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# Minimal position and critical martingale convergence in branching random walks, and directed polymers on disordered trees

by

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**Summary.** We establish a second-order almost sure limit theorem for the minimal position in a one-dimensional super-critical branching random walk, and also prove a martingale convergence theorem which answers a question of Biggins and Kyprianou [7]. Our method applies furthermore to the study of directed polymers on a disordered tree; in particular, we give a rigorous proof of a phase transition phenomenon for the partition function, described by Derrida and Spohn [13].

**Keywords.** Branching random walk, minimal position, martingale convergence, spine, marked tree, directed polymer on a tree.

**2000 Mathematics Subject Classification.** 60J80.

## 1 Introduction

### 1.1 Branching random walk and martingale convergence

We consider a branching random walk on the real line  $\mathbb{R}$ . Initially, a particle sits at the origin. Its children form the first generation; their displacements from the origin correspond to a point process on the line. These children have children of their own (who form the second generation), and behave – relative to their respective positions – like independent copies of the initial particle. And so on.

We write  $|u| = n$  if an individual  $u$  is in the  $n$ -th generation, and denote its position by  $V(u)$ . (In particular, for the initial ancestor  $e$ , we have  $V(e) = 0$ .) We assume throughout

the paper that there exists a constant  $C > 0$  such that  $\sup_{|u|=1} |V(u)| \leq C$ . For technical reasons, we also assume that

$$(1.1) \quad \mathbf{E}\left\{\left(\sum_{|u|=1} 1\right)^{1+\delta}\right\} < \infty, \quad \text{for some } \delta > 0,$$

where  $\mathbf{E}$  denotes expectation with respect to  $\mathbf{P}$ , the law of the branching random walk.

Let us define the (logarithmic) moment generating function

$$\psi(t) := \log \mathbf{E}\left\{\sum_{|u|=1} e^{-tV(u)}\right\}, \quad t \geq 0.$$

Following Biggins and Kyprianou [7], we assume

$$(1.2) \quad \psi(0) > 0, \quad \psi(1) = \psi'(1) = 0.$$

Since the number of particles in each generation forms a Galton–Watson tree, the assumption  $\psi(0) > 0$  in (1.2) says that this Galton–Watson tree is super-critical.

In the study of the branching random walk, there is a fundamental martingale, defined as follows:

$$(1.3) \quad W_n := \sum_{|u|=n} e^{-V(u)}, \quad n = 0, 1, 2, \dots$$

Since  $W_n \geq 0$ , it converges almost surely.

When  $\psi'(1) < 0$ , it is proved by Biggins and Kyprianou [5] that there exists a sequence of constants  $(a_n)$  such that  $\frac{W_n}{a_n}$  converges in probability to a non-degenerate limit which is (strictly) positive upon the survival of the system. This is called the Seneta–Heyde norming in [5] for branching random walk, referring to Seneta [29] and Heyde [17] on the rate of convergence in the classic Kesten–Stigum theorem for Galton–Watson processes.

The case  $\psi'(1) = 0$  is more delicate. In this case, it is known (Lyons [23]) that  $W_n \rightarrow 0$  almost surely. The following question is raised in Biggins and Kyprianou [7]: are there deterministic normalizers  $(a_n)$  such that  $\frac{W_n}{a_n}$  converges?

We aim at answering this question.

**Theorem 1.1** *Assume (1.1) and (1.2). There exists a deterministic positive sequence  $(\lambda_n)$  with  $0 < \liminf_{n \rightarrow \infty} \frac{\lambda_n}{n^{1/2}} \leq \limsup_{n \rightarrow \infty} \frac{\lambda_n}{n^{1/2}} < \infty$ , such that conditionally on the system's survival,  $\lambda_n W_n$  converges in distribution to  $\mathcal{W}$ , with  $\mathcal{W} > 0$  a.s. The distribution of  $\mathcal{W}$  is given in (6.11).*

The almost sure behaviour of  $W_n$  is described in Theorem 1.3 below. The two theorems together give a clear image of the asymptotics of  $W_n$ .

## 1.2 The minimal position in the branching random walk

A natural question in the study of branching random walks is about  $\inf_{|u|=n} V(u)$ , the position of the leftmost individual in the  $n$ -th generation. In the literature, the concentration (in terms of tightness or even weak convergence) of  $\inf_{|u|=n} V(u)$  around its median/quantiles had been studied by many authors. See for example Bachmann [3], Bramson and Zeitouni [11], as well as Section 5 of the survey paper by Aldous and Bandyopadhyay [2]. We also mention the recent paper of Lifshits [20], where an example of branching random walk is constructed such that  $\inf_{|u|=n} V(u) - \text{median}(\{\inf_{|u|=n} V(u)\})$  is tight but does not converge weakly.

We are interested in the asymptotic speed of  $\inf_{|u|=n} V(u)$ . Under assumption (1.2), it is known that

$$(1.4) \quad \frac{1}{n} \inf_{|u|=n} V(u) \rightarrow 0, \quad \text{a.s.}$$

$$(1.5) \quad \inf_{|u|=n} V(u) \rightarrow +\infty, \quad \text{a.s.}$$

The ‘‘law of large numbers’’ in (1.4) is a classic result, and can be found in Hammersley [14], Kingman [18], Biggins [4]. The system’s transience to the right, stated in (1.5), follows from the fact that  $W_n \rightarrow 0$ , a.s.

A refinement of (1.4) is obtained by McDiarmid [25]: there exists a constant  $c_1 < \infty$  such that

$$\limsup_{n \rightarrow \infty} \frac{1}{\log n} \inf_{|u|=n} V(u) \leq c_1, \quad \text{a.s.}$$

We intend to determine the exact rate at which  $\inf_{|u|=n} V(u)$  goes to infinity.

**Theorem 1.2** *Assume (1.1) and (1.2). Conditionally on the system’s survival, we have*

$$\lim_{n \rightarrow \infty} \frac{1}{\log n} \inf_{|u|=n} V(u) = \frac{3}{2}, \quad \text{a.s.}$$

Some brief comments on (1.2) are in order. In general (i.e., without assuming  $\psi(1) = \psi'(1) = 0$ ), the law of large numbers (1.4) reads  $\frac{1}{n} \inf_{|u|=n} V(u) \rightarrow c$ , a.s. (conditionally on the system’s survival), where  $c := \inf\{a \in \mathbb{R} : g(a) \geq 0\}$ , with  $g(a) := \inf_{t \geq 0} \{ta + \psi(t)\}$ . If

$$(1.6) \quad t^* \psi'(t^*) = \psi(t^*)$$

for some  $t_* \in (0, \infty)$ , then the branching random walk associated with the point process  $\widehat{V}(u) := t_* V(u) + \psi(t_*)|u|$  satisfies (1.2). That is, as long as (1.6) has a solution, the study will boil down to the case (1.2).

It is, however, possible that (1.6) has no solution. In such a situation, Theorem 1.2 does not apply. For example, a class of branching random walks is exhibited in Bramson [10], for which  $\inf_{|u|=n} V(u)$  has an exotic  $\log \log n$  behaviour.

We also mention that Addario-Berry [1] obtains a very precise asymptotic estimate of  $\mathbf{E}[\inf_{|u|=n} V(u)]$  under suitable assumptions.

In the case of branching Brownian motion, the analogue of Theorem 1.2 was proved by Bramson [9], by means of some powerful explicit analysis.

### 1.3 Directed polymers on a disordered tree

The following model is borrowed from the well-known paper of Derrida and Spohn [13]: Let  $\mathbb{T}$  be a rooted Cayley tree; we study all self-avoiding walks (= directed polymers) of  $n$  steps on  $\mathbb{T}$  starting from the root. To each edge of the tree, is attached a random variable (= potential). We assume that these random variables are independent and identically distributed. For each walk  $\omega$ , its energy  $E(\omega)$  is the sum of the potentials of the edges visited by the walk. So the partition function is

$$Z_n := \sum_{\omega} e^{-\beta E(\omega)},$$

where the sum is over all self-avoiding walks of  $n$  steps on  $\mathbb{T}$ , and  $\beta > 0$  is the inverse temperature.

More generally, we take  $\mathbb{T}$  to be a Galton–Watson tree, and observe that the energy  $E(\omega)$  corresponds to (the partial sum of) the branching random walk described in the previous sections. The associated partition function becomes

$$(1.7) \quad W_{n,\beta} := \sum_{|u|=n} e^{-\beta V(u)}, \quad \beta > 0.$$

Clearly, when  $\beta = 1$ ,  $W_{n,1}$  is just the  $W_n$  defined in (1.3).

If  $0 < \beta < 1$ , the study of  $W_{n,\beta}$  boils down to the case  $\psi'(1) < 0$  which was investigated by Biggins and Kyprianou [5]. In particular, conditionally on the system's survival,  $\frac{W_{n,\beta}}{\mathbf{E}\{W_{n,\beta}\}}$  converges almost surely to a (strictly) positive random variable.

We study the case  $\beta \geq 1$  in the present paper.

**Theorem 1.3** *Assume (1.1) and (1.2). Conditionally on the system's survival, we have*

$$(1.8) \quad W_n = n^{-1/2+o(1)}, \quad \text{a.s.}$$

$$(1.9) \quad W_{n,\beta} = n^{-3\beta/2+o(1)}, \quad \text{a.s.} \quad (\beta > 1)$$

Thus, there is a phase transition of the partition function at  $\beta = 1$ .

The remark on (1.2), stated after Theorem 1.2, applies to Theorem 1.3 as well.

The rest of the paper is as follows. In Section 2, we introduce a change-of-measures formula (Proposition 2.1) in terms of spines on marked trees. This formula will be of frequent use throughout the paper, its proof being postponed until Section 7. Section 3 contains a few preliminary results of the lower tail probability of the martingale  $W_n$ . Theorems 1.3, 1.2 and 1.1 are proved in Sections 4, 5 and 6, respectively.

Throughout the paper, we write  $q := \mathbf{P}\{\text{the system's survival}\} \in (0, 1)$ . The letter  $c$  with a subscript denotes finite and (strictly) positive constants. We also use the notation  $\sum_{\emptyset} := 0$  and  $\prod_{\emptyset} := 1$ .

## 2 Marked trees and spines

This section is devoted to a change-of-measures result (Proposition 2.1) on marked trees in terms of spines. The material of this section has been presented in the literature in various forms, see for example Chauvin et al. [12], Lyons et al. [24], Biggins and Kyprianou [6], Hardy and Harris [15]. Our approach has the advantages of: (1) allowing the branching random walk to die out; (2) allowing multiple points in the point process governing the branching random walk; and (3) defining the spines backwards.

There is a one-to-one correspondence between branching random walks and marked trees. Let us first introduce some notation. We label individuals in the branching random walk by their line of descent, so if  $u = i_1 \cdots i_n \in \mathcal{U} := \{\emptyset\} \cup \bigcup_{k=1}^{\infty} (\mathbb{N}^*)^k$  (where  $\mathbb{N}^* := \{1, 2, \dots\}$ ), then  $u$  is the  $i_n$ -th child of the  $i_{n-1}$ -th child of  $\dots$  of the  $i_1$ -th child of the initial ancestor  $e$ . It is sometimes convenient to consider an element  $u \in \mathcal{U}$  as a “word” of length  $|u|$ , with  $\emptyset$  corresponding to the initial ancestor  $e$ ; by an abuse of notation, we identify an individual  $u$  with its corresponding word.

If  $u, v \in \mathcal{U}$ , we denote by  $uv$  the concatenated word, with  $u\emptyset = \emptyset u = u$ .

Let  $\overline{\mathcal{U}} := \{(u, V(u)) : u \in \mathcal{U}, V : \mathcal{U} \rightarrow \mathbb{R}\}$ . Let  $\Omega$  be Neveu’s space of marked trees, which consists of all the subsets  $\omega$  of  $\overline{\mathcal{U}}$  such that the first component of  $\omega$  is a tree. [Recall that a tree  $t$  is a subset of  $\mathcal{U}$  satisfying: (i)  $\emptyset \in t$ ; (ii) if  $uj \in t$  for some  $j \in \mathbb{N}^*$ , then  $u \in t$ ; (iii) if  $u \in t$ , then  $uj \in t$  if and only if  $1 \leq j \leq \nu_u(t)$  for some non-negative integer  $\nu_u(t)$ .]

Let  $\mathbb{T} : \Omega \rightarrow \Omega$  be the identity application. According to Neveu [26], there exists a probability  $\mathbf{P}$  on  $\Omega$  such that the law of  $\mathbb{T}$  under  $\mathbf{P}$  is the law of the branching random walk described in the introduction.

Let us make a more intuitive presentation. For any  $\omega \in \Omega$ , let

$$(2.1) \quad \mathbb{T}^{\text{GW}}(\omega) := \text{the set of individuals ever born in } \omega,$$

$$(2.2) \quad \mathbb{T}(\omega) := \{(u, V(u)), u \in \mathbb{T}^{\text{GW}}(\omega), V \text{ such that } (u, V(u)) \in \omega\}.$$

[Of course,  $\mathbb{T}(\omega) = \omega$ .] In words,  $\mathbb{T}^{\text{GW}}$  is a Galton–Watson tree, with the population members as the vertices, whereas the *marked tree*  $\mathbb{T}$  corresponds to the branching random walk. It is

more convenient to write (2.2) in an informal way:

$$\mathbb{T} = \{(u, V(u)), u \in \mathbb{T}^{\text{GW}}\}.$$

For any  $u \in \mathbb{T}^{\text{GW}}$ , the *shifted* Galton–Watson subtree generated by  $u$  is

$$(2.3) \quad \mathbb{T}_u^{\text{GW}} := \{x \in \mathcal{U} : ux \in \mathbb{T}^{\text{GW}}\}.$$

[By shifted, we mean that  $\mathbb{T}_u^{\text{GW}}$  is also rooted at  $e$ .] For any  $x \in \mathbb{T}_u^{\text{GW}}$ , let

$$(2.4) \quad |x|_u := |ux| - |u|,$$

$$(2.5) \quad V_u(x) := V(ux) - V(u).$$

As such,  $|x|_u$  stands for the (relative) generation of  $x$  as a vertex of the Galton–Watson tree  $\mathbb{T}_u^{\text{GW}}$ , and  $(V_u(x), x \in \mathbb{T}_u^{\text{GW}})$  the branching random walk which corresponds to the *shifted marked subtree*

$$\mathbb{T}_u := \{(x, V_u(x)), x \in \mathbb{T}_u^{\text{GW}}\}.$$

Let  $\mathcal{F}_n := \sigma\{(u, V(u)), u \in \mathbb{T}^{\text{GW}}, |u| \leq n\}$ , which is the  $\sigma$ -algebra induced by the first  $n$  generations of the branching random walk. Let  $\mathcal{F}_\infty$  be the  $\sigma$ -algebra induced by the whole branching random walk.

We assume (1.2). Let  $\mathbf{Q}$  be a probability on  $\Omega$  such that for any  $n \geq 1$ ,

$$(2.6) \quad \mathbf{Q}|_{\mathcal{F}_n} := W_n \bullet \mathbf{P}|_{\mathcal{F}_n}.$$

Fix  $n \geq 1$ . Let  $w_n^{(n)}$  be a random variable taking values in  $\{u \in \mathbb{T}^{\text{GW}}, |u| = n\}$  such that for any  $|u| = n$ ,

$$(2.7) \quad \mathbf{Q} \left\{ w_n^{(n)} = u \mid \mathcal{F}_\infty \right\} = \frac{e^{-V(u)}}{W_n}.$$

We write  $\llbracket e, w_n^{(n)} \rrbracket = \{e =: w_0^{(n)}, w_1^{(n)}, w_2^{(n)}, \dots, w_n^{(n)}\}$  for the shortest path in  $\mathbb{T}^{\text{GW}}$  relating the root  $e$  to  $w_n^{(n)}$ , with  $|w_k^{(n)}| = k$  for any  $1 \leq k \leq n$ .

For any individual  $u \in \mathbb{T}^{\text{GW}} \setminus \{e\}$ , let  $\bar{u}$  be the parent of  $u$  in  $\mathbb{T}^{\text{GW}}$ , and

$$\Delta V(u) := V(u) - V(\bar{u}).$$

For  $1 \leq k \leq n$ , we write

$$(2.8) \quad \mathcal{I}_k^{(n)} := \left\{ u \in \mathbb{T}^{\text{GW}} : |u| = k, \bar{u} = w_{k-1}^{(n)}, u \neq w_k^{(n)} \right\}.$$

In words,  $\mathcal{I}_k^{(n)}$  is the set of children of  $w_{k-1}^{(n)}$  except  $w_k^{(n)}$ , or equivalently, the set of the brothers of  $w_k^{(n)}$ , and is possibly empty. Finally, let us introduce the following sigma-algebra:

$$(2.9) \quad \mathcal{G}_n := \sigma \left\{ \sum_{x \in \mathcal{I}_k^{(n)}} \delta_{\Delta V(x)}, V(w_k^{(n)}), w_k^{(n)}, \mathcal{I}_k^{(n)}, 1 \leq k \leq n \right\}.$$

We present the main result of the section, with  $\delta$  denoting the Dirac measure. For any marked tree  $\mathbb{T}$ , we define its truncation  $\mathbb{T}^n$  at level  $n$  by  $\mathbb{T}^n := \{(x, V(x)), x \in \mathbb{T}^{\text{GW}}, |x| \leq n\}$ .

**Proposition 2.1** *Assume (1.2) and fix  $n \geq 1$ . Under probability  $\mathbf{Q}$ ,*

(i) *the random variables  $(\sum_{x \in \mathcal{J}_k^{(n)}} \delta_{\Delta V(x)}, \Delta V(w_k^{(n)}))$ ,  $1 \leq k \leq n$ , are i.i.d., distributed as  $(\sum_{x \in \mathcal{J}_1^{(1)}} \delta_{\Delta V(x)}, \Delta V(w_1^{(1)}))$ ;*

(ii) *conditionally on  $\mathcal{G}_n$ , the truncated shifted marked subtrees  $\mathbb{T}_x^{n-|x|}$ , for  $x \in \cup_{k=1}^n \mathcal{J}_k^{(n)}$ , are independent; the conditional distribution of  $\mathbb{T}_x^{n-|x|}$  (for any  $x \in \cup_{k=1}^n \mathcal{J}_k^{(n)}$ ) under  $\mathbf{Q}$  given  $\mathcal{G}_n$ , identical to the distribution of  $\mathbb{T}^{n-|x|}$  under  $\mathbf{P}$ .*

The proof of Proposition 2.1 is postponed to Section 7.

