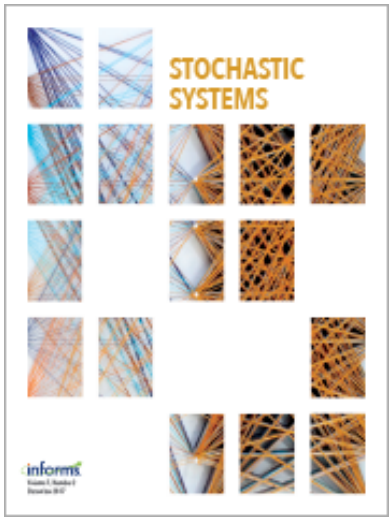
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To cite this article:
Søren Asmussen, Dominik Kortschak (2013) Second Order Corrections for the Limits of Normalized Ruin Times in the Presence of Heavy Tails. Stochastic Systems 3(2):591-633. https://doi.org/10.1287/11-SSY054

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*Stochastic Systems*
2013, Vol. 3, No. 2, 591–633
DOI: 10.1214/11-SSY054

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# SECOND ORDER CORRECTIONS FOR THE LIMITS OF NORMALIZED RUIN TIMES IN THE PRESENCE OF HEAVY TAILS

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In this paper we consider a compound Poisson risk model with regularly varying claim sizes. For this model in [4] an asymptotic formula for the finite time ruin probability is provided when the time is scaled by the mean excess function. In this paper we derive the rate of convergence for this finite time ruin probability when the claims are regularly varying with a finite second moment.

**1. Introduction.** In this paper, we consider the classical Cramér Lundberg risk process with (for convenience) constant premium inflow 1 and claims $X_1, X_2, \ldots$ which are iid random variables with distribution $F$ and arrive at the epochs of an independent Poisson process $N_t$ with parameter $\lambda$. Denote with

$$V_t = \sum_{i=1}^{N_t} X_i - t$$

the claim surplus process at time $t$ and with

$$\tau_u = \inf\{t : u - V_t < 0\}$$

the time of ruin with starting capital $u$. We are interested in the finite time ruin probability

$$\psi(u,t) = \mathbb{P}(\tau_u < t).$$

Further we will denote with $\psi(u) = \psi(u,\infty)$ the infinite time ruin probability. Write $\mu = \mathbb{E}[X]$ and let

$$F_0(x) = \frac{1}{\mu}\int_0^x \overline{F}(x)\mathrm{d}x$$

Received December 2011.

*This work was partially supported by a grant from the Thiele Center at Aarhus University, by the the MIRACCLE-GICC project and the Chaire d'excellence "Generali - Actuariat responsable: gestion des risques naturels et changements climatiques.

*MSC 2010 subject classifications:* Primary 60K30; secondary 60K25.

*Keywords and phrases:* Second order subexponentiality, regular variation, finite time ruin probability, poisson process, risk Process, transient behavior, M/G/1 queue, storage process.

be the integrated tail distribution of $F$. We assume the usual net profit condition $\rho = \lambda\mu < 1$ ensuring that the ruin in infinite time does not occur w.p. 1. See for example [2].

In [4] (see also [2, Section X.4]) it is shown that if $\overline{F}_0$ is subexponential and there exists a non-degenerate random variable $W$ and a function $e(u)$ such that

$$\lim_{u\to\infty} \frac{\overline{F}_0(u + xe(u))}{\overline{F}_0(u)} = \mathbb{P}(W > x), \tag{1.1}$$

then

$$\psi(u, xe(u)) \sim \frac{\rho}{1-\rho}\overline{F}_0(u)\mathbb{P}\left(\frac{W}{1-\rho} \le x\right) \tag{1.2}$$

as $u \to \infty$ (see also [3, 15] and the discussion in [2, p. 318] for further work in this direction).

In this paper we want to give asymptotic expressions for the error in the approximation (1.2). Condition (1.1) (cf. [12]) and results on second order asymptotic approximations for compound sums (cf. [1] for a recent survey) imply that we have to expect three different cases: $\overline{F}_0$ is regularly varying and has finite mean; $\overline{F}_0$ is regularly varying and has infinite mean; $F_0$ is in the maximum domain of attraction of the Gumbel distribution. In this paper we will only consider the first case, where $W$ is regularly varying with finite mean (see further Assumption 1.1 below).

