

# Invariance principles for local times at the maximum of random walks and Lévy processes.

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## Abstract

We prove that when a sequence of Lévy processes  $X^{(n)}$  or a normed sequence of random walks  $S^{(n)}$  converges a.s. on the Skorokhod space toward a Lévy process  $X$ , the sequence  $L^{(n)}$  of local times at the supremum of  $X^{(n)}$  converges uniformly on compact sets in probability toward the local time at the supremum of  $X$ . A consequence of this result is that the sequence of (quadrivariate) ladder processes (both ascending and descending) converges jointly in law towards the ladder processes of  $X$ . As an application, we show that in general, the sequence  $S^{(n)}$  conditioned to stay positive converges weakly, jointly with its local time at the future minimum, towards the corresponding functional for the limiting process  $X$ . From this we deduce an invariance principle for the meander which extends known results for the case of attraction to a stable law.

KEY WORDS AND PHRASES: Invariance principle, local time at the supremum, ladder processes, processes conditioned to stay positive, meander.

MSC 2000 subject classifications: 60F17, (60J55, 60G17, 60J15).

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## 1 Introduction

It is well-known that if a sequence of Lévy processes  $X^{(n)}$  converges a.s. on the Skorokhod space to a limiting Lévy process  $X$ , then the corresponding sequence of local times at a fixed level of  $X^{(n)}$  do not necessarily converge to the local time of  $X$ , whatever the definition the local times of  $X^{(n)}$  is: occupation time, crossing times,... However, in fluctuation theory of Lévy processes, it is the local times at extrema which play a

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major rôle, not the local times at fixed levels, so a natural and important question is whether these local times converge. A similar question can be posed about the local times at extrema of a sequence of normed random walks which converge to a Lévy process.

To our knowledge, the only results known in this vein can be found in Greenwood, Omey and Teugels [17] and in Duquesne and Le Gall [15]. The first paper deals with the "classical" case where  $S^{(n)}$  is got by norming a fixed random walk  $S$ , the assumption being that for some norming sequence  $c_n$ ,  $(S_{[nt]}/c_n, t \geq 0)$  converges in law to  $X$ , necessarily stable, and the conclusion is that a normed version of the bivariate ladder process of  $S$  converges in law to the bivariate ladder process of  $X$ . One easily derives that a normed version of the local time at the maximum of  $S$  converges in law to the local time at the supremum of  $X$ . (A different proof of this result and a converse result can be found in Doney and Greenwood [13].)

The second paper considers a more general scenario where each  $S^{(n)}$  is got by norming a different random walk, but restricts itself to the case that each random walk is downwards skip-free, so that the limiting Lévy process is automatically spectrally positive. (This is because the result, Theorem 2.2.1 of [15], is a tool for the study of the height process of the sequence of Galton-Watson processes related to  $S^{(n)}$ .) Again convergence in law is assumed, and the conclusion is again convergence in law of a normed version of the local time.

In this paper, we give three major extensions of these results. In Theorem 1 we show that whenever  $S^{(n)}$  converges in law to  $X$ , then a normed version of the bivariate ladder process of  $S$  converges in law to the bivariate ladder process of  $X$ . Again, we can deduce that a normed version of the local time at the maximum of  $S$  converges in law to the local time at the supremum of  $X$ . (Our only assumption on  $X$  is that it has a continuous local time  $L$  at the supremum, but if this were to fail a similar result could be formulated.) Next, in Theorem 2, we show that if the assumption is strengthened to a.s. convergence, then the normed sequence of local times converge to  $L$  in probability uniformly on compacts. This result allows us to deduce, in Theorem 3, an analogous result when a sequence  $X^{(n)}$  of Lévy processes converges a.s. to  $X$ . (We stress that for such a result to hold, we have to remove the ambiguity inherent in the definition of local times for Lévy processes by insisting on a standard normalisation for the local times of  $X^{(n)}$  and  $X$ : see (2.1).) An important corollary of these results is the convergence in law of the quadrivariate process of upgoing and downgoing ladder processes: see Corollary 2.

In the last section, we show that if a sequence  $(S_{[nt]}^{(n)}, t \geq 0)$  of continuous time random walks converges in law toward a Lévy process  $X$ , then the sequence of these processes conditioned to stay positive on the whole time interval  $[0, \infty)$  converges in law toward  $X$  conditioned to stay positive. We illustrate the usefulness of the results of Section 3 by showing that this convergence also holds jointly with the local time at the future infimum. Finally, we obtain an invariance principle for the meander, i.e. we show that the sequence  $(S_{[nt]}^{(n)}, t \geq 0)$  conditioned to stay positive over  $[0, 1]$  converges in law towards  $X$  conditioned to stay positive over  $[0, 1]$ . These results extend the "classical" case studied by Bolthausen [5], Doney [10] and Caravenna and Chaumont [6].

## 2 Preliminaries

Let  $X$  be any Lévy process for which 0 is regular for the open half-line  $(0, \infty)$ . Then 0 is also regular for itself for the reflected process  $R := M - X$ , where  $M_t = \sup_{0 \leq s \leq t} X_s$ , and so there exists a continuous local time for  $R$  at 0. This local time  $L$  is only specified up to multiplication by a constant, but we will assume throughout that its normalization is fixed by the requirement that

$$\mathbb{E} \left( \int_0^\infty e^{-t} dL_t \right) = 1. \quad (2.1)$$

The process  $L$  will be called the *local time of  $X$  at its supremum*. It satisfies  $L_\infty < \infty$ , a.s. if and only if  $X$  drifts to  $-\infty$ .

Let us introduce the ascending bivariate ladder process  $(\tau, H)$ : the ladder time process is  $\tau_t = \inf\{s : L_s > t\}$ , with the convention that  $\inf \emptyset = +\infty$ , and the ladder height process is  $H_t = X(\tau_t)$ , if  $\tau_t < \infty$  and  $H_t = \infty$ , if  $\tau_t = \infty$ . The process  $(\tau, H)$  is a (possibly killed) bivariate subordinator whose Laplace exponent is given by Fridstedt's formula:

$$\kappa(\alpha, \beta) = -\log \mathbb{E} \left( e^{-(\alpha\tau_1 + \beta H_1)} \right) = \exp \left( \int_0^\infty \int_0^\infty (e^{-t} - e^{-\alpha t - \beta x}) t^{-1} \mathbb{P}\{X_t \in dx\} dt \right),$$

for  $\alpha, \beta \geq 0$ , with the convention that  $e^{-\infty} = 0$ . See Chapter VI of [2] or Chapter 4 of [11]: note that (2.1) squares with  $\kappa(1, 0) = 1$ . We write  $q^H$ ,  $\delta^H$  and  $\pi^H$  respectively for the killing rate, the drift coefficient and the Lévy measure of  $H$ . In particular, the Laplace exponent of  $H$  is given by

$$\kappa(0, \beta) = q^H + \delta^H \beta + \int_0^\infty (1 - e^{-\beta x}) \pi^H(dx).$$

Note that our assumptions imply that if  $\delta^H = 0$ , then  $\pi^H(0, \infty) = \infty$ , since otherwise 0 would be irregular for the open half-line  $(0, \infty)$  for  $X$ .

A random walk is a discrete time process  $S = (S_k, k = 0, 1, \dots)$  such that  $S_0 = 0$  and, for  $k \geq 1$ ,  $S_k = \sum_1^k Y_r$ , where  $Y_1, Y_2, \dots$  are independent and identically distributed. We define the local time at its maximum of any random walk  $S$  by  $\Lambda_0 = 0$  and for all  $k \geq 1$ ,

$$\Lambda_k = \#\{j \in \{1, \dots, k\} : S_j > \max_{i \leq j-1} S_i\}. \quad (2.2)$$

As in continuous time,  $\Lambda_\infty < \infty$ , a.s. if and only if  $S$  drifts to  $-\infty$ . We also introduce the strict ascending ladder processes for  $S$ . The strict ascending ladder time process  $T$  of  $S$  is defined by  $T_0 = 0$  and for all  $k \geq 0$ ,

$$T_{k+1} = \min\{j > T_k : S_j > S_{T_k}\},$$

with  $\min \emptyset = \infty$ . The strict ascending ladder height process is given by

$$H_k = S(T_k), \text{ if } T_k < \infty \text{ and } H_k = \infty, \text{ if } T_k = \infty.$$

Note that  $T$  is the inverse of  $\Lambda$ , i.e.  $\Lambda_{T_k} = k$ , for all  $k \leq \Lambda_\infty$ . Let us mention that all the results of this paper are still valid if in the statements one replaces the *strict* ladder process and the *strict* local time by the *weak* ladder process, i.e.  $T_0 = 0$  and for all  $k \geq 0$ ,  $T_{k+1} = \min\{j > T_k : S_j \geq S_{T_k}\}$  and the *weak* local time, i.e.  $\Lambda_k = \#\{j \in \{1, \dots, k\} : S_j \geq \max_{i \leq j-1} S_i\}$ .