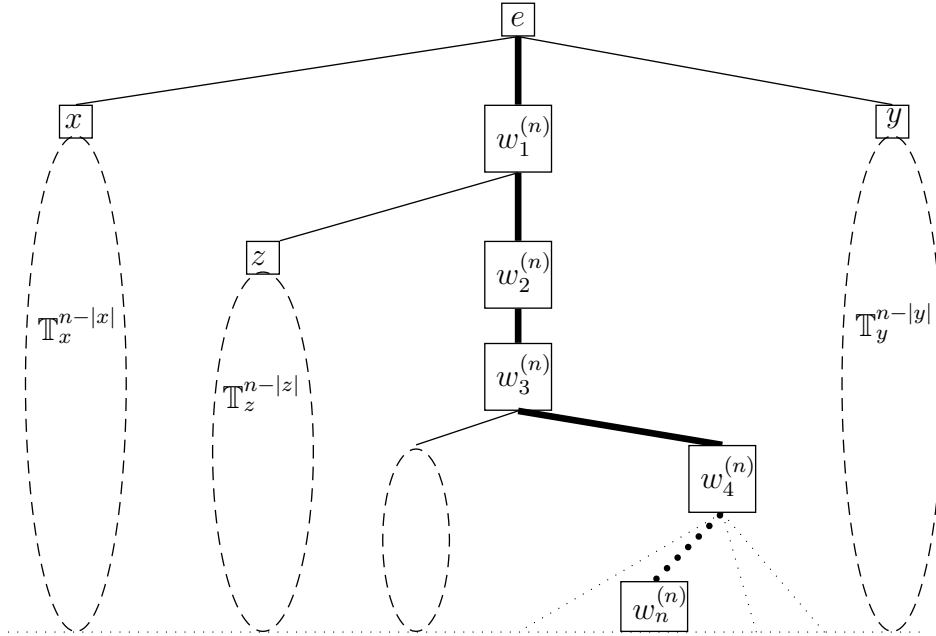


Figure 1: Spine;

The truncated shifted subtrees  $\mathbb{T}_x^{n-|x|}, \mathbb{T}_y^{n-|y|}, \mathbb{T}_z^{n-|z|}, \dots$  are actually rooted at  $e$ .

In general, the (non-truncated) shifted marked subtrees  $\mathbb{T}_x$ , for  $x \in \cup_{k=1}^n \mathcal{J}_k^{(n)}$ , are not conditionally independent under  $\mathbf{Q}$  given  $\mathcal{G}_n$ .

Throughout the paper, let  $((S_i, \sigma_i), i \geq 1)$  be such that  $(S_i - S_{i-1}, \sigma_i - \sigma_{i-1})$ , for  $i \geq 1$  (with  $S_0 = \sigma_0 =: 0$ ), are i.i.d. random vectors under  $\mathbf{Q}$  and distributed as  $(V(w_1^{(1)}), \#\mathcal{J}_1^{(1)})$ .



**Corollary 2.2** Assume (1.2) and fix  $n \geq 1$ .

(i) Under  $\mathbf{Q}$ ,  $((V(w_k^{(n)}), \#\mathcal{I}_k^{(n)}), 1 \leq k \leq n)$  is distributed as  $((S_k, \sigma_k), 1 \leq k \leq n)$ . In particular, under  $\mathbf{Q}$ ,  $(V(w_k^{(n)}), 1 \leq k \leq n)$  is distributed as  $(S_k, 1 \leq k \leq n)$ .

(ii) We have  $\mathbf{E}_{\mathbf{Q}}\{S_1\} = 0$ . More generally, for any measurable function  $F : \mathbb{R} \rightarrow \mathbb{R}_+$ ,

$$(2.10) \quad \mathbf{E}_{\mathbf{Q}}\{F(S_1)\} = \mathbf{E}\left\{\sum_{|u|=1} e^{-V(u)} F(V(u))\right\}.$$

*Proof.* The first part of the corollary is an immediate consequence of Proposition 2.1 (i). To prove (2.10), we observe that by (2.7),

$$\mathbf{E}_{\mathbf{Q}}\left\{F(V(w_1^{(1)}))\right\} = \mathbf{E}_{\mathbf{Q}}\left\{\sum_{|u|=1} F(V(u)) \mathbf{1}_{\{w_1^{(1)}=u\}}\right\} = \mathbf{E}_{\mathbf{Q}}\left\{\sum_{|u|=1} \frac{e^{-V(u)}}{W_1} F(V(u))\right\},$$

which is  $\mathbf{E}\{\sum_{|u|=1} e^{-V(u)} F(V(u))\}$  by the definition of  $\mathbf{Q}$ . This implies (2.10). The fact that  $\mathbf{E}_{\mathbf{Q}}(S_i) = 0$  follows from (1.2) and (2.10).

We mention that (2.10) can also be found in Biggins and Kyprianou [7].  $\square$

**Corollary 2.3** Assume (1.1) and (1.2). Let  $\delta > 0$  be as in (1.1). Then for any  $n \geq k \geq 1$ ,

$$\mathbf{E}_{\mathbf{Q}}\left\{(\#\mathcal{I}_k^{(n)})^\delta\right\} = \mathbf{E}_{\mathbf{Q}}\left\{(\#\mathcal{I}_1^{(1)})^\delta\right\} < \infty.$$

*Proof.* The identity follows from Proposition 2.1 (i). It remains to check  $\mathbf{E}_{\mathbf{Q}}\{(\#\mathcal{I}_1^{(1)})^\delta\} < \infty$ .

By definition,  $\mathbf{E}_{\mathbf{Q}}\{(\sum_{|u|=1} 1)^\delta\} = \mathbf{E}\{(\sum_{|u|=1} 1)^\delta W_1\} = \mathbf{E}\{(\sum_{|u|=1} 1)^\delta \sum_{|v|=1} e^{-V(v)}\} \leq e^C \mathbf{E}\{(\sum_{|u|=1} 1)^{1+\delta}\} < \infty$  (by (1.1)). Since  $\#\mathcal{I}_1^{(1)} = (\sum_{|u|=1} 1) - 1$ , we are done.  $\square$

### 3 Preliminary: small values of $W_n$

This preliminary section is devoted to the study of the small values of  $W_n$ . We define two important events:

$$(3.1) \quad \mathcal{S} := \{\text{the system's ultimate survival}\},$$

$$(3.2) \quad \mathcal{S}_n := \{\text{the system's survival after } n \text{ generations}\} = \{W_n > 0\}.$$

Clearly,  $\mathcal{S} \subset \mathcal{S}_n$ . Recall (see for example Harris [16], p. 16) that for some constant  $c_2$  and all  $n \geq 1$ ,

$$(3.3) \quad \mathbf{P}\{\mathcal{S}_n \setminus \mathcal{S}\} \leq e^{-c_2 n}.$$

Here is the main result of the section.

**Proposition 3.1** For any  $\varepsilon > 0$ , there exists  $\kappa > 0$  such that for all sufficiently large  $n$ ,

$$(3.4) \quad \mathbf{P} \left\{ n^{1/2} W_n < n^{-\varepsilon} \mid \mathcal{S} \right\} \leq \exp(-n^\kappa).$$

The proof of Proposition 3.1 relies on Neveu's multiplicative martingale. Recall that under assumption (1.2), there exists a non-negative random variable  $\xi^*$ , with  $\mathbf{P}\{\xi^* > 0\} > 0$ , such that

$$(3.5) \quad \xi^* \stackrel{law}{=} \sum_{|u|=1} \xi_u^* e^{-V(u)},$$

where, given  $\{(u, V(u)), |u| = 1\}$ ,  $\xi_u^*$  are independent copies of  $\xi^*$ , and “ $\stackrel{law}{=}$ ” stands for identity in distribution. Moreover, there is uniqueness of the distribution of  $\xi^*$  up to a scale change (see Liu [21]); in the rest of the paper, we take the version of  $\xi^*$  as the unique one satisfying  $\mathbf{E}\{e^{-\xi^*}\} = \frac{1}{2}$ .

Let us introduce the Laplace transform of  $\xi^*$ :

$$(3.6) \quad \varphi^*(t) := \mathbf{E} \left\{ e^{-t\xi^*} \right\}, \quad t \geq 0.$$

Let

$$(3.7) \quad W_n^* := \prod_{|u|=n} \varphi^*(e^{-V(u)}), \quad n \geq 1.$$

The process  $(W_n^*, n \geq 1)$  is also a martingale (Liu [21]). Following Neveu [27], we call  $W_n^*$  an associated “*multiplicative martingale*”.

The martingale  $W_n^*$  being bounded, it converges almost surely (when  $n \rightarrow \infty$ ) to, say,  $W_\infty^*$ . Let us recall from Liu [21] that

$$(3.8) \quad \log \frac{1}{W_\infty^*} \stackrel{law}{=} \xi^*,$$

$$(3.9) \quad \log \left( \frac{1}{\varphi^*(t)} \right) \sim t \log \left( \frac{1}{t} \right), \quad t \rightarrow 0.$$

We first prove the following estimates:

**Lemma 3.2** There exist  $\kappa > 0$  and  $a_0 \geq 1$  such that for any  $a \geq a_0$ ,

$$(3.10) \quad \mathbf{E} \left\{ (W_\infty^*)^a \mid W_\infty^* < 1 \right\} \leq \exp(-a^\kappa), \quad \forall a \geq a_0.$$

**Lemma 3.3** Let  $\kappa > 0$  and  $a_0 \geq 1$  be as in Lemma 3.2. Then

$$\mathbf{E} \left\{ (W_n^*)^a \mathbf{1}_{\mathcal{S}_n} \right\} \leq e^{-a^\kappa} + e^{-c_2 n}, \quad \forall n \geq 1, \quad \forall a \geq a_0.$$

*Proof of Lemma 3.2.* [The best possible value of  $\kappa$  is given by Liu [22], under the additional assumption that  $\{u, |u| = 1\}$  contains at least two elements almost surely.]

In view of (3.8), it suffices to show that

$$(3.11) \quad \mathbf{E} \{e^{-a\xi^*} \mid \xi^* > 0\} \leq \exp(-a^\kappa), \quad a \geq a_0.$$

Recall that  $q = \mathbf{P}\{\xi^* = 0\}$  is the system's extinction probability. It is well-known for Galton–Watson trees that  $q$  satisfies  $\mathbf{E}(q^N) = q$ , see for example Harris [16], p. 7. Then

$$\varphi^*(t) = \mathbf{E} \{e^{-t\xi^*}\} = q + (1 - q)\mathbf{E} \{e^{-t\xi^*} \mid \xi^* > 0\}.$$

Let  $\widehat{\xi}$  be a random variable such that  $\mathbf{E}\{e^{-t\widehat{\xi}}\} = \mathbf{E}\{e^{-t\xi^*} \mid \xi^* > 0\}$  for any  $t \geq 0$ . Let  $Y$  be a random variable independent of everything else, such that  $\mathbf{P}\{Y = 0\} = q = 1 - \mathbf{P}\{Y = 1\}$ . Then  $\xi^*$  and  $Y\widehat{\xi}$  have the same law, and by (3.5), so do  $\xi^*$  and  $\sum_{|u|=1} e^{-V(u)} Y_u \widehat{\xi}_u$ , where, given  $\{u, |u| = 1\}$ ,  $(Y_u, \widehat{\xi}_u)$  are independent copies of  $(Y, \widehat{\xi})$ , independent of  $\{V(u), |u| = 1\}$ . Since  $\{\sum_{|u|=1} e^{-V(u)} Y_u \widehat{\xi}_u > 0\} = \{\sum_{|u|=1} Y_u > 0\}$ , this leads to:

$$\mathbf{E}\{e^{-t\widehat{\xi}}\} = \mathbf{E}\left\{e^{-t\sum_{|u|=1} e^{-V(u)} Y_u \widehat{\xi}_u} \mid \sum_{|u|=1} Y_u > 0\right\}, \quad t \geq 0.$$

Let  $\widehat{\psi}(t) := -\log \mathbf{E}\{e^{-t\widehat{\xi}}\}$ ,  $t \geq 0$ ; thus  $e^{-\widehat{\psi}(t)} = \mathbf{E}\{e^{-t\widehat{\xi}}\}$ . Since  $V(u) \leq C$  for  $|u| = 1$ , we have

$$e^{-\widehat{\psi}(t)} \leq \mathbf{E}\left\{e^{-te^{-C}\sum_{|u|=1} Y_u \widehat{\xi}_u} \mid \sum_{|u|=1} Y_u > 0\right\} = \mathbf{E}\left\{e^{-\sum_{|u|=1} \widehat{\psi}(tY_u e^{-C})} \mid \sum_{|u|=1} Y_u > 0\right\}.$$

Note that  $\widehat{\psi}(0) = 0$ , thus  $\sum_{|u|=1} \widehat{\psi}(tY_u e^{-C}) = \widehat{\psi}(te^{-C}) \sum_{|u|=1} Y_u$ . As a consequence, by writing  $h(t) := -\log \mathbf{E}\{e^{-t\sum_{|u|=1} Y_u} \mid \sum_{|u|=1} Y_u > 0\}$ ,  $t \geq 0$ , we have  $e^{-\widehat{\psi}(t)} \leq e^{-h(\widehat{\psi}(te^{-C}))}$ , i.e.,

$$(3.12) \quad \widehat{\psi}(t) \geq h(\widehat{\psi}(te^{-C})), \quad \forall t \geq 0.$$

The function  $h$  is smooth and convex on  $\mathbb{R}_+$ , with  $h(0) = 0$ . Thus  $h(t) \geq h'(0)t$  for all  $t \geq 0$ . Since  $\mathbf{P}\{\sum_{|u|=1} Y_u > 0\} = \mathbf{P}\{\sum_{|u|=1} e^{-V(u)} Y_u \widehat{\xi}_u > 0\} = \mathbf{P}\{\xi^* > 0\} = 1 - q$ , we have  $h'(0) = \mathbf{E}\{\sum_{|u|=1} Y_u \mid \sum_{|u|=1} Y_u > 0\} = \frac{m}{1-q}$ , where  $m := \mathbf{E}\{\sum_{|u|=1} 1\}$ . This yields  $h(t) \geq mt$ ,  $t \geq 0$ . In view of (3.12), we get  $\widehat{\psi}(t) \geq m\widehat{\psi}(te^{-C})$ ,  $\forall t \geq 0$ . Iterating the inequality, we see that  $\widehat{\psi}(t) \geq m^n \widehat{\psi}(te^{-Cn})$ , for  $n \geq 1$  and  $t \geq 0$ . In particular,  $\widehat{\psi}(e^{Cn}) \geq m^n \widehat{\psi}(1)$ . Since  $m > 1$  (assumption (1.2)), this yields (3.11), and completes the proof of Lemma 3.2.  $\square$

*Proof of Lemma 3.3.* Let  $a \geq 1$ . Since  $((W_n^*)^a, n \geq 0)$  is a bounded submartingale,  $\mathbf{E}\{(W_n^*)^a \mathbf{1}_{\mathcal{S}_n}\} \leq \mathbf{E}\{(W_\infty^*)^a \mathbf{1}_{\mathcal{S}_n}\}$ . Recall that  $W_\infty^* \leq 1$ ; thus

$$\mathbf{E}\{(W_n^*)^a \mathbf{1}_{\mathcal{S}_n}\} \leq \mathbf{E}\{(W_\infty^*)^a \mathbf{1}_{\mathcal{S}}\} + \mathbf{P}\{\mathcal{S}_n \setminus \mathcal{S}\}.$$

By (3.3),  $\mathbf{P}\{\mathcal{S}_n \setminus \mathcal{S}\} \leq e^{-c_2 n}$ . On the other hand, since  $\mathcal{S} = \{W_\infty^* < 1\}$ , we have  $\mathbf{E}\{(W_\infty^*)^a \mathbf{1}_{\mathcal{S}}\} = \mathbf{E}\{(W_\infty^*)^a \mathbf{1}_{\{W_\infty^* < 1\}}\}$ , which, according to (3.10), is bounded by  $e^{-a^\kappa}$ , for  $a \geq a_0$ . Lemma 3.3 is proved.  $\square$

We are now ready for the proof of Proposition 3.1.

*Proof of Proposition 3.1.* Let  $c_3 > 0$  be such that  $\mathbf{P}\{\xi^* \leq c_3\} \geq \frac{1}{2}$ . Then  $\varphi^*(t) = \mathbf{E}\{e^{-t\xi^*}\} \geq e^{-c_3 t} \mathbf{P}\{\xi^* \leq c_3\} \geq \frac{1}{2} e^{-c_3 t}$ , and thus  $\log(\frac{1}{\varphi^*(t)}) \leq c_3 t + \log 2$ . Together with (3.9), this yields, on the event  $\mathcal{S}_n$ ,

$$\begin{aligned} \log\left(\frac{1}{W_n^*}\right) &= \sum_{|u|=n} \log\left(\frac{1}{\varphi^*(e^{-V(u)})}\right) \\ &\leq \sum_{|u|=n} \mathbf{1}_{\{V(u) \geq 1\}} c_4 V(u) e^{-V(u)} + \sum_{|u|=n} \mathbf{1}_{\{V(u) < 1\}} (c_3 e^{-V(u)} + \log 2). \end{aligned}$$

Since  $W_n = \sum_{|u|=n} e^{-V(u)}$ , we obtain, on  $\mathcal{S}_n$ , for any  $\lambda \geq 1$ ,

$$(3.13) \quad \log\left(\frac{1}{W_n^*}\right) \leq c_5 \lambda W_n + c_4 \sum_{|u|=n} \mathbf{1}_{\{V(u) \geq \lambda\}} V(u) e^{-V(u)},$$

where  $c_5 := c_3 + c_4 + e \log 2$ . Note that  $c_4$  and  $c_5$  do not depend on  $\lambda$ .