It should be noted that our results also have some relevance for queueing and inventory theory. This is because of the relation between the Cramér-Lundberg model and a dual M/G/1 queue defined by the same arrival process and service times distributed as the $X_i$: $\psi(u,t) = \mathbb{P}(V_t > u)$ where $V_t$ is the workload process in an initially empty queue (see [2, pp. 45–48]). This process is also frequently used as a storage process model.

We start the paper in Section 2 with a survey of recent result on second order subexponential asymptotics. Section 3 then contain the statement of our main result. In addition we give the outline of the proof, which has many very technical steps (though often the crux is just careful Taylor expansions). This proof in turn is modeled after that of [4], where the simple and explicit ladder structure of the Cramér-Lundberg process plays a key role. We also give some discussion of the difficulties in extending to more general models such as Lévy processes or renewal models.

The proofs of the technical estimates omitted in Section 3 then occupy the rest of the paper. A longer version of the paper with some more detail given is available upon request from the authors.

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**2. Subexponential distributions and second order properties.** In this paper we will assume that the distribution function $F$ of $X$ is regularly varying with index $\alpha$, i.e.

$$\lim_{u\to\infty}\frac{\mathbb{P}(X>xu)}{\mathbb{P}(X>u)}=\lim_{u\to\infty}\frac{\overline{F}(xu)}{\overline{F}(X>u)}=x^{-\alpha}.$$

For more information about regularly variation we refer to [8]. Let $X_1,\dots,X_n$ be iid copies of $X$ and $S_n=\sum_{i=1}^n X_i$, $M_n=\max_{i=1,\dots,n}X_i$. The regularly varying distributions are a subclass of the subexponential distributions defined through

$$\lim_{u\to\infty}\frac{\mathbb{P}(S_n>u)}{\mathbb{P}(X_1>u)}=\lim_{u\to\infty}\frac{\mathbb{P}(M_n>u)}{\mathbb{P}(X_1>u)}=n. \tag{2.1}$$

A basic result on second order asymptotics for subexponential distributions concerns the rate of convergence in (2.1). If $\mathbb{E}[X]<\infty$ and $F$ has a regularly varying density $f$, then it is shown in [20] that

$$\mathbb{P}(S_n>u)=n\overline{F}(u)+n(n-1)\mathbb{E}\left[X_1\right]f(u)+o\left(f(u)\right). \tag{2.2}$$

The regularly varying case with $\mathbb{E}[X]=\infty$ is treated in [19]. In [5] the result (2.2) is generalized to a wide class of subexponential distributions. Further [10] and [18] consider cases when a density does not necessarily exists. It is pointed out in [1], that a Taylor expansion shows that (2.2) is equivalent to

$$\mathbb{P}(S_n>u)=n\overline{F}\left(u-(n-1)\mathbb{E}\left[X_1\right]\right)+o\left(f(u)\right),$$

which has the natural interpretation that the sum is large if one component is large and the others behave in a normal way. One should note that in the cited references $n$ can be a (light tailed) random variable. Hence by the Pollaczeck-Khinchine formula these results directly translate to second order results for the infinite time ruin probability. Higher order expansions are provided in [6] and [7]; for a recent survey of this topic, see [1]. Extensions of these results are given in [11] where second order properties for the value-at-risk are provided. [9] considered the absolute ruin probability in a model where the insurance company can borrow money. In [17] dependent but tail independent regularly varying random variables are studied.

Studies in the subexponential area often use the relation to extreme value theory, in our case the fact that condition (1.1) is equivalent to the condition that $F_0$ is in the maximum domain of attraction of the Fréchet extreme value distribution (see e.g. [12]). However, we will not use this connection.

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REMARK 2.1. A result that is related to our paper is provided in [10] where the authors consider a random walk and provide higher order asymptotic expansions for crossing a linear boundary. This result is equivalent to a higher order approximation for the ruin probability before a finite number of claims

$$\psi_d(u,n) = \mathbb{P}\left(\tau(u) < \infty, N_{\tau(u)} \le n\right). \tag{2.3}$$

A question is if we can use this result to derive the results given in this paper. The first idea is to replace the $n$ in (2.3) with $N_{xe(u)}$ and then use the approximation $\psi_d(u,t) \approx \mathbb{E}[\psi_d(u,N_{xe(u)})] \approx \mathbb{E}[\psi_d(u,\mathcal{N}_{xe(u)})]$ where $\mathcal{N}_{xe(u)}$ is normally distributed with mean $\lambda xe(u)$ and variance $\lambda xe(u)$. Although this method gives the same asymptotic expansion it is only heuristically since by conditioning on $N_{xe(u)}$ we change the underlying process that then does not fulfill the conditions in [10].

