left[ \prod_{y \in \mathbb{Z}} \varphi_\xi(tN_n(y)) \right] \quad \text{for all } t \in \mathbb{R}.$$

Notice that  $e^{\frac{2i\pi\xi_1}{d}} = \mathbb{E}[e^{\frac{2i\pi\xi_1}{d}}]$  almost surely. Hence, for any integer  $m \geq 0$  and any  $u \in \mathbb{R}$ ,

$$\varphi_\xi \left( \frac{2m\pi}{d} + u \right) = \varphi_\xi \left( \frac{2\pi}{d} \right)^m \varphi_\xi(u).$$

Therefore

$$\begin{aligned} \mathbb{P}(Z_n = x) &= \frac{1}{2\pi} \sum_{k=0}^{d-1} \int_{-\frac{\pi}{d}}^{\frac{\pi}{d}} \exp\left(-i\left(t + \frac{2k\pi}{d}\right)x\right) \varphi_n\left(\frac{2k\pi}{d} + t\right) dt \\ &= \frac{1}{2\pi} \sum_{k=0}^{d-1} \int_{-\frac{\pi}{d}}^{\frac{\pi}{d}} \exp(-itx) \exp\left(-i\frac{2k\pi}{d}x\right) \mathbb{E}\left[\prod_y \left\{\varphi_\xi\left(\frac{2\pi}{d}\right)^{kN_n(y)} \varphi_\xi(tN_n(y))\right\}\right] dt \\ &= \frac{1}{2\pi} \left(\sum_{k=0}^{d-1} \exp\left(-i\frac{2k\pi}{d}x\right) \varphi_\xi\left(\frac{2\pi}{d}\right)^{kn}\right) \int_{-\frac{\pi}{d}}^{\frac{\pi}{d}} \exp(-itx) \varphi_n(t) dt, \end{aligned}$$

since  $\sum_y N_n(y) = n$ . Moreover,  $\left[e^{-i\frac{2\pi}{d}x} \varphi_\xi\left(\frac{2\pi}{d}\right)^n\right]^d = e^{-i2\pi x} e^{2i\pi n \xi_1} = 1$ , thus  $e^{-i\frac{2\pi}{d}x} \varphi_\xi\left(\frac{2\pi}{d}\right)^n$  is a  $d^{\text{th}}$  root of the unity. Hence

$$\sum_{k=0}^{d-1} e^{-i\frac{2k\pi}{d}x} \varphi_\xi\left(\frac{2\pi}{d}\right)^{kn} = \begin{cases} d & \text{if } \varphi_\xi\left(\frac{2\pi}{d}\right)^n e^{-i\frac{2\pi}{d}x} = 1, \\ 0 & \text{otherwise.} \end{cases}$$

Since  $\varphi_\xi\left(\frac{2\pi}{d}\right) = e^{\frac{2i\pi\xi_1}{d}}$  a.s., the lemma follows.  $\square$

### 2.3. The event $\Omega_n$ . Set

$$N_n^* := \sup_y N_n(y) \quad \text{and} \quad R_n := \#\{y : N_n(y) > 0\}.$$

**Lemma 6.** For every  $n \geq 1$  and  $\gamma > 0$ , set

$$\Omega_n = \Omega_n(\gamma) := \left\{ R_n \leq n^{\frac{1}{\alpha} + \gamma} \quad \text{and} \quad \sup_{y \neq z} \frac{|N_n(y) - N_n(z)|}{|y - z|^{\frac{\alpha-1}{2}}} \leq n^{(1-\frac{1}{\alpha} + \gamma)/2} \right\}.$$

Then  $\mathbb{P}(\Omega_n) = 1 - o(n^{-\delta})$ . Moreover, given  $\eta \geq \gamma \max(\alpha/2, 2(\beta-1)/\beta)$ , the following also holds on  $\Omega_n$ :

$$N_n^* \leq n^{1-\frac{1}{\alpha} + \eta} \quad \text{and} \quad V_n := \sum_z N_n^\beta(z) \geq \begin{cases} n^{\delta\beta - \frac{\eta\beta}{2}} & \text{if } \beta > 1 \\ n^{\delta\beta - \eta(1-\beta)} & \text{if } \beta \leq 1. \end{cases} \quad (7)$$

*Proof.* We prove in the appendix that for every  $\gamma > 0$ , there exists  $C > 0$  such that

$$\mathbb{P}(R_n \leq \mathbb{E}[R_n]n^\gamma) = 1 - \mathcal{O}(e^{-Cn^\gamma}).$$

Since there exists  $c > 0$  such that  $\mathbb{E}[R_n] \sim cn^{\frac{1}{\alpha}}$  (see [32] p.36), we conclude that

$$\mathbb{P}(R_n \leq n^{\frac{1}{\alpha} + \gamma}) = 1 - o(n^{-\delta}).$$

Now let us prove that

$$\mathbb{P}\left(\sup_{y \neq z} \frac{|N_n(y) - N_n(z)|}{|y - z|^{\frac{\alpha-1}{2}}} \geq \sqrt{n^{1-\frac{1}{\alpha} + \gamma}}\right) = o(n^{-\delta}).$$

According to the proof of Proposition 5.4 in [27], we have :  $\mathbb{E}[|S_n|^p] = \mathcal{O}(n^{\frac{p}{\alpha}})$ , for all  $p \in (1, \alpha)$ . Then Doob's inequality gives that, for all  $\delta' > \delta/p$ ,

$$\mathbb{P}\left(\sup_{k=1, \dots, n} |S_k| \geq n^{\frac{1}{\alpha} + \delta'}\right) = \mathcal{O}(n^{-p\delta'}) = o(n^{-\delta}).$$

So we can restrict ourselves to the set  $A_n := \{\sup_{k=1,\dots,n} |S_k| < n^{\frac{1}{\alpha} + \delta'}\}$ . But on  $A_n$ , if  $N_n(z) > 0$  then necessarily  $z \in (-n^{\frac{1}{\alpha} + \delta'}, n^{\frac{1}{\alpha} + \delta'})$ . Thus

$$\mathbb{P} \left( \sup_{y,z} \frac{|N_n(y) - N_n(z)|}{|y - z|^{\frac{\alpha-1}{2}}} \geq \sqrt{n^{1-\frac{1}{\alpha} + \gamma}}; A_n \right) \leq 5n^{\frac{2}{\alpha} + 2\delta'} \sup_{y \neq z} \mathbb{P} \left( \frac{|N_n(y) - N_n(z)|}{|y - z|^{\frac{\alpha-1}{2}}} \geq \sqrt{n^{1-\frac{1}{\alpha} + \gamma}} \right). \quad (8)$$

Moreover the Markov inequality gives for all  $m \geq 1$ :

$$\mathbb{P} \left( \frac{|N_n(y) - N_n(z)|}{|y - z|^{\frac{\alpha-1}{2}}} \geq \sqrt{n^{1-\frac{1}{\alpha} + \gamma}} \right) \leq \frac{\mathbb{E}[|N_n(y) - N_n(z)|^{2m}]}{|y - z|^{(\alpha-1)m} n^{(1-\frac{1}{\alpha} + \gamma)m}} \quad \text{for all } y \neq z. \quad (9)$$

In addition, according to [22] (see the formula in the middle of page 77, with  $m = \mathcal{O}(n)$ ,  $a_m^{-1} = \mathcal{O}(n^{-1/\alpha})$  and  $Q(z)^{-1} = \mathcal{O}(z^\alpha)$ ), we have for all  $m \geq 1$ ,

$$\sup_{y \neq z} \frac{\mathbb{E}[|N_n(y) - N_n(z)|^{2m}]}{|y - z|^{(\alpha-1)m}} = \mathcal{O}(n^{(1-\frac{1}{\alpha})m}). \quad (10)$$

Thus if we take  $m > (\delta + 2/\alpha + 2\delta')/\gamma$ , then by using (8), (9) and (10), we get

$$\mathbb{P} \left( \sup_{y \neq z} \frac{|N_n(y) - N_n(z)|}{|y - z|^{\frac{\alpha-1}{2}}} \geq \sqrt{n^{1-\frac{1}{\alpha} + \gamma}} \right) = \mathcal{O} \left( \frac{n^{\frac{2}{\alpha} + 2\delta'}}{n^{\gamma m}} \right) = o(n^{-\delta}).$$

We now prove (7), starting with the upper bound for  $N_n^*$ . For this let  $y_0$  be such that  $N_n(y_0) = N_n^*$ , and let  $z_0$  be the closest point to  $y_0$  such that  $N_n(z_0) = 0$ . Then on  $\Omega_n$ ,

$$|y_0 - z_0| \leq R_n \leq n^{\frac{1}{\alpha} + \gamma},$$

and thus

$$N_n(y_0) \leq \sqrt{|y_0 - z_0|^{\alpha-1} n^{1-\frac{1}{\alpha} + \gamma}} \leq \sqrt{n^{(\frac{1}{\alpha} + \gamma)(\alpha-1)} n^{1-\frac{1}{\alpha} + \gamma}} = n^{1-\frac{1}{\alpha} + \frac{\alpha\gamma}{2}}. \quad (11)$$

The desired upper bound for  $N_n^*$  follows if  $\eta \geq \alpha\gamma/2$ .

To prove the lower bound for  $V_n$ , we use the fact that  $n = \sum_y N_n(y)$ . When  $\beta > 1$ , this gives by using Hölder's inequality:

$$n \leq \left( \sum_z N_n^\beta(z) \right)^{\frac{1}{\beta}} R_n^{1-\frac{1}{\beta}} \leq (V_n)^{\frac{1}{\beta}} n^{(\frac{1}{\alpha} + \gamma)(1-\frac{1}{\beta})}.$$

Hence  $V_n^{\frac{1}{\beta}} \geq n^{\delta - \gamma \frac{\beta-1}{\beta}}$ , and the desired lower bound for  $V_n$  follows if  $2(\beta - 1)\gamma \leq \eta\beta$ . When  $\beta \leq 1$ , we write

$$n = \sum_y N_n(y) \leq V_n (N_n^*)^{1-\beta},$$

and the desired lower bound follows from the upper bound for  $N_n^*$  proved just above.  $\square$

**2.4. Scheme of the proof.** Let  $\eta > 0$ . Set  $\gamma := \eta\beta/2$ . We observe that  $\gamma \leq \eta$  and that (7) holds with this choice of  $(\eta, \gamma)$ . We also set

$$\bar{\eta} := \begin{cases} \eta & \text{if } \beta \geq 1 \\ \eta/\beta & \text{if } \beta < 1. \end{cases}$$

By Lemmas 5 and 6, we have to estimate

$$\frac{d}{2\pi} \int_{-\frac{\pi}{d}}^{\frac{\pi}{d}} e^{-it[n^\delta x]} \mathbb{E} \left[ \prod_y \varphi_\xi(tN_n(y)) \mathbf{1}_{\Omega_n} \right] dt.$$

This is done in several steps presented in the following propositions.

**Proposition 7.** *Let  $\eta \in \left(0, \frac{1}{2\alpha(\beta+1)}\right)$ . Then, we have*

$$\frac{d}{2\pi} \int_{|t| \leq n^{-\delta+\eta}} e^{-it \lfloor n^\delta x \rfloor} \mathbb{E} \left[ \prod_y \varphi_\xi(tN_n(y)) \mathbf{1}_{\Omega_n} \right] dt = d \frac{C(x)}{n^\delta} + o(n^{-\delta}),$$

uniformly in  $x \in \mathbb{R}$ .

Recall next that the characteristic function  $\phi$  of the stable distribution  $\mathcal{S}_\beta$  has the following form :

$$\phi(u) = e^{-|u|^\beta (A_1 + iA_2 \text{sgn}(u))},$$

for some  $0 < A_1 < \infty$ ,  $|A_1^{-1}A_2| \leq |\tan(\pi\beta/2)|$ . It follows that the characteristic function  $\varphi_\xi$  of  $\xi_1$  satisfies:

$$1 - \varphi_\xi(u) \sim |u|^\beta (A_1 + iA_2 \text{sgn}(u)) \quad \text{when } u \rightarrow 0. \quad (12)$$

Therefore there exist constants  $\varepsilon_0 > 0$  and  $\sigma > 0$  such that

$$\max(|\phi(u)|, |\varphi_\xi(u)|) \leq \exp\left(-\sigma|u|^\beta\right) \quad \text{for all } u \in [-\varepsilon_0, \varepsilon_0]. \quad (13)$$

Since  $\overline{\varphi_\xi(t)} = \varphi_\xi(-t)$  for every  $t \geq 0$ , the following propositions achieve the proof of Theorem 1:

**Proposition 8.** *Let  $\eta$  be as in Proposition 7. Then there exists  $c > 0$  such that*

$$\int_{n^{-\delta+\eta}}^{\varepsilon_0 n^{-1+\frac{1}{\alpha}-\eta}} \mathbb{E} \left[ \prod_y |\varphi_\xi(tN_n(y))| \mathbf{1}_{\Omega_n} \right] dt = o(e^{-n^c}).$$

**Proposition 9.** *Let  $\eta$  be as in Proposition 7 and let  $\varepsilon \in \left(\eta, \frac{\alpha-1}{\alpha(3+2\beta(\alpha-1))}\right)$  be given. Then there exists  $c > 0$  such that*

$$\int_{\varepsilon_0 n^{-1+\frac{1}{\alpha}-\eta}}^{n^{-1+\frac{1}{\alpha}+\varepsilon}} \mathbb{E} \left[ \prod_y |\varphi_\xi(tN_n(y))| \mathbf{1}_{\Omega_n} \right] dt = o(e^{-n^c}).$$

**Proposition 10.** *Let  $\eta$  be such that  $\gamma < \min\left(\frac{1}{2\alpha^2}, \frac{1}{2} \frac{\alpha-1}{\alpha}\right)$  and let  $\varepsilon \in \left(\left(\frac{2\alpha}{\beta} + 1\right)\gamma, 1 - \frac{1}{\alpha}\right)$  be given. Then there exists  $c > 0$  such that*

$$\int_{n^{-1+\frac{1}{\alpha}+\varepsilon}}^{\frac{\pi}{d}} \mathbb{E} \left[ \prod_y |\varphi_\xi(tN_n(y))| \mathbf{1}_{\Omega_n} \right] dt = o(e^{-n^c}).$$

To end the proof of Theorem 1, we observe that there exists  $(\eta, \varepsilon)$  satisfying all the hypotheses of these propositions (by taking  $\eta > 0$  small enough and  $\varepsilon < \frac{\alpha-1}{\alpha(3+2\beta(\alpha-1))}$  large enough).

**2.5. Proof of Proposition 7.** Remember that  $V_n = \sum_{z \in \mathbb{Z}} N_n^\beta(z)$ . We start by a preliminary lemma.