Let  $0 < y \leq 1$ . Since  $\mathcal{S} \subset \mathcal{S}_n$ , it follows that for  $c_6 := c_4 + c_5$ ,

$$\begin{aligned} &\mathbf{P}\left\{\lambda W_n < y \mid \mathcal{S}_n\right\} \\ &\leq \mathbf{P}\left\{\log\left(\frac{1}{W_n^*}\right) < c_6 y \mid \mathcal{S}_n\right\} + \mathbf{P}\left\{\sum_{|u|=n} \mathbf{1}_{\{V(u) \geq \lambda\}} V(u) e^{-V(u)} \geq y \mid \mathcal{S}_n\right\} \\ (3.14) \quad &=: \text{RHS}_{(3.14)}^1 + \text{RHS}_{(3.14)}^2, \end{aligned}$$

with obvious notation.

Recall that  $\mathbf{P}(\mathcal{S}_n) \geq \mathbf{P}(\mathcal{S}) = 1 - q$ . By Chebyshev's inequality,

$$\text{RHS}_{(3.14)}^1 \leq e^{c_6} \mathbf{E}\left\{(W_n^*)^{1/y} \mid \mathcal{S}_n\right\} \leq \frac{e^{c_6}}{1 - q} \mathbf{E}\left\{(W_n^*)^{1/y} \mathbf{1}_{\mathcal{S}_n}\right\}.$$

An application of Lemma 3.3 yields that for  $n \geq 1$  and  $0 < y \leq \frac{1}{a_0}$ ,

$$(3.15) \quad \text{RHS}_{(3.14)}^1 \leq \frac{e^{c_6}}{1 - q} \left[ e^{-1/y^\kappa} + e^{-c_2 n} \right].$$

To estimate  $\text{RHS}_{(3.14)}^2$ , we use the trivial inequality  $V(u) \leq Cn$  for  $|u| = n$ , to see that

$$\begin{aligned} \text{RHS}_{(3.14)}^2 &\leq \frac{1}{1-q} \mathbf{P} \left\{ Cn \sum_{|u|=n} \mathbf{1}_{\{V(u) \geq \lambda\}} e^{-V(u)} \geq y \right\} \\ &\leq \frac{Cn}{(1-q)y} \mathbf{E} \left\{ \sum_{|u|=n} \mathbf{1}_{\{V(u) \geq \lambda\}} e^{-V(u)} \right\}. \end{aligned}$$

By definition,  $\mathbf{E} \left\{ \sum_{|u|=n} \mathbf{1}_{\{V(u) \geq \lambda\}} e^{-V(u)} \right\} = \mathbf{E}_{\mathbf{Q}} \left\{ \sum_{|u|=n} \mathbf{1}_{\{V(u) \geq \lambda\}} \frac{e^{-V(u)}}{W_n} \right\} = \mathbf{Q} \{ V(w_n^{(n)}) \geq \lambda \}$ , which, according to Corollary 2.2 (i), equals  $\mathbf{P} \{ S_n \geq \lambda \}$ . Therefore, if  $\lambda \geq n^{1/2}$ , then  $\mathbf{E} \left\{ \sum_{|u|=n} \mathbf{1}_{\{V(u) \geq \lambda\}} e^{-V(u)} \right\} \leq e^{-c_7 \lambda^2/n}$  for some constant  $c_7$ . Accordingly,  $\text{RHS}_{(3.14)}^2 \leq \frac{Cn e^{-c_7 \lambda^2/n}}{(1-q)y}$ . Together with (3.14) and (3.15), it yields that, for  $0 < y \leq \frac{1}{a_0}$  and  $\lambda \geq n^{1/2} \geq 1$ ,

$$\mathbf{P} \left\{ \lambda W_n < y \mid \mathcal{S}_n \right\} \leq \frac{e^{c_6}}{1-q} \left[ e^{-1/y^\kappa} + e^{-c_2 n} \right] + \frac{Cn e^{-c_7 \lambda^2/n}}{(1-q)y}.$$

Let  $y := x^{2/(\kappa+2)}$  and  $\lambda := n^{1/2} x^{-\kappa/(\kappa+2)}$ . The inequality becomes: for  $0 < x \leq 1$  and  $n \geq 1$ ,

$$(3.16) \quad \mathbf{P} \left\{ n^{1/2} W_n < x \mid \mathcal{S}_n \right\} \leq \frac{e^{c_6}}{1-q} \left[ e^{-1/x^{2\kappa/(\kappa+2)}} + e^{-c_2 n} \right] + \frac{Cn e^{-c_7/x^{2\kappa/(\kappa+2)}}}{(1-q)x^{2/(\kappa+2)}}.$$

This readily yields Proposition 3.1.  $\square$

**Remark.** Recall that  $W_n \geq e^{-Cn}$  on  $\mathcal{S}_n$ . A consequence of (3.16) (noting that we can replace  $\frac{Cn \exp(-c_7/x^{2\kappa/(\kappa+2)})}{(1-q)x^{2/(\kappa+2)}}$  by  $\frac{Cn \exp(-c_7/x^{2\kappa/(\kappa+2)})}{(1-q)x^{2/(\kappa+2)}} \wedge 1$  on the right-hand side) is that for any  $0 < s < \frac{c_2}{C}$ ,

$$(3.17) \quad \mathbf{E} \left\{ \frac{1}{W_n^s} \mathbf{1}_{\mathcal{S}_n} \right\} \leq n^{(s/2)+o(1)}, \quad n \rightarrow \infty.$$

We will make use of this estimate several times.  $\square$

We complete this section with the following estimate which will be useful in the proof of Proposition 6.2.

**Lemma 3.4** *For any  $0 < s < 1$ ,*

$$(3.18) \quad \sup_{n \geq 1} \mathbf{E} \left\{ \left( \log \frac{1}{W_n^*} \right)^s \right\} < \infty.$$

*Proof of Lemma 3.4.* Let  $x > 1$ . By Chebyshev's inequality,  $\mathbf{P} \left\{ \log \left( \frac{1}{W_n^*} \right) \geq x \right\} = \mathbf{P} \{ e^x W_n^* \leq 1 \} \leq e \mathbf{E} \{ e^{-e^x W_n^*} \}$ . Since  $W_n^*$  is a martingale, it follows from Jensen's inequality that  $\mathbf{E} \{ e^{-e^x W_n^*} \} \leq \mathbf{E} \{ e^{-e^x W_\infty^*} \} \leq \mathbf{P} \{ W_\infty^* \leq e^{-x/2} \} + \exp(-e^{x/2})$ . Therefore,

$$(3.19) \quad \mathbf{P} \left\{ \log \left( \frac{1}{W_n^*} \right) \geq x \right\} \leq e \mathbf{P} \{ W_\infty^* \leq e^{-x/2} \} + \exp \left( 1 - e^{x/2} \right).$$

On the other hand, by integration by parts,  $\int_0^\infty e^{-ty} \mathbf{P}(\xi^* \geq y) dy = \frac{1 - \mathbf{E}(e^{-t\xi^*})}{t} = \frac{1 - \phi^*(t)}{t}$ , which, according to (3.8), is  $\leq c_8 \log(\frac{1}{t})$  for  $0 < t \leq \frac{1}{2}$ . Therefore, for  $a \geq 2$ ,  $c_8 \log a \geq \int_0^\infty e^{-y/a} \mathbf{P}(\xi^* \geq y) dy \geq \int_0^a e^{-y/a} \mathbf{P}(\xi^* \geq a) dy = (1 - e^{-1})a \mathbf{P}(\xi^* \geq a)$ . That is,  $\mathbf{P}(\xi^* \geq a) \leq c_9 \frac{\log a}{a}$ , or equivalently,  $\mathbf{P}(W_\infty^* \leq e^{-a}) \leq c_9 \frac{\log a}{a}$ , for  $a \geq 2$ . Substituting this in (3.19) gives that, for any  $x \geq 4$ ,

$$\mathbf{P}\left\{\log\left(\frac{1}{W_n^*}\right) \geq x\right\} \leq c_{10} \frac{\log(x/2)}{x} + \exp\left(1 - e^{x/2}\right),$$

where  $c_{10} := 2e c_9$ . Lemma 3.4 follows immediately.  $\square$

## 4 Proof of Theorem 1.3

This section is devoted to the proof of Theorem 1.3. Let  $W_{n,\beta} := \sum_{|u|=n} e^{-\beta V(u)}$  as in (1.7). The main step in the proof of Theorem 1.3 is the following moment estimate.

**Theorem 4.1** *Assume (1.1) and (1.2). Let  $\beta > 1$ . For any  $0 < r < \frac{1}{\beta}$ , we have*

$$(4.1) \quad \mathbf{E}\{W_{n,\beta}^r\} = n^{-3r\beta/2+o(1)}, \quad n \rightarrow \infty.$$

Before proving Theorem 4.1, we need two preliminary results.

**Lemma 4.2** *Let  $X_1, X_2, \dots, X_N$  be independent non-negative random variables, and let  $T_N := \sum_{i=1}^N X_i$ . For any non-increasing function  $F : (0, \infty) \rightarrow \mathbb{R}_+$ , we have*

$$\mathbf{E}\{F(T_N) \mathbf{1}_{\{T_N > 0\}}\} \leq \max_{1 \leq i \leq N} \mathbf{E}\{F(X_i) \mid X_i > 0\}.$$

Moreover,

$$\mathbf{E}\{F(T_N) \mathbf{1}_{\{T_N > 0\}}\} \leq \sum_{i=1}^N b^{i-1} \mathbf{E}\{F(X_i) \mathbf{1}_{\{X_i > 0\}}\},$$

where  $b := \max_{1 \leq i \leq N} \mathbf{P}\{X_i = 0\}$ .

*Proof.* Let  $\tau := \min\{i \geq 1 : X_i > 0\}$  (with  $\min \emptyset := \infty$ ). Then  $\mathbf{E}\{F(T_N) \mathbf{1}_{\{T_N > 0\}}\} = \sum_{i=1}^N \mathbf{E}\{F(T_N) \mathbf{1}_{\{\tau=i\}}\}$ . Since  $F$  is non-increasing, we have  $F(T_N) \mathbf{1}_{\{\tau=i\}} \leq F(X_i) \mathbf{1}_{\{\tau=i\}} = F(X_i) \mathbf{1}_{\{X_i > 0\}} \mathbf{1}_{\{X_j=0, \forall j < i\}}$ . By independence, this leads to

$$\mathbf{E}\{F(T_N) \mathbf{1}_{\{T_N > 0\}}\} \leq \sum_{i=1}^N \mathbf{E}\{F(X_i) \mathbf{1}_{\{X_i > 0\}}\} \mathbf{P}\{X_j = 0, \forall j < i\}.$$

This yields immediately the second inequality of the lemma, since  $\mathbf{P}\{X_j = 0, \forall j < i\} \leq b^{i-1}$ .

To prove the first inequality of the lemma, we observe that  $\mathbf{E}\{F(X_i) \mathbf{1}_{\{X_i > 0\}}\} \leq \mathbf{P}\{X_i > 0\} \max_{1 \leq k \leq N} \mathbf{E}\{F(X_k) | X_k > 0\}$ . Therefore,

$$\mathbf{E}\{F(T_N) \mathbf{1}_{\{T_N > 0\}}\} \leq \max_{1 \leq k \leq N} \mathbf{E}\{F(X_k) | X_k > 0\} \sum_{i=1}^N \mathbf{P}\{X_i > 0\} \mathbf{P}\{X_j = 0, \forall j < i\}.$$

The  $\sum_{i=1}^N \dots$  expression on the right-hand side is  $= \sum_{i=1}^N \mathbf{P}\{X_i > 0, X_j = 0, \forall j < i\} = \sum_{i=1}^N \mathbb{P}\{\tau = i\} = \mathbb{P}\{T_N > 0\} \leq 1$ . This yields the first inequality of the lemma.  $\square$

To state our second lemma, let  $\underline{w}^{(n)} \in \llbracket e, w_n^{(n)} \llbracket$  be a vertex such that

$$(4.2) \quad V(\underline{w}^{(n)}) = \min_{u \in \llbracket e, w_n^{(n)} \llbracket} V(u).$$

[If there are several such vertices, we choose, say, the oldest.] The following estimate gives a (stochastic) lower bound for  $\frac{1}{W_{n,\beta}}$  under  $\mathbf{Q}$  outside a ‘‘small’’ set. We recall that  $W_{n,\beta} > 0$ ,  $\mathbf{Q}$ -almost surely (but not necessarily  $\mathbf{P}$ -almost surely).

**Lemma 4.3** *Let  $\beta > 0$  and  $K > 0$ . There exist  $\theta > 0$  and  $n_0 < \infty$  such that for  $n \geq n_0$  and  $z \in \mathbb{R}$ ,*

$$\mathbf{Q}\left\{\frac{e^{-\beta V(\underline{w}^{(n)})}}{W_{n,\beta}} > z, E_n\right\} \leq \frac{1}{1-q} \max_{1 \leq k < n} \mathbf{P}\left\{\frac{n^\theta}{W_{k,\beta}} > z, \mathcal{S}_k\right\},$$

where  $E_n$  is a measurable event such that

$$\mathbf{Q}\{E_n\} \geq 1 - \frac{1}{n^K}, \quad n \geq n_0.$$

**Remark.** We insist on the fact that  $n_0$  does not depend on  $z$ . As a consequence, for any non-decreasing function  $G : (0, \infty) \rightarrow (0, \infty)$  and  $n \geq n_0$ ,

$$(4.3) \quad \mathbf{E}_{\mathbf{Q}}\left\{G\left(\frac{e^{-\beta V(\underline{w}^{(n)})}}{W_{n,\beta}}\right) \mathbf{1}_{E_n}\right\} \leq \frac{1}{1-q} \max_{1 \leq k < n} \mathbf{E}\left\{G\left(\frac{n^\theta}{W_{k,\beta}}\right) \mathbf{1}_{\mathcal{S}_k}\right\}.$$

We will later apply the lemma to a function  $G$  depending on  $n$ .

*Proof of Lemma 4.3.* Recall from (2.8) that  $\mathcal{S}_k^{(n)}$  is the set of the brothers of  $w_k^{(n)}$ . For any pair  $0 \leq k < n$ , we say that *the level  $k$  is  $n$ -good* if

$$\mathcal{S}_k^{(n)} \neq \emptyset, \quad \text{and } \mathbb{T}_u^{\text{GW}} \text{ survives at least } n - k \text{ generations, } \forall u \in \mathcal{S}_k^{(n)},$$

where  $\mathbb{T}_u^{\text{GW}}$  is the shifted Galton–Watson subtree generated by  $u$  (see (2.3)). By  $\mathbb{T}_u^{\text{GW}}$  surviving at least  $n - k$  generations, we mean that there exists  $v \in \mathbb{T}_u^{\text{GW}}$  such that  $|v|_u = n - k$  (see (2.4) for notation).

In words,  $k$  is  $n$ -good means any subtree generated by any of the brothers of  $w_k^{(n)}$  has offspring for at least  $n - k$  generations.

Let  $\mathcal{G}_n$  be the sigma-algebra defined in (2.9). By Proposition 2.1,

$$\mathbf{Q}\{k \text{ is } n\text{-good} \mid \mathcal{G}_n\} = \mathbf{1}_{\{\mathcal{S}_k^{(n)} \neq \emptyset\}} (\mathbf{P}\{\mathcal{S}_{n-k}\})^{\#\mathcal{S}_k^{(n)}},$$

where  $\mathcal{S}_n$  denotes the system's survival after  $n$  generations (see (3.2)). Since  $\mathbf{P}\{\mathcal{S}_{n-k}\} \geq \mathbf{P}\{\mathcal{S}\} = 1 - q$ , whereas  $\#\mathcal{S}_k^{(n)}$  and  $\#\mathcal{S}_1^{(1)}$  have the same distribution under  $Q$  (Proposition 2.1), we have

$$\mathbf{Q}\{k \text{ is } n\text{-good}\} \geq \mathbf{E}_{\mathbf{Q}}\left\{\mathbf{1}_{\{\#\mathcal{S}_1^{(1)} \geq 1\}} (1 - q)^{\#\mathcal{S}_1^{(1)}}\right\} = c_{11} \in (0, 1).$$

As a consequence, for all sufficiently large  $n$  and all  $1 \leq \ell < n$ , by Proposition 2.1 again,

$$\mathbf{Q}\left\{\bigcup_{k=1}^{n-\ell} \bigcap_{j=k}^{k+\ell-1} \{j \text{ is not } n\text{-good}\}\right\} \leq \sum_{k=1}^{n-\ell} \prod_{j=k}^{k+\ell-1} \mathbf{Q}\{j \text{ is not } n\text{-good}\}^\ell \leq n(1 - c_{11})^\ell,$$

which is bounded by  $ne^{-c_{11}\ell}$  (using the inequality  $1 - x \leq e^{-x}$ , for  $x \geq 0$ ). Let  $K > 0$ . We take  $\ell = \ell(n) := \lfloor c_{12} \log n \rfloor$  with  $c_{12} := \frac{K+2}{c_{11}}$ , and write

$$(4.4) \quad E_n := \bigcap_{k=1}^{n - \lfloor c_{12} \log n \rfloor} \bigcup_{j=k}^{k + \lfloor c_{12} \log n \rfloor - 1} \{j \text{ is } n\text{-good}\}.$$

Thus, for large  $n$ ,

$$(4.5) \quad \mathbf{Q}\{E_n\} \geq 1 - ne^{-c_{11}(c_{12} \log n - 1)} = 1 - \frac{e^{c_{11}}}{n^{K+1}} \geq 1 - \frac{1}{n^K}.$$

By definition,

$$(4.6) \quad \begin{aligned} W_{n,\beta} &= \sum_{j=1}^n \sum_{u \in \mathcal{S}_j^{(n)}} e^{-\beta V(u)} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} e^{-\beta V_u(x)} \\ &\geq \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{S}_j^{(n)}} e^{-\beta V(u)} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} e^{-\beta V_u(x)} \end{aligned}$$

for any  $\mathcal{L} \subset \{1, 2, \dots, n\}$ . We choose  $\mathcal{L} := \{1 \leq j \leq n : |j - |\underline{w}^{(n)}|| \leq c_{12} \log n\}$ .



