



# Sharp ellipticity conditions for ballistic behavior of random walks in random environment

Élodie Bouchet, Alejandro F. Ramirez, Christophe Sabot

## ► To cite this version:

Élodie Bouchet, Alejandro F. Ramirez, Christophe Sabot. Sharp ellipticity conditions for ballistic behavior of random walks in random environment. 2013. hal-00876077v1

**HAL Id: hal-00876077**

**<https://hal.science/hal-00876077v1>**

Preprint submitted on 23 Oct 2013 (v1), last revised 25 Feb 2014 (v2)

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# SHARP ELLIPTICITY CONDITIONS FOR BALLISTIC BEHAVIOR OF RANDOM WALKS IN RANDOM ENVIRONMENT

ÉLODIE BOUCHET, ALEJANDRO F. RAMÍREZ, AND CHRISTOPHE SABOT

**ABSTRACT.** We sharpen the ellipticity criteria for random walks in i.i.d. random environments introduced by Campos and Ramírez which ensure ballistic behavior. Furthermore, we construct new examples of random environments for which the walk satisfies the polynomial ballisticity criteria of Berger, Drewitz and Ramírez. As a corollary we can exhibit a new range of values for the parameters of Dirichlet random environments in dimension  $d = 2$  under which the corresponding random walk is ballistic.

## 1. INTRODUCTION

We continue the study initiated in [3] sharpening the ellipticity criteria which ensure ballistic behavior of random walks in random environment. Furthermore, we apply our results to exhibit a new class of ballistic random walks in Dirichlet random environments in dimensions  $d = 2$ .

For  $x \in \mathbb{R}^d$ , denote by  $|x|_1$  and  $|x|_2$  its  $L_1$  and  $L_2$  norm respectively. Call  $U := \{e \in \mathbb{Z}^d : |e|_1 = 1\} = \{e_1, \dots, e_{2d}\}$  the canonical vectors with the convention that  $e_{d+i} = -e_i$  for  $1 \leq i \leq d$ . We set  $\mathcal{P} := \{p(e) : p(e) \geq 0, \sum_{e \in U} p(e) = 1\}$ .

An environment is an element  $\omega := \{\omega(x) : x \in \mathbb{Z}^d\}$  of the environment space  $\Omega := \mathcal{P}^{\mathbb{Z}^d}$ . We denote the components of  $\omega(x)$  by  $\omega(x, e)$ .

The random walk in the environment  $\omega$  starting from  $x$  is the Markov chain  $\{X_n : n \geq 0\}$  in  $\mathbb{Z}^d$  with law  $P_{x,\omega}$  defined by the condition  $P_{x,\omega}(X_0 = x) = 1$  and the transition probabilities

$$P_{x,\omega}(X_{n+1} = x + e | X_n = x) = \omega(x, e)$$

for each  $x \in \mathbb{Z}^d$  and  $e \in U$ .

Let  $\mathbb{P}$  be a probability measure defined on the environment space  $\Omega$  endowed with its Borel  $\sigma$ -algebra. We choose  $\{\omega(x) : x \in \mathbb{Z}^d\}$  i.i.d. under  $\mathbb{P}$ . We call  $P_{x,\omega}$  the quenched law of the random walk in random environment (RWRE) starting from  $x$ , and  $P_x := \int P_{x,\omega} d\mathbb{P}$  the averaged or annealed law of the RWRE starting from  $x$ .

The law  $\mathbb{P}$  is said to be elliptic if for every  $x \in \mathbb{Z}^d$  and  $e \in U$ ,  $\mathbb{P}(\omega(x, e) > 0) = 1$ . We say that  $\mathbb{P}$  is uniformly elliptic if there exists a constant  $\gamma > 0$  such that for every  $x \in \mathbb{Z}^d$  and  $e \in U$ ,  $\mathbb{P}(\omega(x, e) \geq \gamma) = 1$ .

Given  $l \in S^{d-1}$  we say that the RWRE is transient in direction  $l$  if

$$P_0(A_l) = 1,$$

with

$$A_l := \left\{ \lim_{n \rightarrow \infty} X_n \cdot l = \infty \right\}.$$

---

2000 *Mathematics Subject Classification.* 60K37, 82D30.

*Key words and phrases.* Random walk in random environment, Dirichlet distribution, Reinforced random walks, Max-flow min-cut theorem.

This work was partially supported by Fondo Nacional de Desarrollo Científico y Tecnológico grant 1100746 and by the ANR project MEMEMO2.

Furthermore, it is ballistic in direction  $l$  if  $P_0$ -a.s.

$$\liminf_{n \rightarrow \infty} \frac{X_n \cdot l}{n} > 0.$$

Given  $U \subset \mathbb{Z}^d$ , we denote its outer boundary by

$$\partial U := \{x \notin U : |x - y|_1 = 1, \text{ for some } y \in U\}.$$

We denote any nearest neighbour path with  $n$  steps joining two points  $x, y \in \mathbb{Z}^d$  by  $(x_1, x_2, \dots, x_n)$ , where  $x_1 = x$  and  $x_n = y$ . We use the notation

$$\Delta x_i := x_{i+1} - x_i,$$

for  $1 \leq i \leq n - 1$ , for the directions of the jumps through this path.

**1.1. Polynomial condition, ellipticity condition.** In [1], Berger, Drewitz and Ramírez introduced a polynomial ballisticity condition within the uniformly elliptic context, which was later extended to the elliptic case by Campos and Ramírez in [3], that will be of interest for our results. This condition is effective, in the sense that it can a priori be verified explicitly for a given environment.

To define it, we need for each  $L, \tilde{L} > 0$  and  $l \in \mathbb{S}^{d-1}$  to consider the box

$$B_{l,L,\tilde{L}} := R \left( (-L, L) \times (-\tilde{L}, \tilde{L})^{d-1} \right) \cap \mathbb{Z}^d,$$

where  $R$  is a rotation of  $\mathbb{R}^d$  that verifies  $R(e_1) = l$ .

For each subset  $A \subset \mathbb{Z}^d$  we note the first exit time from the set  $A$  as

$$T_A := \inf\{n \geq 0 : X_n \notin A\}.$$

**Definition 1.** *Given  $M \geq 1$  and  $L \geq 2$ , we say that condition  $(P)_M$  in direction  $l$  is satisfied on a box of size  $L$  (also written as  $(P)_M|l$ ) if there exists an  $\tilde{L} \leq 70L^3$  such that one has the following upper bound for the probability that the walk does not exit the box  $B_{l,L,\tilde{L}}$  through its front side :*

$$P_0(X_{T_{B_{l,L,\tilde{L}}}} \cdot l < L) \leq \frac{1}{L^M}.$$

This condition has proven useful in the uniformly elliptic case. Indeed,  $(P)_M$  for  $M \geq 15d + 5$  implies ballisticity (see [1]).

For non uniformly elliptic environments in dimensions  $d \geq 2$ , there exist elliptic random walks which are transient in a given direction but not ballistic in that direction (see for example Sabot-Tournier [10], Bouchet [2]). In [3], Campos and Ramírez introduced ellipticity criteria on the law of the environment which ensure ballisticity if condition  $(P)_M$  is satisfied for  $M \geq 15d + 5$ . In this article we will sharpen this ellipticity criteria.

Define  $\eta_\alpha := \max_{e \in U} \mathbb{E} \left( \frac{1}{\omega(0,e)^\alpha} \right)$ ,  $\bar{\alpha} := \sup\{\alpha \geq 0 : \eta_\alpha < \infty\}$ . We need the constant  $c_0 := \frac{2}{3} 3^{120d^4 + 3000d(\log \eta_{\bar{\alpha}/2})^2}$  : throughout the rest of this paper, whenever we assume that the polynomial condition  $(P)_M$  is satisfied, it will be understood that this happens on a box of size  $L \geq c_0$ .

Let us first recall the ellipticity condition of [3]. We say that there exists an asymptotic direction if the limit

$$\hat{v} := \lim_{n \rightarrow \infty} \frac{X_n}{|X_n|_2}$$

exists  $P_0$ -a.s. The polynomial condition  $(P)_M$  implies the existence of an asymptotic direction (see for example Simenhaus [11]). Whenever the asymptotic direction exists, we define the half space

$$H_{\hat{v}} := \{l \in S^{d-1} : l \cdot \hat{v} \geq 0\}.$$

**Definition 2.** Let  $\beta > 0$ . We say that the law of the environment satisfies the ellipticity condition  $(E')_\beta$  if there exists an  $\{\alpha(e) : e \in U\} \in (0, \infty)^{2d}$  such that

$$(1.1) \quad \kappa(\{\alpha(e) : e \in U\}) := 2 \sum_{e'} \alpha(e') - \sup_{e \in U} (\alpha(e) + \alpha(-e)) > \beta$$

and for every  $e \in U$

$$(1.2) \quad \mathbb{E} \left( e^{\sum_{e' \neq e} \alpha(e') \log \frac{1}{\omega(0, e')}} \right) < \infty.$$

Furthermore, we say that the ellipticity condition  $(E')_\beta$  is satisfied towards the asymptotic direction if there exists an  $\{\alpha(e) : e \in U\}$  satisfying (1.1) and (1.2) and such that there exists  $\alpha_1 > 0$  that satisfies  $\alpha(e) = \alpha_1$  for  $e \in H_{\hat{v}}$  while  $\alpha(e) \leq \alpha_1$  for  $e \notin H_{\hat{v}}$ .

**Remark 1.** Replacing (1.2) by  $\mathbb{E} \left( e^{\sum_{e'} \alpha(e') \log \frac{1}{\omega(0, e')}} \right) < \infty$  gives an equivalent condition. The direct implication is straightforward. And since  $1 \leq \sum_{e \in U} 1_{\{\omega(0, e) \geq \frac{1}{2d}\}}$ , we get

$$\mathbb{E} \left( e^{\sum_{e'} \alpha(e') \log \frac{1}{\omega(0, e')}} \right) \leq \sum_{e \in U} e^{\alpha(e) \log(2d)} \mathbb{E} \left( e^{\sum_{e' \neq e} \alpha(e') \log \frac{1}{\omega(0, e')}} \right).$$

This gives the reverse implication.

