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Exact convergence rates in central limit theorems for a branching random walk with a random environment in time*

Zhiqiang Gao† Quansheng Liu ‡

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Abstract

Chen [Ann. Appl. Probab. 11 (2001), 1242–1262] derived exact convergence rates in a central limit theorem and a local limit theorem for a supercritical branching Wiener process. We extend Chen’s results to a branching random walk under weaker moment conditions. For the branching Wiener process, our results sharpen Chen’s by relaxing the second moment condition used by Chen to a moment condition of the form $\mathbb{E}X(\ln^+ X)^{1+\lambda} < \infty$. In the rate functions that we find for a branching random walk, we figure out some new terms which didn’t appear in Chen’s work. The results are established in the more general framework, i.e. for a branching random walk with a random environment in time. The lack of the second moment condition for the offspring distribution and the fact that the exponential moment does not exist necessarily for the displacements make the proof delicate; the difficulty is overcome by a careful analysis of martingale convergence using a truncating argument. The analysis is significantly more awkward due to the appearance of the random environment.

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Key Words and phrases. Branching random walk, random environment in time, central limit theorems, convergence rate.

1 Introduction

The theory of branching random walk has been studied by many authors. It plays an important role, and is closely related to many problems arising in a variety of applied probability setting, including branching processes, multiplicative cascades, infinite particle systems, Quicksort algorithms and random fractals (see e.g. [29, 30]). For recent developments of the subject, see e.g. Hu and Shi [22], Shi [36], Hu [21], Attia and Barral [4] and the references therein.

In the classical branching random walk, the point processes indexed by the particles $u$, formulated by the number of its children and their displacements, have a fixed constant distribution for all particles $u$. In reality this distributions may vary from generation to generation according to a random environment, just as in the case of a branching process in random environment introduced in [2, 3, 37]. In other words, the distributions themselves may be realizations of a stochastic process, rather than being fixed. This property makes the model be closer to the reality compared to the classical branching random walk. In this paper, we shall consider such a model, called a branching random walk with a random environment in time.

Different kinds of branching random walks in random environments have been introduced and studied in the literature. Baillon, Clément, Greven and den Hollander [6, 18] considered the case where the offspring distribution of a particle situated at $z \in \mathbb{Z}^d$ depends on a random environment indexed by the location $z$, while the moving mechanism is controlled by a fixed deterministic law. Comets and Popov [12, 13] studied the case where both the offspring distributions and the moving laws depend on a random environment.

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indexed by the location. In the model studied in [9, 14, 23, 32, 35], the offspring distribution of a particle of generation \( n \) situated at \( z \in \mathbb{Z}^d(d \geq 1) \) depends on a random space-time environment indexed by \( \{(z, n)\} \), while each particle performs a simple symmetric random walk on \( d \)-dimensional integer lattice \( \mathbb{Z}^d(d \geq 1) \).

The model that we study in this paper is different from those mentioned above. It should also be mentioned that recently another different kind of branching random walks in time inhomogeneous environments has been considered extensively, see e.g. Fang and Zeitouni (2012, [16]), Zeitouni (2012, [41]) and Bovier and Hartung (2014, [10]). The readers may refer to these articles and references therein for more information.

Denote by \( Z_n(\cdot) \) the counting measure which counts the number of particles of generation \( n \) situated in a given set. For the classical branching random walk, a central limit theorem on \( Z_n(\cdot) \), first conjectured by Harris (1963, [20]), was shown by Asmussen and Kaplan (1976, [1, 25]), and then extended to a general case by Klebaner (1982, [26]) and Biggins and Kyprianou (2004, [8, Section 6]), where a large time asymptotic expansion in the local limit theorem, the rate functions that we find include some new terms which didn’t appear in Chen’s weak moment conditions. In our results about the exact convergence rate in the central limit theorem and the local limit theorem, the rate functions that we find include some new terms which didn’t appear in Chen’s weak moment conditions.
new particles $\varnothing i = i(1 \leq i \leq N)$ of generation 1, located at $S_i = L_{\varnothing i}(1 \leq i \leq N)$, where $N, L_1, L_2, \cdots$ are mutually independent, $N$ has the law $p(\xi_0)$, and each $L_i$ has the law $G(\xi_0)$. In general, each particle $u = u_1 \cdots u_n$ of generation $n$ is replaced at time $n + 1$ by $N_u$ new particles $u_i(1 \leq i \leq N_u)$ of generation $n + 1$, with displacements $L_{u_i}(1 \leq i \leq N_u)$, so that the $i$-th child $u_i$ is located at

$$S_{ui} = S_u + L_{ui},$$

where $N_u, L_{u1}, L_{u2}, \cdots$ are mutually independent, $N_u$ has the law $p(\xi_n)$, and each $L_{ui}$ has the same law $G(\xi_n)$. By definition, given the environment $\xi$, the random variables $N_{ui}$ and $L_{ui}$, indexed by all the finite sequences $u$ of positive integers, are independent of each other.

For each realization $\xi \in \Theta^N$ of the environment sequence, let $(\Gamma, \mathcal{G}, P_\xi)$ be the probability space under which the process is defined (when the environment $\xi$ is fixed to the given realization). The probability $P_\xi$ is usually called quenched law. The total probability space can be formulated as the product space $(\Theta^N \times \Gamma, \mathcal{E}^N \otimes \mathcal{G}, \mathbb{P})$, where $\mathbb{P} = \mathbb{E}(\delta_\xi \otimes P_\xi)$ with $\delta_\xi$ the Dirac measure at $\xi$ and $\mathbb{E}$ the expectation with respect to the random variable $\xi$, so that for all measurable and positive $g$ defined on $\Theta^N \times \Gamma$, we have

$$\int_{\Theta^N \times \Gamma} g(x, y)d\mathbb{P}(x, y) = \mathbb{E} \int_{\Gamma} g(\xi, y)dP_\xi(y).$$

The total probability $\mathbb{P}$ is usually called annealed law. The quenched law $P_\xi$ may be considered to be the conditional probability of $\mathbb{P}$ given $\xi$. The expectation with respect to $\mathbb{P}$ will still be denoted by $\mathbb{E}$; there will be no confusion for reason of consistence. The expectation with respect to $P_\xi$ will be denoted by $\mathbb{E}_\xi$.

Let $T$ be the genealogical tree with $\{N_u\}$ as defining elements. By definition, we have: (a) $\varnothing \in T$; (b) $u_i \in T$ implies $u \in T$; (c) if $u \in T$, then $u_i \in T$ if and only if $1 \leq i \leq N_u$. Let

$$T_n = \{u \in T : |u| = n\}$$

be the set of particles of generation $n$, where $|u|$ denotes the length of the sequence $u$ and represents the number of generation to which $u$ belongs.

\subsection{2.2 Main results}

Let $Z_n(\cdot)$ be the counting measure of particles of generation $n$: for $B \subset \mathbb{R}$,

$$Z_n(B) = \sum_{u \in T_n} 1_B(S_u).$$

Then $\{Z_n(\mathbb{R})\}$ constitutes a branching process in a random environment (see e.g. [2, 8, 57]). For $n \geq 0$, let $\tilde{N}_n$ (resp. $\hat{N}_n$) be a random variable with distribution $p(\xi_n)$ (resp. $G(\xi_n)$) under the law $P_\xi$, and define

$$m_n = m(\xi_n) = \mathbb{E}_\xi \tilde{N}_n, \quad \Pi_n = m_0 \cdots m_{n-1}, \quad \Pi_0 = 1.$$ 

It is well known that the normalized sequence

$$W_n = \frac{1}{\Pi_n} Z_n(\mathbb{R}), \quad n \geq 1$$

constitutes a martingale with respect to the filtration $(\mathcal{F}_n)$ defined by

$$\mathcal{F}_0 = \{\emptyset, \Omega\}, \quad \mathcal{F}_n = \sigma(\xi, N_u : |u| < n), \quad \text{for } n \geq 1.$$ 

Throughout the paper, we shall always assume the following conditions:

$$\mathbb{E} \ln m_0 > 0 \quad \text{and} \quad \mathbb{E} \left[ \frac{1}{m_0} \left( \ln \tilde{N}_0 \right)^{1+\lambda} \right] < \infty, \quad (2.1)$$

where the value of $\lambda > 0$ is to be specified in the hypothesis of the theorems. Under these conditions, the underlying branching process $\{Z_n(\mathbb{R})\}$ is supercritical, $Z_n(\mathbb{R}) \to \infty$ with positive probability, and the limit

$$W = \lim_n W_n$$

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that Cramér’s condition about the characteristic function of $i$ for all $\eta > \lambda$

Theorem 2.3.

Proposition 2.1.

Assume $\eta > \lambda$.

Proposition 2.2.

$Z$ in the central limit theorem about the counting measure $\eta > \lambda$.

Theorem 2.4.

Assume $\eta > \lambda$.

We will need the following conditions on the motion of particles:

Let $\{N_{i,n}\}$ be two sequences of random variables, defined respectively by

$$N_{1,n} = \frac{1}{\Pi_n} \sum_{u \in S_n} (S_u - \ell_n) \quad \text{and} \quad N_{2,n} = \frac{1}{\Pi_n} \sum_{u \in S_n} (S_u - \ell_n)^2 - s_n^2.$$

We shall prove that they are martingales with respect to the filtration $(\mathcal{G}_n)$ defined by

$$\mathcal{G}_0 = \{\emptyset, \Omega\}, \quad \mathcal{G}_n = \sigma(\xi, N_n, L_{ui} : i \geq 1, |u| < n), \text{ for } n \geq 1.$$

More precisely, we have the following propositions.