For  $u \in \mathcal{I}_j^{(n)}$  with some  $j \in \mathcal{L}$ , we have  $V(u) \leq V(\underline{w}^{(n)}) + C(c_{12} \log n + 2) \leq V(\underline{w}^{(n)}) + 2Cc_{12} \log n$  (for large  $n$ ). Writing  $\theta := 2\beta Cc_{12}$ , this leads to:

$$W_{n,\beta} \geq \frac{e^{-\beta V(\underline{w}^{(n)})}}{n^\theta} \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{I}_j^{(n)}} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} e^{-\beta V_u(x)} =: \frac{e^{-\beta V(\underline{w}^{(n)})}}{n^\theta} \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{I}_j^{(n)}} \xi_u.$$

On the event  $E_n$ , we have  $\sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{I}_j^{(n)}} \xi_u > 0$ . Therefore,

$$\frac{e^{-\beta V(\underline{w}^{(n)})}}{W_{n,\beta}} \mathbf{1}_{E_n} \leq \frac{n^\theta}{\sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{I}_j^{(n)}} \xi_u} \mathbf{1}_{\{\sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{I}_j^{(n)}} \xi_u > 0\}}.$$

Let  $\mathcal{G}_n$  be the sigma-algebra in (2.9). We observe that  $\mathcal{L}$  and  $\mathcal{I}_j^{(n)}$  are  $\mathcal{G}_n$ -measurable. Moreover, an application of Proposition 2.1 tells us that under  $\mathbf{Q}$ , conditionally on  $\mathcal{G}_n$ , the random variables  $\xi_u$ ,  $u \in \mathcal{I}_j^{(n)}$ ,  $j \in \mathcal{L}$ , are independent, and distributed as  $W_{n-j,\beta}$  under  $\mathbf{P}$ . We are thus entitled to apply Lemma 4.2, to see that

$$\begin{aligned} \mathbf{Q} \left\{ \frac{e^{-\beta V(\underline{w}^{(n)})}}{W_{n,\beta}} > z, E_n \mid \mathcal{G}_n \right\} &\leq \max_{j \in \mathcal{L}} \mathbf{P} \left\{ \frac{n^\theta}{W_{n-j,\beta}} > z \mid W_{n-j,\beta} > 0 \right\} \\ &\leq \max_{0 \leq k \leq n} \mathbf{P} \left\{ \frac{n^\theta}{W_{k,\beta}} > z \mid W_{k,\beta} > 0 \right\}. \end{aligned}$$

Since  $\mathbf{P}\{W_{k,\beta} > 0\} = \mathbf{P}\{\mathcal{S}_k\} \geq \mathbf{P}\{\mathcal{S}\} = 1 - q$ , this yields Lemma 4.3.  $\square$

We are now ready for the proof of Theorem 4.1. For the sake of clarity, the upper and lower bounds are proved in distinct parts. Let us start with the upper bound.

*Proof of Theorem 4.1: the upper bound.* Fix  $\beta > 1$ . For any  $Z \geq 0$  which is  $\mathcal{F}_n$ -measurable, we have  $\mathbf{E}\{W_{n,\beta}Z\} = \mathbf{E}_{\mathbf{Q}}\{\sum_{|u|=n} \frac{e^{-\beta V(u)}}{W_n} Z\} = \mathbf{E}_{\mathbf{Q}}\{\sum_{|u|=n} \mathbf{1}_{\{w_n^{(n)}=u\}} e^{-(\beta-1)V(u)} Z\}$ , and thus

$$(4.7) \quad \mathbf{E}\{W_{n,\beta}Z\} = \mathbf{E}_{\mathbf{Q}}\{e^{-(\beta-1)V(w_n^{(n)})} Z\}.$$

Let  $s \in (\frac{\beta-1}{\beta}, 1)$ , and  $\lambda > 0$ . Then

$$\begin{aligned} \mathbf{E}\{W_{n,\beta}^{1-s}\} &\leq n^{-(1-s)\beta\lambda} + \mathbf{E}\{W_{n,\beta}^{1-s} \mathbf{1}_{\{W_{n,\beta} > n^{-\beta\lambda}\}}\} \\ &= n^{-(1-s)\beta\lambda} + \mathbf{E}_{\mathbf{Q}}\left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{\{W_{n,\beta} > n^{-\beta\lambda}\}} \right\}. \end{aligned}$$

Since  $e^{-\beta V(w_n^{(n)})} \leq W_{n,\beta}$ , we have  $\frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \leq \frac{1}{W_{n,\beta}^{s-(\beta-1)/\beta}}$ ; thus on the event  $\{W_{n,\beta} > n^{-\beta\lambda}\}$ ,

we have  $\frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \leq n^{[\beta s - (\beta-1)]\lambda}$ .

Let  $K := [\beta s - (\beta - 1)]\lambda + (1 - s)\beta\lambda$ , and let  $E_n$  be the event in Lemma 4.3. Since  $\mathbf{Q}(E_n^c) \leq n^{-K}$  for all sufficiently large  $n$  (see Lemma 4.3), we obtain: for large  $n$ ,

$$(4.8) \quad \begin{aligned} \mathbf{E} \left\{ W_{n,\beta}^{1-s} \right\} &\leq n^{-(1-s)\beta\lambda} + n^{[\beta s - (\beta - 1)]\lambda - K} + \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{\{W_{n,\beta} > n^{-\beta\lambda}\} \cap E_n} \right\} \\ &= 2n^{-(1-s)\beta\lambda} + \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{\{W_{n,\beta} > n^{-\beta\lambda}\} \cap E_n} \right\}. \end{aligned}$$

We now estimate the expectation expression  $\mathbf{E}_{\mathbf{Q}}\{\cdot\}$  on the right-hand side of (4.8). Let  $a > 0$  and  $\varrho > b > 0$  be constants such that  $(\beta - 1)a > s\beta\lambda + \frac{3}{2}$  and  $[\beta s - (\beta - 1)]b > \frac{3}{2}$ . (The choice of  $\varrho$  will be precised later on.) We recall that  $\underline{w}_n^{(n)} \in \llbracket e, w_n^{(n)} \llbracket$  satisfies  $V(\underline{w}_n^{(n)}) = \min_{u \in \llbracket e, w_n^{(n)} \llbracket} V(u)$ , and consider the following events:

$$\begin{aligned} E_{1,n} &:= \{V(w_n^{(n)}) > a \log n\} \cup \{V(w_n^{(n)}) < -b \log n\}, \\ E_{2,n} &:= \{V(\underline{w}_n^{(n)}) < -\varrho \log n, V(w_n^{(n)}) \geq -b \log n\}, \\ E_{3,n} &:= \{V(\underline{w}_n^{(n)}) \geq -\varrho \log n, V(w_n^{(n)}) \leq 0\}, \\ E_{4,n} &:= \{V(\underline{w}_n^{(n)}) \geq -\varrho \log n, 0 < V(w_n^{(n)}) \leq a \log n\}. \end{aligned}$$

Clearly,  $\cup_{i=1}^4 E_{i,n}$  covers the whole space.

On the event  $E_{1,n} \cap \{W_{n,\beta} > n^{-\beta\lambda}\}$ , we have either  $V(w_n^{(n)}) > a \log n$ , in which case  $\frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \leq n^{s\beta\lambda - (\beta-1)a}$ , or  $V(w_n^{(n)}) < -b \log n$ , in which case we use the trivial inequality  $W_{n,\beta} \geq e^{-\beta V(w_n^{(n)})}$  to see that  $\frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \leq e^{[\beta s - (\beta - 1)]V(w_n^{(n)})} \leq n^{-[\beta s - (\beta - 1)]b}$  (recalling that  $\beta s > \beta - 1$ ). Since  $s\beta\lambda - (\beta - 1)a < -\frac{3}{2}$  and  $[\beta s - (\beta - 1)]b > \frac{3}{2}$ , we obtain:

$$(4.9) \quad \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{1,n} \cap \{W_{n,\beta} > n^{-\beta\lambda}\}} \right\} \leq n^{-3/2}.$$

We now study the integral on  $E_{2,n} \cap \{W_{n,\beta} > n^{-\beta\lambda}\} \cap E_n$ . Since  $s > 0$ , we can chose  $s_1 > 0$  and  $0 < s_2 < \frac{\varrho}{C}$  such that  $s = s_1 + s_2$ . We have, on  $E_{2,n} \cap \{W_{n,\beta} > n^{-\beta\lambda}\}$ ,

$$\frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} = \frac{e^{\beta s_2 V(\underline{w}_n^{(n)}) - (\beta-1)V(w_n^{(n)})} e^{-\beta s_2 V(\underline{w}_n^{(n)})}}{W_{n,\beta}^{s_1} W_{n,\beta}^{s_2}} \leq n^{-\beta s_2 \varrho + (\beta-1)b + \beta \lambda s_1} \frac{e^{-\beta s_2 V(\underline{w}_n^{(n)})}}{W_{n,\beta}^{s_2}}.$$

Therefore, by an application of Lemma 4.3 (or rather, by an application of (4.3) to  $G(x) := x^{s_2}$ ,  $x > 0$ ), we obtain: when  $n \rightarrow \infty$ ,

$$\begin{aligned} \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{2,n} \cap \{W_{n,\beta} > n^{-\beta\lambda}\} \cap E_n} \right\} &\leq \frac{n^{-\beta s_2 \varrho + (\beta-1)b + \beta \lambda s_1}}{1 - q} \max_{1 \leq k < n} \mathbf{E} \left\{ \frac{n^{s_2 \theta}}{W_{k,\beta}^{s_2}} \mathbf{1}_{\mathcal{I}_k} \right\} \\ &\leq n^{-\beta s_2 \varrho + (\beta-1)b + \beta \lambda s_1 + s_2 \theta + (s_2/2) + o(1)}, \end{aligned}$$

the last inequality being a consequence of (3.17). We choose (and fix) the constant  $\rho$  so large that  $-\beta s_2 \rho + (\beta - 1)b + \beta \lambda s_1 + s_2 \theta + \frac{s_2}{2} < -\frac{3}{2}$ . Therefore, for all large  $n$ ,

$$(4.10) \quad \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{2,n} \cap \{W_{n,\beta} > n^{-\beta\lambda}\} \cap E_n} \right\} \leq n^{-3/2}.$$

On  $E_{3,n}$ , since  $W_{n,\beta} \geq e^{-\beta V(w_n^{(n)})}$ , we have  $\frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \leq e^{-[\beta s - (\beta-1)]V(w_n^{(n)})} \leq 1$  (recalling that  $\beta s > \beta - 1$ ). Therefore, by Corollary 2.2,

$$\mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{3,n}} \right\} \leq \mathbf{Q}(E_{3,n}) = \mathbf{Q} \left\{ \min_{0 \leq k < n} S_k \geq -\rho \log n, S_n \leq 0 \right\}.$$

Since  $(S_k)$  is a centered random walk, the probability expression  $\mathbf{Q}\{\cdots\}$  on the right-hand side is  $n^{-(3/2)+o(1)}$ , for  $n \rightarrow \infty$ . Therefore,

$$(4.11) \quad \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{3,n}} \right\} \leq n^{-(3/2)+o(1)}.$$

Combining (4.9), (4.10) and (4.11) yields

$$\sum_{i=1}^3 \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{i,n} \cap \{W_{n,\beta} > n^{-\beta\lambda}\} \cap E_n} \right\} \leq n^{-(3/2)+o(1)}, \quad n \rightarrow \infty.$$

Substituting this in (4.8), we see that

$$\mathbf{E} \left\{ W_{n,\beta}^{1-s} \right\} \leq 2n^{-(1-s)\beta\lambda} + n^{-(3/2)+o(1)} + \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{4,n} \cap \{W_{n,\beta} > n^{-\beta\lambda}\}} \right\}.$$

We make a partition of  $E_{4,n}$ : let  $M \geq 2$  be an integer, and let  $a_i := \frac{ia}{M}$ ,  $0 \leq i \leq M$ . By definition,

$$E_{4,n} = \bigcup_{i=0}^{M-1} \{V(\underline{w}^{(n)}) \geq -\rho \log n, a_i \log n < V(w_n^{(n)}) \leq a_{i+1} \log n\} =: \bigcup_{i=0}^{M-1} E_{4,n,i}.$$

Let  $1 \leq i \leq M$ . There are two possible situations. First situation:  $a_i \leq \lambda$ . In this case, we argue that on the event  $E_{4,n,i}$ , we have  $W_{n,\beta} \geq e^{-\beta V(w_n^{(n)})} \geq n^{-\beta a_{i+1}}$  and  $e^{-(\beta-1)V(w_n^{(n)})} \leq n^{-(\beta-1)a_i}$ , thus  $\frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \leq n^{\beta a_{i+1}s - (\beta-1)a_i} = n^{\beta a_i s - (\beta-1)a_i + \beta sa/M} \leq n^{[\beta s - (\beta-1)]\lambda + \beta sa/M}$ . Accordingly, in this situation,

$$\mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{4,n,i}} \right\} \leq n^{[\beta s - (\beta-1)]\lambda + \beta sa/M} \mathbf{Q}(E_{4,n,i}).$$

Second (and last) situation:  $a_i > \lambda$ . We have, on  $E_{4,n,i} \cap \{W_{n,\beta} > n^{-\beta\lambda}\}$ ,  $\frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \leq n^{\beta\lambda s - (\beta-1)a_i} \leq n^{[\beta s - (\beta-1)]\lambda}$ ; thus, in this situation,

$$\mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{4,n,i} \cap \{W_{n,\beta} > n^{-\beta\lambda}\}} \right\} \leq n^{[\beta s - (\beta-1)]\lambda} \mathbf{Q}(E_{4,n,i}).$$

We have therefore proved that

$$\begin{aligned} \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{4,n} \cap \{W_{n,\beta} > n^{-\beta\lambda}\}} \right\} &= \sum_{i=1}^M \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s} \mathbf{1}_{E_{4,n,i} \cap \{W_{n,\beta} > n^{-\beta\lambda}\}} \right\} \\ &\leq n^{[\beta s - (\beta-1)]\lambda + \beta s a / M} \mathbf{Q}(E_{4,n}). \end{aligned}$$

By Corollary 2.2,  $\mathbf{Q}(E_{4,n}) = \mathbf{P}\{\min_{0 \leq k < n} S_k \geq -\varrho \log n, 0 \leq S_n \leq a \log n\} = n^{-(3/2)+o(1)}$ . As a consequence,

$$\mathbf{E} \{W_{n,\beta}^{1-s}\} \leq 2n^{-(1-s)\beta\lambda} + n^{-(3/2)+o(1)} + n^{[\beta s - (\beta-1)]\lambda + \beta s a / M - (3/2)+o(1)}.$$

We choose  $\lambda := \frac{3}{2}$ . Since  $M$  can be as large as possible, this yields the upper bound in Theorem 4.1 by posing  $r := 1 - s$ .  $\square$

*Proof of Theorem 4.1: the lower bound.* Let  $\beta > 1$  and  $s \in (1 - \frac{1}{\beta}, 1)$ . By means of (4.6) and the elementary inequality  $(a + b)^{1-s} \leq a^{1-s} + b^{1-s}$  (for  $a \geq 0$  and  $b \geq 0$ ), we have

$$\begin{aligned} W_{n,\beta}^{1-s} &\leq \sum_{j=1}^n \sum_{u \in \mathcal{I}_j^{(n)}} e^{-(1-s)\beta V(u)} \left( \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} e^{-\beta V_u(x)} \right)^{1-s} \\ &\leq c_{13} \sum_{j=1}^n e^{-(1-s)\beta V(w_j^{(n)})} \sum_{u \in \mathcal{I}_j^{(n)}} \left( \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} e^{-\beta V_u(x)} \right)^{1-s}, \end{aligned}$$

where  $c_{13} := e^{(1-s)\beta C}$ . Let  $\mathcal{G}_n$  be the sigma-algebra defined in (2.9). Since  $V(w_j^{(n)})$  and  $\mathcal{I}_j^{(n)}$ , for  $1 \leq j \leq n$ , are  $\mathcal{G}_n$ -measurable, it follows from Proposition 2.1 (ii) that

$$\mathbf{E}_{\mathbf{Q}} \{W_{n,\beta}^{1-s} \mid \mathcal{G}_n\} \leq c_{13} \sum_{j=1}^n e^{-(1-s)\beta V(w_j^{(n)})} \mathbf{E}\{W_{n-j,\beta}^{1-s}\} \#\mathcal{I}_j^{(n)}.$$

Let  $\varepsilon > 0$  be small, and let  $r := \frac{3}{2}(1-s)\beta - \varepsilon$ . By means of the already proved upper bound for  $\mathbf{E}(W_{n,\beta}^{1-s})$ , this leads to:

$$(4.12) \quad \mathbf{E}_{\mathbf{Q}} \{W_{n,\beta}^{1-s} \mid \mathcal{G}_n\} \leq c_{14} \sum_{j=1}^n e^{-(1-s)\beta V(w_j^{(n)})} (n-j+1)^{-r} \#\mathcal{I}_j^{(n)}.$$

Since  $\mathbf{E}(W_{n,\beta}^{1-s}) = \mathbf{E}_{\mathbf{Q}}\left\{\frac{e^{-(\beta-1)V(w_n^{(n)})}}{W_{n,\beta}^s}\right\}$  (see (4.7)), we have, by Jensen's inequality (noticing that  $V(w_n^{(n)})$  is  $\mathcal{G}_n$ -measurable),

$$\mathbf{E}(W_{n,\beta}^{1-s}) \geq \mathbf{E}_{\mathbf{Q}}\left\{\frac{e^{-(\beta-1)V(w_n^{(n)})}}{\{\mathbf{E}_{\mathbf{Q}}(W_{n,\beta}^{1-s} | \mathcal{G}_n)\}^{s/(1-s)}}\right\},$$

which, in view of (4.12), yields (with  $c_{15} := c_{14}^{-s/(1-s)}$ )

$$\mathbf{E}(W_{n,\beta}^{1-s}) \geq c_{15} \mathbf{E}_{\mathbf{Q}}\left\{\frac{e^{-(\beta-1)V(w_n^{(n)})}}{\left\{\sum_{j=1}^n e^{-(1-s)\beta V(w_j^{(n)})} (n-j+1)^{-r} \#\mathcal{I}_j^{(n)}\right\}^{s/(1-s)}}\right\}.$$