**Remark 2.** The results of [3] still hold (with no changes in the proofs) if we replace the previous definition of  $\eta_\alpha$  by

$$\eta_\alpha := \max_{e \in H_{\hat{v}}} \mathbb{E} \left( \frac{1}{\omega(0, e)^\alpha} \right).$$

It means that the constant  $c_0$  in the definition of condition  $(P)_M$  depends only of the integrability towards the asymptotic direction.

**1.2. Ballisticity results.** Our main results are a generalization of theorems 1.2 and 1.3 of [3] where we remove the "towards the asymptotic direction" condition of Theorems 1.2 and 1.3 of [3].

Let  $\tau_1^{\hat{v}}$  be the first renewal time in the direction  $\hat{v}$ , its precise definition is recalled in the next section. We prove the following tail estimate on renewal times, which improves proposition 5.1 of [3].

**Theorem 1.** Let  $l \in S^{d-1}$ ,  $\beta > 0$  and  $M \geq 15d + 5$ . Assume that  $(P)_M|l$  is satisfied and that  $(E')_\beta$  holds (cf. (1.1), (1.2)). Then

$$\limsup_{u \rightarrow \infty} (\log u)^{-1} \log P_0(\tau_1^{\hat{v}} > u) \leq -\beta.$$

The condition  $(E')_\beta$  is sharp in a sense that is made precise in remark 3 below.

Together with previous results of Sznitman, Zerner, Seppäläinen and Rassoul-Agha, cf [14, 17, 12, 8], it implies the following

**Theorem 2** (Law of large numbers). Consider a random walk in an i.i.d. environment in dimensions  $d \geq 2$ . Let  $l \in S^{d-1}$  and  $M \geq 15d + 5$ . Assume that the random walk

satisfies condition  $(P)_M|l$  and the ellipticity condition  $(E')_1$ . Then the random walk is ballistic in direction  $l$  and there is a  $v \in \mathbb{R}^d$ ,  $v \neq 0$  such that

$$\lim_{n \rightarrow \infty} \frac{X_n}{n} = v, \quad P_0 - a.s.$$

**Theorem 3** (Central limit theorems). *Consider a random walk in an i.i.d. environment in dimensions  $d \geq 2$ . Let  $l \in \mathbb{S}^{d-1}$  and  $M \geq 15d + 5$ . Assume that the random walk satisfies condition  $(P)_M|l$ .*

a) (Annealed central limit theorem) *If  $(E')_2$  is satisfied then*

$$\varepsilon^{1/2}(X_{[\varepsilon^{-1}n]} - [\varepsilon^{-1}n]v)$$

*converges in law under  $P_0$  as  $\varepsilon \rightarrow 0$  to a Brownian motion with non-degenerate covariance matrix.*

b) (Quenched central limit theorem) *If  $(E')_{176d}$  is satisfied, then  $\mathbb{P}$ -a.s. we have that*

$$\varepsilon^{1/2}(X_{[\varepsilon^{-1}n]} - [\varepsilon^{-1}n]v)$$

*converges in law under  $P_{0,\omega}$  as  $\varepsilon \rightarrow 0$  to a Brownian motion with non-degenerate covariance matrix.*

**Remark 3.** *The condition of theorem 1 is sharp under the following assumption on the tail behavior of the environment at one site: there exists some  $(\beta_e)_{e \in U}$ ,  $\beta_e \geq 0$ , and a positive constant  $C > 1$  such that for all  $e \in U$*

$$C^{-1} \left( \prod_{e' \in U, e' \neq e} t_{e'}^{\beta_{e'}} \right) \leq \mathbb{P}(\omega(0, e') \leq t_{e'}, \forall e' \in U, e' \neq e) \leq C \left( \prod_{e' \in U, e' \neq e} t_{e'}^{\beta_{e'}} \right)$$

for all  $(t_{e'})_{e' \in U \setminus \{e\}}$ ,  $0 \leq t_{e'} \leq 1$ . Dirichlet environment (cf the next section) is a typical example of environment that satisfies this condition. Indeed, in this case we easily see that  $(E')_\beta$  is satisfied if and only if  $\beta < 2 \sum_{e'} \beta(e') - \sup_{e \in U} (\beta(e) + \beta(-e))$ . On the other hand if  $\beta \geq 2 \sum_{e'} \beta(e') - \sup_{e \in U} (\beta(e) + \beta(-e))$  then  $\mathbb{E}((\tau_1^\flat)^\beta) = \infty$ . Indeed, consider a direction  $e_0$  which realizes the maximum in  $\sup_{e \in U} (\beta(e) + \beta(-e))$  and set  $K = \{0, e_0\}$ . We denote by  $\partial_+ K$  the set of edges that exit the set  $K$ , which is composed of the edges  $\{(0, e)\}_{e \neq e_0}$  and  $\{(e_0, e)\}_{e \neq -e_0}$ . For small  $t > 0$ , under the condition that  $\omega(x, y) \leq t$  for all  $(x, y) \in \partial_+ K$  we have  $P_{0,\omega}(T_K \geq n) \geq (1 - (2d - 1)t)^n$ . Hence,

$$\begin{aligned} P_0(T_K \geq n) &\geq (1 - (2d - 1)/n)^n \mathbb{P}(\omega(x, y) \leq 1/n, \forall (x, y) \in \partial_+ K) \\ &\geq (1 - (2d - 1)/n)^n C^{-1} n^{-((\sum_{e'} \beta(e')) - (\beta(e_0) + \beta(-e_0)))} \end{aligned}$$

which implies that  $E_0(T_K^\beta) = \infty$ . Since  $T_K$  is clearly a lower bound for the first renewal time it gives the result.

**Remark 4.** Theorem 1.1 of [3] states that for i.i.d. environments in dimensions  $d \geq 2$  satisfying the ellipticity condition  $(E')_0$ , the polynomial condition  $(P)_M|l$  (for  $l \in \mathbb{S}^{d-1}$  and  $M \geq 15d + 5$ ) is equivalent to Sznitman's condition  $(T')|l$  (see for example [13] for the definition). We can therefore replace  $(P)_M|l$  by  $(T')|l$  in the statements of Theorems 2 and 3.

**1.3. New examples of random walks satisfying the polynomial condition.** In this article we also introduce new examples of RWRE in environments which are not uniformly elliptic and which satisfy the polynomial condition  $(P)_M$  for  $M \geq 15d + 5$ . In subsection 1.3.1 we prove the polynomial condition for a subset of marginal nestling random walks, including a particular environment introduced by Campos and Ramírez

in [3]. In subsection 1.3.2, we prove the polynomial condition for a class of random walks in Dirichlet random environments which do not necessarily satisfy Kalikow's condition.

1.3.1. *Example within the class of marginal nestling random walks.* Following Sznitman [12], we say that a law  $\mathbb{P}$  on  $\Omega$  is *marginal nestling* if the convex hull  $K_o$  of the support of the law of

$$d(0, \omega) := \sum_{e \in U} \omega(0, e)e$$

is such that  $0 \in \partial K_o$ . We will prove in section 4 that a certain subset of the marginal nestling laws satisfies the polynomial condition.

**Theorem 4.** *Consider an elliptic law  $\mathbb{P}$  under which  $\{\omega(x) : x \in \mathbb{Z}^d\}$  are i.i.d. Assume that there exists an  $r > 1$  such that  $\omega(0, e_1) = r\omega(0, e_{1+d})$ . Then the polynomial condition  $(P)_M|_{e_1}$  is satisfied for some  $M \geq 15d + 5$ .*

The above result includes an example suggested in [3], by Campos and Ramírez, of an environment which satisfies the polynomial condition and for which the random walk is directionally transient but not ballistic. They showed that on this environment,  $(E')_\alpha$  is satisfied for  $\alpha$  smaller but arbitrarily close to 1, and that the walk is transient but not ballistic in a given direction. The proof that this environment satisfies the polynomial condition was left for a future work.

Let us define the environment introduced in [3]. Let  $\varphi$  be any random variable taking values on the interval  $(0, 1/4)$  and such that the expected value of  $\varphi^{-1/2}$  is infinite, while for every  $\varepsilon > 0$ , the expected value of  $\varphi^{-(1/2-\varepsilon)}$  is finite. Let  $X$  be a Bernoulli random variable of parameter  $1/2$ . We now define  $\omega(0, e_1) = 2\varphi$ ,  $\omega(0, -e_1) = \varphi$ ,  $\omega(0, e_2) = X\varphi + (1-X)(1-4\varphi)$  and  $\omega(0, -e_2) = X(1-4\varphi) + (1-X)\varphi$ .

For every  $\varepsilon > 0$  this environment satisfies  $(E')_{1-\varepsilon}$ : traps can appear because the random walk can get caught on two edges of the type  $(x, e_2), (x+e_2, -e_2)$ . Furthermore, it is transient in direction  $e_1$  but not ballistic in that direction.

1.3.2. *Examples within the class of Dirichlet random environments.* Random Walks in Dirichlet Environment (RWDE) are interesting because of the analytical simplifications they offer, and because of their link with reinforced random walks. Indeed, the annealed law of a RWDE corresponds to the law of a linearly directed-edge reinforced random walk ([4], [7]).

Given a family of positive weights  $(\beta_1, \dots, \beta_{2d})$ , a random i.i.d. Dirichlet environment is a law on  $\Omega$  constructed by choosing independently at each site  $x \in \mathbb{Z}^d$  the values of  $(\omega(x, e_i))_{i \in [1, 2d]}$  according to a Dirichlet law with parameters  $(\beta_1, \dots, \beta_{2d})$ . That is, at each site we choose independently a law with density

$$\frac{\Gamma\left(\sum_{i=1}^{2d} \beta_i\right)}{\prod_{i=1}^{2d} \Gamma(\beta_i)} \left(\prod_{i=1}^{2d} x_i^{\beta_i-1}\right) dx_1 \dots dx_{2d-1}$$

on the simplex  $\{(x_1, \dots, x_{2d}) \in ]0, 1]^{2d}, \sum_{i=1}^{2d} x_i = 1\}$ . Here  $\Gamma$  denotes the Gamma function  $\Gamma(\beta) = \int_0^\infty t^{\beta-1} e^{-t} dt$ , and  $dx_1 \dots dx_{2d-1}$  represents the image of the Lebesgue measure on  $\mathbb{R}^{2d-1}$  by the application  $(x_1, \dots, x_{2d-1}) \rightarrow (x_1, \dots, x_{2d-1}, 1 - x_1 - \dots - x_{2d-1})$ . Obviously, the law does not depend on the specific role of  $x_{2d}$ .