In the next sections,  $S^{(n)}$  will denote a random walk whose distribution can depend on  $n$  and  $\Lambda^{(n)}, T^{(n)}$  and  $H^{(n)}$  will denote the corresponding local time, ladder time, and ladder height process. We will say that the sequence of random walks  $S^{(n)}$  converges in law (resp. almost surely) toward the Lévy process  $X$  if the sequence of continuous time processes  $(S_{[nt]}^{(n)}, t \geq 0)$  converges in law (resp. almost surely) toward  $X$  on the Skorokhod space  $\mathcal{D}([0, \infty))$  of càdlàg paths. Note that according to Theorem 2.7 of Skorokhod [18], if the process  $(S_{[nt]}^{(n)}, t \geq 0)$  converges in the sense of finite dimensional distributions, then it converges in law. If a stochastic process  $Y$  has lifetime  $\zeta$  and if the  $Y^{(n)}$ 's have lifetimes  $\zeta^{(n)}$ , then we say that the sequence  $Y^{(n)}$  converges toward  $Y$  in some sense if the sequence of processes  $(Y_t^{(n)} \mathbb{1}_{\{t < \zeta^{(n)}\}} + Y_{\zeta^{(n)}-}^{(n)} \mathbb{1}_{\{t \geq \zeta^{(n)}\}}, t \geq 0)$  converges toward the process  $(Y_t \mathbb{1}_{\{t < \zeta\}} + Y_{\zeta-} \mathbb{1}_{\{t \geq \zeta\}}, t \geq 0)$  in this sense on the space  $\mathcal{D}([0, \infty))$ . Note also that convergence in law (resp. almost sure convergence) of stochastic processes on the space  $\mathcal{D}([0, \infty))$  is equivalent to convergence in law (resp. almost sure convergence) on the space  $\mathcal{D}([0, t])$  for all  $t > 0$ , see Theorem 16.7 in [4]. Convergence in law or almost sure convergence of a sequence of stochastic processes  $Y^{(n)}$  toward  $Y$  will be denoted respectively by  $Y^{(n)} \xrightarrow{\text{(law)}} Y$  and  $Y^{(n)} \xrightarrow{\text{(a.s.)}} Y$ .

### 3 Main results

The following result extends Theorem 3.2 in [17] and is the random walk counterpart of lemme 3.4.2, p.54 in [21].

**Theorem 1.** *Let  $X$  be any Lévy process such that 0 is regular for the open half line  $(0, \infty)$  and assume that some sequence of random walks  $S^{(n)}$  converges in law toward  $X$ . Then we have the following convergence in law:*

$$\left[ \left( n^{-1} T_{[a_n t]}^{(n)}, H_{[a_n t]}^{(n)} \right), t \geq 0 \right] \xrightarrow{\text{(law)}} (\tau, H),$$

as  $n \rightarrow \infty$ , where

$$a_n = \exp \left( \sum_{k=1}^{\infty} \frac{1}{k} e^{-k/n} \mathbb{P}(S_k^{(n)} > 0) \right). \quad (3.3)$$

**Remark 1.** *Under the hypothesis of Theorem 1, i.e. when 0 is regular for  $(0, \infty)$ , Rogozin's criterion asserts that  $\int_0^1 t^{-1} \mathbb{P}(X_t > 0) dt = \infty$ , see [2], Proposition VI.3.11. It follows from this result and weak convergence of  $S^{(n)}$  toward  $X$  that in Theorem 1, we necessarily have  $\lim_{n \rightarrow \infty} a_n = \infty$ .*

**Remark 2.** The sequence  $S^{(n)}$  could also be written in the form

$$S^{(n)} = \frac{1}{c_n} \tilde{S}^{(n)}$$

and then we would recover the standard formulation for triangular arrays. But in this case, using obvious notations, the result of Theorem 1 would become:

$$\left[ \left( n^{-1} \tilde{T}_{[a_n t]}^{(n)}, c_n^{-1} \tilde{H}_{[a_n t]}^{(n)} \right), t \geq 0 \right] \xrightarrow{(\text{law})} (\tau, H),$$

which reduces to Theorem 3.2 of [17] if the distribution of  $\tilde{S}^{(n)}$  does not depend on  $n$ .

*Proof.* We first recall Fristedt's formula for random walks, see [11], p.26. For every  $\alpha > 0$  and  $\beta > 0$ ,

$$1 - \mathbb{E} \left( e^{-\alpha T_1^{(n)} - \beta H_1^{(n)}} \right) = \exp \left( - \sum_{k=1}^{\infty} \frac{e^{-\alpha k}}{k} \mathbb{E} \left( e^{-\beta S_k^{(n)}} : S_k^{(n)} > 0 \right) \right).$$

From this formula, we have

$$\begin{aligned} \mathbb{E} \left( e^{-\alpha n^{-1} T_{[a_n]}^{(n)} - \beta H_{[a_n]}^{(n)}} \right) &= \mathbb{E} \left( e^{-\alpha n^{-1} T_1^{(n)} - \beta H_1^{(n)}} \right)^{[a_n]} \\ &= \left( 1 - \exp \left[ - \sum_{k=1}^{\infty} \frac{1}{k} e^{-\alpha n^{-1} k} \mathbb{E} \left( e^{-\beta S_k^{(n)}} : S_k^{(n)} > 0 \right) \right] \right)^{[a_n]} \\ &= \left( 1 - \exp \left[ - \int_1^{\infty} \frac{1}{[s]} e^{-\alpha n^{-1} [s]} \mathbb{E} \left( e^{-\beta S_{[s]}^{(n)}} : S_{[s]}^{(n)} > 0 \right) ds \right] \right)^{[a_n]} \\ &= \left( 1 - \exp \left[ - \int_{1/n}^{\infty} \frac{n}{[nt]} e^{-\alpha n^{-1} [nt]} \mathbb{E} \left( e^{-\beta S_{[nt]}^{(n)}} : S_{[nt]}^{(n)} > 0 \right) dt \right] \right)^{[a_n]} \end{aligned}$$

From the assumptions and Rogozin's criterion recalled in Remark 1, we have

$$\begin{aligned} \lim_{n \rightarrow +\infty} \int_{1/n}^{\infty} \frac{n}{[nt]} e^{-\alpha n^{-1} [nt]} \mathbb{E} \left( e^{-\beta S_{[nt]}^{(n)}} : S_{[nt]}^{(n)} > 0 \right) dt &= \int_0^{\infty} \frac{e^{-\alpha t}}{t} \mathbb{E} \left( e^{-\beta X_t} : X_t > 0 \right) dt \\ &= \infty, \end{aligned}$$

hence

$$- \log \mathbb{E} \left( e^{-\alpha n^{-1} T_{[a_n]}^{(n)} - \beta H_{[a_n]}^{(n)}} \right) \sim [a_n] \exp - \int_{1/n}^{\infty} \frac{n}{[nt]} e^{-\alpha n^{-1} [nt]} \mathbb{E} \left( e^{-\beta S_{[nt]}^{(n)}} : S_{[nt]}^{(n)} > 0 \right) dt.$$

From the expression of  $a_n$  which is given in the statement of this theorem, the right and side of the above expression is

$$\begin{aligned} &\exp \left( - \int_{1/n}^{\infty} \frac{n}{[nt]} e^{-\alpha n^{-1} [nt]} \mathbb{E} \left( e^{-\beta S_{[nt]}^{(n)}} : S_{[nt]}^{(n)} > 0 \right) dt + \sum_{k=1}^{\infty} \frac{1}{k} e^{-k/n} \mathbb{P}(S_k^{(n)} > 0) \right) \\ &= \exp \int_{1/n}^{\infty} \frac{n}{[nt]} \mathbb{E} \left( e^{-n^{-1} [nt]} - e^{-\alpha n^{-1} [nt] - \beta S_{[nt]}^{(n)}} : S_{[nt]}^{(n)} > 0 \right) dt, \end{aligned}$$

which converges as  $n$  goes to  $\infty$  toward

$$\exp \int_0^\infty \frac{1}{t} \mathbb{E} (e^{-t} - e^{-\alpha t - \beta X_t} : X_t > 0) dt = \kappa(\alpha, \beta),$$

since  $X_t \neq 0$ , a.s. It is clear that the process  $X$  drifts to  $-\infty$  if and only if  $S^{(n)}$  drifts to  $-\infty$  for all  $n$  sufficiently large. Suppose first that  $X$  does not drift to  $-\infty$ . The above convergence proves that the sequence  $\left[ \left( n^{-1} T_{[a_n t]}^{(n)}, H_{[a_n t]}^{(n)} \right), t \geq 0 \right]$  converges in the sense of finite dimensional distributions toward  $(\tau, H)$ . We conclude that it converges weakly by applying Theorem 2.7 of Skorokhod [18].

If  $X$  drifts to  $-\infty$ , then the sequence  $(T^{(n)}, H^{(n)})$  and the process  $(\tau, H)$  are obtained respectively from a sequence of bivariate renewal processes, say  $(\bar{T}^{(n)}, \bar{H}^{(n)})$ , and a bivariate subordinator, say  $(\bar{\tau}, \bar{H})$ , all with infinite lifetime, by killing them respectively at independent random times. It readily follows from the convergence of the Laplace exponents which is proved above that

$$\left[ \left( n^{-1} \bar{T}_{[a_n t]}^{(n)}, \bar{H}_{[a_n t]}^{(n)} \right), t \geq 0 \right] \xrightarrow{(\text{law})} (\bar{\tau}, \bar{H})$$

and that the independent killing times of  $\left( n^{-1} \bar{T}_{[a_n t]}^{(n)}, \bar{H}_{[a_n t]}^{(n)} \right)$  converge in law to the one of  $(\bar{\tau}, \bar{H})$ . As a straightforward consequence, the sequence of killed processes  $\left( n^{-1} T_{[a_n t]}^{(n)}, H_{[a_n t]}^{(n)} \right)$  converges to  $(\tau, H)$ , in the sense which is defined in the preliminary section.  $\square$

Since  $\tau$  is an increasing process, we derive from Theorem 1 and Theorem 7.2 of [22] that when  $S^{(n)}$  converges in law to  $X$ , the renormed process  $\left( a_n^{-1} \Lambda_{[nt]}^{(n)}, t \geq 0 \right)$  converges in law to  $(L_t, t \geq 0)$ . We actually establish the following stronger result.