A second simpler method of how to use the results in [10] is to consider the process $V_t$ on a discrete skeleton (with grid size $\epsilon$) then use the results of [10] to get a second order approximation for the discrete process and finally one has to show that one can control the error in the second order approximation as $\epsilon \to 0$. In appendix B we provide a proof of this type with slightly stronger conditions then in the rest of the paper.

**3. Preliminaries and main theorem.** To fix notation, we present the idea of the proof of (1.2) with the notation and the method given in [2]. Therefore denote with

$$\tau_+(0) = 0, \quad \tau_+(i) = \inf\{t > \tau_+(i-1) \,:\, V_t > V_{\tau_+(i-1)})\}, \quad i \ge 1$$

the time of the $i$-th ladder step. Further denote with $Y_i = V_{\tau_+(i)} - V_{\tau_+(i-1)}$ and $Z_i = V_{\tau_+(i-1)} - V_{\tau_+(i)-}$ the overshoot, resp. the capital before each ladder step. It is known that the $(Y_i, Z_i)$ form a sequence of iid random vectors with joint distribution given by $\mathbb{P}(Y > y, Z > z) = \overline{F}_0(y+z)$. Let

$$K(u) = \inf\{n : \tau_+(n) < \infty, Y_1 + \cdots + Y_n > u\}$$

be the number of ladder steps until the time of ruin and $\mathbb{P}^{(u,n)} = \mathbb{P}(\cdot|\tau(u) < \infty, K(u) = n)$.

Let $R_t$ be a stochastic process independent of $V_t$ and $R_t \stackrel{d}{=} -V_t$. Let $w(x) = \inf\{t : R_t = x\}$ be the first time the process $R_t$ reaches level $x$. Under the measure $\mathbb{P}^{(u,n)}$ the distribution of $\tau(u)$ is the same as the one of $w(Z_1) + \cdots + w(Z_n)$ and $w(Z_1 + \cdots + Z_n)$. It follows that for $Z_1, \ldots, Z_n | K(u) = n$ distributed according to $P^{(u,n)}$, the distribution of $\tau(u)$ is the same as the

distribution of $w(Z_1 + \cdots + Z_{K(u)})$. The method of proof for (1.2) is first to find the distribution of $Z_1, \ldots, Z_n$ and then find the connection between $w(A)$ and $A$ for some random variable $A$.

We will use the same ideas to prove our main results. We will work under the following Assumption which will be assumed to hold throughout the paper.

ASSUMPTION 3.1. Let $X, X_1, X_2, \ldots$ be a sequence of iid random variables with distribution function $F$ having a regularly varying tail with index $\alpha$, a regularly varying density $f$. Let $\widehat{F}(s) = \int_0^\infty \mathrm{e}^{-sx} f(x)\,\mathrm{d}x$ be the Laplace transform of the distribution $F$. Assume that $\mathbb{E}[X^2] < \infty$ and that there exists an $M > 0$ with $|s\widehat{F}'''(s)| < M$ for $\mathrm{Re}(s) > 0$ and $|s| < 1$.

It follows in particular that, taking $e(u) = u$, the r.v. $W$ in (1.1) exists and has tail $\mathbb{P}(W > y) = (1+y)^{-\alpha+1}$.

THEOREM 3.1. *Let Assumption 3.1 be fulfilled and define $e(u) = u$. Then*

$$\begin{aligned}
&\mathbb{P}(\tau(u) \le xe(u)) \\
&= \frac{\rho}{1-\rho}\overline{F}_0(u) \;-\; \frac{\rho}{1-\rho}\overline{F}_0(u + x(1-\rho)e(u)) \\
&\quad + \frac{\lambda^2 \mathbb{E}\left[X_1^2\right]\overline{F}(u)}{(1-\rho)^2} - \frac{\alpha\lambda^2 \mathbb{E}\left[X_1^2\right]\overline{F}(u)x(1+(1-\rho)x)^{-\alpha-1}}{2(1-\rho)} \\
&\quad - \frac{\lambda^2 \mathbb{E}\left[X_1^2\right]\overline{F}(u)(1+(1-\rho)x)^{-\alpha}}{(1-\rho)^2} + o(\overline{F}(x)).
\end{aligned}$$

The proof of Theorem 3.1 relies on two facts. The first is that the distribution of the sum of the surpluses before each ladder step has a known distribution, which is related to the distribution that a random sum exceeds a given threshold. Hence we can use methods developed for random sums to get second order properties. Therefore denote with $S_n = \sum_{i=1}^n Y_i$ and with $\widehat{S}_n = \sum_{i=1}^n Z_i$.