**Remark 5.** *Given a Dirichlet law of parameters  $(\beta_1, \dots, \beta_{2d})$ , the ellipticity condition  $(E')_\beta$  is satisfied if and only if*

$$\kappa((\beta_1, \dots, \beta_{2d})) = 2 \left( \sum_{i=1}^{2d} \beta_i \right) - \max_{i=1, \dots, d} (\beta_i + \beta_{i+d}) > \beta.$$

In the case of RWDE, it has been proved that Kalikow's condition, and thus the  $(T')$  condition, is satisfied whenever

$$(1.3) \quad \max_{1 \leq i \leq d} |\beta_i - \beta_{i+d}| > 1$$

(see Enriquez and Sabot in [5] and Tournier in [15]). The characterization of Kalikow's condition in terms of the parameters of a RWDE remains an open question. On the other hand, we believe that for RWDE condition  $(T')$  is satisfied if and only if  $\max_{1 \leq i \leq d} |\beta_i - \beta_{i+d}| > 0$ . Nevertheless, in this article we are able to prove the following result.

**Theorem 5.** *Let  $\beta_1, \beta_2, \dots, \beta_d, \beta_{d+2}, \dots, \beta_{2d}$  be fixed positive numbers. Then, there exists an  $\varepsilon \in (0, 1)$  depending on these numbers such that if  $\beta_{1+d}$  is chosen so that  $\beta_{1+d} \leq \varepsilon$ , the Random Walk in Dirichlet Environment with parameters  $(\beta_1, \dots, \beta_{2d})$  satisfies condition  $(P)_M|e_1$  for  $M \geq 15d + 5$ .*

Theorem 5 gives new examples of RWDE which are ballistic in dimension  $d = 2$  since they do not correspond to ranges of the parameters satisfying condition 1.3 of Tournier [15] and Sabot and Enriquez [5]. Indeed, by Theorem 2, if

$$\sum_{i=1}^{2d} \beta_i - \sup_{1 \leq i \leq d} (\beta_i + \beta_{i+d}) > 1$$

and one of the parameters  $\{\beta_i : 1 \leq i \leq d\}$  is small enough, the walk is ballistic.

**Remark 6.** *In dimension  $d \geq 3$ , in [9, 2], precise conditions on the existence of an invariant measure viewed from the particle absolutely continuous with respect to the law have been given ; this allows to characterize parameters for which there is ballisticity, but it fails to give information on  $(T')$  condition and on tails of renewal times.*

## 2. FIRST TOOLS FOR THE PROOFS

In this section we will introduce some tools that will prove necessary for the proofs of theorems 2 and 3.

**2.1. Regeneration times.** The proofs in [3] are based on finding bounds on the regeneration times. We thus begin by giving the definition and some results about the regeneration times with respect to a direction  $l$ .

We define  $\{\theta_n : n \geq 1\}$  as the canonical time shift on  $\mathbb{Z}^{d^N}$ . For  $l \in S^{d-1}$  and  $u \geq 0$ , we define the times

$$T_u^l := \inf\{n \geq 0 : X_n \cdot l \geq u\}$$

and

$$\tilde{T}_u^l := \inf\{n \geq 0 : X_n \cdot l \leq u\}.$$

Set

$$(2.1) \quad a > 2\sqrt{d}$$

and

$$D^l := \min\{n \geq 0 : X_n \cdot l < X_0 \cdot l\}.$$

We define

$$\begin{aligned} S_0 &:= 0, & M_0 &:= X_0 \cdot l, \\ S_1 &:= T_{M_0+a}^l, & R_1 &:= D^l \circ \theta_{S_1}, \\ M_1 &:= \sup\{X_n \cdot l : 0 \leq n \leq R_1\}, \end{aligned}$$

and recursively for  $k \geq 1$ ,

$$\begin{aligned} S_{k+1} &:= T_{M_k+a}^l, & R_{k+1} &:= D^l \circ \theta_{S_{k+1}} + S_{k+1}, \\ M_{k+1} &:= \sup\{X_n \cdot l : 0 \leq n \leq R_{k+1}\}. \end{aligned}$$

The first regeneration time is then defined as

$$\tau_1 := \min\{k \geq 1 : S_k < \infty, R_k = \infty\}.$$

We can now define recursively in  $n$  the  $(n+1)$ -th regeneration time  $\tau_{n+1}$  as  $\tau_1(X) + \tau_n(X_{\tau_1+} - X_{\tau_1})$ . We will occasionally write  $\tau_1^l, \tau_2^l, \dots$  to emphasize the dependence on the chosen direction.

**Remark 7.** *The condition (2.1) on  $a$  is only necessary to prove the non-degeneracy of the covariance matrix of part (a) of theorem 3.*

It is a standard fact (see for example Sznitman and Zerner [14]) to show that the sequence  $((\tau_1, X_{(\tau_1+.) \wedge \tau_2} - X_{\tau_1}), (\tau_2 - \tau_1, X_{(\tau_2+.) \wedge \tau_3} - X_{\tau_2}), \dots)$  is independent and (except for its first term) i.i.d.. Its law is the same as the law of  $\tau_1$  with respect to the conditional probability measure  $P_0(\cdot | D^l = \infty)$ .

Those regeneration times are particularly useful to us because of the two following theorems :

**Theorem 6** (Sznitman and Zerner [14], Zerner [17], Sznitman [12]). *Consider a RWRE in an elliptic i.i.d. environment. Let  $l \in S^{d-1}$  and assume that there is a neighbourhood  $V$  of  $l$  such that for every  $l' \in V$  the random walk is transient in the direction  $l'$ . Then there is a deterministic  $v$  such that  $P_0$ -a.s.*

$$\lim_{n \rightarrow \infty} \frac{X_n}{n} = v.$$

Furthermore, the following are satisfied.

- a) If  $E_0(\tau_1) < \infty$ , the walk is ballistic and  $v \neq 0$ .
- b) If  $E_0(\tau_1^2) < \infty$ ,

$$\varepsilon^{1/2} (X_{[\varepsilon^{-1}n]} - [\varepsilon^{-1}n]v)$$

converges in law under  $P_0$  to a Brownian motion with non-degenerate covariance matrix.

**Theorem 7** (Rassoul-Agha and Seppäläinen [8]). *Consider a RWRE in an elliptic i.i.d. environment. Take  $l \in S^{d-1}$  and let  $\tau_1$  be the corresponding regeneration time. Assume that*

$$E_0(\tau_1^p) < \infty,$$

for some  $p > 176d$ . Then  $\mathbb{P}$ -a.s. we have that

$$\varepsilon^{1/2} (X_{[\varepsilon^{-1}n]} - [\varepsilon^{-1}n]v)$$

converges in law under  $P_{0,\omega}$  to a Brownian motion with non-degenerate covariance matrix.



**2.2. Atypical Quenched Exit Estimate.** The proof of theorem 1 is based on an atypical quenched exit estimate proved in [3]. We will also need this result, and thus recall it in this section. Let us first introduce some notations.

Without loss of generality, we can assume that  $e_1$  is contained in the open half-space defined by the asymptotic direction so that

$$\hat{v} \cdot e_1 > 0.$$

We define the hyperplane :

$$H := \{x \in \mathbb{R}^d : x \cdot e_1 = 0\}.$$

Let  $P := P_{\hat{v}}$  be the projection on the asymptotic direction along the hyperplane  $H$  defined for  $z \in \mathbb{Z}^d$  by

$$P(z) := \left( \frac{z \cdot e_1}{\hat{v} \cdot e_1} \right) \hat{v},$$

and  $Q := Q_l$  be the projection of  $z$  on  $H$  along  $\hat{v}$  so that

$$Q(z) := z - P(z).$$

Now, for  $x \in \mathbb{Z}^d$ ,  $\beta > 0$ ,  $\rho > 0$  and  $L > 0$ , we define the tilted boxes with respect to the asymptotic direction  $\hat{v}$  by :

$$(2.2) \quad B_{\beta,L}(x) := \{y \in \mathbb{Z}^d \text{ s.t. } -L^\beta < (y-x) \cdot e_1 < L \text{ and } \|Q(y-x)\|_\infty < \rho L^\beta\}.$$

and their front boundary by

$$\partial^+ B_{\beta,L}(x) := \{y \in \partial B_{\beta,L}(x) \text{ s.t. } (y-x) \cdot e_1 = L\}.$$

We have :

**Proposition 8** (Atypical Quenched Exit Estimate, proposition 4.1 of [3]). *Set  $\alpha > 0$  such that  $\eta_\alpha := \sup_{e \in U} \mathbb{E} \left( \left( \frac{1}{\omega(0,e)} \right)^\alpha \right) < \infty$ . Take  $M \geq 15d + 5$  such that  $(P)_M|l$  is satisfied. Let  $\beta_0 \in (1/2, 1)$ ,  $\beta \in (\frac{\beta_0+1}{2}, 1)$  and  $\zeta \in (0, \beta_0)$ . Then, for each  $\gamma > 0$  we have that*

$$\limsup_{L \rightarrow \infty} L^{-g(\beta_0, \beta, \zeta)} \log \mathbb{P} \left( P_{0,\omega} \left( X_{T_{B_{\beta,L}(0)}} \in \partial^+ B_{\beta,L}(0) \right) \leq e^{-\gamma L^\beta} \right) < 0,$$

where

$$g(\beta_0, \beta, \zeta) := \min\{\beta + \zeta, 3\beta - 2 + (d-1)(\beta - \beta_0)\}.$$

**2.3. Some results on flows.** The main tools that enables us to improve the results of [3] is the use of flows and max-flow-min-cut theorems. We need some definitions and properties that we will detail in this section. In the following we consider a finite directed graph  $G = (V, E)$ , where  $V$  is the set of vertices and  $E$  is the set of edges. For all  $e \in E$ , we denote by  $\underline{e}$  and  $\bar{e}$  the vertices that are the head and tail of the edge  $e$  (the edge  $e$  goes from  $\underline{e}$  to  $\bar{e}$ ).

