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# Coalescence in small generations for the diffusive randomly biased walk on Galton-Watson trees

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**Abstract:** We investigate the range  $\mathcal{R}_T$  of the diffusive biased walk  $\mathbb{X}$  on a Galton-Watson tree  $\mathbb{T}$  in random environment, that is to say the sub-tree of  $\mathbb{T}$  of all distinct vertices visited by this walk up to the time  $T$ . We study the volume of the range with constraints and more precisely the number of  $k$ -tuples ( $k \geq 2$ ) of distinct vertices in this sub-tree, in small generations and satisfying an hereditary condition. A special attention is paid to the vertices visited during distinct excursions of  $\mathbb{X}$  above the root of the Galton-Watson tree as we observe they give the major contribution to this range. As an application, we study the genealogy of  $k \geq 2$  distinct vertices of the tree  $\mathcal{R}_T$  picked uniformly from those in small generations. It turns out that two or more vertices among them share a common ancestor for the last time in the remote past. We also point out an hereditary character in their genealogical tree due to the random environment.

MSC2020 : 60K37, 60J80.

**Keywords and phrases:** branching random walks, coalescence, randomly biased random walks.

## 1. Introduction

### 1.1. Randomly biased random walk on trees

Given, under a probability measure  $\mathbf{P}$ , a  $\bigcup_{k \in \mathbb{N}} \mathbb{R}^k$ -valued random variable  $\mathcal{P}$  ( $\mathbb{R}^0$  only contains the sequence with length 0) with  $N := \#\mathcal{P}$  denoting the cardinal of  $\mathcal{P}$ , we consider the following Galton-Watson marked tree  $(\mathbb{T}, (A_x; x \in \mathbb{T}))$  rooted at  $e$ : the generation 0 contains one marked individual  $(e, A_e) = (e, 0)$ . For any  $n \in \mathbb{N}^*$ , assume the generation  $n - 1$  has been built. If it is empty, then the generation  $n$  is also empty. Otherwise, for any vertex  $x$  in the generation  $n - 1$ , let  $\mathcal{P}^x := \{A_{x^1}, \dots, A_{x^{N(x)}}\}$  be a random variable distributed as  $\mathcal{P}$  where  $N(x) := \#\mathcal{P}^x$ . The vertex  $x$  gives progeny to  $N(x)$  marked children  $(x^1, A_{x^1}), \dots, (x^{N(x)}, A_{x^{N(x)}})$  independently of the other vertices in generation  $n - 1$ , thus forming the generation  $n$ , denoted by  $\mathbb{T}_n$ . We assume  $\mathbf{E}[N] > 1$  so that  $\mathbb{T}$  is a supercritical Galton-Watson tree, that is  $\mathbf{P}(\text{non-extinction of } \mathbb{T}) > 0$  and we define  $\mathbf{P}^*(\cdot) := \mathbb{P}(\cdot | \text{non-extinction of } \mathbb{T})$ ,  $\mathbf{E}$  (resp.  $\mathbf{E}^*$ ) denotes the expectation with respect to  $\mathbf{P}$  (resp.  $\mathbf{P}^*$ ).

For any vertex  $x \in \mathbb{T}$ , we denote by  $|x|$  the generation of  $x$ , by  $x_i$  its ancestor in generation  $i \in \{0, \dots, |x|\}$  and  $x^* := x_{|x|-1}$  stands for the parent of  $x$ . In particular,  $x_0 = e$  and  $x_{|x|} = x$ . For any  $x, y \in \mathbb{T}$ , we write  $x \leq y$  if  $x$  is an ancestor of  $y$  ( $y$  is said to be a descendent of  $x$ ) and  $x < y$  if  $x \leq y$  and  $x \neq y$ . We then write  $\llbracket x_i, x \rrbracket := \{x_j; j \in \{i, \dots, |x|\}\}$ . Finally, for any  $x, y \in \mathbb{T}$ , we denote by  $x \wedge y$  the most recent common ancestor of  $x$  and  $y$ , that is the ancestor  $u$  of  $x$  and  $y$  such that  $\max\{|z|; z \in \llbracket e, x \rrbracket \cap \llbracket e, y \rrbracket\} = |u|$ .

Let us introduce the branching potential  $V$ : let  $V(e) = A_e = 0$  and for any  $x \in \mathbb{T} \setminus \{e\}$

$$V(x) := \sum_{e < z \leq x} A_z = \sum_{i=1}^{|x|} A_{x_i}.$$

Under  $\mathbf{P}$ ,  $\mathcal{E} := (\mathbb{T}, (V(x); x \in \mathbb{T}))$  is a real valued branching random walk such that  $(V(x) - V(x^*))_{|x|=1}$  is distributed as  $\mathcal{P}$ . We will then refer to  $\mathcal{E}$  as the random environment.

For convenience, we add a parent  $e^*$  to the root  $e$  and we introduce the  $\mathbb{T} \cup \{e^*\}$ -valued random walk  $\mathbb{X} := (X_j)_{j \in \mathbb{N}}$  reflected in  $e^*$  such that under the quenched probabilities  $\{\mathbb{P}_z^\mathcal{E}; z \in \mathbb{T} \cup \{e^*\}\}$  (that is  $\mathbb{P}_z^\mathcal{E}(X_0 = z) = 1$ ), the transition probabilities are given by: for any  $x \in \mathbb{T}$

$$p^\mathcal{E}(x, x^*) = \frac{e^{-V(x)}}{e^{-V(x)} + \sum_{i=1}^{N_x} e^{-V(x^i)}} \quad \text{and for all } 1 \leq i \leq N_x, \quad p^\mathcal{E}(x, x^i) = \frac{e^{-V(x^i)}}{e^{-V(x)} + \sum_{i=1}^{N_x} e^{-V(x^i)}}.$$

Otherwise,  $p^\mathcal{E}(x, u) = 0$  and  $p^\mathcal{E}(e^*, e) = 1$ . Let  $\mathbb{P}^\mathcal{E} := \mathbb{P}_e^\mathcal{E}$  and we finally define the following annealed probabilities

$$\mathbb{P}(\cdot) := \mathbf{E}[\mathbb{P}^\mathcal{E}(\cdot)] \quad \text{and} \quad \mathbb{P}^*(\cdot) := \mathbf{E}^*[\mathbb{P}^\mathcal{E}(\cdot)].$$

R. Lyons and R. Pemantle [LP92] initiated the study of the randomly biased random walk  $\mathbb{X}$ .

When, for all  $x \in \mathbb{T}$ ,  $V(x) = \log \lambda$  for a some constant  $\lambda > 0$ , the walk  $\mathbb{X}$  is known as the  $\lambda$ -biased random walk on  $\mathbb{T} \cup \{e^*\}$  and was first introduced by R. Lyons (see [Lyo90] and [Lyo92]). The  $\lambda$ -biased random walk is transient unless the bias is strong enough: if  $\lambda \geq \mathbf{E}[N]$  then,  $\mathbf{P}^*$ -almost surely,  $\mathbb{X}$  is recurrent (positive recurrent if  $\lambda > \mathbf{E}[N]$ ). It is known since Y. Peres and O. Zeitouni [PZ06] that when  $\lambda = \mathbf{E}[N]$ ,  $\mathbb{X}$  is diffusive: there exists  $\sigma^2 \in (0, \infty)$  such that  $(|X_{[nt]}|/\sqrt{\sigma^2 n})_{t \geq 0}$  converges in law to a standard reflected brownian motion. R. Lyons, R. Pemantle and Y. Peres (see [LPP96b] and [LPP96a]), later joined by E. Aïdékon [Aïd14] and G. Ben Arous, A. Fribergh, N. Gantert, A. Hammond [AFGH12] for example, studied the transient case and showed that  $\mathbb{X}$  has a deterministic and explicit speed  $v_\lambda := \lim_{n \rightarrow \infty} |X_n|/n$  (see [Aïd14] for the expression of  $v_\lambda$  in the case of positive speed and [AFGH12] for details about the behaviour of  $|X_n|$  when  $v_\lambda = 0$ ). When the bias is random, the behavior of  $\mathbb{X}$  depends on the fluctuations of the following log-Laplace transform  $\psi(t) := \log \mathbf{E}[\sum_{|x|=1} e^{-tV(x)}]$  which we assume to be well defined on  $[0, 1]$ : as stated by R. Lyons and R. Pemantle [LP92], if  $\inf_{t \in [0, 1]} \psi(t) > 0$ , then  $\mathbf{P}^*$ -almost surely,  $\mathbb{X}$  is transient and we refer to the work of E. Aïdékon [Aïd08] for this case. Otherwise, it is recurrent. More specifically, G. Faraud [Far11] proved that the random walk  $\mathbb{X}$  is  $\mathbf{P}^*$ -almost surely positive recurrent either if  $\inf_{t \in [0, 1]} \psi(t) < 0$  or if  $\inf_{t \in [0, 1]} \psi(t) = 0$  and  $\psi'(1) > 0$ . It is null recurrent if  $\inf_{t \in [0, 1]} \psi(t) = 0$  and  $\psi'(1) \leq 0$ . When  $\psi'(1) = 0$ , the largest generation reached by the walk  $\mathbb{X}$  up to time  $n$  is of order  $(\log n)^3$  (and it is usually referred to as the slow regime for the random random  $\mathbb{X}$ , see [HS07a] and [FHS11]) but surprisingly, the generation of the vertex  $X_n$  is of order  $(\log n)^2$  as  $n \rightarrow \infty$ , see [HS16].

In the present paper, we focus on the null recurrent randomly biased walk  $\mathbb{X}$  and assume

**Assumption 1.**

$$\inf_{t \in [0, 1]} \psi(t) = \psi(1) = 0 \quad \text{and} \quad \psi'(1) < 0. \quad (1)$$

Let us introduce

$$\kappa := \inf\{t > 1; \psi(t) = 0\}, \quad (2)$$

and assume  $\kappa \in (1, \infty)$ . Under (1) and some integrability conditions, it has been proven that  $|X_n|$  and  $\max_{1 \leq j \leq n} |X_j|$  are of order  $n^{1-1/\min(\kappa, 2)}$  (see [HS07b], [Far11], [AdR17] and [dR22]). In other words, the random walk  $\mathbb{X}$  is sub-diffusive for  $\kappa \in (1, 2]$  and diffusive for  $\kappa > 2$ . In this paper, we put ourselves in the latter case.

We now define the range of the random walk  $\mathbb{X}$ . Let  $T \in \mathbb{N}^*$ . The range  $\mathcal{R}_T$  of the random walk  $\mathbb{X}$  is the set of distinct vertices of  $\mathbb{T}$  visited by  $\mathbb{X}$  up to the time  $T$ : if  $\mathcal{L}_u^T := \sum_{j=1}^T \mathbf{1}_{\{X_j = u\}}$  denotes the local time of a vertex  $u \in \mathbb{T}$  at time  $T$  then

$$\mathcal{R}_T = \{u \in \mathbb{T}; \mathcal{L}_u^T \geq 1\}, \quad (3)$$

its cardinal is denoted by  $R_T$  and we also called it range. It has been proved by E. Aïdékon and L. de Raphélis that  $R_n$  is of order  $n$  (see the proofs of Theorem 1.1 and Theorem 6.1 in [AdR17]). Moreover,  $(\mathcal{R}_n)$  is a sequence finite sub-trees of  $\mathbb{T}$  and still according to E. Aïdékon and L. de Raphélis (Theorem 6.1 in [AdR17]), after being properly renormalized, this sequence converges in law under both annealed and quenched probabilities to a random real tree when  $n$  goes to infinity. Introduce  $T^j$ , the  $j$ -th return time to  $e^*$ :  $T^0 = 0$  and for any  $j \geq 1$ ,  $T^j = \inf\{i > T^{j-1}; X_i = e^*\}$ . Thanks to a result of Y. Hu ([Hu17], Corollary 1.2), we know that  $T^{n^{1/2}}$  is of order  $n$ . We will be focusing our attention on the range  $\mathcal{R}_{T^{n^{1/2}}}$  and we shall finally present an extension of the range  $\mathcal{R}_n$ . For this purpose, it is convenient to split the tree  $\mathcal{R}_{T^{n^{1/2}}}$  in three: the vertices located in what we call the tiny generations, that is those smaller than  $\bar{\gamma} \log n$  for some constant  $\bar{\gamma} > 0$  defined below (see the subsection 1.5), the critical generations, that is to say of order  $n^{1/2}$  and corresponding to the typical generations but also to the largest reached by the diffusive random walk  $\mathbb{X}$  up to the time  $T^{n^{1/2}}$  and finally, the vertices located in what we are going to be calling the small generations. Let  $(\mathfrak{L}_n)$  be a sequence of positive integers such that  $\mathfrak{L}_n \geq \delta_0^{-1} \log n$  (see Lemma 3.4 for the definition of  $\delta_0$ ). A vertex  $x \in \mathcal{R}_{T^{n^{1/2}}}$  is said to be in a small generation if it is located above the tiny generations but below the critical generations of the diffusive random walk  $\mathbb{X}$ , that is if  $|x| = \mathfrak{L}_n$  and satisfies

**Assumption 2** (The small generations). *Let  $(\Lambda_i)_{i \in \mathbb{N}}$  be the sequence of functions defined recursively by: for all  $t > 0$ ,  $\Lambda_0(t) = t$  and for any  $i \in \mathbb{N}^*$ ,  $\Lambda_{i-1}(t) = e^{\Lambda_i(t)}$ . There exists  $l_0 \in \mathbb{N}$  such that*

$$\lim_{n \rightarrow \infty} \frac{\mathfrak{L}_n}{n^{1/2}} \Lambda_{l_0}(\mathfrak{L}_n) = 0. \quad (4)$$

Assumption 2 ensures that  $\mathfrak{L}_n/n^{1/2}$ , renormalized by a sequence that grows very slowly, goes to 0 when  $n$  goes to  $\infty$ .

Let us now define an extension of the volume  $R_{T^{n^{1/2}}}$ : for any integer  $k \geq 2$  and any subset  $\mathfrak{D}$  of  $\mathbb{T}$  with cardinal  $|\mathfrak{D}| \geq k$ , let  $\mathfrak{D}^{\times k} := \mathfrak{D} \times \dots \times \mathfrak{D}$ , introduce the subset  $\Delta^k$  of  $\mathbb{T}^{\times k}$  such that a  $k$ -tuple  $(x^{(1)}, \dots, x^{(k)})$  belongs to  $\Delta^k$  if and only if for any  $i_1, i_2 \in \{1, \dots, k\}$ ,  $i_1 \neq i_2$ , we have  $x^{(i_1)} \notin \llbracket e, x^{(i_2)} \rrbracket$  and  $x^{(i_2)} \notin \llbracket e, x^{(i_1)} \rrbracket$ . In other words, neither  $x^{(i_1)}$  is an ancestor of  $x^{(i_2)}$ , nor  $x^{(i_2)}$  is an ancestor of  $x^{(i_1)}$ . Also introduce the set (assumed to be nonempty)  $\Delta^k(\mathfrak{D}) := \Delta^k \cap \mathfrak{D}^{\times k}$ . For any  $n \in \mathbb{N}^*$ , any subset  $\mathcal{D}_n$  of  $\mathcal{R}_{T^{n^{1/2}}}$  with cardinal  $D_n$  and for any function  $f : \Delta^k \rightarrow \mathbb{R}^+$ , if  $D_n \geq k$ , we define the range  $\mathcal{A}^k(\mathcal{D}_n, f)$  by

$$\mathcal{A}^k(\mathcal{D}_n, f) := \sum_{\mathbf{x} \in \Delta^k(\mathcal{D}_n)} f(\mathbf{x}). \quad (5)$$

Otherwise,  $\mathcal{A}^k(\mathcal{D}_n, f)$  is equal to 0. The aim of studying the range  $\mathcal{A}^k(\mathcal{D}_n, f)$  is to understand the interactions between the vertices in the tree  $\mathcal{R}_{T^{n^{1/2}}}$  and to give a description of the genealogy of the vertices in  $\mathcal{R}_{T^{n^{1/2}}}$ . Note that the range we investigate here differs from the range studied in [AK23], where authors focus on the interactions between the trajectories of the random walk  $\mathbb{X}$  and on the trajectories of the underlying branching potential  $V$ .

## 1.2. Genealogy of uniformly chosen vertices in the range

For a nonempty subset  $\mathcal{D}_n$  of  $\mathcal{R}_{T^{n^{1/2}}}$ , introduce the random variable  $\mathcal{X}^n = (\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)})$  taking values in  $\Delta^k$  with law defined by: for any  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ , if  $\mathbb{P}^*(D_n \geq k) > 0$ , then

$$\mathbb{P}^*(\mathcal{X}^n = \mathbf{x}) = \frac{1}{\mathbb{P}^*(D_n \geq k)} \mathbb{E}^* \left[ \frac{\mathbb{1}_{\{\mathbf{x} \in \Delta^k(\mathcal{D}_n)\}}}{|\Delta^k(\mathcal{D}_n)|} \mathbb{1}_{\{D_n \geq k\}} \right], \quad (6)$$

and  $\mathbb{P}^*(\mathcal{X}^n = \mathbf{x}) = 0$  otherwise. Note that  $|\Delta^k(\mathcal{D}_n)| = D_n(D_n - 1) \times \cdots \times (D_n - k + 1)$  so the vertices  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$  are nothing but  $k$  vertices picked uniformly and without replacement in the set  $\mathcal{D}_n$ . For any bounded function  $f : \Delta^k \rightarrow \mathbb{R}^+$ , we actually have

$$\mathbb{E}^*[f(\mathcal{X}^n)] = \frac{1}{\mathbb{P}^*(D_n \geq k)} \mathbb{E}^* \left[ \frac{\mathcal{A}^k(\mathcal{D}_n, f)}{\mathcal{A}^k(\mathcal{D}_n, 1)} \mathbf{1}_{\{D_n \geq k\}} \right], \quad (7)$$

thus making a link between the generalized range  $\mathcal{A}^k(\mathcal{D}_n, \cdot)$  and the law of  $\mathcal{X}^n$ . Recall that our main interest is the genealogy of the  $k$  vertices  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$  so let us define the genealogical tree of these  $k$  vertices. First, introduce the largest generation  $M_n := \max_{x \in \mathcal{D}_n} |x|$  of the set  $\mathcal{D}_n$ . Recall that in the diffusive regime (see (1) and (2) with  $\kappa > 2$ ),  $\max_{x \in \mathcal{R}_{T_n^{1/2}}} |x|$ , the largest generation of the tree  $\mathcal{R}_{T_n^{1/2}}$ , is of order  $n^{1/2}$  when  $n \rightarrow \infty$ .

If  $D_n \geq k$ , we then define for any  $m \in \{0, \dots, M_n\}$  the equivalence relation  $\sim_m$  on  $\{1, \dots, k\}$  by:  $i_1 \sim_m i_2$  if and only if  $\mathcal{X}^{(i_1,n)}$  and  $\mathcal{X}^{(i_2,n)}$  share a common ancestor in generation  $m$ . We denote by  $\pi_m^{k,n}$  the partition of  $\{1, \dots, k\}$  whose blocks are given by equivalent classes of the relation  $\sim_m$ . The process  $(\pi_m^{k,n})_{0 \leq m \leq M_n}$  is called the genealogical tree of  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$ . Let  $\mathcal{G}^{(i,n)} = |\mathcal{X}^{(i,n)}|$  be the generation of  $\mathcal{X}^{(i,n)}$ . By definition,

$$\pi_0^{k,n} = \{\{1, \dots, k\}\} \text{ and } \pi_m^{k,n} = \{\{1\}, \dots, \{k\}\} \text{ for any } m \in \{\max_{1 \leq i \leq k} \mathcal{G}^{(i,n)}, \dots, M_n\}.$$

Replacing  $\mathcal{R}_{T_n^{1/2}}$  by a regular Galton-Watson tree  $\mathfrak{T}$  and  $\mathcal{D}_n$  by  $\{x \in \mathfrak{T}; |x| = T\}$  (the  $T$ -th generation of  $\mathfrak{T}$ ), the genealogy of  $k$  vertices  $\mathcal{X}_T^{(1)}, \dots, \mathcal{X}_T^{(k)}$  uniformly chosen in  $\{x \in \mathfrak{T}; |x| = T\}$  has been deeply studied for fixed  $T$  as well as for  $T \rightarrow \infty$ . First, when  $k = 2$ , K.B. Athreya [Ath12b] proved that when  $\mathfrak{T}$  is supercritical (the mean of the reproduction law is larger than 1)  $\mathcal{X}_T^{(1)}$  and  $\mathcal{X}_T^{(2)}$  share a common ancestor for the last time in the remote past: if  $\mathcal{M}_T := |\mathcal{X}_T^{(1)} \wedge \mathcal{X}_T^{(2)}|$  denotes the generation of the most recent common ancestor of  $\mathcal{X}_T^{(1)}$  and  $\mathcal{X}_T^{(2)}$  then  $(\mathcal{M}_T)$  converges in law to a non-negative random variable depending on the reproduction law  $N$  when  $T$  goes to  $\infty$ . However, when  $\mathfrak{T}$  is critical (the mean of the reproduction law is equal to 1),  $\mathcal{X}_T^{(1)}$  and  $\mathcal{X}_T^{(2)}$  share a common ancestor for the last time in the recent past:  $(\mathcal{M}_T/T)$  converges in law to a  $[0, 1]$ -valued random variable which doesn't depend on the reproduction law  $N$  when  $T$  goes to  $\infty$ , see [Ath12a]. K.B. Athreya also dealt with the sub-critical case (the mean of the reproduction law is smaller than 1) in the latter paper and it is quite similar to the critical case. More recently S. Harris, S. Johnston and M. Roberts gave a full description of the genealogy of the vertices  $\mathcal{X}_T^{(1)}, \dots, \mathcal{X}_T^{(k)}$  for a given integer  $k \geq 2$  for both fixed  $T$  and  $T \rightarrow \infty$ , when the underlying process is a continuous-time Galton-Watson process (see [HJR17] and [Joh19]). See also [AD21] for a study of the genealogy of randomly chosen individuals when the underlying process is a continuous-state branching process.

Let us return to the case of the random walk in random environment. The generations at which the vertices  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$  are chosen have a major influence on their genealogical structure. The next three subsections are dedicated to the three regimes we observe: the tiny generations, the small generations, on which we spend most of our time and the critical generations. For the second regime, we are able to give a quite full description of the genealogy of  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$ , displaying five examples we believe to be relevant, see subsection 1.3, and a general result is proven in 1.4. Finally, we show that we can easily extend our results on  $\mathcal{R}_{T_n^{1/2}}$  to the range up to the time  $n$ .

### 1.3. The small generations: examples

In this subsection, we focus on the small generations of the tree  $\mathcal{R}_{T_n^{1/2}}$ , where we recall that  $T^j$  is the  $j$ -th return time to  $e^*$ :  $T^0 = 0$  and for any  $j \geq 1$ ,  $T^j = \inf\{i > T^{j-1}; X_i = e^*\}$ . Let

$(\mathfrak{L}_n)$  be a sequence of positive integers as in (4),  $(\ell_n)$  be a sequence of positive integers such that  $\delta_0^{-1} \log n \leq \ell_n \leq \mathfrak{L}_n$  and introduce the set

$$\mathcal{D}_n := \{x \in \mathcal{R}_{T_n^{1/2}}; \ell_n \leq |x| \leq \mathfrak{L}_n\},$$

with high  $\mathbf{L}_n - 1$  where  $\mathbf{L}_n := \mathfrak{L}_n - \ell_n + 1$ . Recall that  $D_n$  is the cardinal of  $\mathcal{D}_n$ . Note that  $\lim_{n \rightarrow \infty} \mathbb{P}^*(D_n \geq k) = 1$  so we will refer to the set  $\{D_n \geq k\}$  only if necessary.

For any  $m \in \mathbb{N}$ , recall that  $\mathbb{T}_m = \{x \in \mathbb{T}; |x| = m\}$  be the  $m$ -th generation of the tree  $\mathbb{T}$  and let  $\Delta_m^j := \Delta^j(\mathbb{T}_m)$ . In addition, we also require the following technical assumption.

**Assumption 3.** *There exists  $\delta_1 > 0$  such that  $\psi(t) < \infty$  for all  $t \in [1 - \delta_1, \lceil \kappa + \delta_1 \rceil]$  and for all  $1 \leq j \leq \lceil \kappa + \delta_1 \rceil$ , for all  $\beta = (\beta_1, \dots, \beta_j) \in (\mathbb{N}^*)^{\times j}$  such that  $\sum_{i=1}^j \beta_i \leq \lceil \kappa + \delta_1 \rceil$*

$$c_j(\beta) := \mathbf{E} \left[ \sum_{\mathbf{x} \in \Delta_1^j} e^{-\langle \beta, V(\mathbf{x}) \rangle_j} \right] < \infty, \quad (8)$$

where  $\langle \beta, V(\mathbf{x}) \rangle_j := \sum_{i=1}^j \beta_i V(x^{(i)})$ .

The next assumption is an ellipticity condition.

**Assumption 4.** *There exists  $\mathfrak{h} > 0$  such that*

$$\mathbf{P} \left( \inf_{x \in \mathbb{T}} (V(x) - V(x^*)) \geq -\mathfrak{h} \right) = 1. \quad (9)$$

Before stating our first result, we need the following, let  $(S_j - S_{j-1})_{j \in \mathbb{N}^*}$  be a sequence of i.i.d real-valued random variables under  $\mathbf{P}$  such that  $S_0 = 0$  and for any bounded and measurable function  $\mathfrak{t} : \mathbb{R} \rightarrow \mathbb{R}$

$$\mathbf{E}[\mathfrak{t}(S_1)] = \mathbf{E} \left[ \sum_{|x|=1} \mathfrak{t}(V(x)) e^{-V(x)} \right]. \quad (10)$$

**Remark 1.** *Although we assumed  $k \geq 2$ , the case  $k = 1$ , that is to say the volume  $D_n = \sum_{\ell_n \leq |z| \leq \mathfrak{L}_n} \mathbb{1}_{\{z \in \mathcal{R}_{T_n^{1/2}}\}}$  of the regular range  $\mathcal{D}_n$  is interesting. The convergence of  $(D_n / (n^{1/2} \mathbf{L}_n))_n$  does not requires all the previous assumptions and holds for  $\kappa > 2$ . However, since it is an easy consequence of Theorem 1.6 with  $k = 2$  and  $f = 1$ , we state the following result:*

**Theorem 1.1.** *Let  $\kappa > 2$ . Under the assumptions 1, 2, 3 and 4, in  $\mathbb{P}^*$ -probability*

$$\frac{1}{n^{1/2} \mathbf{L}_n} D_n \xrightarrow[n \rightarrow \infty]{} c_\infty W_\infty,$$

where  $c_\infty := \mathbf{E}[(\sum_{j \geq 0} e^{-S_j})^{-1}]$ ,  $W_\infty$  is the limit of the  $\mathcal{F}_n := \sigma((\mathbb{T}; V(x), |x| \leq n))$  additive martingale  $W_n = \sum_{|x|=n} e^{-V(x)}$  and according to [Big77],  $\mathbf{P}^*(W_\infty > 0) = 0$ . Moreover, the limit  $\lim_{t \rightarrow \infty} t^\kappa \mathbf{P}(W_\infty > t)$  exists (see [Liu00]).

In particular, if  $R_n(\ell) = \sum_{|z|=\ell} \mathbb{1}_{\{z \in \mathcal{R}_{T_n^{1/2}}\}}$  denotes the volume of the  $\ell$ -th generation of the range  $\mathcal{R}_{T_n^{1/2}}$  and  $\log n = o(\mathfrak{L}_n)$ , then both  $(R_n(\mathfrak{L}_n) / n^{1/2})$  and  $(\sum_{\ell=\delta_0^{-1} \log n}^{\mathfrak{L}_n} R_n(\ell) / (n^{1/2} \mathfrak{L}_n))$  converge in  $\mathbb{P}^*$ -probability to  $c_\infty W_\infty$ .

Since  $\psi(2) < 0$ ,  $c_\infty$  is well defined in  $(0, \infty)$ . Indeed, the sequence  $((\sum_{j=0}^l e^{-S_j})^{-1})_{l \in \mathbb{N}}$  is bounded and non-increasing and by Jensen inequality,  $1 \geq \mathbf{E}[(\sum_{j=0}^l e^{-S_j})^{-1}] \geq \mathbf{E}[(\sum_{j=0}^l e^{-S_j})^{-1}]^{-1} = (\sum_{j=0}^l e^{j\psi(2)})^{-1} \geq 1 - e^{\psi(2)} > 0$ .

In view of Theorem 1.1, we deduce that whenever  $\mathfrak{L}_n$  is large enough but not too close to the largest generation of the tree  $\mathcal{R}_{T_n^{1/2}}$ , the range  $R_n(\mathfrak{L}_n)$  is of order  $n^{1/2}$ . Moreover,  $\mathbf{L}_n - 1$  denotes the height of the set  $\mathcal{D}_n$  in the tree  $\mathcal{R}_{T_n^{1/2}}$  and the volume of  $\mathcal{D}_n$  behaves like  $\mathbf{L}_n \times R_n(\mathfrak{L}_n)$ .

The following theorems are composed of two parts: the first part will be a convergence of the range  $\mathcal{A}_n^k(f)$  for a given function  $f$  and the second part will be an application of this convergence to the genealogy of the vertices  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$ .

In the second example, we present a range such that for a  $k$ -tuple  $\mathbf{x} \in \Delta^k$ , some of the vertices are free while others are obliged to interact with each other. Let  $\boldsymbol{\lambda} = (\lambda_2, \dots, \lambda_k) \in (\mathbb{N}^*)^{\times(k-1)}$  and introduce

$$f_{\boldsymbol{\lambda}}(x^{(1)}, \dots, x^{(k)}) := \prod_{i=2}^k \mathbb{1}_{\{|x^{(i-1)} \wedge x^{(i)}| < \lambda_i\}}.$$

Note that there is no constraint between  $x^{(i_1)}$  and  $x^{(i_2)}$  if  $i_2 \notin \{i_1 - 1, i_1 + 1\}$ ,  $i_1 \geq 2$ .

**Theorem 1.2.** *Let  $k \geq 2$  and assume  $\kappa > 2k$ . Under the assumptions 1, 2, 3 and 4, in  $\mathbb{P}^*$ -probability*

$$\frac{1}{(n^{1/2} \mathbf{L}_n)^k} \mathcal{A}_n^k(\mathcal{D}_n, f_{\boldsymbol{\lambda}}) \xrightarrow[n \rightarrow \infty]{} (c_{\infty})^k \mathcal{A}_{\infty}^k(f_{\boldsymbol{\lambda}}),$$

where  $\mathcal{A}_{\infty}^k(f_{\boldsymbol{\lambda}}) = \lim_{l \rightarrow \infty} \sum_{\mathbf{x} \in \Delta^k} e^{-V(\mathbf{x}^{(1)})} \prod_{i=2}^k e^{-V(\mathbf{x}^{(i)})} \mathbb{1}_{\{|x^{(i-1)} \wedge x^{(i)}| < \lambda_i\}}$  and this limit holds in  $L^2(\mathbf{P}^*)$ .

In the next example, we are interested in the number of  $k$ -tuples of distinct vertices of  $\mathcal{D}_n$  such that any most recent common ancestor of two vertices among them is located close to the root of  $\mathcal{R}_{T_n^{1/2}}$ . Let  $k \geq 2$  be an integer. For any  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ , let  $\mathcal{S}^k(\mathbf{x})$  be the first generation at which none of  $x^{(1)}, \dots, x^{(k)}$  share a common ancestor:

$$\mathcal{S}^k(\mathbf{x}) := \min\{m \geq 1; \forall i_1 \neq i_2, |x^{(i_1)} \wedge x^{(i_2)}| < m\}, \quad (11)$$

where we recall that  $|x^{(i_1)} \wedge x^{(i_2)}|$  is the most recent common ancestor of  $x^{(i_1)}$  and  $x^{(i_2)}$ . For any  $m \in \mathbb{N}^*$ , introduce  $\mathcal{C}_m^k := \{\mathbf{x} \in \Delta^k; \mathcal{S}^k(\mathbf{x}) \leq m\}$  (see Figure 1).

Let us also introduce the coalescent times (or split times) of the vertices  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$ , uniformly chosen in the set  $\mathcal{D}_n$ . For a given partition  $\boldsymbol{\pi}$  of  $\{1, \dots, k\}$ , we denote by  $|\boldsymbol{\pi}|$  the total number of blocks of  $\boldsymbol{\pi}$ . Define the coalescent times by:  $\mathcal{S}_0^{k,n} := 0$  and for all  $j \in \mathbb{N}^*$ ,  $k \geq 2$

$$\mathcal{S}_j^{k,n} := \min\{m \geq \mathcal{S}_{j-1}^{k,n}; |\pi_m^{k,n}| > |\pi_{\mathcal{S}_{j-1}^{k,n}}^{k,n}| \wedge (k-1)\}. \quad (12)$$

Note that there exists  $\mathcal{J}^{k,n} \in \mathbb{N}$  such that for any  $j \geq \mathcal{J}^{k,n}$ ,  $\mathcal{S}_j^{k,n} = \mathcal{S}^k(\mathcal{X}^{(n)})$  and by definition,  $2 \leq |\{\mathcal{S}_j^{k,n}; j \in \mathbb{N}\}| \leq k$ . One can notice that seen backwards in time, each random time  $\mathcal{S}_j^{k,n} - 1$  with  $0 < j \leq \mathcal{J}^{k,n}$  corresponds to a generation at which two or more vertices among  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$  share a common ancestor for the first time.  $\mathcal{S}_j^{k,n}$  is usually referred to as the  $j$ -th split time while  $\mathcal{S}_{\mathcal{J}^{k,n}-j+1}^{k,n}$  is the  $j$ -th coalescent time.

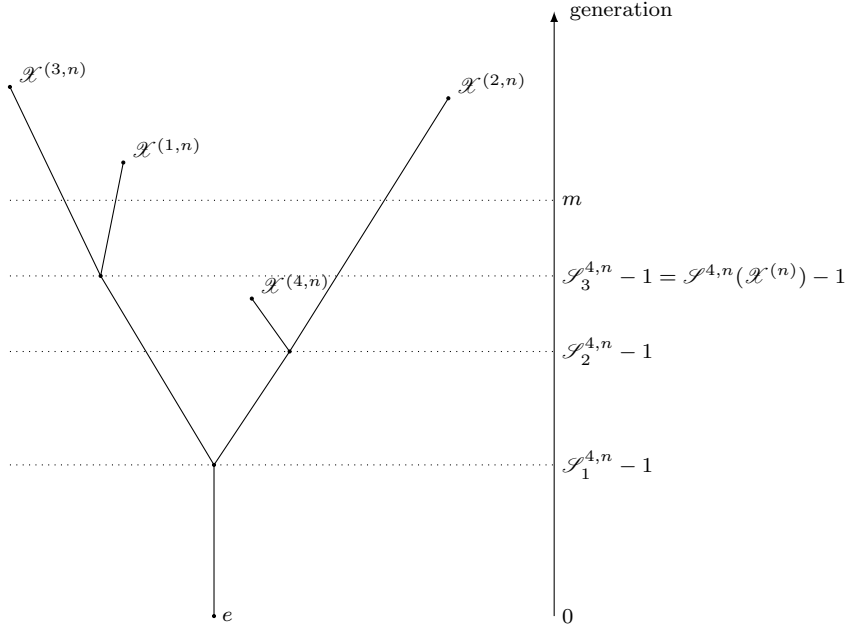


Figure 1: An example of four vertices belonging to  $\mathcal{C}_m^4$  together with their three coalescent times.