**Lemma 11.** *If  $\beta > 1$ , then*

$$\sup_n \mathbb{E} \left[ \left( \frac{n^\delta}{V_n^{\frac{1}{\beta}}} \right)^{\frac{\beta}{\beta-1}} \right] < +\infty.$$

*If  $\beta \leq 1$ , then for all  $p \geq 1$ ,*

$$\sup_n \mathbb{E} \left[ \left( \frac{n^\delta}{V_n^{\frac{1}{\beta}}} \right)^p \right] < +\infty.$$

A direct consequence of this lemma is that the sequence  $(n^\delta V_n^{-\frac{1}{\beta}}, n \geq 1)$  is uniformly integrable.

*Proof.* We start with the case  $\beta > 1$ . We already observed in the proof of Lemma 6 that for every  $n \geq 1$ ,

$$n \leq V_n^{\frac{1}{\beta}} R_n^{1-\frac{1}{\beta}}.$$

But it is proved in [27] Equation (7.a) that  $\mathbb{E}[R_n] = \mathcal{O}(n^{\frac{1}{\alpha}})$ . The result follows.

We suppose now that  $\beta \leq 1$ . Since we have

$$n = \sum_x N_n(x) \leq V_n (N_n^*)^{1-\beta}, \quad (14)$$

we get

$$\frac{n^\delta}{V_n^{1/\beta}} \leq \left( \frac{N_n^*}{n^{1-\frac{1}{\alpha}}} \right)^{\frac{1}{\beta}-1}. \quad (15)$$

We use next the fact that  $N_n^*$  is a subadditive functional:

$$N_{n+m}^* \leq N_n^* + N_m^* \circ \theta_n, \quad (16)$$

where

$$N_m^* \circ \theta_n := \sup_x \sum_{k=0}^{m-1} \mathbf{1}_{\{S_{n+k}=x\}} = \sup_x \sum_{k=0}^{m-1} \mathbf{1}_{\{S_{n+k}-S_n=x\}},$$

is independent of  $\sigma(S_0, \dots, S_{n-1})$ . Moreover,  $0 \leq N_{n+1}^* - N_n^* \leq 1$ . Therefore, we can prove in exactly the same way as for the range (see (46) in the appendix), that

$$\mathbb{P}(N_n^* \geq a + b) \leq \mathbb{P}(N_n^* \geq a) \mathbb{P}(N_n^* \geq b) \quad \text{for all } a, b \in \mathbb{N}. \quad (17)$$

Now it is known (see for example [6]) that  $N_n^*/n^{1-1/\alpha}$  converges in distribution toward  $\sup_x L_1(x)$ . Let  $t > 0$ , be such that  $\mathbb{P}[\sup_x L_1(x) \geq t] \leq 1/2$ . Since

$$\lim_{n \rightarrow \infty} \mathbb{P}\left(N_n^* \geq \lfloor tn^{1-1/\alpha} \rfloor\right) \leq \mathbb{P}\left(\sup_x L_1(x) \geq t\right) \leq 1/2,$$

we obtain that for  $n$  large enough,  $\mathbb{P}(N_n^* \geq \lfloor tn^{1-1/\alpha} \rfloor) \leq 2/3$ . Hence for  $n$  large enough, and all  $p \geq 1$ ,

$$\begin{aligned} \mathbb{E}\left[\left(\frac{N_n^*}{n^{1-1/\alpha}}\right)^p\right] &= p \int_0^\infty x^{p-1} \mathbb{P}\left(N_n^* \geq xn^{1-1/\alpha}\right) dx \leq pt^p \int_0^\infty u^{p-1} \mathbb{P}\left(N_n^* \geq tn^{1-1/\alpha}u\right) du \\ &\leq pt^p \int_0^\infty u^{p-1} \mathbb{P}\left(N_n^* \geq \lfloor tn^{1-1/\alpha} \rfloor\right)^{\lfloor u \rfloor} du \leq pt^p \int_0^\infty u^{p-1} \left(\frac{2}{3}\right)^{\lfloor u \rfloor} du, \end{aligned} \quad (18)$$

where the first inequality in (18) comes from (17). Thus, for all  $p \geq 1$ ,

$$\sup_n \mathbb{E}\left[\left(\frac{N_n^*}{n^{1-1/\alpha}}\right)^p\right] < \infty. \quad (19)$$

The lemma now follows from (15). □

The next step is the

**Lemma 12.** *Under the hypotheses of Proposition 7, we have*

$$\int_{|t| \leq n^{-\delta+\bar{\eta}}} e^{-it \lfloor n^\delta x \rfloor} \mathbb{E}\left[\left\{ \prod_y \varphi_\xi(tN_n(y)) - e^{-|t|^\beta V_n(A_1 + iA_2 \text{sgn}(t))} \right\} \mathbf{1}_{\Omega_n}\right] dt = o(n^{-\delta}),$$

uniformly in  $x \in \mathbb{R}$ , where  $A_1$  and  $A_2$  are the constants appearing in (12).

*Proof.* It suffices to prove that

$$\int_{|t| \leq n^{-\delta + \bar{\eta}}} \left| \mathbb{E} \left[ \prod_y \varphi_\xi(tN_n(y)) \mathbf{1}_{\Omega_n} \right] - \mathbb{E} \left[ e^{-|t|^\beta V_n(A_1 + iA_2 \text{sgn}(t))} \mathbf{1}_{\Omega_n} \right] \right| dt = o(n^{-\delta}).$$

Set

$$E_n(t) := \prod_y \varphi_\xi(tN_n(y)) - \prod_y \exp \left( -|t|^\beta N_n^\beta(y)(A_1 + iA_2 \text{sgn}(t)) \right).$$

Observe that

$$\begin{aligned} E_n(t) &= \sum_y \left( \prod_{z < y} \varphi_\xi(tN_n(z)) \right) \left( \varphi_\xi(tN_n(y)) - e^{-|t|^\beta N_n^\beta(y)(A_1 + iA_2 \text{sgn}(t))} \right) \\ &\quad \times \left( \prod_{z > y} e^{-|t|^\beta N_n^\beta(z)(A_1 + iA_2 \text{sgn}(t))} \right). \end{aligned}$$

But on  $\Omega_n$ , if  $|t| \leq n^{-\delta + \bar{\eta}}$ , then

$$|t|N_n(z) \leq n^{\eta + \bar{\eta} - \frac{1}{\alpha\beta}}. \tag{20}$$

This implies in particular that  $|t|N_n(z) < \varepsilon_0$  for  $n$  large enough, since the hypothesis on  $\eta$  implies  $\eta + \bar{\eta} < 1/(\alpha\beta)$ . Thus by using (13) we get

$$|E_n(t)| \leq \sum_y \left| \varphi_\xi(tN_n(y)) - \exp \left( -|t|^\beta N_n^\beta(y)(A_1 + iA_2 \text{sgn}(t)) \right) \right| \exp \left( -\sigma |t|^\beta \sum_{z \neq y} N_n^\beta(z) \right),$$

for  $n$  large enough. Observe next that (12) implies

$$\left| \varphi_\xi(u) - \exp \left( -|u|^\beta (A_1 + iA_2 \text{sgn}(u)) \right) \right| \leq |u|^\beta h(|u|) \quad \text{for all } u \in \mathbb{R},$$

with  $h$  a continuous and monotone function on  $[0, +\infty)$  vanishing in 0. Therefore by using (20) we get

$$|E_n(t)| \leq |t|^\beta h(n^{\eta + \bar{\eta} - \frac{1}{\alpha\beta}}) \sum_y N_n^\beta(y) \exp \left( -\sigma |t|^\beta \sum_{z \neq y} N_n^\beta(z) \right).$$

Now on  $\Omega_n$ , according to (7) and the hypothesis on  $\eta$ , if  $n$  is large enough,

$$\sum_{z \neq y} N_n^\beta(z) \geq V_n/2 \quad \text{for all } y \in \mathbb{Z}.$$

By using this and the change of variables  $v = tV_n^{1/\beta}$ , we get

$$\int_{|t| \leq n^{-\delta + \bar{\eta}}} \mathbb{E} [|E_n(t)| \mathbf{1}_{\Omega_n}] dt \leq h(n^{\eta + \bar{\eta} - \frac{1}{\alpha\beta}}) \mathbb{E}[V_n^{-1/\beta}] \int_{\mathbb{R}} |v|^\beta \exp \left( -\sigma |v|^\beta / 2 \right) dv = o(\mathbb{E}[V_n^{-1/\beta}]),$$

which proves the result according to Lemma 11.  $\square$

Finally Proposition 7 follows from the

**Lemma 13.** *Under the hypotheses of Proposition 7, we have*

$$\frac{d}{2\pi} \int_{|t| \leq n^{-\delta + \bar{\eta}}} e^{-it[n^\delta x]} \mathbb{E} \left[ e^{-|t|^\beta V_n(A_1 + iA_2 \text{sgn}(t))} \mathbf{1}_{\Omega_n} \right] dt = d \frac{C(x)}{n^\delta} + o(n^{-\delta}),$$

uniformly in  $x \in \mathbb{R}$ .

*Proof.* Set

$$I_{n,x} := \int_{|t| \leq n^{-\delta+\bar{\eta}}} e^{-it \lfloor n^\delta x \rfloor} e^{-|t|^\beta V_n(A_1+iA_2 \text{sgn}(t))} dt.$$

Since  $|\lfloor n^\delta x \rfloor - n^\delta x| \leq 1$ , for all  $n$  and  $x$ , it is immediate that

$$I_{n,x} = \int_{|t| \leq n^{-\delta+\bar{\eta}}} e^{-itn^\delta x} e^{-|t|^\beta V_n(A_1+iA_2 \text{sgn}(t))} dt + \mathcal{O}(n^{-2\delta+2\bar{\eta}}).$$

But  $2\bar{\eta} < 1/(\alpha\beta) < \delta$  by hypothesis. So actually

$$I_{n,x} = \int_{|t| \leq n^{-\delta+\bar{\eta}}} e^{-itn^\delta x} e^{-|t|^\beta V_n(A_1+iA_2 \text{sgn}(t))} dt + o(n^{-\delta}).$$

Next, after some changes of variables, we get:

$$\int_{|t| \leq n^{-\delta+\bar{\eta}}} e^{-itn^\delta x} e^{-|t|^\beta V_n(A_1+iA_2 \text{sgn}(t))} dt = n^{-\delta} \left\{ 2\pi \frac{n^\delta}{V_n^{1/\beta}} f_\beta \left( \frac{n^\delta x}{V_n^{1/\beta}} \right) - J_{n,x} \right\}, \quad (21)$$

where

$$J_{n,x} := \int_{|v| \geq n^{\bar{\eta}}} e^{-ivx} e^{-|v|^\beta \frac{V_n}{n^{\beta\delta}}(A_1+iA_2 \text{sgn}(v))} dv.$$

Now it is known that  $W_n := n^\delta V_n^{-1/\beta}$  converges in distribution, as  $n \rightarrow \infty$ , toward  $W := |L|_\beta^{-1}$  (see [11] Lemma 14 or [23] Lemma 6). Then by Skorohod's representation Theorem, we can find a sequence  $(\widetilde{W}_n, n \geq 1)$  and  $\widetilde{W}$  distributed respectively as  $(W_n, n \geq 1)$  and  $W$  such that  $\widetilde{W}_n$  converges almost surely toward  $\widetilde{W}$ . Moreover, Lemma 11 ensures that the sequence  $(\widetilde{W}_n, n \geq 1)$  is uniformly integrable, so actually the convergence holds in  $\mathbb{L}^1$ . Let us deduce that

$$\mathbb{E}[g_x(W_n)] = \mathbb{E}[g_x(W)] + o(1), \quad (22)$$

where  $g_x : z \mapsto z f_\beta(xz)$  and the  $o(1)$  is uniform in  $x$ . First

$$\begin{aligned} |\mathbb{E}[g_x(W_n)] - \mathbb{E}[g_x(W)]| &\leq \sup_{x,z \in \mathbb{R}} |(g_x)'(z)| \mathbb{E}[|\widetilde{W}_n - \widetilde{W}|] \\ &\leq \sup_u |f_\beta(u) + u f'_\beta(u)| \mathbb{E}[|\widetilde{W}_n - \widetilde{W}|]. \end{aligned}$$

But remember that

$$f_\beta(u) = \frac{1}{2\pi} \int_{\mathbb{R}} e^{itu} e^{-|t|^\beta(A_1+iA_2 \text{sgn}(t))} dt.$$

So after differentiation under the integral sign and integration by parts we get

$$u f'_\beta(u) = -\frac{1}{2\pi} \int_{\mathbb{R}} e^{itu} (1 - \beta \text{sgn}(t) |t|^\beta (A_1 + iA_2 \text{sgn}(t))) e^{-|t|^\beta(A_1+iA_2 \text{sgn}(t))} dt.$$

In particular  $\sup_u |f_\beta(u) + u f'_\beta(u)|$  is finite, and this proves (22).

In view of (21) it only remains to prove that  $\mathbb{E}[J_{n,x} \mathbf{1}_{\Omega_n}] = o(1)$ . But this follows from the basic inequality

$$\mathbb{E}[|J_{n,x} \mathbf{1}_{\Omega_n}|] \leq \int_{|v| \geq n^{\bar{\eta}}} \mathbb{E} \left[ e^{-A_1 |v|^\beta \frac{V_n}{n^{\beta\delta}}} \mathbf{1}_{\Omega_n} \right] dv,$$

and from the lower bound for  $V_n$  given in (7). □

**2.6. Proof of Proposition 8.** Recall that on  $\Omega_n$ ,  $N_n(y) \leq n^{1-\frac{1}{\alpha}+\eta}$ , for all  $y \in \mathbb{Z}$ . Hence by (13),

$$\int_{n^{-\delta+\bar{\eta}}}^{\varepsilon_0 n^{-1+\frac{1}{\alpha}-\eta}} \mathbb{E} \left[ \prod_y |\varphi_\xi(tN_n(y))| \mathbf{1}_{\Omega_n} \right] dt \leq \int_{n^{-\delta+\bar{\eta}}}^{\varepsilon_0 n^{-1+\frac{1}{\alpha}-\eta}} \mathbb{E} \left[ \exp(-\sigma t^\beta V_n) \mathbf{1}_{\Omega_n} \right] dt.$$

But on  $\Omega_n$ , we can also use the lower bound for  $V_n$  given in (7), which implies that

$$\int_{n^{-\delta+\bar{\eta}}}^{\varepsilon_0 n^{-1+\frac{1}{\alpha}-\eta}} \mathbb{E} \left[ \prod_y |\varphi_\xi(tN_n(y))| \mathbf{1}_{\Omega_n} \right] dt \leq e^{-\sigma n^{c\eta}},$$

for some constant  $c > 0$ , depending on  $\beta$ . This proves the proposition.