**Theorem 2.** *Let  $X$  be as in Theorem 1, and assume that*

$$(S_{[nt]}^{(n)}, t \geq 0) \xrightarrow{(\text{a.s.})} (X_t, t \geq 0). \quad (3.4)$$

*Let  $\Lambda^{(n)}$  be the local time at its maximum of  $S^{(n)}$ . Then a normed version of  $\Lambda^{(n)}$  converges uniformly in probability on compact sets towards  $L$ . More specifically, for all  $t \geq 0$  and  $\varepsilon > 0$ ,*

$$\lim_{n \rightarrow \infty} \mathbb{P} \left( \sup_{s \in [0, t]} |a_n^{-1} \Lambda_{[ns]}^{(n)} - L_s| > \varepsilon \right) = 0, \quad (3.5)$$

where  $a_n$  is defined by expression (3.3).

The proof of this theorem requires the two following lemmas. We denote by  $\pi^\tau$  and  $\pi^H$  the Lévy measures of  $\tau$  and  $H$ .

**Lemma 1.** *The Lévy measure  $\pi^H$  has no atom whenever  $X$  is not a compound Poisson process. If moreover 0 is regular for  $(-\infty, 0)$ , then the Lévy measure  $\pi^\tau$  has a density with respect to the Lebesgue measure.*

*Proof.* Let us introduce some notation: we call  $(\hat{\tau}, \hat{H})$  the ladder process associated to  $\hat{X} = -X$  and we call  $\hat{U}$  the renewal measure of this bivariate subordinator. The renewal measure of  $\hat{H}$  is denoted by  $U^{\hat{H}}$  and the Lévy measure of  $X$  is denoted by  $\Pi$ .

From Vigon's équation amicale inversée, see Vigon [20] or [21], p.71, we have for all  $x > 0$  and  $0 < h < x$ ,

$$\pi^H(x-h, x] = \int_0^\infty U^{\hat{H}}(dy) \Pi(x+y-h, x+y].$$

By monotone convergence, we get

$$\pi^H(\{x\}) = \int_0^\infty U^{\hat{H}}(dy) \Pi(\{x+y\}),$$

and this is zero because there are countably many atoms of  $\Pi$ , and  $U^{\hat{H}}$  is diffuse when  $X$  is not a compound Poisson process, see Proposition 1.15, Bertoin [2]. This proves the first assertion.

Corollary 6, page 50 of [11] asserts that whenever  $X$  is not a compound Poisson process, the Lévy measure  $\pi$  of  $(\tau, H)$  is given by

$$\pi(dt, dh) = \int_{[0, \infty)} \hat{U}(dt, dx) \Pi(dh+x).$$

Then from Theorem 5 of [1], under the additional assumption that 0 is regular for  $(-\infty, 0)$ , we have for all  $t > 0$ ,

$$q_t(dx) dt = c \hat{U}(dt, dx),$$

where  $c$  is a constant and  $q_t(dx)$  is the entrance law of the measure of the excursions away from 0 of the process  $X$  reflected at its supremum. The second assertion is proved.  $\square$

The second lemma follows from Theorem 1, Lemma 1 and a standard criterion on convergence of sums of independent random variables, see for instance [16], so we omit its proof.

**Lemma 2.** *Define, for  $0 < a < b \leq \infty$ ,  $0 < c < \infty$  and  $n \geq 1$ ,*

$$\begin{aligned} \pi_n^{a,b} &= \mathbb{P}(H_1^{(n)} \in (a, b]), \quad m_1^{n,a} = \mathbb{E}(H_1^{(n)} : H_1^{(n)} \leq a), \quad m_2^{n,a} = \mathbb{E}((H_1^{(n)})^2 : H_1^{(n)} \leq a) \\ \nu_n^c &= \mathbb{P}(n^{-1}T_1^{(n)} > c). \end{aligned}$$

*Under the assumptions of Theorem 1, the following asymptotics hold:*

$$\begin{aligned} \lim_{n \rightarrow \infty} a_n \pi_n^{a,b} &= \pi^H(a, b], \quad \lim_{n \rightarrow \infty} a_n m_1^{n,a} = \delta^H + \int_0^a x \pi^H(dx), \\ \text{and } \lim_{n \rightarrow \infty} a_n m_2^{n,a} &= \int_0^a x^2 \pi^H(dx). \end{aligned}$$

*If moreover 0 is regular for  $(-\infty, 0)$ , then*

$$\lim_{n \rightarrow +\infty} a_n \nu_n^c = \pi^\tau(c, \infty).$$

*Proof of Theorem 2.* We first observe that since  $(a_n^{-1}\Lambda_{[nt]}^{(n)}, t \geq 0)$  is a sequence of nondecreasing processes which converges toward the continuous process  $L$ , in order to prove the uniform convergence in (3.5), it suffices to establish pointwise convergence in probability, i.e. for all  $t \geq 0$ ,

$$\lim_{n \rightarrow \infty} \mathbb{P} \left( |a_n^{-1}\Lambda_{[nt]}^{(n)} - L_t| > \varepsilon \right) = 0. \quad (3.6)$$

We first treat the case where  $\pi^H[0, \infty) < \infty$ . Since we assumed that 0 is regular for  $(0, \infty)$ , we necessarily have  $\delta^H > 0$  and then

$$\delta^H L_t = \lambda(M_s : s \leq t), \quad (3.7)$$

where  $\lambda$  is the Lebesgue measure. Let  $M_k^{(n)} = \max_{0 \leq j \leq k} S_j^{(n)}$ ,  $k \geq 0$ , and for  $a > 0$ , define the truncated past maxima of  $S^{(n)}$  and  $X$  respectively as

$$M_{[nt]}^{n,a} = M_{[nt]}^{(n)} - \sum_{s \in [0,t]} \Delta M_s^{(n)} \mathbb{1}_{\{\Delta M_s^{(n)} > a\}} \quad \text{and} \quad M_t^a = M_t - \sum_{s \in [0,t]} \Delta M_s \mathbb{1}_{\{\Delta M_s > a\}}.$$

Since in this case,  $M$  has only a finite number of jumps in each interval  $[0, t]$ , we have the almost sure convergence

$$\lim_{n \rightarrow \infty} M_{[nt]}^{n,a} = M_t^a, \quad \text{a.s.} \quad (3.8)$$

Moreover for the same reason and (3.7), for all  $a$  small enough we have

$$\delta^H L_t = M_t^a. \quad (3.9)$$

Then from (3.8) and (3.9), it is enough to prove that

$$\lim_{a \downarrow 0} \limsup_{n \rightarrow \infty} \mathbb{P} \left( |M_{[nt]}^{n,a} - \frac{\delta^H}{a_n} \Lambda_{[nt]}^{(n)}| > \varepsilon \right) = 0. \quad (3.10)$$

Note that for all  $k$ ,  $M_k^{n,a}(T_k^{(n)})$  is the sum of  $k$  i.i.d. random variables with mean  $m_1^{n,a}$  and second moment  $m_2^{n,a}$  defined in Lemma 2. Hence for all  $K > 0$  and  $\varepsilon > 0$ , from Kolmogorov's inequality,

$$\mathbb{P} \left( \max_{0 \leq j \leq T_{[Ka_n]}^{(n)}} |M_j^{n,a} - m_1^{n,a} \Lambda_j^{(n)}| > \varepsilon \right) \leq \frac{K a_n m_2^{n,a}}{\varepsilon^2}.$$

Now write the inequality

$$\begin{aligned} \mathbb{P} \left( \max_{0 \leq j \leq T_{[Ka_n]}^{(n)}} |M_j^{n,a} - \frac{\delta^H}{a_n} \Lambda_j^{(n)}| > 2\varepsilon \right) &\leq \\ &\mathbb{P} \left( \max_{0 \leq j \leq T_{[Ka_n]}^{(n)}} \left| \frac{\delta^H}{a_n} \Lambda_j^{(n)} - m_1^{n,a} \Lambda_j^{(n)} \right| > \varepsilon \right) + \frac{K a_n m_2^{n,a}}{\varepsilon^2}. \end{aligned}$$

Then observe that the first term of the right hand side is nothing but  $\mathbb{I}_{\{|K\delta^H - m_1^{n,a} K a_n| > \varepsilon\}}$  and from Lemma 2,  $\lim_{a \rightarrow 0} \lim_{n \rightarrow \infty} \mathbb{I}_{\{|K\delta^H - m_1^{n,a} K a_n| > \varepsilon\}} = 0$ . From the same lemma, we have for the second term  $\lim_{a \rightarrow 0} \lim_{n \rightarrow \infty} a_n m_2^{n,a} = 0$ . Hence

$$\lim_{a \rightarrow 0} \lim_{n \rightarrow \infty} \mathbb{P} \left( \max_{0 \leq j \leq T_{[K a_n]}^{(n)}} \left| M_j^{n,a} - \frac{\delta^H}{a_n} \Lambda_j^{(n)} \right| > 2\varepsilon \right) = 0.$$

Finally, write

$$\mathbb{P} \left( \left| M_n^{n,a} - \frac{\delta^H}{a_n} \Lambda_n^{(n)} \right| > \varepsilon \right) \leq \mathbb{P} \left( \max_{0 \leq j \leq T_{[K a_n]}^{(n)}} \left| M_j^{n,a} - \frac{\delta^H}{a_n} \Lambda_j^{(n)} \right| > \varepsilon \right) + \mathbb{P}(T_{[K a_n]}^{(n)} < n).$$

But from Theorem 1, we have  $\lim_{K \rightarrow +\infty} \lim_{n \rightarrow \infty} \mathbb{P}(T_{[K a_n]}^{(n)} < n) = 0$  and (3.10) follows for  $t = 1$ . (This proof can readily be extended to any time  $t \geq 0$ .) So we have proved (3.6) in the case  $\pi^H[0, \infty) < \infty$ .