**Proposition 2.1.** Assume $(2.1)$ and $E(\ln^{-n} m_0)^{1+\lambda} < \infty$ for some $\lambda > 1$, and $E(|\tilde{L}_0|^\eta) < \infty$ for some $\eta > 2$. Then the sequence $\{\{N_{1,n}, \mathcal{G}_n\}\}$ is a martingale and converges a.s.:

$$V_1 := \lim_{n \to \infty} N_{1,n} \text{ exists a.s. in } \mathbb{R}.$$

**Proposition 2.2.** Assume $(2.1)$ and $E(\ln^{-n} m_0)^{1+\lambda} < \infty$ for some $\lambda > 2$, and $E(|\tilde{L}_0|^\eta) < \infty$ for some $\eta > 4$. Then the sequence $\{\{N_{2,n}, \mathcal{G}_n\}\}$ is a martingale and converges a.s.:

$$V_2 := \lim_{n \to \infty} N_{2,n} \text{ exists a.s. in } \mathbb{R}.$$

Our main results are the following two theorems. The first theorem concerns the exact convergence rate in the central limit theorem about the counting measure $Z_n$, while the second one is a local limit theorem. We shall use the notation

$$Z_n(t) = Z_n((-\infty, t]), \quad \phi(t) = \frac{1}{\sqrt{2\pi}} e^{-t^2/2}, \quad \Phi(t) = \int_{-\infty}^t \phi(x) dx, \quad t \in \mathbb{R}.$$

**Theorem 2.3.** Assume $(2.1)$ for some $\lambda > 8$, $(2.2)$ for some $\eta > 12$ and $E m_0^{-\delta} < \infty$ for some $\delta > 0$. Then for all $t \in \mathbb{R}$,

$$\sqrt{n} \left[ \frac{1}{\Pi_n} Z_n(\ell_n + s_n t) - \Phi(t) W \right] \xrightarrow{n \to \infty} V(t) \quad \text{a.s.},$$

where

$$V(t) = -\frac{\phi(t) V_1}{(E(\sigma_0^{(2)})^{1/2})^2} + \frac{(E(\sigma_0^{(3)}) (1 - t^2) \phi(t) W)}{6(E(\sigma_0^{(2)})^{3/2})}.$$

**Theorem 2.4.** Assume $(2.1)$ for some $\lambda > 16$, $(2.2)$ for some $\eta > 16$ and $E m_0^{-\delta} < \infty$ for some $\delta > 0$. Then for any bounded measurable set $A \subset \mathbb{R}$ with Lebesgue measure $|A| > 0$,

$$n \left[ \sqrt{2\pi s_n \Pi_n^{-1}} Z_n(A + \ell_n) - W \int_{A} e^{-x^2/2} dx \right] \xrightarrow{n \to \infty} \mu(A) \quad \text{a.s.},$$

(2.4)
where
\[ \mu(A) = \frac{|A|}{2\varepsilon_0^{(2)}} \left(-V_2 + 2 \mathbb{P}_A V_1\right) + \frac{|A|}{8} \frac{c(A)}{(\varepsilon_0^{(2)})^2} \]
with \( \mathbb{P}_A = \frac{1}{|A|} \int_A x dx \) and
\[ c(A) = W \mathbb{E} \left( \sigma_0^{(4)} - 3 \left(\sigma_0^{(2)}\right)^2 + 4 \left(\varepsilon_0^{(3)}(V_1 - \mathbb{P}_A W) - \frac{5}{3} \varepsilon_0^{(3)}\right) - \left(\varepsilon_0^{(2)}\right)^2 W \right). \]

**Remark 2.5.** For a branching Wiener process, Theorems 2.3 and 2.4 improve Theorems 3.1 and 3.2 of Chen (2001, [11]) by relaxing the second moment condition used by Chen to the moment condition of the form \( \mathbb{E}X(\ln^+ X)^{1+\lambda} < \infty \) (cf. (2.1)). For a branching random walk with a constant or random environment, the second terms in \( V(\cdot) \) and \( \mu(\cdot) \) are new: they did not appear in Chen’s results [11] for a branching Wiener process; the reason is that in the case of a Brownian motion, we have \( \lambda > 4 \).

**Remark 2.6.** As will be seen in the proof, if we assume an exponential moment condition for the motion, then the moment condition on the underlying branching mechanism can be weakened: in that case, we only need to assume that \( \lambda > 3/2 \) in Theorem 2.3 and \( \lambda > 4 \) in Theorem 2.4. In particular, for a branching Wiener process, Theorem 2.3 (resp. Theorem 2.4) is valid when (2.1) holds for some \( \lambda > 3/2 \) (resp. \( \lambda > 4 \)).

**Remark 2.7.** In the deterministic case, Theorem 2.3 has been obtained by Kabluchko [40, Theorem 5 and Remark 2] under the second moment condition for the underlying branching mechanism.

**Remark 2.8.** When the Cramér condition \( P \left( \lim \sup_{t \to \infty} |\mathbb{E}(\xi e^{\xi\tau_{\xi,\lambda}})| < 1 \right) > 0 \) fails, the situation is different. Actually, while revising our manuscript we find that a lattice version (about a branching random walk on \( \mathbb{Z} \) in a constant environment, for which the preceding condition fails) of Theorems 2.3 and 2.4 has been established very recently in [19].

For simplicity and without loss of generality, hereafter we always assume that \( l_n = 0 \) (otherwise, we only need to replace \( L_{u,1} \) by \( L_{u,1} - l_n \)) and hence \( \ell_n = 0 \). In the following, we will write \( K_\xi \) for a constant depending on the environment, whose value may vary from lines to lines.

## 3 Notation and Preliminary Results

In this section, we introduce some notation and important lemmas which will be used in the sequel.

### 3.1 Notation

In addition to the \( \sigma \)-fields \( \mathcal{F}_n \) and \( \mathcal{D}_n \), the following \( \sigma \)-fields will also be used:

\[ \mathcal{I}_0 = \{\emptyset, \Omega\}, \quad \mathcal{I}_n = \sigma(\xi_k, N_u, L_{u,1} : k < n, i \geq 1, |u| < n) \text{ for } n \geq 1. \]

For conditional probabilities and expectations, we write:

\[ P_{\xi,n}(\cdot) = P_{\xi}(\cdot | \mathcal{I}_n), \quad E_{\xi,n}(\cdot) = E_{\xi}(\cdot | \mathcal{I}_n); \quad P_n(\cdot) = P(\cdot | \mathcal{I}_n), \quad E_n(\cdot) = E(\cdot | \mathcal{I}_n); \]

\[ P_{\xi,\mathcal{F}_n}(\cdot) = P_{\xi}(\cdot | \mathcal{F}_n), \quad E_{\xi,\mathcal{F}_n}(\cdot) = E_{\xi}(\cdot | \mathcal{F}_n). \]

As usual, we set \( \mathbb{N}^* = \{1, 2, 3, \ldots\} \) and denote by

\[ U = \bigcup_{n=0}^{\infty} (\mathbb{N}^*)^n \]

the set of all finite sequences, where \( (\mathbb{N}^*)^0 = \{\emptyset\} \) contains the null sequence \( \emptyset \).

For all \( u \in U \), let \( T(u) \) be the shifted tree of \( T \) at \( u \) with defining elements \( \{N_{uv}\} \): we have 1) \( \emptyset \in T(u) \), 2) \( v \in T(u) \Rightarrow v \in T(u) \) and 3) if \( v \in T(u) \), then \( v \in T(u) \) if and only if \( 1 \leq i \leq N_{uv} \).

Define \( T_n(u) = \{v \in T(u) : |v| = n\} \). Then \( T = T(\emptyset) \) and \( T_n = T_n(\emptyset) \).
For every integer \( m \geq 0 \), let \( H_m \) be the Chebyshev-Hermite polynomial of degree \( m \): 
\[
H_m(x) = m! \sum_{k=0}^{\lfloor m/2 \rfloor} \frac{(-1)^k x^{m-2k}}{k!(m-2k)^{2k}}.
\] (3.1)

The first few Chebyshev-Hermite polynomials relevant to us are:

\[
\begin{align*}
H_0(x) &= 1, \\
H_1(x) &= x, \\
H_2(x) &= x^2 - 1, \\
H_3(x) &= x^3 - 3x, \\
H_4(x) &= x^4 - 6x^2 + 3, \\
H_5(x) &= x^5 - 10x^3 + 15x, \\
H_6(x) &= x^6 - 15x^4 + 45x^2 - 15, \\
H_7(x) &= x^7 - 21x^5 + 105x^3 - 105x, \\
H_8(x) &= x^8 - 28x^6 + 210x^4 - 420x^2 + 105.
\end{align*}
\]

It is known that (3.3): for every integer \( m \geq 0 \)
\[
\Phi^{(m+1)}(x) = \frac{d^{m+1}}{dx^{m+1}} \Phi(x) = (-1)^m \phi(x) H_m(x).
\]

### 3.2 Two preliminary lemmas

We first give an elementary lemma which will be often used in Section 4.

**Lemma 3.1.** (a) For \( x, y \geq 0 \),
\[
\ln (x + y) \leq 1 + \ln x + \ln y, \quad \ln(1 + x) \leq 1 + \ln x.
\] (3.2)

(b) For each \( \lambda > 0 \), there exists a constant \( K_\lambda > 0 \), such that
\[
(\ln x)^{1+\lambda} \leq K_\lambda x, \quad x > 0,
\] (3.3)

(c) For each \( \lambda > 0 \), the function
\[
x(\ln x)^{-1-\lambda} \text{ is increasing for } x > e^{2\lambda}.
\] (3.4)

**Proof.** Part (a) holds since \( \ln(x + y) \leq \ln(2 \max\{x, y\}) \leq 1 + \ln x + \ln y \). Parts (b) and (c) can be verified easily. \( \square \)

We next present the Edgeworth expansion for sums of independent random variables, that we shall need in Sections 5 and 6 to prove the main theorems. Let us recall the theorem used in this paper obtained by Bai and Zhao (1986, [5]), that generalizing the case for i.i.d random variables (cf. [33, P.159, Theorem 1]).

Let \( \{X_j\} \) be independent random variables, s atisfying for each \( j \geq 1 \)
\[
E X_j = 0, \quad E|X_j|^k < \infty \text{ with some integer } k \geq 3.
\] (3.5)

We write \( B_n^2 = \sum_{j=1}^n E X_j^2 \) and only consider the nontrivial case \( B_n > 0 \). Let \( \gamma_{\nu j} \) be the \( \nu \)-order cumulant of \( X_j \) for each \( j \geq 1 \). Write
\[
\lambda_{\nu,n} = n^{(\nu-2)/2} B_n^{-\nu} \sum_{j=1}^n \gamma_{\nu j}, \quad \nu = 3, 4, \ldots, k;
\]
\[
Q_{\nu,n}(x) = \sum_{m=1}^\nu (-1)^{\nu+2s} \Phi^{(\nu+2s)}(x) \prod_{m=1}^\nu \frac{1}{k_m!} \left( \frac{\lambda_{m+2,n}}{(m+2)!} \right)^{k_m}
\]
\[-\phi(x) \sum H_{\nu+2s-1}(x) \prod_{m=1}^{\nu} \frac{1}{k_m!} \left( \frac{\lambda_{m+2,n}}{(m+2)!} \right)^{k_m},\]

where the summation \(\sum\) is carried out over all nonnegative integer solutions \((k_1, \ldots, k_\nu)\) of the equations:

\[k_1 + \cdots + k_\nu = s \quad \text{and} \quad k_1 + 2k_2 + \cdots + \nu k_\nu = \nu.\]

For \(1 \leq j \leq n\) and \(x \in \mathbb{R}\), define

\[F_n(x) = \mathbb{P}\left( B_n^{-1} \sum_{j=1}^{n} X_j \leq x \right), \quad v_j(t) = \mathbb{E}e^{t X_j};\]

\[Y_{nj} = X_j 1_{\{|X_j| \leq B_n\}}, \quad Z_{nj} = X_j 1_{\{|X_j| \leq B_n(1+\varepsilon)|x|\}}, \quad W_{nj} = X_j 1_{\{|X_j| > B_n(1+\varepsilon)|x|\}}.\]

The Edgeworth expansion theorem can be stated as follows.