**2.7. Proof of Proposition 9.** First note that by using again (13) we get

$$\prod_y |\varphi_\xi(tN_n(y))| \leq \exp \left( -\sigma t^\beta \sum_{z: N_n(z) \leq \varepsilon_0 n^{1-\frac{1}{\alpha}-\varepsilon}} N_n^\beta(z) \right) \quad \text{for all } t \leq n^{-1+\frac{1}{\alpha}+\varepsilon}. \quad (23)$$

The proof will then be a consequence of the

**Lemma 14.** *Under the hypotheses of Proposition 9, for  $n$  large enough and on  $\Omega_n$ , we have*

$$\# \left\{ z : \frac{\varepsilon_0}{10} n^{1-\frac{1}{\alpha}-\varepsilon} \leq N_n(z) \leq \varepsilon_0 n^{1-\frac{1}{\alpha}-\varepsilon} \right\} \geq \left( \frac{\varepsilon_0}{10} \right)^{\frac{2}{\alpha-1}} n^{\frac{1}{\alpha} - \frac{2\varepsilon+\gamma}{\alpha-1}}.$$

Indeed according to this lemma and (23), we get for  $n$  large enough and on  $\Omega_n$ ,

$$\begin{aligned} \prod_y |\varphi_\xi(tN_n(y))| &\leq \exp \left( -\sigma' n^{-\beta(1-\frac{1}{\alpha}+\eta)} n^{\frac{1}{\alpha} - \frac{2\varepsilon+\gamma}{\alpha-1}} n^{\beta(1-\frac{1}{\alpha}-\varepsilon)} \right) \\ &\leq \exp \left( -\sigma' n^{\frac{1}{\alpha} - \beta(\eta+\varepsilon) - \frac{2\varepsilon+\gamma}{\alpha-1}} \right) \quad \text{for all } \varepsilon_0 n^{-1+\frac{1}{\alpha}-\eta} \leq t \leq n^{-1+\frac{1}{\alpha}+\varepsilon}, \end{aligned}$$

for some constant  $\sigma' > 0$ . This proves Proposition 9, since the hypothesis on  $\varepsilon$  and  $\gamma$  implies that

$$\frac{1}{\alpha} - \beta(\eta + \varepsilon) - \frac{2\varepsilon + \gamma}{\alpha - 1} > \frac{1}{\alpha} - 2\beta\varepsilon - \frac{3\varepsilon}{\alpha - 1} > 0.$$

*Proof of Lemma 14.* Let  $y_1$  be such that  $N_n(y_1) = N_n^* = \sup_z N_n(z)$ . Since  $n = \sum_z N_n(z) \leq N_n^* R_n$ , we have  $N_n(y_1) \geq n^{1-\frac{1}{\alpha}-\gamma}$ , on  $\Omega_n$ . Set

$$y_0 := \min \left\{ y \geq y_1 : N_n(y) \leq \frac{\varepsilon_0}{2} n^{1-\frac{1}{\alpha}-\varepsilon} \right\}.$$

Observe that  $y_0 > y_1$  for  $n$  large enough, since  $\varepsilon > \gamma$  by hypothesis. In particular

$$N_n(y_0 - 1) > \frac{\varepsilon_0}{2} n^{1-\frac{1}{\alpha}-\varepsilon} \geq N_n(y_0).$$

But on  $\Omega_n$ ,

$$N_n(y_0 - 1) - N_n(y_0) \leq n^{(1-\frac{1}{\alpha}+\gamma)/2}.$$

Moreover, the hypotheses made on  $\gamma$  and  $\varepsilon$  imply that  $\gamma < (1 - 1/\alpha)/3$  and  $\varepsilon < (1 - 1/\alpha)/3$ . Thus  $\varepsilon < (1 - 1/\alpha - \gamma)/2$ , or equivalently  $(1 - 1/\alpha + \gamma)/2 < 1 - 1/\alpha - \varepsilon$ . Therefore

$$\frac{\varepsilon_0}{4} n^{1-\frac{1}{\alpha}-\varepsilon} \leq N_n(y_0) \leq \frac{\varepsilon_0}{2} n^{1-\frac{1}{\alpha}-\varepsilon}, \quad (24)$$

for  $n$  large enough. Next if  $|y_0 - z| \leq \left( \frac{\varepsilon_0}{10} \right)^{\frac{2}{\alpha-1}} n^{\frac{1}{\alpha} - \frac{2\varepsilon+\gamma}{\alpha-1}}$ , then on  $\Omega_n$ ,

$$|N_n(z) - N_n(y_0)| \leq \sqrt{|y_0 - z|^{\alpha-1} n^{1-\frac{1}{\alpha}+\gamma}} \leq \frac{\varepsilon_0}{10} n^{1-\frac{1}{\alpha}-\varepsilon}.$$

Together with (24), this proves the lemma.  $\square$

**2.8. Proof of Proposition 10.** Let  $M$  and  $N$  be two positive integers such that  $\mathbb{P}(X_1 = N) > 0$  and  $\mathbb{P}(X_1 = -M) > 0$ . We denote by  $\mathcal{C}^+$  the  $(M + N)$ -uple  $(N, \dots, N, -M, \dots, -M)$  in which  $N$  is repeated  $M$  times and then  $-M$  is repeated  $N$  times. We denote by  $\mathcal{C}^-$  the "symmetric"  $(M + N)$ -uple  $(-M, \dots, -M, N, \dots, N)$  in which  $-M$  is repeated  $N$  times and then  $N$  is repeated  $M$  times. Set  $T := M + N$  and observe that

$$p := \mathbb{P}((X_1, \dots, X_T) = \mathcal{C}^+) = \mathbb{P}((X_1, \dots, X_T) = \mathcal{C}^-) > 0.$$

Let us notice that  $(X_1, \dots, X_T) = \mathcal{C}^+$  corresponds to a trajectory going up to  $MN$  (in  $M$  steps) and then coming back down to 0 (in  $N$  steps). Analogously,  $(X_1, \dots, X_T) = \mathcal{C}^-$  corresponds to a trajectory that goes down to  $-MN$  (in  $N$  steps) and comes back up to 0 (in  $M$  steps).

We introduce now the event

$$\mathcal{D}_n := \left\{ C_n > \frac{np}{2T} \right\},$$

where

$$C_n := \# \left\{ k = 0, \dots, \left\lfloor \frac{n}{T} \right\rfloor - 1 : (X_{kT+1}, \dots, X_{(k+1)T}) = \mathcal{C}^\pm \right\}.$$

Since the sequences  $(X_{kT+1}, \dots, X_{(k+1)T})$ , for  $k \geq 0$ , are independent of each other, Chernoff's inequality implies that there exists  $c > 0$  such that

$$\mathbb{P}(\mathcal{D}_n) = 1 - o(e^{-cn}).$$

We introduce now the notion of "peak". We say that there is a peak based on  $y$  at time  $n$  if  $S_n = y$  and  $(X_{n+1}, \dots, X_{n+T}) = \mathcal{C}^\pm$ . We will see (in Lemma 15 below) that, on  $\Omega_n \cap \mathcal{D}_n$ , there is a large number of  $y \in \mathbb{Z}$  on which are based a large number of peaks. For any  $y \in \mathbb{Z}$ , let

$$C_n(y) := \# \left\{ k = 0, \dots, \left\lfloor \frac{n}{T} \right\rfloor - 1 : S_{kT} = y \text{ and } (X_{kT+1}, \dots, X_{(k+1)T}) = \mathcal{C}^\pm \right\},$$

be the number of peaks based on  $y$  before time  $n$  (and at times which are multiple of  $T$ ), and let

$$p_n := \# \{ y \in \mathbb{Z} : C_n(y) \geq n^{1-\frac{1}{\alpha}-2\gamma} \},$$

be the number of sites  $y \in \mathbb{Z}$  on which at least  $n^{1-\frac{1}{\alpha}-2\gamma}$  peaks are based.

**Lemma 15.** *On  $\Omega_n \cap \mathcal{D}_n$ , we have  $p_n \geq 3NMn^{\frac{1}{\alpha}-\alpha\gamma}$ , for  $n$  large enough.*

*Proof.* Note that  $C_n(y) \leq N_n(y)$  for all  $y \in \mathbb{Z}$ . Thus on  $\Omega_n \cap \mathcal{D}_n$ ,

$$\begin{aligned} \frac{np}{2T} &\leq \sum_{y \in \mathbb{Z} : C_n(y) < n^{1-\frac{1}{\alpha}-2\gamma}} C_n(y) + \sum_{y \in \mathbb{Z} : C_n(y) \geq n^{1-\frac{1}{\alpha}-2\gamma}} C_n(y) \\ &\leq n^{1-\frac{1}{\alpha}-2\gamma} R_n + N_n^* p_n \\ &\leq n^{1-\gamma} + p_n n^{1-\frac{1}{\alpha}+\frac{\alpha\gamma}{2}}, \end{aligned}$$

according to (11). This proves the lemma.  $\square$

We have proved that, if  $n$  is large enough, the event  $\Omega_n \cap \mathcal{D}_n$  is contained in the event

$$\mathcal{E}_n := \{ p_n \geq 3NMn^{\frac{1}{\alpha}-\alpha\gamma} \}.$$

Now, on  $\mathcal{E}_n$ , we define  $Y_i$  for  $i = 1, \dots, \left\lfloor n^{\frac{1}{\alpha}-\alpha\gamma} \right\rfloor$ , by

$$Y_1 := \min \left\{ y \in \mathbb{Z} : C_n(y) \geq n^{1-\frac{1}{\alpha}-2\gamma} \right\},$$

and

$$Y_{i+1} := \min \left\{ y \geq Y_i + 3NM : C_n(y) \geq n^{1-\frac{1}{\alpha}-2\gamma} \right\} \quad \text{for } i \geq 1.$$

The  $Y_i$ 's are sites on which at least  $n^{1-\frac{1}{\alpha}-2\gamma}$  peaks are based and are such that  $|Y_i - Y_j| \geq 3NM$ , if  $i \neq j$ . For every  $i = 1, \dots, \lfloor n^{\frac{1}{\alpha}-\alpha\gamma} \rfloor$ , let  $t_i^1, \dots, t_i^{\lfloor n^{1-\frac{1}{\alpha}-2\gamma} \rfloor}$  be the  $\lfloor n^{1-\frac{1}{\alpha}-2\gamma} \rfloor$  first times (which are multiples of  $T$ ) when a peak is based on the site  $Y_i$ . We also define  $N_n^0(Y_i + NM)$  as the number of visits of  $S$  before time  $n$  to  $Y_i + NM$ , which do not occur during the time intervals  $[t_i^j, t_i^j + T]$ , for  $j \leq \lfloor n^{1-\frac{1}{\alpha}-2\gamma} \rfloor$ .

**Lemma 16.** *Conditionally to the event  $\mathcal{E}_n$ ,  $((N_n(Y_i + MN) - N_n^0(Y_i + MN), i \geq 1)$  is a sequence of independent identically distributed random variables with binomial distribution  $\mathcal{B} \left( \lfloor n^{1-\frac{1}{\alpha}-2\gamma} \rfloor; \frac{1}{2} \right)$ . Moreover this sequence is independent of  $((N_n^0(Y_i + MN), i \geq 1)$ .*

*Proof.* On  $\mathcal{E}_n$ , we have

$$N_n(Y_i + MN) - N_n^0(Y_i + MN) = \sum_{j=1}^{\lfloor n^{1-\frac{1}{\alpha}-2\gamma} \rfloor} \mathbf{1}_{\{(X_{t_i^j+1}, \dots, X_{t_i^j+T}) \in \mathcal{C}^+\}},$$

since the peaks based on the other  $Y_k$ 's cannot pass through  $Y_i + MN$ . But conditionally to  $\mathcal{E}_n$ , the sequence  $\left( \mathbf{1}_{\{(X_{t_i^j+1}, \dots, X_{t_i^j+T}) \in \mathcal{C}^+\}} \right)_{i,j}$  is a sequence of independent Bernoulli random variables with parameter  $1/2$ , which is independent of  $(X_k, k \notin \bigcup_{i,j} [t_i^j, \dots, t_i^j + T])$ . Since  $N_n^0(Y_i + MN)$  only depends on the values of the  $X_k$ 's for  $k \notin \bigcup_{i,j} [t_i^j, \dots, t_i^j + T]$ , the result follows.  $\square$

Let now  $\rho := \sup\{|\varphi_\xi(u)| : d(u, \frac{2\pi}{d}\mathbb{Z}) \geq \varepsilon_0\}$ . According to Formula (13),

$$\begin{aligned} |\varphi_\xi(u)| &\leq \rho \mathbf{1}_{\{d(u, \frac{2\pi}{d}\mathbb{Z}) \geq \varepsilon_0\}} + \exp\left(-\sigma d\left(u, \frac{2\pi}{d}\mathbb{Z}\right)^\beta\right) \mathbf{1}_{\{d(u, \frac{2\pi}{d}\mathbb{Z}) < \varepsilon_0\}} \\ &\leq \exp\left(-\sigma n^{-\frac{1}{\alpha}+2\alpha\gamma}\right), \end{aligned}$$

as soon as  $d(u, \frac{2\pi}{d}\mathbb{Z}) \geq n^{-\frac{1}{\alpha\beta}+\frac{2\alpha\gamma}{\beta}}$ , and  $\rho \leq \exp\left(-\sigma n^{-\frac{1}{\alpha}+2\alpha\gamma}\right)$ . But recall that  $\rho < 1$  and  $2\alpha^2\gamma < 1$ . Therefore, for  $n$  large enough,

$$\prod_z |\varphi_\xi(tN_n(z))| \leq \exp\left(-\sigma n^{-\frac{1}{\alpha}+2\alpha\gamma} \# \left\{ z : d\left(tN_n(z), \frac{2\pi}{d}\mathbb{Z}\right) \geq n^{-\frac{1}{\alpha\beta}+\frac{2\alpha\gamma}{\beta}} \right\}\right). \quad (25)$$

Then notice that

$$d\left(tN_n(z), \frac{2\pi}{d}\mathbb{Z}\right) \geq n^{-\frac{1}{\alpha\beta}+\frac{2\alpha\gamma}{\beta}} \iff N_n(z) \in \mathcal{I} := \bigcup_{k \in \mathbb{Z}} I_k, \quad (26)$$

where for all  $k \in \mathbb{Z}$ ,

$$I_k := \left[ \frac{2k\pi}{dt} + \frac{n^{-\frac{1}{\alpha\beta}+\frac{2\alpha\gamma}{\beta}}}{t}, \frac{2(k+1)\pi}{dt} - \frac{n^{-\frac{1}{\alpha\beta}+\frac{2\alpha\gamma}{\beta}}}{t} \right].$$

In particular  $\mathbb{R} \setminus \mathcal{I} = \bigcup_{k \in \mathbb{Z}} J_k$ , where for all  $k \in \mathbb{Z}$ ,

$$J_k := \left( \frac{2k\pi}{dt} - \frac{n^{-\frac{1}{\alpha\beta}+\frac{2\alpha\gamma}{\beta}}}{t}, \frac{2k\pi}{dt} + \frac{n^{-\frac{1}{\alpha\beta}+\frac{2\alpha\gamma}{\beta}}}{t} \right).$$

**Lemma 17.** *Under the hypotheses of Proposition 10, for every  $i \leq \lfloor n^{\frac{1}{\alpha}-\alpha\gamma} \rfloor$ ,  $t \in (n^{-1+\frac{1}{\alpha}+\varepsilon}, \pi/d)$  and  $n$  large enough,*

$$\mathbb{P} \left( N_n(Y_i + MN) \in \mathcal{I} \mid \mathcal{E}_n, N_n^0(Y_i + MN) \right) \geq \frac{1}{3} \quad \text{almost surely.}$$

Assume for a moment that this lemma holds true and let us finish now the proof of Proposition 10. Lemmas 16 and 17 ensure that conditionally to  $\mathcal{E}_n$  and  $((N_n^0(Y_i + MN), i \geq 1)$ , the events  $\{N_n(Y_i + MN) \in \mathcal{I}\}$ ,  $i \geq 1$ , are independent of each other, and all happen with probability at least  $1/3$ . Therefore, since  $\Omega_n \cap \mathcal{D}_n \subseteq \mathcal{E}_n$ , there exists  $c > 0$ , such that

$$\mathbb{P} \left( \Omega_n \cap \mathcal{D}_n, \#\{i : N_n(Y_i + MN) \in \mathcal{I}\} \leq \frac{n^{\frac{1}{\alpha}-\alpha\gamma}}{4} \right) \leq \mathbb{P} \left( B_n \leq \frac{n^{\frac{1}{\alpha}-\alpha\gamma}}{4} \right) = o(\exp(-cn)),$$

where for all  $n \geq 1$ ,  $B_n$  has binomial distribution  $\mathcal{B} \left( \lfloor n^{\frac{1}{\alpha}-\alpha\gamma} \rfloor; \frac{1}{3} \right)$ .