Now let us suppose that  $\pi^H[0, \infty) = \infty$ , and for  $0 < a < b < \infty$ , define the following approximations of the local times  $L$  and  $\Lambda^{(n)}$ :

$$L_t^{a,b} = \#\{s \leq t : \Delta M_s \in (a, b]\} \quad \text{and} \quad \Lambda_k^{n,a,b} = \#\{j \leq k : M_j^{(n)} + a < S_{j+1}^{(n)} \leq M_j^{(n)} + b\}.$$

Since  $L_t^{a,b}$  is a finite integer, it readily follows from the almost sure convergence of  $S_{[n \cdot]}^{(n)}$  toward  $X$  that

$$\lim_{n \rightarrow +\infty} \Lambda_{[nt]}^{n,a,b} = L_t^{a,b}, \quad \text{a.s.} \quad (3.11)$$

On the other hand, observe that  $(L_{\tau_t}^{a,b}, t \geq 0)$  is a Poisson process with intensity  $\pi^H(a, b]$ . Moreover from the hypothesis, we have  $\lim_{a \downarrow 0} \pi^H(a, b] = +\infty$ . So it follows from the law of large numbers that for all  $t > 0$ ,  $\lim_{a \rightarrow 0} \pi^H(a, b]^{-1} L_{\tau_t}^{a,b} = t$ , a.s. From monotonicity, this convergence can be strengthened to uniform convergence: for all  $u > 0$ ,

$$\lim_{a \rightarrow 0} \sup_{t \in [0, u]} |\pi^H(a, b]^{-1} L_{\tau_t}^{a,b} - t| = 0, \quad \text{a.s.}$$

Fix  $\varepsilon > 0$ . For all  $\eta > 0$ , we can chose  $u$  sufficiently large that  $\mathbb{P}(\tau_u < 1) < \eta/2$  and  $a$  sufficiently small that  $\mathbb{P}(\sup_{t \in [0, u]} |\pi^H(a, b]^{-1} L_{\tau_t}^{a,b} - t| > \varepsilon) < \eta/2$ . Then the inequality

$$\mathbb{P} \left( \sup_{t \in [0, 1]} |\pi^H(a, b]^{-1} L_t^{a,b} - L_t| > \varepsilon \right) \leq \mathbb{P} \left( \sup_{t \in [0, \tau_u]} |\pi^H(a, b]^{-1} L_t^{a,b} - L_t| > \varepsilon \right) + \mathbb{P}(\tau_u < 1)$$

allows us to obtain

$$\lim_{a \rightarrow 0} \mathbb{P} \left( \sup_{t \in [0, 1]} |\pi^H(a, b]^{-1} L_t^{a,b} - L_t| > \varepsilon \right) = 0. \quad (3.12)$$

Note that for all  $k$ ,  $\Lambda_k^{n,a,b}(T_k^{(n)})$  is the sum of  $k$  independent Bernoulli random variables with mean  $\pi_n^{a,b}$  defined in Lemma 2. Hence for all  $K > 0$ , from Kolmogorov's inequality,

$$\mathbb{P} \left( \max_{0 \leq j \leq T_{[K a_n]}^{(n)}} \frac{1}{\pi^H(a, b]} \left| \Lambda_j^{a,b,n} - \pi_n^{a,b} \Lambda_j^{(n)} \right| > \varepsilon \right) \leq \frac{K a_n \pi_n^{a,b}}{\pi^H(a, b]^2 \varepsilon^2}.$$

Now write the inequality

$$\begin{aligned} & \mathbb{P} \left( \max_{0 \leq j \leq T_{[Ka_n]}^{(n)}} \left| \frac{1}{\pi^H(a, b)} \Lambda_j^{a, b, n} - \frac{1}{a_n} \Lambda_j^{(n)} \right| > 2\varepsilon \right) \leq \\ & \mathbb{P} \left( \max_{0 \leq j \leq T_{[Ka_n]}^{(n)}} \left| \frac{1}{a_n} \Lambda_j^{(n)} - \frac{\pi_n^{a, b}}{\pi^H(a, b)} \Lambda_j^{(n)} \right| > \varepsilon \right) + \frac{Ka_n \pi_n^{a, b}}{\pi^H(a, b)^2 \varepsilon^2}. \end{aligned}$$

The first term of the right hand side is  $\mathbb{I}_{\{|K - Ka_n \pi_n^{a, b} / \pi^H(a, b)| > \varepsilon\}}$  and from Lemma 2,  $\lim_{n \rightarrow \infty} a_n \pi_n^{a, b} = \pi^H(a, b)$ , so this term converges to 0 for all  $a$  and  $b$ . The second term converges to  $K/\varepsilon^2 \pi^H(a, b)$  as  $n$  tends to  $\infty$ . Since from the hypothesis we have  $\lim_{a \rightarrow 0} \pi^H(a, b) = \infty$ , for all  $b$ , we conclude that

$$\lim_{a \rightarrow 0} \lim_{n \rightarrow \infty} \mathbb{P} \left( \max_{0 \leq j \leq T_{[Ka_n]}^{(n)}} \left| \frac{1}{\pi^H(a, b)} \Lambda_j^{a, b, n} - \frac{1}{a_n} \Lambda_j^{(n)} \right| > 2\varepsilon \right) = 0.$$

Finally, write

$$\begin{aligned} & \mathbb{P} \left( \sup_{t \in [0, 1]} \left| \frac{1}{\pi^H(a, b)} \Lambda_{[nt]}^{a, b, n} - \frac{1}{a_n} \Lambda_{[nt]}^{(n)} \right| > \varepsilon \right) \leq \\ & \mathbb{P} \left( \max_{0 \leq j \leq T_{[Ka_n]}^{(n)}} \left| \frac{1}{\pi^H(a, b)} \Lambda_j^{a, b, n} - \frac{1}{a_n} \Lambda_j^{(n)} \right| > \varepsilon \right) + \mathbb{P}(T_{[Ka_n]}^{(n)} < n). \end{aligned}$$

So (3.6) for  $t = 1$  follows from (3.11), (3.12) and the fact that

$$\lim_{K \rightarrow \infty} \lim_{n \rightarrow \infty} \mathbb{P}(T_{[Ka_n]}^{(n)} < n) = 0,$$

which is a consequence of Theorem 1. Again the proof can readily be extended to any time  $t$ . Hence (3.6) is proved in this case.  $\square$

When 0 is regular for  $(-\infty, 0)$ , we may also define the local time at the infimum of  $X$  to be the local time at the supremum of  $-X$ . Let us denote this process by  $\widehat{L}$  and denote by  $\widehat{\Lambda}^{(n)}$  the local time at the maximum of the approximating sequence  $-S^{(n)}$ . A straightforward consequence of the previous theorem is the following result.

**Corollary 1.** *Under the hypotheses of Theorem 2, the sequence*

$$\left[ \left( S_{[nt]}^{(n)}, \frac{1}{a_n} \Lambda_{[nt]}^{(n)} \right), t \geq 0 \right]$$

converges in probability to  $[(X_t, L_t), t \geq 0]$ . If in addition 0 is regular for  $(-\infty, 0)$  then the sequence

$$\left[ \left( S_{[nt]}^{(n)}, \frac{1}{a_n} \Lambda_{[nt]}^{(n)}, \frac{1}{\hat{a}_n} \widehat{\Lambda}_{[nt]}^{(n)} \right), t \geq 0 \right]$$

converges in probability to  $[(X_t, L_t, \widehat{L}_t), t \geq 0]$ , where  $\hat{a}_n = \exp \left( \sum_{k=1}^{\infty} \frac{1}{k} e^{-k/n} \mathbb{P}(S_k^{(n)} < 0) \right)$ .

In Corollary 1, convergence in probability means that each coordinate converges in probability with respect to some distance which generates the Skorokhod topology on the space  $\mathcal{D}([0, \infty))$ . But more particularly, the first coordinate converges almost surely, whereas the second coordinate converges uniformly in probability on compact sets, in the sense which has been defined in Theorem 2.

When 0 is regular for  $(-\infty, 0)$ , we denote by  $(\hat{\tau}, \hat{H})$  the strict ascending ladder process of  $-X$  and for the sequence of random walks  $S^{(n)}$ , we denote by  $(\hat{T}^{(n)}, \hat{H}^{(n)})$  the strict ascending ladder height process of  $-S$ . Another consequence of Theorem 2 is the following invariance principle for both the ascending and descending ladder processes jointly.