By Corollary 2.2 and in its notation, this leads to

$$\begin{aligned} \mathbf{E}(W_{n,\beta}^{1-s}) &\geq c_{15} \mathbf{E}_{\mathbf{Q}}\left\{\frac{e^{-(\beta-1)S_n}}{\left\{\sum_{j=1}^n (n-j+1)^{-r} e^{-(1-s)\beta S_j} \sigma_j\right\}^{s/(1-s)}}\right\} \\ &= c_{15} \mathbf{E}_{\mathbf{Q}}\left\{\frac{e^{[\beta s - (\beta-1)]\tilde{S}_n}}{\left\{\sum_{k=0}^{n-1} (k+1)^{-r} e^{(1-s)\beta \tilde{S}_k} \tilde{\sigma}_k\right\}^{s/(1-s)}}\right\}, \end{aligned}$$

where

$$\tilde{S}_k := S_n - S_{n-k}, \quad \tilde{\sigma}_k := \sigma_{n-k}, \quad 0 \leq k \leq n-1,$$

and  $\tilde{S}_n := S_n$ . Let  $c_{16} > 0$  be a small constant, and define

$$\begin{aligned} E_{n,1}^{\tilde{S}} &:= \bigcap_{k=1}^{\lfloor n^\varepsilon \rfloor} \left\{ \tilde{S}_k \leq -c_{16} k^{1/3} \right\} \cap \left\{ -2n^{\varepsilon/2} \leq \tilde{S}_{\lfloor n^\varepsilon \rfloor} \leq -n^{\varepsilon/2} \right\}, \\ E_{n,2}^{\tilde{S}} &:= \bigcap_{k=\lfloor n^\varepsilon \rfloor + 1}^{n - \lfloor n^\varepsilon \rfloor - 1} \left\{ \tilde{S}_k \leq -[k^{1/3} \wedge (n-k)^{1/3}] \right\} \cap \left\{ -2n^{\varepsilon/2} \leq \tilde{S}_{n - \lfloor n^\varepsilon \rfloor} \leq -n^{\varepsilon/2} \right\}, \\ E_{n,3}^{\tilde{S}} &:= \bigcap_{k=n - \lfloor n^\varepsilon \rfloor + 1}^{n-1} \left\{ \tilde{S}_k \leq \frac{3}{2} \log n \right\} \cap \left\{ \frac{3-\varepsilon}{2} \log n \leq \tilde{S}_n \leq \frac{3}{2} \log n \right\}. \end{aligned}$$

Let

$$\begin{aligned} E_{n,1}^{\tilde{\sigma}} &:= \bigcap_{k=0}^{\lfloor n^\varepsilon \rfloor} \left\{ \tilde{\sigma}_k \leq n^{3\varepsilon/\delta} \right\} \\ E_{n,2}^{\tilde{\sigma}} &:= \bigcap_{k=\lfloor n^\varepsilon \rfloor + 1}^{n - \lfloor n^\varepsilon \rfloor} \left\{ \tilde{\sigma}_k \leq e^{n^{\varepsilon/4}} \right\}, \\ E_{n,3}^{\tilde{\sigma}} &:= \bigcap_{k=n - \lfloor n^\varepsilon \rfloor + 1}^{n-1} \left\{ \tilde{\sigma}_k \leq n^{3\varepsilon/\delta} \right\}. \end{aligned}$$

On  $\cap_{i=1}^3 (E_{n,i}^{\tilde{S}} \cap E_{n,i}^{\tilde{\sigma}})$ , we have  $\sum_{k=0}^{n-1} (k+1)^{-r} e^{(1-s)\beta\tilde{S}_k} \tilde{\sigma}_k \leq c_{17} n^{2\varepsilon+(3\varepsilon/\delta)}$ , whereas  $e^{[\beta s - (\beta-1)]\tilde{S}_n} \geq n^{(3-\varepsilon)[\beta s - (\beta-1)]/2}$  (recalling that  $\beta s > \beta - 1$ ). Therefore, with  $c_{18} := c_{15}/c_{17}^{s/(1-s)}$  and  $c_{19} := (2 + \frac{3}{\delta})^{\frac{s}{1-s}}$ ,

$$(4.13) \quad \mathbf{E} (W_{n,\beta}^{1-s}) \geq c_{18} n^{-c_{19}\varepsilon} n^{(3-\varepsilon)[\beta s - (\beta-1)]/2} \mathbf{Q}\{\cap_{i=1}^3 (E_{n,i}^{\tilde{S}} \cap E_{n,i}^{\tilde{\sigma}})\}.$$

We need to bound  $\mathbf{Q}(\cap_{i=1}^3 (E_{n,i}^{\tilde{S}} \cap E_{n,i}^{\tilde{\sigma}}))$  from below. For  $j \leq n$ , let  $\tilde{\mathcal{G}}_j$  be the sigma-algebra generated by  $(\tilde{S}_k, \tilde{\sigma}_k)$ ,  $1 \leq k \leq j$ . Then  $E_{n,1}^{\tilde{S}}$ ,  $E_{n,2}^{\tilde{S}}$ ,  $E_{n,1}^{\tilde{\sigma}}$  and  $E_{n,2}^{\tilde{\sigma}}$  are  $\tilde{\mathcal{G}}_{n-\lfloor n^\varepsilon \rfloor}$ -measurable, whereas  $E_{n,3}^{\tilde{\sigma}}$  is independent of  $\tilde{\mathcal{G}}_{n-\lfloor n^\varepsilon \rfloor}$ . Therefore,

$$\mathbf{Q}(\cap_{i=1}^3 (E_{n,i}^{\tilde{S}} \cap E_{n,i}^{\tilde{\sigma}}) | \tilde{\mathcal{G}}_{n-\lfloor n^\varepsilon \rfloor}) \geq [\mathbf{Q}(E_{n,3}^{\tilde{S}} | \tilde{\mathcal{G}}_{n-\lfloor n^\varepsilon \rfloor}) + \mathbf{Q}(E_{n,3}^{\tilde{\sigma}}) - 1] \mathbf{1}_{E_{n,1}^{\tilde{S}} \cap E_{n,2}^{\tilde{S}} \cap E_{n,1}^{\tilde{\sigma}} \cap E_{n,2}^{\tilde{\sigma}}}.$$

It is easy to estimate  $\mathbf{Q}(E_{n,3}^{\tilde{\sigma}})$ : since  $c_{20} := \mathbf{E}_{\mathbf{Q}}(\sigma_1^\delta) < \infty$  (Corollary 2.3), we have  $\mathbf{Q}\{\sigma_1 > n^{3\varepsilon/\delta}\} \leq c_{20} n^{-3\varepsilon}$ , and thus  $\mathbf{Q}(E_{n,3}^{\tilde{\sigma}}) = (\mathbf{Q}\{\sigma_1 \leq n^{3\varepsilon/\delta}\})^{\lfloor n^\varepsilon \rfloor - 1} \geq (1 - c_{20} n^{-3\varepsilon})^{\lfloor n^\varepsilon \rfloor - 1} \geq 1 - c_{21} n^{-2\varepsilon}$ . To estimate  $\mathbf{Q}(E_{n,3}^{\tilde{S}} | \tilde{\mathcal{G}}_{n-\lfloor n^\varepsilon \rfloor})$ , we use the Markov property to see that, if  $\tilde{S}_{n-\lfloor n^\varepsilon \rfloor} \in I_n := [-2n^{\varepsilon/2}, -n^{\varepsilon/2}]$ , the conditional probability is (writing  $N := \lfloor n^\varepsilon \rfloor$ )

$$\geq \inf_{z \in I_n} \mathbf{Q}\left\{S_i \leq \frac{3}{2} \log n - z, \forall 1 \leq i \leq N - 1, \frac{3 - \varepsilon}{2} \log n - z \leq S_N \leq \frac{3}{2} \log n - z\right\},$$

which is greater than  $N^{-(3/2)+o(1)}$ . Therefore,

$$\mathbf{Q}(E_{n,3}^{\tilde{S}} | \tilde{\mathcal{G}}_{n-\lfloor n^\varepsilon \rfloor}) + \mathbf{Q}(E_{n,3}^{\tilde{\sigma}}) - 1 \geq n^{-(3\varepsilon/2)+o(1)} - c_{21} n^{-2\varepsilon} = n^{-(3\varepsilon/2)+o(1)}.$$

As a consequence,

$$(4.14) \quad \mathbf{Q}\{\cap_{i=1}^3 (E_{n,i}^{\tilde{S}} \cap E_{n,i}^{\tilde{\sigma}})\} \geq n^{-(3\varepsilon/2)+o(1)} \mathbf{Q}(E_{n,1}^{\tilde{S}} \cap E_{n,2}^{\tilde{S}} \cap E_{n,1}^{\tilde{\sigma}} \cap E_{n,2}^{\tilde{\sigma}}).$$

To estimate  $\mathbf{Q}(E_{n,1}^{\tilde{S}} \cap E_{n,2}^{\tilde{S}} \cap E_{n,1}^{\tilde{\sigma}} \cap E_{n,2}^{\tilde{\sigma}})$ , we condition on  $\tilde{\mathcal{G}}_{\lfloor n^\varepsilon \rfloor}$ , and note that  $E_{n,1}^{\tilde{S}}$  and  $E_{n,1}^{\tilde{\sigma}}$  are  $\tilde{\mathcal{G}}_{\lfloor n^\varepsilon \rfloor}$ -measurable, whereas  $E_{n,2}^{\tilde{\sigma}}$  is independent of  $\tilde{\mathcal{G}}_{\lfloor n^\varepsilon \rfloor}$ . Since  $\mathbf{Q}(E_{n,2}^{\tilde{S}} | \tilde{\mathcal{G}}_{\lfloor n^\varepsilon \rfloor}) \geq n^{-(3/2)+o(1)}$ , whereas  $\mathbf{Q}(E_{n,2}^{\tilde{\sigma}}) = [\mathbf{Q}\{\sigma_1 \leq e^{n^{\varepsilon/4}}\}]^{n-2\lfloor n^\varepsilon \rfloor} \geq [1 - c_{20} e^{-\delta n^{\varepsilon/4}}]^{n-2\lfloor n^\varepsilon \rfloor} \geq 1 - e^{-n^{\varepsilon/5}}$  (for large  $n$ ), we have

$$\begin{aligned} \mathbf{Q}(E_{n,1}^{\tilde{S}} \cap E_{n,2}^{\tilde{S}} \cap E_{n,1}^{\tilde{\sigma}} \cap E_{n,2}^{\tilde{\sigma}} | \tilde{\mathcal{G}}_{\lfloor n^\varepsilon \rfloor}) &\geq [\mathbf{Q}(E_{n,2}^{\tilde{S}} | \tilde{\mathcal{G}}_{\lfloor n^\varepsilon \rfloor}) + \mathbf{Q}(E_{n,2}^{\tilde{\sigma}}) - 1] \mathbf{1}_{E_{n,1}^{\tilde{S}} \cap E_{n,1}^{\tilde{\sigma}}} \\ &\geq n^{-(3/2)+o(1)} \mathbf{1}_{E_{n,1}^{\tilde{S}} \cap E_{n,1}^{\tilde{\sigma}}}. \end{aligned}$$

Thus,  $\mathbf{Q}(E_{n,1}^{\tilde{S}} \cap E_{n,2}^{\tilde{S}} \cap E_{n,1}^{\tilde{\sigma}} \cap E_{n,2}^{\tilde{\sigma}}) \geq n^{-(3/2)+o(1)} \mathbf{Q}(E_{n,1}^{\tilde{S}} \cap E_{n,1}^{\tilde{\sigma}})$ . Going back to (4.14), we have

$$\begin{aligned} \mathbf{Q}\{\cap_{i=1}^3 (E_{n,i}^{\tilde{S}} \cap E_{n,i}^{\tilde{\sigma}})\} &\geq n^{-(3\varepsilon/2)-(3/2)+o(1)} \mathbf{Q}(E_{n,1}^{\tilde{S}} \cap E_{n,1}^{\tilde{\sigma}}) \\ &\geq n^{-(3\varepsilon/2)-(3/2)+o(1)} [\mathbf{Q}(E_{n,1}^{\tilde{S}}) + \mathbf{Q}(E_{n,1}^{\tilde{\sigma}}) - 1]. \end{aligned}$$

We choose the constant  $c_{16} > 0$  sufficiently small so that  $\mathbf{Q}(E_{n,1}^{\tilde{S}}) \geq n^{-(3\varepsilon/2)+o(1)}$ , whereas  $\mathbf{Q}(E_{n,1}^{\tilde{\sigma}}) = \mathbf{Q}(E_{n,3}^{\tilde{\sigma}}) \geq 1 - c_{21} n^{-2\varepsilon}$ . Accordingly,

$$\mathbf{Q}\{\cap_{i=1}^3 (E_{n,i}^{\tilde{S}} \cap E_{n,i}^{\tilde{\sigma}})\} \geq n^{-3\varepsilon-(3/2)+o(1)}, \quad n \rightarrow \infty.$$

Substituting this into (4.13) yields

$$\mathbf{E}(W_{n,\beta}^{1-s}) \geq c_{18} n^{-c_{19}\varepsilon} n^{(3-\varepsilon)[\beta s - (\beta-1)]/2} n^{-3\varepsilon-(3/2)+o(1)}.$$

Since  $\varepsilon$  can be as small as possible, this implies the lower bound in Theorem 4.1.  $\square$

We now have all of the ingredients needed for the proof of Theorem 1.3.

*Proof of Theorem 1.3.* We start with the proof of the upper bound in (1.9). Fix  $\beta > 1$  and  $\varepsilon > 0$ . Let  $\tau := \inf\{j \geq 1 : \#\{u : |u| = j\} \geq \frac{3}{\varepsilon}\}$ . On  $\{\tau < \infty\}$ , we have  $e^{-\beta V(u)} \geq e^{-C\beta\tau}$  for  $|u| = \tau$ , and thus by (4.6),  $W_{n+\tau,\beta} \geq e^{-C\beta\tau} \sum_{|u|=\tau} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u=n} e^{-\beta V_u(x)}$ . By the branching property, this leads to:

$$\mathbf{P}\{\tau < \infty, W_{n+\tau,\beta} \geq e^{C\beta\tau} n^{-3\beta/2+\varepsilon}\} \leq (\mathbf{P}\{W_{n,\beta} \geq n^{-3\beta/2+\varepsilon}\})^{3/\varepsilon}.$$

By the upper bound in (4.1) and Chebyshev's inequality,  $\mathbf{P}\{W_{n,\beta} \geq n^{-3\beta/2+\varepsilon}\} \leq n^{-\varepsilon/2}$  for large  $n$ ; thus  $\sum_n (\mathbf{P}\{W_{n,\beta} \geq n^{-3\beta/2+\varepsilon}\})^{3/\varepsilon} < \infty$ . The upper bound in (1.9) follows by an application of the Borel–Cantelli lemma, and the fact that  $\{\tau < \infty\} \supset \mathcal{S}$ .

To prove the lower bound in (1.9), we recall the Paley–Zygmund inequality: for any non-negative random variable  $\xi$ ,  $\mathbf{P}\{\xi > \frac{1}{2}\mathbf{E}(\xi)\} \geq \frac{1}{4} \frac{(\mathbf{E}\xi)^2}{\mathbf{E}(\xi^2)}$ . Therefore, if  $0 < r < \frac{1}{2\beta}$ , then

$$\mathbf{P}\left\{W_{n,\beta}^r > \frac{1}{2} \mathbf{E}(W_{n,\beta}^r)\right\} \geq \frac{1}{4} \frac{\{\mathbf{E}(W_{n,\beta}^r)\}^2}{\mathbf{E}\{W_{n,\beta}^{2r}\}} = n^{o(1)},$$

the last identity being a consequence of (4.1). Accordingly,  $\mathbf{P}\{W_{n,\beta} > n^{-3\beta/2+o(1)}\} \geq n^{o(1)}$ . Thus, by the elementary inequality  $1 - x \leq e^{-x}$  (for  $x \geq 0$ ), we get

$$(4.15) \quad \mathbf{P}\{W_{n,\beta} \leq n^{-3\beta/2+o(1)}\} \leq e^{-n^{o(1)}}.$$

Let  $\varepsilon > 0$  and let  $\tau_n := \inf\{k \geq 1 : \#\{u : |u| = k\} \geq n^{2\varepsilon}\}$ . We have

$$\begin{aligned} & \mathbf{P}\left\{\tau_n < \infty, \min_{k \in [\frac{n}{2}, n]} W_{k+\tau_n,\beta} \leq e^{-C\beta\tau_n} n^{-3\beta/2-\varepsilon}\right\} \\ & \leq \sum_{k \in [\frac{n}{2}, n]} \mathbf{P}\{\tau_n < \infty, W_{k+\tau_n,\beta} \leq e^{-C\beta\tau_n} n^{-3\beta/2-\varepsilon}\} \\ & \leq \sum_{k \in [\frac{n}{2}, n]} (\mathbf{P}\{W_{k,\beta} \leq n^{-3\beta/2-\varepsilon}\})^{\lfloor n^{2\varepsilon} \rfloor}. \end{aligned}$$

By (4.15),  $\max_{k \in [\frac{n}{2}, n]} \mathbf{P}\{W_{k,\beta} \leq n^{-3\beta/2-\varepsilon}\} \leq e^{-n^{-\varepsilon}}$  for all sufficiently large  $n$ , say  $n \geq n_0$ . Therefore, for  $n \geq n_0$ ,

$$\mathbf{P}\left\{\tau_n < \infty, \min_{k \in [\frac{n}{2}, n]} W_{k+\tau_n, \beta} \leq e^{-C\beta\tau_n} n^{-3\beta/2-\varepsilon}\right\} \leq n \exp(-n^{-\varepsilon} \lfloor n^{2\varepsilon} \rfloor),$$

which is summable in  $n$ . By the Borel–Cantelli lemma,  $\mathbf{P}$ -almost surely for all large  $n$ , we have either  $\tau_n = \infty$ , or  $\min_{k \in [\frac{n}{2}, n]} W_{k+\tau_n, \beta} > e^{-C\beta\tau_n} n^{-3\beta/2-\varepsilon}$ .