But if  $\#\{z : N_n(z) \in \mathcal{I}\} \geq n^{\frac{1}{\alpha}-\alpha\gamma}/4$ , then by (25) and (26) there exists a constant  $c > 0$ , such that

$$\prod_z |\varphi_\xi(tN_n(z))| \leq \exp \left( -cn^{\frac{1}{\alpha}-\alpha\gamma} n^{-\frac{1}{\alpha}+2\alpha\gamma} \right),$$

which proves Proposition 10.

*Proof of Lemma 17.* First notice that by Lemma 16, for any  $H \geq 0$ ,

$$\mathbb{P}(N_n(Y_i + MN) \in \mathcal{I} \mid \mathcal{E}_n, N_n^0(Y_i + MN) = H) = \mathbb{P}(H + b_n \in \mathcal{I}), \quad (27)$$

where  $b_n$  is a random variable with binomial distribution  $\mathcal{B} \left( \lfloor n^{1-\frac{1}{\alpha}-2\gamma} \rfloor; \frac{1}{2} \right)$ . We will use the following result whose proof is postponed.

**Lemma 18.** *Under the hypotheses of Proposition 10, for every  $t \in (n^{-1+\frac{1}{\alpha}+\varepsilon}, \pi/d)$  and for  $n$  large enough, the following holds:*

- (i) *For any integer  $k$  such that all the elements of  $I_k - H$  are smaller than  $\frac{1}{2} \lfloor n^{1-\frac{1}{\alpha}-2\gamma} \rfloor$ ,*

$$\mathbb{P}(b_n \in (I_k - H)) \geq \mathbb{P}(b_n \in (J_k - H)).$$
- (ii) *For any integer  $k$  such that all the elements of  $I_k - H$  are larger than  $\frac{1}{2} \lfloor n^{1-\frac{1}{\alpha}-2\gamma} \rfloor$ ,*

$$\mathbb{P}(b_n \in (I_k - H)) \geq \mathbb{P}(b_n \in (J_{k+1} - H)).$$

Now call  $k_0$  the largest integer satisfying the condition appearing in (i) and  $k_1$  the smallest integer satisfying the condition appearing in (ii). We have  $k_1 = k_0 + 1$  or  $k_1 = k_0 + 2$ . According to Lemma 18, we have

$$\begin{aligned} \mathbb{P}(H + b_n \in \mathcal{I}) &\geq \sum_{k \leq k_0} \mathbb{P}(H + b_n \in I_k) + \sum_{k \geq k_1} \mathbb{P}(H + b_n \in I_k) \\ &\geq \sum_{k \leq k_0} \mathbb{P}(H + b_n \in J_k) + \sum_{k \geq k_1} \mathbb{P}(H + b_n \in J_{k+1}) \\ &= \mathbb{P}(H + b_n \notin \mathcal{I}) - \mathbb{P}(H + b_n \in J_{k_0+1} \cup J_{k_1}). \end{aligned}$$

Hence,

$$\mathbb{P}(H + b_n \in \mathcal{I}) \geq \frac{1}{2} [1 - \mathbb{P}(H + b_n \in J_{k_0+1} \cup J_{k_1})].$$

Let  $\bar{b}_n := 2 \left( b_n - \frac{1}{2} \left\lfloor n^{1-\frac{1}{\alpha}-2\gamma} \right\rfloor \right) \left\lfloor n^{1-\frac{1}{\alpha}-2\gamma} \right\rfloor^{-1/2}$ , so that  $\bar{b}_n$  converges in distribution to a standard normal variable, whose distribution function is denoted by  $\Phi$ . The interval  $J_{k_1}$  being of length  $2n^{-\frac{1}{\alpha\beta} + \frac{2\alpha\gamma}{\beta}}/t$ ,

$$\begin{aligned} \mathbb{P}(H + b_n \in J_{k_1}) &= \mathbb{P}(\bar{b}_n \in [m_n, M_n]), \text{ with } M_n - m_n = 4 \frac{n^{-\frac{1}{\alpha\beta} + \frac{2\alpha\gamma}{\beta}}}{t \sqrt{\left\lfloor n^{1-\frac{1}{\alpha}-2\gamma} \right\rfloor}} \\ &\leq \Phi(M_n) - \Phi(m_n) + \frac{C}{\sqrt{n^{1-\frac{1}{\alpha}-2\gamma}}} \text{ (by the Berry-Esseen inequality)} \\ &\leq \frac{M_n - m_n}{\sqrt{2\pi}} + \frac{C}{\sqrt{n^{1-\frac{1}{\alpha}-2\gamma}}} \\ &\leq C' n^{\frac{1}{2} + \frac{1}{2\alpha} + \gamma + \frac{2\alpha\gamma}{\beta} - \frac{1}{\alpha\beta} - \frac{1}{\alpha} - \varepsilon} + \frac{C}{\sqrt{n^{1-\frac{1}{\alpha}-2\gamma}}}, \end{aligned}$$

for  $t \geq n^{-1+\frac{1}{\alpha}+\varepsilon}$ , and some constants  $C > 0$  and  $C' > 0$ . Since  $\alpha \leq 2$ ,  $\beta \leq 2$ ,  $\gamma < \frac{1}{2} \frac{\alpha-1}{\alpha}$ , and  $\varepsilon > 2\alpha\gamma/\beta + \gamma$  by hypothesis, we conclude that  $\mathbb{P}(H + b_n \in J_{k_1}) = o(1)$ . The same holds for  $\mathbb{P}(H + b_n \in J_{k_0+1})$ , so that for  $n$  large enough,

$$\mathbb{P}(H + b_n \in \mathcal{I}) \geq \frac{1}{2} [1 - o(1)] \geq \frac{1}{3}.$$

Together with (27), this concludes the proof of Lemma 17.  $\square$

*Proof of Lemma 18.* We only prove (i), since (ii) is similar. So let  $k$  be an integer such that all the elements of  $I_k - H$  are smaller than  $\frac{1}{2} \left\lfloor n^{1-\frac{1}{\alpha}-2\gamma} \right\rfloor$ . Assume that  $(J_k - H) \cap \mathbb{Z}$  contains at least one nonnegative integer (otherwise  $\mathbb{P}(b_n \in (J_k - H)) = 0$  and there is nothing to prove). Let  $z_k$  denote the greatest integer in  $J_k - H$ , so that by our assumption  $\mathbb{P}(b_n = z_k) > 0$  (remind that  $0 \leq z_k < \frac{1}{2} \left\lfloor n^{1-\frac{1}{\alpha}-2\gamma} \right\rfloor$ ). By monotonicity of the function  $z \mapsto \mathbb{P}(b_n = z)$ , for  $z \leq \frac{1}{2} \left\lfloor n^{1-\frac{1}{\alpha}-2\gamma} \right\rfloor$ , we get

$$\mathbb{P}(b_n \in J_k - H) \leq \mathbb{P}(b_n = z_k) \#((J_k - H) \cap \mathbb{Z}) \leq \mathbb{P}(b_n = z_k) \left\lceil \frac{2n^{-\frac{1}{\alpha\beta} + \frac{2\alpha\gamma}{\beta}}}{t} \right\rceil.$$

In the same way,

$$\mathbb{P}(b_n \in I_k - H) \geq \mathbb{P}(b_n = z_k) \#((I_k - H) \cap \mathbb{Z}) \geq \mathbb{P}(b_n = z_k) \left\lfloor \frac{2\pi}{dt} - \frac{2n^{-\frac{1}{\alpha\beta} + \frac{2\alpha\gamma}{\beta}}}{t} \right\rfloor.$$

Hence

$$\mathbb{P}(b_n \in I_k - H) \geq \frac{\left\lfloor \frac{2\pi}{dt} - \frac{2n^{-\frac{1}{\alpha\beta} + \frac{2\alpha\gamma}{\beta}}}{t} \right\rfloor}{\left\lceil \frac{2n^{-\frac{1}{\alpha\beta} + \frac{2\alpha\gamma}{\beta}}}{t} \right\rceil} \mathbb{P}(b_n \in J_k - H).$$

But  $\pi/(dt) \geq 1$  and  $2\alpha^2\gamma < 1$  by hypothesis. It follows immediately that for  $n$  large enough, we have  $2n^{-\frac{1}{\alpha\beta} + \frac{2\alpha\gamma}{\beta}} < \pi/(2d)$ , and so

$$\left\lfloor \frac{2\pi}{dt} - \frac{2n^{-\frac{1}{\alpha\beta} + \frac{2\alpha\gamma}{\beta}}}{t} \right\rfloor \geq \left\lfloor \frac{3\pi}{2dt} \right\rfloor \geq 1 + \left\lfloor \frac{\pi}{2dt} \right\rfloor \geq \left\lceil \frac{\pi}{2dt} \right\rceil \geq \left\lceil \frac{2n^{-\frac{1}{\alpha\beta} + \frac{2\alpha\gamma}{\beta}}}{t} \right\rceil.$$

This concludes the proof of the lemma.  $\square$

3. LATTICE CASE,  $\alpha < 1$ : PROOF OF THEOREM 2

We only sketch the proof, since it is very similar and simpler than in the case  $\alpha > 1$ . In particular we keep the same notation, for instance for  $N_n^*$ ,  $R_n$ ,  $V_n$ ,  $\varepsilon_0, \dots$

We first introduce the analogue  $\Omega'_n$  of  $\Omega_n$ :

$$\Omega'_n = \Omega'_n(\varepsilon) := \{N_n^* \leq n^\varepsilon\},$$

which is well defined for any  $\varepsilon$ . Note that on  $\Omega'_n$ , we have

$$V_n \geq R_n \geq n^{1-\varepsilon}. \tag{28}$$

Since  $N_n^* = \sup_{k=0}^{n-1} [N_n(S_k) - N_k(S_k)]$ , we obtain that

$$\mathbb{P}(N_n^* \geq n^\varepsilon) \leq n\mathbb{P}\left(\sup_m N_m(0) \geq n^\varepsilon\right) \leq np_0^{n^\varepsilon-1},$$

where  $p_0 := \mathbb{P}(\exists k \geq 1 : S_k = 0)$ . Since  $\alpha < 1$ , the random walk  $S$  is transient and  $p_0 < 1$ . It follows that  $\mathbb{P}(\Omega'_n) = 1 - o(\exp(-n^c))$ , for some constant  $c > 0$ , and we can restrict our study to this set. Moreover, it is known (see for instance the introduction in [23] for an argument) that

$$\frac{1}{n}V_n = \frac{1}{n} \sum_{y \in \mathbb{Z}} N_n^\beta(y) \xrightarrow{n \rightarrow +\infty} \mathbb{E}[\tilde{N}_\infty^{\beta-1}(0)] = r^{-\beta} \text{ a.s..}$$

We claim now that  $(n^{1/\beta}V_n^{-1/\beta}, n \geq 1)$  is uniformly integrable. Indeed, if  $\beta \geq 1$ , this comes from the fact that  $V_n$  is larger than  $n$ , and when  $\beta < 1$ , this follows from the

**Lemma 19.** *If  $\beta < 1$ , there exists  $\gamma > 0$  such that*

$$\sup_n \mathbb{E} \left[ \exp \left( \gamma \frac{n}{V_n} \right) \right] < \infty. \tag{29}$$

*Proof.* Since  $n = \sum_x N_n(x)$ , Hölder's inequality gives

$$\frac{n}{V_n} \leq \frac{\sum_x N_n(x)^2}{n}.$$

Since

$$\frac{1}{n} \sum_x N_n(x)^2 = \frac{1}{n} \sum_{k=0}^{n-1} N_n(S_k),$$

Jensen's inequality gives

$$\exp \left( \gamma \frac{\sum_x N_n(x)^2}{n} \right) \leq \frac{1}{n} \sum_{k=0}^{n-1} \exp(\gamma N_n(S_k)).$$

Hence,

$$\begin{aligned} \mathbb{E} \left[ \exp \left( \gamma \frac{\sum_x N_n(x)^2}{n} \right) \right] &\leq \frac{1}{n} \sum_{k=0}^{n-1} \mathbb{E} [\exp(\gamma N_n(S_k))] \\ &\leq \mathbb{E} \left[ \exp \left( \gamma \tilde{N}_\infty(0) \right) \right]. \end{aligned}$$

Then, (29) directly follows from the fact that  $\tilde{N}_\infty(0)$  is equal to 1 plus the sum of two independent geometric variables with positive parameter, and thus has finite exponential moments.  $\square$

Let  $\varepsilon > 0$  and  $\eta > 0$  be such that  $\eta + \varepsilon < 1/\beta$  and  $\varepsilon < \eta\beta < 1/2$ . As in the proof of Proposition 7, we deduce that

$$\frac{d}{2\pi} \int_{|t| \leq n^{-\frac{1}{\beta} + \eta}} e^{-it \left[ n^{\frac{1}{\beta}} x \right]} \mathbb{E} \left[ \prod_y \varphi_\xi(tN_n(y)) \right] dt = \frac{D(x)}{n^{\frac{1}{\beta}}} + o(n^{-\frac{1}{\beta}}),$$

where the  $o(n^{-1/\beta})$  is uniform in  $x$ . It remains to prove that

$$\frac{d}{2\pi} \int_{n^{-\frac{1}{\beta} + \eta}}^{\frac{\pi}{d}} \left| \mathbb{E} \left[ \prod_y \varphi_\xi(tN_n(y)) \mathbf{1}_{\Omega'_n} \right] \right| dt = o(n^{-\frac{1}{\beta}}). \quad (30)$$

As in the proof of Proposition 10 (see the beginning of Section 2.8. for the definitions of  $\mathcal{D}_n$ ,  $C_n, C_n(y), \dots$ ), we are led to prove that

$$\frac{d}{2\pi} \int_{n^{-\frac{1}{\beta} + \eta}}^{\frac{\pi}{d}} \left| \mathbb{E} \left[ \prod_y \varphi_\xi(tN_n(y)) \mathbf{1}_{\Omega'_n \cap \mathcal{D}_n} \right] \right| dt = o(n^{-\frac{1}{\beta}}).$$

Let  $p'_n := \#\{y : C_n(y) \geq 1\}$  be the random variable equal to the number of sites of  $\mathbb{Z}$  on which at least one peak is based. Let us notice that on  $\Omega'_n \cap \mathcal{D}_n$ , we have

$$\frac{np}{2T} \leq C_n = \sum_y C_n(y) \leq \sum_{y : C_n(y) \geq 1} N_n(y) \leq p'_n n^\varepsilon.$$

Thus  $\Omega'_n \cap \mathcal{D}_n \subseteq \mathcal{E}'_n$ , where  $\mathcal{E}'_n := \{p'_n \geq c_0 n^{1-\varepsilon}\}$ , for a well chosen constant  $c_0 > 0$ . As in the proof of Proposition 10, we construct  $(Y_i)_i$  such that  $C_n(Y_i) \geq 1$  and  $Y_{i+1} - Y_i > MN$ . For every  $i$ , we define  $N_n^0(Y_i + MN)$  as the number of visits to the site  $Y_i + MN$  without taking into account the possible visit during the first peak based on  $Y_i$ . Next we see that, on  $\mathcal{E}'_n$ ,  $(N_n(Y_i + MN) - N_n^0(Y_i + MN), i \leq c_0 n^{1-\varepsilon})$  is a sequence of i.i.d. random variables with Bernoulli distribution with parameter  $1/2$ .