LEMMA 3.2. *Let $(Y_1, Z_1), \ldots, (Y_1, Z_1)$ be iid vectors with distribution $F_0(y+z)$ where $F_0 = \frac{1}{\mu}\int_0^x \overline{F}(t)\,\mathrm{d}t$. Then*

$$\begin{aligned}
&\mathbb{P}(S_n > u, S_{n-1} \le u, \widehat{S}_n > xe(u)) \\
&\sim \overline{F}_0(u + xe(u)) + \frac{1}{\mu}\mathbb{E}\left[S_{n-1} + \widehat{S}_{n-1} + (n-1)Y_n\right]\overline{F}(u + xe(u)) \\
&= \overline{F}_0(u + xe(u)) + \frac{3(n-1)\mathbb{E}\left[X^2\right]}{2\mu^2}\overline{F}(u + xe(u)).
\end{aligned}$$

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*Further for all $\epsilon > 0$ there exists a constant $M$ such that for all $n$*

$$\mathbb{P}(S_n > u, S_{n-1} \le u, Z > x(e(u))) - \overline{F}_0(u + xe(u)) \le M(1+\epsilon)^n \overline{F}(u).$$

We also need some properties of the density of $Z$. As in Lemma 3.2, we can get upper bounds such that with dominated convergence we can use a random $n$.

LEMMA 3.3.

$$\frac{\mathrm{d}\mathbb{P}(S_{n-1} \le u, S_n > u, \widehat{S}_n \le x)}{\mathrm{d}x}\Big|_{x=yu} \sim \frac{1}{\mu}\overline{F}(u+yu).$$

Next we consider the derivative of the density of $\widehat{S}_n$.

LEMMA 3.4.

$$\frac{\mathrm{d}^2\mathbb{P}(S_{n-1} \le u, S_n > u, \widehat{S}_n \le x)}{\mathrm{d}x^2}\Big|_{x=yu} \sim \frac{1}{\mu} f(u+yu).$$

The second fact that we use is that we know the connection between the time of ruin and the sum of the surpluses. This connection allows to involve the central limit theorem for compound Poisson sums (cf. Section 4) and hence higher order asymptotics can be found.

LEMMA 3.5. *Let $W_u$ be a family of random variables with distribution function $G_u(w)$ with $\lim_{u\to\infty} \overline{G}_u(w) = \overline{G}_\infty(w) = (1 + x(1-\rho)w)^{-\alpha+1}$. Further assume that $W_u$ has a density $g_u(x)$ that is continuously differentiable and $\lim_{u\to\infty} g_u(w) = g_\infty(w)$ as well as $\lim_{u\to\infty} g'_u(w) = g'_\infty(w)$. Then*

$$\begin{aligned}&\mathbb{P}(w((1-\rho)xe(u)W_u) > xe(u))\\ &= \mathbb{P}(W_u > 1) - \frac{\lambda\mathbb{E}\left[X_1^2\right]}{2e(u)(1-\rho)}\left(\frac{1}{x(1-\rho)}g_\infty(1) + \frac{1}{x(1-\rho)}g'_\infty(1)\right)\\ &\quad + o\left(\frac{1}{e(u)}\right).\end{aligned}$$

REMARK 3.1. These two properties of compound Poisson processes are not straightforward to generalize to more general risk models like renewal models since they heavily rely on the fact that the considered risk process is Markovian. Similarly, the extension to general Lévy processes meets the difficulty that the ladder structure here is more complicated.

Another interesting extension is to consider the case where $F$ has finite mean but infinite variance. The difficulty here is that the CLT for Poisson sums has to be replaced with some sort of stable limit.