**Definition 3.** *We consider a finite directed graph  $G = (V, E)$ . A flow from a set  $A \subset V$  to a set  $Z \subset V$  is a non-negative function  $\theta : E \rightarrow \mathbb{R}_+$  such that :*

- $\forall x \in (A \cup Z)^c$ ,  $\text{div } \theta(x) = 0$ .
- $\forall x \in A$ ,  $\text{div } \theta(x) \geq 0$ .
- $\forall x \in Z$ ,  $\text{div } \theta(x) \leq 0$ .

where the divergence operator is  $\operatorname{div} : \mathbb{R}^E \rightarrow \mathbb{R}^V$  such that for all  $x \in V$ ,

$$\operatorname{div} \theta(x) = \sum_{e \in E, \underline{e}=x} \theta(e) - \sum_{e \in E, \bar{e}=x} \theta(e).$$

A unit flow from  $A$  to  $Z$  is a flow such that  $\sum_{x \in A} \operatorname{div} \theta(x) = 1$ . (Then we have also  $\sum_{x \in Z} \operatorname{div} \theta(x) = -1$ ).

We will need the following generalized version of the max-flow-min-cut theorem :

**Proposition 9** (proposition 1 of [9]). *Let  $G = (V, E)$  be a finite directed graph. Let  $(c(e))_{e \in E}$  be a set of non-negative reals (called capacities). Let  $x_0$  be a vertex and  $(p_x)_{x \in V}$  be a set of non-negative reals. There exists a non-negative function  $\theta : E \rightarrow \mathbb{R}_+$  such that*

$$(2.3) \quad \operatorname{div} \theta = \sum_{x \in V} p_x (\delta_{x_0} - \delta_x),$$

$$(2.4) \quad \forall e \in E, \theta(e) \leq c(e),$$

if and only if for all subset  $K \subset V$  containing  $x_0$  we have

$$(2.5) \quad c(\partial_+ K) \geq \sum_{x \in K^c} p_x,$$

where  $\partial_+ K = \{e \in E, \underline{e} \in K, \bar{e} \in K^c\}$  and  $c(\partial_+ K) = \sum_{e \in \partial_+ K} c(e)$ . The same is true if we restrict the condition (2.5) to the subsets  $K$  such that any  $y \in K$  can be reached from  $x_0$  following a directed path in  $K$ .

*Idea of the proof.* If  $\theta$  satisfies (2.3) and (2.4) then

$$\sum_{e, \underline{e} \in K, \bar{e} \in K^c} \theta(e) - \sum_{e, \bar{e} \in K, \underline{e} \in K^c} \theta(e) = \sum_{x \in K} \operatorname{div} \theta(x) = \sum_{x \in K^c} p_x.$$

It implies (2.5) by (2.4) and positivity of  $\theta$ .

The reversed implication is an easy consequence of the classical max-flow min-cut theorem on finite directed graphs (see for example [6] section 3.1). If  $(c(e))_{e \in E}$  satisfies (2.5), we consider the new graph  $\tilde{G} = (V \cup \{\delta\}, \tilde{E})$ , where

$$\tilde{E} = E \cup \{(x, \delta), x \in V\}.$$

We define a new set of capacities  $(\tilde{c}(e))_{e \in \tilde{E}}$  where  $c(e) = \tilde{c}(e)$  for  $e \in E$  and  $\tilde{c}((x, \delta)) = p_x$ . The strategy is to apply the max-flow min-cut theorem with capacities  $\tilde{c}$  and with source  $x_0$  and sink  $\delta$ . It gives a flow  $\tilde{\theta}$  on  $\tilde{G}$  between  $x_0$  and  $\delta$  with strength  $\sum_{x \in V} p_x$  and such that  $\tilde{\theta} \leq \tilde{c}$ . The function  $\theta$  obtained by restriction of  $\tilde{\theta}$  to  $E$  satisfies (2.4) and (2.3).  $\square$

For the proof of theorem 1, we will consider the oriented graph  $(\mathbb{Z}^d, E_{\mathbb{Z}^d})$  where  $E_{\mathbb{Z}^d} := \{(x, y) \in (\mathbb{Z}^d)^2 \text{ s.t. } |x - y|_1 = 1\}$ . This graph is not finite, but we will only consider flows with compact support ( $\theta(e) = 0$  for all  $e$  except in a finite subset of  $E_{\mathbb{Z}^d}$ ). We can then proceed as if the graph were finite, and use the previous definition and proposition.

## 3. PROOF OF THEOREM 1

Let  $l \in \mathbb{S}^{d-1}$ ,  $\beta > 0$  and  $M \geq 15d + 5$ . Assume that  $(P)_M|l$  is satisfied and that  $(E')_\beta$  holds.

Let us take a rotation  $\hat{R}$  such that  $\hat{R}(e_1) = \hat{v}$ . We fix  $\beta' \in (\frac{5}{6}, 1)$ ,  $M > 0$  and for simplicity we will write  $\tau_1$  instead of  $\tau_1^{\hat{v}}$ .

For  $u > 0$ , take

$$L = L(u) := \left( \frac{1}{4M\sqrt{d}} \right)^{\frac{1}{\beta'}} (\log u)^{\frac{1}{\beta'}},$$

$$C_L := \left\{ x \in \mathbb{Z}^d : \frac{-L}{2(\hat{v} \cdot e_1)} \leq x \cdot \hat{R}(e_i) \leq \frac{L}{2(\hat{v} \cdot e_1)}, \text{ for } 0 \leq i \leq 2d \right\}$$

Following the proof of proposition 5.1 in [3], we write

$$P_0(\tau_1 > u) \leq P_0\left(\tau_1 > u, T_{C_{L(u)}} \leq \tau_1\right) + \mathbb{E}\left(F_1^c, P_{0,\omega}\left(T_{C_{L(u)}} > u\right)\right) + \mathbb{P}(F_1),$$

with

$$F_1 := \left\{ \omega \in \Omega : t_\omega(C_{L(u)}) > \frac{u}{(\log u)^{\frac{1}{\beta'}}} \right\}$$

and

$$t_\omega(A) := \inf \left\{ n \geq 0 : \sup_x P_{x,\omega}(T_A > n) \leq \frac{1}{2} \right\}.$$

As in [3], the term  $P_0\left(\tau_1 > u, T_{C_{L(u)}} \leq \tau_1\right)$  is bounded thanks to condition  $(P)_M|l$ , and the term  $\mathbb{E}\left(F_1^c, P_{0,\omega}\left(T_{C_{L(u)}} > u\right)\right)$  is bounded thanks to the strong Markov property. This part of the original proof is not modified, so we will not give more details here. It gives the existence for every  $\gamma \in (\beta', 1)$  of a constant  $c > 0$  such that :

$$P_0(\tau_1 > u) \leq \frac{e^{-cL^\gamma(u)}}{c} + \left(\frac{1}{2}\right)^{\left\lfloor (\log u)^{\frac{1}{\beta'}} \right\rfloor} + \mathbb{P}(F_1).$$

It only remains to show that we can find a constant  $C > 0$  such that  $\mathbb{P}(F_1) \leq Cu^{-\beta}$  for  $u$  big enough.

For each  $\omega \in \Omega$ , still as in [3], there exists  $x_0 \in C_{L(u)}$  such that

$$P_{x_0,\omega}(\tilde{H}_{x_0} > T_{C_{L(u)}}) \leq \frac{2|C_{L(u)}|}{t_\omega(C_{L(u)})}$$

where for  $y \in \mathbb{Z}^d$ ,  $\tilde{H}_y = \inf\{n \geq 1 : X_n = y\}$ . It gives

$$\mathbb{P}(F_1) \leq \mathbb{P}\left(\omega \in \Omega \text{ s.t. } \exists x_0 \in C_{L(u)} \text{ s.t. } P_{x_0,\omega}(\tilde{H}_{x_0} > T_{C_{L(u)}}) \leq \frac{2(\log u)^{\frac{1}{\beta'}}}{u} |C_{L(u)}|\right).$$

We define for each point  $x \in C_{L(u)}$  a point  $y_x$ , closest from  $x + 2\frac{L^{\beta'}}{\hat{v} \cdot e_1}\hat{v}$ . To bound  $\mathbb{P}(F_1)$ , we will need paths that go from  $x$  to  $y_x$  with probability big enough and the atypical quenched exit estimate (proposition 8).

Define :

$$N := \frac{|\hat{v}| \log u}{2M\sqrt{d}(\hat{v} \cdot e_1)}.$$

It is straightforward that

$$N - 1 \leq |y_x - x|_1 \leq N + 1.$$

The following of the proof will be developed in three parts : first we will construct unit flows  $\theta_{i,x}$  going from  $\{x, x + e_i\}$  to  $\{y_x, y_x + e_i\}$ , for all  $x \in C_{L(u)}$ . Then we will construct paths with those flows, and use the atypical quenched exit estimate to bound  $\mathbb{P}(F_1)$  in the case that those paths are big enough. We will conclude by bounding the probability that the paths are not big enough.

**3.1. Construction of the flows  $\theta_{i,x}$ .** We consider the oriented graph  $(\mathbb{Z}^d, E_{\mathbb{Z}^d})$  where  $E_{\mathbb{Z}^d} := \{(x, y) \in (\mathbb{Z}^d)^2 \text{ s.t. } |x - y|_1 = 1\}$ . We want to construct unit flows  $\theta_{i,x}$  going from  $\{x, x + e_i\}$  to  $\{y_x, y_x + e_i\}$ , for all  $x \in C_{L(u)}$ . But there are additional constraints, as we will need them to construct paths that have a probability big enough. The aim of this section is to prove the following proposition :

**Proposition 10.** *For all  $x \in C_{L(u)}$ , for all  $\alpha_1, \dots, \alpha_{2d}$  positive constants, there exists  $2d$  unit flows  $\theta_{i,x} : E_{\mathbb{Z}^d} \rightarrow \mathbb{R}_+$ , respectively going from  $\{x, x + e_i\}$  to  $\{y_x, y_x + e_i\}$ , such that :*

$$(3.1) \quad \forall e \in E_{\mathbb{Z}^d}, \theta_{i,x}(e) \leq \frac{\alpha(e)}{\kappa_i},$$

where  $\kappa_i := 2 \sum_{j=1}^{2d} \alpha_j - (\alpha_i + \alpha_{i+d})$ , and  $\alpha(e) := \alpha_i$  for  $e$  of the type  $(z, e_i)$ .

Furthermore, we can construct  $\theta_{i,x}$  with a compact support, and in a way that allows to find  $\gamma$  and  $S \subset E_{\mathbb{Z}^d}$ ,  $|S|$  independent of  $u$ , such that  $\theta_{i,x}(e)\kappa_i \leq \gamma < \alpha(e)$  for all  $e \in S^c$ .