Let  $t \in [n^{-\frac{1}{\beta} + \eta}, \frac{\pi}{d}]$ . We define the good and bad intervals respectively by

$$I'_k := \left[ \frac{2k\pi}{dt} + \frac{1}{2}, \frac{2(k+1)\pi}{dt} - \frac{1}{2} \right] \text{ and } J'_k := \left( \frac{2k\pi}{dt} - \frac{1}{2}, \frac{2k\pi}{dt} + \frac{1}{2} \right).$$

Set also  $\mathcal{I}' := \bigcup_{k \in \mathbb{Z}} I'_k$ . We observe that  $J'_k$  is an open interval of length 1 and  $I'_k$  is a closed interval of length  $2\pi/(dt) - 1 \geq 1$  (since  $t \leq \pi/d$ ). Hence, if  $N_n^0(Y_i + MN)$  is not in  $\mathcal{I}'$ , then  $N_n^0(Y_i + MN) + 1$  is in  $\mathcal{I}'$ . This ensures that, on  $\mathcal{E}'_n$ ,  $N_n(Y_i + MN)$  belongs to  $\mathcal{I}'$  with probability at least  $1/2$ . Therefore, as after Lemma 17, we get

$$\mathbb{P} \left( \Omega_n \cap \mathcal{D}_n; \#\{i : N_n(Y_i + MN) \in \mathcal{I}'\} < \frac{c_0 n^{1-\varepsilon}}{3} \right) = o(n^{-\frac{1}{\beta}}).$$

Hence, we just have to prove that

$$\frac{d}{2\pi} \int_{n^{-\frac{1}{\beta} + \eta}}^{\frac{\pi}{d}} \left| \mathbb{E} \left[ \prod_y \varphi_\xi(tN_n(y)) \mathbf{1}_{\mathcal{H}_{n,t}} \right] \right| dt = o(n^{-\frac{1}{\beta}}),$$

with  $\mathcal{H}_{n,t} := \left\{ \#\{y : N_n(y) \in \mathcal{I}'\} \geq \frac{c_0 n^{1-\varepsilon}}{3} \right\}$ . As after Lemma 16, we notice that, if  $n$  is large enough, we have

$$d \left( u, \frac{2\pi}{d} \mathbb{Z} \right) \geq \frac{n^{-\frac{1}{\beta} + \eta}}{2} \Rightarrow |\varphi_\xi(u)| \leq \exp \left( -\frac{\sigma}{2\beta} n^{-1+\beta\eta} \right).$$

We notice also that if  $N_n(y) \in \mathcal{I}'$ , then  $d(tN_n(y), \frac{2\pi}{d}\mathbb{Z}) \geq t/2$ , and thus  $d(tN_n(y), \frac{2\pi}{d}\mathbb{Z}) \geq n^{-\frac{1}{\beta}+\eta}/2$ . Now, on  $\mathcal{H}_{n,t}$ , we know that at least  $c_0 n^{1-\varepsilon}/3$  sites  $y$  satisfy this property. Therefore

$$\left| \mathbb{E} \left[ \prod_y \varphi_\xi(tN_n(y)) \mathbf{1}_{\mathcal{H}_{n,t}} \right] \right| \leq \exp \left( -\frac{c_0 \sigma}{2^{\beta 3}} n^{1-\varepsilon} n^{-1+\beta\eta} \right) = o(n^{-\frac{1}{\beta}}),$$

since  $\varepsilon < \beta\eta$ . This gives (30) and achieves the proof of Theorem 2.  $\square$

#### 4. THE STRONGLY NONLATTICE CASE: PROOF OF THEOREM 3

We assume here that  $\xi$  is strongly nonlattice. In that case, there exist  $\varepsilon_0 > 0$ ,  $\sigma > 0$  and  $\rho < 1$  such that

- $|\varphi_\xi(u)| \leq \rho$  if  $|u| \geq \varepsilon_0$ ,
- $|\varphi_\xi(u)| \leq \exp(-\sigma|u|^\beta)$  if  $|u| < \varepsilon_0$ .

**Case  $\alpha > 1$ .** We use here the notations of Section 2 with the hypotheses on  $\gamma$ ,  $\eta$ ,  $\bar{\eta}$  and  $\varepsilon$  of propositions 7, 8, 9 and 10. Let  $h_0$  be the density of Polya's distribution:

$$h_0(y) = \frac{1}{\pi} \frac{1 - \cos(y)}{y^2}.$$

Its Fourier transform is  $\hat{h}_0(t) = (1 - |t|)_+$ . For  $\theta \in \mathbb{R}$ , let  $h_\theta(y) = \exp(i\theta y)h_0(y)$  with Fourier transform  $\hat{h}_\theta(t) = \hat{h}_0(t + \theta)$ . As is proved in [16] (see the proof of Theorem 5.4 p.114), it is enough to show that for all  $\theta \in \mathbb{R}$ ,

$$\lim_{n \rightarrow \infty} n^\delta \mathbb{E} \left[ h_\theta(Z_n - n^\delta x) \right] = C(x) \hat{h}_\theta(0). \tag{31}$$

By Fourier inverse transform,

$$n^\delta \mathbb{E} \left[ h_\theta(Z_n - n^\delta x) \right] = \frac{n^\delta}{2\pi} \int_{\mathbb{R}} e^{-iun^\delta x} \mathbb{E} \left[ \prod_{x \in \mathbb{Z}} \varphi_\xi(uN_n(x)) \right] \hat{h}_\theta(u) du.$$

Since  $\hat{h}_\theta \in L^1$ , we can restrict our study to the event  $\Omega_n$  of Lemma 6. The part of the integral corresponding to  $|u| \leq n^{-\delta+\bar{\eta}}$  is treated exactly as in Proposition 7. The only change is that we have to check that

$$\lim_{n \rightarrow \infty} n^\delta \int_{|u| \leq n^{-\delta+\bar{\eta}}} \mathbb{E} \left[ e^{-|u|^\beta V_n(A_1 + iA_2 \operatorname{sgn}(u))} \mathbf{1}_{\Omega_n} \right] (\hat{h}_\theta(u) - \hat{h}_\theta(0)) du = 0,$$

which is obviously the case since  $2\bar{\eta} < \delta$ , using the fact that  $\hat{h}_\theta$  is a Lipschitz function.

Now since  $\hat{h}_\theta$  is bounded, the part corresponding to  $n^{-\delta+\bar{\eta}} \leq |u| \leq n^{-1+\frac{1}{\alpha}+\varepsilon}$  doesn't need any additional treatment. Actually, the proofs of Propositions 8 and 9 only use the behavior of  $\varphi_\xi$  around 0, which is the same in the lattice or nonlattice case.

We now turn our attention to the part of the integral corresponding to  $|u| \geq n^{-1+\frac{1}{\alpha}+\varepsilon}$  and prove that

$$\lim_{n \rightarrow \infty} n^\delta \int_{|u| \geq n^{-1+\frac{1}{\alpha}+\varepsilon}} e^{-iun^\delta x} \mathbb{E} \left[ \prod_x \varphi_\xi(uN_n(x)) \mathbf{1}_{\Omega_n} \right] \hat{h}_\theta(u) du = 0. \tag{32}$$

To this end, note that

$$\left| \mathbb{E} \left[ \prod_x \varphi_\xi(uN_n(x)) \mathbf{1}_{\Omega_n} \right] \right| \leq \mathbb{E} \left[ \rho^{\#\{x : |uN_n(x)| \geq \varepsilon_0\}} \mathbf{1}_{\Omega_n} \right],$$

and that on  $\Omega_n$ , for  $|u| \geq n^{-1+\frac{1}{\alpha}+\varepsilon}$ ,

$$\begin{aligned} n = \sum_x N_n(x) &\leq \frac{\varepsilon_0}{|u|} R_n + N_n^* \#\{x : |uN_n(x)| \geq \varepsilon_0\} \\ &\leq \varepsilon_0 n^{1-\varepsilon+\eta\beta/2} + n^{1-\frac{1}{\alpha}+\eta} \#\{x : |uN_n(x)| \geq \varepsilon_0\}. \end{aligned}$$

Hence, since  $\varepsilon > \eta\beta/2$ , for  $n$  large enough, on  $\Omega_n$ , and for  $|u| \geq n^{-1+\frac{1}{\alpha}+\varepsilon}$ ,

$$\#\{x : |uN_n(x)| \geq \varepsilon_0\} \geq \frac{1}{2} n^{\frac{1}{\alpha}-\eta}.$$

Therefore, for  $n$  large enough,

$$\left| n^\delta \int_{|u| \geq n^{-1+\frac{1}{\alpha}+\varepsilon}} e^{-iun^\delta x} \mathbb{E} \left[ \prod_x \varphi_\xi(uN_n(x)) \mathbf{1}_{\Omega_n} \right] \hat{h}_\theta(u) du \right| \leq n^\delta \rho^{\frac{1}{2}n^{\frac{1}{\alpha}-\eta}} \int_{\mathbb{R}} \hat{h}_\theta(u) du,$$

which tends to zero since  $\eta < 1/\alpha$ .

**Case  $\alpha < 1$ .** Using the notations and hypotheses on  $\varepsilon, \eta, \gamma$  of Section 3, one has to prove that for all  $\theta \in \mathbb{R}$  and all  $x \in \mathbb{R}$ ,

$$\lim_{n \rightarrow \infty} n^{1/\beta} \int_{\mathbb{R}} e^{-iun^{1/\beta}x} \mathbb{E} \left[ \prod_x \varphi_\xi(uN_n(x)) \mathbf{1}_{\Omega'_n} \right] \hat{h}_\theta(u) du = D(x) \hat{h}_\theta(0). \quad (33)$$

Again, the only change in the proof concerns the part of the integral corresponding to  $|u| \geq n^{-1/\beta+\eta}$ . We use here the bound

$$\begin{aligned} |\varphi_\xi(uN_n(x))| &\leq \exp(-\sigma|u|^\beta N_n^\beta(x)) \mathbf{1}_{\{|uN_n(x)| \leq \varepsilon_0\}} + \rho \mathbf{1}_{\{|uN_n(x)| \geq \varepsilon_0\}} \\ &\leq \exp(-\sigma n^{-1+\eta\beta} N_n^\beta(x)) \mathbf{1}_{\{|uN_n(x)| \leq \varepsilon_0\}} + \rho \mathbf{1}_{\{|uN_n(x)| \geq \varepsilon_0\}}. \end{aligned}$$

If  $\eta < 1/\beta$ , then for  $n$  large enough,  $\rho \leq \exp(-\sigma n^{-1+\eta\beta})$ . Therefore, if  $n$  is large enough, then for all  $x$  and  $u$  such that  $N_n(x) \geq 1$  and  $|u| \geq n^{-1/\beta+\eta}$ , we have

$$|\varphi_\xi(uN_n(x))| \leq \exp(-\sigma n^{-1+\eta\beta}).$$

Hence,

$$\left| \mathbb{E} \left[ \prod_x \varphi_\xi(uN_n(x)) \mathbf{1}_{\Omega'_n} \right] \right| \leq \mathbb{E} \left[ \exp(-\sigma n^{-1+\eta\beta} R_n) \mathbf{1}_{\Omega'_n} \right] \leq \exp(-\sigma n^{\eta\beta-\varepsilon}).$$

Therefore, since  $\varepsilon < \eta\beta$ ,

$$\lim_{n \rightarrow \infty} n^{1/\beta} \int_{|u| \geq n^{-1/\beta+\eta}} e^{-iun^{1/\beta}x} \mathbb{E} \left[ \prod_x \varphi_\xi(uN_n(x)) \mathbf{1}_{\Omega'_n} \right] \hat{h}_\theta(u) du = 0.$$

This concludes the proof of Theorem 3. □

## 5. RANDOM WALKS ON RANDOMLY ORIENTED LATTICES

**5.1. Model and result.** We consider parallel moving pavements with different fixed speeds, independently chosen at the beginning with the same distribution. We study the random walk  $(M_n, n \geq 0)$  representing the position of a walker who at each time stays on the same moving pavement with probability  $p \in (0, 1)$ , or jumps to another one with probability  $1 - p$ .