Recall that the number of particles in each generation forms a Galton–Watson tree, which is super-critical under assumption (1.2) (because  $m := \mathbf{E}\{\sum_{u:|u|=1} 1\} > 1$ ). In particular, conditionally on the system’s ultimate survival,  $\frac{\#\{u:|u|=j\}}{m^j}$  converges  $\mathbf{P}$ -almost surely to a (strictly) positive random variable when  $j \rightarrow \infty$ , which implies  $\tau_n \sim \frac{2\varepsilon \log n}{\log m}$  ( $n \rightarrow \infty$ )  $\mathbf{P}$ -almost surely. As a consequence, upon the system’s survival, we have,  $\mathbf{P}$ -almost surely for all large  $n$ ,

$$W_{n,\beta} \geq \min_{k \in [\frac{n}{2}, n]} W_{k+\tau_n, \beta} > e^{-C\beta\tau_n} n^{-3\beta/2-\varepsilon} \geq n^{-3\beta/2-\varepsilon-3C\beta\varepsilon/\log m}.$$

This yields the desired lower bound in (1.9).

The proof of (1.8) goes along exactly the same lines, by means of Proposition 6.2 (which is going to be proved in Section 6) instead of Theorem 1.3.  $\square$

## 5 Proof of Theorem 1.2

Assume (1.1) and (1.2). Let  $1 < \beta_1 < \beta_2$ . Since  $W_{n,\beta_2} \leq W_{n,\beta_1} \exp\{-(\beta_2 - \beta_1) \inf_{|u|=n} V(u)\}$ , it follows from Theorem 1.3 that, conditionally on the system’s survival,

$$\inf_{|u|=n} V(u) \leq \left(\frac{3}{2} + o(1)\right) \log n, \quad \mathbf{P}\text{-a.s.}$$

On the other hand,  $W_{n,\beta} \geq \exp\{-\beta \inf_{|u|=n} V(u)\}$ , so by the upper bound in Theorem 1.3, we have, conditionally on the system’s survival,

$$\inf_{|u|=n} V(u) \geq \left(\frac{3}{2} + o(1)\right) \log n, \quad \mathbf{P}\text{-a.s.}$$

Theorem 1.2 is proved.  $\square$

## 6 Proof of Theorem 1.1

The proof of Theorem 1.1 relies on two results, stated below as Propositions 6.2 and 6.3, respectively. Proposition 6.2 yields the tightness of  $(n^{1/2}W_n, n \geq 1)$ , whereas Proposition 6.3 implies that  $\frac{W_{n+1}}{W_n}$  converges to 1 in probability (conditionally on the system’s survival).

We start with a lemma, which is a very simple variant of a result of Kozlov [19].



**Lemma 6.1** Assume that  $\{(X_k, \eta_k), k \geq 1\}$  is a sequence of i.i.d. random vectors defined on  $(\Omega, \mathcal{F}, \mathbb{P})$ , with  $\mathbb{P}\{\eta_1 \geq 0\} = 1$  and  $\mathbb{E}\{\eta_1^\theta\} < \infty$  for some  $\theta > 0$ . We assume that  $X_1$  is non-degenerate and bounded with  $\mathbb{E}(X_1) = 0$ , and set  $S_n := X_1 + \dots + X_n$  (for  $n \geq 1$ ). Then

$$(6.1) \quad \lim_{n \rightarrow \infty} \mathbb{E} \left\{ \frac{1}{1 + \sum_{k=1}^n \eta_k e^{-S_k}} \mid \min_{1 \leq k \leq n} S_k > 0 \right\} = c_{22} \in (0, \infty).$$

*Proof.* The lemma is an analogue of the identity (26) of Kozlov [19], except that the distribution of our  $\eta_1$  is slightly different from that of Kozlov's, which explains the moment condition  $\mathbb{E}\{\eta_1^\theta\} < \infty$ : this condition will be seen to guarantee

$$(6.2) \quad \lim_{j \rightarrow \infty} \limsup_{n \rightarrow \infty} \mathbb{E} \left\{ \frac{1}{1 + \sum_{k=1}^j \eta_k e^{-S_k}} - \frac{1}{1 + \sum_{k=1}^n \eta_k e^{-S_k}} \mid \min_{1 \leq k \leq n} S_k > 0 \right\} = 0.$$

The identity (6.2), which plays the role of Kozlov's Lemma 1 in [19], is the key ingredient in the proof of (6.1). Since the rest of the proof goes along the lines of [19] with obvious modifications, we only prove (6.2) here.

Without loss of generality, we assume  $\theta \leq 1$  (otherwise, we can replace  $\theta$  by 1). We observe that for  $n > j$ , the integrand in (6.2) is non-negative, and is

$$\leq \frac{\sum_{k=j+1}^n \eta_k e^{-S_k}}{1 + \sum_{k=1}^n \eta_k e^{-S_k}} \leq \left( \frac{\sum_{k=j+1}^n \eta_k e^{-S_k}}{1 + \sum_{k=1}^n \eta_k e^{-S_k}} \right)^\theta \leq \left( \sum_{k=j+1}^n \eta_k e^{-S_k} \right)^\theta,$$

which is bounded by  $\sum_{k=j+1}^n \eta_k^\theta e^{-\theta S_k}$ . Since  $\mathbb{P}\{\min_{1 \leq k \leq n} S_k > 0\} \sim c_{23}/n^{1/2}$  (Bingham [8]), we only need to check that

$$(6.3) \quad \lim_{j \rightarrow \infty} \limsup_{n \rightarrow \infty} n^{1/2} \sum_{k=j+1}^n \mathbb{E} \left\{ \eta_k^\theta e^{-\theta S_k} \mathbf{1}_{\{\min_{1 \leq i \leq n} S_i > 0\}} \right\} = 0.$$

Let  $j < k < n$ . Then  $\{\min_{1 \leq i \leq n} S_i > 0\} \subset \{\min_{k \leq i \leq n} (S_i - S_k) > -S_k\}$ . By boundedness of  $X_1$ , we have  $S_{k-1} - C \leq S_k \leq S_{k-1} + C$  for some constant  $C > 0$ . Recall that  $S_k = \sum_{i=1}^k X_i$  and that  $(X_i, \eta_i)$  are i.i.d. Therefore, the expectation term in (6.3) is bounded by

$$e^{\theta C} \mathbb{E}\{\eta_k^\theta\} \mathbb{E} \left\{ e^{-\theta S_{k-1}} \mathbf{1}_{\{\min_{1 \leq i < k} S_i > 0, \min_{k \leq i \leq n} (S_i - S_k) > -S_{k-1} - C\}} \right\}.$$

By assumption,  $\mathbb{E}\{\eta_k^\theta\} = \mathbb{E}\{\eta_1^\theta\} < \infty$ . Let  $(Y_i, i \geq 1)$  be i.i.d. random variables distributed as  $X_1$ , independent of  $(X_i, i \geq 1)$ . Since  $Y_1$  is non-degenerate with  $\mathbb{E}(Y_1) = 0$ , there exists  $\varepsilon > 0$  such that  $\mathbb{P}\{Y_1 > \varepsilon\} > 0$ . Let  $N := \lfloor \frac{1}{\varepsilon} \rfloor + 1$ . Then  $c_{24} := \mathbb{P}\{\min_{1 \leq i \leq N} Y_i > 0, Y_1 + \dots + Y_N > C\} \geq \mathbb{P}\{\min_{1 \leq i \leq N} Y_i > \varepsilon\} > 0$ . By independence,

$$\begin{aligned} & \mathbb{E} \left\{ e^{-\theta S_{k-1}} \mathbf{1}_{\{\min_{1 \leq i < k} S_i > 0, \min_{k \leq i \leq n} (S_i - S_k) > -S_{k-1} - C\}} \right\} \\ &= \frac{1}{c_{24}} \mathbb{E} \left\{ e^{-\theta S_{k-1}} \mathbf{1}_{\{\min_{1 \leq i < k} S_i > 0, \min_{k \leq i \leq n} (S_i - S_k) > -S_{k-1} - C\}} \mathbf{1}_{\{\min_{1 \leq i \leq N} Y_i > 0, Y_1 + \dots + Y_N > C\}} \right\} \\ &\leq \frac{1}{c_{24}} \mathbb{E} \left\{ e^{-\theta S_{k-1}} \mathbf{1}_{\{\min_{1 \leq i \leq n+N-1} S_i > 0\}} \right\}. \end{aligned}$$

Therefore,

$$\begin{aligned} & \limsup_{j \rightarrow \infty} \limsup_{n \rightarrow \infty} n^{1/2} \sum_{k=j+1}^n \mathbb{E} \left\{ \eta_k^\theta e^{-\theta S_k} \mathbf{1}_{\{\min_{1 \leq i \leq n} S_i > 0\}} \right\} \\ & \leq c_{25} \limsup_{j \rightarrow \infty} \limsup_{n \rightarrow \infty} n^{1/2} \sum_{k=j}^{n-1} \mathbb{E} \left\{ e^{-\theta S_k} \mathbf{1}_{\{\min_{1 \leq i \leq n+N-1} S_i > 0\}} \right\}, \end{aligned}$$

which equals 0 by Lemma 1 of Kozlov [19] (applied to  $\eta_i = 1, \forall i$ ). This yields (6.3).  $\square$

**Proposition 6.2** *For any  $\gamma \in [0, 1)$ , we have*

$$(6.4) \quad 0 < \liminf_{n \rightarrow \infty} \mathbf{E} \left\{ (n^{1/2} W_n)^\gamma \mid \mathcal{S} \right\} \leq \limsup_{n \rightarrow \infty} \mathbf{E} \left\{ (n^{1/2} W_n)^\gamma \mid \mathcal{S} \right\} < \infty.$$

*Proof.* The basic idea in the proof of Proposition 6.2 is the same as in the proof of Theorem 4.1.

We first prove the upper bound, via  $n^{1/2} W_n \leq \bar{Y}_n$ , where

$$\bar{Y}_n := \sum_{|u|=n} (n^{1/2} \vee V(u)^+) e^{-V(u)}.$$

Recall  $W_n^*$  from (3.7). Applying (3.13) to  $\lambda = 1$ , we see that  $\bar{Y}_n \geq c_{26} \log(\frac{1}{W_n^*})$ , with  $c_{26} := \frac{1}{c_4 + c_5}$ . Thus  $\mathbf{P}\{\bar{Y}_n < x, \mathcal{S}_n\} \leq \mathbf{P}\{\log(\frac{1}{W_n^*}) < c_{26} x, \mathcal{S}_n\} \leq e^{c_{26}} \mathbf{E}\{(W_n^*)^{1/x} \mathbf{1}_{\mathcal{S}_n}\}$ , which, according to Lemma 3.3, is bounded by  $e^{c_{26}} (e^{-1/x^{\kappa}} + e^{-c_2 n})$  for  $0 < x \leq \frac{1}{a_0}$ . Since  $\bar{Y}_n \geq e^{-Cn}$  on  $\mathcal{S}_n$ , this yields

$$(6.5) \quad \sup_{n \geq 1} \mathbf{E} \left\{ \frac{1}{\bar{Y}_n^s} \mathbf{1}_{\mathcal{S}_n} \right\} < \infty, \quad \forall s \in (0, \frac{c_2}{C}).$$

We now fix  $0 < s < \min\{\frac{1}{2}, \frac{c_2}{C}\}$ . Let  $K \geq 1$  and let  $E_n$  be the event in (4.4), satisfying  $\mathbf{Q}\{E_n\} \geq 1 - n^{-K}$  for large  $n$  (say  $n \geq n_0$ ). We write

$$\mathbf{E} \left\{ (n^{1/2} W_n)^{1-s} \mathbf{1}_{\mathcal{S}_n} \right\} \leq \mathbf{E} \left\{ (n^{1/2} W_n)^{1-s} \mathbf{1}_{\mathcal{S}_n \cap E_n} \right\} + \mathbf{E} \left\{ (n^{1/2} W_n)^{1-s} \mathbf{1}_{E_n^c} \right\}.$$

For  $n \geq n_0$ ,  $\mathbf{E}\{W_n^{1-s} \mathbf{1}_{E_n^c}\} \leq [\mathbf{E}\{W_n^{1-2s}\}]^{1/2} [\mathbf{E}\{W_n \mathbf{1}_{E_n^c}\}]^{1/2} = [\mathbf{E}\{W_n^{1-2s}\}]^{1/2} [\mathbf{Q}\{E_n^c\}]^{1/2} \leq [\mathbf{E}\{W_n\}]^{(1/2)-s} n^{-K/2}$ , which equals  $n^{-K/2}$  (since  $\mathbf{E}\{W_n\} = 1$ ). Therefore, for  $n \rightarrow \infty$ ,

$$\mathbf{E} \left\{ (n^{1/2} W_n)^{1-s} \mathbf{1}_{\mathcal{S}_n} \right\} \leq \mathbf{E} \left\{ \bar{Y}_n^{1-s} \mathbf{1}_{\mathcal{S}_n \cap E_n} \right\} + o(1).$$

Exactly as in (4.7), we have  $\mathbf{E}\{\bar{Y}_n^{1-s} \mathbf{1}_{\mathcal{S}_n \cap E_n}\} = \mathbf{E}_{\mathbf{Q}}\{(n^{1/2} \vee V(w_n^{(n)})^+) \bar{Y}_n^{-s} \mathbf{1}_{E_n}\}$ . Thus, for  $n \rightarrow \infty$ ,

$$(6.6) \quad \mathbf{E} \left\{ (n^{1/2} W_n)^{1-s} \mathbf{1}_{\mathcal{S}_n} \right\} \leq \mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} + V(w_n^{(n)})^+) \bar{Y}_n^{-s} \mathbf{1}_{E_n} \right\} + o(1).$$

Recall that  $\underline{w}^{(n)} \in \llbracket e, w_n^{(n)} \rrbracket$  is such that  $V(\underline{w}^{(n)}) = \min_{u \in \llbracket e, w_n^{(n)} \rrbracket} V(u)$ . We have, for any subset  $\mathcal{L} \subset \{1, 2, \dots, n\}$ ,

$$\begin{aligned} \bar{Y}_n &\geq \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{J}_j^{(n)}} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} \max \{n^{1/2}, V(x)^+\} e^{-V(u)} \\ &= \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{J}_j^{(n)}} e^{-V(u)} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} \max \{n^{1/2}, [V(u) + V_u(x)]^+\} e^{-V_u(x)}. \end{aligned}$$

We choose  $\mathcal{L} := \{1 \leq j \leq n : |j - |\underline{w}^{(n)}|| \leq c_{12} \log n\}$  ( $c_{12}$  being the constant in  $E_n$ , defined in (4.4)), and observe that for any  $u \in \mathcal{J}_j^{(n)}$  (with  $j \in \mathcal{L}$ ), we have  $|V(u) - V(\underline{w}^{(n)})| \leq C(c_{12} \log n + 2) \leq 2Cc_{12} \log n$  (for  $n \geq 2$ ).

We now distinguish two possible situations, depending on whether  $V(\underline{w}^{(n)}) \geq -c_{27} \log n$ , where  $c_{27} := \frac{1}{s} + 2Cc_{12}$ . In both situations, we consider a sufficiently large  $n$  and an arbitrary  $u \in \mathcal{J}_j^{(n)}$  (with  $j \in \mathcal{L}$ ).

On  $\{V(\underline{w}^{(n)}) \geq -c_{27} \log n\}$ , we have  $\max\{n^{1/2}, [V(u) + V_u(x)]^+\} \geq \frac{1}{2}(n^{1/2} \vee V_u(x)^+)$  (this holds trivially in case  $V_u(x) \leq n^{1/2}$ ; otherwise  $[V(u) + V_u(x)]^+ \geq V_u(x) - (c_{27} + 2Cc_{12}) \log n \geq \frac{1}{2}V_u(x)^+$ ), and thus

$$\begin{aligned} \bar{Y}_n &\geq \frac{1}{2} \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{J}_j^{(n)}} e^{-V(u)} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} \max \{(n-j)^{1/2}, V_u(x)^+\} e^{-V_u(x)} \\ &\geq \frac{e^{-2C}}{2} \sum_{j \in \mathcal{L}} e^{-V(w_j^{(n)})} \sum_{u \in \mathcal{J}_j^{(n)}} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} \max \{(n-j)^{1/2}, V_u(x)^+\} e^{-V_u(x)} \\ &=: \frac{e^{-2C}}{2} \sum_{j \in \mathcal{L}} e^{-V(w_j^{(n)})} \sum_{u \in \mathcal{J}_j^{(n)}} \xi_u. \end{aligned}$$

If, however,  $V(\underline{w}^{(n)}) < -c_{27} \log n$ , then  $V(u) \leq -\frac{1}{s} \log n$ , and since  $\max\{n^{1/2}, [V(u) + V_u(x)]^+\} \geq n^{1/2}$ , we have, in this case,

$$\bar{Y}_n \geq n^{(1/s)+(1/2)} \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{J}_j^{(n)}} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} e^{-V_u(x)} =: n^{(1/s)+(1/2)} \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{J}_j^{(n)}} \eta_u.$$

Therefore, in both situations, we have ( $c_{28} := 2^s e^{2sC}$ )

$$(6.7) \quad \bar{Y}_n^{-s} \mathbf{1}_{E_n} \leq c_{28} \left( \sum_{j \in \mathcal{L}} e^{-V(w_j^{(n)})} \sum_{u \in \mathcal{J}_j^{(n)}} \xi_u \right)^{-s} \mathbf{1}_{E_n} + n^{-(s/2)-1} \left( \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{J}_j^{(n)}} \eta_u \right)^{-s} \mathbf{1}_{E_n}.$$

[By definition, on the event  $E_n$ , we have  $\sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{J}_j^{(n)}} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|_u = n-j} 1 > 0$ , so the  $(\dots)^{-s}$  expressions on the right-hand side are well-defined.]