**Lemma 3.2**. Let \(n \geq 1\) and \(X_1, \ldots, X_n\) be a sequence of independent random variables satisfying (3.5) and \(B_n > 0\). Then for the integer \(k \geq 3\),

\[|F_n(x) - \Phi(x) - \sum_{\nu=1}^{k-2} Q_{\nu n}(x)n^{-\nu/2}| \leq C(k) \left\{ (1 + |x|)^{-k} B_n^{-k} \sum_{j=1}^{n} \mathbb{E}|W_{nj}|^k + (1 + |x|)^{-k-1} B_n^{-k-1} \sum_{j=1}^{n} \mathbb{E}|Z_{nj}|^k + (1 + |x|)^{-k-1} n^{k(k+1)/2} \left( \sup_{|t| \geq \delta_n} \frac{1}{n} \sum_{j=1}^{n} |v_j(t)| \right) + \frac{1}{2n} \right\},\]

where \(\delta_n = \frac{1}{12} B_n^2 \left( \sum_{j=1}^{n} \mathbb{E}|Y_{nj}|^3 \right)^{-1}\), \(C(k) > 0\) is a constant depending only on \(k\).

# 4 Convergence of the martingales \(((N_{1,n}, D_n))\) and \(((N_{2,n}, D_n))\)

Now we can proceed to prove the convergence of the two martingales defined in Section 2.

## 4.1 Convergence of the martingale \(((N_{1,n}, D_n))\)

**Proof of Proposition 2.7.** The fact that \(((N_{1,n}, D_n))\) is a martingale can be easily shown: it suffices to notice that

\[\mathbb{E}_{\xi_n} N_{1,n+1} = \mathbb{E}_{\xi_n} \left( \frac{1}{\Pi_{n+1}} \sum_{u \in T_{n+1}} S_u \right) = \frac{1}{\Pi_{n+1}} \mathbb{E}_{\xi_n} \left( \sum_{u \in T_n} \sum_{i=1}^{N_u} (S_u + L_{ui}) \right) = \frac{1}{\Pi_{n+1}} \sum_{u \in T_n} \mathbb{E}_{\xi_n} \left( \sum_{i=1}^{N_u} (S_u + L_{ui}) \right) = \frac{1}{\Pi_{n+1}} \sum_{u \in T_n} m_n S_u = N_{1,n}.\]

Observe that

\[N_{1,n+1} = N_{1,n} \frac{1}{\Pi_n} \sum_{u \in T_n} S_u (N_u / m_n - 1) + \frac{1}{\Pi_n} \sum_{u \in T_n} \frac{1}{m_n} \sum_{i=1}^{N_u} L_{ui} =: I_{1,n} + I_{2,n}.\]  

(4.1)

We shall prove the convergence of the martingale by showing that both of the series

\[\sum_{n=1}^{\infty} I_{1,n} \quad \text{and} \quad \sum_{n=1}^{\infty} I_{2,n}\]

converge a.s.  

(4.2)
Define
\[ I_{1,n}' = \frac{1}{\Pi_n} \sum_{u \in T_n} S_u \left( \frac{N_u}{m_n} - 1 \right) 1_{\{N_u/m_n \leq \Pi_n\}} \quad (4.3) \]
\[ I_{2,n}' = \frac{1}{\Pi_n} \sum_{u \in T_n} Y_u 1_{\{|Y_u| \leq \Pi_n\}} \quad \text{with} \quad Y_u = \frac{1}{m_{|u|}} \sum_{i=1}^{N_u} L_{ui}. \quad (4.4) \]

Since
\[ \lim_{n \to \infty} \frac{1}{n} \sum_{j=1}^{n} E \xi |\hat{L}_j|^q = E |\hat{L}_1|^q < \infty, \quad q = 1, 2, \]
there exists a constant \( K_\xi < \infty \) depending only on \( \xi \) such that for \( n \geq 1 \) and \(|u| = n\),
\[ E \xi |\hat{L}_n| \leq K_\xi n, \quad E \xi |S_u| \leq \sum_{j=1}^{n} E \xi |\hat{L}_j| \leq K_\xi n, \quad E \xi |S_u|^2 = \sum_{j=1}^{n} E \xi |\hat{L}_j|^2 \leq K_\xi n. \quad (4.5) \]

To prove the convergence a.s. of the series \( \sum_{n=1}^{\infty} I_{q,n} \) \((q = 1, 2)\), we only need to show that the following series converges a.s.:
\[ \sum_{n=1}^{\infty} (I_{1,n} - I_{1,n}'), \quad \sum_{n=1}^{\infty} (I_{2,n}' - E \xi_n I_{2,n}''), \quad \text{and} \quad \sum_{n=1}^{\infty} E \xi_n I_{1,n}'. \]

First for \( q = 1 \), we see that
\[ E \xi |I_{1,n} - I_{1,n}'| = E \xi |\frac{1}{\Pi_n} \sum_{u \in T_n} S_u \left( \frac{N_u}{m_n} - 1 \right) 1_{\{N_u/m_n > \Pi_n\}}| \]
\[ \leq E \xi \frac{1}{\Pi_n} \sum_{u \in T_n} E \xi |S_u| E \xi \left( \frac{N_u}{m_n} + 1 \right) 1_{\{N_u/m_n > \Pi_n\}} \]
\[ \leq K_\xi n E \xi \left( \frac{\hat{N}_n}{m_n} + 1 \right) 1_{\{\hat{N}_n/m_n > \Pi_n\}} \]
\[ \leq K_\xi \left( \frac{\ln(\Pi_n + 1)}{m_n} \right)^{1+\lambda} E \xi \left( \frac{\hat{N}_n}{m_n} + 1 \right) \left( \ln \left( 1 + \frac{\hat{N}_n}{m_n} \right) \right)^{1+\lambda} \]
\[ \leq K_\xi n^{-\lambda} E \xi \left( \frac{\hat{N}_n}{m_n} + 1 \right) \left( \ln \left( 1 + \frac{\hat{N}_n}{m_n} \right) \right)^{1+\lambda}. \]

Observe that for \( \lambda > 1 \),
\[ E \sum_{n=1}^{\infty} \frac{1}{n^\lambda} \left[ E \xi \left( \frac{\hat{N}_n}{m_n} + 1 \right) \ln(\hat{N}_n)^{1+\lambda} + \ln(m_n)^{1+\lambda} \right] \]
\[ = \sum_{n=1}^{\infty} \frac{1}{n^\lambda} \left[ E \xi \left( \frac{\hat{N}_n}{m_n} + 1 \right) \ln(\hat{N}_n)^{1+\lambda} + \ln(m_n)^{1+\lambda} \right] < \infty, \]
which implies that
\[ \sum_{n=1}^{\infty} \frac{1}{n^\lambda} \left[ E \xi \left( \frac{\hat{N}_n}{m_n} + 1 \right) \ln(\hat{N}_n)^{1+\lambda} + \ln(m_n)^{1+\lambda} \right] < \infty \quad \text{a.s.} \quad (4.6) \]

Hence
\[ E \xi |\sum_{n=1}^{\infty} (I_{1,n} - I_{1,n}')| \leq \sum_{n=1}^{\infty} E \xi |I_{1,n} - I_{1,n}'| < \infty, \]
\[ E \xi |\sum_{n=1}^{\infty} E \xi_n I_{1,n}'| = E \xi |\sum_{n=1}^{\infty} E \xi_n (I_{1,n} - I_{1,n}')| \leq \sum_{n=1}^{\infty} E \xi |I_{1,n} - I_{1,n}'| < \infty. \]

It follows that the series \( \sum_{n=1}^{\infty} (I_{1,n} - I_{1,n}') \) and \( \sum_{n=1}^{\infty} E \xi_n I_{1,n}' \) converge a.s.
Observe that $\sum_{k=1}^{n}(I'_{1,k} - \mathbb{E}_{\xi_n}I'_{1,k})$ is a martingale w.r.t. \(\mathcal{F}_{n+1}\). By the a.s. convergence of an \(\mathbb{L}^2\) bounded martingale (see e.g. [13, P. 251, Ex. 4.9]), we prove the convergence a.s. of the series $\sum_{n=1}^{\infty}(I'_{1,n} - \mathbb{E}_{\xi_n}I'_{1,n})$ by showing that of the series

$$\sum_{n=1}^{\infty} \mathbb{E}_{\xi}(I'_{1,n} - \mathbb{E}_{\xi_n}I'_{1,n})^2.$$

It is immediate from the following:

$$\mathbb{E}_{\xi}(I'_{1,n} - \mathbb{E}_{\xi_n}I'_{1,n})^2 = \mathbb{E}_{\xi}
\left[\frac{1}{\Pi_n} \sum_{u \in \mathcal{T}_n} \left(\frac{N_u}{m_n} - 1\right) \mathbf{1}_{\left\{\frac{N_u}{m_n} \leq \Pi_n\right\}} - \mathbb{E}_{\xi_n} \left(\frac{N_u}{m_n} - 1\right) \mathbf{1}_{\left\{\frac{N_u}{m_n} \leq \Pi_n\right\}}\right]^2
$$

$$= \mathbb{E}_{\xi}
\left[\frac{1}{\Pi_n} \sum_{u \in \mathcal{T}_n} \sum_{i=1}^{N_u} \mathbf{1}_{\left\{\frac{N_u}{m_n} \leq \Pi_n\right\}} \xi_n \mathbf{1}_{\left\{\frac{N_u}{m_n} \leq \Pi_n\right\}}\right]^2
$$

$$\leq \mathbb{E}_{\xi}
\left[\frac{1}{\Pi_n} \sum_{u \in \mathcal{T}_n} \sum_{i=1}^{N_u} \xi_n \mathbf{1}_{\left\{\frac{N_u}{m_n} \leq \Pi_n\right\}}\right]^2.$$

Combining the above results, we see that the series $\sum I_{1,n}$ converges a.s.

Next we turn to the proof of the convergence a.s. of the series $\sum I_{2,n}$.