It appears that the number of vertices visited by the random walk  $\mathbb{X}$  belonging to  $\mathcal{C}_m^k$  for any  $m \in \mathbb{N}^*$  is large and as a consequence, the sequence of random times  $(\mathcal{S}^k(\mathcal{X}^{(n)})) = \inf\{m \geq 1; \pi_m^{k,n} = \{\{1\}, \dots, \{k\}\}\}_n$  converges in law.

**Theorem 1.3.** *Let  $k \geq 2$ . Assume that  $\kappa > 2k$  and for any  $m \in \mathbb{N}^*$ ,  $\mathbf{x} \in \Delta^k$ ,  $f_m(\mathbf{x}) = \mathbf{1}_{\mathcal{C}_m^k}(\mathbf{x})$ . Recall that  $\mathcal{A}^k(\mathcal{D}_n, f_m)$  is the number of  $k$ -tuples  $\mathbf{x}$  of distinct vertices of  $\mathcal{D}_n$  such that  $\mathcal{S}^k(\mathbf{x}) \leq m$ . Under the assumptions 1, 2, 3 and 4*

1. in  $\mathbb{P}^*$ -probability

$$\frac{1}{(n^{1/2} \mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_n, f_m) \xrightarrow{n \rightarrow \infty} (c_\infty)^k \mathcal{A}_\infty^k(f_m),$$

where  $\mathcal{A}_\infty^k(f_m)$  is an explicit random variable such that  $\lim_{m \rightarrow \infty} \mathcal{A}_\infty^k(f_m) = (W_\infty)^k$  in  $L^2(\mathbf{P}^*)$ .

2. Moreover, the sequence of random times  $(\mathcal{S}^k(\mathcal{X}^{(n)}))$  converges in law, under  $\mathbb{P}^*$ : for any  $m \in \mathbb{N}^*$

$$\mathbb{P}^*(\mathcal{S}^k(\mathcal{X}^{(n)}) \leq m) \xrightarrow{n \rightarrow \infty} \mathbf{E}^* \left[ \frac{\mathcal{A}_\infty^k(f_m)}{(W_\infty)^k} \right]. \quad (13)$$

The convergence in (13) is somewhat reminiscent of the result of K.B Athreya ([Ath12b], Theorem 2) for a supercritical Galton-Watson tree stated earlier: each coalescence occurs in a generation close to the root.

In the following result, we compute the law of  $\pi^{k,n}$ . Before that, we add, for convenience, a collection  $\{e^{(i)}; i \in \mathbb{N}^*\}$  of distinct leaves in the generation 0. Let  $q \geq 2$  be an integer and  $\pi$  be a partition of  $\{1, \dots, q\}$ . For any  $m \in \mathbb{N}^*$ , define the set  $\Upsilon_{m,\pi}$  by:  $\mathbf{x} = (x^{(1)}, \dots, x^{(q)}) \in \Upsilon_{m,\pi}$  if and only if



$\mathbf{x} \in \Delta^q$  and

$$\forall \mathbf{B} \in \pi, \forall i_1, i_2 \in \mathbf{B} : (x^{(i_1)})_m = (x^{(i_2)})_m,$$

and if  $|\pi| \geq 2$

$$\forall \mathbf{B} \neq \tilde{\mathbf{B}} \in \pi, \forall i_1 \in \mathbf{B}, i_2 \in \tilde{\mathbf{B}} : (x^{(i_1)})_m \neq (x^{(i_2)})_m,$$

where we recall that, when  $|x^{(i)}| \geq m$ ,  $(x^{(i)})_m$  denotes the ancestor of  $x^{(i)}$  in generation  $m$ . Otherwise, if  $|x^{(i)}| < m$ , we set  $(x^{(i)})_m := e^{(i)}$  so  $\Upsilon_{m,\pi}$  is well defined.

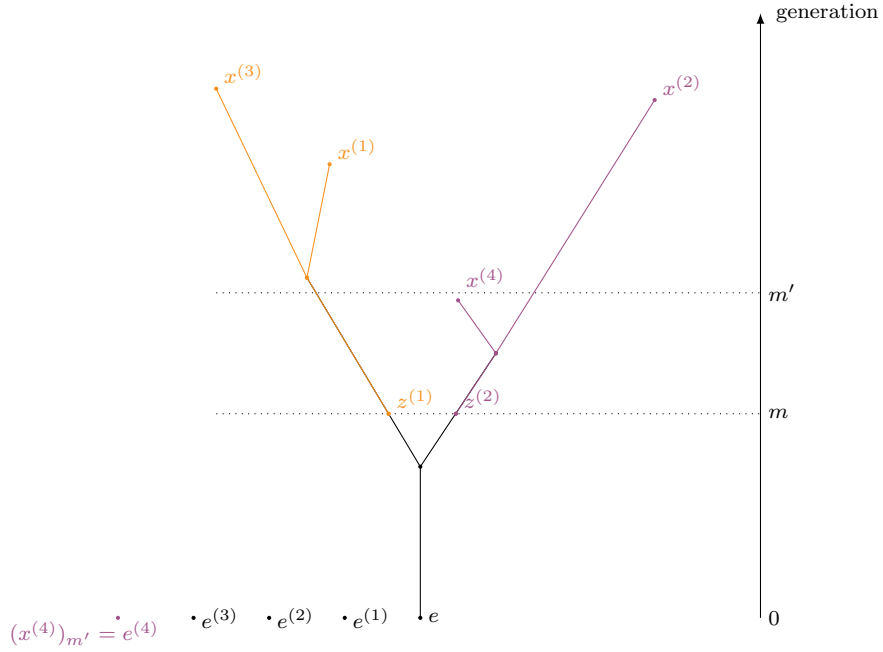


Figure 2: In the present illustration, the 4-tuple of vertices  $(x^{(1)}, x^{(2)}, x^{(3)}, x^{(4)})$  belongs to  $\Upsilon_{m,\pi}$  with  $\pi = \{\{1, 3\}, \{2, 4\}\}$ , since  $z^{(1)} = (x^{(1)})_m = (x^{(3)})_m$ ,  $z^{(2)} = (x^{(2)})_m = (x^{(4)})_m$  and  $z^{(1)} \neq z^{(2)}$ . However, it doesn't belong to  $\Upsilon_{m',\pi}$ .

Now, let  $1 \leq d < q$  be two integers. A collection  $(\Xi_i)_{0 \leq i \leq d}$  of partitions of  $\{1, \dots, q\}$  is said to be increasing if it satisfies  $\Xi_0 = \{\{1, \dots, q\}\}$ ,  $\Xi_d = \{\{1\}, \dots, \{q\}\}$  and for all  $i \in \{1, \dots, d\}$ ,  $|\Xi_{i-1}| < |\Xi_i|$ , where we recall that  $|\Xi_i|$  is the total number of blocks of the partition  $\Xi_i$ . For  $p \in \{1, \dots, d\}$ , the  $j$ -th block  $\mathbf{B}_j^{p-1}$  of the partition  $\Xi_{p-1}$  (blocks are ordered by their least element) is the union of  $b_{p-1}(\mathbf{B}_j^{p-1}) \geq 1$  (we will write  $b_{p-1}(\mathbf{B}_j)$  instead) block(s)  $\mathbf{B}_{l_1}^p, \dots, \mathbf{B}_{l_{b_{p-1}(\mathbf{B}_j)}}^p$ ,  $1 \leq l_1 < \dots < l_{b_{p-1}(\mathbf{B}_j)} \leq |\Xi_p|$ , of the partition  $\Xi_p$  and for any  $i \in \{1, \dots, b_{p-1}(\mathbf{B}_j)\}$ , define

$$\beta_{j,i}^{p-1} := |\mathbf{B}_{l_i}^p|, \quad (14)$$

to be the cardinal of the block  $\mathbf{B}_{l_i}^p$ .

Let  $(\Xi_i)_{0 \leq i \leq d}$  be an increasing collection of partitions of  $\{1, \dots, q\}$  and let  $\mathbf{t} = (t_1, \dots, t_d) \in \mathbb{N}^d$  such that  $t_1 < \dots < t_d$ . Introduce the set  $\Gamma_{\mathbf{t}, \Xi}^i := \Upsilon_{t_{i-1}, \Xi_{i-1}} \cap \Upsilon_{t_i, \Xi_i}$ . We then define the function

$f_{\mathbf{t}, \Xi}^d$  by: for all  $\mathbf{x} \in \Delta^q$

$$f_{\mathbf{t}, \Xi}^d(\mathbf{x}) = \prod_{i=1}^d \mathbf{1}_{\Gamma_{\mathbf{t}, \Xi}^i}(\mathbf{x}). \quad (15)$$

The function defined in (15) plays a key role in our study:  $f_{\mathbf{t}, \Xi}^d(\mathbf{x})$  characterizes the genealogy of  $\mathbf{x} := (x^{(1)}, \dots, x^{(q)})$ . Indeed, for any  $i \in \{1, \dots, d\}$ , the partition  $\Xi_i$  corresponds to the  $i$ -th generation of the genealogical tree of  $x^{(1)}, \dots, x^{(q)}$  while  $t_i - 1$  denotes the  $i$ -th generation at which at least two branches of this genealogical tree split ( $t_i - 1$  therefore corresponds to a coalescent/split time, see Figure 3 for instance). We are now ready to state our result:

**Theorem 1.4.** *Let  $k \geq 2$  and assume that  $\kappa > 2k$ . Under the assumptions 1, 2, 3 and 4, for any  $\ell \in \mathbb{N}^*$  such that  $\ell < k$ , any  $\mathbf{s} = (s_1, \dots, s_\ell) \in \mathbb{N}^{\times \ell}$  such that  $s_1 < \dots < s_\ell$  and any increasing collection  $\Pi = (\pi_i)_{0 \leq i \leq \ell}$  of partitions of  $\{1, \dots, k\}$*

1. in  $\mathbb{P}^*$ -probability

$$\frac{1}{(n^{1/2} \mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_n, f_{\mathbf{s}, \Pi}^\ell) \xrightarrow[n \rightarrow \infty]{} (c_\infty)^k \mathcal{A}_\infty^k(f_{\mathbf{s}, \Pi}^\ell), \quad (16)$$

where  $\mathcal{A}_\infty^k(f_{\mathbf{s}, \Pi}^\ell)$  is a random variable satisfying

$$\sum_{\Pi \text{ increasing}} \sum_{\substack{\mathbf{s}=(s_1, \dots, s_\ell) \\ m_{i-1} < s_i \leq m_i}} \mathcal{A}_\infty^k(f_{\mathbf{s}, \Pi}^\ell) = (W_\infty)^k,$$

and

$$\mathbf{E}^*[\mathcal{A}_\infty^k(f_{\mathbf{s}, \Pi}^\ell)] = e^{\psi(k)} \prod_{i=1}^{\ell} \prod_{j=1}^{|\pi_{i-1}|} c_{b_{i-1}(\mathbf{B}_j)}(\beta_j^{i-1}) \prod_{\substack{\mathfrak{B} \in \pi_i \\ |\mathfrak{B}| \geq 2}} e^{s_{i+1}^* \psi(|\mathfrak{B}|)}, \quad (17)$$

with  $s_{i+1}^* = s_{i+1} - s_i - 1$ ,  $s_{\ell+1}^* = 1$ ,  $\beta_j^p := (\beta_{j,1}^p, \dots, \beta_{j, b_p(\mathbf{B}_j)}^p)$  (see (14)). We also use the convention  $\prod_{\emptyset} = 1$  and see the assumption 3 for the definition of  $c_i(\beta)$ .

2. Moreover, for any non-negative integers  $m_0 < m_1 < \dots < m_\ell$

$$\mathbb{P}^*(\pi_{m_0}^{k,n} = \pi_0, \dots, \pi_{m_\ell}^{k,n} = \pi_\ell) \xrightarrow[n \rightarrow \infty]{} \mathbf{E}^* \left[ \frac{1}{(W_\infty)^k} \sum_{\substack{\mathbf{s}=(s_1, \dots, s_\ell) \\ m_{i-1} < s_i \leq m_i}} \mathcal{A}_\infty^k(f_{\mathbf{s}, \Pi}^\ell) \right]. \quad (18)$$

**Remark 2** (An hereditary character). *There is an hereditary character hidden in the previous formula (17) due to the random environment. The fact is, unlike the case of regular supercritical Galton-Watson trees depending on  $(b_i(\mathbf{B}); \mathbf{B} \in \pi_i, 0 \leq i \leq \ell - 1)$  (see [Joh19], Theorem 3.5), the limit law of the present genealogical tree depends on the collection  $(\beta_j^i; 0 \leq i \leq \ell - 1, 1 \leq j \leq |\pi_{i-1}|)$  and on  $(|\mathfrak{B}|; \mathfrak{B} \in \pi_i, 1 \leq i \leq \ell)$ , making a huge difference. Indeed, by definition, the latter take more account of the genealogical structure than  $(b_i(\mathbf{B}); \mathbf{B} \in \pi_i, 0 \leq i \leq \ell - 1)$ . For instance, let  $k = 4$ ,  $\ell = 3$  and define the increasing collection of partitions  $\Pi = (\pi_i)_{0 \leq i \leq \ell}$  by  $\pi_3 = \{\{1\}, \{2\}, \{3\}, \{4\}\}$ ,  $\pi_2 = \{\{1, 3\}, \{2\}, \{4\}\}$ ,  $\pi_1 = \{\{1, 3\}, \{2, 4\}\}$  and  $\pi_0 = \{1, 2, 3, 4\}$ . We have  $\beta_1^2 = (1, 1)$ ,  $\beta_2^2 = 1$ ,  $\beta_1^1 = 1$ ;  $\beta_1^1 = 2$ ,  $\beta_2^1 = (1, 1)$ ;  $\beta_1^0 = (2, 2)$  and thanks to (17), for any*

$\mathbf{t} = (t_1, t_2, t_3) \in \mathbb{N}^{\times 3}$  such that  $t_1 < t_2 < t_3$

$$\mathbf{E}^*[\mathcal{A}_\infty^4(f_{\mathbf{t}, \Pi}^3)] = \mathbf{E}\left[\sum_{|x|=1} e^{-2V(x)}\right] \mathbf{E}\left[\sum_{\substack{x \neq y \\ |x|=|y|=1}} e^{-V(x)-V(y)}\right]^2 \mathbf{E}\left[\sum_{\substack{x \neq y \\ |x|=|y|=1}} e^{-2V(x)-2V(y)}\right] \\ \times e^{t_3^* \psi(2) + 2t_2^* \psi(2) + \psi(4)}.$$

Also introduce the increasing collection of partitions  $\Pi' = (\pi'_i)_{1 \leq i \leq \ell}$  such that  $\pi'_3 = \pi_3$ ,  $\pi'_2 = \pi_2$ ,  $\pi'_1 = \{\{1, 3, 4\}, \{2\}\}$  and  $\pi'_0 = \pi_0$ . We have  $\beta_1^2 = (1, 1)$ ,  $\beta_2^2 = 1$ ,  $\beta_3^2 = 1$ ;  $\beta_1^1 = (2, 1)$ ,  $\beta_2^1 = 1$ ;  $\beta_1^0 = (3, 1)$  and thanks to (17), for any  $\mathbf{t} = (t_1, t_2, t_3) \in \mathbb{N}^{\times 3}$  such that  $t_1 < t_2 < t_3$

$$\mathbf{E}^*[\mathcal{A}_\infty^4(f_{\mathbf{s}, \Pi'}^3)] = \mathbf{E}\left[\sum_{\substack{x \neq y \\ |x|=|y|=1}} e^{-V(x)-V(y)}\right] \mathbf{E}\left[\sum_{\substack{x \neq y \\ |x|=|y|=1}} e^{-2V(x)-V(y)}\right] \mathbf{E}\left[\sum_{\substack{x \neq y \\ |x|=|y|=1}} e^{-3V(x)-V(y)}\right] \\ \times e^{s_3^* \psi(2) + s_2^* \psi(3) + \psi(4)}.$$

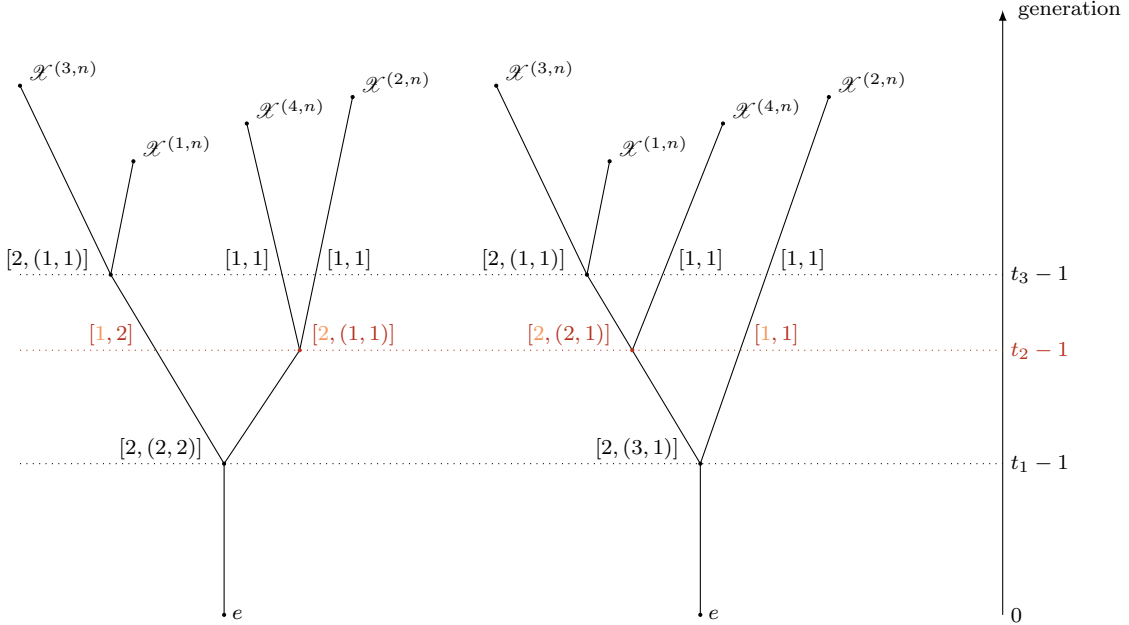


Figure 3: An example of a genealogical tree of the four vertices  $\mathcal{X}^{(1,n)}$ ,  $\mathcal{X}^{(2,n)}$ ,  $\mathcal{X}^{(3,n)}$ ,  $\mathcal{X}^{(4,n)}$  associated to  $\Pi$  (left) and associated to  $\Pi'$  (right).  $[1, 2]$  means that  $b_{1, \Pi}(\{1, 3\}) = 1$  and  $\beta_1^{2, \Pi} = 2$ ,  $[2, (1, 1)]$  means that  $b_{2, \Pi}(\{2, 4\}) = 2$  and  $\beta_2^{2, \Pi} = (1, 1)$ . In the same way,  $[2, (2, 1)]$  means that  $b_{1, \Pi'}(\{1, 3\}) = 2$  and  $\beta_1^{2, \Pi'} = (2, 1)$ ,  $[1, 1]$  means that  $b_{2, \Pi'}(\{2\}) = 1$  and  $\beta_2^{2, \Pi'} = 1$ .

The difference between these two examples is that in the second one, we ask  $(\mathcal{X}^{(4,n)})_{t_2-1}$  (the ancestor of  $\mathcal{X}^{(4,n)}$  of in generation  $t_2 - 1$ ) to belong to both genealogical line  $\llbracket (\mathcal{X}^{(1,n)})_{t_1-1}, \mathcal{X}^{(1,n)} \rrbracket$  and  $\llbracket (\mathcal{X}^{(3,n)})_{t_1-1}, \mathcal{X}^{(3,n)} \rrbracket$ . This constraint can be satisfied only if the vertex  $(\mathcal{X}^{(4,n)})_{t_1-1}$  is often visited by the random walk  $\mathbb{X}$ , inducing more dependence in the trajectories of  $\mathbb{X}$  thus giving the factor  $t_2^* \psi(3)$  instead of  $2t_2^* \psi(2) = t_2^* \psi(2) + t_2^* \psi(2)$ .

However, in the case of regular supercritical Galton-Watson trees, the events  $\cap_{i=0}^3 \{\pi_i\}$  and  $\cap_{i=0}^3 \{\tilde{\pi}_i\}$  have the same probability under the limit law of the genealogical tree. Indeed, one can notice (see Figure 3) that for all  $i \in \{1, 2, 3\}$  and all  $j \in \{1, \dots, |\pi_i|\}$  ( $|\pi_i| = |\tilde{\pi}'_i|$  by definition),  $b_{i,\Pi}(\mathbf{B}_j) = b_{i,\Pi'}(\mathbf{B}_{\mathbf{p}(j)})$  for some permutation  $\mathbf{p}$  on  $\llbracket 1, |\pi_i| \rrbracket$ , but this not the case when replacing  $b_{i,\Pi}(\mathbf{B}_.)$  by  $\beta^{i,\Pi}$  and  $b_{i,\Pi'}(\mathbf{B}_.)$  by  $\beta^{i,\Pi'}$ .

Since all coalescences of the genealogical lines of  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$  occur in the remote past with large probability, one could focus on this particular vertices of the tree  $\mathcal{R}_{T_n^{1/2}}$ . To do that, we pick a  $k$ -tuple  $\mathcal{Y}^{(n)} = (\mathcal{Y}^{(1,n)}, \dots, \mathcal{Y}^{(k,n)})$  uniformly in the set  $\mathcal{D}_n^{\times k} \cap \mathcal{C}_s^k$  for  $\mathbf{s} \in \mathbb{N}^*$ . In other words, the law of  $\mathcal{Y}^{(n)}$  is given in (6) by replacing  $\Delta^k(\mathcal{D}_n)$  with  $\Delta^k(\mathcal{D}_n) \cap \mathcal{C}_s^k$ . We keep the same notations for  $\mathcal{Y}^{(n)}$  as for  $\mathcal{X}^{(n)}$ .

The last example gives the law of the coalescent times  $(\mathcal{J}^{k,n})_{1 \leq j \leq \mathcal{J}^{k,n}}$  of  $\mathcal{Y}^{(1,n)}, \dots, \mathcal{Y}^{(k,n)}$ :

**Theorem 1.5.** *Let  $k \geq 2$  and assume that  $\kappa > 2k$ . Let  $1 \leq \ell < k$ ,  $\mathbf{s} \in \mathbb{N}^*$  be two integers, and  $\mathbf{s} = (s_1, \dots, s_\ell) \in \mathbb{N}^{\times \ell}$  such that  $s_1 < \dots < s_\ell \leq \mathbf{s}$ . Assume that for all  $\mathbf{x} \in \Delta^k$ ,*

$$F_{\mathbf{s}}^\ell(\mathbf{x}) = \sum_{\Xi \text{ increasing}} f_{\mathbf{s}, \Xi}^\ell(\mathbf{x}),$$

where  $\Xi$  increasing means here that  $\Xi = (\Xi_i)_{0 \leq i \leq \ell}$  is an increasing collection of partitions of  $\{1, \dots, k\}$ . Under the assumptions 1, 2, 3 and 4,

1. in  $\mathbb{P}^*$ -probability

$$\frac{\mathcal{A}^k(\mathcal{D}_n, F_{\mathbf{s}}^\ell)}{\mathcal{A}^k(\mathcal{D}_n, \mathbb{1}_{\mathcal{C}_s^k})} \mathbb{1}_{\{D_n \geq k\}} \xrightarrow{n \rightarrow \infty} \frac{\mathcal{A}_\infty^k(F_{\mathbf{s}}^\ell)}{\mathcal{A}_\infty^k(\mathbb{1}_{\mathcal{C}_s^k})}, \quad (19)$$

where  $\mathcal{A}_\infty^k(\mathbb{1}_{\mathcal{C}_s^k})$  is defined in Theorem 1.3 and  $\mathcal{A}_\infty^k(F_{\mathbf{s}}^\ell)$  is a random variable satisfying

$$\sum_{\ell=1}^{k-1} \sum_{\substack{\mathbf{s}=(s_1, \dots, s_\ell) \\ s_1 < \dots < s_\ell \leq \mathbf{s}}} \mathcal{A}_\infty^k(F_{\mathbf{s}}^\ell) = \mathcal{A}_\infty^k(\mathbb{1}_{\mathcal{C}_s^k}).$$

2. Moreover

$$\mathbb{P}^*(\mathcal{J}_1^{k,n} = s_1, \dots, \mathcal{J}_\ell^{k,n} = s_\ell, \mathcal{J}^{k,n} = \ell) \xrightarrow{n \rightarrow \infty} \mathbf{E}^* \left[ \frac{\mathcal{A}_\infty^k(F_{\mathbf{s}}^\ell)}{\mathcal{A}_\infty^k(\mathbb{1}_{\mathcal{C}_s^k})} \right], \quad (20)$$

#### 1.4. The small generations: a general result

In this section, we present results for the range  $\mathcal{A}^k(\mathcal{D}_n, f)$  with  $f$  non-negative and bounded satisfying a very natural heredity condition we will discuss later and including previous examples. First, recall that  $\mathcal{D}_n = \{x \in \mathcal{R}_{T_n^{1/2}}; \ell_n \leq |x| \leq \mathfrak{L}_n\}$  with  $(\mathfrak{L}_n)$  a sequence of positive integers such that  $\delta_0^{-1} \log n \leq \mathfrak{L}_n \leq n^{1/2}$  (see Lemma 3.4 for the definition of  $\delta_0$ ) and  $(\ell_n)$  is a sequence of positive integers such that  $\delta_0^{-1} \log n \leq \ell_n \leq \mathfrak{L}_n$ . Then recall the definition of  $\mathcal{A}^k(\mathcal{D}_n, f)$  defined in (5): if  $D_n \geq k$

$$\mathcal{A}^k(\mathcal{D}_n, f) := \sum_{\mathbf{x} \in \Delta^k(\mathcal{D}_n)} f(\mathbf{x}),$$

with  $\Delta^k(\mathcal{D}_n) = \{\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \mathcal{D}_n^{\times k}; \forall i_1 \neq i_2, x^{(i_1)} \neq x^{(i_2)}\}$  and equal to 0 otherwise. Although we obtain quite general results, we however require the following assumption on  $f$ : recall

that for all  $k \geq 2$ ,  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ ,  $\mathcal{C}_m^k = \{\mathbf{x} \in \Delta^k; \mathcal{S}^k(\mathbf{x}) \leq m\}$  where  $\mathcal{S}^k(\mathbf{x}) - 1$  denotes the last generation at which two or more vertices among  $x^{(1)}, \dots, x^{(k)}$  share a common ancestor (see (11)). Assume

**Assumption 5.** *there exists  $\mathfrak{g} \in \mathbb{N}^*$  such that for all integer  $p \geq \mathfrak{g}$  and all  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ , if  $\min_{1 \leq i \leq k} |x^{(i)}| \geq p$  and  $\mathbf{x} \in \mathcal{C}_p^k$  then*

$$f((x^{(1)}, \dots, x^{(k)})) = f((x^{(1)})_p, \dots, (x^{(k)})_p), \quad (21)$$

where we recall that  $(x^{(i)})_p$  is the ancestor of  $x^{(i)}$  in the generation  $p$ . In other words, we ask the constraint  $f$  to be hereditary from a given generation  $\mathfrak{g}$ .

Introduce the local time  $\mathcal{L}^n := \sum_{j=1}^n \mathbb{1}_{\{X_j = e^*\}}$  of the parent  $e^*$  of the root  $e$  at time  $n$ . Recall that  $T^j$  is the  $j$ -th return time to  $e^*$ :  $T^0 = 0$  and for any  $j \geq 1$ ,  $T^j = \inf\{i > T^{j-1}; X_i = e^*\}$ . Let  $s \in \mathbb{N}^*$  and introduce  $\mathcal{D}_{n, T^s} := \{x \in \mathcal{R}_{T^s}; \ell_n \leq |x| \leq \mathfrak{L}_n\}$ . We denote by  $\mathfrak{E}^{k, s}$  the set defined by: for a given  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ ,  $\mathbf{x} \in \mathfrak{E}^{k, s}$  if and only if the vertices of  $x^{(1)}, \dots, x^{(k)}$  are visited during  $k$  distinct excursions before the instant  $T^s$ :

$$\mathfrak{E}^{k, s} := \bigcup_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \bigcap_{i=1}^k \{\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k; \mathcal{L}_{x^{(i)}}^{T^{j_i}} - \mathcal{L}_{x^{(i)}}^{T^{j_i-1}} \geq 1\}, \quad (22)$$

where we denote by  $\llbracket 1, s \rrbracket_k$  the set of  $k$ -tuples  $\mathbf{j}$  of  $\{1, \dots, s\}$  such that for all  $i_1 \neq i_2 \in \{1, \dots, s\}$ ,  $j_{i_1} \neq j_{i_2}$ . Our first proposition is a convergence of the range  $\mathcal{A}^k(\mathcal{D}_{n, T^s}, f \mathbb{1}_{\mathfrak{E}^{k, s}})$  for any  $\varepsilon_1 n^{1/2} \leq s \leq n^{1/2}/\varepsilon_1$ ,  $\varepsilon_1 \in (0, 1)$ .

**Proposition 1.** *Let  $k \geq 2$  and assume  $\kappa > 2k$ . Under the assumptions 1, 2, 3 and 4, if  $f$  satisfies the hereditary assumption 5 then for all  $\varepsilon, \varepsilon_1 \in (0, 1)$ ,  $\varepsilon_1 n^{1/2} \leq s \leq n^{1/2}/\varepsilon_1$*

$$\mathbb{P}^* \left( \left| \frac{1}{(s \mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_{n, T^s}, f \mathbb{1}_{\mathfrak{E}^{k, s}}) - (c_\infty)^k \mathcal{A}_\infty^k(f) \right| > \varepsilon \right) \xrightarrow{n \rightarrow \infty} 0,$$

and, in  $L^2(\mathbf{P}^*)$

$$\mathcal{A}_\infty^k(f) := \lim_{l \rightarrow \infty} \mathcal{A}_l^k(f), \quad (23)$$

with  $\mathcal{A}_l^k(f, \beta) := \sum_{\mathbf{x} \in \Delta_l^k} f(\mathbf{x}) e^{-\langle \beta, V(\mathbf{x}) \rangle_k}$ ,  $\mathcal{A}_l(f) := \mathcal{A}_l(f, \mathbf{1})$  and  $\mathbf{1} := (1, \dots, 1) \in \mathbb{N}^{\times k}$ .

In the next proposition, we claim  $k$ -tuples in  $\Delta^k \setminus \mathfrak{E}^{k, s}$  with  $s \leq n^{1/2}/\varepsilon_1$  and  $\varepsilon_1 \in (0, 1)$ , that is  $k$ -tuples of vertices such that at least two among them are visited during the same excursion above  $e^*$  and before  $T^s$ , have a minor contribution to the range  $\mathcal{A}^k(\mathcal{D}_n, \mathbf{1})$ .

**Proposition 2.** *Let  $\varepsilon \in (0, 1)$ ,  $k \geq 2$  and assume  $\kappa > 2k$ . Under the assumptions 1, 2, 3 and 4*

$$\mathbb{P}^* \left( \sup_{s \leq n^{1/2}/\varepsilon_1} \mathcal{A}^k(\mathcal{D}_{n, T^s}, \mathbb{1}_{\Delta^k \setminus \mathfrak{E}^{k, s}}) > \varepsilon (n^{1/2} \mathbf{L}_n)^k \right) \xrightarrow{n \rightarrow \infty} 0 \quad (24)$$

We are now ready to state our main result:

**Theorem 1.6.** *Let  $k \geq 2$  and assume  $\kappa > 2k$ . Under the assumptions 1, 2, 3 and 4, if  $f$  satisfies the hereditary assumption 5 then, in  $\mathbb{P}^*$ -probability*

$$\frac{\mathcal{A}^k(\mathcal{D}_n, f)}{(n^{1/2} \mathbf{L}_n)^k} \xrightarrow{n \rightarrow \infty} (c_\infty)^k \mathcal{A}_\infty^k(f), \quad (25)$$

and if  $g \neq 0$  also satisfies assumption 5 then in  $\mathbb{P}^*$ -probability

$$\frac{\mathcal{A}^k(\mathcal{D}_n, f)}{\mathcal{A}^k(\mathcal{D}_n, g)} \mathbb{1}_{\{D_n \geq k\}} \xrightarrow{n \rightarrow \infty} \frac{\mathcal{A}_\infty^k(f)}{\mathcal{A}_\infty^k(g)}, \quad (26)$$

where  $\mathbf{L}_n = \mathfrak{L}_n - \ell_n + 1$  and  $\mathcal{A}_\infty^k(f)$  is defined in (23). Note that a constraint satisfying assumption 5 doesn't have any influence on the normalization of the range. Moreover,  $\mathcal{A}^k(\mathcal{D}_n, f)$  behaves like  $(\mathbf{L}_n \max_{x \in \mathcal{R}_{T_n^{1/2}}} |x|)^k$  and the limiting value  $\mathcal{A}_\infty(f)$  contains all the information about the interactions between the vertices of the tree.

We end this subsection by stating an extension of Theorem 1.6 to the range  $\mathcal{R}_n$ . Before that, introduce  $\tilde{\mathcal{D}}_n := \{x \in \mathcal{R}_n; \ell_n \leq |x| \leq \mathfrak{L}_n\}$  with cardinal  $\tilde{D}_n$ .

**Theorem 1.7.** *Let  $k \geq 2$ . There exists a non-increasing sequence of positive integers  $(q(j))_j$ , satisfying  $q(j) \in (0, 1/2)$  and  $q(j) \rightarrow 0$  when  $j \rightarrow \infty$  such that if  $\kappa > 2\xi k$  for some integer  $\xi \geq 2$  and  $\mathfrak{L}_n = o(n^{1/2 - q(\xi)})$ , then, in law, under  $\mathbb{P}^*$*

$$\frac{\mathcal{A}^k(\tilde{\mathcal{D}}_n, f)}{(n^{1/2} \mathbf{L}_n)^k} \xrightarrow{n \rightarrow \infty} \frac{\mathcal{A}_\infty^k(f)}{(W_\infty)^k} (c_\infty c_0^{1/2} |\mathcal{N}|)^k, \quad (27)$$

where  $c_0 := \mathbf{E}[\sum_{x \neq y; |x|=|y|=1} e^{-V(x)-V(y)}] / (1 - e^{\psi(2)})$  and  $\mathcal{N}$  is a standard Gaussian random variable.

Moreover, if  $g \neq 0$  also satisfies assumption 5 then in  $\mathbb{P}^*$ -probability

$$\frac{\mathcal{A}^k(\tilde{\mathcal{D}}_n, f)}{\mathcal{A}^k(\tilde{\mathcal{D}}_n, g)} \mathbb{1}_{\{D_n \geq k\}} \xrightarrow{n \rightarrow \infty} \frac{\mathcal{A}_\infty^k(f)}{\mathcal{A}_\infty^k(g)}, \quad (28)$$

In particular, all the previous results on  $\mathcal{D}_n$  hold for  $\tilde{\mathcal{D}}_n$  with  $\mathfrak{L}_n = o(n^{1/2 - q(\xi)})$ .