**Corollary 2.** *Let  $X$  be any Lévy process such that 0 is regular for both the open half lines  $(0, \infty)$  and  $(-\infty, 0)$  and assume that some sequence of random walks  $S^{(n)}$  converges in law toward  $X$ . Then the process*

$$\left[ \left( n^{-1}T_{[a_n t]}^{(n)}, H_{[a_n t]}^{(n)}, n^{-1}\hat{T}_{[\hat{a}_n t]}^{(n)}, \hat{H}_{[\hat{a}_n t]}^{(n)} \right), t \geq 0 \right]$$

converges toward the process

$$[(\tau_t, H_t, \hat{\tau}_t, \hat{H}_t), t \geq 0]$$

in the sense of finite dimensional distributions as  $n \rightarrow \infty$ , where  $a_n$  and  $\hat{a}_n$  are defined respectively in Theorem 1 and Corollary 1.

**Remark 3.** *Note that in this case, we cannot conclude that weak convergence holds by using Skorokhod's Theorem as in Theorem 1 since the quadrivariate processes which are involved in Corollary 2 do not have independent increments.*

*Proof.* By virtue of the Skorokhod representation theorem, there exists a sequence  $\tilde{S}^{(n)}$  (possibly defined on an enlarged probability space) such that for each  $n$ ,  $\tilde{S}^{(n)} \stackrel{(d)}{=} S^{(n)}$  and such that  $\tilde{S}^{(n)}$  converges almost surely toward  $X$ . Let  $(\mathcal{T}^{(n)}, \mathcal{H}^{(n)})$  and  $(\hat{\mathcal{T}}^{(n)}, \hat{\mathcal{H}}^{(n)})$  be respectively the strict ascending and the strict descending ladder processes of  $\tilde{S}^{(n)}$ .

Recall that if a sequence of stochastic processes converges almost surely on the Skorokhod space, then the sequence defined by the first passage time processes converges at all continuity points of the limit process, see the remark after Theorem 7.1 in [22]. Moreover it is clear that the subordinators  $\tau$  and  $\hat{\tau}$  are a.s. continuous at each  $t \geq 0$ . Therefore, from Theorem 2 applied to  $\tilde{S}^{(n)}$  and  $-\tilde{S}^{(n)}$ , for fixed  $t \geq 0$ , there exists a subsequence  $(k_n)$  such that  $k_n^{-1}\mathcal{T}_{[a_{k_n} t]}^{(k_n)}$  and  $k_n^{-1}\hat{\mathcal{T}}_{[\hat{a}_{k_n} t]}^{(k_n)}$  converge almost surely toward  $\tau_t$  and  $\hat{\tau}_t$  respectively.

Since  $\tau_t$  and  $\hat{\tau}_t$  are announceable stopping times in the filtration generated by  $X$ , it follows from the quasi-left continuity of  $X$  that this process is a.s. continuous at times  $\tau_t$  and  $\hat{\tau}_t$ , see Ex. 3, Chap. I in [2].

We deduce from the almost sure convergence of  $\tilde{S}^{(k_n)}$  toward  $X$  that for every (possibly random) continuity point  $u$  of  $X$ ,  $\tilde{S}_{[k_n u]}^{(k_n)}$  converges almost surely to  $X_u$ , see [4], p.112. Therefore the sequence

$$\begin{aligned} & \left( k_n^{-1}\mathcal{T}_{[a_{k_n} t]}^{(k_n)}, \mathcal{H}_{[a_{k_n} t]}^{(k_n)}, k_n^{-1}\hat{\mathcal{T}}_{[\hat{a}_{k_n} t]}^{(k_n)}, \hat{\mathcal{H}}_{[\hat{a}_{k_n} t]}^{(k_n)} \right) \\ &= \left( k_n^{-1}\mathcal{T}_{[a_{k_n} t]}^{(k_n)}, \tilde{S}^{(k_n)} \left( \mathcal{T}_{[a_{k_n} t]}^{(k_n)} \right), k_n^{-1}\hat{\mathcal{T}}_{[\hat{a}_{k_n} t]}^{(k_n)}, -\tilde{S}^{(k_n)} \left( \hat{\mathcal{T}}_{[\hat{a}_{k_n} t]}^{(k_n)} \right) \right) \end{aligned}$$

converges almost surely toward  $(\tau_t, X(\tau_t), \hat{\tau}_t, -X(\hat{\tau}_t)) = (\tau_t, H_t, \hat{\tau}_t, \hat{H}_t)$ , as  $n \rightarrow \infty$ . This almost sure convergence is easily extended to the multidimensional case, i.e. there is a subsequence  $(k'_n)$  such that it holds simultaneously at any sequence of times  $t_1, \dots, t_j$ . So we have proved that the variables  $\left\{ n^{-1} \mathcal{T}_{[a_n t_i]}^{(n)}, \mathcal{H}_{[a_n t_i]}^{(n)}, n^{-1} \hat{\mathcal{T}}_{[\hat{a}_n t_i]}^{(n)}, \hat{\mathcal{H}}_{[\hat{a}_n t_i]}^{(n)}, i = 1, \dots, j \right\}$  converge in probability, and we conclude from the identity in law

$$(\mathcal{T}^{(n)}, \mathcal{H}^{(n)}, \hat{\mathcal{T}}^{(n)}, \hat{\mathcal{H}}^{(n)}) \stackrel{(d)}{=} (T^{(n)}, H^{(n)}, \hat{T}^{(n)}, \hat{H}^{(n)}),$$

which holds for each  $n$ , as a consequence of the identity  $\tilde{S}^{(n)} \stackrel{(d)}{=} S^{(n)}$ .  $\square$

Now we suppose that there is a sequence of Lévy processes  $X^{(n)}$ , all of which satisfy the same hypothesis as  $X$ , i.e. 0 is regular for  $(0, \infty)$ . Call  $L^{(n)}$  the version of the local time of  $X^{(n)}$  at its supremum, as it is defined in Section 2.

**Theorem 3.** *Suppose that as  $n$  tends to  $\infty$ ,*

$$X^{(n)} \xrightarrow{\text{a.s.}} X.$$

*Then the sequence of local times  $L^{(n)}$  converges uniformly on compact sets in probability toward  $L$ , i.e. for all  $t > 0$  and  $\varepsilon > 0$ ,*

$$\lim_{n \rightarrow \infty} \mathbb{P} \left( \sup_{s \in [0, t]} |L_t^{(n)} - L_t| > \varepsilon \right) = 0.$$

*Proof.* For each  $n$ , we define a sequence of random walks  $(S^{n, k}, k \geq 0)$  whose paths are embedded in those of  $X^{(n)}$  as follows:

$$S_j^{n, k} = X_{j/k}^{(n)}, \quad j \geq 0.$$

Then we may readily check that for each  $n$ , as  $k$  tends to  $\infty$ ,

$$(S_{[kt]}^{n, k}, t \geq 0) \xrightarrow{\text{a.s.}} X^{(n)}.$$

Call  $\Lambda^{n, k}$  the local time at its maximum of  $S^{n, k}$  as it is defined for  $S^{(n)}$  in (2.2). From Theorem 2, we have for all  $n \geq 1, t \geq 0$  and  $\varepsilon > 0$ ,

$$\lim_{k \rightarrow \infty} \mathbb{P} \left( \sup_{s \in [0, t]} \left| \frac{1}{a_k^n} \Lambda_{[ns]}^{n, k} - L_s^{(n)} \right| > \varepsilon \right) = 0,$$

where  $\log a_k^n = \sum_{j=1}^{\infty} \frac{1}{j} e^{-j/k} \mathbb{P}(S_j^{n, k} > 0)$ . We can chose a sequence of integers  $(k_n)_{n \geq 1}$  such that

$$\lim_{n \rightarrow \infty} \mathbb{P} \left( \sup_{s \in [0, t]} \left| \frac{1}{a_{k_n}^n} \Lambda_{[ns]}^{n, k_n} - L_s^{(n)} \right| > \varepsilon \right) = 0$$

and, as  $n$  goes to  $\infty$ ,

$$(S_{[k_n t]}^{n, k_n}, t \geq 0) \xrightarrow{\text{a.s.}} X.$$

Hence by applying again Theorem 2, we have

$$\lim_{n \rightarrow \infty} \mathbb{P} \left( \sup_{s \in [0, t]} \left| \frac{1}{a_{k_n}^n} \Lambda_{[ns]}^{n, k_n} - L_s \right| > \varepsilon \right) = 0,$$

which allows us to conclude.  $\square$

It is clear that the equivalent results to Corollaries 1 and 2 are also valid in the setting of Theorem 3, that is replacing the approximating sequence  $S^{(n)}$  by the sequence  $X^{(n)}$ .

## 4 Applications to conditioned processes

In this section we will prove that if a sequence  $S^{(n)}$  of random walks converges weakly toward a Lévy process  $X$ , then the sequence  $S^{(n)}$  conditioned to stay positive also converges weakly toward  $X$  conditioned to stay positive. For simplicity in the statements and proofs, we will always suppose that  $S^{(n)}$  and  $X$  do not drift to  $-\infty$  and that for  $X$ , the state 0 is regular for both  $(-\infty, 0)$  and  $(0, \infty)$ .