We will construct the  $\theta_{i,x}$  to prove their existences. For this we need three steps. Let  $B(x, R)$  be the box of  $\mathbb{Z}^d$  of center  $x$  and radius  $R$ , and  $B_i(x, R)$  be the same box, where the vertices  $x$  and  $x + e_i$  are merged (and we suppress the edge between them). We note  $E_{B(x, R)} := \{(x, y) \in E_{\mathbb{Z}^d} \cap (B(x, R))^2\}$  and  $E_{B_i(x, R)} := \{(x, y) \in E_{\mathbb{Z}^d} \cap (B_i(x, R))^2\}$  the corresponding sets of edges. We will construct a unit flow in the graph  $(B_i(x, R), E_{B_i(x, R)})$  from  $\{x, x + e_i\}$  to  $B_i(x, R)^c$ , a unit flow in the graph  $(B_i(y_x, R), E_{B_i(y_x, R)})$  from  $B_i(y_x, R)^c$  to  $\{y_x, y_x + e_i\}$ , and then connect them. At each step, we will ensure that condition 3.1 is fulfilled.

**First step :** construction of a unit flow from  $\{x, x + e_i\}$  to  $B_i(x, R)^c$  :

**Lemma 1.** *Set  $x \in C_{L(u)}$ , and  $\alpha_1, \dots, \alpha_{2d}$  positive constants. If  $R \geq \frac{\max_i \kappa_i}{\min_j \alpha_j}$ , there exists  $2d$  unit flows  $\theta_{i,x} : E_{B_i(x, R)} \rightarrow \mathbb{R}_+$  such that :*

$$\operatorname{div} \theta_{i,x} = \sum_{z \in \partial B_i(x, R)} \frac{1}{|\partial B_i(x, R)|} (\delta_x - \delta_z)$$

and

$$\forall e \in E_{B_i(x, R)}, \theta_{i,x}(e) \leq \frac{\alpha(e)}{\kappa_i}$$

where  $\partial B_i(x, R) = \{z \in B_i(x, R) \text{ that has a neighbour in } B_i(x, R)^c\}$ .

The divergence condition ensures that the flow will be a unit flow, that it goes from  $x$ , and that it leaves  $B_i(x, R)$  uniformly on the boundary of the box.

*Proof.* The result is a simple application of proposition 9. We fix  $x \in C_{L(u)}$  and  $i$  between 1 and  $2d$ . Define  $p_z = \frac{1}{|\partial B_i(x, R)|}$  if  $z \in \partial B_i(x, R)$ ,  $p_z = 0$  if  $z \notin \partial B_i(x, R)$ .

To prove the result we only have to check that  $\forall K \subset B_i(x, R)$  containing  $x$ ,  $\sum_{e \in \partial_+ K} \frac{\alpha(e)}{\kappa_i} \geq \sum_{z \notin K} p_z$ , where  $\partial_+ K = \{e \in E_{B_i(x, R)} \text{ s.t. } \underline{e} \in K \text{ and } \bar{e} \notin K\}$ .

We have two cases to examine:

- If  $K \cap \partial B_i(x, R) = \emptyset$ ,  $\sum_{z \notin K} p_z = 1$ . We then need  $\sum_{e \in \partial_+ K} \alpha(e) \geq \kappa_i$ . For  $K = \{x\}$ ,  $\sum_{e \in \partial_+ K} \alpha(e) = \kappa_i$  as we merged  $x$  and  $x + e_i$ . For bigger  $K$ , we consider for all  $j \neq i$  the paths  $(x + ne_j)_{n \in \mathbb{N}}$  and for all  $j \neq i + d$  the paths  $(x + e_i + ne_j)_{n \in \mathbb{N}}$ . They intersect the boundary of  $K$  in  $2d + 1$  different points, and the exit directions give us the corresponding  $\alpha_j$ , that sum to  $\kappa_i$ . It gives that  $\sum_{e \in \partial_+ K} \alpha(e) \geq \kappa_i$ .
- If  $K \cap \partial B_i(x, R) \neq \emptyset$ ,  $\sum_{z \notin K} p_z < 1$ . As  $K$  contains a path from  $x$  to  $\partial B_i(x, R)$ ,  $\sum_{e \in \partial_+ K} \frac{\alpha(e)}{\kappa_i} \geq \frac{R \min_j (\alpha_j + \alpha_{j+d})}{\kappa_i}$ . It is bigger than 1 thanks to the hypothesis on  $R$ . It gives the result.

□

**Second step :** by the same way, we construct a flow  $\theta_{i,x} : E_{B_i(y_x, R)} \rightarrow \mathbb{R}_+$  such that

$$\operatorname{div} \theta_{i,x} = \sum_{z \in \partial B_i(y_x, R)} \frac{1}{|\partial B_i(y_x, R)|} (\delta_z - \delta_{y_x}).$$

and

$$\forall e \in E_{B_i(y_x, R)}, \theta_{i,x}(e) \leq \frac{\alpha(e)}{\kappa_i}.$$

**Third step :** we will join the flows on  $E_{B_i(x, R)}$  and  $E_{B_i(y_x, R)}$  with simple paths, to get a flow on  $E_{\mathbb{Z}^d}$ . Take  $R \geq \frac{\max_i \kappa_i}{\min_j \alpha_j}$ , and make sure that  $\frac{1}{|\partial B(x, R)|} < \frac{\alpha(e)}{\kappa_i}$  for all  $e \in E_{\mathbb{Z}^d}$  (always possible by taking  $R$  big enough,  $R$  depends only on the  $\alpha_i$  and the dimension).

We can find  $\partial B(x, R)$  simple paths  $\pi_j \subset E_{\mathbb{Z}^d}$  satisfying :

- $\forall j$ ,  $\pi_j$  connects a point of  $\partial B(x, R)$  to a point of  $\partial B(y_x, R)$ .
- $\forall j$ ,  $\pi_j$  stays outside of  $B(x, R)$  and  $B(y_x, R)$ , except from the departure and arrival points.
- If two paths intersect, they perform jumps in different direction after the intersection (no edge is used by two paths). If  $(x, e_i)$  is in a path, then  $(x + e_i, -e_i)$  is not in any path.
- The number of steps of each path is close to  $N$  : there exists constants  $K_1$  and  $K_2$  independent of  $u$  such that the length of  $\pi_j$  is smaller than  $K_1 N + K_2$ .

(For example we can use the paths  $\pi^{(i,j)}$  p45 of [3], and make them exit the ball  $B(x, R)$  instead of  $\{x, x + e_i\}$ ).

For all  $i$ ,  $\partial B_i(x, R) = \partial B(x, R)$  and  $\partial B_i(y_x, R) = \partial B(y_x, R)$  as soon as  $R > 1$ . By construction,  $-\operatorname{div} \theta_{i,x}(z_1) = \operatorname{div} \theta_{i,x}(z_2) = \frac{1}{|\partial B(x, R)|}$  for any  $z_1 \in \partial B_i(x, R)$  and  $z_2 \in \partial B_i(y_x, R)$ . We can then join the flows of the first two steps by defining a flow  $\theta_{i,x}(e) = \frac{1}{|\partial B(y_x, R)|}$  for all  $e \in \pi_j$  (and 0 on all the other edges of  $E_{\mathbb{Z}^d}$ ).

We have thus constructed a unit flow  $\theta_{i,x}$  on  $E_{\mathbb{Z}^d}$ , from  $\{x, x + e_i\}$  to  $\{y_x, y_x + e_i\}$ , satisfying (3.1) ( (3.1) is satisfied on  $E_{B_i(x, R)}$  and  $E_{B_i(y_x, R)}$  as  $R \geq \frac{\max_i \kappa_i}{\min_j \alpha_j}$  thanks to lemma 1, and outside those balls as  $\frac{1}{|\partial B(x, R)|} < \frac{\alpha(e)}{\kappa_i}$  for all  $e \in E_{\mathbb{Z}^d}$ ). It concludes the proof of the first part of proposition 10.

As  $\theta_{i,x}(e) = 0$  out of the finite set  $E_{B_i(x, R)} \cup E_{B_i(y_x, R)} \cup \{e \in \pi_j, 1 \leq j \leq \partial B(x, R)\}$ , the flow has a compact support. And as we made sure that  $\frac{1}{|\partial B(x, R)|} < \frac{\alpha(e)}{\kappa_i}$ , we can take  $S = B(x, R) \cup B(y_x, R)$  and  $\gamma = \frac{\kappa_i}{|\partial B(x, R)|}$  to conclude the proof.

**3.2. Bounds for  $\mathbb{P}(F_1)$ .** We apply proposition 10 for the  $\alpha_1, \dots, \alpha_{2d}$  of the definition of  $(E')_\beta$  (see (1.1) and (1.2)). It gives flows  $\theta_{i,x}$  on  $E_{\mathbb{Z}^d}$ , constructed as in the previous section.

We can decompose a given  $\theta_{i,x}$  (for  $i$  and  $x$  fixed) in a finite set of weighted paths, each path starting from  $x$  or  $x + e_i$  and arriving to  $y_x$  or  $y_x + e_i$ . It suffices to choose a path  $\sigma$  where the flow is always positive, to give it a weight  $p_\sigma := \min_{e \in \sigma} \theta_{i,x}(e) > 0$  and to iterate with the new flow  $\theta(e) := \theta_{i,x}(e) - p_\sigma 1_{e \in \sigma}$ .

The weigh  $p_\sigma$  of a path  $\sigma$  then satisfies : for all  $e \in E_{\mathbb{Z}^d}$ ,  $\theta_{i,x}(e) = \sum_{\sigma \text{ containing } e} p_\sigma$ . As  $\theta_{i,x}$  is a unit flow we get  $\sum_{\sigma \text{ path of } \theta_{i,x}} p_\sigma = 1$ . We will use those weights in the next section, to prove that those paths are "big enough" with high probability.