### 1.5. The tiny and the critical generations

Recall that  $\psi(t) = \log \mathbf{E}[\sum_{|x|=1} e^{-tV(x)}]$  and introduce  $\tilde{\gamma} := \sup\{a \in \mathbb{R}; \inf_{t \geq 0} (\psi(-t) - at) > 0\}$ . By tiny generations, we mean those of order  $\ell_n$  where  $\ell_n \rightarrow \infty$  when  $n \rightarrow \infty$  and  $\ell_n \leq G \log n$  with  $G \in (0, (2\tilde{\gamma})^{-1})$ . The fact is that for these generations, the random environment has a uniform impact. Indeed, P. Andreatti and P. Debs proved in [AD14] that with high probability,  $\{x \in \mathcal{R}_n; |x| \leq G \log n\} = \{x \in \mathbb{T}; |x| \leq G \log n\}$  for all  $G \in (0, (2\tilde{\gamma})^{-1})$ . Moreover, the value  $(2\tilde{\gamma})^{-1}$  is optimal: if  $G_n$  denotes the largest generation entirely visited by the random walk  $\mathbb{X}$  up to the time  $n$ , then  $\mathbb{P}^*$ -almost surely

$$\frac{G_n}{\log n} \xrightarrow{n \rightarrow \infty} \frac{1}{2\tilde{\gamma}}.$$

For this case, we are therefore capable of giving a description of the genealogy of  $k \geq 2$  vertices uniformly chosen by adapting the results on the genealogical structure of continuous-time Galton-Watson trees of S. Harris, S. Johnston and M. Roberts (see [HJR17] and [Joh19]) to discrete supercritical Galton-Watson trees.

The critical generations, that is to say of order  $n^{1/2}$ , correspond to the typical generations but also to the largest reached by the diffusive random walk  $\mathbb{X}$  up to the time  $n$ . E. Aidékon and L. de Raphélys [AdR17] showed that  $n^{1/2}$  is also the right normalisation for the tree  $\mathcal{R}_n$ : in law, under  $\mathbb{P}^*$

$$\frac{c_0^{1/2}}{n^{1/2}} \mathcal{R}_n \xrightarrow{n \rightarrow \infty} \mathcal{T}_{|B|},$$

where for any  $\mathfrak{c} > 0$ ,  $\mathfrak{c}\mathcal{R}_T$  is tree  $\mathcal{R}_T$  with edge lengths equal to  $\mathfrak{c}$  and  $\mathcal{T}_{|B|}$  is the real tree coded by the standard reflected Brownian motion  $|B| = (|B_t|)_{t \in [0,1]}$  on  $[0, 1]$  (see [Gal06]).  $\mathcal{T}_{|B|}$  is what we can call a Brownian forest thus suggesting that two vertices  $\mathcal{X}^{(1,n)}$  and  $\mathcal{X}^{(2,n)}$  chosen uniformly in the range  $\mathcal{R}_n$  at a generation of order  $n^{1/2}$  can share a common ancestor in both remote past and recent past. That is actually what is happening when considering two vertices  $\tilde{\mathcal{X}}^{(1,n)}$  and  $\tilde{\mathcal{X}}^{(2,n)}$  picked uniformly at generation  $n^{1/2}$  in the tree  $\mathcal{R}_{T^{n^{1/2}}}$ , where we recall that  $T^{n^{1/2}}$  is the  $n^{1/2}$ -th return time of  $\mathbb{X}$  to  $e^*$  (which is quite similar to  $\mathcal{R}_n$ ): let  $\tilde{\mathcal{M}}_n$  be the most recent common ancestor of  $\tilde{\mathcal{X}}^{(1,n)}$  and  $\tilde{\mathcal{X}}^{(2,n)}$ . First observe that

$$\lim_{\varepsilon \rightarrow 0} \liminf_{n \rightarrow \infty} \mathbb{P}^*(\tilde{\mathcal{M}}_n < 1/\varepsilon) > 0 \quad \text{and} \quad \lim_{\varepsilon \rightarrow 0} \limsup_{n \rightarrow \infty} \mathbb{P}^*(\varepsilon n^{1/2} \leq \tilde{\mathcal{M}}_n < n^{1/2}) > 0. \quad (29)$$

Moreover, coalescence can't occur anywhere else:

$$\lim_{\varepsilon \rightarrow 0} \limsup_{n \rightarrow \infty} \mathbb{E}^* \left[ \frac{1}{n} \sum_{\substack{x \neq y \\ |x|=|y|=n^{1/2}}} \mathbb{1}_{\{x,y \in \mathcal{R}_{T^{n^{1/2}}}, 1/\varepsilon \leq |x \wedge y| < \varepsilon n^{1/2}\}} \right] = 0.$$

Although  $\mathbb{T}$  is a supercritical Galton-Watson tree, the genealogy of  $\mathcal{R}_{T^{n^{1/2}}}$  (or  $\mathcal{R}_n$ ) is a mix of the supercritical case and the critical case for a regular Galton-Watson trees (see subsection 1.2).

The fact is using standard techniques for randomly biased random walks and branching random walks, we are able to deal with the quenched mean of  $(D_{T^{n^{1/2}}})^{p_1}$  for  $p_1 \leq \lfloor \kappa \rfloor$  and  $(\mathcal{A}^2(\mathcal{D}_{T^{n^{1/2}}}, f))^{p_2}$  with  $p_2 \leq \lfloor \kappa/2 \rfloor$  but not with the actual random variables.

The computation for any  $m > 0$  and any  $0 < a < b < 1$  of  $\mathbb{P}^*(\tilde{\mathcal{M}}_n < m)$  and  $\mathbb{P}^*(an^{1/2} \leq \tilde{\mathcal{M}}_n < bn^{1/2})$  is part of an ongoing work with P. Andreatti and L. de Raphélis.

The present paper aims in some way to describe the interaction between the vertices of the tree  $\mathcal{R}_{T^{n^{1/2}}}$  in the set of generations «squashed» when rescaling the tree by  $n^{1/2}$ .

**Remark 3.** *The curiosity here is the fact that critical generations and small generations equally contributed to the range. Indeed, whether  $\mathfrak{L}_n$  is negligible with respect to  $n^{1/2}$  (with  $\mathfrak{L}_n \geq \delta_0^{-1} \log n$ ) or not,  $\sum_{|u|=\mathfrak{L}_n} \mathbb{1}_{\{u \in \mathcal{R}_{T^{n^{1/2}}}\}}$  is of order  $n^{1/2}$ . This fact makes a deep difference with the slow regime in which only the critical generations (that is typical generations, of order  $(\log n)^2$ ) contribute significantly to the range (see [AC18], Theorem 1.2 and Proposition 1.4).*

**Remark 4** (The sub-diffusive and the slow regimes). *In the sub-diffusive case for the random  $\mathbb{X}$ , that is when  $\kappa \in (1, 2]$ , there is no reason to believe that the genealogical structure of the range is different from the diffusive case. Indeed, as in the case  $\kappa > 2$ , we have the convergence of the rescaled range, no longer to a Brownian forest but towards a Lévy forest (see Theorem 1 in [dR22]), suggesting that if we sample two vertices uniformly in a critical generation (that is a generation of order  $n^{1-1/\kappa}$  for  $\kappa \in (1, 2)$  and  $(n/\log n)^{1/2}$  for  $\kappa = 2$ ) in the range up to  $n$ , the coalescence happens either in the recent past or in the remote past. When we sample two vertices uniformly in a small generation, again, the coalescence should happen close to the root. However, in the slow regime for the random walk  $\mathbb{X}$ , that is when  $\psi(1) = \psi'(1) = 0$ , it is expected that the most recent common ancestor of two vertices sampled uniformly in a generation of order  $(\log n)^2$  in the range up to the time  $n$  is located in a generation of order  $(\log n)^2$ , see Remark 3.*

## 2. Proofs of the theorems

In this section, we prove theorems presented as examples and end it with the proofs of Theorem 1.6 and Theorem 1.7.

### 2.1. Proofs of Theorems 1.2 to 1.5

In this subsection, we give a proof of each example stated above except for the Theorem 1.1 which is the simplest application of Theorem 1.6, taking  $f = 1$ . For each example, the procedure is as follows: we first prove the function  $f$  we consider satisfies the hereditary assumption 5 and we then give useful precisions on  $\mathcal{A}_\infty^k(f)$  for the description of the genealogy of the vertices  $\mathcal{X}^{(1,n)}, \dots, \mathcal{X}^{(k,n)}$ .

*Proof of Theorem 1.2.* Recall that for  $\boldsymbol{\lambda} = (\lambda_2, \dots, \lambda_k) \in (\mathbb{N}^*)^{\times(k-1)}$  and  $\boldsymbol{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$  such that  $\min_{1 \leq i \leq k} |x^{(i)}| \geq \max_{2 \leq i \leq k} \lambda_i$

$$f_{\boldsymbol{\lambda}}(x^{(1)}, \dots, x^{(k)}) := \prod_{i=2}^k \mathbb{1}_{\{|x^{(i-1)} \wedge x^{(i)}| < \lambda_i\}}.$$

Let us prove that the hereditary assumption 5 is satisfied by  $f_{\boldsymbol{\lambda}}$ . Recall that for  $\boldsymbol{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ ,  $\mathcal{S}^k(\boldsymbol{x}) - 1$  denotes the last generation at which two or more vertices among  $x^{(1)}, \dots, x^{(k)}$  share a common ancestor. Let  $p \geq \max_{2 \leq i \leq k} \lambda_i$  and  $\boldsymbol{x} \in \Delta^k$  such that  $p \leq \min_{1 \leq i \leq k} |x^{(i)}|$ . If  $\mathcal{S}^k(\boldsymbol{x}) \leq p$  then, for any  $\boldsymbol{z} \in \llbracket (x^{(1)})_p, x^{(1)} \rrbracket \times \dots \times \llbracket (x^{(k)})_p, x^{(k)} \rrbracket$  and  $i \in \{2, \dots, k\}$ ,  $|x^{(i-1)} \wedge x^{(i)}| < \lambda_i$  if and only if  $|z^{(i-1)} \wedge z^{(i)}| < \lambda_i$ , meaning that  $f_{\boldsymbol{\lambda}}(\boldsymbol{x}) = f_{\boldsymbol{\lambda}}(\boldsymbol{z})$ . Consequently, assumption 5 holds for  $\mathfrak{g} = \max_{2 \leq i \leq k} \lambda_i$ . We conclude using Theorem 1.6.  $\square$

We now prove Theorem 1.3:

*Proof of Theorem 1.3.* Recall that for  $\boldsymbol{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ ,  $\mathcal{S}^k(\boldsymbol{x}) - 1$  denotes the last generation at which two or more vertices among  $x^{(1)}, \dots, x^{(k)}$  share a common ancestor and for  $m \in \mathbb{N}^*$ , recall that

$$f_m(\boldsymbol{x}) = \mathbb{1}_{\{\mathcal{S}^k(\boldsymbol{x}) \leq m\}}.$$

First, note that the hereditary assumption 5 is satisfied by  $f_m$ . Indeed, if  $p \geq m$  and  $\boldsymbol{x} \in \Delta^k$  such that  $p \leq \min_{1 \leq i \leq k} |x^{(i)}|$ , then  $\mathcal{S}^k(\boldsymbol{x}) \leq p$  implies that for any  $\boldsymbol{z} \in \llbracket (x^{(1)})_p, x^{(1)} \rrbracket \times \dots \times \llbracket (x^{(k)})_p, x^{(k)} \rrbracket$ , we have  $\mathcal{S}^k(\boldsymbol{z}) = \mathcal{S}^k(\boldsymbol{x})$ . Thus,  $\mathcal{S}^k((x^{(1)})_p, \dots, (x^{(k)})_p) \leq m$ . Moreover, by definition,  $\mathcal{S}^k((x^{(1)})_p, \dots, (x^{(k)})_p) \leq m$  implies  $\mathcal{S}^k(\boldsymbol{x}) \leq m$ . Consequently, assumption 5 holds for  $\mathfrak{g} = m$ .

We then deduce the converge of the trace in (16) by using Theorem 1.6.

We now move to the limit law of  $(\mathcal{S}^k(\mathcal{X}^{(n)}))$  in (13). Note, by definition, that

$$\mathbb{P}^*(\mathcal{S}^k(\mathcal{X}^{(n)}) \leq m) = \frac{1}{\mathbb{P}^*(D_n \geq k)} \mathbb{E}^* \left[ \frac{\mathcal{A}^k(\mathcal{D}_n, f_m)}{\mathcal{A}^k(\mathcal{D}_n, 1)} \mathbb{1}_{\{D_n \geq k\}} \right],$$

so  $\mathbb{P}^*(\mathcal{S}^k(\mathcal{X}^{(n)}) \leq m)$  goes to  $\mathbf{E}^*[\mathcal{A}_\infty^k(f_m)/(W_\infty)^k]$  when  $n$  goes to  $\infty$  thanks to Theorem 1.6 with  $f = f_m$  and  $g = 1$  together with the fact that  $\lim_{n \rightarrow \infty} \mathbb{P}^*(D_n \geq k) = 1$ . It is left to show that  $\lim_{m \rightarrow \infty} \mathcal{A}_\infty^k(f_m) = (W_\infty)^k$ . For that, we use Lemma 3.9 with  $f = 1$  and  $\boldsymbol{p} = (l, \dots, l) \in (\mathbb{N}^*)^{\times k}$

$$\sup_{l > m} \mathbf{E}^* \left[ |\mathcal{A}_l^k(f_m) - \mathcal{A}_l^k(1)|^2 \right] \xrightarrow{m \rightarrow \infty} 0.$$

Moreover,  $\lim_{l \rightarrow \infty} \mathcal{A}_l^k(1) = (W_\infty)^k$  and  $\lim_{l \rightarrow \infty} \mathcal{A}_l^k(f_m) = \mathcal{A}_\infty^k(f_m)$  so  $(\mathcal{A}_\infty^k(f_m))_m$  converges to  $(W_\infty)^k$  in  $L^2(\mathbf{P}^*)$ , which allows to end the proof.  $\square$

We now turn to the proof of Theorem 1.4.



*Proof of Theorem 1.4.* Recall that for any  $1 \leq d < q \in \mathbb{N}^*$ , for an increasing collection  $\Xi = (\Xi_i)_{0 \leq i \leq d}$  of partitions of  $\{1, \dots, q\}$ , for all  $\mathbf{x} = (x^{(1)}, \dots, x^{(q)}) \in \Delta^q$  and all  $\mathbf{t} = (t_1, \dots, t_d) \in \mathbb{N}^{\times d}$  such that  $t_1 < t_2 < \dots < t_d$ ,

$$f_{\mathbf{t}, \Xi}^d(\mathbf{x}) = \prod_{i=1}^d \mathbf{1}_{\Gamma_{\mathbf{t}, \Xi}^i}(\mathbf{x}),$$

where  $\Gamma_{\mathbf{t}, \Xi}^i = \Upsilon_{t_{i-1}, \Xi_{i-1}} \cap \Upsilon_{t_i, \Xi_i}$  and for any  $r \in \{1, \dots, d\}$  and any  $m \in \mathbb{N}^*$ ,  $\mathbf{x}$  belongs to  $\Upsilon_{m, \Xi_r}$  if and only if

$$\forall \mathbf{B} \in \Xi_r, \forall i_1, i_2 \in \mathbf{B} : (x^{(i_1)})_m = (x^{(i_2)})_m,$$

and for  $r \neq 0$

$$\forall \mathbf{B} \neq \tilde{\mathbf{B}} \in \Xi_r, \forall i_1 \in \mathbf{B}, i_2 \in \tilde{\mathbf{B}} : (x^{(i_1)})_m \neq (x^{(i_2)})_m,$$

where we recall that  $(x^{(i)})_m$  denotes the ancestor of  $x^{(i)}$  in generation  $m$  if exists,  $(x^{(i)})_m = e^{(i)}$  otherwise. Recall that  $\mathcal{C}_{\mathbf{g}}^k = \{\mathbf{y} \in \Delta^q; \mathcal{S}^q(\mathbf{y}) \leq \mathbf{g}\}$  where  $\mathcal{S}^q(\mathbf{y}) - 1$  is the last generation at which two or more vertices among  $y^{(1)}, \dots, y^{(q)}$  share a common ancestor. Let  $p \geq t_d$  such that  $\min_{1 \leq i \leq q} x^{(i)} \geq p$  and  $\mathbf{x} \in \mathcal{C}_p^k$ . If  $\mathbf{x} \in \cap_{j=1}^d \Gamma_{\mathbf{t}, \Xi}^j$ , then  $(z^{(i)})_t = (x^{(i)})_t$  for all  $\mathbf{z} \in \llbracket (x^{(1)})_p, x^{(1)} \rrbracket \times \dots \times \llbracket (x^{(q)})_p, x^{(q)} \rrbracket$ ,  $1 \leq i \leq q$  and  $t \in \{0, \dots, p\}$  thus giving  $((x^{(1)})_p, \dots, (x^{(q)})_p) \in \cap_{j=1}^d \Gamma_{\mathbf{t}, \Xi}^j$ . Moreover, by definition,  $((x^{(1)})_p, \dots, (x^{(q)})_p) \in \cap_{j=1}^d \Gamma_{\mathbf{t}, \Xi}^j$  implies  $\mathbf{x} \in \cap_{j=1}^d \Gamma_{\mathbf{t}, \Xi}^j$ . Consequently,  $f_{\mathbf{t}, \Xi}^d$  satisfies assumption 5 with  $\mathbf{g} = t_d$  and this prove that the convergence in (16) holds.

We move to the limit law of  $(\pi^{k,n})$  in (18). Recall the definition of  $\mathcal{S}_i^{k,n}$  in (12). First, note that

$$\mathbb{P}^*(\pi_{m_0}^{k,n} = \pi_0, \dots, \pi_{m_\ell}^{k,n} = \pi_\ell) = \mathbb{P}^*\left(\bigcap_{i=1}^{\ell} \{\pi_{m_{i-1}}^{k,n} = \pi_{i-1}, \pi_{m_i}^{k,n} = \pi_i, m_{i-1} < \mathcal{S}_i^{k,n} \leq m_i\}\right).$$

Indeed, for all  $1 \leq i \leq \ell$ ,  $|\pi_{i-1}| < |\pi_i|$  so the interval  $(m_{i-1}, m_i]$  necessarily contains at least one coalescent time. But since  $\pi_0 = \{\{1, \dots, k\}\}$  and  $\pi_\ell = \{\{1\}, \dots, \{k\}\}$ ,  $\cup_{i=1}^{\ell} (m_{i-1}, m_i]$  can't contain more than  $\ell$  coalescent times so  $\mathcal{S}_i^{k,n}$  is the only one belonging to  $(m_{i-1}, m_i]$ . We now write

$$\begin{aligned} & \mathbb{P}^*\left(\bigcap_{i=1}^{\ell} \{\pi_{m_{i-1}}^{k,n} = \pi_{i-1}, m_{i-1} < \mathcal{S}_i^{k,n} \leq m_i\}\right) \\ &= \sum_{s_1=m_0+1}^{m_1} \dots \sum_{s_\ell=m_{\ell-1}+1}^{m_\ell} \mathbb{P}^*\left(\bigcap_{i=1}^{\ell} \{\pi_{m_{i-1}}^{k,n} = \pi_{i-1}, \pi_{m_i}^{k,n} = \pi_i, \mathcal{S}_i^{k,n} = s_i\}\right) \\ &= \sum_{s_1=m_0+1}^{m_1} \dots \sum_{s_\ell=m_{\ell-1}+1}^{m_\ell} \mathbb{P}^*\left(\bigcap_{i=1}^{\ell} \{\pi_{s_{i-1}}^{k,n} = \pi_{i-1}, \pi_{s_i}^{k,n} = \pi_i\}\right), \end{aligned}$$

Moreover,  $\pi_{s_{i-1}}^{k,n} = \pi_{i-1}, \pi_{s_i}^{k,n} = \pi_i$  means nothing but  $\mathcal{X}^{(n)} \in \Gamma_{\mathbf{s}, \Pi}^i$  and it follows that

$$\begin{aligned} \mathbb{P}^*\left(\bigcap_{i=1}^{\ell} \{\pi_{m_{i-1}}^{k,n} = \pi_{i-1}, \pi_{m_i}^{k,n} = \pi_i, \mathcal{S}_i^{k,n} = s_i\}\right) &= \mathbb{E}^*[f_{\mathbf{s}, \Pi}^\ell(\mathcal{X}^{(n)})] \\ &= \mathbb{E}^*\left[\frac{\mathcal{A}^k(\mathcal{D}_n, f_{\mathbf{s}, \Pi}^\ell)}{\mathcal{A}^k(\mathcal{D}_n, 1)} \mathbb{1}_{\{D_n \geq k\}}\right], \end{aligned}$$

where we have used the definition of  $\mathcal{X}^{(n)}$  (see (7)) in the last equation. Since  $f_{\mathbf{s},\Pi}^\ell$  satisfies the hereditary assumption 5, we finally get (16) from (25) with  $f = f_{\mathbf{s},\Pi}^\ell$  and by (26) with  $g = 1$

$$\lim_{n \rightarrow \infty} \mathbb{P}^*(\pi_{m_0}^{k,n} = \boldsymbol{\pi}_0, \dots, \pi_{m_\ell}^{k,n} = \boldsymbol{\pi}_\ell) = \sum_{s_1=m_0+1}^{m_1} \cdots \sum_{s_\ell=m_{\ell-1}+1}^{m_\ell} \mathbf{E}^* \left[ \frac{\mathcal{A}_\infty^k(f_{\mathbf{s},\Pi}^\ell)}{(W_\infty)^k} \right].$$

We now compute the conditional expectation of  $\mathcal{A}_\infty^k(f_{\mathbf{s},\Pi}^\ell)$  conditionally given the sigma-algebra  $\mathcal{F}_{s_p-1} = \sigma(\mathbb{T}; (V(x); |x| < s_p))$ . Start with  $p = \ell$ . Let  $s_i \in \{m_{i-1}+1, \dots, m_i\}$  for all  $i \in \{1, \dots, \ell\}$ . Using the definition of  $\mathcal{A}_\infty^k(f_{\mathbf{s},\Pi}^\ell)$  and the fact that  $\mathbf{x} \in \Delta_t^k \cap \Gamma_{\mathbf{s},\Pi}^\ell$  for  $l > s_\ell$  implies  $\mathcal{S}^k(\mathbf{x}) \leq s_\ell$ , we obtain, on the set of non-extinction

$$\mathbf{E}^* [\mathcal{A}_\infty^k(f_{\mathbf{s},\Pi}^\ell) | \mathcal{F}_{s_\ell}] = \lim_{l \rightarrow \infty} \mathbf{E}^* \left[ \sum_{\mathbf{x} \in \Delta_t^k} f_{\mathbf{s},\Pi}^\ell(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_k} | \mathcal{F}_{s_\ell} \right] = \sum_{\mathbf{x} \in \Delta_{s_\ell}^k} f_{\mathbf{s},\Pi}^\ell(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_k},$$

since  $s_\ell - 1$  corresponds to the last generation at which two or more vertices among  $x^{(1)}, \dots, x^{(l)}$  share a common ancestor and we recall that  $\langle \mathbf{1}, V(\mathbf{x}) \rangle_k = \sum_{i=1}^k V(x^{(i)})$ . In particular, these vertices don't share any common ancestor in generation  $s_\ell$  and last equality comes from independence of the increments of the branching random walk  $(\mathbb{T}, (V(x), x \in \mathbb{T}))$  together with the fact that  $\psi(1) = 0$ . Before going any further, let us define a transformation of the increasing collection  $\Pi = (\boldsymbol{\pi}_i)_{0 \leq i \leq \ell}$  of partitions of  $\{1, \dots, k\}$ . We build from  $\Pi$  (which is by definition a collection of partitions of the set  $\{1, \dots, k\}$ ) a new collection  $\Pi^{\ell-1} = (\tilde{\boldsymbol{\pi}}_i)_{0 \leq i \leq \ell-1}$  of partitions of the set  $\{1, \dots, |\boldsymbol{\pi}_{\ell-1}|\}$  as follows:

- $\tilde{\boldsymbol{\pi}}_{\ell-1} = \{\{1\}, \dots, \{|\boldsymbol{\pi}_{\ell-1}|\}\}$ ;
- for any  $1 \leq i \leq \ell - 2$  and any  $1 \leq j \leq |\boldsymbol{\pi}_i|$ , the  $j$ -th block  $\mathbf{B}_j^i$  of the partition  $\boldsymbol{\pi}_i$  is the union of  $\mathbf{b}_{\ell-1}(\mathbf{B}_j^i) \geq 1$  block(s) of the partition  $\boldsymbol{\pi}_{\ell-1}$ . We then denote by  $\tilde{\mathbf{B}}_j^i$  the subset of  $\{1, \dots, |\boldsymbol{\pi}_{\ell-1}|\}$  composed of all indices of these  $\mathbf{b}_{\ell-1}(\mathbf{B}_j^i)$  block(s) and let  $\tilde{\boldsymbol{\pi}}_i = \{\tilde{\mathbf{B}}_1^i, \dots, \tilde{\mathbf{B}}_{|\boldsymbol{\pi}_i|}^i\}$ . By definition,  $\tilde{\boldsymbol{\pi}}_0$  remains a one-block partition:  $\tilde{\boldsymbol{\pi}}_0 = \{\{1, \dots, |\boldsymbol{\pi}_{\ell-1}|\}\}$ .

Note that for any  $0 \leq i \leq \ell - 1$ ,  $|\tilde{\boldsymbol{\pi}}_i| = |\boldsymbol{\pi}_i|$  and for any  $0 \leq i \leq \ell - 2$ ,  $1 \leq j \leq |\boldsymbol{\pi}_i|$ ,  $b_i(\mathbf{B}_j) = \tilde{b}_i(\tilde{\mathbf{B}}_j)$ , where  $\tilde{\mathbf{B}}_j \in \tilde{\boldsymbol{\pi}}_i$  is the union of  $\tilde{b}_i(\tilde{\mathbf{B}}_j) \geq 1$  block(s) of  $\tilde{\boldsymbol{\pi}}_{i+1}$ .

**Example 5.** If  $\Pi$  is defined by  $\boldsymbol{\pi}_4 = \{\{1\}, \{2\}, \{3\}, \{4\}, \{5\}\}$ ,  $\boldsymbol{\pi}_3 = \{\{1, 3\}, \{2\}, \{4\}, \{5\}\}$ ,  $\boldsymbol{\pi}_2 = \{\{1, 3\}, \{2, 5\}, \{4\}\}$ ,  $\boldsymbol{\pi}_1 = \{\{1, 3, 4\}, \{2, 5\}\}$  and  $\boldsymbol{\pi}_0 = \{\{1, 2, 3, 4, 5\}\}$  then we have:  $\tilde{\boldsymbol{\pi}}_3 = \{\{1\}, \{2\}, \{3\}, \{4\}\}$ ,  $\tilde{\boldsymbol{\pi}}_2 = \{\{1\}, \{2, 4\}, \{3\}\}$ ,  $\tilde{\boldsymbol{\pi}}_1 = \{\{1, 3\}, \{2, 4\}\}$ , and  $\tilde{\boldsymbol{\pi}}_0 = \{\{1, 2, 3, 4\}\}$ .

If we set  $\Pi^\ell := \Pi$ , then for any  $i \in \{0, \dots, \ell - 1\}$ , let  $\Pi^i$  be the collection of partitions of  $\{1, \dots, |\boldsymbol{\pi}_i|\}$  resulting from the previous procedure applied to  $\Pi^{i+1}$ . Note that  $\Pi^i$  is an increasing collection of partitions of  $\{1, \dots, |\boldsymbol{\pi}_i|\}$ . This construction is a way of preserving the genealogical information through the generations.

Let  $\mathbf{s}^{\ell-1} = (s_1, \dots, s_{\ell-1})$  and recall the definitions regarding partitions in (14). One can now notice that, since that the number of vertices of the  $k$ -tuple  $\mathbf{x} \in \Delta_{s_\ell}^k$  sharing the same parent  $u^{(j)}$  is  $b_{\ell-1}(\mathbf{B}_j)$  (where we recall that  $b_{\ell-1}(\mathbf{B}_j)$  stands for  $b_{\ell-1}(\mathbf{B}_j^{\ell-1})$ ), we have

$$\begin{aligned} \sum_{\mathbf{x} \in \Delta_{s_\ell}^k} f_{\mathbf{s},\Pi}^\ell(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_k} &= \sum_{\mathbf{u} \in \Delta_{s_{\ell-1}}^{|\boldsymbol{\pi}_{\ell-1}|}} f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}(\mathbf{u}) \prod_{j=1}^{|\boldsymbol{\pi}_{\ell-1}|} \sum_{\mathbf{x}^{(j)} \in \Delta_{s_\ell}^{b_{\ell-1}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-1}(\mathbf{B}_j)} \mathbb{1}_{\{(x^{(j,i)})^* = u^{(j)}\}} \\ &\quad \times e^{-V(x^{(j,i)})}, \end{aligned}$$

where  $\mathbf{x}^{(j)} = (x^{(j,1)}, \dots, x^{(j,b_{\ell-1}(\mathbf{B}_j))})$  and  $(x^{(j,i)})^*$  is the parent of  $x^{(j,i)}$ . Moreover, by definition,  $b_{\ell-1}(\mathbf{B}_j) = |\mathbf{B}_j^{\ell-1}|$  (it comes from the fact that  $\pi_\ell = \{\{1\}, \dots, \{k\}\}$ ) so

$$\begin{aligned} \prod_{j=1}^{|\pi_{\ell-1}|} \sum_{\mathbf{x}^{(j)} \in \Delta_{s_\ell}^{b_{\ell-1}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-1}(\mathbf{B}_j)} \mathbb{1}_{\{(x^{(j,i)})^* = u^{(j)}\}} e^{-V(x^{(j,i)})} &= e^{-\langle \beta^{\ell-1}, V(\mathbf{u}) \rangle_{|\pi_{\ell-1}|}} \prod_{j=1}^{|\pi_{\ell-1}|} \sum_{\mathbf{x}^{(j)} \in \Delta_{s_\ell}^{b_{\ell-1}(\mathbf{B}_j)}} \\ &\times \prod_{i=1}^{b_{\ell-1}(\mathbf{B}_j)} \mathbb{1}_{\{(x^{(j,i)})^* = u^{(j)}\}} e^{-V_{u^{(j)}}(x^{(j,i)})}, \end{aligned}$$

where  $\beta^{\ell-1} = (|\mathbf{B}_1^{\ell-1}|, \dots, |\mathbf{B}_{|\pi_{\ell-1}|}^{\ell-1}|)$  and  $V_{u^{(j)}}(x^{(j,i)}) = V(x^{(j,i)}) - V(u^{(j)})$ . By independence of the increments of the branching random walk  $(\mathbb{T}, (V(x), x \in \mathbb{T}))$ , since  $\psi(1) = 0$

$$\begin{aligned} \mathbf{E} \left[ \sum_{\mathbf{x} \in \Delta_{s_\ell}^k} f_{\mathbf{s}, \Pi}^\ell(\mathbf{x}) e^{-\langle 1, V(\mathbf{x}) \rangle_k} | \mathcal{F}_{s_{\ell-1}} \right] &= \mathcal{A}_{s_{\ell-1}}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \beta^{\ell-1}) \prod_{j=1}^{|\pi_{\ell-1}|} c_{b_{\ell-1}(\mathbf{B}_j)}(\mathbf{1}) \prod_{\substack{\mathfrak{B} \in \pi_\ell \\ |\mathfrak{B}| \geq 2}} e^{\psi(|\mathfrak{B}|)} \\ &= \mathcal{A}_{s_{\ell-1}}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \beta^{\ell-1}) \prod_{j=1}^{|\pi_{\ell-1}|} c_{b_{\ell-1}(\mathbf{B}_j)}(\beta_j^{\ell-1}), \end{aligned}$$

where  $\beta_j^{\ell-1} := (\beta_{j,1}^{\ell-1}, \dots, \beta_{j,b_{\ell-1}(\mathbf{B}_j)}^{\ell-1}) = (1, \dots, 1)$ , see (14). We also recall that  $\mathcal{A}_l^m(g, \beta) = \sum_{\mathbf{x} \in \Delta_l^m} g(\mathbf{x}) e^{-\langle \beta, V(\mathbf{x}) \rangle_m}$  and see assumption 3 for the definition of  $c_l(\beta)$ . Now recall that  $\Pi^{\ell-2}$  is the collection of partitions of  $\{1, \dots, |\pi_{\ell-2}|\}$  obtain from  $\Pi^{\ell-1}$  with the same procedure as above (see Example 5). Let  $\mathbf{s}^{\ell-2} = (s_1, \dots, s_{\ell-2})$ . Again, exactly  $b_{\ell-2}(\mathbf{B}_j)$  vertices in generation  $s_{\ell-1}$  are sharing the same parent  $z^{(j)}$  so

$$\begin{aligned} \mathcal{A}_{s_{\ell-1}}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \beta^{\ell-1}) &= \sum_{\mathbf{z} \in \Delta_{s_{\ell-1}-1}^{|\pi_{\ell-2}|}} f_{\mathbf{s}^{\ell-2}, \Pi^{\ell-2}}^{\ell-2}(\mathbf{z}) \prod_{j=1}^{|\pi_{\ell-2}|} \sum_{\mathbf{u}^{(j)} \in \Delta_{s_{\ell-1}}^{b_{\ell-2}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} \mathbb{1}_{\{(u^{(j,i)})^* = z^{(j)}\}} \\ &\times e^{-\beta_{j,i}^{\ell-2} V(u^{(j,i)})} \sum_{\mathbf{x}^{(j)} \in \Delta_{s_{\ell-1}}^{b_{\ell-2}(\mathbf{B}_j)}} \mathbb{1}_{\{x^{(j,i)} \geq u^{(j,i)}\}} e^{-\beta_{j,i}^{\ell-2} V_{u^{(j,i)}}(x^{(j,i)})}, \end{aligned}$$

where  $\mathbf{u}^{(j)} = (u^{(j,1)}, \dots, u^{(j,b_{\ell-2}(\mathbf{B}_j))})$ ,  $\mathbf{x}^{(j)} = (x^{(j,1)}, \dots, x^{(j,b_{\ell-2}(\mathbf{B}_j))})$  and  $V_{u^{(j,i)}}(x^{(j,i)})$  is the increment  $V(x^{(j,i)}) - V(u^{(j,i)})$ . Then, by independence of the increments of the branching random walk  $(\mathbb{T}, (V(x), x \in \mathbb{T}))$ , denoting  $s_\ell^* = s_\ell - s_{\ell-1} - 1$

$$\begin{aligned} \mathbf{E} \left[ \mathcal{A}_{s_{\ell-1}}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \beta^{\ell-1}) | \mathcal{F}_{s_{\ell-1}} \right] &= \sum_{\mathbf{z} \in \Delta_{s_{\ell-1}-1}^{|\pi_{\ell-2}|}} f_{\mathbf{s}^{\ell-2}, \Pi^{\ell-2}}^{\ell-2}(\mathbf{z}) \prod_{j=1}^{|\pi_{\ell-2}|} \sum_{\mathbf{u}^{(j)} \in \Delta_{s_{\ell-1}}^{b_{\ell-2}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} \\ &\times \mathbb{1}_{\{(u^{(j,i)})^* = z^{(j)}\}} e^{-\beta_{j,i}^{\ell-2} V(u^{(j,i)})} e^{s_\ell^* \psi(\beta_{j,i}^{\ell-2})}, \end{aligned}$$

which is also equal to

$$\begin{aligned} \sum_{\mathbf{z} \in \Delta_{s_{\ell-1}-1}^{|\pi_{\ell-2}|}} f_{\mathbf{s}^{\ell-2}, \Pi^{\ell-2}}^{\ell-2}(\mathbf{z}) \prod_{j=1}^{|\pi_{\ell-2}|} \sum_{\mathbf{u}^{(j)} \in \Delta_{s_{\ell-1}}^{b_{\ell-2}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} \mathbb{1}_{\{(u^{(j,i)})^* = z^{(j)}\}} e^{-\beta_{j,i}^{\ell-2} V(u^{(j,i)})} \\ \times \prod_{j=1}^{|\pi_{\ell-2}|} \prod_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} e^{s_\ell^* \psi(\beta_{j,i}^{\ell-2})}. \end{aligned}$$