We first define  $S^{(n)}$  and  $X$  conditioned to stay positive on the whole time interval  $[0, \infty)$ . Let  $V^{(n)}(x) = \sum_{k \geq 0} \mathbb{P}(\widehat{H}_k^{(n)} \leq x)$ ,  $x \geq 0$  be the renewal function of  $\widehat{H}^{(n)}$  and let  $S^{(n)*}$  be the process  $S^{(n)}$  killed when it enters the negative half-line. The Markovian transition function which is given by

$$q^\uparrow(x, dy) = \frac{V^{(n)}(y)}{V^{(n)}(x)} \mathbb{P}(S_{k+1}^{(n)*} \in dy | S_k^{(n)*} = x),$$

for  $x > 0, y > 0$  if  $k \geq 1$ , and for  $x \geq 0, y > 0$  if  $k = 0$ , characterizes the law of an  $h$ -process of  $S^{(n)*}$  which is called *the law of  $S^{(n)}$  conditioned to stay positive*. Similarly, denote by  $X^*$  the Lévy process  $X$  killed when it enters the negative halfline. Suppose that 0 is regular for  $(-\infty, 0)$  and let  $h(x)$  be the renewal function of the subordinator  $\widehat{H}$ , i.e.  $h(x) = \mathbb{E} \left( \int_0^\infty \mathbb{1}_{\{\widehat{H}_t \leq x\}} dt \right)$ , then the Markovian semigroup

$$p_t^\uparrow(x, dy) = \frac{h(y)}{h(x)} \mathbb{P}(X_{t+s}^* \in dy | X_s^* = x), \quad \text{for } x, y > 0 \text{ and } s, t > 0$$

is that of the Lévy process  $X$  *conditioned to stay positive*. For  $x = 0$ , this semigroup admits a unique entrance law which is specified in terms of the measure of the excursions above the infimum of the process  $X$ . We refer to [3], [7] and [8] for a more complete account on random walks and Lévy processes conditioned to stay positive.

The proof of our invariance principle bears upon a pathwise construction of  $S^{(n)}$  and  $X$  conditioned to stay positive which is due to Tanaka and Doney, see [19], [12] and [11], p.91. Let us briefly recall it both in discrete time and in continuous time. For  $k \geq 0$ , call  $e^{(k)}$  the  $k$ -th excursion of the reflected process  $M^{(n)} - S^{(n)}$ :

$$e_i^{(k)} = (M^{(n)} - S^{(n)})_{T_k^{(n)+i}, \quad 0 \leq i \leq T_{k+1}^{(n)} - T_k^{(n)},$$

and denote by  $\hat{e}^{(k)}$  the time reversal of  $e^{(k)}$ , i.e.

$$\hat{e}_i^{(k)} = H_{k+1}^{(n)} - S^{(n)}(T_{k+1}^{(n)} - i), \quad 0 \leq i \leq T_{k+1}^{(n)} - T_k^{(n)}.$$

The process  $S^{(n)\uparrow}$  which is obtained from the concatenation of  $\hat{e}^{(0)}, \hat{e}^{(1)}, \dots$ , i.e:

$$S_i^{(n)\uparrow} = H_k^{(n)} + \hat{e}_{i-T_k^{(n)}}^{(k)}, \quad \text{if } T_k^{(n)} \leq i \leq T_{k+1}^{(n)}, \quad (4.13)$$

has the law of  $S^{(n)}$  conditioned to stay positive. A similar construction in continuous time has been obtained in [11]: for  $t > 0$ , let

$$g(t) = \sup\{s < t : X_s = M_s\} \quad \text{and} \quad d(t) = \inf\{s > t : X_s = M_s\},$$

then the process defined by

$$X_0^\uparrow = 0 \quad \text{and} \quad X_t^\uparrow = M_{d(t)} + \mathbb{1}_{\{d(t) > g(t)\}}(M - X)_{(d(t)+g(t)-t)-}, \quad t > 0 \quad (4.14)$$

has the law of  $X$  conditioned to stay positive.

Let us also define the local time at the future minimum of  $S^{(n)\uparrow}$  and  $X^\uparrow$ . The first of these processes is simply the counting process defined by  $\underline{\underline{\Lambda}}_0^{(n)} = 0$  and for  $k \geq 1$ ,

$$\underline{\underline{\Lambda}}_k^{(n)} = \#\{j \in \{1, \dots, k\} : S_{j-1}^{(n)\uparrow} < \min_{i \geq j} S_i^{(n)\uparrow}\}.$$

Recall that in continuous time the set  $\{t : X_t^\uparrow = \inf_{s \geq t} X_s^\uparrow\}$  is regenerative so that we may define on this set a local time  $\underline{\underline{L}}$ , see [7], p.44. This local time is unique up to a normalizing constant and we will normalize it by  $\mathbb{E} \left( \int_0^\infty e^{-t} d\underline{\underline{L}}_t \right) = 1$ . One easily derives from the above pathwise constructions the identities

$$\{j \geq 1 : S_{j-1}^{(n)\uparrow} < \min_{i \geq j} S_i^{(n)\uparrow}\} = \{j \geq 1 : S_j > \max_{i \leq j-1} S_i\}$$

and  $\{t : X_t^\uparrow = \inf_{s \geq t} X_s^\uparrow\} = \{t : X_t = \sup_{s \leq t} X_s\}$ . In particular, we have

$$\underline{\underline{\Lambda}}^{(n)} = \Lambda^{(n)} \quad \text{and} \quad \underline{\underline{L}} = L, \quad \text{a.s.} \quad (4.15)$$

The following theorem has been partially obtained in the particular setting of stable processes in [6], see Theorem 1.1.

**Theorem 4.** *Suppose that some sequence of random walks  $S^{(n)}$  converges almost surely toward  $X$ . Recall the definition of  $a_n$  from Theorem 1. Then,*

1. *the sequence of processes  $(S_{[nt]}^{(n)\uparrow}, t \geq 0)$  converges almost surely toward  $X^\uparrow$ ,*
2. *the sequence  $[(S_{[nt]}^{(n)\uparrow}, a_n^{-1} \underline{\underline{\Lambda}}_{[nt]}^{(n)}), t \geq 0]$  converges in probability toward  $(X^\uparrow, \underline{\underline{L}})$ .*

*Consequently, if some sequence of random walks  $S^{(n)}$  converges weakly toward  $X$ , then the sequence  $[(S_{[nt]}^{(n)\uparrow}, a_n^{-1} \underline{\underline{\Lambda}}_{[nt]}^{(n)}), t \geq 0]$  converges weakly toward  $(X^\uparrow, \underline{\underline{L}})$ .*

Actually, the result displayed in Theorem 4 holds in the very general case, although as stated at the beginning of this section, for simplicity in its statement and proof we restrict ourself to the case where 0 is regular for both halflines  $(-\infty, 0)$  and  $(0, \infty)$ .

The time reversal relationships between  $X$  and  $X^\uparrow$  and between  $S^{(n)}$  and  $S^{(n)\uparrow}$  which are presented below, in Theorem 5 and Lemma 3, are required for the proof of Theorem 4. Let us denote by  $U^{(n)}$  and  $\sigma$  respectively, the inverses of  $\underline{\underline{\Lambda}}^{(n)}$  and  $\underline{\underline{L}}$ , i.e:

$$U_k^{(n)} = \min\{i : \underline{\underline{\Lambda}}_i^{(n)} = k\}, \quad k \geq 0 \quad \text{and} \quad \sigma_t = \inf\{s : \underline{\underline{L}}_s > t\}, \quad t \geq 0.$$

We also set

$$G_k^{(n)\uparrow} = \max\{j \leq k : S_j^{(n)\uparrow} = \inf_{i \geq j} S_i^{(n)\uparrow}\} \quad \text{and} \quad g_t^\uparrow = \sup\{s \leq t : X_s^\uparrow = \inf_{u \geq s} X_u^\uparrow\},$$

and  $G_k^{(n)} = \max\{j \leq k : M_j^{(n)} = S_j^{(n)}\}$ .

**Theorem 5.** *The following time reversal relationships hold between  $X$  and  $X^\uparrow$ :*

1. *For all  $t > 0$ , the law of the process  $[(X_{\tau_t} - X_{(\tau_t-s)-}, L_{\tau_t} - L_{\tau_t-s}), 0 \leq s < \tau_t]$  is the same as that of the process  $[(X_s^\uparrow, \underline{\underline{L}}_s), 0 \leq s < \sigma_t]$ .*
2. *For all  $t > 0$ , the law of the process  $[(X_{g(t)} - X_{(g(t)-s)-}, L_{g(t)} - L_{g(t)-s}), 0 \leq s \leq g(t)]$  (with the convention that  $X_{0-} = X_0$ ) is the same as that of the process  $[(X_s^\uparrow, \underline{\underline{L}}_s), 0 \leq s \leq g_t^\uparrow]$ .*

Note that in the above statement, we have  $X_{g(t)} = M_t$  and  $L_{\tau_t} = t$ , almost surely. Part 1. of this theorem is Lemma 4.3 of Duquesne [14]. The case where these processes have no positive jumps is treated in Theorem VII.18 of [2]. It generalizes a well known transformation between Brownian motion and the three dimensional Bessel process due to Williams. Here we show that this result can easily be derived from simple arguments involving Tanaka-Doney's transformation. Our next lemma states the discrete time counterpart of Theorem 5. Its proof is very similar to that of Theorem 5, hence we will only prove the discrete time case.