Let us define  $(M_n, n \geq 0)$  more precisely. Let  $\mu_X$  be a distribution on  $\mathbb{Z}$  in the normal domain of attraction of a centered stable distribution with index  $1 < \alpha \leq 2$  and density function denoted by  $f_\alpha(\cdot)$ . Let also  $\xi := (\xi_y, y \in \mathbb{Z})$  be a sequence of independent centered  $\mathbb{Z}$ -valued random variables with distribution  $\mu_\xi$  belonging to the normal domain of attraction of a stable

distribution with index  $1 < \beta \leq 2$  and density function denoted by  $f_\beta(\cdot)$ . For each  $y \in \mathbb{Z}$ ,  $\xi_y$  will be the only horizontal displacement allowed on line  $y$ . Let  $p \in (0, 1)$ . Given  $\xi$ , the random walk  $(M_n = (M_n^{(1)}, M_n^{(2)}), n \geq 0)$  is a Markov chain starting from  $M_0 := (0, 0)$  and such that at time  $n + 1$ , it moves either horizontally of  $\xi_{M_n^{(2)}}$  (with probability  $p$ ) or makes a vertical jump with distribution  $\mu_X$  (with probability  $(1 - p)$ ), i.e.

$$\begin{aligned} \mathbb{P}\left(M_{n+1} - M_n = (\xi_{M_n^{(2)}}, 0) \mid \xi, M_1, \dots, M_n\right) &= p \text{ if } \xi_{M_n^{(2)}} \neq 0, \\ \mathbb{P}\left(M_{n+1} - M_n = (0, x) \mid \xi, M_1, \dots, M_n\right) &= (1 - p)\mu_X(x) \text{ if } x \neq 0 \end{aligned}$$

and

$$\mathbb{P}\left(M_{n+1} = M_n \mid \xi, M_1, \dots, M_n\right) = p + (1 - p)\mu_X(0) \text{ if } \xi_{M_n^{(2)}} = 0.$$

These random walks were first introduced by Campanino and P  tritis in [7] in the particular case when  $p = 1/3$  and when  $\mu_X$  and  $\mu_\xi$  are Rademacher distributions, i.e. take values  $\pm 1$  with probability  $1/2$ . They proved the transience of  $M$  as well as a law of large numbers. In [19], Guillotin-Plantard and Le Ny established the link between the Campanino and P  tritis random walk and the random walk in random scenery and proved a functional limit theorem for the first one. It was also conjectured there that the probability of return to the origin of the Campanino and P  tritis random walk is equivalent to a constant times  $n^{-5/4}$ . We prove this result here, as well as a generalization to the case of the random walks  $M$  considered above.

To state our result, we will use the following representation of  $M$ :

Let  $X := (X_n, n \geq 1)$  be a sequence of independent random variables with distribution  $\mu_X$ . The random variable  $X_n$  corresponds to the vertical move at time  $n$  which will be chosen with probability  $1 - p$ . Let also  $(\varepsilon_n, n \geq 0)$  be a sequence of independent Bernoulli random variables with parameter  $p$ , i.e. such that  $\mathbb{P}(\varepsilon_1 = 1) = 1 - \mathbb{P}(\varepsilon_1 = 0) = p$ , and independent of  $X$ . If  $\varepsilon_n = 1$ , the particle  $M$  moves horizontally at time  $n$ , otherwise it moves vertically. We then first define  $S$  by  $S_0 := 0$  and

$$S_n := \sum_{k=1}^n Y_k \text{ for } n \geq 1,$$

where  $Y_k := X_k(1 - \varepsilon_k)$ . We next define  $\tilde{Z}$  by  $\tilde{Z}_0 := 0$  and

$$\tilde{Z}_n := \sum_{k=1}^n \xi_{S_{k-1}} \varepsilon_k = \sum_{y \in \mathbb{Z}} \xi_y \tilde{N}_n(y) \text{ for } n \geq 1,$$

where

$$\tilde{N}_n(y) := \#\{k = 1, \dots, n : S_{k-1} = y \text{ and } \varepsilon_k = 1\}.$$

Then it is straightforward that the couple  $(\tilde{Z}, S)$  has the same distribution as  $M$ .

We just notice that the process  $S$  in this section is not exactly the same as in the previous sections (it is the same if we replace  $X$  by  $Y$ ). However, we use the same notation just for convenience.

Now it is known that  $(n^{-1/\alpha} S_{[nt]}, t \geq 0)$  converges in distribution, when  $n \rightarrow \infty$ , to a L  vy process  $\tilde{U} = (\tilde{U}_t, t \geq 0)$  where  $\tilde{U} = (1 - p)^{\frac{1}{\alpha}} U$  and  $U$  is the process introduced in the introduction. We will use the fact that  $(n^{-1/\alpha} S_{[nt]}, t \geq 0 \mid S_n = 0)$  converges in distribution to  $\tilde{U}^0 = (\tilde{U}_t^0, t \geq 0)$  the associated bridge, i.e. the process  $\tilde{U}$  starting from 0 and conditioned by  $\tilde{U}_1 = 0$ . Let  $(L_t^0(x), t \in [0, 1], x \in \mathbb{R})$  be the local time process of  $\tilde{U}^0$  and set  $|L^0|_\beta := (\int_{\mathbb{R}} (L_1^0(x))^\beta dx)^{1/\beta}$ .

Let  $\varphi_\xi$  be the characteristic functions of  $\xi_1$ . Recall that  $d$  is the positive integer such that  $\{u : |\varphi_\xi(u)| = 1\} = (2\pi/d)\mathbb{Z}$ . Let  $d_0$  be the smallest positive integer  $m$  such that  $\varphi_\xi(2\pi/d)^m = 1$  and let  $d_1$  be the greatest common divisor of  $\{m \geq 1 : \mathbb{P}(X_1 + \dots + X_m) > 0\}$ .

**Theorem 20.** *Assume that  $d_1$  is a multiple of  $d_0$ , and let  $E = dp^{-1}f_\alpha(0)f_\beta(0)\mathbb{E}(|L^0|_\beta^{-1})$ . Then,*

$$\mathbb{P}(M_n = (0, 0)) = \begin{cases} E \times n^{-1-\frac{1}{\alpha\beta}} + o(n^{-1-\frac{1}{\alpha\beta}}) & \text{if } n \text{ is a multiple of } d_0; \\ 0 & \text{otherwise.} \end{cases}$$

**Remark 21.** In the case of the Campanino and Pétritis random walk,  $d_0 = d_1 = 2$ . So the hypothesis of the theorem is satisfied.

**Remark 22.** A corollary of our result is that the processes  $M$  considered here are transient, this can be seen by using Borel–Cantelli lemma.

**Remark 23.** It is most likely that an analogue result can be proved when  $\alpha < 1$  or  $\beta \leq 1$ . We leave the details to the interested reader. In the same way one could certainly obtain similar estimates for the probabilities of return in  $([n^\delta x], [n^{1/\alpha}y])$ , with a constant  $E$  depending on  $x$  and  $y$ .

**5.2. The event  $\tilde{\Omega}_n$ .** Let  $(N_n(y), y \in \mathbb{Z})$  and  $R_n$  denote respectively the local time process and the range of  $S$  at time  $n$ :

$$N_n(y) := \#\{k = 0, \dots, n-1 : S_k = y\} \quad \text{and} \quad R_n := \#\{y : N_n(y) > 0\}.$$

For  $\gamma > 0$ , set  $\tilde{\Omega}_n = \tilde{\Omega}_n(\gamma) := \mathcal{A}_n \cap \mathcal{B}_n \cap \mathcal{C}_n$ , where

$$\mathcal{A}_n := \left\{ R_n \leq n^{\frac{1}{\alpha}+\gamma} \quad \text{and} \quad \sup_y N_n(y) \leq n^{1-\frac{1}{\alpha}+\gamma} \right\},$$

$$\mathcal{B}_n := \left\{ \sum_{k=1}^n \varepsilon_k \geq \frac{np}{2} \right\},$$

and

$$\mathcal{C}_n := \left\{ \sup_{y \neq z} \frac{|\tilde{N}_n(y) - \tilde{N}_n(z)|}{|y - z|^{\frac{\alpha-1}{2}}} \leq n^{(1-\frac{1}{\alpha}+\gamma)/2} \right\}.$$

**Lemma 24.** *For all  $\gamma > 0$ ,  $\mathbb{P}(\tilde{\Omega}_n) = 1 - o(n^{-1-\frac{1}{\alpha\beta}})$ .*

*Proof.* According to the proof of Lemma 6,  $\mathbb{P}(R_n \leq n^{\frac{1}{\alpha}+\gamma}) = 1 - o(n^{-1-\frac{1}{\alpha\beta}})$ . Moreover, according to the proof of Lemma 11 (see (19)), we have for all  $\nu \geq 1$ ,

$$\mathbb{E} \left[ \sup_y N_n^\nu(y) \right] = \mathcal{O} \left( n^{\nu(1-\frac{1}{\alpha})} \right). \tag{34}$$

Hence by the use of the Markov inequality, we get

$$\mathbb{P} \left( \sup_{y \in \mathbb{Z}} N_n(y) \geq n^{1-\frac{1}{\alpha}+\gamma} \right) = o(n^{-1-\frac{1}{\alpha\beta}}).$$

It follows that  $\mathbb{P}(\mathcal{A}_n) = 1 - o(n^{-1-\frac{1}{\alpha\beta}})$ .

Next it is well known that  $\mathbb{P}(\mathcal{B}_n) = 1 - o(n^{-1-\frac{1}{\alpha\beta}})$ .

Finally, as in the proof of Lemma 6, the estimate of  $\mathbb{P}(\mathcal{C}_n)$  comes from the following lemma:

**Lemma 25.** *For any integer  $\nu \geq 1$ , there exists a constant  $C_\nu > 0$  such that, for every  $n \geq 1$  and every  $x, y \in \mathbb{Z}$*

$$\mathbb{E} \left[ (\tilde{N}_n(x) - \tilde{N}_n(y))^{2\nu} \right] \leq C_\nu |x - y|^{\nu(\alpha-1)} n^{\nu(1-\frac{1}{\alpha})}.$$

*Proof.* Let  $x$  and  $y$  be fixed, with  $x \neq y$  (otherwise, there is nothing to prove). We have

$$\tilde{N}_n(x) = pN_n(x) + \sum_{k=1}^n \mathbf{1}_{\{S_{k-1}=x\}} \bar{\epsilon}_k, \quad (35)$$

where  $\bar{\epsilon}_k = \mathbf{1}_{\{\epsilon_k=1\}} - p$ . Set  $H_n(x) := \sum_{k=1}^n \mathbf{1}_{\{S_{k-1}=x\}} \bar{\epsilon}_k$ . For all  $x \in \mathbb{Z}$ ,  $(H_n(x), n \geq 1)$  is a martingale with respect to the filtration  $\mathcal{F}_n = \sigma(X_k, \epsilon_k, k \leq n)$ . Hence,  $(H_n(x) - H_n(y), n \geq 1)$  is a martingale as well. According to the B urkholder's inequality (see [21] Theorem 2.11. p.23), for all integer  $\nu \geq 1$ , there exists a constant  $C = C(\nu)$  such that for all  $n \geq 1$ ,

$$\mathbb{E} [(H_n(x) - H_n(y))^{2\nu}]^{\frac{1}{2\nu}} \leq C \left\{ \mathbb{E} \left[ \left( \sum_{k=1}^n \mathbb{E}(d_k^2(x, y) \mid \mathcal{F}_{k-1}) \right)^\nu \right]^{\frac{1}{2\nu}} + \mathbb{E} \left[ \sup_{k=1, \dots, n} |d_k(x, y)|^{2\nu} \right]^{\frac{1}{2\nu}} \right\},$$

where  $d_k(x, y)$  is the martingale increment

$$d_k(x, y) := H_k(x) - H_{k-1}(x) - H_k(y) + H_{k-1}(y) = (\mathbf{1}_{\{S_{k-1}=x\}} - \mathbf{1}_{\{S_{k-1}=y\}}) \bar{\epsilon}_k.$$

Note that for all  $k \geq 1$ , and all  $x, y \in \mathbb{Z}$ ,  $|d_k(x, y)| \leq 1$ , and that

$$\sum_{k=1}^n \mathbb{E}(d_k^2(x, y) \mid \mathcal{F}_{k-1}) = \text{Var}(\epsilon) \sum_{k=1}^n (\mathbf{1}_{\{S_{k-1}=x\}} - \mathbf{1}_{\{S_{k-1}=y\}})^2 = \text{Var}(\epsilon)(N_n(y) + N_n(x)).$$

Therefore,

$$\begin{aligned} \mathbb{E} [(H_n(x) - H_n(y))^{2\nu}]^{\frac{1}{2\nu}} &\leq C \left\{ 1 + \mathbb{E} [N_n^\nu(y)]^{\frac{1}{2\nu}} + \mathbb{E} [N_n^\nu(x)]^{\frac{1}{2\nu}} \right\} \\ &\leq C(1 + 2n^{(1-1/\alpha)/2}) \quad (\text{by using (34)}) \\ &\leq 3Cn^{(1-1/\alpha)/2} |x - y|^{(\alpha-1)/2}, \end{aligned}$$

since  $|x - y| \geq 1$ , and  $n \geq 1$ . Hence, according to [22] (see Equation (10)),

$$\begin{aligned} \mathbb{E} \left\{ (\tilde{N}_n(x) - \tilde{N}_n(y))^{2\nu} \right\}^{\frac{1}{2\nu}} &\leq p \mathbb{E} \left\{ (N_n(x) - N_n(y))^{2\nu} \right\}^{\frac{1}{2\nu}} + \mathbb{E} \left\{ (H_n(x) - H_n(y))^{2\nu} \right\}^{\frac{1}{2\nu}} \\ &\leq C_\nu n^{(1-1/\alpha)/2} |x - y|^{(\alpha-1)/2}, \end{aligned}$$

for some constant  $C_\nu > 0$ . This proves Lemma 25. □

This concludes also the proof of Lemma 24. □

**5.3. Expression of the return probability by an integral.** According to the result of the previous subsection, we are led to the study of  $\mathbb{P}(\tilde{Z}_n = 0, S_n = 0, \tilde{\Omega}_n)$ . As in Lemma 5, we have :

$$\mathbb{P}(M_n = (0, 0), \tilde{\Omega}_n) = \mathbb{P}(\tilde{Z}_n = 0, S_n = 0, \tilde{\Omega}_n) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \mathbb{E} \left[ \prod_{y \in \mathbb{Z}} \varphi_\xi(t \tilde{N}_n(y)) \mathbf{1}_{\{S_n=0\}} \mathbf{1}_{\tilde{\Omega}_n} \right] dt.$$

By following the proof of Lemma 5 (note that a priori  $\sum_y \tilde{N}_n(y)$  is not equal to  $n$  here), we get

$$\mathbb{P}(\tilde{Z}_n = 0, S_n = 0, \tilde{\Omega}_n) = \frac{d}{2\pi} \int_{-\pi/d}^{\pi/d} \mathbb{E} \left[ \prod_{y \in \mathbb{Z}} \varphi_\xi(t \tilde{N}_n(y)) \mathbf{1}_{\{\sum_y \tilde{N}_n(y) \in d_0 \mathbb{Z}\}} \mathbf{1}_{\{S_n=0\}} \mathbf{1}_{\tilde{\Omega}_n} \right] dt. \quad (36)$$

In the sequel we consider  $\eta$ ,  $\gamma$  and  $\varepsilon$  satisfying all the hypotheses of Section 2.4 and  $\gamma < (\alpha - 1)/(4\alpha)$ .