Moreover, since  $\sum_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} \beta_{j,i}^{\ell-2} = |\mathbf{B}_j^{\ell-2}|$  (see (14)), we have

$$\begin{aligned} & \prod_{j=1}^{|\pi_{\ell-2}|} \sum_{\mathbf{u}^{(j)} \in \Delta_{s_{\ell-1}}^{b_{\ell-2}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} \mathbb{1}_{\{(u^{(j,i)})^* = z^{(j)}\}} e^{-\beta_{j,i}^{\ell-2} V(u^{(j,i)})} \\ &= e^{-\langle \beta^{\ell-2}, V(z) \rangle_{|\pi_{\ell-2}|}} \prod_{j=1}^{|\pi_{\ell-2}|} \sum_{\mathbf{u}^{(j)} \in \Delta_{s_{\ell-1}}^{b_{\ell-2}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} \mathbb{1}_{\{(u^{(j,i)})^* = z^{(j)}\}} e^{-\beta_{j,i}^{\ell-2} V_{z^{(j)}}(u^{(j,i)})}, \end{aligned}$$

with  $\beta^{\ell-2} = (|\mathbf{B}_1^{\ell-2}|, \dots, |\mathbf{B}_{|\pi_{\ell-2}|}^{\ell-2}|)$  and again, by independence of the increments of the branching random walk  $(\mathbb{T}, (V(x), x \in \mathbb{T}))$ , using that  $\prod_{j=1}^{|\pi_{\ell-2}|} \prod_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} e^{s_{\ell}^* \psi(\beta_{j,i}^{\ell-2})} = \prod_{\mathfrak{B} \in \pi_{\ell-1}} e^{s_{\ell}^* \psi(|\mathfrak{B}|)} = \prod_{\mathfrak{B} \in \pi_{\ell-1}, |\mathfrak{B}| \geq 2} e^{s_{\ell}^* \psi(|\mathfrak{B}|)}$ , we have

$$\begin{aligned} \mathbf{E} \left[ \mathcal{A}_{s_{\ell-1}}^{|\pi_{\ell-2}|} (f_{s_{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \beta^{\ell-1}) \middle| \mathcal{F}_{s_{\ell-1}-1} \right] &= \mathcal{A}_{s_{\ell-1}-1}^{|\pi_{\ell-2}|} (f_{s_{\ell-2}, \Pi^{\ell-2}}^{\ell-2}, \beta^{\ell-2}) \prod_{j=1}^{|\pi_{\ell-2}|} c_{b_{\ell-2}(\mathbf{B}_j)}(\beta_j^{\ell-2}) \\ &\quad \times \prod_{\substack{\mathfrak{B} \in \pi_{\ell-1} \\ |\mathfrak{B}| \geq 2}} e^{s_{\ell}^* \psi(|\mathfrak{B}|)}, \end{aligned}$$

where  $\beta_j^{\ell-2} = (\beta_{j,1}^{\ell-2}, \dots, \beta_{j,b_{\ell-2}(\mathbf{B}_j)}^{\ell-2})$ . Thus, we obtain

$$\begin{aligned} \mathbf{E} \left[ \sum_{\mathbf{x} \in \Delta_{s_{\ell}}^k} f_{s, \Pi}^{\ell}(\mathbf{x}) e^{-\langle 1, V(\mathbf{x}) \rangle_k} \middle| \mathcal{F}_{s_{\ell-1}-1} \right] &= \mathcal{A}_{s_{\ell-1}-1}^{|\pi_{\ell-2}|} (f_{s_{\ell-2}, \Pi^{\ell-2}}^{\ell-2}, \beta^{\ell-2}) \prod_{i=\ell-1}^{\ell} \prod_{j=1}^{|\pi_{i-1}|} c_{b_{i-1}(\mathbf{B}_j)}(\beta_j^{i-1}) \\ &\quad \times \prod_{\substack{\mathfrak{B} \in \pi_i \\ |\mathfrak{B}| \geq 2}} e^{s_{\ell}^* \psi(|\mathfrak{B}|)}. \end{aligned}$$

By induction on  $2 \leq p \leq \ell$ , we finally get, on the set of non-extinction

$$\mathbf{E}^* \left[ \mathcal{A}_{\infty}^k (f_{s, \Pi}^{\ell}) \middle| \mathcal{F}_{s_p-1} \right] = \mathcal{A}_{s_p-1}^{|\pi_{p-1}|} (f_{s^{p-1}, \Pi^{p-1}}^{p-1}, \beta^{p-1}) \prod_{i=p}^{\ell} \prod_{j=1}^{|\pi_{i-1}|} c_{b_{i-1}(\mathbf{B}_j)}(\beta_j^{i-1}) \prod_{\substack{\mathfrak{B} \in \pi_i \\ |\mathfrak{B}| \geq 2}} e^{s_{i+1}^* \psi(|\mathfrak{B}|)}.$$

Taking  $p = 2$  in the above formula, we have, on the set of non-extinction

$$\mathbf{E}^* \left[ \mathcal{A}_{\infty}^k (f_{s, \Pi}^{\ell}) \middle| \mathcal{F}_{s_2-1} \right] = \mathcal{A}_{s_2-1}^{|\pi_1|} (f_{s^1, \Pi^1}^1, \beta^1) \prod_{i=2}^{\ell} \prod_{j=1}^{|\pi_{i-1}|} c_{b_{i-1}(\mathbf{B}_j)}(\beta_j^{i-1}) \prod_{\substack{\mathfrak{B} \in \pi_i \\ |\mathfrak{B}| \geq 2}} e^{s_{i+1}^* \psi(|\mathfrak{B}|)},$$

where for any  $i \in \{2, \dots, \ell\}$ ,  $s_i^* = s_i - s_{i-1} - 1$  and  $s_{\ell+1}^* = 1$ . Since  $\sum_{j=1}^{b_0(\mathbf{B}_1)} |\mathbf{B}_j^1| = k$  (it comes from the fact that  $\pi_0 = \{\{1, \dots, k\}\}$ ), we have

$$\begin{aligned} \mathbf{E}^* \left[ \mathcal{A}_{s_2-1}^{|\pi_1|} (f_{s^1, \Pi^1}^1, \beta^1) \middle| \mathcal{F}_{s_1-1} \right] &= \sum_{|z|=s_1-1} e^{-kV(z)} c_{b_0(\mathbf{B}_1)}(\beta^1) \prod_{\substack{\mathfrak{B} \in \pi_1 \\ |\mathfrak{B}| \geq 2}} e^{s_2^* \psi(|\mathfrak{B}|)} \\ &= \sum_{|z|=s_1-1} e^{-kV(z)} \prod_{j=1}^{|\pi_0|} c_{b_0(\mathbf{B}_j)}(\beta_j^0) \prod_{\substack{\mathfrak{B} \in \pi_1 \\ |\mathfrak{B}| \geq 2}} e^{s_2^* \psi(|\mathfrak{B}|)}, \end{aligned}$$

the last equality coming from the fact  $\beta_j^0 = \beta^1 = (|\mathbf{B}_1^1|, \dots, |\mathbf{B}_{|\pi_1^1|}^1|)$ . Finally,

$$\mathbf{E}^*[\mathcal{A}_\infty^k(f_{\mathbf{s}, \Pi}^\ell)] = e^{\psi(k)} \prod_{i=1}^{\ell} \prod_{j=1}^{|\pi_{i-1}|} c_{b_{i-1}(\mathbf{B}_j)}(\beta_j^{i-1}) \prod_{\substack{\mathfrak{B} \in \pi_i \\ |\mathfrak{B}| \geq 2}} e^{s_{i+1}^* \psi(|\mathfrak{B}|)},$$

thus completing to proof.  $\square$

We end this subsection with the proof of Theorem 1.5.

*Proof of Theorem 1.5.* First recall that for  $1 \leq \ell < k$ ,  $\mathbf{s} \in \mathbb{N}^*$  and  $\mathbf{s} = (s_1, \dots, s_\ell) \in \mathbb{N}^{\times \ell}$  such that  $s_1 < \dots < s_\ell \leq \mathbf{s}$ , for all  $\mathbf{x} \in \Delta^k$  such that  $\min_{1 \leq j \leq k} |x^{(j)}| \geq \mathbf{s}$ ,

$$F_{\mathbf{s}}^\ell(\mathbf{x}) = \sum_{\Xi \text{ increasing}} f_{\mathbf{s}, \Xi}^\ell(\mathbf{x}).$$

By  $\Xi$  increasing, we mean here that  $\Xi = (\Xi_i)_{0 \leq i \leq \ell}$  is an increasing collection of partitions of  $\{1, \dots, k\}$ . Since  $f_{\mathbf{s}, \Xi}^\ell$  satisfies the hereditary assumption 5, the same goes for  $F_{\mathbf{s}}^\ell$  by taking  $\mathbf{g} = \mathbf{s}$ . Using the linearity of  $g \mapsto \mathcal{A}_\infty^k(g)$ , we get (19) thanks to Theorem 1.6.

First note that

$$\{\mathcal{J}^{k,n} = \ell, \mathcal{J}^k(\mathcal{Y}^{(n)}) \leq \mathbf{s}\} = \bigcup_{\mathbf{m}; m_1 < \dots < m_\ell \leq \mathbf{s}} \bigcup_{\Pi \text{ increasing}} \bigcap_{i=1}^{\ell} \{\pi_{m_i-1}^{k,n} = \pi_{i-1}, \pi_{m_i}^{k,n} = \pi_i\},$$

where  $\Pi$  increasing means here that  $\Pi = (\pi_i)_{0 \leq i \leq \ell}$  is an increasing collection of partitions of  $\{1, \dots, k\}$ . It follows that

$$\mathbb{P}^*(\mathcal{J}_1^{k,n} = s_1, \dots, \mathcal{J}_\ell^{k,n} = s_\ell, \mathcal{J}^{k,n} = \ell) = \mathbb{E}^* \left[ \frac{\mathcal{A}^k(\mathcal{D}_n, F_{\mathbf{s}}^\ell)}{\mathcal{A}^k(\mathcal{D}_n, \mathbf{1}_{\mathcal{E}_s^k})} \mathbf{1}_{\{D_n \geq k\}} \right],$$

and we conclude using Theorem 1.6.  $\square$

## 2.2. Proof of Theorem 1.6 and Theorem 1.7

*Proof of Theorem 1.6.* First,  $\mathcal{A}^k(\mathcal{D}_n, f) = \mathcal{A}^k(\mathcal{D}_n, f \mathbf{1}_{\mathcal{E}^{k,n^{1/2}}}) + \mathcal{A}^k(\mathcal{D}_n, f \mathbf{1}_{\Delta^k \setminus \mathcal{E}^{k,n^{1/2}}})$  and then for any  $\varepsilon \in (0, 1)$

$$\begin{aligned} & \mathbb{P}^* \left( \left| \frac{1}{(n^{1/2} \mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_n, f) - (c_\infty)^k \mathcal{A}_\infty^k(f) \right| > \varepsilon \right) \\ & \leq \mathbb{P}^* \left( \left| \frac{1}{(n^{1/2} \mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_n, f \mathbf{1}_{\mathcal{E}^{k,n^{1/2}}}) - (c_\infty)^k \mathcal{A}_\infty^k(f) \right| > \frac{\varepsilon}{2} \right) \\ & \quad + \mathbb{P}^* \left( \mathcal{A}^k(\mathcal{D}_n, \mathbf{1}_{\Delta^k \setminus \mathcal{E}^{k,n^{1/2}}}) > \frac{\varepsilon}{2} (n^{1/2} \mathbf{L}_n)^k \right). \end{aligned}$$

Noticing that  $\mathcal{D}_n = \mathcal{D}_{n, T_n^{1/2}}$ , the first probability in this sum goes to 0 when  $n \rightarrow \infty$  thanks to Proposition 1 with  $s = n^{1/2}$  and the second one also goes to 0 thanks to Proposition 2 thus giving (25). For the convergence in  $\mathbb{P}^*$ -probability (26), note that

$$\begin{aligned} & \mathbb{P}^* \left( \left| \frac{\mathcal{A}^k(\mathcal{D}_n, f)}{\mathcal{A}^k(\mathcal{D}_n, g)} \mathbf{1}_{\{D_n \geq k\}} - \frac{\mathcal{A}_\infty^k(f)}{\mathcal{A}_\infty^k(g)} \right| > \varepsilon \right) \\ & \leq \mathbb{P}^* \left( \left| \frac{\mathcal{A}^k(\mathcal{D}_n, f)}{\mathcal{A}^k(\mathcal{D}_n, g)} - \frac{\mathcal{A}_\infty^k(f)}{\mathcal{A}_\infty^k(g)} \right| > \varepsilon, D_n \geq k \right) + \mathbb{P}^*(D_n < k), \end{aligned}$$

these two probabilities go to 0 when  $n \rightarrow \infty$  and the proof is completed.  $\square$

We now prove Theorem 1.7. Recall that  $\tilde{\mathcal{D}}_n = \{x \in \mathcal{D}_n; \ell_n \leq |x| \leq \mathfrak{L}_n\}$ . The main idea of the proof is to show that, when  $\kappa > 2\xi k$ ,  $\xi \geq 2$ , and  $\mathfrak{L}_n = o(n^{1/2-q(\xi)})$  for some non-increasing sequence  $\mathfrak{q}$  such that  $\mathfrak{q}(j) \rightarrow 0$  when  $j \rightarrow \infty$ , the volume  $\tilde{D}_n$  of the range  $\tilde{\mathcal{D}}_n$  behaves like the volume of the range up to the last complete excursion of  $(X)_{j \leq n}$  above the parent  $e^*$  of the root  $e$ .

For that, one can notice that for this choice of  $\kappa$ , Proposition 1 holds uniformly in  $s$  (in the sense of (30)): there exists a non-increasing sequence of positive integers  $(\mathfrak{q}(j))_j$ , satisfying  $\mathfrak{q}(j) \in (0, 1/2)$  and  $\mathfrak{q}(j) \rightarrow 0$  when  $j \rightarrow \infty$  such that if  $\kappa > 2\xi k$  for some integer  $\xi \geq 2$  and  $\mathfrak{L}_n = o(n^{1/2-q(\xi)})$  then, for any  $\varepsilon_1 \in (0, 1)$

$$\mathbb{P}^* \left( \bigcup_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \left| \frac{1}{(s\mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_{n,T^s}, f \mathbf{1}_{\mathfrak{E}^k, s}) - (c_\infty)^k \mathcal{A}_\infty^k(f) \right| > \varepsilon \right) \xrightarrow{n \rightarrow \infty} 0. \quad (30)$$

The proof of (30) is the same as the proof of Proposition 1 but for any  $\varepsilon, \varepsilon_1 \in (0, 1)$ , by Markov inequality

$$\begin{aligned} & \mathbb{P} \left( \bigcup_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \left\{ \left| \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f \mathbf{1}_{\mathfrak{E}_{a_n}^k}) - \mathbb{E}^\mathfrak{E} \left[ \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f \mathbf{1}_{\mathfrak{E}_{a_n}^k}) \right] \right| > \varepsilon (s\mathbf{L}_n)^k / 16 \right\} \right) \\ & \leq \sum_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \frac{16^{2\xi k}}{\varepsilon^{2\xi k} (s\mathbf{L}_n)^{2\xi k}} \mathbb{E} \left[ \left( \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f \mathbf{1}_{\mathfrak{E}_{a_n}^k}) - \mathbb{E}^\mathfrak{E} \left[ \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f \mathbf{1}_{\mathfrak{E}_{a_n}^k}) \right] \right)^{2\xi k} \right] \\ & \leq 16^{2\xi k} \mathfrak{C}_{3.7} \sum_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \left( \frac{\mathfrak{L}_n}{s} \right)^{\tilde{\mathfrak{q}}(\xi)} \leq \mathfrak{C}_1 \frac{(\mathfrak{L}_n)^{\tilde{\mathfrak{q}}(\xi)}}{n^{(\tilde{\mathfrak{q}}(\xi)-1)/2}}, \end{aligned}$$

where we have used Lemma 3.7 with  $\mathfrak{a} = \xi$  for second inequality. Note that  $\tilde{\mathfrak{q}}(\xi) \geq 2$  since  $\xi \geq 2$  so, as in the proof of Proposition 1, we obtain (30) by taking  $\mathfrak{q}(j) := (2\tilde{\mathfrak{q}}(j))^{-1}$ .

*Proof of Theorem 1.7.* First, let us state the following fact, proved by Y. Hu ([Hu17], Corollary 1.2): in law, under  $\mathbb{P}^*$

$$\frac{1}{n^{1/2}} \sum_{j=1}^n \mathbf{1}_{\{X_k=e\}} \xrightarrow{n \rightarrow \infty} \frac{1}{p^\mathfrak{E}(e, e^*)} \frac{c_0^{1/2}}{W_\infty} |_{\mathcal{N}}.$$

We can actually adapt this result to the local time  $\mathcal{L}^n$  of the parent  $e^*$  of the root  $e$ : in law, under  $\mathbb{P}^*$

$$\frac{1}{n^{1/2}} \mathcal{L}^n \xrightarrow{n \rightarrow \infty} \frac{c_0^{1/2}}{W_\infty} |_{\mathcal{N}}, \quad (31)$$

where  $c_0$  is defined in (27). Moreover, recall that  $\mathcal{N}$  denotes a standard Gaussian variable. Then, we show that  $\mathcal{A}^k(\mathcal{D}_{n,T^{\mathcal{L}^n}}, f)$  and  $\mathcal{A}^k(\tilde{\mathcal{D}}_n, f)$  are close in the following:

$$\mathbb{P}^* \left( \frac{1}{(\mathfrak{L}_n \mathbf{L}_n)^k} \left| \mathcal{A}^k(\mathcal{D}_{n,T^{\mathcal{L}^n}}, f) - \mathcal{A}^k(\tilde{\mathcal{D}}_n, f) \right| > \varepsilon \right) \xrightarrow{n \rightarrow \infty} 0. \quad (32)$$

For that, introduce  $T_z := \inf\{i \geq 1 \mid X_i = z\}$ , the hitting time of the vertex  $z \in \mathbb{T}$  and for any  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ ,  $T_{\mathbf{x}} := \max_{1 \leq i \leq k} T_{x^{(i)}}$ . Assume  $\mathcal{L}^n = s \in \{\varepsilon_1 n^{1/2}, \dots, n^{1/2}/\varepsilon_1\}$ . By definition,  $\mathcal{L}^n = \sup\{j \geq 1; T^j \leq n\}$  so on the set  $\{D_{n,T^s} \geq k\}$ , where  $D_{n,T^s}$  is the cardinal of

$\mathcal{D}_{n,T^s}$ , both  $\mathcal{D}_{n,T^s}$  and  $\tilde{\mathcal{D}}_n$  are nonempty and note that

$$\begin{aligned} \mathcal{A}^k(\tilde{\mathcal{D}}_n, f) - \mathcal{A}^k(\mathcal{D}_{n,T^s}, f) &= \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}} \sum_{\mathbf{x} \in \Delta^k} f(\mathbf{x}) \mathbb{1}_{\{|\mathbf{x}|=\mathbf{p}, T^s < T_{\mathbf{x}} \leq n\}} \\ &\leq \|f\|_{\infty} \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}} \sum_{\mathbf{x} \in \Delta^k} \mathbb{1}_{\{|\mathbf{x}|=\mathbf{p}, T^s < T_{\mathbf{x}} < T^{s+1}\}}, \end{aligned}$$

where  $\|f\|_{\infty} := \sup_{\mathbf{z} \in \Delta^k} f(\mathbf{z})$  and  $|\mathbf{x}| = |\mathbf{p}|$  means that for all  $1 \leq i \leq k$ ,  $x^{(i)} = p_i$ . We now aim to provide an upper bound to  $\mathbb{E}[(\sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}} \sum_{\mathbf{x} \in \Delta^k} \mathbb{1}_{\{|\mathbf{x}|=\mathbf{p}, T^s < T_{\mathbf{x}} < T^{s+1}\}})^2]$ . We have

$$\begin{aligned} &\mathbb{E}^{\mathcal{E}} \left[ \left( \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}} \sum_{\mathbf{x} \in \Delta^k} \mathbb{1}_{\{|\mathbf{x}|=\mathbf{p}, T^s < T_{\mathbf{x}} < T^{s+1}\}} \right)^2 \right] \\ &= \sum_{\substack{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k} \\ \mathbf{p}' \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}}} \sum_{\mathbf{x} \in \Delta^k} \mathbb{1}_{\{|\mathbf{x}|=\mathbf{p}, |\mathbf{y}|=\mathbf{p}'\}} \mathbb{P}^{\mathcal{E}}(T^s < T_{\mathbf{x}} < T^{s+1}, T^s < T_{\mathbf{y}} < T^{s+1}). \end{aligned}$$

Without loss of generality, we only deal with the case  $x^{(i)} \neq y^{(i)}$  for all  $i \in \{1, \dots, k\}$ , that is the case such that the concatenation  $\mathbf{x}\mathbf{y}$  of  $\mathbf{x}$  and  $\mathbf{y}$  belongs to  $\Delta^{2k}$ . One can see that for any  $k$ -tuple  $\mathbf{u} = (u^{(1)}, \dots, u^{(k)}) \in \Delta^k$  such that  $T^s < T_{\mathbf{u}} < T^{s+1}$ , we have, for any  $i \in \{1, \dots, k\}$ , that either  $u^{(i)}$  is visited during that  $s$ -th excursion or  $T_{u^{(i)}} < T^s$  (at least one vertex among  $(u^{(1)}, \dots, u^{(k)})$  must be visited during the  $s$ -th excursion). Hence  $\sum_{\mathbf{x}, \mathbf{y} \in \Delta^k, \mathbf{x}\mathbf{y} \in \Delta^{2k}, |\mathbf{x}|=\mathbf{p}, |\mathbf{y}|=\mathbf{p}'} \mathbb{P}^{\mathcal{E}}(T^s < T_{\mathbf{x}} < T^{s+1}, T^s < T_{\mathbf{y}} < T^{s+1})$  is equal to

$$\begin{aligned} &\sum_{\substack{I \subset \{1, \dots, k\} \\ |I| \leq k-1}} \sum_{\substack{J \subset \{1, \dots, k\} \\ |J| \leq k-1}} \sum_{\substack{\mathbf{x}, \mathbf{y} \in \Delta^k, \mathbf{x}\mathbf{y} \in \Delta^{2k} \\ |\mathbf{x}|=\mathbf{p}, |\mathbf{y}|=\mathbf{p}'}} \\ &\times \mathbb{P}^{\mathcal{E}} \left( \max_{i \in I, j \in J} T_{x^{(i)}} \vee T_{y^{(j)}} < T^s, T^s < T_{x^{(i')}} < T^{s+1}, T^s < T_{y^{(j')}} < T^{s+1} \forall i' \notin I, \forall j' \notin J \right) \end{aligned}$$

where  $t \vee s = \max(t, s)$  and  $i' \notin I$  (resp.  $j' \notin J$ ) means  $i' \in \{1, \dots, k\} \setminus I$  (resp.  $j' \in \{1, \dots, k\} \setminus J$ ), with  $I$  and  $J$  possibly empty. Thanks to the strong Markov property at time  $T^s$ , the latter probability is smaller than

$$\mathbb{P}^{\mathcal{E}} \left( \max_{i \in I, j \in J} T_{x^{(i)}} \vee T_{y^{(j)}} < T^s \right) \prod_{i' \notin I} \mathbb{P}^{\mathcal{E}}(T_{x^{(i')}} < T^1) \prod_{j' \notin J} \mathbb{P}^{\mathcal{E}}(T_{y^{(j')}} < T^1).$$

By Lemma 3.5, we can restrict to vertices visited during a single excursion before  $T^s$ . Moreover, for any  $i \in I$  and  $j \in J$ ,  $x^{(i)}$  and  $y^{(j)}$  are possibly visited during the same excursion. Hence

$$\begin{aligned} \mathbb{P}^{\mathcal{E}} \left( \max_{i \in I, j \in J} T_{x^{(i)}} \vee T_{y^{(j)}} < T^s, \mathbf{x}, \mathbf{y} \in \mathfrak{S}^{k,s} \right) &\leq \sum_{e_1, \dots, e_{|I|}=1}^s \sum_{e'_1, \dots, e'_{|J|}=1}^s \\ &\times \mathbb{P}^{\mathcal{E}} \left( T^{e_i-1} < T_{x^{(i)}} < T^{e_i}, T^{e'_j-1} < T_{y^{(j)}} < T^{e'_j} \forall i \in I, j \in J \right). \end{aligned}$$

where  $|I|$  (resp.  $|J|$ ) denotes the cardinal of  $I$  (resp.  $J$ ), we use the convention  $\sum_{\emptyset} = 0$  and see (37) for the definition of  $\mathfrak{S}^{k,s}$ . Note that, if two distinct vertices  $u$  and  $v$  among  $((x^{(i)})_{i \in I}, (y^{(j)})_{j \in J})$  are visited during the same excursion, then we can assume that  $|u \wedge v| < a_n$  (see for example the proof of Lemma 3.9). Hence, thanks to Lemma 3.2 and the fact that  $\mathfrak{L}_n \leq s$  for  $n$  large enough,

we have that

$$\mathbf{E} \left[ \sum_{\substack{\mathbf{x}, \mathbf{y} \in \Delta^k, \mathbf{x}\mathbf{y} \in \Delta^{2k} \\ |\mathbf{x}|=p, |\mathbf{y}|=p'}} \times \mathbb{P}^\varepsilon \left( \max_{i \in I, j \in J} T_{x^{(i)}} \vee T_{y^{(j)}} < T^s, T^s < T_{x^{(i')}} < T^{s+1}, T^s < T_{y^{(j')}} < T^{s+1} \forall i' \notin I, \forall j' \notin J \right) \right]$$

is smaller than  $\mathfrak{C}_{1.7}(a_n)^{2k} s^{|I|+|J|}$  for some constant  $\mathfrak{C}_{1.7}$  only depending on  $k$ . Since  $|I|$  and  $|J|$  are smaller than  $k-1$ , we finally obtain for  $n$  large enough and any  $s \in \{\varepsilon_1 n^{1/2}, \dots, n^{1/2}/\varepsilon_1\}$

$$\mathbb{E}^\varepsilon \left[ \left( \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\} \times k} \sum_{\mathbf{x} \in \Delta^k} \mathbb{1}_{\{|\mathbf{x}|=p, T^s < T_{\mathbf{x}} < T^{s+1}\}} \right)^2 \right] \leq \mathfrak{C}_{1.7,1} (\mathbf{L}_n a_n)^{2k} s^{2k-2},$$

for some constant  $\mathfrak{C}_{1.7,1} > 0$ , thus giving, thanks to Markov inequality

$$\mathbb{P}^* \left( \frac{1}{(s\mathbf{L}_n)^k} |\mathcal{A}^k(\tilde{\mathcal{D}}_n, f) - \mathcal{A}^k(\mathcal{D}_{n,T^s}, f)| > \varepsilon, D_{n,T^s} \geq k, \mathcal{L}^n = s \right) \leq \|f\|_\infty^2 \mathfrak{C}_{1.7,1} (a_n)^{2k} s^{-2} \varepsilon^{-2}.$$

Hence, for all  $\varepsilon_1 \in (0, 1)$  and  $n$  large enough,  $\mathbb{P}^* \left( \left\{ \frac{1}{(s\mathbf{L}_n)^k} |\mathcal{A}^k(\tilde{\mathcal{D}}_n, f) - \mathcal{A}^k(\mathcal{D}_{n,T^{s^n}}, f)| > \varepsilon \right\} \right)$  is smaller than

$$\begin{aligned} & \mathbb{P}^*(D_{n,T^{s^n}} < k) + \mathbb{P}^*(\mathcal{L}^n < \varepsilon_1 n^{1/2}) + \mathbb{P}^*(\mathcal{L}^n > n^{1/2}/\varepsilon_1) \\ & + \sum_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \mathbb{P}^* \left( \frac{1}{(s\mathbf{L}_n)^k} |\mathcal{A}^k(\tilde{\mathcal{D}}_n, f) - \mathcal{A}^k(\mathcal{D}_{n,T^s}, f)| > \varepsilon, D_{n,T^s} \geq k, \mathcal{L}^n = s \right) \\ & \leq \mathbb{P}^*(D_{n,T^{s^n}} < k) + \mathbb{P}^*(\mathcal{L}^n < \varepsilon_1 n^{1/2}) + \mathbb{P}^*(\mathcal{L}^n > n^{1/2}/\varepsilon_1) + \|f\|_\infty^2 \mathfrak{C}_{1.7,1} \sum_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \frac{(a_n)^{2k}}{s^2 \varepsilon^2}. \end{aligned}$$

$\|f\|_\infty^2 \mathfrak{C}_{1.7,1} \sum_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \frac{(a_n)^{2k}}{s^2 \varepsilon^2}$  is smaller than  $\mathfrak{C}_{1.7,2} (a_n)^{2k} / n^{1/2}$  for some constant  $\mathfrak{C}_{1.7,2} > 0$ . Note that  $\lim_{n \rightarrow \infty} \mathbb{P}^*(D_{n,T^{s^n}} < k) = 0$  and using (31) with the definition of  $a_n = (2\delta_0)^{-1} \log n$ , we have  $\lim_{\varepsilon_1 \rightarrow 0} \limsup_{n \rightarrow \infty} ((a_n)^{2k} / n^{1/2} + \mathbb{P}^*(\mathcal{L}^n < \varepsilon_1 n^{1/2}) + \mathbb{P}^*(\mathcal{L}^n > n^{1/2}/\varepsilon_1)) = 0$ , which yields (32).

Now, since  $\mathcal{A}^k(\mathcal{D}_{n,T^{s^n}}, f \mathbb{1}_{\Delta^k \setminus \mathfrak{E}^k, \mathcal{L}^n}) / (\mathcal{L}^n \mathbf{L}_n)^k \rightarrow 0$  when  $n \rightarrow \infty$ , in  $\mathbb{P}^*$ -probability and thanks to (32), we can focus our attention on  $\mathcal{A}^k(\mathcal{D}_{n,T^{s^n}}, f \mathbb{1}_{\mathfrak{E}^k, \mathcal{L}^n}) / (\mathcal{L}^n \mathbf{L}_n)^k$ .

Note the  $\mathcal{A}^k(\mathcal{D}_{n,T^{s^n}}, f \mathbb{1}_{\mathfrak{E}^k, \mathcal{L}^n})$  concentrates around  $(c_\infty)^k \mathcal{A}_\infty^k(f)$ . Indeed, for any  $\varepsilon, \varepsilon_1 \in (0, 1)$

$$\begin{aligned} & \mathbb{P}^* \left( \left| \frac{1}{(\mathcal{L}^n \mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_{n,T^{s^n}}, f \mathbb{1}_{\mathfrak{E}^k, \mathcal{L}^n}) - (c_\infty)^k \mathcal{A}_\infty^k(f) \right| > \varepsilon \right) \\ & \leq \mathbb{P}^* \left( \bigcup_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \left\{ \left| \frac{1}{(s\mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_{n,T^s}, f \mathbb{1}_{\mathfrak{E}^k, s}) - (c_\infty)^k \mathcal{A}_\infty^k(f) \right| > \varepsilon \right\} \right) + \mathbb{P}^*(\mathcal{L}^n < \varepsilon_1 n^{1/2}) \\ & + \mathbb{P}^*(\mathcal{L}^n > n^{1/2}/\varepsilon_1). \end{aligned}$$

Thanks to equation (30), the first probability above goes to 0 when  $n$  goes to  $\infty$  and by (31),  $\lim_{\varepsilon_1 \rightarrow 0} \lim_{n \rightarrow \infty} (\mathbb{P}^*(\mathcal{L}^n < \varepsilon_1 n^{1/2}) + \mathbb{P}^*(\mathcal{L}^n > n^{1/2}/\varepsilon_1)) = 0$  thus giving

$$\lim_{n \rightarrow \infty} \mathbb{P}^* \left( \left| \frac{1}{(\mathcal{L}^n \mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_{n,T^{s^n}}, f \mathbb{1}_{\mathfrak{E}^k, \mathcal{L}^n}) - (c_\infty)^k \mathcal{A}_\infty^k(f) \right| > \varepsilon \right) = 0. \quad (33)$$



We obtain from (33), together with (32) that

$$\lim_{n \rightarrow \infty} \mathbb{P}^* \left( \left| \frac{1}{(\mathcal{L}^n \mathbf{L}_n)^k} \mathcal{A}^k(\tilde{\mathcal{D}}_n, f) - (c_\infty)^k \mathcal{A}_\infty^k(f) \right| > \varepsilon \right) = 0,$$

which gives (27) by using (31). For the convergence in  $\mathbb{P}^*$ -probability (28), note that

$$\begin{aligned} & \mathbb{P}^* \left( \left| \frac{\mathcal{A}^k(\tilde{\mathcal{D}}_n, f)}{\mathcal{A}^k(\tilde{\mathcal{D}}_n, g)} \mathbb{1}_{\{D_n \geq k\}} - \frac{\mathcal{A}_\infty^k(f)}{\mathcal{A}_\infty^k(g)} \right| > \varepsilon \right) \\ & \leq \mathbb{P}^* \left( \left| \frac{\mathcal{A}^k(\tilde{\mathcal{D}}_n, f)}{\mathcal{A}^k(\tilde{\mathcal{D}}_n, g)} - \frac{\mathcal{A}_\infty^k(f)}{\mathcal{A}_\infty^k(g)} \right| > \varepsilon, D_n \geq k \right) + \mathbb{P}^*(D_n < k), \end{aligned}$$

which goes to 0 when  $n$  goes to  $\infty$  and the proof is completed.  $\square$

### 3. Proofs of Propositions 1 and 2

This section is devoted to the proofs of our two propositions. We show that relevant  $k$ -tuples of visited vertices are those in the set  $\mathfrak{C}^{k, \cdot}$ .

Let us recall the well-known many-to-one lemma:

**Lemma 3.1** (many-to-one). *For any  $p \in \mathbb{N}^*$  and any bounded function  $\mathbf{h} : \mathbb{R}^k \rightarrow \mathbb{R}$*

$$\mathbf{E}[\mathbf{h}(S_1, \dots, S_p)] = \mathbf{E} \left[ \sum_{|x|=p} e^{-V(x)} \mathbf{h}(V(x_1), \dots, V(x_p)) \right],$$

where  $(S_i)_{i \in \mathbb{N}}$  is the real valued random walk defined in (10).

We now state and prove a lemma that will be useful all along this section. For any vertex  $z \in \mathbb{T}$ , recall that  $T_z = \inf\{i \geq 1 : X_i = z\}$ , the hitting time of  $z$  and for any  $\mathbf{x} = (x^{(1)}, \dots, x^{(q)}) \in \Delta^q$ ,  $T_{\mathbf{x}} = \max_{1 \leq i \leq q} T_{x^{(i)}}$ . Recall that for any  $j \in \mathbb{N}^*$ ,  $T^j$  denotes the  $j$ -th return time to the parent  $e^*$  of the root  $e$ . For  $1 \leq \ell < q$  two integers,  $\mathbf{m} = (m_1, \dots, m_\ell) \in \mathbb{N}^{\times \ell}$  such that  $m_1 < \dots < m_\ell$  and  $\Pi = (\boldsymbol{\pi})_{0 \leq i \leq \ell}$  an increasing collection of partitions of  $\{1, \dots, q\}$  that is to say  $|\boldsymbol{\pi}_{i-1}| < |\boldsymbol{\pi}_i|$  with  $\boldsymbol{\pi}_0 = \{\{1, \dots, q\}\}$  and  $\boldsymbol{\pi}_\ell = \{\{1\}, \dots, \{q\}\}$ , recall the definition of  $f_{\mathbf{m}, \Pi}^\ell$  in (15).