Recall  $\mathcal{G}_n$  from (2.9). We observe that by Proposition 2.1, under  $\mathbf{Q}$  and conditionally on  $\mathcal{G}_n$ , the random variables  $\xi_u$ , for  $u \in \mathcal{J}_j^{(n)}$  and  $j \in \mathcal{L}$ , are i.i.d. and are distributed as  $\bar{Y}_{n-j}$  under  $\mathbf{P}$ . By applying the second part of Lemma 4.2, we obtain:

$$\begin{aligned} & \mathbf{E}_{\mathbf{Q}} \left\{ \left( \sum_{j \in \mathcal{L}} e^{-V(w_j^{(n)})} \sum_{u \in \mathcal{J}_j^{(n)}} \xi_u \right)^{-s} \mathbf{1}_{E_n} \mid \mathcal{G}_n \right\} \\ & \leq \sum_{j \in \mathcal{L}} b^{|j-j_0|} \mathbf{E}_{\mathbf{Q}} \left\{ \frac{e^{sV(w_j^{(n)})}}{\left[ \sum_{u \in \mathcal{J}_j^{(n)}} \xi_u \right]^s} \mathbf{1}_{\{\sum_{u \in \mathcal{J}_j^{(n)}} \xi_u > 0\}} \mid \mathcal{G}_n \right\}, \end{aligned}$$

for any  $j_0 \in \mathcal{L}$ , with  $b := \max_{j \in \mathcal{L}} \max_{u \in \mathcal{J}_j^{(n)}} \mathbf{Q}\{\xi_u = 0\} \leq \max_{1 \leq j \leq n} \mathbf{P}\{\mathcal{S}_{n-j}^c\} \leq \mathbf{P}\{\mathcal{S}^c\} = q$ . [We mention that Lemma 4.2 applies to any (deterministic) permutation of the random variables  $X_1, \dots, X_N$ , which allows us to choose an arbitrary  $j_0$  here.]

The first part of Lemma 4.2 tells us that for any  $j \in \mathcal{L}$ ,

$$\mathbf{E}_{\mathbf{Q}} \left\{ \frac{1}{\left[ \sum_{u \in \mathcal{J}_j^{(n)}} \xi_u \right]^s} \mathbf{1}_{\{\sum_{u \in \mathcal{J}_j^{(n)}} \xi_u > 0\}} \mid \mathcal{G}_n \right\} \leq \frac{1}{1-q} \max_{u \in \mathcal{J}_j^{(n)}} \mathbf{E}_{\mathbf{Q}} \left\{ \frac{1}{\xi_u^s} \mathbf{1}_{\{\xi_u > 0\}} \mid \mathcal{G}_n \right\},$$

which equals  $\frac{1}{1-q} \mathbf{E}\left\{\frac{1}{\bar{Y}_{n-j}^s} \mathbf{1}_{\mathcal{S}_{n-j}}\right\}$  (Proposition 2.1), and is hence bounded in  $n$  and  $j$  (by (6.5)). Summarizing, we have proved that

$$\mathbf{E}_{\mathbf{Q}} \left\{ \left( \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{J}_j^{(n)}} e^{-V(w_j^{(n)})} \xi_u \right)^{-s} \mathbf{1}_{E_n} \mid \mathcal{G}_n \right\} \leq c_{29} \sum_{j \in \mathcal{L}} q^{|j-j_0|} e^{sV(w_j^{(n)})},$$

where the constant  $c_{29}$  does not depend on the choice of  $j_0$ . We choose  $j_0 := |\underline{w}_n| \in \mathcal{L}$ . Then  $V(w_j^{(n)}) \leq V(\underline{w}_n) + C|j - j_0|$ . As long as  $s < \frac{1}{C} \log(\frac{1}{q})$ , we have  $\sum_{j \in \mathcal{L}} q^{|j-j_0|} e^{sV(w_j^{(n)})} \leq c_{30} e^{sV(\underline{w}_n)}$ . As a consequence,

$$\begin{aligned} & \mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} + V(w_n^{(n)})^+) \left( \sum_{j \in \mathcal{L}} e^{-V(w_j^{(n)})} \sum_{u \in \mathcal{J}_j^{(n)}} \xi_u \right)^{-s} \mathbf{1}_{E_n} \right\} \\ & \leq c_{31} \mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} + V(w_n^{(n)})^+) e^{sV(\underline{w}_n)} \right\} \\ & = c_{31} \mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} + S_n^+) \exp \left( s \min_{1 \leq j < n} S_j \right) \right\} \leq c_{32}. \end{aligned}$$

Similarly, using (3.17) in place of (6.5), we have

$$\mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} + V(w_n^{(n)})^+) \left( \sum_{j \in \mathcal{L}} \sum_{u \in \mathcal{J}_j^{(n)}} \eta_u \right)^{-s} \mathbf{1}_{E_n} \right\} \leq n^{(1/2)+(s/2)+o(1)}.$$

In view of (6.7), we obtain: for  $0 < s < s_0 := \min\{\frac{1}{2}, \frac{c_2}{C}, \frac{1}{C} \log(\frac{1}{q})\}$ ,

$$\mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} + V(w_n^{(n)})^+) \bar{Y}_n^{-s} \mathbf{1}_{E_n} \right\} \leq c_{28} c_{32} + n^{-(1/2)+o(1)}.$$

Substituting this in (6.6), we see that  $\sup_{n \geq 1} \mathbf{E}\{(n^{1/2}W_n)^{1-s} \mathbf{1}_{\mathcal{S}_n}\} < \infty$  for any  $s \in (0, s_0)$ . This yields the last inequality in (6.4) when  $\gamma$  is close to 1. By Hölder's inequality, it holds for all  $\gamma \in [0, 1)$ .

We now turn to the proof of the first inequality in (6.4). We start with

$$n^{1/2}W_n \geq \underline{Y}_n := \sum_{|u|=n} (n^{1/2} \wedge V(u)^+) e^{-V(u)}.$$

Let  $s \in (0, 1)$ . Exactly as in (4.7), we have

$$(6.8) \quad \mathbf{E}\{\underline{Y}_n^{1-s} \mathbf{1}_{\mathcal{S}_n}\} = \mathbf{E}_{\mathbf{Q}}\{(n^{1/2} \wedge V(w_n^{(n)})^+) \underline{Y}_n^{-s}\}.$$

By definition,

$$\begin{aligned} \underline{Y}_n &= \sum_{j=1}^n \sum_{u \in \mathcal{S}_j^{(n)}} e^{-V(u)} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|=n-j} \min\{n^{1/2}, [V(u) + V_u(x)]^+\} e^{-V_u(x)} \\ &\leq e^C \sum_{j=1}^n e^{-V(w_j^{(n)})} \sum_{u \in \mathcal{S}_j^{(n)}} \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|=n-j} [V(w_j^{(n)})^+ + C + V_u(x)^+] e^{-V_u(x)}. \end{aligned}$$

By means of the elementary inequality  $(\sum_i a_i)^{-s} \geq (\sum_i a_i^s)^{-1}$  and  $(\sum_i b_i)^s \leq \sum_i b_i^s$  (for positive  $a_i$  and  $b_i$ ), this leads to, on  $\mathcal{S}_n$ :

$$\underline{Y}_n^{-s} \geq \frac{e^{-sC}}{\sum_j e^{-sV(w_j^{(n)})} \sum_u \{(V(w_j^{(n)})^+)^s + C^s\} (\sum_x e^{-V_u(x)})^s + (\sum_x V_u(x)^+ e^{-V_u(x)})^s},$$

where, as before,  $\sum_j := \sum_{j=1}^n$ ,  $\sum_u := \sum_{u \in \mathcal{S}_j^{(n)}}$ , and  $\sum_x := \sum_{x \in \mathbb{T}_u^{\text{GW}}, |x|=n-j}$ . We now condition upon  $\mathcal{G}_n$ , and note that  $V(w_j^{(n)})$  and  $\mathcal{S}_j^{(n)}$  are  $\mathcal{G}_n$ -measurable. We apply Jensen's inequality  $\mathbf{E}\{\frac{1}{Z} | \mathcal{G}_n\} \geq \frac{1}{\mathbf{E}\{Z | \mathcal{G}_n\}}$  (for positive random variables  $Z$ ). By Proposition 2.1, we have

$$\mathbf{E}\{\underline{Y}_n^{-s} | \mathcal{G}_n\} \geq \frac{e^{-sC}}{\sum_j e^{-sV(w_j^{(n)})} \sum_u \{(V(w_j^{(n)})^+)^s + C^s\} \mathbf{E}(W_{n-j}^s) + \mathbf{E}(U_{n-j}^s)},$$

where, for any  $k \geq 0$ ,  $U_k := \sum_{|y|=k} V(y)^+ e^{-V(y)}$ . By Jensen's inequality,  $\mathbf{E}(W_{n-j}^s) \leq [\mathbf{E}(W_{n-j})]^s = 1$ . On the other hand, by (3.9),  $U_k \leq c_{33} \log \frac{1}{W_k^*}$ , and thus by Lemma 3.4,  $\mathbf{E}(U_k^s) \leq c_{33}^s \mathbf{E}\{[\log \frac{1}{W_k^*}]^s\} \leq c_{34}$ . Therefore,

$$\mathbf{E}\{\underline{Y}_n^{-s} | \mathcal{G}_n\} \geq \frac{c_{35}}{\sum_{j=1}^n e^{-sV(w_j^{(n)})} \{(V(w_j^{(n)})^+)^s + 1\} \#\mathcal{S}_j^{(n)}}.$$

As a consequence (in the notation of Corollary 2.2),

$$\begin{aligned} \mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} \wedge V(w_n^{(n)})^+) \underline{Y}_n^{-s} \right\} &\geq c_{35} \mathbf{E}_{\mathbf{Q}} \left\{ \frac{n^{1/2} \wedge S_n^+}{\sum_{j=1}^n e^{-sS_j} [(S_j^+)^s + 1] \sigma_j} \right\} \\ &\geq c_{35} \mathbf{E}_{\mathbf{Q}} \left\{ \frac{(n^{1/2} \wedge S_n) \mathbf{1}_{\{\min_{1 \leq j \leq n} S_j > 0\}}}{\sum_{j=1}^n e^{-sS_j} [S_j^s + 1] \sigma_j} \right\}. \end{aligned}$$

Note that if  $S_j > 0$ , then  $e^{-sS_j} [S_j^s + 1] \leq c_{36} e^{-tS_j}$  with  $t := \frac{s}{2}$ . Therefore, by writing

$$\mathbf{Q}^{(n)} \{ \cdot \} := \mathbf{Q} \left\{ \cdot \mid \min_{1 \leq j \leq n} S_j > 0 \right\},$$

and  $\mathbf{E}_{\mathbf{Q}}^{(n)}$  the expectation with respect to  $\mathbf{Q}^{(n)}$ , we get that

$$\begin{aligned} \mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} \wedge V(w_n^{(n)})^+) \underline{Y}_n^{-s} \right\} &\geq c_{37} \mathbf{Q} \left\{ \min_{1 \leq j \leq n} S_j > 0 \right\} \mathbf{E}_{\mathbf{Q}}^{(n)} \left\{ \frac{n^{1/2} \wedge S_n}{\sum_{j=1}^n e^{-tS_j} \sigma_j} \right\} \\ &\geq c_{37} \mathbf{Q} \left\{ \min_{1 \leq j \leq n} S_j > 0 \right\} \mathbf{E}_{\mathbf{Q}}^{(n)} \left\{ \frac{\varepsilon n^{1/2} \mathbf{1}_{\{S_n > \varepsilon n^{1/2}\}}}{\sum_{j=1}^n e^{-tS_j} \sigma_j} \right\}. \end{aligned}$$

Since  $\mathbf{Q} \{ \min_{1 \leq j \leq n} S_j > 0 \} \geq c_{38} n^{-1/2}$ , this leads to

$$\begin{aligned} \mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} \wedge V(w_n^{(n)})^+) \underline{Y}_n^{-s} \right\} &\geq c_{39} \varepsilon \mathbf{E}_{\mathbf{Q}}^{(n)} \left\{ \frac{\mathbf{1}_{\{S_n > \varepsilon n^{1/2}\}}}{\sum_{j=1}^n e^{-tS_j} \sigma_j} \right\} \\ &\geq c_{39} \varepsilon \left[ \mathbf{E}_{\mathbf{Q}}^{(n)} \left\{ \frac{1}{\sum_{j=1}^n e^{-tS_j} \sigma_j} \right\} - \mathbf{Q}^{(n)} \{ S_n \leq \varepsilon n^{1/2} \} \right]. \end{aligned}$$

Of course,  $\frac{1}{\sum_{j=1}^n e^{-tS_j} \sigma_j} \geq \frac{1}{1 + \sum_{j=1}^n e^{-tS_j} \sigma_j}$ . By Corollary 2.3,  $\mathbf{E}_{\mathbf{Q}} \{ \sigma_1^\delta \} < \infty$ ; we are thus entitled to apply Lemma 6.1 to see that  $\mathbf{E}_{\mathbf{Q}}^{(n)} \left\{ \frac{1}{1 + \sum_{j=1}^n e^{-tS_j} \sigma_j} \right\} \geq c_{40}$  for some  $c_{40} \in (0, \infty)$  and all  $n \geq n_0$ . On the other hand, it is known that  $S_n/n^{1/2}$  under  $\mathbf{Q}^{(n)}$  converges weakly to the terminal value of a Brownian meander; in particular,  $\lim_{\varepsilon \rightarrow 0} \lim_{n \rightarrow \infty} \mathbf{Q}^{(n)} \{ S_n \leq \varepsilon n^{1/2} \} = 0$ . We can thus choose (and fix) a small  $\varepsilon > 0$  such that  $\mathbf{Q}^{(n)} \{ S_n \leq \varepsilon n^{1/2} \} \leq \frac{c_{40}}{2}$  for all  $n \geq n_1$ . Therefore, for  $n \geq n_0 + n_1$ ,

$$\mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} \wedge V(w_n^{(n)})^+) \underline{Y}_n^{-s} \right\} \geq c_{39} \varepsilon \left[ c_{40} - \frac{c_{40}}{2} \right].$$

As a consequence, we have proved that for  $0 < s < 1$ ,

$$\liminf_{n \rightarrow \infty} \mathbf{E}_{\mathbf{Q}} \left\{ (n^{1/2} \wedge V(w_n^{(n)})^+) \underline{Y}_n^{-s} \right\} > 0,$$

which, in view of (6.8), yields the first inequality in (6.4), and thus completes the proof of Proposition 6.2.  $\square$

**Proposition 6.3** For any  $\gamma \in (0, 1)$ , we have  $n \rightarrow \infty$ ,

$$(6.9) \quad \mathbf{P} \left\{ \left| \frac{W_{n+1}}{W_n} - 1 \right| \geq n^{-\gamma} \mid \mathcal{S} \right\} \leq n^{-(1-\gamma)/2+o(1)}, \quad n \rightarrow \infty.$$

*Proof.* Let  $1 < \beta \leq 2$ . We use a probability estimate of Petrov [28], p. 82: for centered random variables  $\xi_1, \dots, \xi_\ell$  with  $\mathbf{E}(|\xi_i|^\beta) < \infty$  (for  $1 \leq i \leq \ell$ ), we have  $\mathbf{E}\{|\sum_{i=1}^\ell \xi_i|^\beta\} \leq 2 \sum_{i=1}^\ell \mathbf{E}\{|\xi_i|^\beta\}$ .

By definition, on the set  $\mathcal{S}_n$ , we have

$$\frac{W_{n+1}}{W_n} - 1 = \sum_{|u|=n} \frac{e^{-V(u)}}{W_n} \left( \sum_{x \in \mathbb{T}_u^{\text{GW}}: |x|=1} e^{-V_u(x)} - 1 \right),$$

where  $\mathbb{T}^{\text{GW}}$  and  $|x|_u$  are as in (2.1) and (2.4), respectively. Conditioning on  $\mathcal{F}_n$ , and applying Petrov's probability inequality recalled above, we see that on  $\mathcal{S}_n$ ,

$$(6.10) \quad \mathbf{E} \left\{ \left| \frac{W_{n+1}}{W_n} - 1 \right|^\beta \mid \mathcal{F}_n \right\} \leq 2 \sum_{|u|=n} \frac{e^{-\beta V(u)}}{W_n^\beta} \mathbf{E} \left\{ \left| \sum_{|y|=1} e^{-V(y)} - 1 \right|^\beta \right\} = c_{41} \frac{W_{n,\beta}}{W_n^\beta},$$

where  $c_{41} := 2\mathbf{E}\{|\sum_{|v|=1} e^{-V(v)} - 1|^\beta\}$ , and  $W_{n,\beta}$  is as in (1.7).

Fix  $0 < \gamma < 1$ . Let  $\varepsilon > 0$  and  $b > 0$ . Let  $s \in (\frac{\beta-1}{\beta}, 1)$  and  $s < \frac{\varepsilon}{C}$  (which is possible if  $\beta$  is close to 1). Define  $D_n := \{W_n \geq n^{-(1/2)-\varepsilon}\} \cap \{W_{n,\beta} \leq n^{-(3\beta/2)+b}\}$ . By Proposition 3.1, there exists  $\kappa = \kappa(\varepsilon)$  such that  $\mathbf{P}\{W_n < n^{-(1/2)-\varepsilon}, \mathcal{S}\} \leq \exp(-n^\kappa)$  for all large  $n$ , whereas by Theorem 4.1,  $\mathbf{P}\{W_{n,\beta} > n^{-(3\beta/2)+b}\} \leq n^{3\beta(1-s)/2-(1-s)b} \mathbf{E}\{W_{n,\beta}^{1-s}\} = n^{-(1-s)b+o(1)}$ . Therefore,

$$\mathbf{P}\{\mathcal{S} \setminus D_n\} \leq e^{-n^\kappa} + n^{-(1-s)b+o(1)} = n^{-(1-s)b+o(1)}, \quad n \rightarrow \infty.$$

On the other hand, since  $\mathcal{S} \subset \mathcal{S}_n$ , it follows from (6.10) and Chebyshev's inequality that for  $n \rightarrow \infty$ ,

$$\begin{aligned} \mathbf{P} \left\{ \left| \frac{W_{n+1}}{W_n} - 1 \right| \geq n^{-\gamma}, D_n, \mathcal{S} \right\} &\leq n^{\gamma\beta} \mathbf{E} \left\{ c_{41} \frac{W_{n,\beta}}{W_n^\beta} \mathbf{1}_{D_n \cap \mathcal{S}_n} \right\} \\ &\leq n^{\gamma\beta - (3\beta/2) + b + [(1/2) + \varepsilon]\beta + o(1)}. \end{aligned}$$

As a consequence, when  $n \rightarrow \infty$ ,

$$\mathbf{P} \left\{ \left| \frac{W_{n+1}}{W_n} - 1 \right| \geq n^{-\gamma}, \mathcal{S} \right\} \leq n^{-(1-s)b+o(1)} + n^{\gamma\beta - \beta + b + \varepsilon\beta + o(1)}.$$

We choose  $b := \frac{1-\gamma}{2}$ . By sending  $\varepsilon \rightarrow 0$ ,  $\beta \rightarrow 1$  and then  $s \rightarrow 0$ , we obtain (6.9).  $\square$

We now have all of the ingredients needed for the proof of Theorem 1.1.