We now introduce :

$$F_{2,i} = \left\{ \omega \in \Omega \text{ s.t. } \forall x \in C_{L(u)}, \forall \sigma \text{ path of } \theta_{i,x}, \omega_\sigma := \prod_{e \in \sigma} \omega_e \geq u^{\frac{1}{M}-1} \right\}$$

and

$$F_2 = \bigcap_{i=1}^{2d} F_{2,i}.$$

Define

$$F_3 := \left\{ \omega \in \Omega \text{ s.t. } \exists x_0 \in C_{L(u)} \text{ s.t. } P_{x_0, \omega}(\tilde{H}_{x_0} > T_{C_{L(u)}}) \leq \frac{2(\log u)^{\frac{1}{\beta'}}}{u} |C_{L(u)}|, F_2 \right\}.$$

We get immediately :

$$\mathbb{P}(F_1) \leq \mathbb{P}(F_3) + \mathbb{P}(F_2^c).$$

It gives two new terms to bound. We start by bounding  $\mathbb{P}(F_3)$ . For this we will use the same method as in [3] : on the event  $F_3$ , for all  $1 \leq i \leq 2d$  we can use a path  $\sigma$  of  $\theta_{i,x}$  to join  $x$  or  $x + e_i$  to  $y_x$  or  $y_x + e_i$ . It gives :

$$\omega(x_0, e_i) u^{\frac{1}{M}-1} \inf_{z \in \{y_{x_0}, y_{x_0} + e_i\}} P_{z, \omega}(T_{C_{L(u)}} < H_{x_0}) \leq P_{x_0, \omega}(T_{C_{L(u)}} < \tilde{H}_{x_0}) \leq \frac{2(\log u)^{\frac{1}{\beta'}}}{u} |C_{L(u)}|,$$

where the factor  $\omega(x_0, e_i)$  corresponds to the probability of jumping from  $x$  to  $x + e_i$ , in the case where the path  $\sigma$  starts from  $x + e_i$ .

As  $\sum_{i=1}^{2d} \omega(x_0, e_i) = 1$ , it gives

$$u^{\frac{1}{M}-1} \inf_{z \in V(y_{x_0})} P_{z, \omega}(T_{C_{L(u)}} < H_{x_0}) \leq \frac{4d(\log u)^{\frac{1}{\beta'}}}{u} |C_{L(u)}|,$$

where  $V(y_{x_0}) := \{y_{x_0}, (y_{x_0} + e_i)_{i=1, \dots, 2d}\}$ .

In particular, on  $F_3$ , we can see that for  $u$  large enough  $V(y_{x_0}) \subset C_{L(u)}$ . As a result, on  $F_3$ , we have for  $u$  large enough

$$\inf_{z \in V(y_{x_0})} P_{z, \omega}(X_{T_z + U_{\beta', L}} \cdot e_1 > z \cdot e_1) \leq \inf_{z \in V(y_{x_0})} P_{z, \omega}(T_{C_{L(u)}} < H_{x_0}) \leq \frac{1}{u^{\frac{1}{2M}}} = e^{-2\sqrt{d}L(u)^{\beta'}},$$

where

$$U_{\beta', L} := \{x \in \mathbb{Z}^d : -L^{\beta'} < x \cdot e_1 < L\}.$$

From this and using the translation invariance of the measure  $\mathbb{P}$ , we conclude that :

$$\begin{aligned} & \mathbb{P} \left( \exists x_0 \in C_{L(u)} \text{ s.t. } P_{x_0, \omega}(\tilde{H}_{x_0} > T_{C_{L(u)}}) \leq \frac{4d(\log u)^{\frac{1}{\beta'}}}{u} |C_{L(u)}|, F_2 \right) \\ & \leq \mathbb{P} \left( \exists x_0 \in C_{L(u)} \text{ s.t. } \inf_{z \in V(y_{x_0})} P_{z, \omega}(X_{T_z + U_{\beta', L}} \cdot e_1 > z \cdot e_1) \leq e^{-2\sqrt{d}L(u)^{\beta'}} \right) \\ & \leq (2d+1) |C_{L(u)}| \mathbb{P} \left( P_{0, \omega}(X_{T_{U_{\beta', L}(u)}} \cdot e_1 > 0) \leq e^{-2\sqrt{d}L(u)^{\beta'}} \right) \\ & \leq (2d+1) |C_{L(u)}| \mathbb{P} \left( P_{0, \omega}(X_{T_{B_{\beta', L(u)}}} \cdot e_1 > 0) \leq e^{-2\sqrt{d}L(u)^{\beta'}} \right), \end{aligned}$$

where the titled box  $B_{\beta', L(u)}$  is defined as in (2.2).

We conclude with the atypical quenched exit estimate (proposition 8) : there exists a constant  $c > 0$  such that for each  $\beta_0 \in (\frac{1}{2}, 1)$  one has :

$$\mathbb{P}(F_3) \leq \frac{1}{c} e^{-cL(u)^{g(\beta_0, \beta', \zeta)}},$$

where  $g(\beta_0, \beta', \zeta)$  is defined as in proposition 8.

Note that for each  $\beta' \in (\frac{5}{6}, 1)$  there exists a  $\beta_0 \in (\frac{1}{2}, \beta)$  such that for every  $\zeta \in (0, \frac{1}{2})$  one has  $g(\beta_0, \beta', \zeta) > \beta'$ . Therefore, replacing  $L$  by its value, we proved that there exists  $c > 0$  such that :

$$\mathbb{P}(F_3) \leq cu^{-\beta}.$$

**3.3. Bound for  $\mathbb{P}(F_2^c)$ .** To conclude the bound for  $\mathbb{P}(F_1)$  and the proof of theorem 1, it only remains to control  $\mathbb{P}(F_2^c)$ . It is in this section that we will use the conditions that were imposed on  $\theta_{i,x}$  during the construction of the flows.

$$\begin{aligned} \mathbb{P}(F_2^c) & \leq \sum_{i=1}^{2d} \mathbb{P}(F_{2,i}^c) \\ & \leq \sum_{i=1}^{2d} \sum_{x \in C_{L(u)}} \mathbb{P}(\forall \sigma \text{ path of } \theta_{i,x}, \omega_\sigma \leq u^{\frac{1}{M}-1}) \end{aligned}$$

As  $\theta_{i,x}$  is a unit flow, if  $\forall \sigma$  path of  $\theta_{i,x}$ ,  $\omega_\sigma \leq u^{\frac{1}{M}-1}$  then :

$$\sum_{\sigma \text{ path of } \theta_{i,x}} p_\sigma \omega_\sigma \leq u^{\frac{1}{M}-1} \sum_{\sigma \text{ path of } \theta_{i,x}} p_\sigma = u^{\frac{1}{M}-1}.$$

Jensen's inequality then gives :

$$\prod_{\sigma \text{ path of } \theta_{i,x}} \omega_\sigma^{p_\sigma} = \prod_{e \in E_{\mathbb{Z}^d}} \omega_e^{\theta_{i,x}(e)} \leq u^{\frac{1}{M}-1}.$$

It allows to write :

$$\begin{aligned} \mathbb{P}(F_2^c) & \leq \sum_{i=1}^{2d} \sum_{x \in C_{L(u)}} \mathbb{P} \left( \prod_{e \in E_{\mathbb{Z}^d}} \omega_e^{\theta_{i,x}(e)} \leq u^{\frac{1}{M}-1} \right) \\ & \leq \sum_{i=1}^{2d} \sum_{x \in C_{L(u)}} \frac{\mathbb{E} \left( \prod_{e \in E_{\mathbb{Z}^d}} \omega_e^{-\kappa_i \theta_{i,x}(e)} \right)}{u^{-\kappa_i(\frac{1}{M}-1)}} \end{aligned}$$

We will use the integrability given by the flows to bound the expectations. The independence of the environment gives (for  $i$  and  $x$  fixed) :

$$\begin{aligned} \mathbb{E} \left( \prod_e \omega_e^{-\kappa_i \theta_{i,x}(e)} \right) &= \prod_{z \in \mathbb{Z}^d} \mathbb{E} \left( \prod_{e \text{ s.t. } \underline{e}=z} \omega_e^{-\kappa_i \theta_{i,x}(e)} \right) \\ &= \prod_{z \in S} \mathbb{E} \left( \prod_{e \text{ s.t. } \underline{e}=z} \omega_e^{-\kappa_i \theta_{i,x}(e)} \right) \prod_{z \notin S} \mathbb{E} \left( \prod_{e \text{ s.t. } \underline{e}=z} \omega_e^{-\kappa_i \theta_{i,x}(e)} \right) \end{aligned}$$

where we recall that  $S = B(x, R) \cup B(y_x, R)$ .

As  $\theta_{i,x}$  satisfies (3.1), the ellipticity condition  $(E')_\beta$  gives that each of the expectations  $\mathbb{E} \left( \prod_{e \text{ s.t. } \underline{e}=z} \omega_e^{-\kappa_i \theta_{i,x}(e)} \right)$  are finite.

By construction  $|S|$  is finite and does not depend on  $u$  :  $\prod_{z \in S} \mathbb{E} \left( \prod_{e \text{ s.t. } \underline{e}=z} \omega_e^{-\kappa_i \theta_{i,x}(e)} \right)$  is a finite constant independent on  $u$ .

It remains to deal with the case of  $z \notin S$ . As we chose  $R$  to get  $\theta_{i,x}(e)\kappa_i < \gamma$  for the edges outside  $S$ , and thanks to the bounds on the number of edges with positive flow (there is a finite number of paths, and each path has a bounded length), we have :

$$\prod_{z \notin S} \mathbb{E} \left( \prod_{e \text{ s.t. } \underline{e}=z} \omega_e^{-\kappa_i \theta_{i,x}(e)} \right) \leq \mathbb{E} \left( \prod_{e \text{ s.t. } \underline{e}=0} \omega_e^{-\gamma} \right)^{c_1 N + c_2},$$

where  $c_1$  and  $c_2$  are positive constants, independent of  $u$ . Then, putting all of those bounds together,

$$\begin{aligned} \mathbb{P}(F_2^c) &\leq \sum_{i=1}^{2d} \sum_{x \in C_L(u)} C_1 C_2^{C_3 N} u^{\kappa_i(\frac{1}{M}-1)} \\ &\leq \sum_{i=1}^{2d} \sum_{x \in C_L(u)} C_4 u^{\frac{C_5 + \kappa_i}{M} - \kappa_i} \\ &\leq C_6 (\log u)^{C_7} u^{\frac{C_8}{M} - \min_i \kappa_i} \end{aligned}$$

where all the constants  $C_i$  are positive and do not depend on  $u$ . As remark 4 tells us that we can choose  $M$  as large as we want, we can get  $\frac{C_8}{M}$  as small as we want.