**Lemma 3.2.** *Let  $k \geq 2$  and  $\mathbf{a} \geq 1$  be two integers and assume  $\kappa > 2\mathbf{a}k$ . Let  $q \in \{k, \dots, 2\mathbf{a}k\}$  and  $\mathbf{p} = (p_1, \dots, p_q) \in \mathbb{N}^{\times q}$ . Under the assumptions 1 and 3, there exists a constant  $\mathfrak{C} > 0$  doesn't depending neither on  $\mathbf{p}$ , nor on  $\mathbf{m}$  such that*

$$\mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} f_{\mathbf{m}, \Pi}^\ell(\mathbf{x}) \mathbb{P}^\mathfrak{E}(T_{\mathbf{x}} < T^1) \right] \leq \mathfrak{C},$$

where  $|\mathbf{x}| = \mathbf{p}$  means that  $|x^{(i)}| = p_i$  for any  $i \in \{1, \dots, q\}$ . In particular, for any integer  $m \in \mathbb{N}^*$ ,  $q' \leq q$  and any distinct  $i_1, \dots, i_{q'} \in \{1, \dots, k\}$ , there exists a constant  $C_{3.2} > 0$  doesn't depending on  $\mathbf{p}$  such that

$$\mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\mathcal{C}_m^{q'}}(\mathbf{x}_{q'}) \mathbb{1}_{\mathcal{C}_m^{q-q'}}(\bar{\mathbf{x}}_{q'}) \mathbb{P}^\mathfrak{E}(T_{\mathbf{x}} < T^1) \right] \leq C_{3.2} \left( \max_{1 \leq i \leq q} p_i \right)^{q' \wedge (q-q')} m^{q' \vee (q-q') - 1}, \quad (34)$$

where  $\mathbf{x}_{q'} := (x^{(i_1)}, \dots, x^{(i_{q'})})$  and  $\bar{\mathbf{x}}_{q'} := (x^{(i)})_{i \in \{1, \dots, k\} \setminus \{i_1, \dots, i_{q'}\}}$ .

*Proof in the case  $\cap_{j=1}^{\ell} \Gamma_{\mathbf{m}, \Pi}^j \subset \{\mathbf{x} \in \Delta^q; \mathcal{C}^q(\mathbf{x}) < \min_{1 \leq i \leq q} p_i\}$ .* First recall that  $\Pi^i$  is the partition of  $\{1, \dots, |\pi_i|\}$  obtained via the procedure defined above Example 5 and for any  $i \in \{1, \dots, \ell\}$ , any  $j \in \{1, \dots, |\pi_{i-1}|\}$ , the  $j$ -th block  $\mathbf{B}_j^i$  of the partition  $\pi_{i-1}$  is the union of  $b_{i-1}(\mathbf{B}_j) \geq 1$  block(s) of the partition  $\pi_i$ . Note (see the proof of Theorem 1.4) that

$$\begin{aligned} \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} f_{\mathbf{m}, \Pi}^{\ell}(\mathbf{x}) \mathbb{P}^{\mathcal{E}}(T_{\mathbf{x}} < T^1) &= \sum_{\mathbf{z} \in \Delta_{m_{\ell-1}}^{|\pi_{\ell-1}|}} f_{\mathbf{m}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}(\mathbf{z}) \prod_{j=1}^{|\pi_{\ell-1}|} \sum_{\mathbf{u}^{(j)} \in \Delta_{m_{\ell}}^{b_{\ell-1}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-1}(\mathbf{B}_j)} \mathbf{1}_{\{(u^{(j,i)})^* = z^{(j)}\}} \\ &\quad \times \sum_{\mathbf{x} \in \Delta^q} \mathbf{1}_{\{|\mathbf{x}| = \mathbf{p}, \mathbf{x} \geq \mathbf{u}\}} \mathbb{P}^{\mathcal{E}}(T_{\mathbf{x}} < T^1), \end{aligned}$$

where  $\mathbf{m}^{\ell-1} = (m_1, \dots, m_{\ell-1})$ ,  $\mathbf{u}$  is the concatenation of  $\mathbf{u}^{(1)}, \dots, \mathbf{u}^{(|\pi_{\ell-1}|)}$  and  $\mathbf{x} \geq \mathbf{u}$  means that  $x^{(p)} \geq u^{(p)}$ . Thanks to the strong Markov property at time  $T_{z^{(i)}}$ , there exists a constant  $C_q \geq 1$  such that

$$\begin{aligned} \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} f_{\mathbf{m}, \Pi}^{\ell}(\mathbf{x}) \mathbb{P}^{\mathcal{E}}(T_{\mathbf{x}} < T^1) &\leq C_q \sum_{\mathbf{z} \in \Delta_{m_{\ell-1}}^{|\pi_{\ell-1}|}} f_{\mathbf{m}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}(\mathbf{z}) \mathbb{P}^{\mathcal{E}}(T_{\mathbf{z}} < T^1) \prod_{j=1}^{|\pi_{\ell-1}|} \sum_{\mathbf{u}^{(j)} \in \Delta_{m_{\ell}}^{b_{\ell-1}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-1}(\mathbf{B}_j)} \\ &\quad \times \mathbf{1}_{\{(u^{(j,i)})^* = z^{(j)}\}} \sum_{\substack{\mathbf{x}^{(j)} \in \Delta_{m_{\ell}}^{b_{\ell-1}(\mathbf{B}_j)} \\ |\mathbf{x}^{(j)}| = \mathbf{p}^{(j)}}} \mathbf{1}_{\{x^{(j,i)} \geq u^{(j,i)}\}} \mathbb{P}_{z^{(j)}}^{\mathcal{E}}(T_{x^{(j,i)}} < T^1), \end{aligned}$$

where  $\mathbf{p}$  is now seen as the concatenation of  $\mathbf{p}^{(1)}, \dots, \mathbf{p}^{(|\pi_{\ell-1}|)}$ . Moreover, it is known that for all  $z \leq x$  in  $\mathbb{T}$ ,

$$\mathbb{P}_z^{\mathcal{E}}(T_x < T^1) = \frac{\sum_{e \leq w \leq z} e^{V(w)}}{\sum_{e \leq w \leq x} e^{V(w)}} \quad \text{if } z \neq e, \quad \mathbb{P}_z^{\mathcal{E}}(T_x < T^1) = \frac{1}{\sum_{e \leq w \leq x} e^{V(w)}} \quad \text{otherwise,} \quad (35)$$

so  $\mathbb{P}_z^{\mathcal{E}}(T_x < T^1) \leq e^{-V(x)} \sum_{e \leq w \leq z} e^{V(w)}$ . By independence of the increments of the branching random walk  $(\mathbb{T}, (V(x), x \in \mathbb{T}))$ , using that  $b_{\ell-1}(\mathbf{B}_j) = |\mathbf{B}_j^{\ell-1}|$  and  $\psi(1) = 0$

$$\begin{aligned} \mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} f_{\mathbf{m}, \Pi}^{\ell}(\mathbf{x}) \mathbb{P}^{\mathcal{E}}(T_{\mathbf{x}} < T^1) \right] &\leq \mathfrak{C}_{\ell-1} \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{m_{\ell-1}}^{|\pi_{\ell-1}|}} f_{\mathbf{m}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}(\mathbf{z}) \mathbb{P}^{\mathcal{E}}(T_{\mathbf{z}} < T^1) \prod_{j=1}^{|\pi_{\ell-1}|} (H_{z^{(j)}})^{|\mathbf{B}_j^{\ell-1}|} \right] \\ &\quad \times C_q \prod_{\mathbf{B} \in \pi_{\ell-1}} c_{|\mathbf{B}|}(\mathbf{1}), \end{aligned}$$

with  $H_z = \sum_{e \leq w \leq z} e^{V(w) - V(z)}$  and  $\mathfrak{C}_{\ell-1} = C_q \prod_{\mathbf{B} \in \pi_{\ell-1}} c_{|\mathbf{B}|}(\mathbf{1}) \in (0, \infty)$  thanks to assumption 3 since for any  $\mathbf{B} \in \pi_{\ell-1}$ ,  $|\mathbf{B}| < q \leq 4k < \kappa$ . Again, thanks to the strong Markov property at time

$T_{w^{(i)}}$

$$\begin{aligned}
 & \sum_{\mathbf{z} \in \Delta_{m_{\ell-1}}^{|\pi_{\ell-1}|}} f_{\mathbf{m}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}(\mathbf{z}) \mathbb{P}^{\mathcal{E}}(T_{\mathbf{z}} < T^1) \prod_{j=1}^{|\pi_{\ell-1}|} (H_{z^{(j)}})^{|\mathbf{B}_j^{\ell-1}|} \\
 & \leq C_{\ell-1} \sum_{\mathbf{w} \in \Delta_{m_{\ell-1}-1}^{|\pi_{\ell-2}|}} f_{\mathbf{m}^{\ell-2}, \Pi^{\ell-2}}^{\ell-2}(\mathbf{w}) \mathbb{P}^{\mathcal{E}}(T_{\mathbf{w}} < T^1) \prod_{j=1}^{|\pi_{\ell-2}|} \sum_{\mathbf{v}^{(j)} \in \Delta_{m_{\ell-1}}^{b_{\ell-2}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} \mathbb{1}_{\{(v^{(j,i)})^* = w^{(j)}\}} \\
 & \times \sum_{\mathbf{z}^{(j)} \in \Delta_{s_{\ell-1}}^{|\pi_{\ell-1}|}} \mathbb{1}_{\{z^{(j,i)} \geq v^{(j,i)}\}} (H_{z^{(j,i)}})^{\beta_{j,i}^{\ell-2}} \mathbb{P}_{w^{(j)}}^{\mathcal{E}}(T_{z^{(j,i)}} < T^1),
 \end{aligned}$$

for some constant  $C_{\ell-1} \geq 1$ , where  $\mathbf{v}^{(j)} = (v^{(j,1)}, \dots, v^{(j, b_{\ell-2}(\mathbf{B}_j))})$  and recall the definition of  $\beta_{j,i}^{\ell-2}$  in (14). Thanks to (35)

$$(H_{z^{(j,i)}})^{\beta_{j,i}^{\ell-2}} \mathbb{P}_{w^{(j)}}^{\mathcal{E}}(T_{z^{(j,i)}} < T^1) \leq H_{w^{(j)}} e^{-V_{w^{(j)}}(z^{(j,i)})} (H_{z^{(j,i)}})^{\beta_{j,i}^{\ell-2}-1},$$

and  $H_{z^{(j,i)}} = H_{v^{(j,i)}} e^{-V_{v^{(j,i)}}(z^{(j,i)})} + \tilde{H}_{v^{(j,i)}, z^{(j,i)}}$  where, for any  $u < x$ ,  $\tilde{H}_{u,x} := \sum_{u < w \leq x} e^{V(w)-V(x)}$ . Since  $H_u \geq 1$  for all  $u \in \mathbb{T}$ , we have

$$H_{z^{(j,i)}} \leq H_{w^{(j)}} (e^{-V_{w^{(j)}}(v^{(j,i)})} + 1) (e^{-V_{v^{(j,i)}}(z^{(j,i)})} + \tilde{H}_{v^{(j,i)}, z^{(j,i)}}),$$

thus giving that  $(H_{z^{(j,i)}})^{\beta_{j,i}^{\ell-2}} \mathbb{P}_{w^{(j)}}^{\mathcal{E}}(T_{z^{(j,i)}} < T^1)$  is smaller than

$$\begin{aligned}
 & (H_{w^{(j)}})^{\beta_{j,i}^{\ell-2}} e^{-V_{w^{(j)}}(v^{(j,i)})} (e^{-V_{v^{(j,i)}}(v^{(j,i)})} + 1)^{\beta_{j,i}^{\ell-2}-1} e^{-V_{v^{(j,i)}}(z^{(j,i)})} \\
 & \times (e^{-V_{v^{(j,i)}}(z^{(j,i)})} + \tilde{H}_{v^{(j,i)}, z^{(j,i)}})^{\beta_{j,i}^{\ell-2}-1}.
 \end{aligned}$$

By independence of the increments of the branching random walk  $(\mathbb{T}, (V(x), x \in \mathbb{T}))$ , using that  $\sum_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} \beta_{j,i}^{\ell-2} = |\mathbf{B}_j^{\ell-2}|$

$$\begin{aligned}
 & \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{m_{\ell-1}}^{|\pi_{\ell-1}|}} f_{\mathbf{m}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}(\mathbf{z}) \mathbb{P}^{\mathcal{E}}(T_{\mathbf{z}} < T^1) \prod_{j=1}^{|\pi_{\ell-1}|} (H_{z^{(j)}})^{|\mathbf{B}_j^{\ell-1}|} \right] \\
 & \leq \mathfrak{C}_{\ell-2} \mathbf{E} \left[ \sum_{\mathbf{w} \in \Delta_{m_{\ell-1}-1}^{|\pi_{\ell-2}|}} f_{\mathbf{m}^{\ell-2}, \Pi^{\ell-2}}^{\ell-2}(\mathbf{w}) \mathbb{P}^{\mathcal{E}}(T_{\mathbf{w}} < T^1) \prod_{j=1}^{|\pi_{\ell-2}|} (H_{w^{(j)}})^{|\mathbf{B}_j^{\ell-2}|} \right],
 \end{aligned}$$

where, thanks to the many-to-one Lemma 3.1

$$\mathfrak{C}_{\ell-2} = \prod_{j=1}^{|\pi_{\ell-2}|} \mathbf{E} \left[ \sum_{\mathbf{v} \in \Delta_{\mathbf{1}}^{b_{\ell-2}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} e^{-V(v^{(i)})} (e^{-V(v^{(i)})} + 1)^{\beta_{j,i}^{\ell-2}} \right] \prod_{\mathbf{B} \in \pi_{\ell-1}} \mathbf{E}[(e^{-S_{m_{\ell}^*}} + H_{m_{\ell}^*}^S)^{|\mathbf{B}|-1}],$$

$m_{\ell}^* = m_{\ell} - m_{\ell-1} - 1$ ,  $H_m^S := \sum_{p=0}^m e^{S_p - S_m}$  (the random walk  $(S_p)$  is defined in (10)). Note that  $\mathfrak{C}_{\ell-2} \in (0, \infty)$ . Indeed, the first mean in the definition of  $\mathfrak{C}_{\ell-2}$  belongs to  $(0, \infty)$  thanks to assumption 3 since for any  $1 \leq j \leq |\pi_{\ell-2}|$ ,  $b_{\ell-2}(\mathbf{B}_j) < q \leq 2ak < \kappa$  and  $\sum_{i=1}^{b_{\ell-2}(\mathbf{B}_j)} \beta_{j,i}^{\ell-2} = |\mathbf{B}_j^{\ell-2}| < q$ . The second one also belongs to  $(0, \infty)$  since for all  $\mathbf{B} \in \pi_{\ell-1}$ ,  $|\mathbf{B}| - 1 \leq q - 2 < \kappa - 2$

and as it is proved in [AD20] that  $\sup_{m \in \mathbb{N}^*} \mathbf{E}[(H_m^S)^{\kappa-1-\varepsilon}] < \infty$  for any  $\varepsilon > 0$ . We also deduce from this, together with the fact that  $\psi'(1) < 0$  and  $m_\ell^* \geq 0$  that  $\mathfrak{C}_{\ell-2}$  is bounded by a positive constant doesn't depending on  $\mathbf{m}$ . By induction, there exists a constant  $\mathfrak{C}_2 \in (0, \infty)$  (still not depending on  $\mathbf{m}$ ) such that

$$\mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}|=p}} f_{\mathbf{m}, \Pi}^\ell(\mathbf{x}) \mathbb{P}^\mathcal{E}(T_{\mathbf{x}} < T^1) \right] \leq \mathfrak{C}_2 \mathbf{E} \left[ \sum_{|z|=m_1-1} \sum_{\mathbf{u} \in \Delta_{m_2-1}^{|\pi_1|}} \mathbb{P}^\mathcal{E}(T_{\mathbf{u}} < T^1) \prod_{i=1}^{|\pi_1|} (H_{u^{(i)}})^{|\mathcal{B}_i^1|} \mathbb{1}_{\{u^{(i)} > z\}} \right].$$

Thanks to the strong Markov property,  $\mathbb{P}^\mathcal{E}(T_{\mathbf{u}} < T^1) \leq C_{|\pi_1|} \mathbb{P}^\mathcal{E}(T_z < T^1) \prod_{i=1}^{|\pi_1|} \mathbb{P}_z^\mathcal{E}(T_{u^{(i)}} < T^1) = C_{|\pi_1|} e^{-V(z)} (H_z)^{|\pi_1|-1} \prod_{i=1}^{|\pi_1|} e^{-V_z(u^{(i)})} / H_{u^{(i)}}$  for some constant  $C_{|\pi_1|} \geq 1$  and the last equality comes from (35). Then, using the many-to-one Lemma 3.1

$$\mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}|=p}} f_{\mathbf{m}, \Pi}^\ell(\mathbf{x}) \mathbb{P}^\mathcal{E}(T_{\mathbf{x}} < T^1) \right] \leq \mathfrak{C}_1 \mathbf{E} \left[ \sum_{|z|=m_1-1} e^{-V(z)} (H_z)^{|\pi_1|-1} \right] = \mathfrak{C}_1 \mathbf{E}[(H_{m_1-1}^S)^{|\pi_1|-1}].$$

Again,  $|\pi_1|-1 \leq q-1 \leq 2ak-1 < \kappa-1$  so  $\mathbf{E}[(H_{m_1-1}^S)^{|\pi_1|-1}] \leq \sup_{m \in \mathbb{N}^*} \mathbf{E}[(H_{m-1}^S)^{|\pi_1|-1}] \in (0, \infty)$  which ends the proof.  $\square$

### 3.1. The range on $\mathfrak{E}^{k,\cdot}$

This section is dedicated to the proof of Proposition 1 in which the range is restricted to the  $k$ -tuples of vertices belonging to the set  $\mathfrak{E}^{k,\cdot}$ , that is such that the vertices are visited during  $k$  distinct excursions, see (22) for the definition of  $\mathfrak{E}^{k,\cdot}$ .

#### 3.1.1. The relevant vertices: the set $\mathcal{C}_{a_n}^k$

First recall that  $\mathcal{C}_m^k = \{\mathbf{x} \in \Delta^k; \mathcal{S}^k(\mathbf{x}) \leq m\}$  where, for any  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$  and  $\mathcal{S}^k(\mathbf{x})-1$  is the last generation at which two or more vertices among  $x^{(1)}, \dots, x^{(k)}$  share a common ancestor (see (11)). In this subsection, we focus on the range on  $\mathfrak{E}^{k,\cdot} \cap \mathcal{C}_{a_n}^k$  with  $a_n = (2\delta_0)^{-1} \log n$ , which is the set of relevant  $k$ -tuples of vertices in the case of small generations. Before going any further, let us state and prove the following lemma. Recall that  $H_u = \sum_{e \leq z \leq u} e^{V(z)-V(u)}$ .

**Lemma 3.3.** *Let  $k \geq 2$  and  $\mathbf{a} \geq 1$  be two integers and assume  $\kappa > 2ak$ . Under the assumptions 1, 3 and 4*

- (i) *for any integer  $q \in \{k, \dots, 2ak\}$  and any  $\boldsymbol{\beta} = (\beta_1, \dots, \beta_q) \in (\mathbb{N}^*)^{\times q}$  such that  $\sum_{j=1}^q \beta_j \leq 2ak$ , there exists a constant  $\mathfrak{C}_{3.3,1} > 0$  such that*

$$\sup_{\mathbf{p} \in (\mathbb{N}^*)^{\times q}} \mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}|=p}} e^{-\langle \boldsymbol{\beta}, V(\mathbf{x}) \rangle_q} \right] \leq \mathfrak{C}_{3.3,1};$$

- (ii) *for any integer  $q \in \{k, \dots, 2ak\}$  there exists a constant  $\mathfrak{C}_{3.3,2} > 0$  such that for  $n$  large enough and any  $h > 0$*

$$\mathbf{E} \left[ \sum_{\mathbf{x} \in \Delta_{a_n}^q} \mathbb{1}_{\{\max_{1 \leq i \leq q} H_{x^{(i)}} > h\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] \leq \frac{\mathfrak{C}_{3.3,2}}{h^{\kappa-1}} + o(1).$$

*Proof in the case*  $\cap_{j=1}^{\ell} \Gamma_{\mathbf{m}, \Pi}^j \subset \{\mathbf{x} \in \Delta^q; \mathcal{C}^q(\mathbf{x}) < \min_{1 \leq i \leq q} p_i\}$ . Not that, since  $H_u \geq 1$ , we have  $\mathbf{E}[\sum_{\mathbf{x} \in \Delta_{a_n}^q} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q}] = \mathbf{E}[\sum_{\mathbf{x} \in \Delta_{a_n}^q} \mathbb{1}_{\{\max_{1 \leq i \leq q} H_{x(i)} > h\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q}]$  for all  $h \leq 1$ . The proof of (i) is similar to the proof of Theorem 1.4 and Lemma 3.2 so we focus on (ii). In order to avoid unnecessary technical difficulties, we prove it for any  $\mathbf{a} \geq 2$ . Recall the definition of  $f_{\mathbf{s}, \Pi}^\ell$  in (15) for  $\ell \in \{1, \dots, q-1\}$ ,  $\mathbf{s} = (s_1, \dots, s_\ell) \in \mathbb{N}^{\times \ell}$  such that  $s_1 < \dots < s_\ell$  and  $\Pi = (\pi_i)_{0 \leq i \leq \ell}$  an increasing collection of partitions of  $\{1, \dots, q\}$ . Note that

$$\sum_{\mathbf{x} \in \Delta_{a_n}^q} \sum_{j=1}^q \mathbb{1}_{\{\max_{1 \leq i \leq q} H_{x(i)} > h\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} = \sum_{\ell=1}^{q-1} \sum_{\mathbf{s}; s_1 < \dots < s_\ell \leq a_n} \sum_{\Pi \text{ increasing}} \sum_{\mathbf{x} \in \Delta_{a_n}^q} f_{\mathbf{s}, \Pi}^\ell(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \times \mathbb{1}_{\{\max_{1 \leq i \leq q} H_{x(i)} > h\}},$$

and  $\sum_{\mathbf{x} \in \Delta_{a_n}^q} f_{\mathbf{s}, \Pi}^\ell(\mathbf{x}) \mathbb{1}_{\{\max_{1 \leq i \leq q} H_{x(i)} > h\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q}$  is equal to

$$\sum_{\mathbf{z} \in \Delta_{s_{\ell-1}}^{|\pi_{\ell-1}|}} f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}(\mathbf{z}) \prod_{j=1}^{|\pi_{\ell-1}|} \sum_{\mathbf{u}^{(j)} \in \Delta_{s_\ell}^{b_{\ell-1}(\mathbf{B}_j)}} \prod_{i=1}^{b_{\ell-1}(\mathbf{B}_j)} \mathbb{1}_{\{(u^{(j,i)})^* = z^{(j)}\}} \sum_{\mathbf{x}^{(j)} \in \Delta_{a_n}^{b_{\ell-1}(\mathbf{B}_j)}} \mathbb{1}_{\{x^{(j,i)} \geq u^{(j,i)}\}} \times e^{-V(x^{(j,i)})} \mathbb{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-1}|} \max_{1 \leq i' \leq b_{\ell-1}(\mathbf{B}_{j'})} H_{x^{(j',i')}} > h\}}.$$

For any  $u \leq x$ , introduce  $H_{u,x} := \sum_{u \leq z \leq x} e^{V(z) - V(x)}$ . Thanks to assumption 4 together with the fact that  $H_{z^{(j')}} \geq 1$

$$H_{x^{(j',i')}} \leq H_{z^{(j')}} e^h e^{-V_{u^{(j',i')}}(x^{(j',i')})} + H_{u^{(j',i')}, x^{(j',i')}},$$

so  $H_{x^{(j',i')}} > h$  implies that  $H_{z^{(j')}} e^h e^{-V_{u^{(j',i')}}(x^{(j',i')})} > h/2$  or  $H_{u^{(j',i')}, x^{(j',i')}} > h/2$ . We also decompose according to the values of  $H_{z^{(j')}}$ :

$$\begin{aligned} & \mathbb{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-1}|} \max_{1 \leq i' \leq b_{\ell-1}(\mathbf{B}_{j'})} H_{z^{(j')}} e^h e^{-V_{u^{(j',i')}}(x^{(j',i')})} > h/2\}} \\ & \leq \mathbb{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-1}|} H_{z^{(j')}} > h\}} + \mathbb{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-1}|} \max_{1 \leq i' \leq b_{\ell-1}(\mathbf{B}_{j'})} 2e^h e^{-V_{u^{(j',i')}}(x^{(j',i')})} > 1\}}. \end{aligned}$$

We therefore deduce that  $\mathbb{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-1}|} \max_{1 \leq i' \leq b_{\ell-1}(\mathbf{B}_{j'})} H_{x^{(j',i')}} > h\}}$  is smaller than

$$\mathbb{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-1}|} H_{z^{(j')}} > h\}} + \sum_{j'=1}^{|\pi_{\ell-1}|} \sum_{i'=1}^{b_{\ell-1}(\mathbf{B}_{j'})} \left( \mathbb{1}_{\{H_{u^{(j',i')}, x^{(j',i')}} > h/2\}} + \mathbb{1}_{\{2e^h e^{-V_{u^{(j',i')}}(x^{(j',i')})} > 1\}} \right).$$

By independence of the increments of the branching random walk  $(\mathbb{T}, (V(x), x \in \mathbb{T}))$ , since  $\psi(1) = 0$

$$\begin{aligned} & \mathbf{E} \left[ \sum_{\mathbf{x} \in \Delta_{a_n}^q} f_{\mathbf{s}, \Pi}^\ell(\mathbf{x}) \mathbb{1}_{\{\max_{1 \leq i \leq q} H_{x(i)} > h\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] \\ & \leq \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{s_{\ell-1}}^{|\pi_{\ell-1}|}} f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}(\mathbf{z}) \mathbb{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-1}|} H_{z^{(j')}} > h\}} e^{-\langle \beta^{\ell-1}, V(\mathbf{z}) \rangle_{|\pi_{\ell-1}|}} \right] \prod_{j=1}^{|\pi_{\ell-1}|} c_{b_{\ell-1}(\mathbf{B}_j)}(\mathbf{1}) \\ & + q(\mathfrak{z}_{1,n} + \mathfrak{z}_{2,n}) \prod_{j=1}^{|\pi_{\ell-1}|} c_{b_{\ell-1}(\mathbf{B}_j)}(\mathbf{1}) \mathbf{E} \left[ \mathcal{A}_{s_{\ell-1}}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \beta^{\ell-1}) \right], \end{aligned}$$

where we recall that  $\mathcal{A}_l^q(g, \beta) = \sum_{\mathbf{x} \in \Delta_l^q} e^{-\langle \beta, V(\mathbf{x}) \rangle_q}$ ,

$$\mathfrak{z}_{1,n} = \mathbf{E} \left[ \sum_{|x|=a_n-s_\ell} e^{-V(x)} \mathbf{1}_{\{H_x > h/2\}} \right] \quad \text{and} \quad \mathfrak{z}_{2,n} = \mathbf{E} \left[ \sum_{|x|=a_n-s_\ell} e^{-V(x)} \mathbf{1}_{\{2e^b e^{-V(x)} > 1\}} \right].$$

Thanks to the many-to-one Lemma 3.1

$$\mathfrak{z}_{1,n} = \mathbf{P}(H_{a_n-s_\ell}^S > h/2) \leq \mathfrak{C}_{3.3,3}/h^{\kappa-1},$$

for some constant  $\mathfrak{C}_{3.3,3} > 0$ , the last inequality coming from ([AD20], Lemma 2.2). We now turn to  $\mathfrak{z}_{2,n}$ . If  $s_\ell \leq a_n/2$  then, for any  $\rho \in (0, \kappa - 1)$

$$\mathfrak{z}_{2,n} \leq 2^\rho (1 + e^b)^\rho e^{a_n \psi(1+\rho)/2}.$$

Otherwise  $s_\ell - 1 \geq a_n/2$  and thanks to the Cauchy-Schwarz inequality

$$\begin{aligned} \mathbf{E} \left[ \mathcal{A}_{s_\ell-1}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \boldsymbol{\beta}^{\ell-1}) \right] &\leq \mathbf{E} \left[ \mathcal{A}_{s_\ell-1}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \boldsymbol{\beta}^{\ell-1}) \mathbf{1}_{\tilde{\mathcal{Y}}_n} \right] + \\ &\quad + (1 - \mathbf{P}(\tilde{\mathcal{Y}}_n))^{1/2} \mathbf{E} \left[ \left( \mathcal{A}_{s_\ell-1}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \boldsymbol{\beta}^{\ell-1}) \right)^2 \right]^{1/2}, \end{aligned}$$

where  $\tilde{\mathcal{Y}}_n := \{\min_{a_n/2 \leq |z| \leq a_n} V(z) > 3/2 \log n\}$  (recall that  $a_n = (2\delta_0)^{-1} \log n$ ). On the one hand, by definition, there exists  $i_\alpha \in \{1, \dots, |\pi_{\ell-1}|\}$  such that  $|\mathbf{B}_{i_\alpha}^{\ell-1}| \geq 2$ . It follows that

$$\mathbf{E} \left[ \mathcal{A}_{s_\ell-1}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \boldsymbol{\beta}^{\ell-1}) \mathbf{1}_{\tilde{\mathcal{Y}}_n} \right] \leq n^{-3/2} \mathbf{E} \left[ \mathcal{A}_{s_\ell-1}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \tilde{\boldsymbol{\beta}}^{\ell-1}) \right],$$

where  $\tilde{\boldsymbol{\beta}}_j^{\ell-1} = |\mathbf{B}_j^{\ell-1}|$  for all  $j \neq i_\alpha$  and  $\tilde{\boldsymbol{\beta}}_{i_\alpha}^{\ell-1} = |\mathbf{B}_{i_\alpha}^{\ell-1}| - 1 \geq 1$ . On the other hand,  $1 - \mathbf{P}(\tilde{\mathcal{Y}}_n) \leq n^{-\rho_5}$  with  $\rho_5 > 0$  thanks to Lemma 3.4. Moreover, both  $\sum_{j=1}^{|\pi_{\ell-1}|} \boldsymbol{\beta}_j^{\ell-1}$  and  $\sum_{j=1}^{|\pi_{\ell-1}|} \tilde{\boldsymbol{\beta}}_j^{\ell-1}$  are smaller than  $2k$  since  $q \leq 2k$ . Hence, thanks to (i)

$$\mathbf{E} \left[ \mathcal{A}_{s_\ell-1}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \tilde{\boldsymbol{\beta}}^{\ell-1}) \right] + \mathbf{E} \left[ \left( \mathcal{A}_{s_\ell-1}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \boldsymbol{\beta}^{\ell-1}) \right)^2 \right]^{1/2} \leq \mathfrak{C}_{3.3,4},$$

for some constant  $\mathfrak{C}_{3.3,4} > 0$ . We obtain

$$\begin{aligned} &\mathbf{E} \left[ \sum_{\mathbf{x} \in \Delta_{a_n}^q} f_{\mathbf{s}, \Pi}^\ell(\mathbf{x}) \mathbf{1}_{\{\max_{1 \leq i \leq q} H_{x(i)} > h\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] \\ &\leq \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{s_\ell-1}^{|\pi_{\ell-1}|}} f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}(\mathbf{z}) \mathbf{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-1}|} H_{z(j')} > h\}} e^{-\langle \boldsymbol{\beta}^{\ell-1}, V(\mathbf{z}) \rangle_{|\pi_{\ell-1}|}} \right] \prod_{j=1}^{|\pi_{\ell-1}|} c_{b_{\ell-1}(\mathbf{B}_j)}(\mathbf{1}) \\ &\quad + q \mathfrak{z}_{1,n} \prod_{j=1}^{|\pi_{\ell-1}|} c_{b_{\ell-1}(\mathbf{B}_j)}(\mathbf{1}) \mathbf{E} \left[ \mathcal{A}_{s_\ell-1}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \boldsymbol{\beta}^{\ell-1}) \right] + n^{-\rho_6}, \end{aligned}$$

thanks to the assumption 3 and for  $\rho_6 > 0$ . Note (see the proof of Theorem 1.4) that

$$\mathbf{E} \left[ \mathcal{A}_{s_\ell-1}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \boldsymbol{\beta}^{\ell-1}) \right] = \mathcal{A}_{s_\ell-1-1}^{|\pi_{\ell-2}|} (f_{\mathbf{s}^{\ell-2}, \Pi^{\ell-2}}^{\ell-2}, \boldsymbol{\beta}^{\ell-2}) \prod_{j=1}^{|\pi_{\ell-2}|} c_{b_{\ell-2}(\mathbf{B}_j)}(\boldsymbol{\beta}_j^{\ell-2}) \prod_{\substack{\mathfrak{B} \in \pi_{\ell-1} \\ |\mathfrak{B}| \geq 2}} e^{s_\ell^* \psi(|\mathfrak{B}|)},$$

with  $\beta_j^{\ell-2} = (\beta_{j,1}^{\ell-2}, \dots, \beta_{j,b_{\ell-2}(\mathbf{B}_j)}^{\ell-2})$  and  $s_\ell^* = s_\ell - s_{\ell-1} - 1$ . Since for any  $\mathfrak{B} \in \pi_{\ell-1}$  such that  $|\mathfrak{B}| \geq 2$ ,  $\psi(|\mathfrak{B}|) < 0$ , we have

$$\sum_{s_\ell = s_{\ell-1} + 1}^{a_n} \mathbf{E} \left[ \mathcal{A}_{s_{\ell-1}}^{|\pi_{\ell-1}|} (f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}, \beta^{\ell-1}) \right] \leq \mathbf{E} \left[ \mathcal{A}_{s_{\ell-1}-1}^{|\pi_{\ell-2}|} (f_{\mathbf{s}^{\ell-2}, \Pi^{\ell-2}}^{\ell-2}, \beta^{\ell-2}) \right] \prod_{\mathbf{B} \in \pi_{\ell-2}} c_{b_{\ell-2}(\mathbf{B})}(\beta^{\ell-1}) \left( 1 - \prod_{\substack{\mathfrak{B} \in \pi_{\ell-1} \\ |\mathfrak{B}| \geq 2}} e^{\psi(|\mathfrak{B}|)} \right)^{-1}.$$

Doing the same for  $\mathbf{E}[\sum_{\mathbf{z} \in \Delta_{s_{\ell-1}}^{|\pi_{\ell-1}|}} f_{\mathbf{s}^{\ell-1}, \Pi^{\ell-1}}^{\ell-1}(\mathbf{z}) \mathbf{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-1}|} H_{z(j')} > h\}} e^{-\langle \beta^{\ell-1}, V(\mathbf{z}) \rangle_{|\pi_{\ell-1}|}}]$ , we obtain, thanks to assumption 3

$$\begin{aligned} & \sum_{\mathbf{s}; s_1 < \dots < s_\ell \leq a_n} \mathbf{E} \left[ \sum_{\mathbf{x} \in \Delta_{a_n}^q} f_{\mathbf{s}, \Pi}^\ell(\mathbf{x}) \mathbf{1}_{\{\max_{1 \leq i \leq q} H_{x(i)} > h\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] \\ & \leq \sum_{s_1 < \dots < s_{\ell-1} \leq a_n} \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{s_{\ell-1}-1}^{|\pi_{\ell-2}|}} f_{\mathbf{s}^{\ell-2}, \Pi^{\ell-2}}^{\ell-2}(\mathbf{z}) \mathbf{1}_{\{\max_{1 \leq j' \leq |\pi_{\ell-2}|} H_{z(j')} > h\}} e^{-\langle \beta^{\ell-2}, V(\mathbf{z}) \rangle_{|\pi_{\ell-2}|}} \right] \\ & + \frac{\mathfrak{C}_{3.3,5}}{h^{\kappa-1}} + n^{-\rho_7}, \end{aligned}$$

for some constant  $\mathfrak{C}_{3.3,5} > 0$  and  $\rho_7 > 0$ . We conclude by induction together with assumption 3.  $\square$

We remind the definition of the range  $\mathcal{A}^k(\mathcal{D}_n, T^s, g)$

$$\mathcal{A}^k(\mathcal{D}_n, T^s, g) = \sum_{\substack{\mathbf{x} \in \Delta^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} g(\mathbf{x}) \mathbf{1}_{\{T_{\mathbf{x}} < T^s\}},$$

where  $T_{\mathbf{x}} = \max_{1 \leq i \leq k} T_{x(i)}$  and  $\ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n$  means that  $\ell_n \leq |x^{(i)}| \leq \mathfrak{L}_n$  for all  $i \in \{1, \dots, k\}$ . Vertices with high potential have a major contribution to the range. One can note that under the assumption 1, the potential  $V(u)$  of the vertex  $u \in \mathbb{T}$  behaves like  $|u|$  when  $|u|$  is large (see [Big76] and [HS09] for instance). It allows to say that

**Fact 1.** For all  $\varepsilon \in (0, 1)$ , there exists  $a_\varepsilon > 0$  such that

$$\mathbf{P}^* \left( \inf_{z \in \mathbb{T}} V(z) \geq -a_\varepsilon \right) \geq 1 - \varepsilon. \quad (36)$$

Moreover,

**Lemma 3.4.** Under the assumption 1, there exists  $\delta_0 > 0$  and  $\rho_1 > 1/2$  such that for any positive integer  $\zeta$

$$\mathbf{P} \left( \min_{|z| = \delta_0^{-1} \zeta} V(z) \geq 3\zeta \right) \geq 1 - e^{-\rho_1 \zeta},$$

Using Lemma 3.4, we are able to prove that any vertex  $x \in \mathbb{T}$  in a generation between  $\delta_0^{-1} \log n$  and  $n^{1/2}$  is visited during a single excursion above the parent  $e^*$  of the root  $e$ . For that, let us define the edge local time  $N_u^T := \sum_{j=1}^T \mathbf{1}_{\{X_{j-1} = u^*, X_j = u\}}$  of the vertex  $u \in \mathbb{T}$  and introduce

$$E_u^s := \sum_{j=1}^s \mathbf{1}_{\{N_u^{T^j} - N_u^{T^{j-1}} \geq 1\}},$$

the number of excursions during which the vertex  $x$  is visited by the random walk  $\mathbb{X}$ .