To begin with, we prove that

$$\mathbb{E}_{\xi}|Y_u|(\ln^+ |Y_u|)^{1+\lambda} \leq K_\xi n + K_\xi n (\ln^{-m_n})^{1+\lambda}.$$  (4.7)

This follows from the fact:

$$\mathbb{E}_{\xi}|Y_u|(\ln^+ |Y_u|)^{1+\lambda} \leq \mathbb{E}_{\xi}
\left[\frac{1}{m_n} \sum_{i=1}^{N_u} \mathbf{1}_{\left\{\frac{N_u}{m_n} \leq \Pi_n\right\}}\right]^2 + \mathbb{E}_{\xi} \left(\ln^+ |Y_u|\right)^{1+\lambda} + \mathbb{E}_{\xi} \left(\mathbf{1}_{\left\{\frac{N_u}{m_n} \leq \Pi_n\right\}}\right)^{1+\lambda}.$$

Observe that

$$\mathbb{E}_{\xi}|I_{2,n} - I'_{2,n}| = \mathbb{E}_{\xi} \left[\frac{1}{\Pi_n} \sum_{u \in \mathcal{T}_n} |Y_u| \mathbf{1}_{|Y_u| > \Pi_n}\right].$$
Combining the above results, we see that the series

$$\sum_{n=1}^{\infty} n^{-\lambda} (1 + (\ln - m_n)^{1+\lambda})$$

converges a.s. Thus

$$E_\xi \left| \sum_{n=1}^{\infty} (I_{2,n} - I'_{2,n}) \right| \leq \sum_{n=1}^{\infty} E_\xi |I_{2,n} - I'_{2,n}| < \infty,$$

$$E_\xi \left| \sum_{n=1}^{\infty} E_\xi, n I'_{2,n} \right| = E_\xi \left| \sum_{n=1}^{\infty} E_\xi(n (I_{2,n} - I'_{2,n})) \right| \leq \sum_{n=1}^{\infty} E_\xi |I_{2,n} - I'_{2,n}| < \infty.$$

This implies the convergence a.s. of the series $\sum_{n=1}^{\infty} (I_{2,n} - I'_{2,n})$ and $\sum_{n=1}^{\infty} E_\xi, n I'_{2,n}$.

To prove the convergence a.s. of the series $\sum_{n=1}^{\infty} (I'_{2,n} - E_\xi, n I'_{2,n})$, we only need to show the convergence of the series: $\sum_{n=1}^{\infty} E_\xi \left( I'_{2,n} - E_\xi, n I'_{2,n} \right)^2$. This is implied by the following observation:

$$E_\xi \left( I'_{2,n} - E_\xi, n I'_{2,n} \right)^2 = E_\xi \frac{1}{\Pi_n^2} \sum_{u \in \mathcal{T}_n} E_\xi \left( |Y_u|^2 \mathbf{1}_{\{|Y_u| \leq \Pi_n\}} - (E_\xi |Y_u| \mathbf{1}_{\{|Y_u| \leq \Pi_n\}}) \right)^2$$

$$\leq E_\xi \frac{1}{\Pi_n^2} \sum_{u \in \mathcal{T}_n} E_\xi \left( |Y_u|^2 \mathbf{1}_{\{|Y_u| \leq \Pi_n\}} \right)$$

$$\leq E_\xi \frac{1}{\Pi_n} \sum_{u \in \mathcal{T}_n} E_\xi \left( |Y_u|^2 \mathbf{1}_{\{|Y_u| \leq \min(e^{2\lambda}, \Pi_n)\}} + |Y_u|^2 \mathbf{1}_{\{e^{2\lambda} < |Y_u| \leq \Pi_n\}} \right)$$

$$\leq E_\xi \frac{e^{4\lambda}}{\Pi_n} + e^{4\lambda} \frac{1}{\Pi_n} \sum_{u \in \mathcal{T}_n} E_\xi |Y_u|^2 \Pi_n (\ln \Pi_n)^{-1-\lambda} (|Y_u| (\ln^+ |Y_u|))^{-1-\lambda)^{-1}}$$

$$\leq E_\xi \frac{e^{4\lambda}}{\Pi_n} + e^{4\lambda} \frac{1}{\Pi_n} \sum_{u \in \mathcal{T}_n} E_\xi |Y_u|^2 \Pi_n (\ln \Pi_n)^{-1+\lambda}$$

$$\leq e^{4\lambda} + K_{\xi} n + K_{\xi} n (\ln - m_n)^{1+\lambda}$$

$$\leq e^{4\lambda} + K_{\xi} n (1 + (\ln - m_n)^{1+\lambda}).$$

Combining the above results, we see that the series $\sum I_{2,n}$ converges a.s.

Therefore we have proved (4.2) and the martingale $\{N_{1,n}\}$ converges a.s. to

$$V_1 := \sum_{n=1}^{\infty} (N_{1,n} - N_{1,n}) + N_{1,1}.$$

\[\square\]

### 4.2 Convergence of the martingale $\{(N_{2,n}, \mathcal{D}_n)\}$

**Proof of Proposition** To see that $\{(N_{2,n}, \mathcal{D}_n)\}$ is a martingale, it suffices to notice that (remind that we have assumed $\ell_n = 0$)

$$E_{\xi, n} N_{2,n+1} = E_{\xi, n} \left( \frac{1}{\Pi_{n+1}} \sum_{u \in \mathcal{T}_{n+1}} (S_u^2 - s_{n+1}^2) \right)$$

$$= \frac{1}{\Pi_{n+1}} \sum_{u \in \mathcal{T}_n} E_{\xi, n} \left( \sum_{i=1}^{N_i} (S_u + Lu_i)^2 - s_{n+1}^2 \right)$$
\[
\sum_{i=1}^{N_u} (S_u^2 + \sigma_n^2 - s_{n+1}^2) \right)
\]
\[
= \frac{1}{\Pi_{u+1}} \sum_{u \in \mathbb{T}_u} \mathbb{E}_t \left( \sum_{i=1}^{N_u} (S_u^2 + 2S_uL_{u1} + L_{u1}^2 - s_{n+1}^2) \right)
\]
\[
= \frac{1}{\Pi_{n+1}} \sum_{u \in \mathbb{T}_u} m_n (S_u^2 + \sigma_n^2 - s_{n+1}^2) = \frac{1}{\Pi_{n+1}} \sum_{u \in \mathbb{T}_u} (S_u^2 - s_n^2) = N_{2,n}.
\]

As in the proof of Proposition 2.1, we will prove the convergence of the martingale \((N_{2,n}, \mathcal{F}_n)\) by showing that
\[
\sum_{n=1}^{\infty} (N_{2,n+1} - N_{2,n}) \text{ converges a.s.}
\]

We start by giving some notation. For \(n \geq 1\) and \(|u| = n\), set
\[
J_{1,n} := \frac{1}{\Pi_n} \sum_{u \in \mathbb{T}_u} (S_u^2 - s_n^2) \left( \frac{N_u}{m_n} - 1 \right), \quad J_{1,n}^* := \frac{1}{\Pi_n} \sum_{u \in \mathbb{T}_u} (S_u^2 - s_n^2) \left( \frac{N_u}{m_n} - 1 \right) 1_{\{u \leq \Pi_n\}};
\]
\[
J_{2,n} := \frac{1}{\Pi_n} \sum_{u \in \mathbb{T}_u} Q_u, \quad J_{2,n}^* := \frac{1}{\Pi_n} \sum_{u \in \mathbb{T}_u} Q_u 1_{\{|Q_u| \leq \Pi_n\}}, \text{ with } Q_u = \frac{1}{m_n} \sum_{i=1}^{N_u} (L_{ui}^2 - \sigma_n^2);
\]
\[
J_{3,n} := \frac{1}{\Pi_n} \sum_{u \in \mathbb{T}_u} S_u Y_u, \quad J_{3,n}^* := \frac{1}{\Pi_n} \sum_{u \in \mathbb{T}_u} S_u Y_u 1_{\{|Y_u| \leq \Pi_n\}}, \text{ with } Y_u = \frac{1}{m_n} \sum_{i=1}^{N_u} L_{ui}.
\]

Then we see that \(N_{2,n+1} - N_{2,n} = J_{1,n} + J_{2,n} + 2J_{3,n}\). Thus the convergence a.s. of the martingale \(\{N_{2,n}\}\) will follow from the convergence a.s. of the series \(\sum J_{q,n}(q = 1, 2, 3)\). Using the above truncation and following the same procedure as in the proofs of Proposition 2.1, we can prove the convergence a.s. of the series \(\sum J_{q,n}(q = 1, 2, 3)\). We omit the details and only stress the following estimate:
\[
\mathbb{E}_t[Q_u | (\ln^+ |Q_u|)^{1+\lambda}] = \mathbb{E}_t \left( \frac{1}{m_n} \sum_{i=1}^{N_u} (L_{ui}^2 - \sigma_n^2)^{1+\lambda} \right) \leq K_{\lambda} \mathbb{E}_t \left( \frac{1}{m_n} \sum_{i=1}^{N_u} (L_{ui}^2 - \sigma_n^2)^{1+\lambda} \right)
\]
\[
\leq K_{\lambda} \mathbb{E}_t \left( \frac{1}{m_n} \sum_{i=1}^{N_u} (L_{ui}^2 - \sigma_n^2)^{1+\lambda} \right).
\]

So the martingale \(N_{2,n}\) converges a.s. to the limit
\[
V_2 := \sum_{n=1}^{\infty} (N_{2,n+1} - N_{2,n}) + N_{2,1}.
\]

5 Proof of Theorem 2.3

5.1 A key decomposition

For \(u \in (\mathbb{N}^+)^k (k \geq 0)\) and \(n \geq 1\), write for \(B \subset \mathbb{R}\),
\[
Z_n(u, B) = \sum_{v \in \mathbb{T}_n(u)} 1_B(S_{uv} - S_u).
\]
It can be easily seen that the law of $Z_u(B)$ under $P_\xi$ is the same as that of $Z_n(B)$ under $P_{\delta^k \xi}$. Define

$$W_n(u, B) = Z_n(u, B) / \Pi_n(\theta^k \xi), \quad W_n(u, t) = W_n(u, (-\infty, t]),$$

$$W_n(B) = Z_n(B) / \Pi_n, \quad W_n(t) = W_n((-\infty, t]).$$

By definition, we have $\Pi_n(\theta^k \xi) = m_k \cdots m_{k+n-1}$. $Z_n(B) = Z_n(\emptyset, B)$, $W_n(B) = W_n(\emptyset, B)$, $W_n = W_n(\mathbb{R})$. The following decomposition will play a key role in our approach: for $k \leq n$,

$$Z_n(B) = \sum_{u \in T_k} Z_{n-k}(u, B - S_u).$$

(5.1)

Remark that by our definition, for $u \in T_k$,

$$Z_{n-k}(u, B - S_u) = \sum_{u_1 \cdots u_{n-k} \in T_{n-k}(u)} 1_B(S_{u_1 \cdots u_{n-k}})$$

represents number of the descendants of $u$ at time $n$ situated in $B$.

For each $n$, we choose an integer $k_n < n$ as follows. Let $\beta$ be a real number such that $\max \left\{ \frac{k}{3}, \frac{2}{3} \right\} < \beta < \frac{1}{3}$ and set $k_n = \lceil n^\beta \rceil$, the integral part of $n^\beta$. Then on the basis of (5.1), the following decomposition will hold:

$$\Pi_n^{-1} Z_n(s_n t) \to P \Phi(t) = A_n + B_n + C_n,$$

(5.2)

where

$$A_n = \frac{1}{\Pi_{k_n}} \sum_{u \in T_{k_n}} \left[ W_{n-k_n}(u, s_n t - S_u) - \mathbb{E}_{\xi, k_n} W_{n-k_n}(u, s_n t - S_u) \right],$$

$$B_n = \frac{1}{\Pi_{k_n}} \sum_{u \in T_{k_n}} \left[ \mathbb{E}_{\xi, k_n} W_{n-k_n}(u, s_n t - S_u) - \Phi(t) \right],$$

$$C_n = \left( W_{k_n} - W \right) \Phi(t).$$

Here we remind that the random variables $W_{n-k_n}(u, s_n t - S_u)$ are independent of each other under the conditional probability $P_{\xi, k_n}$.