Then we can find a constant  $C > 0$  such that  $\mathbb{P}(F_2^c) \leq C u^{-\beta}$  for  $u$  big enough. It concludes the proof.

#### 4. NEW EXAMPLES OF RANDOM WALKS SATISFYING THE POLYNOMIAL CONDITION

**4.1. Proof of Theorem 4.** Consider the box  $B_{e_1, L, \tilde{L}}$  for  $\tilde{L} = 70L^3$ . We want to find some  $L > c_0$  such that

$$P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 < L \right) \leq \frac{1}{L^M},$$

for some  $M \geq 15d + 5$ . We first decompose this probability according to whether the exit point of the random walk from the box  $B_{e_1, L, \tilde{L}}$  is on the bottom or on one of the



sides of the box, so that,

$$\begin{aligned} & P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 < L \right) \\ &= P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 = -L \right) + P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = \tilde{L} \right) + P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = -\tilde{L} \right). \end{aligned}$$

We will first bound the probability to exit through the sides. We do the computations for  $P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = \tilde{L} \right)$  but the other term can be dealt with in the same way. Suppose that  $X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = \tilde{L}$ , and define  $n_0, \dots, n_{\tilde{L}-1}$  the finite hitting times of new levels in direction  $e_2$  as follows :

$$n_k := \inf \{ n \geq 0 \text{ s.t. } X_n \cdot e_2 \geq k \}.$$

To simplify notation define  $\varphi(x) := \omega(x, e_{1+d})$ . We now choose a constant  $1 > \delta > 0$ , and we will call "good point" any  $x \in \mathbb{Z}^2$  such that  $\varphi(x) > \delta$ . We define  $p := \mathbb{P}(\varphi(x) > \delta)$ . Note that  $p$  does not depend on  $x$  since the environment is i.i.d., so that it depends only on  $\delta$  and the law of  $\varphi$ .

We now introduce the event that a great number of the  $X_{n_k}$  are good points :

$$C_1 := \left\{ X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = \tilde{L} \text{ and at least } \frac{p}{2} \tilde{L} \text{ of the } X_{n_k}, 1 \leq k \leq \tilde{L} - 1, \text{ are good} \right\}.$$

We get immediately

$$P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = \tilde{L} \right) = P_0(C_1) + P_0 \left( \left\{ X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = \tilde{L} \right\} \cap (C_1^c) \right).$$

By construction of the  $X_{n_k}$  and independence of the environment, and with  $Z$  an independent random variable following a binomial law of parameters  $p$  and  $\tilde{L}$ , we can bound the second term of the sum :

$$\begin{aligned} P_0 \left( \left\{ X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = \tilde{L} \right\} \cap (C_1^c) \right) &\leq P \left( Z \leq \frac{p}{2} \tilde{L} \right) \\ &\leq \exp \left( -2 \frac{(p\tilde{L} - p\tilde{L}/2)^2}{\tilde{L}} \right) \\ &= \exp \left( -\frac{p^2 \tilde{L}}{2} \right) \end{aligned}$$

where the last inequality is Hoeffding's inequality.

It only remains to bound  $P_0(C_1)$ . For that, we introduce the following new event

$$C_2 := \left\{ C_1 \text{ and } X_{n_{k+1}} - X_{n_k} = e_1 \text{ for at least } \frac{\delta p}{4} \tilde{L} \text{ of the good } X_{n_k} \right\},$$

that states that the walk goes often in direction  $e_1$  just after reaching a  $X_{n_k}$  that is a good point.

We can then write

$$P_0(C_1) = P_0(C_2) + P_0(C_1 \cap (C_2^c)).$$

To bound  $P_0(C_1 \cap (C_2^c))$ , we use the uniform bound " $\varphi(x) > \delta$ " for good points that gives us that  $\omega(x, e_1) > r\delta$  on those points. And we get  $Z'$  an independent random

variable following a binomial law of parameters  $r\delta$  and  $\frac{p}{2}\tilde{L}$  :

$$\begin{aligned} P_0(C_1 \cap (C_2^c)) &\leq P\left(Z' \leq \frac{\delta p}{4}\tilde{L}\right) \\ &\leq \exp\left(-p\delta^2\tilde{L}\left(r - \frac{1}{2}\right)^2\right). \end{aligned}$$

It only remains to bound  $P_0(C_2)$ . Set  $n^+$  (respectively  $n^-$ ) the total number of jumps in direction  $e_1$  (respectively  $-e_1$ ) before exiting the box  $B_{e_1, L, \tilde{L}}$ . We will need a third new event

$$C_3 := \left\{n^+ \geq \frac{1+r}{r}n^-\right\},$$

that allows us to write

$$P_0(C_2) = P_0(C_2 \cap C_3) + P_0(C_2 \cap (C_3^c)).$$

First notice that for  $L$  big enough,  $C_2 \cap C_3 = \emptyset$ . Indeed,  $C_1$  implies that we exit the box  $B_{e_1, L, \tilde{L}}$  by the side " $x \cdot e_2 = \tilde{L}$ ". Now, since the vertical displacement of the walk before exiting the box  $B_{e_1, L, \tilde{L}}$  is  $n^+ - n^-$ , on the event  $C_3$  we know that this displacement is at least equal to  $\frac{1}{1+r}n^+$ . Therefore, since on  $C_2$  the walk makes at least  $\frac{\delta p}{4}\tilde{L} = \frac{35\delta p}{2}L^3$  moves in the direction  $e_1$ , on  $C_2 \cap C_3$  its vertical displacement before exiting the box is at least  $\frac{35\delta p}{2(1+r)}L^3$ . Since on  $C_2 \cap C_3$  the walk exits the box by the " $x \cdot e_2 = \tilde{L}$ " side

we see that for  $L$  larger than  $L_1 := \sqrt{\frac{2(1+r)}{35\delta p}}$  the event  $C_2 \cap C_3$  is empty.

We now want to bound  $P_0(C_2 \cap (C_3^c))$ .

$$\begin{aligned} P_0(C_2 \cap (C_3^c)) &\leq P_0\left(n^+ \geq \frac{\delta p}{4}\tilde{L} \text{ and } n^+ < \frac{1+r}{r}n^-\right) \\ &\leq P_0\left(n^+ + n^- \geq \frac{\delta p}{4}\tilde{L} \text{ and } (n^+ + n^-)\frac{r}{1+2r} < n^-\right). \end{aligned}$$

Now note that whenever we go through a vertical edge from a point  $x$ , the law of the environment tells us that it is an edge  $(x, e_1)$  with probability  $\frac{r}{1+r}$ , and  $(x, -e_1)$  with probability  $\frac{1}{1+r}$ . Then, defining  $Z''$  as a random variable following a binomial law of parameters  $\frac{1}{1+r}$  and  $\frac{p\delta}{4}\tilde{L}$ , we have the bound :

$$\begin{aligned} P_0(C_2 \cap (C_3^c)) &\leq P\left(Z'' \geq \frac{r}{1+2r}\frac{p\delta}{4}\tilde{L}\right) \\ &\leq \exp\left(-4p\delta\tilde{L}\left(\frac{r}{r+1} + \frac{r}{1+2r} - \frac{1}{4p\delta\tilde{L}}\right)^2\right), \end{aligned}$$

where we need  $1 \leq \frac{rp\delta\tilde{L}}{4}\left(\frac{1}{1+r} + \frac{1}{1+2r}\right)$  to apply Hoeffding's inequality in the last inequality. We can find  $L_2$  such that this is true for  $L \geq L_2$ .

Choose  $M \geq 15d + 5$ . By putting all of our previous bounds together, we finally get, for all  $L \geq L_2$ ,

$$\begin{aligned} &P_0\left(X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = \tilde{L}\right) \\ &\leq \exp\left(-\frac{p^2\tilde{L}}{2}\right) + \exp\left(-p\delta^2\tilde{L}\left(r - \frac{1}{2}\right)^2\right) + \exp\left(-4p\delta\tilde{L}\left(\frac{r}{r+1} + \frac{r}{1+2r} - \frac{1}{4p\delta\tilde{L}}\right)^2\right), \end{aligned}$$

where we recall that  $\tilde{L} = 70L^3$ ,  $\delta > 0$  and  $p = \mathbb{P}(\varphi(x) > \delta)$ . Then, for any choice of  $\delta$ , we can find  $L_3 \geq \max(c_0, L_1, L_2)$  such that for all  $L \geq L_3$ ,

$$P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = \tilde{L} \right) + P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_2 = -\tilde{L} \right) \leq \frac{1}{2L^M}.$$

We now only need to bound  $P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 = -L \right)$  to prove  $(P)_M|_{e_1}$ . We will use again the notations  $n^+$  (respectively  $n^-$ ) for the total number of jumps in direction  $e_1$  (respectively  $-e_1$ ) before exiting the box  $B_{e_1, L, \tilde{L}}$ . Suppose that  $X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 = -L$ . Then necessarily  $n^+ < n^-$ , which gives  $n^+ < \frac{n^+ + n^-}{2}$ . As  $n^+$  conditioned to  $n^+ + n^-$  follows a binomial law of parameters  $\frac{r}{1+r}$  and  $n^+ + n^-$ , Hoeffding's inequality gives the bound :

$$P_0 \left( n^+ < \frac{n^+ + n^-}{2} \mid n^+ + n^- \right) \leq \exp \left( -2(n^+ + n^-) \left( \frac{r}{1+r} - \frac{1}{2} \right)^2 \right).$$

But  $X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 = -L$  also gives that necessarily,  $n^- \geq L$ . Then

$$\begin{aligned} P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 = -L \right) &\leq P_0 \left( n^+ < \frac{n^+ + n^-}{2} \text{ and } n^- \geq L \right) \\ &\leq \sum_{m=L}^{\infty} \exp \left( -2m \left( \frac{r}{1+r} - \frac{1}{2} \right)^2 \right). \end{aligned}$$

Therefore we can find  $L_4 \geq L_3$  such that for all  $L \geq L_4$ ,

$$P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 = -L \right) \leq \frac{1}{2L^M},$$

from where we conclude that for all  $L \geq L_4$ ,

$$P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 < L \right) \leq \frac{1}{L^M}.$$

**4.2. Proof of Theorem 5.** It is classical to represent Dirichlet distributions with independent gamma random variables : if  $\gamma_1, \dots, \gamma_N$  are independent gamma random variables with parameters  $\beta_1, \dots, \beta_N$ , then  $\frac{\gamma_1}{\sum \gamma_i}, \dots, \frac{\gamma_N}{\sum \gamma_i}$  is a Dirichlet random variable with parameters  $(\beta_1, \dots, \beta_N)$ . We get a restriction property as an easy consequence of this representation (see [16], pages 179-182) : for  $J$  a non-empty subset of  $\{1, \dots, N\}$ , the random variable  $\left( \frac{x_j}{\sum_{i \in J} x_i} \right)_{j \in J}$  follows a Dirichlet law with parameters  $(\beta_j)_{j \in J}$  and is independent of  $\sum_{i \in J} x_i$ . This property will be useful in the following.