**5.4. Estimate of the integral away from the origin.** The following is very similar to the case of RWRS.

**Lemma 26.** *We have*

$$\int_{n^{-\delta+\eta}}^{\pi/d} \mathbb{E} \left[ \prod_{y \in \mathbb{Z}} |\varphi_\xi(t\tilde{N}_n(y))| \mathbf{1}_{\tilde{\Omega}_n} \right] dt = o(n^{-1-\frac{1}{\alpha\beta}}).$$

*Proof.* First set

$$\tilde{V}_n := \sum_{y \in \mathbb{Z}} \tilde{N}_n(y)^\beta.$$

Since on  $\tilde{\Omega}_n$ ,  $\sum_y \tilde{N}_n(y) = \sum_{k=1}^n \varepsilon_k \geq np/2$  and  $\tilde{N}_n(y) \leq N_n(y) \leq n^{1-\frac{1}{\alpha}+\gamma}$ , by following the proof of Lemma 6, we get on  $\tilde{\Omega}_n$ :

$$\tilde{V}_n \geq cn^{\delta\beta-\gamma},$$

for some constant  $c > 0$ . Let now  $\varepsilon$  be as in Proposition 9. Then the proofs of Proposition 8 and 9 lead to

$$\int_{n^{-\delta+\eta}}^{n^{-1+\frac{1}{\alpha}+\varepsilon}} \mathbb{E} \left[ \prod_{y \in \mathbb{Z}} |\varphi_\xi(t\tilde{N}_n(y))| \mathbf{1}_{\tilde{\Omega}_n} \right] dt = o(n^{-1-\frac{1}{\alpha\beta}}).$$

But we can also easily adapt the proof of Proposition 10 to obtain :

$$\int_{n^{-1+\frac{1}{\alpha}+\varepsilon}}^{\pi/d} \mathbb{E} \left[ \prod_{y \in \mathbb{Z}} |\varphi_\xi(t\tilde{N}_n(y))| \mathbf{1}_{\tilde{\Omega}_n} \right] dt = o(n^{-1-\frac{1}{\alpha\beta}}).$$

Indeed we just need to use "flat peaks" instead of peaks. These "flat peaks" are defined as follows. Let  $M$  and  $N$  be such that  $\mathbb{P}(Y_1 = N) > 0$  and  $\mathbb{P}(Y_1 = -M) > 0$ . Then an "upper flat peak" is a sequence of the type

$$(Y_{H+1}, \dots, Y_{H+M}, \varepsilon_{H+M+1}, Y_{H+M+2}, \dots, Y_{H+M+N+1}) = (N, \dots, N, 1, -M, \dots, -M),$$

where  $H$  is any multiple of  $M + N + 1$ , and one can define analogously a "lower flat peak". We leave to the reader to check that we can then follow the proof of Proposition 10 simply by replacing everywhere peaks by flat peaks. This concludes the proof of Lemma 26.  $\square$

**5.5. Estimate of the integral near the origin.** We turn now to the estimate of the integral in (36) on the interval  $[-n^{-\delta+\eta}, n^{-\delta+\eta}]$ . For this we will roughly follow the same lines as for the proof of Proposition 7. However the technical details are more involved here, since we have to make all calculus conditionally to  $\{S_n = 0\}$ . The first step is the following lemma:

**Lemma 27.** *We have*

$$\sup_n \mathbb{E} \left[ \left( \frac{n^{\delta\beta}}{\tilde{V}_n} \right)^{\frac{1}{\beta-1}} \mathbf{1}_{\tilde{\Omega}_n} \mid S_n = 0 \right] < +\infty. \quad (37)$$

*Proof.* Remind that on  $\tilde{\Omega}_n$ ,  $np/2 \leq \sum_y \tilde{N}_n(y) \leq \tilde{V}_n^{1/\beta} R_n^{1-1/\beta}$ . Observe on the other hand that  $\delta\beta/(\beta-1) = \beta/(\beta-1) - 1/\alpha$ . Thus there is a constant  $C > 0$  such that for all  $n \geq 1$ , on  $\tilde{\Omega}_n$ ,

$$\left( \frac{n^{\delta\beta}}{\tilde{V}_n} \right)^{\frac{1}{\beta-1}} \leq C \frac{R_n}{n^{\frac{1}{\alpha}}}.$$

It follows from the above inequality that

$$\mathbb{E} \left[ \left( \frac{n^{\delta\beta}}{\tilde{V}_n} \right)^{\frac{1}{\beta-1}} \mathbf{1}_{\tilde{\Omega}_n} \mathbf{1}_{\{S_n=0\}} \right] \leq C \mathbb{E} \left[ \frac{R_n}{n^{\frac{1}{\alpha}}} \mathbf{1}_{\{S_n=0\}} \right].$$

Set  $m := \lfloor n/2 \rfloor$  and  $m' := \lceil n/2 \rceil$ . By using that  $R_n \leq R_{m'} + \#\{S_{m'+1}, \dots, S_n\} = R_{m'} + \#\{S_{m'+1} - S_n, \dots, S_{n-1} - S_n, 0\}$  and Markov property (respectively on the sequences  $(S_k, k \geq 0)$  and  $(S_n - S_{n-k}, 0 \leq k \leq n)$ ), we get

$$\begin{aligned} \mathbb{E} \left[ \left( \frac{n^{\delta\beta}}{\tilde{V}_n} \right)^{\frac{1}{\beta-1}} \mathbf{1}_{\tilde{\Omega}_n} \mathbf{1}_{\{S_n=0\}} \right] &\leq C \mathbb{E} \left[ \frac{R_{m'}}{n^{\frac{1}{\alpha}}} \right] \times \sup_x \mathbb{P}_x(S_m = 0) \\ &= \mathcal{O} \left( n^{-\frac{1}{\alpha}} \right), \end{aligned}$$

since  $\sup_x \mathbb{P}_x(S_m = 0) = \mathcal{O}(n^{-1/\alpha})$  and  $\mathbb{E}(R_{m'}) = \mathcal{O}(n^{1/\alpha})$  (see [27] Equation (7.a) p.703). We next divide all terms by  $\mathbb{P}(S_n = 0)$  which is of order  $n^{-1/\alpha}$  and this proves the lemma.  $\square$

We deduce the

**Lemma 28.** *We have*

$$\mathbb{P}(\tilde{Z}_n = 0, S_n = 0, \tilde{\Omega}_n) = n^{-1-\frac{1}{\alpha\beta}} d \mathbb{E} \left[ \frac{n^\delta}{\tilde{V}_n^{\frac{1}{\beta}}} \mathbf{1}_{\{\sum_y \tilde{N}_n(y) \in d_0 \mathbb{Z}\}} \mathbf{1}_{\tilde{\Omega}_n} \mid S_n = 0 \right] f_\alpha(0) f_\beta(0) + o(n^{-1-\frac{1}{\alpha\beta}}).$$

*Proof.* By following the proof of Lemma 12, we see that, uniformly on  $\tilde{\Omega}_n$ , we have:

$$\int_{|t| \leq n^{-\delta+\eta}} \left| \prod_y \varphi_\xi(t \tilde{N}_n(y)) - e^{-|t|^\beta \tilde{V}_n(A_1 + iA_2 \text{sgn}(t))} \right| dt = o(\tilde{V}_n^{-\frac{1}{\beta}}).$$

By using Lemma 27, we get

$$\begin{aligned} &\int_{|t| \leq n^{-\delta+\eta}} \mathbb{E} \left[ \left| \prod_y \varphi_\xi(t \tilde{N}_n(y)) - e^{-|t|^\beta \tilde{V}_n(A_1 + iA_2 \text{sgn}(t))} \right| \mathbf{1}_{\tilde{\Omega}_n} \mathbf{1}_{\{S_n=0\}} \right] dt \\ &= o(1) \times \mathbb{E} \left[ \tilde{V}_n^{-\frac{1}{\beta}} \mathbf{1}_{\tilde{\Omega}_n} \mathbf{1}_{\{S_n=0\}} \right] \\ &= o(n^{-\delta-\frac{1}{\alpha}}) \times \mathbb{E} \left[ (n^{\delta\beta} \tilde{V}_n^{-1})^{\frac{1}{\beta-1}} \mathbf{1}_{\tilde{\Omega}_n} \mid S_n = 0 \right]^{\frac{\beta-1}{\beta}} \quad (\text{since } \mathbb{P}(S_n = 0) = \mathcal{O}(n^{-\frac{1}{\alpha}})), \\ &= o(n^{-1-\frac{1}{\alpha\beta}}). \end{aligned}$$

By using (36) and Lemma 26, we see that it remains to estimate

$$\int_{|t| \leq n^{-\delta+\eta}} \mathbb{E} \left[ e^{-|t|^\beta \tilde{V}_n(A_1 + iA_2 \text{sgn}(t))} \mathbf{1}_{\{\sum_y \tilde{N}_n(y) \in d_0 \mathbb{Z}\}} \mathbf{1}_{\{S_n=0\}} \mathbf{1}_{\tilde{\Omega}_n} \right] dt.$$

But, as in the proof of Lemma 13, we have

$$\int_{|t| \leq n^{-\delta+\eta}} e^{-|t|^\beta \tilde{V}_n(A_1 + iA_2 \text{sgn}(t))} dt = n^{-\delta} \left\{ 2\pi \frac{n^\delta}{\tilde{V}_n^{\frac{1}{\beta}}} f_\beta(0) \right\} + o(n^{-\delta}),$$

uniformly on  $\tilde{\Omega}_n$ . We next take the expectation in both sides and we conclude the proof by using that  $\mathbb{P}(S_n = 0) \sim f_\alpha(0)n^{-1/\alpha}$ .  $\square$

The following lemma allows us to get rid of  $\mathbf{1}_{\{\sum_y \tilde{N}_n(y) \in d_0 \mathbb{Z}\}}$ .

**Lemma 29.** *Assume that  $d_1$  is a multiple of  $d_0$ . On  $\{S_n = 0\}$ , we have*

$$\sum_y \tilde{N}_n(y) \in d_0\mathbb{Z} \Leftrightarrow n \in d_0\mathbb{Z}.$$

*Proof.* Let  $m_n := \sum_y \tilde{N}_n(y) = \sum_{k=1}^n \varepsilon_k$  be the number of horizontal moves before time  $n$ .

If  $S_n = 0$ , the number  $n - m_n$  of vertical moves is necessarily in  $d_1\mathbb{Z}$  and so in  $d_0\mathbb{Z}$ , since  $d_1$  is a multiple of  $d_0$  by hypothesis. Hence  $m_n$  is in  $d_0\mathbb{Z}$  if and only if  $n$  is in  $d_0\mathbb{Z}$ .  $\square$

We will need the following estimate:

**Lemma 30.** *Let  $V_n := \sum_{x \in \mathbb{Z}} N_n(x)^\beta$ . Then*

$$\mathbb{E} \left[ |\tilde{V}_n - p^\beta V_n| \mid S_n = 0 \right] = \mathcal{O}(n^{\delta\beta - \frac{\alpha-1}{2\alpha}}).$$

*Proof.* Set again  $m = \lfloor n/2 \rfloor$  and  $m' = \lceil n/2 \rceil$ . By using the inequality  $|a^\beta - b^\beta| \leq \beta|a - b|(a^{\beta-1} + b^{\beta-1})$  and the Cauchy–Schwarz inequality, we get

$$\begin{aligned} \mathbb{E} \left[ |\tilde{V}_n - p^\beta V_n| \mid S_n = 0 \right] &\leq \beta \mathbb{E} \left[ \sum_{x \in \mathbb{Z}} (\tilde{N}_n(x)^{\beta-1} + p^{\beta-1} N_n(x)^{\beta-1})^2 \mid S_n = 0 \right]^{1/2} \\ &\quad \times \mathbb{E} \left[ \sum_{x \in \mathbb{Z}} (\tilde{N}_n(x) - p N_n(x))^2 \mid S_n = 0 \right]^{1/2}. \end{aligned} \quad (38)$$

We now estimate both expectations in the right hand-side of the above inequality. First note that  $N_n(x) = N_m(x) + (N_n(x) - N_m(x))$  and that the sequence  $((N_n(x) - N_m(x), x \in \mathbb{Z}) \mid S_n = 0)$  has the same distribution as  $((N_{m'+1}(-x) - N_1(-x), x \in \mathbb{Z}) \mid S_n = 0)$ . Thus the Markov property gives

$$\begin{aligned} &\mathbb{E} \left[ \sum_{x \in \mathbb{Z}} (\tilde{N}_n(x)^{\beta-1} + p^{\beta-1} N_n(x)^{\beta-1})^2 \mid S_n = 0 \right] \leq 4 \sum_{x \in \mathbb{Z}} \mathbb{E} \left[ N_n(x)^{2(\beta-1)} \mid S_n = 0 \right] \\ &\leq C \left\{ \sum_{x \in \mathbb{Z}} \sum_{M \in \mathbb{Z}} \mathbb{E} \left[ N_m(x)^{2(\beta-1)} \mathbf{1}_{\{S_m=M\}} \right] \frac{\mathbb{P}(S_{m'} = -M)}{\mathbb{P}(S_n = 0)} \right. \\ &\quad \left. + \sum_{x \in \mathbb{Z}} \sum_{M \in \mathbb{Z}} \mathbb{E} \left[ (N_{m'}(x))^{2(\beta-1)} \mathbf{1}_{\{S_{m'}=-M\}} \right] \frac{\mathbb{P}(S_m = M)}{\mathbb{P}(S_n = 0)} \right\}, \end{aligned}$$

for some constant  $C > 0$ . Since  $\sup_M \mathbb{P}(S_{m'} = -M)/\mathbb{P}(S_n = 0) < +\infty$  and  $\sup_M \mathbb{P}(S_m = M)/\mathbb{P}(S_n = 0) < +\infty$ , we get

$$\mathbb{E} \left[ \sum_{x \in \mathbb{Z}} (\tilde{N}_n(x)^{\beta-1} + p^{\beta-1} N_n(x)^{\beta-1})^2 \mid S_n = 0 \right] \leq C \sum_{x \in \mathbb{Z}} \mathbb{E} \left[ N_{m'}(x)^{2(\beta-1)} \right].$$

Then Markov property again and (34) show that

$$\begin{aligned} \mathbb{E} \left[ \sum_{x \in \mathbb{Z}} (\tilde{N}_n(x)^{\beta-1} + p^{\beta-1} N_n(x)^{\beta-1})^2 \mid S_n = 0 \right] &\leq C \mathbb{E}[R_{m'}] \times \mathbb{E} \left[ N_{m'}(0)^{2(\beta-1)} \right] \\ &= \mathcal{O} \left( n^{2(\beta-1)(1-\frac{1}{\alpha}) + \frac{1}{\alpha}} \right). \end{aligned} \quad (39)$$

The same argument gives

$$\begin{aligned} & \sum_{x \in \mathbb{Z}} \mathbb{E} \left[ (\tilde{N}_n(x) - pN_n(x))^2 \mid S_n = 0 \right] \\ & \leq C \left\{ \sum_{x \in \mathbb{Z}} \mathbb{E} \left[ (\tilde{N}_m(x) - pN_m(x))^2 \right] + \sum_{x \in \mathbb{Z}} \mathbb{E} \left[ (\tilde{N}_{m'}(x) - pN_{m'}(x))^2 \right] \right\}, \end{aligned}$$

for some constant  $C > 0$ . Then by using (35) (note that  $\bar{\varepsilon}_k$  is centered and independent of  $(S_{\ell-1}, \varepsilon_\ell, S_{k-1})$  if  $\ell < k$ ), we get

$$\sum_{x \in \mathbb{Z}} \mathbb{E} \left[ (\tilde{N}_n(x) - pN_n(x))^2 \mid S_n = 0 \right] = \mathcal{O}(n). \quad (40)$$

The lemma now follows by combining (38), (39) and (40) since  $(\beta - 1) \left(1 - \frac{1}{\alpha}\right) + \frac{1}{2\alpha} + \frac{1}{2} = \delta\beta - \frac{\alpha-1}{2\alpha}$ .  $\square$

**Lemma 31.** *Conditionally to the event  $\{S_n = 0\}$ , the sequence  $(V_n/n^{\delta\beta}, n \geq 0)$  converges in distribution to the random variable  $\int_{\mathbb{R}} (L_1^0(x))^\beta dx$ .*

*Proof.* According to [15], the lemma will essentially follow from the two following statements :

**(RW1)** The sequence of conditioned processes  $((n^{-1/\alpha} S_{\lfloor nt \rfloor} \mid S_n = 0), t \in [0, 1])$  converges in distribution to the bridge  $(\tilde{U}_t^0, t \in [0, 1])$ , as  $n \rightarrow \infty$ .