*Proof of Theorem 1.1.* Let  $\lambda_n > 0$  be such that  $\mathbf{E}\{(\lambda_n W_n)^{1/2}\} = 1$ . That is,

$$\lambda_n := \{\mathbf{E}(W_n^{1/2})\}^{-2}.$$

By Proposition 6.2, we have  $0 < \liminf_{n \rightarrow \infty} \frac{\lambda_n}{n^{1/2}} \leq \limsup_{n \rightarrow \infty} \frac{\lambda_n}{n^{1/2}} < \infty$ , and  $(\lambda_n W_n)$  is tight. Let  $\mathscr{W}$  be any possible (weak) limit of  $(\lambda_n W_n)$  along a subsequence. By Proposition 6.2 and dominated convergence,  $\mathbf{E}(\mathscr{W}^{1/2}) = 1$ . We now prove the uniqueness of  $\mathscr{W}$ .

By definition,

$$W_{n+1} = \sum_{|u|=n+1} e^{-V(u)} = \sum_{|v|=1} e^{-V(v)} \sum_{x \in \mathbb{T}_v^{\text{GW}}, |x|_v=n} e^{-V_v(x)}.$$

By assumption,  $\lambda_n W_n \rightarrow \mathscr{W}$  in distribution when  $n$  goes to infinity along a certain subsequence. Thus  $\lambda_n W_{n+1}$  converges weakly (when  $n$  goes along the same subsequence) to  $\sum_{|v|=1} e^{-V(v)} \mathscr{W}_v$ , where, conditionally on  $(v, |v|=1)$ ,  $\mathscr{W}_v$  are independent copies of  $\mathscr{W}$ .

On the other hand, by Proposition 6.3,  $\lambda_n W_{n+1}$  also converges weakly (along the same subsequence) to  $\mathscr{W}$ . Therefore,

$$\mathscr{W} \stackrel{\text{law}}{=} \sum_{|v|=1} e^{-V(v)} \mathscr{W}_v.$$

This is the same equation for  $\xi^*$  in (3.5). Since (3.5) has a unique solution up to a scale change, and since  $\mathbf{E}(\mathscr{W}^{1/2}) = 1$ , we have

$$(6.11) \quad \mathscr{W} \stackrel{\text{law}}{=} c_{42} \xi^*,$$

where  $c_{42} := [\mathbf{E}\{(\xi^*)^{1/2}\}]^{-2}$ . The uniqueness (in law) of  $\mathscr{W}$  shows that  $\lambda_n W_n$  converges weakly to  $\mathscr{W}$  when  $n \rightarrow \infty$ . Since by (3.3),  $\mathbf{P}\{W_n > 0\} = \mathbf{P}\{\mathcal{S}_n\} \rightarrow \mathbf{P}\{\mathcal{S}\} = \mathbf{P}\{\xi^* > 0\}$ , it follows that  $\mathscr{W} > 0$  a.s., conditionally upon the system's survival.  $\square$

## 7 Proof of Proposition 2.1

We start with a simple preliminary result. For any individual  $u \in \mathbb{T}^{\text{GW}}$ , we write  $\llbracket e, u \rrbracket = \{e =: u_0, u_1, u_2, \dots, u_{|u|} := u\}$ , with  $|u_k| = k$ ,  $\forall 0 \leq k \leq |u|$ . Recall  $\mathcal{U}$ ,  $\Omega$  and  $\mathcal{F}_n$  from Section 2. Let  $\mathcal{U}_k := \{u \in \mathcal{U} : |u| = k\}$ ,  $k \geq 1$ .

**Lemma 7.1** *Fix  $n \geq 1$ . For  $1 \leq k \leq n$ , let  $f_k : \mathcal{U}_k \times \Omega \rightarrow \mathbb{R}_+$  be such that  $\forall u \in \mathcal{U}_k$ ,  $f_k(u, \bullet)$  is  $\mathcal{F}_n$ -measurable. Then*

$$(7.1) \quad \mathbf{E}_{\mathbf{Q}} \left\{ \prod_{k=1}^n f_k(w_k^{(n)}) \right\} = \mathbf{E} \left\{ \sum_{|u|=n} e^{-V(u)} \prod_{k=1}^n f_k(u_k) \right\}.$$



*Proof.* The expectation expression on the left-hand side is

$$= \mathbf{E}_{\mathbf{Q}} \left\{ \sum_{|u|=n} \mathbf{1}_{\{w_n^{(n)}=u\}} \prod_{k=1}^n f_k(w_k^{(n)}) \right\} = \mathbf{E}_{\mathbf{Q}} \left\{ \sum_{|u|=n} \mathbf{1}_{\{w_n^{(n)}=u\}} \prod_{k=1}^n f_k(u_k) \right\},$$

which, by the definition of  $w_n^{(n)}$ , equals  $\mathbf{E}_{\mathbf{Q}} \left\{ \sum_{|u|=n} \frac{e^{-V(u)}}{W_n} \prod_{k=1}^n f_k(u_k) \right\}$ . This implies the lemma using the definition of  $\mathbf{Q}$ .  $\square$

We now proceed to the proof of Proposition 2.1.

*Proof of Proposition 2.1.* We start with the proof of (i). It suffice to check that

$$(7.2) \quad \begin{aligned} & \mathbf{E}_{\mathbf{Q}} \left\{ \prod_{k=1}^n \exp \left( - \sum_{u \in \mathcal{I}_k^{(n)}} \varphi_k(\Delta V(u)) - \lambda_k \Delta V(w_k^{(n)}) \right) \right\} \\ &= \prod_{k=1}^n \mathbf{E}_{\mathbf{Q}} \left\{ \exp \left( - \sum_{x \in \mathcal{I}_1^{(1)}} \varphi_k(\Delta V(x)) - \lambda_k \Delta V(w_1^{(1)}) \right) \right\}, \end{aligned}$$

for any positive Borel functions  $\varphi_1, \varphi_2, \dots, \varphi_n$ , and any real numbers  $\lambda_1, \lambda_2, \dots, \lambda_n$ .

For any individual  $|v| \geq 1$ , let

$$(7.3) \quad \mathcal{I}(v) := \{x : \bar{x} = \bar{v}, x \neq v\},$$

$$(7.4) \quad \Phi_k(v) := \exp \left( - \sum_{x \in \mathcal{I}(v_k)} \varphi_k(\Delta V(x)) - \lambda_k \Delta V(v_k) \right), \quad 1 \leq k \leq |v|.$$

[In words,  $\mathcal{I}(v)$  is the set of the brothers of  $v$ ; in particular,  $\mathcal{I}(w_k^{(n)}) = \mathcal{I}_k^{(n)}$ .] Thus (7.2) can be rewritten as

$$(7.5) \quad \mathbf{E}_{\mathbf{Q}} \left\{ \prod_{k=1}^n \Phi_k(w_k^{(n)}) \right\} = \prod_{k=1}^n \mathbf{E}_{\mathbf{Q}} \left\{ \exp \left( - \sum_{x \in \mathcal{I}_1^{(1)}} \varphi_k(\Delta V(x)) - \lambda_k \Delta V(w_1^{(1)}) \right) \right\}.$$

To prove (7.5), we observe that by (7.1),

$$\mathbf{E}_{\mathbf{Q}} \left\{ \prod_{k=1}^n \Phi_k(w_k^{(n)}) \right\} = \mathbf{E} \left\{ \sum_{|u|=n} e^{-V(u)} \prod_{k=1}^n \Phi_k(u_k) \right\}.$$

Of course,

$$\sum_{|u|=n} e^{-V(u)} \prod_{k=1}^n \Phi_k(u_k) = \sum_{|v|=n-1} e^{-V(v)} \prod_{k=1}^{n-1} \Phi_k(v_k) \sum_{u: \bar{u}=v} e^{-[V(u)-V(v)]} \Phi_n(u).$$

By the branching property (see Neveu [26]),

$$\mathbf{E}\left\{\sum_{|u|=n} e^{-V(u)} \prod_{k=1}^n \Phi_k(u_k) \middle| \mathcal{F}_{n-1}\right\} = b_n \sum_{|v|=n-1} e^{-V(v)} \prod_{k=1}^{n-1} \Phi_k(v_k),$$

where

$$b_n := \mathbf{E}\left\{\sum_{|x|=1} e^{-V(x)} \exp\left(-\sum_{|y|=1, y \neq x} \varphi_n(\Delta V(y)) - \lambda_n \Delta V(x)\right)\right\}.$$

Therefore,

$$\mathbf{E}_{\mathbf{Q}}\left\{\prod_{k=1}^n \Phi_k(w_k^{(n)})\right\} = b_n \mathbf{E}\left\{\sum_{|v|=n-1} e^{-V(v)} \prod_{k=1}^{n-1} \Phi_k(v_k)\right\} = b_n \mathbf{E}_{\mathbf{Q}}\left\{\prod_{k=1}^{n-1} \Phi_k(w_k^{(n-1)})\right\},$$

the last identity being a consequence of (7.1). By induction, we obtain:  $\mathbf{E}_{\mathbf{Q}}\{\prod_{k=1}^n \Phi_k(w_k^{(n)})\} = \prod_{k=1}^n b_k$ , where

$$\begin{aligned} b_k &:= \mathbf{E}\left\{\sum_{|x|=1} e^{-V(x)} \exp\left(-\sum_{|y|=1, y \neq x} \varphi_k(\Delta V(y)) - \lambda_k \Delta V(x)\right)\right\} \\ &= \mathbf{E}_{\mathbf{Q}}\left\{\exp\left(-\sum_{y \in \mathcal{J}_1^{(1)}} \varphi_k(\Delta V(y)) - \lambda_k \Delta V(w_1^{(1)})\right)\right\}. \end{aligned}$$

(We used (7.1) again in the last equality.) This yields (7.5), thus part (i) of Proposition 2.1.

We now turn to the proof of part (ii) of the proposition. Recall that the vertices of the Galton–Watson tree  $\mathbb{T}^{\text{GW}}$  are elements of  $\mathcal{U} := \{\emptyset\} \cup \bigcup_{n=1}^{\infty} (\mathbb{N}^*)^n$ . We need to check that

$$\begin{aligned} &\mathbf{E}_{\mathbf{Q}}\left\{\prod_{k=1}^n \prod_{x \in \mathcal{J}_k^{(n)}} h_x(\mathbb{T}_x^{n-k}) \prod_{k=1}^n G_k\left(\sum_{x \in \mathcal{J}_k^{(n)}} \varphi_k(\Delta V(x)), \Delta V(w_k^{(n)}), w_k^{(n)}, \mathcal{J}_k^{(n)}\right)\right\} \\ (7.6) \quad &= \mathbf{E}_{\mathbf{Q}}\left\{\prod_{k=1}^n \prod_{x \in \mathcal{J}_k^{(n)}} H_{n-k}(x) \prod_{k=1}^n G_k\left(\sum_{x \in \mathcal{J}_k^{(n)}} \varphi_k(\Delta V(x)), \Delta V(w_k^{(n)}), w_k^{(n)}, \mathcal{J}_k^{(n)}\right)\right\}, \end{aligned}$$

where  $\varphi_1, \varphi_2, \dots, \varphi_n$  are positive Borel functions,  $(h_x, x \in \mathcal{U})$  measurable functions  $\Omega \rightarrow \mathbb{R}_+$ ,  $G_1, \dots, G_n$  positive Borel functionals on  $\mathbb{R}_+ \times \mathbb{R} \times \mathcal{U} \times \bigcup_{j=0}^{\infty} \mathcal{U}^{\otimes j}$ , and  $H_j(x) := \int_{\Omega} h_x(T^j(\omega)) d\mathbf{P}(\omega)$  (for  $j \geq 0$  and  $x \in \mathcal{U}$ ).

To check (7.6), we see by Lemma 7.1 that the expression on the left-hand side is

$$\mathbf{E}\left\{\sum_{|u|=n} e^{-V(u)} \prod_{k=1}^n \prod_{x \in \mathcal{J}(u_k)} h_x(\mathbb{T}_x^{n-k}) \prod_{k=1}^n G_k\left(\sum_{x \in \mathcal{J}(u_k)} \varphi_k(\Delta V(x)), \Delta V(u_k), u_k, \mathcal{J}(u_k)\right)\right\},$$

where  $\mathcal{I}(\cdot)$  is defined in (7.3). The integrand within  $\mathbf{E}\{\cdots\}$  on the left-hand side is ( $vz$  being the concatenated word of  $v \in \mathcal{U}$  and  $z \in \mathcal{U}$ )

$$\begin{aligned} & \sum_{|v|=1} e^{-V(v)} \prod_{x \in \mathcal{I}(v)} h_x(\mathbb{T}_x^{n-1}) G_1 \left( \sum_{x \in \mathcal{I}(v)} \varphi_1(\Delta V(x)), \Delta V(v), v, \mathcal{I}(v) \right) \times \\ & \times \sum_{y \in \mathbb{T}_v^{\text{GW}}, |y|_v = n-1} e^{-V(y)} \prod_{\ell=1}^{n-1} \prod_{z \in \mathcal{I}_v(y_\ell)} h_{vz}(\mathbb{T}_{vz}^{n-\ell-1}) \times \\ & \times \prod_{\ell=1}^{n-1} G_{\ell+1} \left( \sum_{z \in \mathcal{I}_v(y_\ell)} \varphi_{\ell+1}(\Delta V_v(z)), \Delta V_v(y_\ell), vy_\ell, v\mathcal{I}_v(y_\ell) \right), \end{aligned}$$

where, for  $y \in \mathbb{T}_v^{\text{GW}}$  with  $|y|_v = n-1$ ,  $\{e =: y_0, y_1, \dots, y_{n-1} := y\}$  denotes the shortest path on  $\mathbb{T}_v^{\text{GW}}$  relating  $e$  and  $y$ , with  $|y_\ell|_v = \ell$  for  $1 \leq \ell \leq n-1$ ,  $\mathcal{I}_v(y_\ell) := \{z \in \mathbb{T}_v^{\text{GW}} : \overline{z} = y_{\ell-1}, z \neq y_\ell\}$ , and  $v\mathcal{I}_v(y_\ell) := \{vx : x \in \mathcal{I}_v(y_\ell)\} = \mathcal{I}(vy_\ell)$ .

The conditional expectation (under  $\mathbf{P}$ ) of the above expression given  $\mathcal{F}_1$  is, by the branching property,

$$\sum_{|v|=1} e^{-V(v)} \prod_{x \in \mathcal{I}(v)} H_{n-1}(x) G_1 \left( \sum_{x \in \mathcal{I}(v)} \varphi_1(\Delta V(x)), \Delta V(v), v, \mathcal{I}(v) \right) \Psi_{n-1}(v),$$

where, for any  $x \in \mathcal{U}$ ,

$$\begin{aligned} \Psi_{n-1}(x) & := \mathbf{E} \left\{ \sum_{|y|=n-1} e^{-V(y)} \prod_{\ell=1}^{n-1} \prod_{z \in \mathcal{I}(y_\ell)} h_{xz}(\mathbb{T}_{xz}^{n-\ell-1}) \times \right. \\ & \quad \left. \times \prod_{\ell=1}^{n-1} G_{\ell+1} \left( \sum_{z \in \mathcal{I}(y_\ell)} \varphi_{\ell+1}(\Delta V(z)), \Delta V(y_\ell), xy_\ell, x\mathcal{I}(y_\ell) \right) \right\}. \end{aligned}$$

Using the argument backwards, we obtain:

$$\begin{aligned} & \mathbf{E}_{\mathbf{Q}} \left\{ \prod_{k=1}^n \prod_{x \in \mathcal{I}_k^{(n)}} h_x(\mathbb{T}_x^{n-k}) \prod_{k=1}^n G_k \left( \sum_{x \in \mathcal{I}_k^{(n)}} \varphi_k(\Delta V(x)), \Delta V(w_k^{(n)}), w_k^{(n)}, \mathcal{I}_k^{(n)} \right) \right\} \\ & = \mathbf{E}_{\mathbf{Q}} \left\{ \prod_{x \in \mathcal{I}_1^{(n)}} H_{n-1}(x) G_1 \left( \sum_{x \in \mathcal{I}_1^{(n)}} \varphi_1(\Delta V(x)), \Delta V(w_1^{(n)}), w_1^{(n)}, \mathcal{I}_1^{(n)} \right) \times \right. \\ & \quad \left. \times \prod_{k=2}^n \prod_{x \in \mathcal{I}_k^{(n)}} H_{n-k}(x) \prod_{k=2}^n G_k \left( \sum_{x \in \mathcal{I}_k^{(n)}} \varphi_k(\Delta V(x)), \Delta V(w_k^{(n)}), w_k^{(n)}, \mathcal{I}_k^{(n)} \right) \right\}. \end{aligned}$$

Iterating the procedure by gradually conditioning on  $\mathcal{F}_2, \mathcal{F}_3, \dots$ , and  $\mathcal{F}_n$ , this yields (7.6), and thus part (ii) of Proposition 2.1.  $\square$

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