### 5.2 Proof of Theorem 2.3

First, observe that the condition $\mathbb{E} m_0^{-\delta} < \infty$ implies that $\mathbb{E}\left( \ln m_0 \right)^{\kappa} < \infty$ for all $\kappa > 0$. So the hypotheses of Propositions 2.1 and 2.2 are satisfied under the conditions of Theorem 2.3.

By virtue of the decomposition (5.2), we shall divide the proof into three lemmas.

**Lemma 5.1.** Under the hypothesis of Theorem 2.3

$$\sqrt{n} A_n \xrightarrow{n \to \infty} 0 \ a.s. \quad (5.3)$$

**Lemma 5.2.** Under the hypothesis of Theorem 2.3

$$\sqrt{n} B_n \xrightarrow{n \to \infty} \frac{1}{6} \mathbb{E}_{\sigma_0}^{(3)} \left( \mathbb{E}_{\sigma_0}^{(2)} \right)^2 (1 - t^2) \phi(t) W - \left( \mathbb{E}_{\sigma_0}^{(2)} \right)^2 \cdot \frac{t}{4} \phi(t) V_1 \ a.s. \quad (5.4)$$

**Lemma 5.3.** Under the hypothesis of Theorem 2.3

$$\sqrt{n} C_n \xrightarrow{n \to \infty} 0 \ a.s. \quad (5.5)$$

Now we go to prove the lemmas subsequently.

**Proof of Lemma 5.1.**

For ease of notation, we define for $|u| = k_n$,

$$X_{n,u} = W_{n-k_n}(u, s_n t - S_u) - \mathbb{E}_{\xi, k_n} W_{n-k_n}(u, s_n t - S_u), \quad \tilde{X}_{n,u} = X_{n,u} 1_{\{|X_{n,u}| \leq \Pi_{k_n}\}},$$

$$\tilde{A}_n = \frac{1}{\Pi_{k_n}} \sum_{u \in T_{k_n}} \tilde{X}_{n,u}.$$
Then we see that $|X_{k,u}| \leq W_{n-k_n}(u) + 1$.

To prove Lemma 5.1 we will use the extended Borel-Cantelli Lemma. We can obtain the required result once we prove that $\forall \varepsilon > 0$,

$$\sum_{n=1}^{\infty} \mathbb{P}_{k_n}(\sqrt{n} |A_n| > 2\varepsilon) < \infty.$$

(5.6)

Notice that

$$\mathbb{P}_{k_n}(\sqrt{n} |A_n| > 2\frac{\varepsilon}{\sqrt{n}}) \leq \mathbb{P}_{k_n}(A_n \neq \bar{A}_n) + \mathbb{P}_{k_n}(|\bar{A}_n - \mathbb{E}_{\xi,k_n}\bar{A}_n| > \frac{\varepsilon}{\sqrt{n}}) + \mathbb{P}_{k_n}(\|\mathbb{E}_{\xi,k_n}\bar{A}_n| > \frac{\varepsilon}{\sqrt{n}}).

We will proceed the proof in 3 steps.

**Step 1** We first prove that

$$\sum_{n=1}^{\infty} \mathbb{P}_{k_n}(A_n \neq \bar{A}_n) < \infty.$$

(5.7)

To this end, define

$$W^* = \sup_n W_n,$$

and we need the following result:

**Lemma 5.4.** (Th. 1.2) Assume (2.1) for some $\lambda > 0$ and $E_{m_0}^{-\delta} < \infty$ for some $\delta > 0$. Then

$$\mathbb{E}(W^* + 1)(\ln(W^* + 1))^\lambda < \infty.$$

(5.8)

We observe that

$$\mathbb{P}_{k_n}(A_n \neq \bar{A}_n) \leq \sum_{u \in T_{k_n}} \mathbb{P}_{k_n}(X_{n,u} \neq \bar{X}_{n,u}) = \sum_{u \in T_{k_n}} \mathbb{P}_{k_n}(|X_{n,u}| \geq \Pi_{k_n})$$

$$\leq \sum_{u \in T_{k_n}} \mathbb{P}_{k_n}(W_{n-k_n}(u) + 1 \geq \Pi_{k_n})$$

$$= W_{k_n}\left[r_n\mathbb{P}(W_{n-k_n} + 1 \geq r_n)\right]_{r_n=\Pi_{k_n}}$$

$$\leq W_{k_n}\mathbb{E}((W_{n-k_n} + 1)1_{\{W_{n-k_n} + 1 \geq r_n\}})_{r_n=\Pi_{k_n}}$$

$$\leq W_{k_n}\mathbb{E}((W^* + 1)1_{\{W^* + 1 \geq r_n\}})_{r_n=\Pi_{k_n}}$$

$$\leq W^*(\ln \Pi_{k_n})^{-\lambda}\mathbb{E}(W^* + 1)(\ln(W^* + 1))^\lambda$$

$$\leq K_\varepsilon W^* n^{-\alpha} \mathbb{E}(W^* + 1)(\ln(W^* + 1))^\lambda,$$

where the last inequality holds since

$$\frac{1}{n} \ln \Pi_n \to \mathbb{E} \ln m_0 > 0 \text{ a.s.},$$

(5.9)

and $k_n \sim n^\beta$. By the choice of $\beta$ and Lemma 5.4 we obtain (5.7).

**Step 2**. We next prove that $\forall \varepsilon > 0$,

$$\sum_{n=1}^{\infty} \mathbb{P}_{k_n}(\bar{A}_n - \mathbb{E}_{\xi,k_n}\bar{A}_n| > \frac{\varepsilon}{\sqrt{n}}) < \infty.$$

(5.10)

Take a constant $b \in (1, e^{E \ln m_0})$. Observe that $\forall u \in T_{k_n}, n \geq 1$,

$$\mathbb{E}_{k_n} \bar{X}_{n,u}^2 = \int_0^\infty 2x \mathbb{P}_{k_n}(|X_{n,u}| > x)dx = 2 \int_0^\infty x \mathbb{P}_{k_n}(|X_{n,u}|1_{|X_{n,u}| < \Pi_{k_n}} > x)dx$$

$$\leq 2 \int_0^{\Pi_{k_n}} x \mathbb{P}_{k_n}(|W_{n-k_n}(u) + 1| > x)dx = 2 \int_0^{\Pi_{k_n}} x \mathbb{P}(|W_{n-k_n} + 1| > x)dx$$

$$\leq 2 \int_0^{\Pi_{k_n}} x \mathbb{P}(\bar{A}_n - \mathbb{E}_{\xi,k_n}\bar{A}_n| > \frac{\varepsilon}{\sqrt{n}}) < \infty.$$
Then we have that

$$\sum_{n=1}^{\infty} P_{n}^{*}\left(\left|\mathcal{A}_{n} - \mathbb{E}_{\xi,k_{n}} \mathcal{A}_{n}\right| > \frac{\varepsilon}{\sqrt{n}}\right)$$

$$= \sum_{n=1}^{\infty} E_{k_{n}}^{*} P_{\xi,k_{n}}\left(\left|\mathcal{A}_{n} - \mathbb{E}_{\xi,k_{n}} \mathcal{A}_{n}\right| > \frac{\varepsilon}{\sqrt{n}}\right)$$

$$\leq \varepsilon^{-2} \sum_{n=1}^{\infty} n E_{k_{n}}\left(\Pi_{k_{n}}^{*} \sum_{u \in \Pi_{k_{n}}} E_{\xi,k_{n}} X_{n,u}^{2}\right) > \varepsilon^{-2} \sum_{n=1}^{\infty} n \left(\Pi_{k_{n}}^{*} \sum_{u \in \Pi_{k_{n}}} E_{k_{n}} X_{n,u}^{2}\right)$$

$$\leq \varepsilon^{-2} \sum_{n=1}^{\infty} n W_{k_{n}}^{*} \left[2 E(W^{*} + 1)(\ln(W^{*} + 1)^{\lambda})(b^{k_{n}} + (\Pi_{k_{n}} - b^{k_{n}})(k_{n} \ln b)^{-\lambda}) + 9\right]$$

$$\leq 2\varepsilon^{-2} W^{*}E(W^{*} + 1)(\ln(W^{*} + 1)^{\lambda})\left(\sum_{n=1}^{\infty} n^{2} b^{k_{n}} + \sum_{n=1}^{\infty} n(k_{n} \ln b)^{-\lambda}\right) + 9\varepsilon^{-2} W^{*} \sum_{n=1}^{\infty} \frac{n}{\Pi_{k_{n}}}.$$ 

By \((5.9)\) and \(\lambda b > 2\), the three series in the last expression above converge under our hypothesis and hence \((5.10)\) is proved.

**Step 3.** Observe

$$P_{k_{n}}\left(\left|\mathbb{E}_{\xi,k_{n}} \mathcal{A}_{n}\right| > \frac{\varepsilon}{\sqrt{n}}\right)$$

$$\leq \frac{\sqrt{n}}{\varepsilon} E_{k_{n}}\left|\mathbb{E}_{\xi,k_{n}} \mathcal{A}_{n}\right| = \frac{1}{\Pi_{k_{n}}} \sum_{u \in \Pi_{k_{n}}} E_{\xi,k_{n}} X_{n,u}^{2}\left(\mathcal{A}_{n} = \mathcal{A}_{n}\right)$$

$$= \frac{\sqrt{n}}{\varepsilon} E_{k_{n}}\left|\frac{1}{\Pi_{k_{n}}} \sum_{u \in \Pi_{k_{n}}} (-E_{\xi,k_{n}} X_{n,u} 1_{\{|X_{n,u}| \geq \Pi_{k_{n}}\}})\right|$$

$$\leq \frac{\sqrt{n}}{\varepsilon} \sum_{u \in \Pi_{k_{n}}} E_{k_{n}}(W_{n-k_{n}}(u) + 1) 1_{\{W_{n-k_{n}}(u) + 1 \geq \Pi_{k_{n}}\}}$$

$$= \frac{\sqrt{n} W_{k_{n}}}{\varepsilon} E\left(W_{n-k_{n}} + 1\right) 1_{\{W_{n-k_{n}} + 1 \geq r_{n} = \Pi_{k_{n}}\}}$$

$$\leq \frac{W^{*}}{\varepsilon} \sqrt{n} E\left(W^{*} + 1\right) 1_{\{W^{*} + 1 \geq r_{n} = \Pi_{k_{n}}\}}$$

$$\leq \frac{W^{*}}{\varepsilon} \sqrt{n} E\left(W^{*} + 1\right) \ln\left(W^{*} + 1\right)$$