**Lemma 3.5.** *Under the assumption 1, for all  $\varepsilon_1 \in (0, 1)$ , there exists  $\rho_2 := \rho_2(\varepsilon_1) > 0$  such that for  $n$  large enough*

$$\mathbb{P}^* \left( \bigcup_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \bigcup_{|z|=\delta_0^{-1} \log n}^{n^{1/2}} \{E_z^s \geq 2\} \right) \leq n^{-\rho_2}.$$

The proof of Lemma 3.5 is similar to the one of Lemma 3.5 in [AD20].

Introduce the set  $\mathfrak{S}^{k,s}$  of  $k$ -tuples of vertices visited during a single excursion:

$$\mathfrak{S}^{k,s} := \{\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k; \forall 1 \leq i \leq k, E_{x^{(i)}}^s = 1\}. \quad (37)$$

In other words, Lemma 3.5 says that we can restrict the study of the range  $\mathcal{A}^k(\mathcal{D}_{n,T^s}, f \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathcal{C}_{a_n}^k})$  to the set  $\mathfrak{S}^{k,s}$ . This restriction allows to get quasi-independence in the trajectory of the random walk  $\mathbb{X}$  and the resulting quasi-independent version of the range  $\mathcal{A}^k(\mathcal{D}_{n,T^s}, f \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathcal{C}_{a_n}^k})$  is easier to deal with. A similar idea is developed in [AD20] and [AK23]. Let  $\mathbf{j} \in \llbracket 1, s \rrbracket_k$ ,  $\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}$  and define

$$\mathcal{A}_{\mathbf{p}}^{k,n}(\mathbf{j}, g) := \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}| = \mathbf{p}}} g(\mathbf{x}) \prod_{i=1}^k \mathbf{1}_{\{N_{x^{(i)}}^{T^{j_i}} - N_{x^{(i)}}^{T^{j_i-1}} \geq 1\}} \quad \text{and} \quad \mathcal{A}^{k,n}(\mathbf{j}, g) := \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}} \mathcal{A}_{\mathbf{p}}^{k,n}(\mathbf{j}, g), \quad (38)$$

where for any  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)})$ ,  $|\mathbf{x}| = \mathbf{p}$  means nothing but  $|x^{(i)}| = p_i$  for all  $i \in \{1, \dots, k\}$ . In the next lemma, we show that  $\mathcal{A}^k(\mathcal{D}_{n,T^s}, f \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathcal{C}_{a_n}^k})$  and  $\sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k})$  have the same behavior

**Lemma 3.6.** *Let  $k \geq 2$  be an integer and assume  $\kappa > 2k$ . Under the assumptions 1 and 3, for all bounded and non-negative function  $g$ , any  $\varepsilon, \varepsilon_1 \in (0, 1)$ , there exists  $\rho_4 := \rho_4(\varepsilon, \varepsilon_1) > 0$  such that for  $n$  large enough*

$$\mathbb{P}^* \left( \bigcup_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \left\{ \left| \mathcal{A}^k(\mathcal{D}_{n,T^s}, g \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathcal{C}_{a_n}^k}) - \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, g \mathbf{1}_{\mathcal{C}_{a_n}^k}) \right| > \varepsilon (s \mathbf{L}_n)^k \right\} \right) \leq n^{-\rho_4}.$$

*Proof.* We first decompose as follows

$$\mathcal{A}^k(\mathcal{D}_{n,T^s}, g \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathcal{C}_{a_n}^k}) = \mathcal{A}^k(\mathcal{D}_{n,T^s}, \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathcal{C}_{a_n}^k \cap \mathfrak{S}^{k,s}}) + \mathcal{A}^k(\mathcal{D}_{n,T^s}, g \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathcal{C}_{a_n}^k \cap \Delta^k \setminus \mathfrak{S}^{k,s}}).$$

By Lemma 3.5, we have that for  $n$  large enough

$$\mathbb{P}^* \left( \bigcup_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \mathcal{A}^k(\mathcal{D}_{n,T^s}, g \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathcal{C}_{a_n}^k \cap \Delta^k \setminus \mathfrak{S}^{k,s}}) > \varepsilon (s \mathbf{L}_n)^k / 2 \right) \leq n^{-\rho_2},$$

so we can focus on  $\mathcal{A}^k(\mathcal{D}_{n,T^s}, g \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathfrak{S}^{k,s} \cap \mathcal{C}_{a_n}^k})$ . Note that  $\mathbf{x} \in \mathfrak{C}^{k,s} \cap \mathfrak{S}^{k,s}$  means nothing but there exists  $\mathbf{j} \in \llbracket 1, s \rrbracket_k$  such that for any  $i \in \{1, \dots, k\}$ ,  $N_{x^{(i)}}^{T^{j_i}} - N_{x^{(i)}}^{T^{j_i-1}} \geq 1$  and for all  $j \neq j_i$ ,  $N_{x^{(i)}}^{T^j} - N_{x^{(i)}}^{T^{j-1}} = 0$ , thus giving that  $\mathcal{A}^k(\mathcal{D}_{n,T^s}, g \mathbf{1}_{\mathfrak{C}^{k,s} \cap \mathfrak{S}^{k,s} \cap \mathcal{C}_{a_n}^k})$  is equal to

$$\sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}} \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}| = \mathbf{p}}} g \mathbf{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \mathbf{1}_{\{N_{x^{(i)}}^{T^{j_i}} - N_{x^{(i)}}^{T^{j_i-1}} \geq 1; \forall j \neq j_i, N_{x^{(i)}}^{T^j} - N_{x^{(i)}}^{T^{j-1}} = 0\}}.$$



Hence, for any  $s \in \{\varepsilon_1 n^{1/2}, \dots, n^{1/2}/\varepsilon_1\}$

$$\sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, g\mathbf{1}_{\mathcal{C}_{a_n}^k}) - \mathcal{A}^k(\mathcal{D}_{n,T^s}, g\mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{S}^{k,s} \cap \mathcal{C}_{a_n}^k}) \geq 0,$$

and thanks to Markov inequality

$$\begin{aligned} & \mathbb{P}^\mathcal{E} \left( \bigcup_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \left\{ \left| \mathcal{A}^k(\mathcal{D}_{n,T^s}, g\mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{S}^{k,s} \cap \mathcal{C}_{a_n}^k}) - \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, g\mathbf{1}_{\mathcal{C}_{a_n}^k}) \right| > \varepsilon (s\mathbf{L}_n)^k / 2 \right\} \right) \\ & \leq \frac{2}{\varepsilon (\varepsilon_1 n^{1/2} \mathbf{L}_n)^k} \mathbb{E}^\mathcal{E} \left[ \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, g\mathbf{1}_{\mathcal{C}_{a_n}^k}) - \mathcal{A}^k(\mathcal{D}_{n,T^s}, g\mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{S}^{k,s} \cap \mathcal{C}_{a_n}^k}) \right]. \end{aligned} \quad (39)$$

One can see that we can restrict ourselves to the  $k$ -tuples  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \mathcal{C}_{a_n}^k$ ,  $\mathbf{x} = \mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}$ , such that for all  $i, j \in \{1, \dots, k\}$  with  $i \neq j$ ,  $H_{x^{(i)} \wedge x^{(j)}} \leq e^{\omega_0 a_n / 2}$  and  $V_{x^{(i)} \wedge x^{(j)}}(x^{(j)}) \geq \omega_0 a_n$  for some  $\omega_0 > 0$ . Indeed, if this subset of  $\Delta^k$  is denoted by  $\mathcal{H}_n^k$ , then, using similar arguments as the ones we have used several times, it can be proved that for a given  $\omega_0 > 0$  and  $n$  large enough

$$\mathbb{E}^* \left[ \frac{1}{(n^{1/2} \mathbf{L}_n)^k} \sup_{s \leq n^{1/2}/\varepsilon_1} \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, g\mathbf{1}_{\mathcal{C}_{a_n}^k} \mathbf{1}_{\Delta^k \setminus \mathcal{H}_n^k}) \right] \leq n^{\rho'_2}, \quad (40)$$

for some  $\rho'_2 > 0$ .

We now aim to provide a lower bound for  $\mathbb{E}^\mathcal{E}[\mathcal{A}^k(\mathcal{D}_{n,T^s}, g\mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{S}^{k,s} \cap \mathcal{C}_{a_n}^k \cap \mathcal{H}_n^k})]$ . Thanks to the strong Markov property, the random variables  $N_z^{T^l} - N_z^{T^{l-1}}$ ,  $l \in \mathbb{N}^*$ , are i.i.d under  $\mathbb{P}^\mathcal{E}$  and distributed as  $N_z^{T^1}$ . It follows that

$$\begin{aligned} & \mathbb{E}^\mathcal{E} \left[ \mathcal{A}^k(\mathcal{D}_{n,T^s}, g\mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{S}^{k,s} \cap \mathcal{C}_{a_n}^k}) \right] \\ & = \sum_{\substack{\mathbf{x} \in \mathcal{H}_n^k \\ |\mathbf{x}|=p}} g\mathbf{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \mathbb{P}^\mathcal{E}(\forall j \neq i, T_{x^{(i)}} > T^1 > T_{x^{(j)}}) \mathbb{P}^\mathcal{E}(T_{x^{(i)}} > T^1)^{s-k} \\ & \geq \sum_{\substack{\mathbf{x} \in \mathcal{H}_n^k \\ |\mathbf{x}|=p}} g\mathbf{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \left( \mathbb{P}^\mathcal{E}(T_{x^{(i)}} < T^1) - \sum_{j=1; j \neq i}^k \mathbb{P}^\mathcal{E}(T_{x^{(i)}} < T^1, T_{x^{(j)}} < T^1) \right) \mathbb{P}^\mathcal{E}(T_{x^{(i)}} > T^1)^{s-k}. \end{aligned}$$

One can see that for any  $\mathbf{x} \in \mathcal{H}_n^k$ ,  $\sum_{j=1; j \neq i}^k \mathbb{P}^\mathcal{E}(T_{x^{(i)}} < T^1, T_{x^{(j)}} < T^1)$  is very small with respect to  $\mathbb{P}^\mathcal{E}(T_{x^{(i)}} < T^1)$ . Indeed, by the strong Markov property and (35), we have, for any  $j \neq i$

$$\begin{aligned} \mathbb{P}^\mathcal{E}(T_{x^{(i)}} < T^1, T_{x^{(j)}} < T^1) & \leq \mathbb{P}^\mathcal{E}(T_{x^{(i)}} < T^1) \mathbb{P}_{x^{(i)} \wedge x^{(j)}}^\mathcal{E}(T_{x^{(j)}} < T^1) \\ & \quad + \mathbb{P}^\mathcal{E}(T_{x^{(j)}} < T^1) \mathbb{P}_{x^{(i)} \wedge x^{(j)}}^\mathcal{E}(T_{x^{(i)}} < T^1) \\ & \leq 2H_{x^{(i)} \wedge x^{(j)}} e^{-V_{x^{(i)} \wedge x^{(j)}}(x^{(j)})} \mathbb{P}^\mathcal{E}(T_{x^{(i)}} < T^1) \\ & \leq 2n^{-\omega_0(4\delta_0)} \mathbb{P}^\mathcal{E}(T_{x^{(i)}} < T^1), \end{aligned}$$

recalling that  $a_n = (2\delta_0)^{-1} \log n$ . Using (35) again, we have, on  $\mathcal{V}_n = \{\min_{\delta_0^{-1} \log n \leq |x| \leq n^{1/2}} V(z) \geq 3 \log n\}$ , that

$$\mathbb{P}^\mathcal{E}(T_{x^{(i)}} > T^1)^{s-k} \geq (1 - \mathbb{P}^\mathcal{E}(T_{x^{(i)}} < T^1))^s \geq (1 - e^{-V(x^{(i)})})^s \geq (1 - n^{-3})^s \geq (1 - n^{-3})^{n^{1/2}/\varepsilon_1}.$$

Hence,  $\mathbb{E}^{\mathcal{E}}[\mathcal{A}^k(\mathcal{D}_{n,T^s}, g\mathbb{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{E}^{k,s} \cap \mathcal{C}_{a_n}^k})]$  is larger than

$$(1 - n^{-3})^{n^{1/2}/\varepsilon_1} (1 - 2kn^{-\omega_0(4\delta_0)^{-1}})^k \sum_{\substack{\mathbf{x} \in \mathcal{H}_n^k \\ |\mathbf{x}|=p}} g\mathbb{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \mathbb{P}^{\mathcal{E}}(T_{x^{(i)}} < T^1).$$

It follows that

$$\begin{aligned} & \mathbb{E} \left[ \mathbb{1}_{\mathcal{V}_n} \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, g\mathbb{1}_{\mathcal{C}_{a_n}^k \cap \mathcal{H}_n^k}) - \mathcal{A}^k(\mathcal{D}_{n,T^s}, g\mathbb{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{E}^{k,s} \cap \mathcal{C}_{a_n}^k \cap \mathcal{H}_n^k}) \right] \\ & \leq \|g\|_{\infty} (s\mathbf{L}_n)^k \left( 1 - (1 - n^{-3})^{n^{1/2}/\varepsilon_1} (1 - 2kn^{-\omega_0(4\delta_0)^{-1}})^k \right) \sup_{\substack{\mathbf{p} \in (\mathbb{N}^*)^{\times k} \\ |\mathbf{x}|=p}} \mathbb{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta_p^k \\ i=1}}^k \prod_{i=1}^k \mathbb{P}^{\mathcal{E}}(T_{x^{(i)}} < T^1) \right], \end{aligned}$$

and by (39) and (40),  $\mathbb{P}^*(\bigcup_{s=\varepsilon_1 n^{1/2}}^{n^{1/2}/\varepsilon_1} \{|\mathcal{A}^k(\mathcal{D}_{n,T^s}, g\mathbb{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{E}^{k,s} \cap \mathcal{C}_{a_n}^k}) - \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, g\mathbb{1}_{\mathcal{C}_{a_n}^k})| > \varepsilon(s\mathbf{L}_n)^k/2\})$  is smaller, for  $n$  large enough, than

$$\begin{aligned} & 1 - \mathbf{P}^*(\mathcal{V}_n) + \mathfrak{C}_{3.6} n^{-\rho'_2} + \mathfrak{C}_{3.6,1} \left( 1 - (1 - n^{-3})^{n^{1/2}/\varepsilon_1} (1 - 2kn^{-\omega_0(4\delta_0)^{-1}})^k \right) \\ & \quad \times \sup_{\substack{\mathbf{p} \in (\mathbb{N}^*)^{\times k} \\ |\mathbf{x}|=p}} \mathbb{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta_p^k \\ i=1}}^k e^{-\langle \beta, V(\mathbf{x}) \rangle_k} \right], \end{aligned}$$

for some constant  $\mathfrak{C}_{3.6} > 0$  and  $\mathfrak{C}_{3.6,1} > 0$ . Finally, by Lemma 3.4, for  $n$  large enough  $1 - \mathbf{P}^*(\mathcal{V}_n) \leq n^{-\rho'_1}$  for some  $\rho'_1 > 0$ ,  $(1 - (1 - n^{-3})^{n^{1/2}/\varepsilon_1} (1 - 2kn^{-\omega_0(4\delta_0)^{-1}})^k) \leq n^{-\rho_{2,k}}$  for  $n$  large enough and some  $\rho_{2,k} > 0$  and thanks to Lemma 3.3 (i) with  $\beta = \mathbf{1}$ ,  $\sup_{\mathbf{p} \in (\mathbb{N}^*)^{\times k}} \mathbb{E}[\sum_{\mathbf{x} \in \Delta_p^k; |\mathbf{x}|=p} e^{-\langle \beta, V(\mathbf{x}) \rangle_k}]$  is finite which completes the proof.  $\square$

The next lemma relates  $\sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f\mathbb{1}_{\mathcal{C}_{a_n}^k})$  with its quenched mean and illustrates why this quasi-independent version of the range is easier to deal with.

**Lemma 3.7.** *Let  $k \geq 2$  and  $\mathfrak{a} \geq 1$  be two integers and assume  $\kappa > 2\mathfrak{a}k$ . Under the assumptions 1, 2 and 3, there exists a constant  $\mathfrak{C}_{3.7} > 0$  and a non-decreasing sequence of positive numbers  $(\tilde{\mathfrak{q}}(j))_{j \geq 2}$  satisfying  $\tilde{\mathfrak{q}}_2 = 1$  and  $\tilde{\mathfrak{q}}(j) \rightarrow \infty$  when  $j \rightarrow \infty$  such that for  $n$  large enough and any  $\varepsilon_1 n^{1/2} \leq s \leq n^{1/2}/\varepsilon_1$*

$$\mathbb{E} \left[ \left( \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f\mathbb{1}_{\mathcal{C}_{a_n}^k}) - \mathbb{E}^{\mathcal{E}} \left[ \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f\mathbb{1}_{\mathcal{C}_{a_n}^k}) \right] \right)^{2\mathfrak{a}} \right] \leq \mathfrak{C}_{3.7} (\mathbf{L}_n)^{2\mathfrak{a}k} (\mathfrak{L}_n)^{\tilde{\mathfrak{q}}_{\mathfrak{a}}} s^{2\mathfrak{a}k - \tilde{\mathfrak{q}}_{\mathfrak{a}}}.$$

*Proof.* Recall the definition of  $\mathcal{A}^{k,n}(j, f\mathbb{1}_{\mathcal{C}_{a_n}^k})$  in (38). For  $\mathfrak{a} = 1$ , note that

$$\begin{aligned} & \mathbb{E}^{\mathcal{E}} \left[ \left( \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f\mathbb{1}_{\mathcal{C}_{a_n}^k}) \right)^2 \right] \\ & = \sum_{j, j' \in \llbracket 1, s \rrbracket_k} \sum_{\mathbf{p}, \mathbf{p}' \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}} \sum_{\substack{\mathbf{x}, \mathbf{y} \in \mathcal{C}_{a_n}^k \\ |\mathbf{x}|=p, |\mathbf{y}|=p'}} f(\mathbf{x})f(\mathbf{y}) \mathbb{E}^{\mathcal{E}} \left[ \prod_{i=1}^k \mathbb{1}_{\{N_{x^{(i)}}^{T^{j_i}} - N_{x^{(i)}}^{T^{j_i-1}} \geq 1, N_{y^{(i)}}^{T^{j'_i}} - N_{y^{(i)}}^{T^{j'_i-1}} \geq 1\}} \right], \end{aligned}$$

with the notations  $\mathbf{j} = (j_1, \dots, j_k)$  and  $\mathbf{j}' = (j'_1, \dots, j'_k)$ . Thanks to the strong Markov property, the random variables  $N_z^{T^i} - N_z^{T^{i-1}}$  are i.i.d under  $\mathbb{P}^{\mathcal{E}}$  and distributed as  $N_z^{T^1}$  for any  $z \in \mathbb{T}$ .

In particular, the term  $s^{2k}$  in  $\mathbb{E}^\mathcal{E}[(\sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) - \mathbb{E}^\mathcal{E}[\sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k})])^2]$  is equal to zero and we actually have

$$\begin{aligned} & \mathbb{E} \left[ \left( \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) - \mathbb{E}^\mathcal{E} \left[ \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) \right] \right)^2 \right] \\ & \leq \mathfrak{C}_{3.7,1} (\mathbf{L}_n)^{2k} ((\mathfrak{L}_n)^2 s^{2k-2} + \mathfrak{L}_n s^{2k-1}) \leq 2\mathfrak{C}_{3.7,1} (\mathbf{L}_n)^{2k} \mathfrak{L}_n s^{2k-1}, \end{aligned}$$

where the constant  $\mathfrak{C}_{3.7,1} > 0$  comes from Lemma 3.2 and the last inequality comes the fact that  $\mathfrak{L}_n \leq s$  for  $n$  large enough.

When  $\mathfrak{a} \geq 2$ , using similar arguments we have

$$\begin{aligned} & \mathbb{E} \left[ \left( \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) - \mathbb{E}^\mathcal{E} \left[ \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) \right] \right)^{2\mathfrak{a}} \right] \\ & \leq \mathfrak{C}_{3.7,2} (\mathbf{L}_n)^{2\mathfrak{a}k} (\mathfrak{L}_n)^{2\lfloor \mathfrak{a}/2 \rfloor} s^{2\mathfrak{a}k - 2\lfloor \mathfrak{a}/2 \rfloor}. \end{aligned}$$

We finally obtain the result by taking  $\mathfrak{q}_\mathfrak{a} := \mathfrak{a} \mathbf{1}_{\{\mathfrak{a}=1\}} + 2\lfloor \mathfrak{a}/2 \rfloor \mathbf{1}_{\{\mathfrak{a} \geq 2\}}$ .  $\square$

### 3.1.2. Convergence of the quenched mean of the range on $\mathcal{C}_{a_n}^k$

We prove that the quenched mean of the quasi-independent version  $\sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^k(\mathbf{j}, f \mathcal{C}_{a_n}^k)$  of the range on the set  $\mathcal{C}_{a_n}^k$  converges in  $\mathbf{P}^*$ -probability by using the hereditary assumption 5.

**Lemma 3.8.** *Let  $k \geq 2$  be an integer and assume  $\kappa > 2k$ . Under the assumptions 1, 3 and 4, if  $f$  satisfies the hereditary assumption 5 then*

$$\lim_{n \rightarrow \infty} \mathbf{E}^* \left[ \left| \frac{1}{(\mathbf{L}_n)^k} \sum_{\substack{\mathbf{x} \in \Delta^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} f \mathbf{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} - (c_\infty)^k \mathcal{A}_{a_n}^k(f) \right| \right] = 0$$

*Proof.* Let us first prove that

$$\lim_{n \rightarrow \infty} \mathbf{E} \left[ \left( \frac{1}{(\mathbf{L}_n)^k} \sum_{\substack{\mathbf{x} \in \mathcal{C}_{a_n}^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} f(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} - \sum_{\mathbf{x} \in \Delta_{a_n}^k} f(\mathbf{x}) \prod_{i=1}^k e^{-V(x^{(i)})} \tilde{\varphi}_n(H_{x^{(i)}}) \right)^2 \right] = 0, \quad (41)$$

where, for any  $r \geq 1$ ,  $\tilde{\varphi}_n(r) := \sum_{p=\ell_n}^{\mathfrak{L}_n} \varphi_{n,p}(r)/\mathbf{L}_n$  and

$$\varphi_{n,p}(r) = \mathbf{E} \left[ \sum_{|x|=p-a_n} e^{-V(x)} ((r-1)e^{-V(x)} + H_x)^{-1} \right].$$

For that, the first step is to decompose  $\sum_{\mathbf{x} \in \Delta^k; \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n} f \mathbf{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k e^{-V(x^{(i)})}/H_{x^{(i)}}$ :

$$\begin{aligned} \sum_{\substack{\mathbf{x} \in \Delta^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} f \mathbf{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} &= \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\} \times k} \sum_{\mathbf{z} \in \Delta_{a_n}^k} \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}|=\mathbf{p}; x^{(i)} > z^{(i)}}} f \mathbf{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \\ &= \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\} \times k} \sum_{\mathbf{z} \in \Delta_{a_n}^k} f(\mathbf{z}) \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}|=\mathbf{p}; x^{(i)} > z^{(i)}}} \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}}, \end{aligned}$$

where the last equality comes from the hereditary assumption 5. As we did above, we decompose  $H_{x^{(i)}}: H_{x^{(i)}} = (H_{z^{(i)}} - 1)e^{-V_{z^{(i)}}(x^{(i)})} + H_{z^{(i)}, x^{(i)}}$ . By independence of the increments of the branching random walk  $(\mathbb{T}, (V(x), x \in \mathbb{T}))$

$$\mathbf{E}\left[\sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}|=p}} f \mathbf{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \Big| \mathcal{F}_{a_n}\right] = \sum_{\mathbf{z} \in \Delta_{a_n}^k} f(\mathbf{z}) \prod_{i=1}^k e^{-V(z^{(i)})} \varphi_{n, p_i}(H_{z^{(i)}}), \quad (42)$$

where  $\mathcal{F}_{a_n} = \sigma(\mathbb{T}, (V(x); |x| \leq a_n))$ . Thanks to (42), we have that the expectation in equation (41) is equal to

$$\mathbf{E}\left[\left(\frac{1}{(\mathcal{L}_n)^k} \sum_{\substack{\mathbf{x} \in \mathcal{C}_{a_n}^k \\ \ell_n \leq |\mathbf{x}| \leq \mathcal{L}_n}} f(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}}\right)^2\right] - \mathbf{E}\left[\left(\sum_{\mathbf{x} \in \Delta_{a_n}^k} f(\mathbf{x}) \prod_{i=1}^k e^{-V(x^{(i)})} \tilde{\varphi}_n(H_{x^{(i)}})\right)^2\right].$$

For  $\mathbf{x}, \mathbf{y} \in \Delta^k$ , denote by  $\mathbf{xy} = (x^{(1)}, \dots, x^{(k)}, y^{(1)}, \dots, y^{(k)})$  the concatenation of  $\mathbf{x}$  and  $\mathbf{y}$ . Note that

$$\begin{aligned} \left(\sum_{\substack{\mathbf{x} \in \mathcal{C}_{a_n}^k \\ \ell_n \leq |\mathbf{x}| \leq \mathcal{L}_n}} f(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}}\right)^2 &= \sum_{\substack{\mathbf{x}, \mathbf{y} \in \mathcal{C}_{a_n}^k; \mathbf{xy} \notin \Delta^{2k} \\ \ell_n \leq |\mathbf{x}|, |\mathbf{y}| \leq \mathcal{L}_n}} f(\mathbf{x}) f(\mathbf{y}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \frac{e^{-V(y^{(i)})}}{H_{y^{(i)}}} \\ &+ \sum_{\substack{\mathbf{x}, \mathbf{y} \in \mathcal{C}_{a_n}^k; \mathbf{xy} \in \Delta^{2k} \setminus \mathcal{C}_{a_n}^{2k} \\ \ell_n \leq |\mathbf{x}|, |\mathbf{y}| \leq \mathcal{L}_n}} f(\mathbf{x}) f(\mathbf{y}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \frac{e^{-V(y^{(i)})}}{H_{y^{(i)}}} \\ &+ \sum_{\substack{\mathbf{x}, \mathbf{y} \in \Delta^k; \mathbf{xy} \in \mathcal{C}_{a_n}^{2k} \\ \ell_n \leq |\mathbf{x}|, |\mathbf{y}| \leq \mathcal{L}_n}} f(\mathbf{x}) f(\mathbf{y}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \frac{e^{-V(y^{(i)})}}{H_{y^{(i)}}}, \end{aligned}$$

where for any  $\mathbf{x}, \mathbf{y} \in \Delta^k$ ,  $\mathbf{xy} \notin \Delta^{2k}$  means that there exists  $\alpha \in \{1, \dots, k\}$  and  $i_1, \dots, i_\alpha \in \{1, \dots, k\}$  distinct such that  $x^{(i_j)} = y^{(i_j)}$  for all  $j \in \{1, \dots, \alpha\}$  and  $\ell_n \leq |\mathbf{x}|, |\mathbf{y}| \leq \mathcal{L}_n$  means nothing but  $\ell_n \leq |\mathbf{x}| \leq \mathcal{L}_n$  and  $\ell_n \leq |\mathbf{y}| \leq \mathcal{L}_n$ . It follows

$$\lim_{n \rightarrow \infty} \frac{1}{(\mathcal{L}_n)^{2k}} \mathbf{E}\left[\sum_{\substack{\mathbf{x}, \mathbf{y} \in \mathcal{C}_{a_n}^k; \mathbf{xy} \notin \Delta^{2k} \\ \ell_n \leq |\mathbf{x}|, |\mathbf{y}| \leq \mathcal{L}_n}} f(\mathbf{x}) f(\mathbf{y}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \frac{e^{-V(y^{(i)})}}{H_{y^{(i)}}}\right] = 0.$$

Indeed, using that  $H_z \geq 1$  for any  $z \in \mathbb{T}$ , we have

$$\begin{aligned} &\mathbf{E}\left[\sum_{\substack{\mathbf{x}, \mathbf{y} \in \mathcal{C}_{a_n}^k; \mathbf{xy} \notin \Delta^{2k} \\ \ell_n \leq |\mathbf{x}|, |\mathbf{y}| \leq \mathcal{L}_n}} f(\mathbf{x}) f(\mathbf{y}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \frac{e^{-V(y^{(i)})}}{H_{y^{(i)}}}\right] \\ &\leq \|f\|_\infty^2 (\mathcal{L}_n)^{2k} \sum_{\alpha=1}^k \sum_{i_1 \neq i_2 \dots \neq i_\alpha=1}^k \sup_{\ell_n \leq q \leq \mathcal{L}_n} \mathbf{E}\left[\sum_{\substack{\mathbf{u} \in \Delta^{2k-\alpha} \\ |\mathbf{u}|=q}} \prod_{j=1}^\alpha e^{-2V(u^{(i_j)})} \prod_{\substack{i'=1 \\ i' \notin \{i_1, \dots, i_\alpha\}}}^k e^{-V(u^{(i')})}\right]. \end{aligned}$$

One can decompose according to the value of  $\mathcal{S}^{2k-\alpha}(\mathbf{u})$ . We have (see the proof of Lemma 3.9 for example)

$$\lim_{n \rightarrow \infty} \sup_{\ell_n \leq \mathbf{q} \leq \mathfrak{L}_n} \mathbf{E} \left[ \sum_{\substack{\mathbf{u} \in \Delta^{2k-\alpha} \\ |\mathbf{u}| = \mathbf{q}}} \mathbb{1}_{\{\mathcal{S}^{2k-\alpha}(\mathbf{u}) > a_n\}} \prod_{j=1}^{\alpha} e^{-2V(u^{(i_j)})} \prod_{\substack{i'=1 \\ i' \notin \{i_1, \dots, i_\alpha\}}}^k e^{-V(u^{(i')})} \right] = 0,$$

and by independence of the increments of the branching random walk  $(\mathbb{T}, (V(x), x \in \mathbb{T}))$  and the facts that  $\psi(1) = 0$  and  $\psi(2) < 0$

$$\begin{aligned} & \sup_{\ell_n \leq \mathbf{q} \leq \mathfrak{L}_n} \mathbf{E} \left[ \sum_{\substack{\mathbf{u} \in \mathcal{C}_{a_n}^{2k-\alpha} \\ |\mathbf{u}| = \mathbf{q}}} \prod_{j=1}^{\alpha} e^{-2V(u^{(i_j)})} \prod_{\substack{i'=1 \\ i' \notin \{i_1, \dots, i_\alpha\}}}^k e^{-V(u^{(i')})} \right] \\ &= \sup_{\ell_n \leq \mathbf{q} \leq \mathfrak{L}_n} \prod_{j=1}^{\alpha} e^{(q_{i_j} - a_n)\psi(2)} \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{a_n}^{2k-\alpha}} \prod_{j=1}^{\alpha} e^{-2V(z^{(i_j)})} \prod_{\substack{i'=1 \\ i' \notin \{i_1, \dots, i_\alpha\}}}^k e^{-V(z^{(i')})} \right] \\ &\leq \mathfrak{C}_{3.8} e^{\alpha(\ell_n - a_n)\psi(2)}, \end{aligned}$$

where  $\mathfrak{C}_{3.8} > 0$  is a constant coming from Lemma 3.3, thus giving the convergence we wanted, recalling that  $a_n \leq \ell_n/2$ . Similarly, we have

$$\lim_{n \rightarrow \infty} \frac{1}{(\mathfrak{L}_n)^{2k}} \mathbf{E} \left[ \sum_{\substack{\mathbf{x}, \mathbf{y} \in \mathcal{C}_{a_n}^k; \mathbf{xy} \in \Delta^{2k} \setminus \mathcal{C}_{a_n}^{2k} \\ \ell_n \leq |\mathbf{x}|, |\mathbf{y}| \leq \mathfrak{L}_n}} f(\mathbf{x})f(\mathbf{y}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \frac{e^{-V(y^{(i)})}}{H_{y^{(i)}}} \right] = 0,$$

thus giving

$$\begin{aligned} & \lim_{n \rightarrow \infty} \frac{1}{(\mathfrak{L}_n)^{2k}} \mathbf{E} \left[ \left( \sum_{\substack{\mathbf{x} \in \mathcal{C}_{a_n}^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} f(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \right)^2 \right. \\ & \quad \left. - \sum_{\substack{\mathbf{x}, \mathbf{y} \in \Delta^k; \mathbf{xy} \in \mathcal{C}_{a_n}^{2k} \\ \ell_n \leq |\mathbf{x}|, |\mathbf{y}| \leq \mathfrak{L}_n}} f(\mathbf{x})f(\mathbf{y}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \frac{e^{-V(y^{(i)})}}{H_{y^{(i)}}} \right] = 0. \quad (43) \end{aligned}$$

Exact same arguments yield

$$\begin{aligned} & \lim_{n \rightarrow \infty} \mathbf{E} \left[ \left( \sum_{\mathbf{x} \in \Delta_{a_n}^k} f(\mathbf{x}) \prod_{i=1}^k e^{-V(x^{(i)})} \tilde{\varphi}_n(H_{x^{(i)}}) \right)^2 \right. \\ & \quad \left. - \sum_{\mathbf{x}, \mathbf{y} \in \Delta_{a_n}^k; \mathbf{xy} \in \Delta_{a_n}^{2k}} f(\mathbf{x})f(\mathbf{y}) \prod_{i=1}^k e^{-V(x^{(i)})} \tilde{\varphi}_n(H_{x^{(i)}}) e^{-V(y^{(i)})} \tilde{\varphi}_n(H_{y^{(i)}}) \right] = 0. \quad (44) \end{aligned}$$

Finally, similarly as equation (42), using again the hereditary assumption 5, we have

$$\begin{aligned} & \mathbf{E} \left[ \frac{1}{(\mathbf{L}_n)^{2k}} \sum_{\substack{\mathbf{x}, \mathbf{y} \in \Delta^k; \mathbf{x}\mathbf{y} \in \mathcal{C}_{a_n}^{2k} \\ \ell_n \leq |\mathbf{x}|, |\mathbf{y}| \leq \mathfrak{L}_n}} f(\mathbf{x})f(\mathbf{y}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}} \frac{e^{-V(y^{(i)})}}{H_{y^{(i)}}} \right] \\ &= \mathbf{E} \left[ \sum_{\substack{\mathbf{x}, \mathbf{y} \in \Delta_{a_n}^k; \mathbf{x}\mathbf{y} \in \Delta_{a_n}^{2k}} f(\mathbf{x})f(\mathbf{y}) \prod_{i=1}^k e^{-V(x^{(i)})} \tilde{\varphi}_n(H_{x^{(i)}}) e^{-V(y^{(i)})} \tilde{\varphi}_n(H_{y^{(i)}}) \right], \end{aligned}$$

so (43) and (44) yield (41). We now prove that

$$\lim_{n \rightarrow \infty} \mathbf{E} \left[ \left[ (c_\infty)^k \sum_{\mathbf{z} \in \Delta_{a_n}^k} f(\mathbf{z}) \prod_{i=1}^k e^{-V(z^{(i)})} - \sum_{\mathbf{z} \in \Delta_{a_n}^k} f(\mathbf{z}) \prod_{i=1}^k e^{-V(z^{(i)})} \tilde{\varphi}_n(H_{z^{(i)}}) \right] \right] = 0. \quad (45)$$

Let  $h_n = \log n$  (the choice of  $h_n$  is almost arbitrary,  $h_n \rightarrow \infty$  with  $h_n = o(n^\theta)$  for all  $\theta > 0$  should be enough). Note that  $|(c_\infty)^k - \prod_{i=1}^k \tilde{\varphi}_n(H_{z^{(i)}})| \leq 2$  so

$$\begin{aligned} & \mathbf{E} \left[ \left[ (c_\infty)^k \sum_{\mathbf{z} \in \Delta_{a_n}^k} f(\mathbf{z}) \prod_{i=1}^k e^{-V(z^{(i)})} - \sum_{\mathbf{z} \in \Delta_{a_n}^k} f(\mathbf{z}) \prod_{i=1}^k e^{-V(z^{(i)})} \tilde{\varphi}_n(H_{z^{(i)}}) \right] \right] \\ & \leq \|f\|_\infty \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{a_n}^k} \left( \prod_{i=1}^k e^{-V(z^{(i)})} \mathbf{1}_{\{H_{z^{(i)}} \leq h_n\}} \right) \left| (c_\infty)^k - \prod_{i=1}^k \tilde{\varphi}_n(H_{z^{(i)}}) \right| \right] \\ & \quad + 2\|f\|_\infty \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{a_n}^k} \mathbf{1}_{\{\max_{1 \leq i \leq k} H_{z^{(i)}} > h_n\}} e^{-\langle \mathbf{1}, V(\mathbf{z}) \rangle_k} \right]. \end{aligned}$$

We show that  $\lim_{n \rightarrow \infty} \sup_{1 \leq r_1, \dots, r_k \leq h_n} |(c_\infty)^k - \prod_{i=1}^k \tilde{\varphi}_n(r_i)| = 0$ . For that, on the first hand, one can see that  $\varphi_{n,p}(r) \leq \mathbf{E}[1/H_{\ell_n - a_n}^S]$  where we recall that  $H_m^S = \sum_{j=0}^m e^{S_j - S_m}$  (see (10) for the definition of the random walk  $S$ ). On the other, for any  $\ell_n \leq p \leq \mathfrak{L}_n$  and  $1 \leq r \leq h_n$ ,  $\varphi_{n,p}(r)$  is larger, for any  $\tilde{r} > 0$ , than

$$\mathbf{E} \left[ \sum_{|x|=p-a_n} \frac{e^{-V(x)}}{h_n e^{-V(x)} + H_x} \mathbf{1}_{\{V(x) \geq \tilde{r} \log n\}} \right] \geq \mathbf{E} \left[ \frac{1}{h_n n^{-\tilde{r}} + H_{\mathfrak{L}_n - a_n}^S} \right] - \mathbf{P}(S_{p-a_n} < \tilde{r} \log n).$$

where we have used the many-to-one Lemma 3.1.