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PROOF OF THEOREM 3.1. From [2] we get that for $S_n = Y_1 + \cdots + Y_n$

$$\mathbb{P}(K(u) = n) = \frac{\rho^n}{\psi(u)} \mathbb{P}(S_n > u, S_{n-1} \leq u).$$

From Lemma 3.2 we get that

$$\begin{aligned}&\mathbb{P}^{(u,n)}(Z_1 + \cdots + Z_n > xe(u))\mathbb{P}(K(u) = n)\\ &= \frac{\rho^n \overline{F}_0(u + xe(u))}{\psi(u)} + \frac{3\mathbb{E}\left[(n-1)X_1^2\right]}{2\mu^2} \frac{\rho^n \overline{F}(u + xe(u))}{\psi(u)} + o\left(\frac{\overline{F}(u)}{\psi(u)}\right).\end{aligned}$$

Summing over $n$ we get that

$$\begin{aligned}&\mathbb{P}^{(u)}(Z_1 + \cdots + Z_{K(u)} > xe(u))\\ &= \frac{\rho \overline{F}_0(u + xe(u))}{(1-\rho)\psi(u)} + \frac{3\mathbb{E}\left[X_1^2\right]}{2\mu^2} \frac{\rho^2 \overline{F}(u + xe(u))}{(1-\rho)^2\psi(u)} + o\left(\frac{\overline{F}(u)}{\psi(u)}\right).\end{aligned}$$

From Lemmas 3.3 and 3.4 we get that

$$W_u = \frac{Z_1 + \cdots + Z_{K(u)}}{x(1-\rho)e(u)}$$

fulfills the conditions of Lemma 3.5 and hence

$$\begin{aligned}1 - \frac{\psi(u, xe(u))}{\psi(u)} &= \frac{\rho \overline{F}_0(u + x(1-\rho)e(u))}{(1-\rho)\psi(u)}\\ &\quad + \frac{3\mathbb{E}\left[X_1^2\right]}{2\mu^2} \frac{\rho^2 \overline{F}(u + x(1-\rho)e(u))}{(1-\rho)^2\psi(u)}\\ &\quad - \frac{\lambda \mathbb{E}\left[X_1^2\right]}{2e(u)(1-\rho)} \left(\frac{1}{x(1-\rho)} g_\infty(1) + \frac{1}{x(1-\rho)} g'_\infty(1)\right)\\ &\quad + o\left(\frac{1}{e(u)}\right) + o\left(\frac{\overline{F}(u)}{\psi(u)}\right).\end{aligned}$$

The Theorem follows from (e.g. [1])

$$\psi(u) = \frac{\rho}{1-\rho} \overline{F}_0(u) + \frac{\lambda^2}{2(1-\rho)^2} \mathbb{E}\left[X_1^2\right] \overline{F}(u) + o(\overline{F}(u)). \qquad \square$$

**4. Some notation.** The notation of this section will be used in the rest of the paper without further mentioning. Recall from Assumption 3.1 that $\widehat{F}(s) = \mathbb{E}[\mathrm{e}^{-sX}]$ is the Laplace transform of the claim size distribution $F$ and let $\kappa(s) = s + \lambda(\widehat{F}(s) - 1)$. Then we have

$$\mathbb{E}\left[\mathrm{e}^{-sV_t}\right] = \mathrm{e}^{t\kappa(s)}.$$

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We get from [2, Lemma XI.3.1]

$$\mathbb{E}\left[\mathrm{e}^{-sw(z)}\right] = \mathrm{e}^{-\kappa^{-1}(s)z}.$$

For a function $g(x)$ we denote with $\widehat{L}_g(s) = \int_0^\infty \mathrm{e}^{-sx} g(x)\mathrm{d}x$ the Laplace transform. Note that

$$\widehat{L}_F(s) = \frac{1}{s}\widehat{F}(s).$$

To study the distribution of $w(z)$, note that we can write

$$w(z) = z + \sum_{i=1}^{N_z} E_i,$$

where the $E_i$ are iid having the distribution of $E = w(X)$ (the $E_i$ represent the excursions of $R_t$ away from its running maximum). Also, as a sample path inspection immediately shows, $E$ has the busy period distribution in the usual dual M/G/1 queue (see [2, pp. 45–48]). Since the Laplace transform is $\widehat{F}_E(s) = \widehat{F}(\kappa^{-1}(s))$, it follows that

$$\mathbb{E}[E] = \mathbb{E}[X]/(1-\lambda\mathbb{E}[X]) = \mathbb{E}[X]/(1-\rho)$$
$$\mathbb{E}\left[E^2\right] = \frac{\mathbb{E}\left[X^2\right]}{(1-\rho)^2}\left(1+\frac{\lambda\mathbb{E}[X]}{1-\rho}\right) = \frac{\mathbb{E}\left[X^2\right]}{(1-\rho)^3}.$$