Then by \((5.9)\) and \(\lambda b > 2\), it follows that

$$\sum_{n=1}^{\infty} P_{k_{n}}\left(\left|\mathbb{E}_{\xi,k_{n}} \mathcal{A}_{n}\right| > \frac{\varepsilon}{\sqrt{n}}\right) < \infty.$$ 

Combining Steps 1-3, we obtain \((5.6)\). Hence the lemma is proved.
Proof of Lemma 5.2. For ease of notation, set

\[ D_1(t) = (1 - t^2)\phi(t), \quad \kappa_{1,n} = \frac{s_n(3) - s_{kn}(3)}{6(s_n^2 - s_{kn}^2)^{1/2}}. \]

Observe that

\[ B_n = B_{n1} + B_{n2} + B_{n3} + B_{n4}, \]

where

\[
\begin{align*}
B_{n1} &= \frac{1}{\Pi_{kn}} \sum_{u \in T_{kn}} \left( \mathbb{E}_{\xi,k_n} W_{n-k_n}(u, s_n t - S_u) - \Phi\left( \frac{s_n t - S_u}{(s_n^2 - s_{kn}^2)^{1/2}} \right) - \kappa_{1,n} D_1 \left( \frac{s_n t - S_u}{(s_n^2 - s_{kn}^2)^{1/2}} \right) \right); \\
B_{n2} &= \frac{1}{\Pi_{kn}} \sum_{u \in T_{kn}} \left( \Phi\left( \frac{s_n t - S_u}{(s_n^2 - s_{kn}^2)^{1/2}} \right) - \Phi(t) \right); \\
B_{n3} &= \kappa_{1,n} \frac{1}{\Pi_{kn}} \sum_{u \in T_{kn}} \left( D_1 \left( \frac{s_n t - S_u}{(s_n^2 - s_{kn}^2)^{1/2}} \right) - D_1(t) \right); \\
B_{n4} &= \kappa_{1,n} D_1(t) W_{kn}.
\end{align*}
\]

Then the lemma will be proved once we show that

\[
\begin{align*}
\sqrt{n}B_{n1} &\xrightarrow{n \to \infty} 0; \\
\sqrt{n}B_{n2} &\xrightarrow{n \to \infty} -(\mathbb{E}\sigma_0^{(2)})^{-\frac{1}{2}}\phi(t)V_1; \\
\sqrt{n}B_{n3} &\xrightarrow{n \to \infty} 0; \\
\sqrt{n}B_{n4} &\xrightarrow{n \to \infty} \frac{1}{6}\mathbb{E}\sigma_0^{(3)}(\mathbb{E}\sigma_0^{(2)})^{-\frac{1}{2}}D_1(t)W.
\end{align*}
\]

We will prove these results subsequently.

We first prove (5.12). The proof will mainly be based on the following result about asymptotic expansion of the distribution of the sum of independent random variables:

Proposition 5.5. Under the hypothesis of Theorem 2.3 for a.e. \( \xi \),

\[
\epsilon_n = n^{1/2} \sup_{x \in \mathbb{R}} \left| \mathbb{P}_\xi \left( \frac{\sum_{k=k_n}^{n-1} \hat{L}_k}{(s_n^2 - s_{kn}^2)^{1/2}} \leq x \right) - \Phi(x) - \kappa_{1,n} D_1(x) \right| \xrightarrow{n \to \infty} 0.
\]

Proof. Let \( X_k = 0 \) for \( 0 \leq k \leq k_n - 1 \) and \( X_k = \hat{L}_k \) for \( k_n \leq k \leq n - 1 \). Then the random variables \( \{X_k\} \) are independent under \( \mathbb{P}_\xi \). Denote by \( v_k(\cdot) \) the characteristic function of \( X_k \): \( v_k(t) := \mathbb{E}_\xi e^{itX_k} \). Using the Markov inequality and Lemma 3.2 we obtain the following result:

\[
\sup_{x \in \mathbb{R}} \left| \mathbb{P}_\xi \left( \frac{\sum_{k=k_n}^{n-1} \hat{L}_k}{(s_n^2 - s_{kn}^2)^{1/2}} \leq x \right) - \Phi(x) - \kappa_{1,n} D_1(x) \right| \lesssim K_\xi \left( s_n^2 - s_{kn}^2 \right)^{-2} \sum_{j=k_n}^{n-1} \mathbb{E}_\xi |\hat{L}_j|^4 + n^6 \left( \sup_{|t| > n} \frac{1}{n} \left( k_n + \sum_{j=k_n}^{n-1} |v_j(t)| \right) + \frac{1}{2n} \right)^2.
\]

By our conditions on the environment, we know that

\[
\lim_{n \to \infty} n(s_n^2 - s_{kn}^2)^{-2} \sum_{j=k_n}^{n-1} \mathbb{E}_\xi |\hat{L}_j|^4 = \mathbb{E}|\hat{L}_0|^4/(\mathbb{E}\sigma_0^{(2)})^2.
\]

By (2.2), \( \hat{L}_n \) satisfies

\[
\mathbb{P} \left( \limsup_{|t| \to \infty} |v_n(t)| < 1 \right) > 0.
\]
So there exists a constant $c_n \leq 1$ depending on $\xi_n$ such that
\[
\sup_{|t|>T} |v_n(t)| \leq c_n \quad \text{and} \quad \mathbb{P}(c_n < 1) > 0.
\]

Then $\mathbb{E}c_0 < 1$. By the Birkhoff ergodic theorem, we have
\[
\sup_{|t|>T} \left( \frac{1}{n} \sum_{j=k_n}^{n-1} |v_j(t)| \right) \leq \frac{1}{n} \sum_{j=1}^{n-1} c_j \to \mathbb{E}c_0 < 1.
\]

Then for $n$ large enough,
\[
\left( \sup_{|t|>T} \frac{1}{n} \left( k_n + \sum_{j=k_n}^{n-1} |v_j(t)| \right) + \frac{1}{2n} \right)^n = o(n^{-m}), \quad \forall m > 0. \tag{5.17}
\]

From (5.16) and (5.17), we get the conclusion of the proposition.

From Proposition 5.5, it is easy to see that
\[
\sqrt{n}|B_{n1}| \leq W_{k_n} c_n \xrightarrow{n \to \infty} 0.
\]

Hence (5.12) is proved.

We next prove (5.13). Observe that
\[
B_{n2} = B_{n21} + B_{n22} + B_{n23} + B_{n24} + B_{n25},
\]
with
\[
B_{n21} = \frac{1}{\Pi_{k_n}} \sum_{u \in \mathcal{T}_{k_n}} \Phi\left( \frac{s_{n}u - S_u}{(s_n^2 - s_{k_n}^2)^{1/2}} \right) - \Phi\left( \frac{s_{n}u - S_u}{(s_n^2 - s_{k_n}^2)^{1/2}} - t \right) \mathbf{1}_{\{|S_u| \leq k_n\}},
\]

\[
B_{n22} = \frac{1}{\Pi_{k_n}} \sum_{u \in \mathcal{T}_{k_n}} \Phi\left( \frac{s_{n}u - S_u}{(s_n^2 - s_{k_n}^2)^{1/2}} \right) - \Phi\left( \frac{s_{n}u - S_u}{(s_n^2 - s_{k_n}^2)^{1/2}} - t \right) \mathbf{1}_{\{|S_u| > k_n\}},
\]

\[
B_{n23} = -\frac{1}{\Pi_{k_n}} \sum_{u \in \mathcal{T}_{k_n}} \left( \frac{s_{n}u - S_u}{(s_n^2 - s_{k_n}^2)^{1/2}} - t \right) \Phi\left( \frac{s_{n}u - S_u}{(s_n^2 - s_{k_n}^2)^{1/2}} - t \right) \mathbf{1}_{\{|S_u| > k_n\}},
\]

\[
B_{n24} = \frac{1}{(s_n^2 - s_{k_n}^2)^{1/2}} \left( s_{n} - (s_n^2 - s_{k_n}^2)^{1/2} \right) W_{k_n} \phi(t) t,
\]

\[
B_{n25} = \frac{1}{(s_n^2 - s_{k_n}^2)^{1/2}} \phi(t) N_{1, k_n}.
\]

By Taylor’s formula and the choice of $\beta$ and $k_n$, we get
\[
\bar{c}_n = \sqrt{n} \sup_{|y| \leq k_n} \left| \Phi\left( \frac{s_{n}u - y}{(s_n^2 - s_{k_n}^2)^{1/2}} \right) - \Phi\left( \frac{s_{n}u - y}{(s_n^2 - s_{k_n}^2)^{1/2}} - t \right) \right|
\]
\[
\leq \sqrt{n} \sup_{|y| \leq k_n} \left| \frac{s_{n}u - y}{(s_n^2 - s_{k_n}^2)^{1/2}} - t \right|^2 \xrightarrow{n \to \infty} 0.
\]

Thus
\[
|\sqrt{n}B_{n21}| \leq W_{k_n} \bar{c}_n \xrightarrow{n \to \infty} 0. \tag{5.18}
\]

We continue to prove that
\[
\sqrt{n}B_{n22} \xrightarrow{n \to \infty} 0; \quad \sqrt{n}B_{n23} \xrightarrow{n \to \infty} 0. \tag{5.19}
\]

This will follow from the facts:
\[
\frac{1}{\Pi_{k_n}} \sum_{u \in \mathcal{T}_{k_n}} |S_u| \mathbf{1}_{\{|S_u| > k_n\}} \xrightarrow{n \to \infty} 0 \text{ a.s.}; \quad \sqrt{n} \frac{1}{\Pi_{k_n}} \sum_{u \in \mathcal{T}_{k_n}} \mathbf{1}_{\{|S_u| > k_n\}} \xrightarrow{n \to \infty} 0 \text{ a.s.} \tag{5.20}
\]
In order to prove (5.20), we firstly observe that
\[
E \left( \sum_{n=1}^{\infty} \frac{1}{\Pi_{k_n}} \sum_{u \in T_{k_n}} |S_u| 1\{|S_u| > k_n\} \right)
\]
\[
= \sum_{n=1}^{\infty} E|\hat{S}_{k_n}| 1\{|\hat{S}_{k_n}| > k_n\} \leq \sum_{n=1}^{\infty} k_n^{1-\eta} E|\hat{S}_{k_n}|^\eta \leq \sum_{n=1}^{\infty} k_n^{-\frac{1}{2}} \sum_{j=0}^{k_n-1} E|\hat{L}_j|^\eta = \sum_{n=1}^{\infty} k_n^{-\frac{1}{2}} E|\hat{L}_0|^\eta,
\]
and
\[
E \left( \sum_{n=1}^{\infty} \sqrt{n} \frac{1}{\Pi_{k_n}} \sum_{u \in T_{k_n}} 1\{|S_u| > k_n\} \right)
\]
\[
= \sum_{n=1}^{\infty} \sqrt{n} E|\hat{S}_{k_n}| 1\{|\hat{S}_{k_n}| > k_n\} \leq \sum_{n=1}^{\infty} \sqrt{n} k_n^{-\eta} E|\hat{S}_{k_n}|^\eta \leq \sum_{n=1}^{\infty} \sqrt{n} k_n^{-\frac{1}{2}} \sum_{j=0}^{k_n-1} E|\hat{L}_j|^\eta = \sum_{n=1}^{\infty} \sqrt{n} k_n^{-\frac{1}{2}} E|\hat{L}_0|^\eta.
\]
The assumptions on \(\beta, k_n\) and \(\eta\) ensure that the series in the right hand side of the above two expressions converge. Hence
\[
\sum_{n=1}^{\infty} \frac{1}{\Pi_{k_n}} \sum_{u \in T_{k_n}} |S_u| 1\{|S_u| > k_n\} < \infty, \quad \sum_{n=1}^{\infty} \sqrt{n} \frac{1}{\Pi_{k_n}} \sum_{u \in T_{k_n}} 1\{|S_u| > k_n\} < \infty \quad \text{a.s.,}
\]
which deduce (5.20), and consequently, (5.19) is proved.