**Lemma 3.** *For any  $k \geq 1$ ,*

1. *the law of the process  $[(S_{T_k^{(n)}}^{(n)} - S_{T_k^{(n)}-i}^{(n)}, k - \Lambda^{(n)}(T_k^{(n)} - i)), 0 \leq i \leq T_k^{(n)}]$  is the same as that of the process  $[(S_i^{(n)\uparrow}, \underline{\underline{\Lambda}}_i^{(n)}), 0 \leq i \leq U_k^{(n)}]$ ,*
2. *the law of the process  $[(S_{G_k^{(n)}}^{(n)} - S_{G_k^{(n)}-i}^{(n)}, \Lambda_{G_k^{(n)}}^{(n)} - \Lambda_{G_k^{(n)}-i}^{(n)}), 0 \leq i \leq G_k^{(n)}]$  is the same as that of the process  $[(S_i^{(n)\uparrow}, \underline{\underline{\Lambda}}_i^{(n)}), 0 \leq i \leq G_k^{(n)\uparrow}]$ .*

*Proof.* From the transformation which is recalled in (4.13), the process  $S^{(n)\uparrow}$  is the concatenation of the time reversed excursions  $\hat{e}^{(0)}, \hat{e}^{(1)}, \dots$ . It is clear that the times where this process reaches its future minimum occur at the end of each of these reversed excursions. Therefore  $T_k^{(n)} = U_k^{(n)}$ , a.s. and the concatenation of the  $k$  excursions  $\hat{e}^{(0)}, \hat{e}^{(1)}, \dots, \hat{e}^{(k)}$  is the process  $(S_i^{(n)\uparrow}, 0 \leq i \leq U_k^{(n)})$ .

From the Markov property, these excursions are i.i.d., so that the concatenation of  $\hat{e}^{(0)}, \hat{e}^{(1)}, \dots, \hat{e}^{(k)}$  has the same law as the concatenation of  $\hat{e}^{(k)}, \hat{e}^{(k-1)}, \dots, \hat{e}^{(1)}$ . But the latter concatenation is precisely the process  $(S_{T_k^{(n)}}^{(n)} - S_{T_k^{(n)}-i}^{(n)}, 0 \leq i \leq T_k^{(n)})$ . The same reasoning justifies the identity on the second coordinate.

The second part of the statement follows from the same arguments together with the identity  $G_k^{(n)} = G_k^{(n)\uparrow}$  which holds for all  $k \geq 0$ .  $\square$

Actually in the proof of Theorem 4 we will only use the second part of Theorem 5 which says that the returned pre-supremum part of  $X$  before time  $t$  has the same law as  $X^\uparrow$  up to its last passage time at the future infimum before  $t$ . However, in order to avoid the need to justify an invariance principle for returned processes, we will reformulate this identity in law in terms of the post-infimum process.

*Proof of Theorem 4.* From identity (4.15) and Theorem 2, we only have to prove part 1. of Theorem 4. Define

$$K_j^{(n)} = \max\{i \leq j : S_i^{(n)} = \min_{l \leq i} S_l^{(n)}\} \quad \text{and} \quad k(t) = \sup\{s \leq t : X_s = \inf_{u \leq s} X_u\}.$$

From time reversal properties of  $S^{(n)}$  and  $X$ , we have:

$$\left( S_{K_k^{(n)}+i}^{(n)} - S_{K_k^{(n)}}^{(n)}, 0 \leq i \leq k - K_k^{(n)} \right) \stackrel{(d)}{=} \left( S_{G_k^{(n)}}^{(n)} - S_{G_k^{(n)}-i}^{(n)}, 0 \leq i \leq G_k^{(n)} \right)$$

and

$$(X_{k(t)+s} - X_{k(t)}, 0 \leq s \leq t - k(t)) \stackrel{(d)}{=} (X_{g(t)} - X_{(g(t)-s)-}, 0 \leq s \leq g(t)).$$

(Recall the convention:  $X_{0-} = X_0$ ). Since 0 is regular for both  $(-\infty, 0)$  and  $(0, \infty)$ , the time  $k(t)$  is a continuity point of  $X$ , hence the almost sure convergence of  $S^{(n)}$  toward  $X$  implies that  $\lim_n n^{-1} K_{[nt]}^{(n)} = k(t)$ , a.s. for all  $t \geq 0$ . Then recall from the preliminary section our definition of the a.s. convergence of stochastic processes with finite lifetime. We clearly have the almost sure convergence of the sequence of processes

$$Y^{(n)} = \left( S_{K_{[nt]}^{(n)}+[ns]}^{(n)} - S_{K_{[nt]}^{(n)}}^{(n)}, 0 \leq s \leq n^{-1}([nt] - K_{[nt]}^{(n)}) \right)$$

toward the process  $(X_{k(t)+s}, 0 \leq s \leq t - k(t))$ . From Lemma 3 and the time reversal property of  $S^{(n)}$ , the sequence  $Y^{(n)}$ ,  $n \geq 0$  has the same law as the sequence

$$\left( S_{[ns]}^{(n)\uparrow}, 0 \leq s \leq n^{-1}G_{[nt]}^{(n)\uparrow} \right).$$

Therefore the sequence  $\left( S_{[ns]}^{(n)\uparrow}, 0 \leq s \leq n^{-1}G_{[nt]}^{(n)\uparrow} \right)$  converges almost surely toward the process  $(X_s^\uparrow, 0 \leq s \leq g_t^\uparrow)$ .

Let  $(t_k)$  be an increasing sequence of positive reals which tends to  $\infty$ . We deduce from the above convergence that for each  $k$ ,  $\lim_{n \rightarrow \infty} n^{-1}G_{[nt_k]}^{(n)\uparrow} = g^\uparrow(t_k)$ , a.s. and more generally,

$$\left( S_{[ns]}^{(n)\uparrow} \mathbb{1}_{\{n^{-1}G_{[nt_k]}^{(n)\uparrow} \leq 1 < n^{-1}G_{[nt_{k+1}]}^{(n)\uparrow}\}}, 0 \leq s \leq 1 \right)$$

converges a.s. toward  $(X_s^\uparrow \mathbb{1}_{\{g^\uparrow(t_k) \leq 1 < g^\uparrow(t_{k+1})\}}, 0 \leq s \leq 1)$ . Since all processes  $S^{(n)\uparrow}$  and  $X^\uparrow$  drift to  $+\infty$ , we have  $\lim_{k \rightarrow \infty} G_{[nt_k]}^{(n)\uparrow} = \infty$  and  $\lim_{k \rightarrow \infty} g^\uparrow(t_k) = +\infty$ , a.s., so that

with  $t_0 = 0$ , we have

$$\begin{aligned} \left( S_{[ns]}^{(n)\uparrow}, 0 \leq s \leq 1 \right) &= \left( \sum_{k \geq 0} S_{[ns]}^{(n)\uparrow} \mathbb{I}_{\left\{ n^{-1}G_{[nt_k]}^{(n)\uparrow} \leq 1 < n^{-1}G_{[nt_{k+1}]}^{(n)\uparrow} \right\}}, 0 \leq s \leq 1 \right) \quad \text{and} \\ \left( X_s^\uparrow, 0 \leq s \leq 1 \right) &= \left( \sum_{k \geq 0} X_s^\uparrow \mathbb{I}_{\{g^\uparrow(t_k) \leq 1 < g^\uparrow(t_{k+1})\}}, 0 \leq s \leq 1 \right). \end{aligned}$$

But almost surely there is  $k$  and  $n_0$  such that for all  $n \geq n_0$ , the processes on the right hand sides of the two equalities above are respectively equal to

$$\left( S_{[ns]}^{(n)\uparrow} \mathbb{I}_{\left\{ n^{-1}G_{[nt_k]}^{(n)\uparrow} \leq 1 < n^{-1}G_{[nt_{k+1}]}^{(n)\uparrow} \right\}}, 0 \leq s \leq 1 \right)$$

and  $(X_s^\uparrow \mathbb{I}_{\{g^\uparrow(t_k) \leq 1 < g^\uparrow(t_{k+1})\}}, 0 \leq s \leq 1)$ . Therefore  $\left( S_{[ns]}^{(n)\uparrow}, 0 \leq s \leq 1 \right)$  converges toward  $(X_s^\uparrow, 0 \leq s \leq 1)$  on the space  $\mathcal{D}([0, 1])$ . The same arguments holds on each space  $\mathcal{D}([0, t])$ ,  $t > 0$  so we deduce the convergence on  $\mathcal{D}([0, \infty))$  from Theorem 16.7 in [4] as recalled in the preliminary section.  $\square$

We now define  $S^{(n)}$  and  $X$  conditioned to stay positive respectively on  $\{0, 1, \dots, k\}$  and  $[0, t]$ , where  $k$  and  $t$  are deterministic. Let  $\mathcal{C}_k^{(n)} = \{S_1^{(n)} \geq 0, \dots, S_k^{(n)} \geq 0\}$  then we denote by  $S^{(n,k)}$  a process whose law is defined on  $\{0, 1, \dots, k\}$  by  $S_0^{(n,k)} = 0$  and

$$\mathbb{P}(S_1^{(n,k)} \in dx_1, \dots, S_k^{(n,k)} \in dx_k) = \mathbb{P}(S_1^{(n)} \in dx_1, \dots, S_k^{(n)} \in dx_k | \mathcal{C}_k^{(n)}).$$

It clearly follows from the definitions that this law is absolutely continuous with respect to the law of  $S^{(n)\uparrow}$ : for  $x_1 > 0, \dots, x_k > 0$ ,

$$\mathbb{P}(S_1^{(n,k)} \in dx_1, \dots, S_k^{(n,k)} \in dx_k) = \frac{1}{\mathbb{P}(\mathcal{C}_k^{(n)})V^{(n)}(x_k)} \mathbb{P}(S_1^{(n)\uparrow} \in dx_1, \dots, S_k^{(n)\uparrow} \in dx_k). \quad (4.16)$$

See also (3.2) in [6]. The process  $S^{(n,k)}$  is called the (discrete time) *meander* with length  $k$ .