**(RW2)** (i)

$$\sup_y \mathbb{E} [N_n(y)^2 \mid S_n = 0] = \mathcal{O}(n^{2-\frac{2}{\alpha}}).$$

(ii) There exists a constant  $C > 0$  such that for every  $x, y \in \mathbb{R}$ ,

$$\mathbb{E} \left[ \left( N_n \left( \lfloor n^{\frac{1}{\alpha}} x \rfloor \right) - N_n \left( \lfloor n^{\frac{1}{\alpha}} y \rfloor \right) \right)^2 \mid S_n = 0 \right] \leq C n^{2-\frac{2}{\alpha}} |x - y|^{\alpha-1}.$$

Part **(RW1)** is proved in [28].

We prove now **(RW2)** starting with Part (i). By using the same argument as in the proof of Lemma 30, we get

$$\mathbb{E} [N_n(y)^2 \mid S_n = 0] \leq C(\mathbb{E}[N_m(y)^2] + \mathbb{E}[N_{m'+1}(-y)^2]),$$

for some constant  $C > 0$ , with  $m$  and  $m'$  as in the previous lemma. The desired result now follows from Lemma 1 in [23].

For Part (ii), set  $N_n(x, y) := N_n(x) - N_n(y)$ . Then use again the argument of the previous lemma, which gives

$$\mathbb{E}[N_n(x, y)^2 \mid S_n = 0] \leq C(\mathbb{E}[N_m(x, y)^2] + \mathbb{E}[N_{m'+1}(-x, -y)^2] + 1),$$

for some constant  $C > 0$ . The result then follows from Lemma 3 in [23].

We can now apply Theorem 4.1 in [15] in the case when the random scenery is a sequence of i.i.d. random variables with  $\beta$ -stable distribution and with characteristic function of the form  $\theta \mapsto \exp(-c|\theta|^\beta)$ . We deduce that conditionally to  $\{S_n = 0\}$ ,

$$n^{-\delta} \sum_{k=1}^n \xi_{S_k} \xrightarrow[n \rightarrow \infty]{\mathcal{L}} \int_{\mathbb{R}} L_1^0(x) dY_x,$$

where  $(Y_x, x \in \mathbb{R})$  is a two-sided  $\beta$ -stable Lévy process independent of  $\tilde{U}^0$  and limit in distribution of  $\left(n^{-\frac{1}{\beta}} \sum_{k=0}^{\lfloor nx \rfloor} \xi_k, x \in \mathbb{R}\right)$ , when  $n \rightarrow \infty$ . Therefore (see for instance Lemma 5 in [23]), for every  $\theta \in \mathbb{R}$ ,

$$\mathbb{E} \left( \exp \left( -c|\theta|^\beta n^{-\delta\beta} V_n \right) \mid S_n = 0 \right) \rightarrow \mathbb{E} \left( e^{-c|\theta|^\beta \int_{\mathbb{R}} (L_1^0(x))^\beta dx} \right) \quad \text{when } n \rightarrow \infty,$$

which proves the lemma.  $\square$

**Lemma 32.** *Conditionally to the event  $\{S_n = 0\}$ , the sequence  $(n^{\delta\beta} \tilde{V}_n^{-1} \mathbf{1}_{\tilde{\Omega}_n}, n \geq 0)$  converges in distribution to the random variable  $(p|L^0|_\beta)^{-\beta}$ .*

*Proof.* By Lemma 31, the sequence  $(n^{\delta\beta} V_n^{-1}, n \geq 0)$  converges in distribution to  $|L^0|_\beta^{-\beta}$ , conditionally to  $\{S_n = 0\}$ . On the other hand, Lemma 24 implies that the sequence  $(\mathbf{1}_{\tilde{\Omega}_n}, n \geq 0)$  converges in distribution to the constant 1, conditionally to  $\{S_n = 0\}$ . Hence, the sequence  $(n^{\delta\beta} V_n^{-1} \mathbf{1}_{\tilde{\Omega}_n}, n \geq 0)$  converges in distribution to  $|L^0|_\beta^{-\beta}$ , conditionally to  $\{S_n = 0\}$ . Next recall that on  $\tilde{\Omega}_n$ ,  $V_n \geq \tilde{V}_n \geq cn^{\delta\beta-\gamma}$ , for some constant  $c > 0$ . Thus Lemma 30 gives

$$\mathbb{E} \left[ \left| \frac{n^{\delta\beta}}{\tilde{V}_n} - \frac{n^{\delta\beta}}{p^\beta V_n} \mathbf{1}_{\tilde{\Omega}_n} \mid S_n = 0 \right] = \mathcal{O} \left( n^{-2\delta\beta+2\gamma+2\delta\beta-\frac{\alpha-1}{2\alpha}} \right) = \mathcal{O} \left( n^{2\gamma-\frac{\alpha-1}{2\alpha}} \right).$$

Therefore, since  $\gamma < (\alpha - 1)/(4\alpha)$ , the left hand side in the above equation converges to 0 when  $n \rightarrow \infty$ . The lemma follows.  $\square$

We finally obtain the

*Proof of Theorem 20.* The uniform integrability of the sequence  $(n^\delta \tilde{V}_n^{-1/\beta} \mathbf{1}_{\tilde{\Omega}_n}, n \geq 0)$  conditionally to  $\{S_n = 0\}$  is deduced from Lemma 27. It then follows from Lemma 32 that

$$\mathbb{E} \left[ \frac{n^\delta}{\tilde{V}_n^{1/\beta}} \mathbf{1}_{\tilde{\Omega}_n} \mid S_n = 0 \right] \rightarrow p^{-1} \mathbb{E}[|L^0|_\beta^{-1}] \quad \text{when } n \rightarrow \infty.$$

The theorem now follows from Lemmas 28 and 29.

## APPENDIX A. CONTROL OF THE RANGE

We first gather some known facts about the range  $R_n$  of the random walk  $(S_n, n \geq 0)$ . First of all, this walk is transient if, and only if,  $\alpha < 1$ . Moreover, there exists a constant  $c > 0$  such that

$$\mathbb{E}[R_n] \sim c \begin{cases} n & \text{if } \alpha < 1 \text{ ( see [32] p.36) ,} \\ \frac{n}{\log(n)} & \text{if } \alpha = 1 \text{ ( see [27] Theorem 6.9 p.698) ,} \\ n^{1/\alpha} & \text{if } \alpha > 1 \text{ ( see [27] Equation (7.a) p.703) .} \end{cases} \quad (41)$$

In addition, if  $\alpha \leq 1$  (see [32] p.38-40 for  $\alpha < 1$ , and [27] Theorem 6.9 for  $\alpha = 1$ ), then

$$\frac{R_n}{\mathbb{E}[R_n]} \rightarrow 1 \text{ a.s.} \quad (42)$$

If  $\alpha > 1$ , it is proved in [27] Theorem 7.1 p.703, that

$$\frac{R_n}{n^{1/\alpha}} \rightarrow \lambda(U([0, 1])) \text{ in distribution,}$$

where  $\lambda$  denotes the Lebesgue measure, and  $(U(s), s \in [0, 1])$  is an  $\alpha$ -stable process. In this case, it is also proved in [27] that the constant  $c$  appearing in (41) is  $\mathbb{E}[\lambda(U([0, 1]))]$ , so that

$$\frac{R_n}{\mathbb{E}[R_n]} \rightarrow \frac{\lambda(U([0, 1]))}{\mathbb{E}[\lambda(U([0, 1]))]} \text{ in distribution.} \quad (43)$$

Our aim in this appendix is to prove the following result:

**Lemma 33.** *Assume that  $\alpha \in (0, 2]$ . Let  $\gamma \in (0, 1/\alpha)$ , and set*

$$\mathcal{R}_n := \{ \mathbb{E}[R_n]n^{-\gamma} \leq R_n \leq \mathbb{E}[R_n]n^\gamma \} .$$

*Then there exists a constant  $C > 0$ , such that*

$$\mathbb{P}(\mathcal{R}_n) = 1 - \mathcal{O}(\exp(-Cn^\gamma)). \quad (44)$$

*Proof.* We first prove that for  $n$  large enough,

$$\mathbb{P}[R_n \geq \mathbb{E}[R_n]n^\gamma] \leq \exp(-Cn^\gamma). \quad (45)$$

Let us recall that for every  $a, b \in \mathbb{N}$ , we have

$$\mathbb{P}(R_n \geq a + b) \leq \mathbb{P}(R_n \geq a)\mathbb{P}(R_n \geq b). \quad (46)$$

The proof is given for instance in [10] and goes as follows. Let  $\tau := \inf \{k : R_k \geq a\}$ . Note that  $\tau$  is a stopping time, and that  $R_\tau = a$  on  $\{\tau < \infty\}$ . Moreover,

$$\begin{aligned} \mathbb{P}(R_n \geq a + b) &= \mathbb{P}(\tau \leq n; R_n \geq a + b) \\ &= \sum_{j=1}^n \mathbb{P}(\tau = j; R_n \geq R_j + b) \end{aligned}$$

Now, for  $j \leq n$ ,  $R_n \leq R_j + \# \{S_{j+1}, \dots, S_n\} = R_j + \# \{S_{j+1} - S_j, \dots, S_n - S_j\}$ . By independence, we have

$$\begin{aligned} \mathbb{P}(R_n \geq a + b) &\leq \sum_{j=1}^n \mathbb{P}(\tau = j)\mathbb{P}(R_{n-j} \geq b) \\ &\leq \mathbb{P}(R_n \geq b)\mathbb{P}(\tau \leq n), \end{aligned}$$

proving (46). Hence,

$$\begin{aligned} \mathbb{P}(R_n \geq \mathbb{E}[R_n]n^\gamma) &\leq \mathbb{P}\left(R_n \geq \lfloor 3\mathbb{E}[R_n] \rfloor \left\lfloor \frac{n^\gamma}{3} \right\rfloor\right) \leq \mathbb{P}\left(R_n \geq \lfloor 3\mathbb{E}[R_n] \rfloor \left\lfloor \frac{n^\gamma}{3} \right\rfloor\right) \\ &\leq \left(\frac{\mathbb{E}[R_n]}{\lfloor 3\mathbb{E}[R_n] \rfloor}\right)^{\lfloor \frac{n^\gamma}{3} \rfloor} \leq \left(\frac{\mathbb{E}[R_n]}{3\mathbb{E}[R_n] - 1}\right)^{\lfloor \frac{n^\gamma}{3} \rfloor} \leq \left(\frac{1}{2}\right)^{\lfloor \frac{n^\gamma}{3} \rfloor}. \end{aligned}$$

This finishes the proof of (45). It remains now to prove that for  $n$  large enough,

$$\mathbb{P}(R_n \leq \mathbb{E}[R_n]n^{-\gamma}) \leq \exp(-Cn^\gamma). \quad (47)$$

To this end, let  $I_1, \dots, I_N$  be disjoint subsequent intervals of  $\{0, \dots, n\}$ , of the same length  $l_n$  depending on  $n$ , so that  $l_n \gg 1$  and  $N = \lfloor n/l_n \rfloor$ . Note that

$$R_n \geq \max_{j=1}^N (\# \{S_k, k \in I_j\}) ,$$

and that the random variables  $(\# \{S_k, k \in I_j\}, 1 \leq j \leq N)$  are i.i.d with the same law as  $R_{l_n}$ . Hence

$$\mathbb{P}(R_n \leq \mathbb{E}[R_n]n^{-\gamma}) \leq \mathbb{P}\left(\max_{j=1}^N (\# \{S_k, k \in I_j\}) \leq \mathbb{E}(R_n)n^{-\gamma}\right) = \mathbb{P}(R_{l_n} \leq \mathbb{E}[R_n]n^{-\gamma})^N. \quad (48)$$

Choose now  $l_n$  such that  $\mathbb{E}[R_{l_n}] \sim 3\mathbb{E}[R_n]n^{-\gamma}$ . By (41), this gives

$$l_n \sim \begin{cases} 3n^{1-\gamma} & \text{if } \alpha < 1 \\ 3(1-\gamma)n^{1-\gamma} & \text{if } \alpha = 1 \\ 3^\alpha n^{1-\alpha\gamma} & \text{if } \alpha > 1, \end{cases}$$

so that

$$N \sim \begin{cases} \frac{1}{3}n^\gamma & \text{if } \alpha < 1 \\ \frac{1}{3(1-\gamma)}n^\gamma & \text{if } \alpha = 1 \\ \frac{1}{3^\alpha}n^{\alpha\gamma} & \text{if } \alpha > 1. \end{cases} \tag{49}$$

For  $n$  large enough,  $\mathbb{E}[R_{l_n}] \geq 2\mathbb{E}[R_n]n^{-\gamma}$ , and it follows from (48) that

$$\mathbb{P}(R_n \leq \mathbb{E}[R_n]n^{-\gamma}) \leq \mathbb{P}\left(R_{l_n} \leq \frac{\mathbb{E}[R_{l_n}]}{2}\right)^N. \tag{50}$$

For  $\alpha \leq 1$ ,  $\mathbb{P}\left(R_{l_n} \leq \frac{\mathbb{E}[R_{l_n}]}{2}\right)$  tends to zero by (42). By (43), for  $\alpha > 1$ , we have

$$\limsup_{n \rightarrow \infty} \mathbb{P}\left(R_{l_n} \leq \frac{\mathbb{E}[R_{l_n}]}{2}\right) \leq \mathbb{P}\left[\lambda(U([0, 1])) \leq \frac{1}{2}\mathbb{E}[\lambda(U([0, 1]))]\right] < 1,$$

since a.s.  $\lambda(U([0, 1])) > 0$ . In any case there exists  $p < 1$ , such that for all  $\gamma \in (0, 1/\alpha)$ , and for  $n$  large enough,

$$\mathbb{P}\left(R_{l_n} \leq \frac{\mathbb{E}[R_{l_n}]}{2}\right) \leq p.$$

Together with (50) and (49), this proves (47) and the lemma.  $\square$

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