We consider the box  $B_{e_1, L, \tilde{L}}$  for  $\tilde{L} = 70L^3$ , and want to find some  $L > c_0$  such that  $P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 < L \right) \leq \frac{1}{L^M}$  to prove  $(P)_M|_{e_1}$ .

Let  $l_i := \{x \in \mathbb{Z}^d \text{ s.t. } x \cdot e_1 = i\}$  and  $t_i := \inf\{n \geq 0 : X_n \in l_i, X_{n+1} \notin l_i\}$ . We first consider the events that, when the walk arrives on  $l_i$  for the first time, it gets out of it by an edge in direction  $e_1$  (the alternative being getting out by an edge in direction  $-e_1$ ) :

$$G_{1,i} := \{X_{t_i+1} - X_{t_i} = e_1\}.$$

At the point  $X_{t_i}$ , we know that the walk will go either to  $X_{t_i} + e_1$  or to  $X_{t_i} - e_1$ . Thanks to the restriction property of the Dirichlet laws, we know that  $\frac{\omega(X_{t_i}, e_1)}{\omega(X_{t_i}, e_1) + \omega(X_{t_i}, -e_1)}$

follows a beta law of parameters  $(\beta_1, \beta_1 + \beta_{1+d})$  and is independent of the previous trajectory of the walk on  $l_i$ . Then

$$P_0(G_{1,i}) = \frac{\beta_1}{\beta_1 + \beta_{1+d}}.$$

Now define

$$G_1 := \bigcap_{i=0}^{L-1} G_{1,i},$$

and note that

$$P_0(G_1^c) \leq L \frac{\beta_{1+d}}{\beta_1 + \beta_{1+d}}.$$

We can now write

$$\begin{aligned} P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 < L \right) &\leq P_0 \left( \left\{ X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 < L \right\} \cap G_1 \right) + P_0(G_1^c) \\ &\leq P_0 \left( \left\{ X_{T_{B_{e_1, L, \tilde{L}}}} \cdot e_1 < L \right\} \cap G_1 \right) + L \frac{\beta_{1+d}}{\beta_1 + \beta_{1+d}}, \end{aligned}$$

and we only need to bound the first term of this sum. If  $G_1$  is satisfied, the walk cannot get out of the box  $B_{e_1, L, \tilde{L}}$  by the "lower boundary"  $\{x \in \mathbb{Z}^d \text{ s.t. } x \cdot e_1 = -L\}$ . Then the walk has to get out by one of the  $2d - 2$  "side boundaries" :

$$P_0 \left( \left\{ X_{T_{B_{e_1, L, \tilde{L}}}}} \cdot e_1 < L \right\} \cap G_1 \right) = P_0 \left( \bigcup_{j=2}^d \left\{ X_{T_{B_{e_1, L, \tilde{L}}}}} \cdot e_j = \pm \tilde{L} \right\} \cap G_1 \right).$$

On the event  $\bigcup_{j=1}^d \{X_{T_{B_{e_1, L, \tilde{L}}}}} \cdot e_j = \pm \tilde{L}\}$  define  $n_0, \dots, n_{\tilde{L}-1}$  as the finite hitting times of new levels in any direction perpendicular to  $e_1$  as follows :

$$n_k := \inf \{n \geq 0 \text{ s.t. } \sup_{2 \leq j \leq d} |X_n \cdot e_j| \geq k\}.$$

Let now  $p = \frac{\beta_1}{1 + \sum_{i \neq 1+d} \beta_i}$  and consider the event

$$G_3 := \left\{ G_1 \text{ and } X_{n_k+1} - X_{n_k} = e_1 \text{ for at least } \frac{p}{2} \tilde{L} \text{ of the points } X_{n_k} \right\}.$$

Suppose  $\beta_{1+d} \leq 1$ , then  $p \leq \mathbb{E}(\omega(0, e_1))$ . Consider now a random variable  $Z$  with a binomial law of parameters  $p$  and  $\tilde{L}$ . Using Hoeffding's inequality, we see that

$$P(G_3^c) \leq P \left( Z \leq \frac{p\tilde{L}}{2} \right) \leq \exp \left( -\frac{p^2}{2} \tilde{L} \right).$$

But clearly  $G_1 \cap G_3 = \emptyset$  for  $L \geq L_0 := \sqrt{\frac{1}{35p}}$ . Therefore we have in this case

$$P_0 \left( \bigcup_{j=2}^d \left\{ X_{T_{B_{e_1, L, \tilde{L}}}}} \cdot e_j = \pm \tilde{L} \right\} \cap G_1 \right) \leq \exp \left( -\frac{p^2}{2} \tilde{L} \right).$$

Putting the previous bounds together, we finally get for all  $L \geq L_0$  :

$$P_0 \left( X_{T_{B_{e_1, L, \tilde{L}}}}} \cdot e_1 < L \right) \leq L \frac{\beta_{1+d}}{\beta_1 + \beta_{1+d}} + \exp \left( -\frac{p^2}{2} \tilde{L} \right).$$

Let now  $L_1$  be such that for all  $L \geq L_1$

$$\exp \left( -\frac{p^2}{2} \tilde{L} \right) \leq \frac{1}{2L^M}.$$

Take now  $L_2 := \max\{c_0, L_0, L_1\}$  and then choose  $\beta_{1+d} (\leq 1)$  so that

$$L_2 \frac{\beta_{1+d}}{\beta_1 + \beta_{1+d}} \leq \frac{1}{2L_2^M}.$$

We then conclude that for this choice of  $\beta_{1+d}$  there exists an  $L \geq c_0$  such that

$$P_0 \left( X_{T_{B_{e_1, L_2, \tilde{L}}}} \cdot e_1 < L \right) \leq \frac{1}{L^M}.$$

**Acknowledgements.** The authors would like to thank Alexander Drewitz for pointing out the ideas of the proof of Theorem 4.

## REFERENCES

- [1] Berger, Noam; Drewitz, Alexander; Ramírez, Alejandro F.; *Effective polynomial ballisticity condition for random walk in random environment*. Accepted for publication in Comm. Pure Appl. Math. arXiv:1206.6377.
- [2] Bouchet, Elodie; *Sub-ballistic random walk in Dirichlet environment*, Electron. J. Probab. 18 (2013), no. 58, 1-25.
- [3] Campos, David; Ramírez, Alejandro F.; *Ellipticity criteria for ballistic behavior of random walks in random environment*. Accepted for publication in Probab. Theory Related Fields. arXiv:1212.4020.
- [4] Enriquez, Nathanaël; Sabot, Christophe; *Edge oriented reinforced random walks and RWRE*. C. R. Math. Acad. Sci. Paris 335 (2002), no. 11, 941–946
- [5] Enriquez, Nathanaël; Sabot, Christophe; *Random walks in a Dirichlet environment*. Electron. J. Probab. 11 (2006), no. 31, 802–817.
- [6] Lyons, Russell; Peres, Yuval; *Probabilities on trees and networks*. Cambridge University Press. In preparation, available at <http://mypage.iu.edu/~rdlyons/>.
- [7] Pemantle, Robin; *Phase transition in reinforced random walk and RWRE on trees*. Ann. Probab. 16 (1988), no. 3, 1229–1241.
- [8] Rassoul-Agha, Firas; Seppäläinen, Timo; *Almost sure functional central limit theorem for ballistic random walk in random environment*. Ann. Inst. Henri Poincaré Probab. Stat. 45 (2009), no. 2, 373–420.
- [9] Sabot, Christophe; *Random Dirichlet environment viewed from the particle in dimension  $d \geq 3$* , The Annals of Probability. Volume 41, Number 2 (2013), 722-743.
- [10] Sabot, Christophe; Tournier, Laurent; *Reversed Dirichlet environment and directional transience of random walks in Dirichlet environment*. Ann. Inst. Henri Poincaré Probab. Stat. 47 (2011), no. 1, 1–8.
- [11] Simenhaus, François; *Asymptotic direction for random walks in random environment*. Ann. Inst. H. Poincaré 43 (6), 751-761, (2007).
- [12] Sznitman, Alain-Sol; *Slowdown estimates and central limit theorem for random walks in random environment*. J. Eur. Math. Soc. (JEMS) 2 (2000), no. 2, 93–143.
- [13] Sznitman, Alain-Sol; *On a class of transient random walks in random environment*. Ann. Probab. 29 (2001), no. 2, 724–765.
- [14] Sznitman, Alain-Sol; Zerner, Martin; *A law of large numbers for random walks in random environment*. Ann. Probab. 27 (1999), no. 4, 1851–1869.
- [15] Tournier, Laurent; *Integrability of exit times and ballisticity for random walks in Dirichlet environment*. Electron. J. Probab. 14 (2009), no. 16, 431–451.
- [16] Wilks, Samuel S.; *Mathematical statistics*. A Wiley Publication in Mathematical Statistics John Wiley & Sons, Inc., New York-London 1962 xvi+644 pp.
- [17] Zerner, Martin; *A non-ballistic law of large numbers for random walks in i.i.d. random environment*. Electron. Comm. Probab. 7 (2002), 191–197.

UNIVERSITÉ DE LYON, UNIVERSITÉ LYON 1, INSTITUT CAMILLE JORDAN, CNRS UMR 5208, 43, BOULEVARD DU 11 NOVEMBRE 1918, 69622 VILLEURBANNE CEDEX, FRANCE

*E-mail address:* bouchet@math.univ-lyon1.fr

*E-mail address:* sabot@math.univ-lyon1.fr

FACULTAD DE MATEMÁTICAS, PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE, VICUÑA MACKENNA  
4860, MACUL SANTIAGO, CHILE

*E-mail address:* `aramirez@mat.puc.cl`