The definition of the analogous conditional law in continuous time requires some care since the set  $\{X_t \geq 0 : t \in [0, 1]\}$  has always probability 0 when 0 is regular for  $(-\infty, 0)$ .

**Lemma 4.** *For  $x_1 > 0, \dots, x_j > 0$  and  $t_1, \dots, t_j \in [0, 1]$ , we have*

$$\begin{aligned} \lim_{x \downarrow 0} \mathbb{P}_x(X_{t_1} \in dx_1, \dots, X_{t_j} \in dx_j | X_t > 0, t \in [0, 1]) \\ = \frac{1}{\beta h(x_j)} \mathbb{P}(X_{t_1}^\uparrow \in dx_1, \dots, X_{t_j}^\uparrow \in dx_j), \end{aligned}$$

where  $\beta = \mathbb{E}(h(X_1^\uparrow)^{-1})$ .

*Proof.* This is a direct application of Corollary 1 in [8], see also [9].  $\square$

Clearly the weak limit obtained in this lemma defines a unique probability measure on the space  $\mathcal{D}([0, 1])$ . We will denote by  $X^+$  a process with this law, i.e. for  $x_1 > 0, \dots, x_j > 0$  and  $t_1, \dots, t_j \in [0, 1]$ ,

$$\mathbb{P}(X_{t_1}^+ \in dx_1, \dots, X_{t_j}^+ \in dx_j) = \frac{1}{\beta h(x_j)} \mathbb{P}(X_{t_1}^\uparrow \in dx_1, \dots, X_{t_j}^\uparrow \in dx_j). \quad (4.17)$$

This process is called the *meander* with length 1.

**Lemma 5.** *Assume that  $S^{(n)}$  converges weakly to  $X$ . Recall the definition of the renewal function  $V^{(n)}(x) = \sum_{k \geq 0} \mathbb{P}(\widehat{H}_k^{(n)} \leq x)$ , for  $x \geq 0$ .*

1. *Let  $\pi^{\hat{\tau}}$  be the Lévy measure of the ladder time process  $\hat{\tau}$ , then*

$$\lim_{n \rightarrow +\infty} \hat{a}_n \mathbb{P}(\mathcal{C}_n^{(n)}) = \pi^{\hat{\tau}}(1, \infty).$$

2. *The sequence of functions  $\mathbb{P}(\mathcal{C}_n^{(n)})V^{(n)}(x)$  converges uniformly on compact sets toward  $\gamma h(x) = \gamma \mathbb{E} \left( \int_0^\infty \mathbb{1}_{\{\widehat{H}_t \leq x\}} dt \right)$ , with  $\gamma = \pi^{\hat{\tau}}(1, \infty)$ .*

*Proof.* To prove the first part, it suffices to note that  $\mathbb{P}(\mathcal{C}_n^{(n)}) = \mathbb{P}(n^{-1}\widehat{T}_1^{(n)} > 1)$  and to apply Lemma 2. To prove the second part, observe that from the hypothesis, Theorem 1 and dominated convergence, we have for every  $x \geq 0$ ,

$$\lim_{n \rightarrow \infty} \int_0^\infty \mathbb{P}(\widehat{H}_{[\hat{a}_n t]}^{(n)} \leq x) dt = \lim_{n \rightarrow \infty} \hat{a}_n^{-1} V^{(n)}(x) = h(x).$$

Then the result follows from part 1., the fact that  $V^{(n)}(x)$  is a sequence of increasing functions and the continuity of  $h$ .  $\square$

The following invariance principle for the meander has been obtained in the case where all  $S^{(n)}$  have the same law (in particular  $X$  is stable) in [5] and [10].

**Theorem 6.** *Suppose that some sequence of random walks  $S^{(n)}$  converges weakly toward  $X$ . Then the sequence of discrete meanders  $(S_{[nt]}^{(n,n)}, 0 \leq t \leq 1)$  converges weakly toward the meander  $X^+$ .*

*Proof.* We will prove that for all continuous and bounded functionals  $F$  on  $\mathcal{D}([0, 1])$ ,

$$\mathbb{E} \left( F(S_{[nt]}^{(n,n)}, 0 \leq t \leq 1) \right) \longrightarrow \mathbb{E} \left( F(X_t^+, 0 \leq t \leq 1) \right), \quad \text{as } n \rightarrow \infty.$$

From the absolute continuity relations (4.16) and (4.17), it suffices to prove that

$$\begin{aligned} \mathbb{E} \left( \frac{1}{\mathbb{P}(\mathcal{C}_n^{(n)})V^{(n)}(S_n^{(n)\uparrow})} F(S_{[nt]}^{(n)\uparrow}, 0 \leq t \leq 1) \right) \\ \longrightarrow \mathbb{E} \left( \frac{1}{\beta h(X_1^\uparrow)} F(X_t^\uparrow, 0 \leq t \leq 1) \right), \quad \text{as } n \rightarrow \infty. \end{aligned}$$

For  $\eta > 0$ , write

$$\begin{aligned}
& \left| \mathbb{E} \left( \frac{1}{\mathbb{P}(\mathcal{C}_n^{(n)})V^{(n)}(S_n^{(n)\uparrow})} F(S_{[nt]}^{(n)\uparrow}, 0 \leq t \leq 1) \right) - \mathbb{E} \left( \frac{1}{\gamma h(X_1^\uparrow)} F(X_t^\uparrow, 0 \leq t \leq 1) \right) \right| \\
& \leq \left| \mathbb{E} \left( \frac{1}{\mathbb{P}(\mathcal{C}_n^{(n)})V^{(n)}(S_n^{(n)\uparrow})} \mathbb{I}_{\{S_n^{(n)\uparrow} \geq \eta\}} F(S_{[nt]}^{(n)\uparrow}, 0 \leq t \leq 1) \right) \right. \\
& \quad \left. - \mathbb{E} \left( \frac{1}{\gamma h(X_1^\uparrow)} \mathbb{I}_{\{X_1^\uparrow \geq \eta\}} F(X_t^\uparrow, 0 \leq t \leq 1) \right) \right| \\
& + \mathbb{E} \left( \frac{1}{\mathbb{P}(\mathcal{C}_n^{(n)})V^{(n)}(S_n^{(n)\uparrow})} \mathbb{I}_{\{S_n^{(n)\uparrow} < \eta\}} F(S_{[nt]}^{(n)\uparrow}, 0 \leq t \leq 1) \right) \\
& \quad + \mathbb{E} \left( \frac{1}{\gamma h(X_1^\uparrow)} \mathbb{I}_{\{X_1^\uparrow < \eta\}} F(X_t^\uparrow, 0 \leq t \leq 1) \right).
\end{aligned}$$

Since  $F$  is bounded by a constant, say  $B$  and

$$\mathbb{E} \left( \frac{1}{\mathbb{P}(\mathcal{C}_n^{(n)})V^{(n)}(S_n^{(n)\uparrow})} \right) = 1 \quad \text{and} \quad \mathbb{E} \left( \frac{1}{\gamma h(X_1^\uparrow)} \right) = \beta/\gamma, \quad (4.18)$$

it follows from Hölder's inequality that the two last terms of the right hand side of the above inequality are bounded above respectively by  $B\mathbb{P}(S_n^{(n)\uparrow} < \eta)$  and  $B\mathbb{P}(X_1^\uparrow < \eta)\beta/\gamma$ . From the assumption of convergence and the fact that  $\mathbb{P}(X_1^\uparrow > 0) = 1$ , for every  $\varepsilon > 0$ , there exist  $n_0$  and  $\eta > 0$  such that for all  $n \geq n_0$ ,  $B\mathbb{P}(S_n^{(n)\uparrow} < \eta) < \varepsilon$  and  $B\mathbb{P}(X_1^\uparrow < \eta)\beta/\gamma < \varepsilon$ . Finally, note that from the hypothesis of convergence and Lemma 5, we easily derive that for all  $\eta > 0$ ,

$$\begin{aligned}
& \mathbb{E} \left( \frac{1}{\mathbb{P}(\mathcal{C}_n^{(n)})V^{(n)}(S_n^{(n)\uparrow})} \mathbb{I}_{\{S_n^{(n)\uparrow} \geq \eta\}} F(S_{[nt]}^{(n)\uparrow}, 0 \leq t \leq 1) \right) \\
& \quad \longrightarrow \mathbb{E} \left( \frac{1}{\gamma h(X_1^\uparrow)} \mathbb{I}_{\{X_1^\uparrow \geq \eta\}} F(X_t^\uparrow, 0 \leq t \leq 1) \right), \quad \text{as } n \rightarrow \infty.
\end{aligned}$$

Then we have proved that

$$\begin{aligned}
& \mathbb{E} \left( \frac{1}{\mathbb{P}(\mathcal{C}_n^{(n)})V^{(n)}(S_n^{(n)\uparrow})} F(S_{[nt]}^{(n)\uparrow}, 0 \leq t \leq 1) \right) \\
& \quad \longrightarrow \mathbb{E} \left( \frac{1}{\gamma h(X_1^\uparrow)} F(X_t^\uparrow, 0 \leq t \leq 1) \right), \quad \text{as } n \rightarrow \infty.
\end{aligned}$$

Taking  $F \equiv 1$  in this relation and comparing with (4.18), we obtain  $\beta = \gamma$ , which proves the result.  $\square$

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