Write $h(z) = w(z) - z(\lambda\mathbb{E}[E]+1) = w(z) - z/(1-\rho)$ and $U(z) = h(z)/\sqrt{z}$. By the central limit theorem, $U(z) \to N(0, \lambda\mathbb{E}[E^2])$. For the proof it would be helpful if also the density and the derivative of the density of the distribution of $U(z)$ would converge to the same quantities of the normal distribution and fulfill certain boundedness conditions. Now in practice this leads to two problems. First $U(z)$ has point mass in $-\sqrt{z}\lambda\mathbb{E}[E]$ and hence no density. Nevertheless since we are interested in the tail this is no real problem. The technical bigger problem is to show that $U(z)$ has a differentiable density. This more or less leads to the question whether $E$ has a differentiable derivative. Since the claim size density $f$ and the density of $E$ have the same degree of smoothness and we did not assume that $f$ is differentiable, this is not straightforward to prove. Hence we will use smoothing with a normal random variable. This will cause some extra technicalities in some other places but simplifies the discussion of the existence of differentiable densities and corresponding bounds. Therefore denote with $\mathcal{N}_u$ a normal random variable with mean zero and variance $\sigma_u^2 = e(u)^{-4}$.

In the proofs of this paper we will often rely on Taylor approximations with remainder terms. Therefore we will need to evaluate a function on an

interim value which we will denote with $\xi_\Theta$ where $\Theta$ stands for the parameters on which $\xi$ depends. With a little abuse of notation we will also use this notation when we use Taylor expansions for a complex function (in this case one would have for the real and the imaginary part a different $\xi$) and when the derivative is not continuous.

**5. Proof of Lemma 3.5 (The connection between $w(W)$ and $W$).** Before the proof of Lemma 3.5 we need some technical Lemmas.

LEMMA 5.1. *Let*

$$x(w,u) = \frac{x(1-\rho)}{1+(1-\rho)\frac{w}{\sqrt{e(u)}}}. \tag{5.1}$$

*Then uniformly for $w < M$*

$$\begin{aligned}
&\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}} > w\sqrt{x(w,u)}\right)\\
&= \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right)\\
&\quad + w^2\sqrt{x(1-\rho)}\frac{1-\rho}{\sqrt{e(u)}} f_{0,\infty}(w\sqrt{x(1-\rho)})\\
&\quad + \frac{(1-\rho)w}{2\sqrt{e(u)}}\lambda\mathbb{E}\left[E^2\right] f'_{w,\infty}\left(w\sqrt{x(1-\rho}\right)\\
&\quad + o(1/\sqrt{e(u)}).
\end{aligned}$$

*where $f_{w,\infty} = f_{0,\infty}$ is the density of a normal distribution with mean 0 and variance $\lambda\mathbb{E}[E^2]$.*

PROOF. Denote with $f_{w,u}(x)$ the density of

$$Z_u = \mathcal{N}_u + \frac{h\left(x(w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}}.$$

and with $\widehat{f}_{w,u}(x)$ the density of

$$\widehat{Z}_u = \widehat{\mathcal{N}}_u + \frac{\widehat{h}\left((x(0,u)-x(w,u))e(u)\right)}{\sqrt{(x(0,u)-x(w,u))e(u)}}.$$

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where $\widehat{\mathcal{N}}_u$ is an independent copy of $\mathcal{N}_u$ and $\widehat{h}(z)$ is an independent copy of $h(z)$. $Z_u$ and $\widehat{Z}_u$ are independent. Note that

$$\mathcal{N}_u \stackrel{d}{=} \sqrt{\frac{x(w,u)}{x(0,u)}}\left(\mathcal{N}_u + \sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\widehat{\mathcal{N}}_u\right)$$