Note that  $\mathbf{P}(S_{p-a_n} < \tilde{r} \log n) \leq \mathbf{P}(\min_{2\delta_0^{-1} \log n \leq j \leq \mathfrak{L}_n} S_j < \tilde{r} \log n) \rightarrow 0$  when  $n \rightarrow \infty$  for some  $\tilde{r} > 0$  since  $a_n = (2\delta_0)^{-1} \log n$  and  $\psi'(1) < 0$ . Moreover, by definition, both  $(\mathbf{E}[1/H_{\ell_n - a_n}^S])$  and  $(\mathbf{E}[1/(h_n n^{-\tilde{r}} + H_{\mathfrak{L}_n - a_n}^S)])$  goes to  $c_\infty$  when  $n$  goes to  $\infty$  and we obtain the convergence. Then

$$\begin{aligned} & \mathbf{E} \left[ \left[ (c_\infty)^k \sum_{\mathbf{z} \in \Delta_{a_n}^k} f(\mathbf{z}) \prod_{i=1}^k e^{-V(z^{(i)})} - \sum_{\mathbf{z} \in \Delta_{a_n}^k} f(\mathbf{z}) \prod_{i=1}^k e^{-V(z^{(i)})} \tilde{\varphi}_n(H_{z^{(i)}}) \right] \right] \\ & \leq \|f\|_\infty \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{a_n}^k} e^{-\langle \mathbf{1}, V(\mathbf{z}) \rangle_k} \right] \sup_{1 \leq r_1, \dots, r_k \leq h_n} \left| (c_\infty)^k - \prod_{i=1}^k \tilde{\varphi}_n(r_i) \right| \\ & \quad + 2\|f\|_\infty \mathbf{E} \left[ \sum_{\mathbf{z} \in \Delta_{a_n}^k} \mathbf{1}_{\{\max_{1 \leq i \leq k} H_{z^{(i)}} > h_n\}} e^{-\langle \mathbf{1}, V(\mathbf{z}) \rangle_k} \right]. \end{aligned}$$

Using Lemma 3.3, first (i), then (ii) with  $h = h_n$ ,  $\sup_{n \in \mathbb{N}} \mathbf{E}[\sum_{\mathbf{z} \in \Delta_{a_n}^k} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_k}] < \infty$  and  $\lim_{n \rightarrow \infty} \mathbf{E}[\sum_{\mathbf{z} \in \Delta_{a_n}^k} \mathbb{1}_{\{\max_{1 \leq i \leq k} H_{z^{(i)}} > h_n\}} e^{-\langle \mathbf{1}, V(\mathbf{z}) \rangle_k}] = 0$  thus giving (45). Finally, putting together (41) and (45) yields the result.  $\square$

### 3.1.3. Convergence of the quasi-martingale $\mathcal{A}_l^k(f)$

Recall that

$$\mathcal{A}_l^k(f, \beta) = \sum_{\mathbf{x} \in \Delta_l^k} f(\mathbf{x}) e^{-\langle \beta, V(\mathbf{x}) \rangle_k} = \sum_{\mathbf{x} \in \Delta_l^k} f(\mathbf{x}) \prod_{i=1}^k e^{-\beta_i V(x^{(i)})} \quad \text{and} \quad \mathcal{A}_l^k(f) = \mathcal{A}_l^k(f, \mathbf{1}).$$

The aim of this subsection is to prove that  $\mathcal{A}_\infty^k := \lim_{l \rightarrow \infty} \mathcal{A}_l^k(f)$  exists when  $f$  satisfies our hereditary assumption 5. For that, let us define for any  $\mathbf{p} \in (\mathbb{N}^*)^{\times k}$

$$\mathcal{A}_{\mathbf{p}}^k(f) := \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}| = \mathbf{p}}} f(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_k},$$

where we recall that for any  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ ,  $|\mathbf{x}| = \mathbf{p}$  if and only if  $|x^{(i)}| = p_i$  for all  $i \in \{1, \dots, k\}$ . One can notice that when  $\mathbf{p} = (l, \dots, l) \in (\mathbb{N}^*)^{\times k}$ , we have  $\mathcal{A}_l^k(f) = \mathcal{A}_{\mathbf{p}}^k(f)$ .

**Lemma 3.9.** *Let  $k \geq 2$  be an integer and assume  $\kappa > 2k$ . Under the assumptions 1, 3 and 4, for any bounded function  $f : \Delta^k \rightarrow \mathbb{R}^+$ , there exists two constants  $\mathfrak{C}_{3.9} > 0$  and  $\mathfrak{b} \in (0, 1)$  such that for any  $\mathbf{p} \in (\mathbb{N}^*)^{\times k}$  and any integer  $m \geq 1$  such that  $m \leq \max \mathbf{p} := \max_{1 \leq i \leq k} p_i$*

$$\mathbf{E}^* [|\mathcal{A}_{\mathbf{p}}^k(f \mathbb{1}_{\mathcal{E}_m^k}) - \mathcal{A}_{\mathbf{p}}^k(f)|^2] \leq \mathfrak{C}_{3.9} e^{-\mathfrak{b}m}.$$

*Proof.* In order to avoid unnecessary technical difficulties, we prove it for any  $\kappa > 4$ . First note that  $\mathcal{A}_{\mathbf{p}}^k(f) - \mathcal{A}_{\mathbf{p}}^k(f \mathbb{1}_{\mathcal{E}_m^k}) = \sum_{\mathbf{x} \in \Delta^k; |\mathbf{x}| = \mathbf{p}} f(\mathbf{x}) \mathbb{1}_{\{\mathcal{S}^k(\mathbf{x}) > m\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_k}$  which is smaller than  $\|f\|_\infty \sum_{\mathbf{x} \in \Delta^k; |\mathbf{x}| = \mathbf{p}} \mathbb{1}_{\{\mathcal{S}^k(\mathbf{x}) > m\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_k}$ . Using a similar argument as we developed in the proof of Lemma 3.8, it is enough to show the following estimation:

$$\mathbf{E}^* \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\{\mathcal{S}^q(\mathbf{x}) > m\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] \leq \mathfrak{C}_{3.9,1} e^{-\mathfrak{b}m}, \quad (46)$$

for any  $q \in \{k, \dots, 2k\}$  and some constant  $\mathfrak{C}_{3.9,1} > 0$ . Assume that  $\min \mathbf{p} < \max \mathbf{p}$  (the proof is similar when  $\min \mathbf{p} = \max \mathbf{p}$ ). Note that if  $m < \min \mathbf{p}$ , then

$$\begin{aligned} \mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\{\mathcal{S}^q(\mathbf{x}) > m\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] &= \mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\{m < \mathcal{S}^q(\mathbf{x}) \leq \min \mathbf{p}\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] \\ &\quad + \mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\{\mathcal{S}^q(\mathbf{x}) > \min \mathbf{p}\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right]. \end{aligned}$$

One can notice that, if  $|\mathbf{x}| = \mathbf{p}$  and  $\mathcal{S}^q(\mathbf{x}) \leq \min \mathbf{p}$ , then  $\mathcal{S}^q(\mathbf{x}) = \mathcal{S}^q(\mathbf{u})$  for any  $\mathbf{u} \in \Delta^q$  such that  $\max |\mathbf{u}| = \min |\mathbf{u}| = \min \mathbf{p}$ . Hence, as usual

$$\begin{aligned} \mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\{m < \mathcal{S}^q(\mathbf{x}) \leq \min \mathbf{p}\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] &= \mathbf{E} \left[ \sum_{\mathbf{u} \in \Delta_{\min \mathbf{p}}^q} \mathbb{1}_{\{\mathcal{S}^q(\mathbf{u}) > m\}} \sum_{\mathbf{x} \in \Delta^q; \mathbf{x} \geq \mathbf{u}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] \\ &= \mathbf{E} \left[ \sum_{\mathbf{u} \in \Delta_{\min \mathbf{p}}^q} \mathbb{1}_{\{\mathcal{S}^q(\mathbf{u}) > m\}} e^{-\langle \mathbf{1}, V(\mathbf{u}) \rangle_q} \right], \end{aligned}$$

thus giving

$$\begin{aligned} \mathbf{E}\left[\sum_{\substack{\mathbf{x}\in\Delta^q \\ |\mathbf{x}|=p}} \mathbb{1}_{\{\mathcal{C}^q(\mathbf{x})>m\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q}\right] &= \mathbf{E}\left[\sum_{\substack{\mathbf{u}\in\Delta^q \\ |\mathbf{u}|=\min \mathbf{p}}} \mathbb{1}_{\{\mathcal{C}^q(\mathbf{u})>m\}} e^{-\langle \mathbf{1}, V(\mathbf{u}) \rangle_q}\right] \\ &\quad + \mathbf{E}\left[\sum_{\substack{\mathbf{x}\in\Delta^q \\ |\mathbf{x}|=p}} \mathbb{1}_{\{\mathcal{C}^q(\mathbf{x})>\min \mathbf{p}\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q}\right]. \end{aligned}$$

We deduce from this equality that it is enough to prove (46) for any  $m \leq \min \mathbf{p}$  with  $q \geq 3$ . Again, we focus on the case  $\min \mathbf{p} < \max \mathbf{p}$ .

Assume  $m \leq \min \mathbf{p}$ . Let  $\mathbf{x} \in \Delta^q$  such that  $|\mathbf{x}| = \mathbf{p}$  and  $\mathcal{C}^q(\mathbf{x}) > m$ . There exists an integer  $\mathfrak{f} \in \{m+1, \dots, \max \mathbf{p}\}$  such that, seen backwards in time, at least two vertices among  $x^{(1)}, \dots, x^{(q)}$  share a common ancestor for the first times in the generation  $\mathfrak{f}-1$  and there exists at least one vertex among these vertices in a generation smaller or equal to  $\mathfrak{f}-1$ . Then, one can notice that

$$\sum_{\substack{\mathbf{x}\in\Delta^q \\ |\mathbf{x}|=p}} \mathbb{1}_{\{\mathcal{C}^q(\mathbf{x})>m\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} = \sum_{\mathfrak{f}=m+1}^{\max \mathbf{p}} \sum_{\substack{\pi \text{ partition of } \\ \{1, \dots, q\}, |\pi| < q}} \sum_{\substack{\mathbf{x}\in\Delta^q \\ |\mathbf{x}|=p}} \mathbb{1}_{\Upsilon_{\mathfrak{f}-1, \pi} \cap \Upsilon_{\mathfrak{f}, \eta}}(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q},$$

where  $\eta = \{\{1\}, \dots, \{q\}\}$  (recall the definition of  $\Upsilon_{p-1, \pi} \cap \Upsilon_{p, \eta}$  in (15)).

By definition, there exists  $\eta \in \{1, \dots, q-2\}$  and  $(i_1, \dots, i_\eta, i_{\eta+1}, \dots, i_q) \in \llbracket 1, q \rrbracket_q$  such that  $\max_{1 \leq l \leq \eta} p_{i_l} \leq \mathfrak{f}-1$  and  $\min_{\eta+1 \leq l \leq q} p_{i_l} \geq \mathfrak{f}-1$ . By definition of the set  $\Upsilon_{\dots}$ , for all  $l \in \{1, \dots, \eta\}$ , if  $i_l$  belongs to the block  $\mathbf{B}$  of the partition  $\pi$ , then  $\mathbf{B} = \{i_l\}$ . Let  $\bar{\pi} := \pi \setminus \{\{i_1\}, \dots, \{i_\eta\}\}$  and for all  $j \in \{1, \dots, |\pi| - \eta\}$ , denote by  $\bar{\mathbf{B}}_j$  the  $j$ -th block (ordered by their least element) of the partition  $\bar{\pi}$  of the set  $\{i_{\eta+1}, \dots, i_q\} = \{1, \dots, q\} \setminus \{i_1, \dots, i_\eta\}$ . We have

$$\begin{aligned} \mathbf{E}\left[\sum_{\substack{\mathbf{x}\in\Delta^q \\ |\mathbf{x}|=p}} \mathbb{1}_{\Upsilon_{\mathfrak{f}-1, \pi} \cap \Upsilon_{\mathfrak{f}, \eta}}(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \middle| \mathcal{F}_{\mathfrak{f}}\right] &= \sum_{\substack{\mathbf{u}\in\Delta^\eta \\ |\mathbf{u}|=p}} e^{-\langle \mathbf{1}, V(\mathbf{u}) \rangle_\eta} \sum_{\mathbf{z}\in\Delta_{\mathfrak{f}-1}^{|\pi|-\eta}} \prod_{j=1}^{|\pi|-\eta} \sum_{\mathbf{v}^{(j)} \in \Delta_{\mathfrak{f}}^{|\bar{\mathbf{B}}_j|}} \prod_{i=1}^{|\bar{\mathbf{B}}_j|} \\ &\quad \times \mathbb{1}_{\{(v^{(j,i)})^* = z^{(j)}\}} e^{-V(v^{(j,i)})}, \end{aligned}$$

where  $|\mathbf{u}| = \mathbf{p}$  means that  $u^{(l)} = p_{i_l}$  for all  $l \in \{1, \dots, \eta\}$ ,  $\mathbf{v}^{(j)} = (v^{(j,1)}, \dots, v^{(j,|\bar{\mathbf{B}}_j|)})$ . Thus

$$\begin{aligned} \mathbf{E}\left[\sum_{\substack{\mathbf{x}\in\Delta^q \\ |\mathbf{x}|=p}} \mathbb{1}_{\Upsilon_{\mathfrak{f}-1, \pi} \cap \Upsilon_{\mathfrak{f}, \eta}}(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \middle| \mathcal{F}_{\mathfrak{f}-1}\right] &= \sum_{\substack{\mathbf{u}\in\Delta^\eta \\ |\mathbf{u}|=p}} e^{-\langle \mathbf{1}, V(\mathbf{u}) \rangle_\eta} \sum_{\mathbf{z}\in\Delta_{\mathfrak{f}-1}^{|\pi|-\eta}} e^{-\langle \bar{\boldsymbol{\beta}}, V(\mathbf{z}) \rangle_{|\pi|-\eta}} \prod_{\bar{\mathbf{B}} \in \bar{\pi}} c_{\bar{\mathbf{B}}}(\mathbf{1}) \\ &= \prod_{\bar{\mathbf{B}} \in \bar{\pi}} c_{\bar{\mathbf{B}}}(\mathbf{1}) \sum_{\substack{\mathbf{u}\in\Delta^{|\pi|} \\ |\mathbf{u}|=\tilde{\mathbf{p}}}} e^{-\langle \tilde{\boldsymbol{\beta}}, V(\mathbf{u}) \rangle_{|\pi|}}, \end{aligned}$$

where  $\tilde{\mathbf{p}} = (p_1, \dots, p_\eta, \mathfrak{f}-1, \dots, \mathfrak{f}-1) \in (\mathbb{N}^*)^{\times |\pi|}$  and  $\tilde{\boldsymbol{\beta}} = (1, \dots, 1, \bar{\mathbf{B}}_1, \dots, \bar{\mathbf{B}}_{|\pi|-\eta}) \in (\mathbb{N}^*)^{\times |\pi|}$ . One can notice that there exists  $r_0 > 0$  such that

$$\mathbf{E}\left[\sum_{\substack{\mathbf{u}\in\Delta^{|\pi|} \\ |\mathbf{u}|=\tilde{\mathbf{p}}}} e^{-\langle \tilde{\boldsymbol{\beta}}, V(\mathbf{u}) \rangle_{|\pi|}} \mathbb{1}_{\{\min_{|w|=\mathfrak{f}-1} V(w) < r_0(\mathfrak{f}-1)\}}\right] \leq \mathfrak{C}_{3.9,2} e^{-(\mathfrak{f}-1)}, \quad (47)$$



for some constant  $\mathfrak{C}_{3.9,2} > 0$ . Indeed, By the Cauchy–Schwarz inequality,

$$\begin{aligned} \mathbf{E} \left[ \left( \sum_{\substack{\mathbf{u} \in \Delta^{|\pi|} \\ |\mathbf{u}| = \tilde{\mathbf{p}}}} e^{-\langle \mathbf{1}, V(\mathbf{u}) \rangle_{|\pi|}} \mathbf{1}_{\{\min_{|w|=f-1} V(w) < r_0(f-1)\}} \right)^2 \right] &\leq \mathbf{E} \left[ \sum_{\substack{\mathbf{u} \in \Delta^{|\pi|} \\ |\mathbf{u}| = \tilde{\mathbf{p}}}} e^{-\langle \mathbf{1}, V(\mathbf{u}) \rangle_{|\pi|}} \right]^2 \\ &\times \mathbf{P} \left( \min_{|w|=f-1} V(w) < r_0(f-1) \right)^{1/2}, \end{aligned}$$

and thanks to Lemma 3.3 (i),  $\mathbf{E}[(\sum_{\mathbf{u} \in \Delta^{|\pi|}; |\mathbf{u}| = \tilde{\mathbf{p}}} e^{-\langle \mathbf{1}, V(\mathbf{u}) \rangle_{|\pi|}})^2] \leq \mathfrak{C}_{3.3,1}$ , where we recall that  $\mathfrak{C}_{3.3,1} > 0$  is a constant doesn't depending on  $\mathbf{p}$  (or  $\tilde{\mathbf{p}}$ ) since  $|\pi| < q \leq 2k$ . Moreover, since  $\psi'(1) < 0$ , we can find  $r_0 > 0$  and a constant  $\mathfrak{C}_{3.9,3} > 0$  such that  $\mathbf{P}(\min_{|w|=f-1} V(w) < r_0(f-1)) \leq \mathfrak{C}_{3.9,3} e^{2(f-1)}$ . This yields (47).

Now, note that, since  $|\pi| < q$ , there is at least one block of the partition  $\pi$  with cardinal larger or equal to 2 so  $\langle \tilde{\beta}, V(\mathbf{z}) \rangle_{|\pi|} \geq \langle \mathbf{1}, V(\mathbf{z}) \rangle_{|\pi|} + \min_{|w|=f-1} V(w)$  thus giving that the mean  $\mathbf{E}[\sum_{\mathbf{x} \in \Delta^q; |\mathbf{x}| = \mathbf{p}} \mathbf{1}_{\Upsilon_{f-1, \pi} \cap \Upsilon_{f, \eta}}(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q}]$  is smaller than

$$\begin{aligned} &\prod_{\tilde{\mathbf{B}} \in \tilde{\pi}} c_{\tilde{\mathbf{B}}}(\mathbf{1}) \left( \mathbf{E} \left[ \left( \sum_{\substack{\mathbf{u} \in \Delta^{|\pi|} \\ |\mathbf{u}| = \tilde{\mathbf{p}}}} e^{-\langle \tilde{\beta}, V(\mathbf{u}) \rangle_{|\pi|}} \mathbf{1}_{\{\min_{|w|=f-1} V(w) < r_0(f-1)\}} \right)^2 \right] \right. \\ &\left. + \mathbf{E} \left[ e^{-\min_{|w|=f-1} V(w)} \sum_{\substack{\mathbf{u} \in \Delta^{|\pi|} \\ |\mathbf{u}| = \tilde{\mathbf{p}}}} e^{-\langle \mathbf{1}, V(\mathbf{u}) \rangle_{|\pi|}} \mathbf{1}_{\{\min_{|w|=f-1} V(w) \geq r_0(f-1)\}} \right] \right), \end{aligned}$$

which, thanks to Lemma 3.3 (i) and (47), is smaller than  $\mathfrak{C}_{3.9,4} e^{-(1 \wedge r_0)(f-1)}$  for some constant  $\mathfrak{C}_{3.9,4} > 0$ . Finally

$$\mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^q \\ |\mathbf{x}| = \mathbf{p}}} \mathbf{1}_{\{\mathcal{S}^q(\mathbf{x}) > m\}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_q} \right] \leq \mathfrak{C}_{3.9,5} \sum_{f=m+1}^{\max \mathbf{p}} e^{-(1 \wedge r_0)(f-1)} \leq \mathfrak{C}_{3.9,1} e^{-(1 \wedge r_0)m},$$

for some constant  $\mathfrak{C}_{3.9,5} > 0$  and (46) is proved.  $\square$

The convergence of the sequence of random variables  $(\mathcal{A}_l^k(f))_l$  directly follows from Lemma 3.9. Indeed, let  $f$  be a bounded function satisfying the hereditary assumption 5. For any  $l > l' > m > \mathfrak{g}$

$$\mathcal{A}_l^k(f \mathbf{1}_{\mathcal{E}_m^k}) = \sum_{\mathbf{x} \in \Delta_l^k} f \mathbf{1}_{\mathcal{E}_m^k}(\mathbf{x}) e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_k} = \sum_{\mathbf{u} \in \Delta_{l'}^k} f \mathbf{1}_{\mathcal{E}_m^k}(\mathbf{u}) \sum_{\substack{\mathbf{x} \in \Delta_l^k \\ \mathbf{x} > \mathbf{u}}} e^{-\langle \mathbf{1}, V(\mathbf{x}) \rangle_k},$$

so  $\mathbf{E}[\mathcal{A}_l^k(f \mathbf{1}_{\mathcal{E}_m^k}) | \mathcal{F}_{l'}] = \mathcal{A}_{l'}^k(f \mathbf{1}_{\mathcal{E}_m^k})$  where  $\mathcal{F}_m = \sigma(\mathbb{T}, (V(x); |x| \leq m))$  and  $(\mathcal{A}_l^k(f \mathbf{1}_{\mathcal{E}_m^k}))_{l > m}$  is a martingale bounded in  $L^2(\mathbf{P})$ . In particular, for any integer  $m > \mathfrak{g}$ ,  $(\mathcal{A}_l^k(f \mathbf{1}_{\mathcal{E}_m^k}))_{l > m}$  converges in  $L^2(\mathbf{P}^*)$  and  $\mathbf{P}^*$ -almost surely. Hence, thanks to Lemma 3.9,  $(\mathcal{A}_l(f))_l$  is a Cauchy sequence in  $L^2(\mathbf{P}^*)$  and therefore,  $\mathcal{A}_\infty^k(f)$  exists.

### 3.1.4. $k$ -tuples in the set $\Delta^k \setminus \mathcal{E}_{a_n}^k$

Before proving Proposition 1, let us show that the contribution of the  $k$ -tuples in the set  $\mathfrak{E}^{k, \cdot} \cap \Delta^k \setminus \mathcal{E}_{a_n}^k$  is not significant. To do that, the following lemma provides an estimation for the quasi-independent version (38) of the range on the set  $\mathcal{E}_{a_n}^k$ :

**Lemma 3.10.** *Let  $\varepsilon_1 \in (0, 1)$ ,  $k \geq 2$  and assume  $\kappa > 2k$ . Under the assumptions 1, 3 and 4, there exist two constants  $C_{3.10} > 0$  and  $\rho_8 > 0$  such that*

$$\mathbb{E}^* \left[ \frac{1}{(n^{1/2} \mathbf{L}_n)^k} \sum_{\mathbf{j} \in \llbracket 1, \mathfrak{s}_n \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, \mathbf{1}_{\Delta^k \setminus \mathcal{C}_{a_n}^k}) \right] \leq C_{3.10} n^{-\rho_8}, \quad (48)$$

with  $\mathfrak{s}_n = n^{1/2}/\varepsilon_1$ .

*Proof.* Recall that, thanks to the strong Markov property together with (35)

$$\mathbb{E}^{\mathcal{E}} \left[ \mathcal{A}^{k,n}(\mathbf{j}, \mathbf{1}_{\Delta^k \setminus \mathcal{C}_{a_n}^k}) \right] = \sum_{\substack{\mathbf{x} \in \Delta^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} \mathbf{1}_{\Delta^k \setminus \mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}},$$

and since  $H_{x^{(i)}} \geq 1$

$$\begin{aligned} \mathbb{E}^* \left[ \sum_{\mathbf{j} \in \llbracket 1, \mathfrak{s}_n \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, \mathbf{1}_{\Delta^k \setminus \mathcal{C}_{a_n}^k}) \right] &\leq (\mathfrak{s}_n)^k \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}} \mathbf{E}^* \left[ \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}| = \mathbf{p}}} \mathbf{1}_{\{\mathcal{S}^k(\mathbf{x}) > a_n\}} e^{-\langle 1, V(\mathbf{x}) \rangle_k} \right] \\ &\leq (\mathfrak{s}_n \mathbf{L}_n)^k \mathfrak{C}_{3.9} e^{-b a_n} = (\mathfrak{s}_n \mathbf{L}_n)^k \mathfrak{C}_{3.9} n^{-b(2\delta_0)^{-1}}, \end{aligned}$$

which ends the proof.  $\square$

We are now ready to prove Proposition 1.

*Proof of Proposition 1.* We have to prove that for any  $\varepsilon_1 n^{1/2} \leq s \leq n^{1/2}/\varepsilon_1$ ,  $\varepsilon_1 \in (0, 1)$

$$\mathbb{P}^* \left( \left| \frac{1}{(s \mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_{n, T^s}, f \mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathcal{C}_{a_n}^k}) - (c_\infty)^k \mathcal{A}_\infty^k(f) \right| > \varepsilon/2 \right) \xrightarrow{n \rightarrow \infty} 0. \quad (49)$$

We deduce from Lemma 3.7 with  $\mathbf{a} = 1$  that the range  $\sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k})$  concentrates around its quenched mean. Indeed, for any  $\varepsilon \in (0, 1)$ , by Markov inequality

$$\begin{aligned} &\mathbb{P} \left( \left| \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) - \mathbb{E}^{\mathcal{E}} \left[ \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) \right] \right| > \varepsilon (s \mathbf{L}_n)^k / 16 \right) \\ &\leq \frac{16^2}{\varepsilon^1 (s \mathbf{L}_n)^{2k}} \mathbb{E} \left[ \left( \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) - \mathbb{E}^{\mathcal{E}} \left[ \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) \right] \right)^2 \right] \\ &\leq 16^2 \mathfrak{C}_{3.7} \frac{\mathfrak{L}_n}{s} \leq \mathfrak{C}_1 \frac{\mathfrak{L}_n}{n^{1/2}} \xrightarrow{n \rightarrow \infty} 0, \end{aligned}$$

where the last inequality comes from the fact that  $\mathfrak{L}_n = o(n^{1/2})$ . Then, we know, thanks to Lemma 3.6 with  $g = f$ , that  $\mathcal{A}^k(\mathcal{D}_{n, T^s}, f \mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathcal{C}_{a_n}^k})$  behaves like its quasi-independent version  $\sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k})$ : for  $n$  large enough

$$\mathbb{P}^* \left( \left| \mathcal{A}^k(\mathcal{D}_{n, T^s}, f \mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathcal{C}_{a_n}^k}) - \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) \right| > \varepsilon (s \mathbf{L}_n)^k / 16 \right) \leq n^{-\rho_4},$$

hence

$$\lim_{n \rightarrow \infty} \mathbb{P}^* \left( \left| \mathcal{A}^k(\mathcal{D}_{n, T^s}, f \mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathcal{C}_{a_n}^k}) - \mathbb{E}^{\mathcal{E}} \left[ \sum_{\mathbf{j} \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(\mathbf{j}, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) \right] \right| > \varepsilon (s \mathbf{L}_n)^k / 8 \right) = 0.$$

One can notice that

$$\mathbb{E}^{\mathcal{E}} \left[ \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f \mathbf{1}_{\mathcal{C}_{a_n}^k}) \right] = s(s-1) \cdots (s-k+1) \sum_{\substack{\mathbf{x} \in \Delta^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} f \mathbf{1}_{\mathcal{C}_{a_n}^k}(\mathbf{x}) \prod_{i=1}^k \frac{e^{-V(x^{(i)})}}{H_{x^{(i)}}}.$$

Finally, Lemma 3.8 yields

$$\mathbb{P}^* \left( \left| \frac{1}{(s\mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_{n,T^s}, f \mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathcal{C}_{a_n}^k}) - (c_\infty)^k \mathcal{A}_{a_n}^k(f) \right| > \varepsilon/4 \right) \xrightarrow{n \rightarrow \infty} 0,$$

and the result of the subsection 3.1.3 leads to the convergence in (49).

Now using Lemma 3.10, we show that

$$\mathbb{P}^* \left( \frac{1}{(s\mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_{n,T^s}, f \mathbf{1}_{\mathfrak{E}^{k,s} \cap \Delta^k \setminus \mathcal{C}_{a_n}^k}) > \varepsilon/2 \right) \xrightarrow{n \rightarrow \infty} 0. \quad (50)$$

Indeed

$$\begin{aligned} \frac{1}{(s\mathbf{L}_n)^k} \mathcal{A}^k(\mathcal{D}_{n,T^s}, f \mathbf{1}_{\mathfrak{E}^{k,s} \cap \Delta^k \setminus \mathcal{C}_{a_n}^k}) &\leq \frac{1}{(s\mathbf{L}_n)^k} \sum_{j \in \llbracket 1, s \rrbracket_k} \mathcal{A}^{k,n}(j, f \mathbf{1}_{\Delta^k \setminus \mathcal{C}_{a_n}^k}) \\ &\leq \frac{1}{(\varepsilon_1 n^{1/2} \mathbf{L}_n)^k} \sum_{j \in \llbracket 1, n^{1/2}/\varepsilon_1 \rrbracket_k} \mathcal{A}^{k,n}(j, f \mathbf{1}_{\Delta^k \setminus \mathcal{C}_{a_n}^k}), \end{aligned}$$

so Markov inequality together with Lemma 3.10 leads to (50). We end the proof putting together (49) and (50).  $\square$

### 3.2. The range on $\Delta^k \setminus \mathfrak{E}^{k,\cdot}$ .

Recall

$$\mathcal{A}^k(\mathcal{D}_{n,T^s}, g) = \sum_{\substack{\mathbf{x} \in \Delta^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} g(\mathbf{x}) \mathbf{1}_{\{T_{\mathbf{x}} < T^s\}},$$

where  $T_{\mathbf{x}} = \max_{1 \leq i \leq k} T_{x^{(i)}}$ ,  $T_z = \min\{j \geq 0; X_j = z\}$ ,  $T^0 = 0$  and  $T^s = \min\{j > T^{s-1}; X_j = e\}$  for  $s \in \mathbb{N}^*$ . Also recall that  $(\ell_n)$  and  $(\mathfrak{L}_n)$  are two sequences of positive integers such that  $\delta_0^{-1} \log n \leq \ell_n \leq \mathfrak{L}_n \leq n^{1/2}$ .