By the Birkhoff ergodic theorem, we have
\[
\lim_{n \to \infty} \frac{S_n^2}{n} = \mathbb{E} \sigma_0^{(2)},
\]
whence by the choice of \(\beta < 1/4\) and the conditions on the environment,
\[
\sqrt{n} B_{24} = \frac{\sqrt{n} s_{k_n}^2}{(s_n^2 - s_{k_n}^2)^{1/2} s_n + (s_n^2 - s_{k_n}^2)^{1/2}} W_{k_n} \phi(t) t \xrightarrow{n \to \infty} 0. \quad (5.21)
\]
Due to Proposition 2.1 and (5.21), we conclude that
\[
\sqrt{n} B_{25} \xrightarrow{n \to \infty} -(\mathbb{E} \sigma_0^{(2)})^{-\frac{1}{2}} \phi(t) V_1 \quad \text{a.s.} \quad (5.22)
\]
From (5.21), (5.19), (5.22) and (5.23), we derive (5.13).

Now we turn to the proof of (5.14).

According to the hypothesis of Theorem 2.3 it follows from the Birkhoff ergodic theorem that
\[
\lim_{n \to \infty} \sqrt{n} k_{1,n} = \frac{1}{6} (\mathbb{E} \sigma_0^{(2)})^{-3/2} \mathbb{E} \sigma_0^{(3)}.
\]
Notice that
\[
\left| \frac{1}{\Pi_{k_n}} \sum_{u \in T_{k_n}} \left( D_1 \left( \frac{s_n t - S_u}{(s_n^2 - s_{k_n}^2)^{1/2}} \right) - D_1(t) \right) \right| \leq \frac{2}{\Pi_{k_n}} \sum_{u \in T_{k_n}} 1\{|S_u| > k_n\} + \frac{1}{\Pi_{k_n}} \sum_{u \in T_{k_n}} \left| D_1 \left( \frac{s_n t - S_u}{(s_n^2 - s_{k_n}^2)^{1/2}} \right) - D_1(t) \right| 1\{|S_u| \leq k_n\}.
\]
The first term in the last expression above tends to 0 a.s. by (5.20), and the second one tends to 0 a.s. because the martingale \(\{W_n\}\) converges and
\[
\sup_{|y| \leq k_n} \left| D_1 \left( \frac{s_n t - y}{(s_n^2 - s_{k_n}^2)^{1/2}} \right) - D_1(t) \right| \xrightarrow{n \to \infty} 0.
\]
Combining the above results, we obtain (5.14).

It remains to prove (5.15), which is immediate from (5.24) and the fact \(W_n \xrightarrow{n \to \infty} W\).

So Lemma 5.2 has been proved.
Lemma 6.2. Under the hypothesis of Theorem 2.4, a.s.

\[ W - W_n = o(n^{-\lambda}) \quad \text{a.s.} \]

By the choice of \( \beta \) and \( k_n \), we see that

\[ \sqrt{n}(W - W_{k_n}) = o(n^{\frac{1}{2} - \lambda \beta}) \xrightarrow{n \to \infty} 0. \]

Now Theorem 2.4 follows from the decomposition (6.1) and Lemmas 5.1–5.3.

6 Proof of Theorem 2.4

We will follow the similar procedure as in the proof of Theorem 2.3. We remind that \( \lambda, \eta > 10 \infty \) in the current setting. Hereafter we will choose \( \lambda, \eta > 10 \infty \) and let \( k_n = \lfloor n^{\beta} \rfloor \) (the integral part of \( n^{\beta} \)). By (6.1), we have

\[
\sqrt{2\pi s_n n^{-1}} Z_n(A) - W \int_A \exp\left( -\frac{x^2}{2s_n^2} \right) dx = \Lambda_{1,n} + \Lambda_{2,n} + \Lambda_{3,n},
\]

with

\[
\Lambda_{1,n} = \sqrt{2\pi s_n n^{-1}} \sum_{u \in E_n} \left( W_{n-k_n}(u, A - S_n) - \mathbb{E}_{\xi,k_n} W_{n-k_n}(u, A - S_n) \right) - \int_A \exp\left( -\frac{x^2}{2s_n^2} \right) dx;
\]

\[
\Lambda_{2,n} = \int_A \exp\left( -\frac{x^2}{2s_n^2} \right) dx.
\]

On basis of this decomposition, we shall divide the proof of Theorem 2.4 into the following lemmas.

Lemma 6.1. Under the hypothesis of Theorem 2.4 a.s.

\[ n \Lambda_{1,n} \xrightarrow{n \to \infty} 0. \]

Lemma 6.2. Under the hypothesis of Theorem 2.4 a.s.

\[ n \Lambda_{2,n} \xrightarrow{n \to \infty} \left( \mathbb{E} \sigma_0^{(2)} \right)^{-1} \left( -\frac{1}{2} V_2 + \pi_A V_1 \right) |A| + \frac{1}{2} \mathbb{E} \sigma_0^{(3)} \left( \mathbb{E} \sigma_0^{(2)} \right)^{-2} (V_1 - \pi_A W) |A| \]

\[ + \frac{1}{8} (\mathbb{E} \sigma_0^{(2)})^{-2} \mathbb{E} (\sigma_0^{(2)})^{-3} (\sigma_0^{(2)})^2 W |A| - \frac{5}{24} (\mathbb{E} \sigma_0^{(2)})^{-3} (\mathbb{E} \sigma_0^{(3)})^2 W |A|. \]

Lemma 6.3. Under the hypothesis of Theorem 2.4 a.s.

\[ n \Lambda_{3,n} \xrightarrow{n \to \infty} 0. \]

Now we go to prove the lemmas subsequently.

Proof of Lemma 6.7. The proof of Lemma 6.1 follows the same procedure as that of Lemma 5.1 with minor changes in scaling. We omit the details.
Define for \( x \in \mathbb{R} \),

\[
D_1(x) = -H_2(x)\phi(x), \quad D_2(x) = -H_3(x)\phi(x), \quad D_3(x) = -H_3(x)\phi(x),
\]

\[
R_n(x) = -\frac{(s^{(3)}_n - s^{(3)}_{kn})^3}{1296(s^2_n - s^2_{kn})^{3/2}}H_6(x)\phi(x) - \sum_{j=k_n}^{n-1} \frac{(s^{(3)}_j - 10s^{(3)}_j\sigma_j^{(2)})}{120(s^2_n - s^2_{kn})^{3/2}}H_4(x)\phi(x)
\]

\[
= \frac{(s^{(3)}_n - s^{(3)}_{kn})\sum_{j=k_n}^{n-1} (\sigma_j^{(4)} - 3(\sigma_j^{(2)})^2)}{144(s^2_n - s^2_{kn})^{3/2}}H_6(x)\phi(x),
\]

where \( H_n \) are Chebyshev-Hermite polynomials defined in (5.1). We decompose \( \Lambda_{2,n} \) into 7 terms:

\[
\Lambda_{2,n} = \Lambda_{2,n1} + \Lambda_{2,n2} + \Lambda_{2,n3} + \Lambda_{2,n4} + \Lambda_{2,n5} + \Lambda_{2,n6} + \Lambda_{2,n7},
\]

where

\[
\Lambda_{2,n1} = \sqrt{2\pi s_n} \Pi_{kn}^{-1} \sum_{u \in T_{kn}} \left[ E_{\xi, kn} W_{n-k_n}(u, A - S_u) - \int_A \left( \phi \left( \frac{x - S_u}{(s^2_n - s^2_{kn})^{1/2}} \right) \right) dx \right] + \sum_{\nu=1}^3 \kappa_{\nu,n} D_{\nu} \left( \frac{x - S_u}{(s^2_n - s^2_{kn})^{1/2}} \right) \exp \left( -\frac{(x - S_u)^2}{2(s^2_n - s^2_{kn})} \right) \exp \left( -\frac{x^2}{2s^2_n} \right) dx,
\]

\[
\Lambda_{2,n2} = \Pi_{kn}^{-1} \sum_{u \in T_{kn}} 1_{\{S_u \leq k_n\}} \int_A \left[ D_{\nu} \left( \frac{x - S_u}{(s^2_n - s^2_{kn})^{1/2}} \right) \right] dx,
\]

\[
\Lambda_{2,n3} = \frac{\sqrt{2\pi s_n} \Pi_{kn}^{-1} \sum_{u \in T_{kn}} 1_{\{S_u \leq k_n\}} \int_A D_{\nu} \left( \frac{x - S_u}{(s^2_n - s^2_{kn})^{1/2}} \right) dx},
\]

\[
\Lambda_{2,n4} = \frac{\sqrt{2\pi s_n} \Pi_{kn}^{-1} \sum_{u \in T_{kn}} 1_{\{S_u \leq k_n\}} \int_A D_{\nu} \left( \frac{x - S_u}{(s^2_n - s^2_{kn})^{1/2}} \right) dx},
\]

\[
\Lambda_{2,n5} = \frac{\sqrt{2\pi s_n} \Pi_{kn}^{-1} \sum_{u \in T_{kn}} 1_{\{S_u \leq k_n\}} \int_A R_{\nu} \left( \frac{x - S_u}{(s^2_n - s^2_{kn})^{1/2}} \right) dx},
\]

\[
\Lambda_{2,n6} = \frac{\sqrt{2\pi s_n} \Pi_{kn}^{-1} \sum_{u \in T_{kn}} 1_{\{S_u \leq k_n\}} \int_A R_{\nu} \left( \frac{x - S_u}{(s^2_n - s^2_{kn})^{1/2}} \right) dx},
\]

\[
\Lambda_{2,n7} = \frac{\sqrt{2\pi s_n} \Pi_{kn}^{-1} \sum_{u \in T_{kn}} \left( \int_A \left( \phi \left( \frac{x - S_u}{(s^2_n - s^2_{kn})^{1/2}} \right) + R_{\nu} \left( \frac{x - S_u}{(s^2_n - s^2_{kn})^{1/2}} \right) \right) dx \right) 1_{\{S_u > k_n\}}.}
\]