where $\stackrel{d}{=}$ means equality in distribution and for $a, b \geq 0$

$$h(a) + \widehat{h}(b) \stackrel{d}{=} h(a+b).$$

Since $x(w,u)$ is monotonically decreasing in $w$, we get that

$$\begin{aligned}
&\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\frac{x(w,u)}{\sqrt{x(0,u)}}\right)\\
&= \mathbb{P}\left(\sqrt{\frac{x(w,u)}{x(0,u)}}\left(\mathcal{N}_u + \sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\widehat{\mathcal{N}}_u\right)\right.\\
&\qquad \left. + \frac{h\left(x(w,u)e(u)\right) + \widehat{h}\left(\left(x(0,u)-x(w,u)\right)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\frac{x(w,u)}{\sqrt{x(0,u)}}\right)\\
&= \mathbb{P}\left(Z_u + \sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\widehat{Z}_u > w\sqrt{x(w,u)}\right)\\
&= \mathbb{P}\left(Z_u > w\sqrt{x(w,u)}\right) + \sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\mathbb{E}\left[\widehat{Z}_u\right] f_{w,u}(w\sqrt{x(w,u)})\\
&\quad - \frac{(1-\rho)w}{2\sqrt{e(u)}}\mathbb{E}\left[\widehat{Z}_u^2 f'_{w,u}(w\sqrt{x(w,u)} + \xi_{w,u})\right]\\
&= \mathbb{P}\left(Z_u > w\sqrt{x(w,u)}\right) - \frac{(1-\rho)w}{2\sqrt{e(u)}}\mathbb{E}\left[\widehat{Z}_u^2\right] f'_{w,\infty}\left(w\sqrt{x(1-\rho)}\right)\\
&\quad + o\left(\frac{1}{\sqrt{e(u)}}\right).
\end{aligned}$$

Here the last equality follows by bounded convergence (for large enough $u$ $f_{w,u}(x)$ can be bounded compare Lemma A.2). Finally note that

$$\begin{aligned}
&\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\frac{x(w,u)}{\sqrt{x(0,u)}}\right)\\
&= \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right)
\end{aligned}$$

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$$+\left(w\frac{x(0,u)-x(w,u)}{\sqrt{x(0,u)}}\right)f_{0,u}(w\sqrt{x(0,u)}+\xi_{u,w})$$
$$=\mathbb{P}\left(\mathcal{N}_u+\frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}}>w\sqrt{x(0,u)}\right)$$
$$+w^2\sqrt{x(1-\rho)}\frac{1-\rho}{\sqrt{e(u)}}f_{0,\infty}(w\sqrt{x(0,u)})+o\left(\frac{1}{\sqrt{e(u)}}\right).$$

□

LEMMA 5.2. *For every $c>0$,*

$$\left|\mathbb{P}\left(\mathcal{N}_u+\frac{h\left(x(w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}}>w\sqrt{x(w,u)}\right)\right.$$
$$\left.-\mathbb{P}\left(\mathcal{N}_u+\frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}}>w\frac{x(w,u)}{\sqrt{x(0,u)}}\right)\right|$$
$$\le\frac{C_1}{w^2\sqrt{e(u)}}+C_2w\sqrt{e(u)}\mathbb{P}\left(E>\frac{\epsilon_1}{2}w\sqrt{e(u)}\sqrt{(1-\rho)x(w,u)}\right)+o\left(\frac{1}{e(u)}\right)$$

*uniformly in $M\le w<c\sqrt{e(u)}$, where $x(w,u)$ is defined by (5.1).*

PROOF. We use the notation of the proof of Lemma 5.1.

Choose an $0<\epsilon_1<1$. Since $x(w,u)$ is monotonically decreasing in $w$, we get that

$$\mathbb{P}\left(\mathcal{N}_u+\frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}}>w\frac{x(w,u)}{\sqrt{x(0,u)}}\right)$$
$$=\mathbb{P}\left(Z_u+\sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\widehat{Z}_u>w\sqrt{x(w,u)},|\widehat{Z}_u|\le\epsilon_1\sqrt{w\sqrt{e(u)}}\right)$$
$$+\mathbb{P}\left(Z_u+\sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\widehat{Z}_u>w\sqrt{x(w,u)},|\widehat{Z}_u|>\epsilon_1\sqrt{w\sqrt{e(u)}}\right).$$

Note that

$$\mathbb{P}\left(Z_u+\sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\widehat{Z}_u>w\sqrt{x(w,u)},|\widehat{Z}_u|\le\epsilon_1\sqrt{w\sqrt{e(u)}}\right)$$
$$=\mathbb{P}\left(Z_u>w\sqrt{x(w,u)},|\widehat{Z}_u|\le\epsilon_1\sqrt{w\sqrt{e(u)}}\right)$$