The last step of our study is to show that the contribution of the  $k$ -tuples of vertices in small generations (see (4)) and such that at least two of these vertices are visited during the same excursion is not significant. This section is thus devoted to the proof of Proposition 2, claiming that

$$\mathbb{P}^* \left( \sup_{s \leq n^{1/2}/\varepsilon_1} \mathcal{A}^k(\mathcal{D}_{n,T^s}, \mathbf{1}_{\Delta^k \setminus \mathfrak{E}^{k,s}}) > \varepsilon (n^{1/2} \mathbf{L}_n)^k \right) \xrightarrow{n \rightarrow \infty} 0$$

**Lemma 3.11.** *Let  $\varepsilon_1 \in (0, 1)$ ,  $k \geq 2$ , let  $\mathfrak{s}_n = n^{1/2}/\varepsilon_1$  and assume  $\kappa > 2k$ . Assume that the assumptions 1, 3, 4 hold and that  $\mathfrak{L}_n = o(n^{1/2})$ .*

(i) If

$$\mathfrak{E}_1^{k,s} := \bigcup_{j=1}^s \bigcap_{i=1}^k \{ \mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k; \mathcal{L}_{x^{(i)}}^{T^j} - \mathcal{L}_{x^{(i)}}^{T^{j-1}} \geq 1 \}$$

denotes the set of  $k$ -tuples of vertices visited during the same excursion before the instant  $T^s$ , then

$$\lim_{n \rightarrow \infty} \mathbb{E}^* \left[ \frac{1}{(n^{1/2} \mathbf{L}_n)^k} \sup_{s \leq s_n} \mathcal{A}^k(\mathcal{D}_{n, T^s}, \mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{E}_1^{k,s}}) \right] = 0.$$

(ii) Let  $\mathfrak{E}_2^{k,s} := \Delta^k \setminus (\mathfrak{E}^{k,s} \cup \mathfrak{E}_1^{k,s})$ . If  $k \geq 3$  and the assumption 2 hold, then, for all  $B > 0$

$$\lim_{n \rightarrow \infty} \mathbb{E}^* \left[ \frac{1}{(n^{1/2} \mathbf{L}_n)^k} \sup_{s \leq s_n} \mathcal{A}^k(\mathcal{D}_{n, T^s}, \mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{E}_2^{k,s}} \mathbf{1}_{\{V(\cdot) \geq -B\}}) \right] = 0,$$

with  $V(\mathbf{x}) \geq -B$  if and only if  $V(x^{(i)}) \geq -B$  for all  $i \in \{1, \dots, k\}$ .

*Proof.* In order to avoid unnecessary technical difficulties, we prove it for any  $\kappa > 4$ . Let us start with the proof of (i). By definition,  $\mathbf{x} \in \mathfrak{E}^{k,s} \cap \mathfrak{E}_1^{k,s}$  if and only if there exists  $j \in \{1, \dots, s\}$  such that for all  $1 \leq i \leq k$ ,  $N_{x^{(i)}}^{T^j} - N_{x^{(i)}}^{T^{j-1}} \geq 1$  and for all  $p \neq j$ ,  $N_{x^{(i)}}^{T^p} - N_{x^{(i)}}^{T^{p-1}} = 0$ . Thus, using again the strong Markov property

$$\begin{aligned} \mathbb{E} \left[ \sup_{s \leq s_n} \mathcal{A}^k(\mathcal{D}_{n, T^s}, \mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{E}_1^{k,s}}) \right] &= \mathbb{E} \left[ \sup_{s \leq s_n} \sum_{j=1}^s \sum_{\substack{\mathbf{x} \in \Delta^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} \mathbf{1}_{\cap_{i=1}^k \cap_{p \neq j} \{N_{x^{(i)}}^{T^j} - N_{x^{(i)}}^{T^{j-1}} \geq 1, N_{x^{(i)}}^{T^p} - N_{x^{(i)}}^{T^{p-1}} = 0\}} \right] \\ &\leq \sum_{j=1}^{s_n} \mathbb{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^k \\ \ell_n \leq |\mathbf{x}| \leq \mathfrak{L}_n}} \prod_{i=1}^k \mathbf{1}_{\{N_{x^{(i)}}^{T^j} - N_{x^{(i)}}^{T^{j-1}} \geq 1\}} \right] \\ &\leq s_n \sum_{\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}} \mathbb{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{P}^{\mathcal{E}}(T_{\mathbf{x}} < T^1) \right] \\ &\leq \mathfrak{C}_{2,1} s_n (\mathbf{L}_n)^k (\mathfrak{L}_n)^{k-1}, \end{aligned}$$

where we have used Lemma 3.2 (34) with  $m = \mathfrak{L}_n$  for the last inequality, recalling that the constant  $\mathfrak{C}'_{2,1} > 0$  doesn't depend on  $\mathbf{p}$ . By definition of  $s_n$

$$\mathbb{E} \left[ \frac{1}{(n^{1/2} \mathbf{L}_n)^k} \sup_{s \leq s_n} \mathcal{A}^k(\mathcal{D}_{n, T^s}, \mathbf{1}_{\mathfrak{E}^{k,s} \cap \mathfrak{E}_1^{k,s}}) \right] \leq \frac{\mathfrak{C}_{2,1}}{\varepsilon_1} \left( \frac{\mathfrak{L}_n}{n^{1/2}} \right)^{k-1},$$

which goes to 0 when  $n$  goes to  $\infty$  since  $\mathfrak{L}_n = o(n^{1/2})$  and this yields (i).

We now focus on (ii). Since  $k \geq 3$ ,  $\mathfrak{E}_2^{k,s}$  is nothing but the set of  $k$ -tuples in  $\Delta^k$  of vertices neither visited during  $k$  distinct excursions, nor during the same excursion. Therefore, there exists  $\mathfrak{e} \in \{2, \dots, k-1\}$  and  $\mathfrak{e}$  disjoint subsets  $I_1, \dots, I_{\mathfrak{e}}$  of  $\{1, \dots, k\}$  such that  $\{1, \dots, k\} = I_1 \cup \dots \cup I_{\mathfrak{e}}$  and for any  $j \in \{1, \dots, \mathfrak{e}\}$ ,  $i, i' \in I_j$  if and only if  $x^{(i)}$  and  $x^{(i')}$  are visited during the same excursion before the instant  $T^s$ :

$$\exists j \in \{1, \dots, \mathfrak{e}\} : (\mathcal{L}_{x^{(i)}}^{T^j} - \mathcal{L}_{x^{(i)}}^{T^{j-1}}) \wedge (\mathcal{L}_{x^{(i')}}^{T^j} - \mathcal{L}_{x^{(i')}}^{T^{j-1}}) \geq 1.$$

Let  $m \in \mathbb{N}^*$  and introduce the following subset of  $\Delta^k$

$$\Upsilon_m^{k,s} := \{\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k; \forall j \neq j' \in \{1, \dots, \mathfrak{e}\}, \forall i \in I_j, \forall i' \in I_{j'} : |x^{(i)} \wedge x^{(i')}| < m\},$$

where we recall that  $u \wedge v$  is the most recent common ancestor (MRCA) of  $u$  and  $v$ .  $\Upsilon_m^k$  is the set of  $k$ -tuples of vertices such that the MRCA of two vertices visited during two distinct excursions

before the instant  $T^s$  has to be in a generation smaller than  $m$ . Note that the MRCA of two vertices visited during the same excursion can be in a generation larger or equal to  $m$ .

Recall that  $(\Lambda_l)_{l \in \mathbb{N}}$  is the sequence of functions such that for all  $t > 0$ ,  $\Lambda_0(t) = t$  and for any  $l \in \{1, \dots, l_0\}$ ,  $\Lambda_{l-1}(t) = e^{\Lambda_l(t)}$  (see the assumption 2). Introduce  $\mathfrak{g}_{l,n} := 4k\delta_0^{-1}\Lambda_l(\mathfrak{L}_n)$ . Note that  $\mathfrak{g}_{0,n} > \mathfrak{L}_n$  so

$$\mathbb{E} \left[ \sup_{s \leq \mathfrak{s}_n} \mathcal{A}^k(\mathcal{D}_{n,T^s}, \mathbb{1}_{\mathfrak{G}^{k,s} \cap \mathfrak{E}_2^{k,s}} \mathbb{1}_{\{V(\cdot) \geq -B\}} \right] = \mathbb{E} \left[ \sup_{s \leq \mathfrak{s}_n} \mathcal{A}^k(\mathcal{D}_{n,T^s}, \mathbb{1}_{\mathfrak{G}^{k,s} \cap \mathfrak{E}_2^{k,s}} \mathbb{1}_{\{V(\cdot) \geq -B\} \cap \mathcal{C}_{\mathfrak{g}_{0,n}}^k} \right].$$

Recall that for any  $\mathbf{x} = (x^{(1)}, \dots, x^{(k)}) \in \Delta^k$ , it belongs to  $\mathfrak{G}^{k,s}$  if and only if  $x^{(i)}$  is visited during a single excursion before the instant  $T^s$  for all  $i \in \{1, \dots, k\}$ . Using what we previously said, we have, for any  $s \leq \mathfrak{s}_n$

$$\begin{aligned} \mathbb{1}_{\mathfrak{G}^{k,s} \cap \mathfrak{E}_2^{k,s}}(\mathbf{x}) &\leq \sum_{\mathfrak{e}=2}^{k-1} \sum_{j \in \llbracket 1, s \rrbracket_{\mathfrak{e}}} \sum_{\substack{I_1, \dots, I_{\mathfrak{e}} \text{ sets} \\ \cup_{i=1}^{\mathfrak{e}} I_i = \{1, \dots, k\}}} \prod_{p=1}^{\mathfrak{e}} Y_p \\ &\leq \sum_{\mathfrak{e}=2}^{k-1} \sum_{j \in \llbracket 1, \mathfrak{s}_n \rrbracket_{\mathfrak{e}}} \sum_{\substack{I_1, \dots, I_{\mathfrak{e}} \text{ sets} \\ \cup_{i=1}^{\mathfrak{e}} I_i = \{1, \dots, k\}}} \prod_{p=1}^{\mathfrak{e}} Y_p, \end{aligned}$$

where, for any  $p \in \{1, \dots, \mathfrak{e}\}$ ,  $Y_p := \mathbb{1}_{\cap_{i \in I_p} \{\mathcal{L}_{x^{(i)}}^{T^{j_p}} - \mathcal{L}_{x^{(i)}}^{T^{j_p-1}} \geq 1\}}$ . It follows that

$$\begin{aligned} &\mathbb{E} \left[ \sup_{s \leq \mathfrak{s}_n} \mathcal{A}^k(\mathcal{D}_{n,T^s}, \mathbb{1}_{\mathfrak{G}^{k,s} \cap \mathfrak{E}_2^{k,s}} \mathbb{1}_{\{V(\cdot) \geq -B\} \cap \mathcal{C}_{\mathfrak{g}_{0,n}}^k} \right) \\ &\leq \sum_{\mathbf{p} \in \{\ell, \dots, \mathfrak{L}_n\}^{\times k}} \sum_{l=1}^{l_0} \sum_{\mathfrak{e}=2}^{k-1} \sum_{j \in \llbracket 1, \mathfrak{s}_n \rrbracket_{\mathfrak{e}}} \sum_{\substack{I_1, \dots, I_{\mathfrak{e}} \text{ sets} \\ \cup_{i=1}^{\mathfrak{e}} I_i = \{1, \dots, k\}}} \mathbb{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\{V(\mathbf{x}) \geq -B\}} \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1,n}}^{k, \mathfrak{s}_n} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{k, \mathfrak{s}_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} Y_p \right] \\ &+ \sum_{\mathbf{p} \in \{\ell, \dots, \mathfrak{L}_n\}^{\times k}} \sum_{\mathfrak{e}=2}^{k-1} \sum_{j \in \llbracket 1, \mathfrak{s}_n \rrbracket_{\mathfrak{e}}} \sum_{\substack{I_1, \dots, I_{\mathfrak{e}} \text{ sets} \\ \cup_{i=1}^{\mathfrak{e}} I_i = \{1, \dots, k\}}} \mathbb{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\{V(\mathbf{x}) \geq -B\}} \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l_0,n}}^{k, \mathfrak{s}_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} Y_p \right]. \end{aligned} \quad (51)$$

First, let us prove that for any  $\mathbf{p} \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}$ ,

$$\mathbb{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\{V(\mathbf{x}) \geq -B\}} \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1,n}}^{k, \mathfrak{s}_n} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{k, \mathfrak{s}_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} Y_p \right] \leq \mathfrak{C}_{3.11,1}(\mathfrak{L}_n)^{k-\mathfrak{e}}. \quad (52)$$

The proof of (52) is quite technical so in order to keep it as clear as possible, as one can notice in the proof of Lemmas 3.3 (i) and 3.2 (34) with  $m = \mathfrak{L}_n$ , we can and shall restrict to the case  $\mathbf{p} = (m, \dots, m) \in \{\ell_n, \dots, \mathfrak{L}_n\}^{\times k}$ .

Thanks to the strong Markov property, the random variables  $Y_1, \dots, Y_{\mathfrak{e}}$  are i.i.d under  $\mathbb{P}^{\mathfrak{G}}$  and

$$\begin{aligned} &\mathbb{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}| = \mathbf{p}}} \mathbb{1}_{\{V(\mathbf{x}) \geq -B\}} \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1,n}}^{k, \mathfrak{s}_n} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{k, \mathfrak{s}_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} Y_p \right] \\ &= \sum_{\mathbf{x} \in \Delta_n^k} \mathbb{1}_{\{V(\mathbf{x}) \geq -B\}} \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1,n}}^{k, \mathfrak{s}_n} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{k, \mathfrak{s}_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} \mathbb{P}^{\mathfrak{G}}(\max_{i \in I_p} T_{x^{(i)}} < T^1). \end{aligned}$$

As usual,  $\sum_{\mathbf{x} \in \Delta_m^k} \mathbb{1}_{\{V(\mathbf{x}) \geq -B\}} \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1,n}}^{k,s_n} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{k,s_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} \mathbb{P}^{\mathfrak{E}}(\max_{i \in I_p} T_{x^{(i)}} < T^1)$  is equal to

$$\sum_{\ell=1}^{k-1} \sum_{\Pi \text{ increasing}} \sum_{\mathbf{t}; t_1 < \dots < t_\ell < m} \sum_{\mathbf{x} \in \Delta_m^k} \mathbb{1}_{\{V(\mathbf{x}) \geq -B\}} f_{\mathbf{t}, \Pi}^\ell \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1,n}}^{k,s_n} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{k,s_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} \mathbb{P}^{\mathfrak{E}}(\max_{i \in I_p} T_{x^{(i)}} < T^1), \tag{53}$$

where the genealogical tree function  $f_{\mathbf{t}, \Pi}^\ell$  is defined in (15). Recall that  $t_1 - 1, \dots, t_\ell - 1$  correspond to the consecutive coalescent/split times. We then define

$$\tau^\ell := \max\{j \in \{1, \dots, \ell\}; \exists p \neq p' \in \{2, \dots, \mathfrak{e}\}, \exists \mathbf{B} \in \pi_{j-1} : \mathbf{B} \cap I_p \neq \emptyset \text{ and } \mathbf{B} \cap I_{p'} \neq \emptyset\},$$

and the  $\mathbf{x}$ -version  $\tau^\ell(\mathbf{x})$  of  $\tau^\ell$ :

$$\tau^\ell(\mathbf{x}) := \max\{j \in \{1, \dots, \ell\}; \exists p \neq p' \in \{2, \dots, \mathfrak{e}\}, \exists i \in I_p, i' \in I_{p'} : |x^{(i)} \wedge x^{(i')}| = t_j - 1\}.$$

In other words, if the genealogical tree of  $\mathbf{x} \in \Delta^k$  is given by  $f_{\mathbf{t}, \Pi}^\ell$ , then  $\tau^\ell = \tau^\ell(\mathbf{x})$  and  $t_{\tau^\ell} - 1$  is the last generation at which two or more vertices visited during two distinct excursions share a common ancestor.

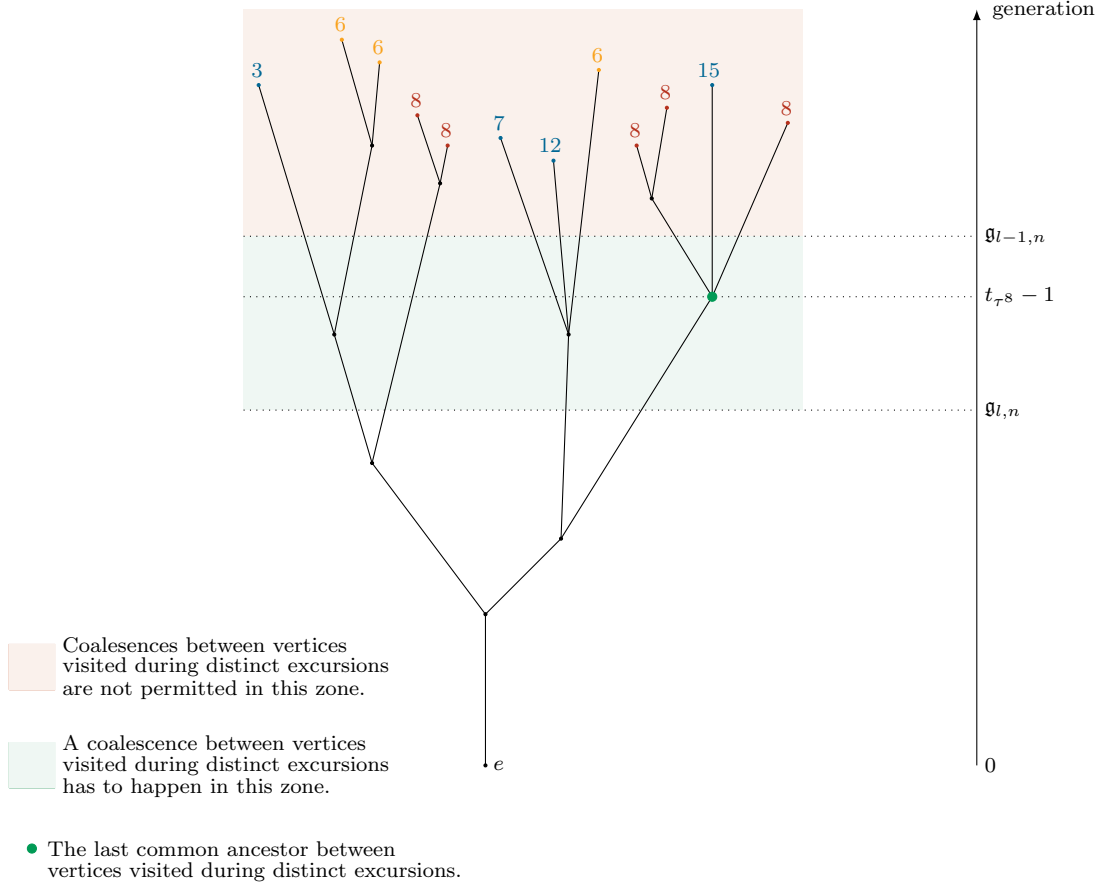


Figure 4: An example of a 12-tuple belonging to  $\Upsilon_{\mathfrak{g}_{l-1,n}}^{12,\cdot} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{12,\cdot}$  whose genealogical tree is given by  $f_{\mathbf{t},\Pi}^\ell$ . 6 means that the corresponding **vertex** is visited during the 6-th excursion above  $e^*$ . In the present example,  $\ell = 8$  and  $\tau^8 = 4$ .

By definition of  $\tau^\ell$ , for all  $j \geq \tau^\ell$ , if  $\mathbf{B} \in \pi_j$ , then  $\mathbf{B}$  is necessarily a subset of  $I_{p'}$  for some  $p' \in \{1, \dots, \mathfrak{e}\}$ . In other words, each coalescence that occurs between  $t_{\tau^\ell+1}$  and  $t_\ell$  involves exclusively two or more vertices visited during the same excursion. As a consequence, for any  $i \in \{\tau^\ell, \dots, \ell\}$  and  $p \in \{1, \dots, \mathfrak{e}\}$ , we can define the set  $I_p^i$  as follows: we first set  $I_p^\ell := I_p$  so  $I_1^\ell, \dots, I_\mathfrak{e}^\ell$  form a partition of  $\{1, \dots, k\}$ . As we said before, by definition of  $\tau^\ell$ , coalescences can only happen between two or more vertices which indexes belong to the same  $I_p^\ell$ . Thus, for any  $p \in \{1, \dots, \mathfrak{e}\}$ , there exists an integer  $\mathfrak{e}_p^{\ell-1} \geq 1$  and  $\mathfrak{e}_p^{\ell-1}$  distinct integers  $k_{p,1}^{\ell-1}, \dots, k_{p,\mathfrak{e}_p^{\ell-1}}^{\ell-1}$  in  $\{1, \dots, |\pi_{\ell-1}|\}$  such that for any  $j \in \{k_{p,1}^{\ell-1}, \dots, k_{p,\mathfrak{e}_p^{\ell-1}}^{\ell-1}\}$ , the block  $\mathbf{B}_j^{\ell-1}$  of the partition  $|\pi_{\ell-1}|$  is the union of  $b_{\ell-1}(\mathbf{B}_j)$  block(s) of the partition  $\pi_\ell$  of elements of  $F_p^\ell$ . We set  $F_p^{\ell-1} := \{k_{p,1}^{\ell-1}, \dots, k_{p,\mathfrak{e}_p^{\ell-1}}^{\ell-1}\}$  so  $I_1^{\ell-1}, \dots, I_\mathfrak{e}^{\ell-1}$  form a partition of  $\{1, \dots, |\pi_{\ell-1}|\}$ . Now, let  $i \in \{\tau^\ell + 1, \dots, \ell\}$  and assume that  $F_p^i$  has been built. By definition of  $\tau^\ell$ , for any  $p \in \{1, \dots, \mathfrak{e}\}$ , there exists an integer  $\mathfrak{e}_p^{i-1} \geq 1$  and  $\mathfrak{e}_p^{i-1}$  distinct integer  $k_{p,1}^{i-1}, \dots, k_{p,\mathfrak{e}_p^{i-1}}^{i-1}$  in  $\{1, \dots, |\pi_{i-1}|\}$  such that for any  $j \in \{k_{p,1}^{i-1}, \dots, k_{p,\mathfrak{e}_p^{i-1}}^{i-1}\}$ , the block  $\mathbf{B}_j^{i-1}$  of the partition  $|\pi_{i-1}|$  is the union of  $b_{i-1}(\mathbf{B}_j)$  block(s) of the partition  $\pi_i$  of elements of  $I_p^i$ . We set  $I_p^{i-1} := \{k_{p,1}^{i-1}, \dots, k_{p,\mathfrak{e}_p^{i-1}}^{i-1}\}$  so  $I_1^{i-1}, \dots, I_\mathfrak{e}^{i-1}$  form a partition of  $\{1, \dots, |\pi_{i-1}|\}$ . Hence, noticing that

$$f_{\mathbf{t},\Pi}^\ell \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1,n}}^{k,s_n} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{k,s_n}}(\mathbf{x}) \leq f_{\mathbf{t},\Pi}^\ell(\mathbf{x}) \mathbb{1}_{\{\mathfrak{g}_{l,n} \leq t_{\tau^\ell} - 1 < \mathfrak{g}_{l-1,n}\}} = f_{\mathbf{t},\Pi}^\ell(\mathbf{x}) \mathbb{1}_{\{\mathfrak{g}_{l,n} \leq t_{\tau^\ell} - 1 < \mathfrak{g}_{l-1,n}\}},$$

it is enough to show (52) for  $\mathfrak{g}_{l,n} \leq t_{\tau^\ell} - 1 < \mathfrak{g}_{l-1,n}$ . We then have

$$\begin{aligned} & \mathbf{E} \left[ \sum_{\mathbf{x} \in \Delta_m^k} \mathbb{1}_{\{\underline{V}(\mathbf{x}) \geq -B\}} f_{\mathbf{t},\Pi}^\ell \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1,n}}^{k,s_n} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{k,s_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} \mathbb{P}^\mathfrak{E} \left( \max_{i \in I_p} T_{x^{(i)}} < T^1 \right) \middle| \mathcal{F}_{t_{\tau^\ell}} \right] \\ & \leq \mathfrak{C}_{3.11,2} \sum_{\mathbf{u} \in \Delta_{\tau^\ell}^{|\pi_{\tau^\ell}|}} \mathbb{1}_{\{\underline{V}(\mathbf{u}) \geq -B\}} f_{\mathbf{t}^{\tau^\ell}, \Pi^{\tau^\ell}}^{\tau^\ell}(\mathbf{u}) \prod_{p=1}^{\mathfrak{e}} \mathbb{P}^\mathfrak{E} \left( \max_{i \in I_p^{\tau^\ell}} T_{u^{(i)}} < T^1 \right) \prod_{j=1}^{|\pi_{\tau^\ell}|} (H_{u^{(j)}})^{|\mathbf{B}_j^{\tau^\ell}|}, \end{aligned}$$

for some constant  $\mathfrak{C}_{3.11,2} > 0$  where  $\mathbf{t}^{\tau^\ell}$  and  $\Pi^{\tau^\ell}$  are defined in Example 5.

Note that  $t_{\tau^\ell} - 1$  is the first generation (backwards in time) at which a coalescence between two or more vertices visited during distinct excursions occurs so there exists a subset  $J_\ell$  of  $\{1, \dots, |\pi_{t_{\tau^\ell}-1}|\}$  and a collection  $\{\alpha_i; i \in J_\ell\}$  of  $|J_\ell|$  integers satisfying  $\alpha_i \geq 1$  for all  $i \in J_\ell$  and  $\sum_{i \in J_\ell} \alpha_i \leq k$  such that

$$\begin{aligned} & \mathbf{E} \left[ \sum_{\mathbf{x} \in \Delta_m^k} \mathbb{1}_{\{\underline{V}(\mathbf{x}) \geq -B\}} f_{\mathbf{t},\Pi}^\ell \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1,n}}^{k,s_n} \setminus \Upsilon_{\mathfrak{g}_{l,n}}^{k,s_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} \mathbb{P}^\mathfrak{E} \left( \max_{i \in I_p} T_{x^{(i)}} < T^1 \right) \middle| \mathcal{F}_{t_{\tau^\ell}-1} \right] \\ & \leq \mathfrak{C}_{3.11,3} \sum_{\mathbf{z} \in \Delta_{t_{\tau^\ell}-1}^{|\pi_{t_{\tau^\ell}-1}|}} f_{\mathbf{t}^{\tau^\ell-1}, \Pi^{\tau^\ell-1}}^{\tau^\ell-1}(\mathbf{z}) \mathbb{P}^\mathfrak{E} (T_{\mathbf{z}} < T^1) \prod_{j=1}^{|\pi_{\tau^\ell-1}|} (H_{z^{(j)}})^{|\mathbf{B}_j^{\tau^\ell-1}|} \prod_{i \in J_\ell} e^{-\alpha_i V(z^{(i)})} \mathbb{1}_{\{\underline{V}(\mathbf{z}) \geq -B\}}. \end{aligned}$$

Note that

$$\begin{aligned} \prod_{i \in J_\ell} e^{-\alpha_i V(z^{(i)})} \mathbb{1}_{\{\underline{V}(\mathbf{z}) \geq -B\}} &\leq \prod_{i \in J_\ell} e^{-\alpha_i V(z^{(i)})} \mathbb{1}_{\{\min_{i \in J_\ell} V(z^{(i)}) \geq -B, \min_{|z|=t_{\tau_\ell-1}} V(z) < \delta_0(t_{\tau_\ell-1})\}} \\ &\quad + e^{-\min_{|z|=t_{\tau_\ell-1}} V(z)} \mathbb{1}_{\{\min_{|z|=t_{\tau_\ell-1}} V(z) \geq \delta_0(t_{\tau_\ell-1})\}}, \end{aligned}$$

so  $\mathbf{E}[\sum_{\mathbf{x} \in \Delta_m^k} \mathbb{1}_{\{\underline{V}(\mathbf{x}) \geq -B\}} f_{\mathbf{t}, \Pi}^\ell \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1}, n}^{k, s_n}} \setminus \Upsilon_{\mathfrak{g}_{l, n}^{k, s_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} \mathbb{P}^\mathfrak{E}(\max_{i \in I_p} T_{x^{(i)}} < T^1)]$  is smaller than

$$\begin{aligned} \mathbf{E} \left[ \mathfrak{C}_{3.11,3} \sum_{\mathbf{z} \in \Delta_{t_{\tau_\ell-1}}^{|\pi_{\tau_\ell-1}|}} f_{\mathbf{t}_{\tau_\ell-1}, \Pi_{\tau_\ell-1}}^{\tau_\ell-1}(\mathbf{z}) \mathbb{P}^\mathfrak{E}(T_{\mathbf{z}} < T^1) \prod_{j=1}^{|\pi_{\tau_\ell-1}|} (H_{u^{(j)}})^{|B_j^{\tau_\ell-1}|} \right. \\ \left. \times (e^{kB} \mathbb{1}_{\{\min_{|z|=t_{\tau_\ell-1}} V(z) < \delta_0(t_{\tau_\ell-1})\}} + e^{-3\delta_0(t_{\tau_\ell-1})}) \right]. \end{aligned}$$

Using the same argument as the one we used in the proof of Lemma 3.2 together with the Cauchy–Schwarz inequality, we obtain that the previous mean is smaller than

$$\begin{aligned} \mathfrak{C}_{3.11,3} \sup_{d \in \mathbb{N}^*} \mathbf{E}[(H_{d-1}^S)^{4k-1}] \left( e^{kB} \mathbb{P} \left( \min_{|z|=t_{\tau_\ell-1}} V(z) < \delta_0(t_{\tau_\ell-1}) \right)^{1/2} + e^{-3\delta_0(t_{\tau_\ell-1})} \right) \\ \leq \mathfrak{C}_{3.11,3} \sup_{d \in \mathbb{N}^*} \mathbf{E}[(H_{d-1}^S)^{4k-1}] (e^{kB} + 1) e^{-k\Lambda_l(\mathfrak{L}_n)}, \end{aligned}$$

where we have used Lemma 3.4 with  $\zeta = \delta_0 t_{\tau_\ell}$  and the fact that  $t_{\tau_\ell} - 1 \geq \mathfrak{g}_{l, n}$ .

Back to (53) together with what we have just obtained and the fact that for all  $j \in \{1, \dots, \tau_\ell\}$ ,  $t_j \leq \mathfrak{g}_{l-1, n}$ ,  $\mathbf{E}[\sum_{\mathbf{x} \in \Delta^k, |\mathbf{x}|=p} \mathbb{1}_{\{\underline{V}(\mathbf{x}) \geq -B\}} \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1}, n}^{k, s_n}} \setminus \Upsilon_{\mathfrak{g}_{l, n}^{k, s_n}}(\mathbf{x}) \mathbb{1}_{\mathfrak{S}^{k, s_n} \cap \mathfrak{C}_2^{k, s_n}}(\mathbf{x})]$  is smaller than

$$\mathfrak{C}_{3.11,3} \sup_{d \in \mathbb{N}^*} \mathbf{E}[(H_{d-1}^S)^{4k-1}] (e^{kB} + 1) e^{-k\Lambda_l(\mathfrak{L}_n)} \sum_{\ell=1}^{k-1} \sum_{\Pi \text{ increasing}} (\mathfrak{g}_{l-1, n})^{\tau_\ell} (\mathfrak{L}_n)^{\ell - \tau_\ell}.$$

Note that  $\tau_\ell \leq \ell < k$ . Moreover, by definition,  $\ell - \tau_\ell$  is smaller than the total number of coalescences occurring between two or more vertices which indexes belong to the same set  $I_p^\ell$  and this number is smaller than  $\sum_{p=1}^{\mathfrak{e}} (|I_p^\ell| - 1) = k - \mathfrak{e}$  thus giving

$$\mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}|=p}} \mathbb{1}_{\{\underline{V}(\mathbf{x}) \geq -B\}} \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l-1}, n}^{k, s_n}} \setminus \Upsilon_{\mathfrak{g}_{l, n}^{k, s_n}}(\mathbf{x}) \prod_{p=1}^{\mathfrak{e}} Y_p \right] \leq \mathfrak{C}_{3.11,1} (\Lambda_{l-1}(\mathfrak{L}_n) e^{-\Lambda_l(\mathfrak{L}_n)})^k (\mathfrak{L}_n)^{k-\mathfrak{e}},$$

which, by definition of  $\Lambda_l(\mathfrak{L}_n)$ , is equal to  $\mathfrak{C}_{3.11,1}(\mathfrak{L}_n)^{k-\mathfrak{e}}$  and it yields (52).

In the same way, we can prove that

$$\mathbf{E} \left[ \sum_{\substack{\mathbf{x} \in \Delta^k \\ |\mathbf{x}|=p}} \mathbb{1}_{\{\underline{V}(\mathbf{x}) \geq -B\}} \mathbb{1}_{\Upsilon_{\mathfrak{g}_{l, n}^{k, s_n}}(\mathbf{x})} \prod_{p=1}^{\mathfrak{e}} Y_p \right] \leq \mathfrak{C}'_{3.11,1} (1 + \Lambda_{l+1}(\mathfrak{L}_n)^k) (\mathfrak{L}_n)^{k-\mathfrak{e}}, \quad (54)$$

for some constant  $\mathfrak{C}'_{3.11,1} > 0$ . Putting together (51), (52) and (54), we obtain, for some constant  $\mathfrak{C}_{3.11,4} > 0$

$$\begin{aligned} \mathbf{E} \left[ \frac{1}{(n^{1/2} \mathbf{L}_n)^k} \sup_{s \leq s_n} \mathcal{A}^k(\mathcal{D}_{n, T^s}, \mathbb{1}_{\mathfrak{S}^{k, s} \cap \mathfrak{C}_2^{k, s}} \mathbb{1}_{\{\underline{V}(\cdot) \geq -B\} \cap \mathfrak{C}_{\mathfrak{g}_{0, n}^k}}) \right] \\ \leq \mathfrak{C}_{3.11,4} \sum_{\mathfrak{e}=2}^{k-1} \left( \frac{\mathfrak{L}_n}{n^{1/2}} \right)^{k-\mathfrak{e}} (2 + \Lambda_{l_0+1}(\mathfrak{L}_n)^k). \end{aligned}$$

Using the fact that  $\Lambda_{l_0+1}(\mathfrak{L}_n)^k = (\log \Lambda_{l_0}(\mathfrak{L}_n))^k$ , we obtain (ii) thanks to the assumption 2.  $\square$



We are now ready to prove Proposition 2:

*Proof of Proposition 2.* Let  $\varepsilon' > 0$ . First, note that thanks to Lemma 3.5 and Fact 1 (36) there exists  $a_{\varepsilon'} > 0$  such that we can restrict our study to the  $k$ -tuples of vertices in the set  $\mathfrak{S}^{k,s} \cap \{V(\cdot) \geq -a_{\varepsilon'}\}$

$$\lim_{\varepsilon' \rightarrow 0} \limsup_{n \rightarrow \infty} \mathbb{P}^* \left( \sup_{s \leq \mathfrak{s}_n} \mathcal{A}^k(\mathcal{D}_{n,T^s}, \mathbb{1}_{\Delta^k \setminus \mathfrak{E}^{k,s}} (1 - \mathbb{1}_{\mathfrak{S}^{k,s} \cap \{V(\cdot) \geq -a_{\varepsilon'}\}})) > \varepsilon (n^{1/2} \mathbf{L}_n)^k \right) = 0,$$

where we recall that  $\mathfrak{s}_n = n^{1/2}/\varepsilon_1$ . Then, note that  $\mathcal{A}^k(\mathcal{D}_{n,T^s}, \mathbb{1}_{\Delta^k \setminus \mathfrak{E}^{k,s}} \mathbb{1}_{\mathfrak{S}^{k,s} \cap \{V(\cdot) \geq -a_{\varepsilon'}\}})$  is smaller than

$$\mathcal{A}^k(\mathcal{D}_{n,T^s}, \mathbb{1}_{\mathfrak{S}^{k,s} \cap \mathfrak{E}_1^{k,s}}) + \mathcal{A}^k(\mathcal{D}_{n,T^s}, \mathbb{1}_{\mathfrak{S}^{k,s} \cap \mathfrak{E}_2^{k,s}} \mathbb{1}_{\{V(\cdot) \geq -a_{\varepsilon'}\}}).$$

Hence, by Markov inequality, the result follows using Lemma 3.11 with  $B = a_{\varepsilon'}$ .  $\square$

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