The lemma will follow once we prove that a.s.

\[
n_{\Lambda_{2,n1}} \to 0, \quad n_{\Lambda_{2,n2}} \to 0, \quad n_{\Lambda_{2,n3}} \to 0, \quad n_{\Lambda_{2,n4}} \to 0, \quad n_{\Lambda_{2,n5}} \to 0, \quad n_{\Lambda_{2,n6}} \to 0, \quad n_{\Lambda_{2,n7}} \to 0.
\]

The proof of (6.6) is based on the following result on the asymptotic expansion of the distribution of the sum of independent random variables.
Proposition 6.4. Under the hypothesis of Theorem 6.4 for a.e. \( \xi \),

\[
\epsilon_n = n^{3/2} \sup_{x \in \mathbb{R}} | \mathbb{P}_\xi \left( \sum_{k=k_n}^{n-1} \frac{\hat{L}_k}{(s_n^2 - s_k^2)^{1/2}} \leq x \right) - \Phi(x) - \sum_{\nu=1}^{3} \kappa_{\nu,n} D_\nu(x) - R_n(x) | \xrightarrow{n \to \infty} 0.
\]

Proof. Let \( X_k = 0 \) for \( 0 \leq k \leq k_n - 1 \) and \( X_k = \hat{L}_k \) for \( k_n \leq k \leq n - 1 \). Then the random variables \( \{X_k\} \) are independent under \( \mathbb{P}_\xi \). By Markov’s inequality and Lemma 3.2, we obtain the following result:

\[
\sup_{x \in \mathbb{R}} | \mathbb{P}_\xi \left( \sum_{k=k_n}^{n-1} \frac{\hat{L}_k}{(s_n^2 - s_k^2)^{1/2}} \leq x \right) - \Phi(x) - \sum_{\nu=1}^{3} \kappa_{\nu,n} D_\nu(x) - R_n(x) | \leq K_\xi \left\{ (s_n^2 - s_{k_n}^2)^{-3} \sum_{j=k_n}^{n-1} \mathbb{E}_\xi |L_j|^6 + n^{15} \sup_{|t| > T_n} \left( \frac{1}{k_n} + \sum_{j=k_n}^{n-1} |v_j(t)| \right) + \frac{1}{2n} \right\}.
\]

By our conditions on the environment, we know that

\[
\lim_{n \to \infty} n^2(s_n^2 - s_{k_n}^2)^{-3} \sum_{j=k_n}^{n-1} \mathbb{E}_\xi |L_j|^6 = \mathbb{E} |\hat{L}_0|^6 / (\mathbb{E} \sigma_0^2)^3.
\]  

(6.13)

The required proposition concludes from (6.13) and (5.17).

Using Proposition 6.4, we deduce that

\[
|n \Lambda_{2,n1}| \leq \sqrt{2\pi s_n n^{-*}} W_{\kappa_n} \epsilon_n \xrightarrow{n \to \infty} 0,
\]

and (6.6) is proved.

Next we turn to the proof of (6.7). Using Taylor’s expansion and the boundedness of the set \( A \), together with the choice of \( \beta \) and \( k_n \), we get that

\[
\frac{s_n}{(s_n^2 - s_{k_n}^2)^{1/2}} \exp\left\{ -\frac{(x - y)^2}{2(s_n^2 - s_{k_n}^2)} \right\} - \exp\left\{ -\frac{x^2}{2s_n^2} \right\} = \frac{1}{2(s_n^2 - s_{k_n}^2)} (s_{k_n}^2 - y^2 + 2xy + o(1)),
\]

uniformly for all \( |y| \leq k_n \) and \( x \in A \) as \( n \to \infty \). By the same arguments as in the proof of (5.20), we can show that for \( \eta > 16 \), with \( \beta, k_n \) chosen above,

\[
n \Pi_{k_n}^{-1} \sum_{u \in T_{k_n}} 1_{\{|S_u| > k_n\}} \xrightarrow{n \to \infty} 0 \quad \text{and} \quad \Pi_{k_n}^{-1} \sum_{u \in T_{k_n}} S_u^2 1_{\{|S_u| \leq k_n\}} \xrightarrow{n \to \infty} 0 \quad \text{a.s. (6.14)}
\]

Therefore as \( n \) tends to infinity, we have a.s.

\[
n \Lambda_{2,n2} = n \frac{1}{2(s_n^2 - s_{k_n}^2)^{1/2}} \left( -|A| \Pi_{k_n}^{-1} \sum_{u \in T_{k_n}} (S_u^2 - s_{k_n}^2) 1_{\{|S_u| \leq k_n\}} + 2 \int_A x dx \Pi_{k_n}^{-1} \sum_{u \in T_{k_n}} S_u 1_{\{|S_u| \leq k_n\}} + o(1) \right)
\]

\[
= \frac{n}{2(s_n^2 - s_{k_n}^2)} \left( -N_{2,k_n} |A| + 2|A| \bar{\tau}_A N_{1,k_n} + o(1) \right)
\]

\[
= (2 \mathbb{E} \sigma_0^2)^{-1} (-V_2 + 2 \bar{\tau}_A V_1) |A| + o(1),
\]

which proves (6.7).

To prove (6.8), we observe that

\[
\Lambda_{2,n3} = \frac{\kappa_{1,n} s_n}{(s_n^2 - s_{k_n}^2)^{1/2}} \Pi_{k_n}^{-1} \sum_{u \in T_{k_n}} 1_{\{|S_u| \leq k_n\}} \int_A \left( \frac{(x - S_u)^3}{(s_n^2 - s_{k_n}^2)^{3/2}} - \frac{3(x - S_u)}{(s_n^2 - s_{k_n}^2)^{1/2}} \right) e^{-\frac{(x - S_u)^2}{(s_n^2 - s_{k_n}^2)\hat{L}_k}} dx
\]

\[
= \Lambda_{2,n31} + \Lambda_{2,n32} + \Lambda_{2,n33} + \Lambda_{2,n34}.
\]
Combining (6.14), (6.15), (6.16) and (6.17), we deduce (6.9) and (6.10). Whence (6.11) follows.

By Proposition 5.6, under our assumption, we have

It is clear that

By the choice of \( \beta \), we see that

Finally because

\[ | x | \leq n \kappa, \quad \text{if } n \to \infty, \]

so the required result (6.3) follows from (6.6) – (6.12).

| 1 | \{ | x | \leq k_n \} \int_A \frac{3(x - S_n)}{(s_n^2 - s_n^2)^{1/2}} \left( 1 - e^{- \frac{(x - S_n)^2}{s_n^2}} \right) dx; \\
| 1 | \{ | x | > k_n \} \int_A \frac{3(x - S_n)}{(s_n^2 - s_n^2)^{1/2}} dx; \\
| 1 | \{ | x | > k_n \} \int_A \frac{3(x - S_n)}{(s_n^2 - s_n^2)^{1/2}} dx.

It is clear that

whence (6.3) follows.

By the Birkhoff ergodic theorem, we see that

\[ n | A_{2, n, 31} | \leq \frac{n \kappa_1 s_n}{(s_n^2 - s_n^2)^{1/2}} \int_A (| x | + k_n)^3 dx W_{k_n} \xrightarrow{n \to \infty} 0 \ a.s., \]

\[ n | A_{2, n, 32} | \leq \frac{n \kappa_1 s_n}{(s_n^2 - s_n^2)^{1/2}} \int_A \frac{3}{2} (| x | + k_n)^3 dx W_{k_n} \xrightarrow{n \to \infty} 0 \ a.s. \quad (1 - e^{-x} \leq x, \text{ for } x > 0), \]

\[ n | A_{2, n, 33} | = \frac{n (s_2 - s_2)}{(s_n^2 - s_n^2)^{1/2}} 3 | A | \Pi_{k_n} (N_1, k_n - \mathbf{F}_A W_{k_n}) \xrightarrow{n \to \infty} \frac{1}{2} \mathbb{E} \sigma_0^3 (\mathbb{E} \sigma_0)^2 - (V_1 - \mathbf{F}_A W) \cdot | A | \ a.s., \]

\[ n | A_{2, n, 34} | \leq \frac{3n \kappa_1 s_n}{(s_n^2 - s_n^2)^{1/2}} \left( \int_A | x | dx \Pi_{k_n} \sum_{u \in T_{k_n}} 1_{\{ | x | > k_n \}} + | A | \Pi_{k_n} \sum_{u \in T_{k_n}} | S_u | 1_{\{ | S_u | > k_n \}} \right) \xrightarrow{n \to \infty} 0 \ a.s. \quad (\text{by } 5.20), \]

whence (6.8) follows.

By the Birkhoff ergodic theorem, we see that

\[ \lim_{n \to \infty} \frac{n \kappa_2 s_n}{(s_n^2 - s_n^2)^{1/2}} = \frac{(\mathbb{E} \sigma_0^3)^2}{72(\mathbb{E} \sigma_0^{10})^3}, \quad \lim_{n \to \infty} \frac{n \kappa_3 s_n}{(s_n^2 - s_n^2)^{1/2}} = \frac{\mathbb{E} \sigma_0^3 - 3(\mathbb{E} \sigma_0^{10})^2}{24(\mathbb{E} \sigma_0^{10})^2}, \]

(6.15)

Elementary calculus shows that, uniformly for \( | y | \leq k_n \)

\[ \text{if } \nu \geq 1, \quad \int_A \left( \frac{x - y}{(s_n^2 - s_n^2)^{1/2}} \right)^\nu \exp \left( - \frac{(x - y)^2}{2(s_n^2 - s_n^2)} \right) dx \xrightarrow{n \to \infty} 0 \ a.s., \]

\[ \text{and} \quad \int_A \exp \left( - \frac{(x - y)^2}{2(s_n^2 - s_n^2)} \right) dx \xrightarrow{n \to \infty} 1 \ a.s., \]

(6.16) (6.17)

Combining (6.14), (6.15), (6.16) and (6.17), we deduce (6.9) and (6.10).

By the Birkhoff ergodic theorem and the definition of \( H_n(x) \) and \( \phi(x) \), we see that

\[ \sup_{x \in \mathbb{R}} | R_n'(x) | = O \left( \frac{1}{n^{3/2}} \right), \]

whence (6.11) follows.

Finally because \( | A_{2, n, 7} | \) is bounded by \( K \epsilon \cdot \Pi_{k_n} \sum_{u \in T_{k_n}} 1_{\{ | S_u | > k_n \}} \), (6.14) implies (6.12).

So the required result (6.3) follows from (6.6) – (6.12). \( \blacksquare \)

**Proof of Lemma 6.3** By Proposition 5.6, under our assumption, we have

\[ W - W_n = o(n^{-\lambda}) \quad a.s. \]

By the choice of \( \beta \) and \( k_n \), we see that

\[ n^{\frac{\beta}{2}} (W - W_k_n) = o(n^{-\lambda \beta}) \xrightarrow{n \to \infty} 0. \]
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