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$$+\sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\mathbb{E}\left[\widehat{Z}_u 1_{\left\{|\widehat{Z}_u|\le\epsilon_1\sqrt{w\sqrt{e(u)}}\right\}}\right] f_{w,u}(w\sqrt{x(w,u)})$$
$$+\frac{(1-\rho)w}{\sqrt{e(u)}}\mathbb{E}\left[\widehat{Z}_u^2 f'_{w,u}(w\sqrt{x(w,u)}+\xi_{w,u})1_{\left\{|\widehat{Z}_u|\le\epsilon_1\sqrt{w\sqrt{e(u)}}\right\}}\right].$$

Since $\mathbb{E}[\widehat{Z}_u]=0$ we get that

$$\left|\mathbb{E}\left[\widehat{Z}_u 1_{\left\{|\widehat{Z}_u|\le\epsilon_1\sqrt{w\sqrt{e(u)}}\right\}}\right]\right| = \left|\mathbb{E}\left[\widehat{Z}_u 1_{\left\{|\widehat{Z}_u|>\epsilon_1\sqrt{w\sqrt{e(u)}}\right\}}\right]\right|$$
$$\le \frac{1}{\epsilon_1\sqrt{w\sqrt{e(u)}}}\left|\mathbb{E}\left[\widehat{Z}_u^2 1_{\left\{|\widehat{Z}_u|>\epsilon_1\sqrt{w\sqrt{e(u)}}\right\}}\right]\right|.$$

By Lemma A.3 $x^2 f_{w,u}(x)$ is bounded and hence for some $c_1>0$

$$\sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\mathbb{E}\left[\widehat{Z}_u 1_{\left\{|\widehat{Z}_u|\le\epsilon_1\sqrt{w\sqrt{e(u)}}\right\}}\right] f_{w,u}(w\sqrt{x(w,u)}))$$
$$\le c_1\mathbb{E}\left[\widehat{Z}_u^2\right]\frac{1}{w^2\sqrt{e(u)}}.$$

Denote with

$$a=\left(\frac{(1-\rho)x}{1+c(1-\rho)}-\epsilon_1\sqrt{1-\rho}\right)\quad\text{and}\quad b=\left((1-\rho)x+\epsilon_1\sqrt{1-\rho}\right).$$

We will assume that $\epsilon_1$ is chosen such that $a>0$. From

$$\mathbb{E}\left[\widehat{Z}_u^2 f'_{w,u}(w\sqrt{x(w,u)})+\xi_{w,u})1_{\left\{|\widehat{Z}_u|\le\epsilon_1\sqrt{w\sqrt{e(u)}}\right\}}\right]$$
$$\le \mathbb{E}\left[\widehat{Z}_u^2\right]\sup_{aw<x<bw} f'_{w,u}(x)$$

and Lemma A.3 we get that $\sup_{aw<x<bw} f'_{w,u}(x)\le c_2/w^3$ and for some $c_3>0$

$$\frac{(1-\rho)w}{\sqrt{e(u)}}\mathbb{E}\left[\widehat{Z}_u^2 f'_{w,u}(w\sqrt{x(w,u)})+\xi_{w,u})1_{\left\{|\widehat{Z}_u|\le\epsilon_1\sqrt{w\sqrt{e(u)}}\right\}}\right]$$
$$\le c_3\mathbb{E}\left[\widehat{Z}_u^2\right]\frac{1}{w^2\sqrt{e(u)}}.$$

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Further we have with Lemma A.5 and $\mathbb{P}(|X+Y|>u) \le \mathbb{P}(|X|>u/2) + \mathbb{P}(|Y|>u/2)$ that for a standard normal distributed random variable $\mathcal{N}$

$$\begin{aligned}
&\mathbb{P}\left(Z_u + \sqrt{\frac{(1-\rho)w}{\sqrt{e(u)}}}\widehat{Z}_u > w\sqrt{x(w,u)}, |\widehat{Z}_u| > \epsilon_1\sqrt{w\sqrt{e(u)}}\right)\\
&\le \mathbb{P}\left(|\widehat{Z}_u| > \epsilon_1\sqrt{w\sqrt{e(u)}}\right)\\
&\le C_2 w(1-\rho)x(w,u)\sqrt{e(u)}\sqrt{x(w,u)}\mathbb{P}\left(E > \frac{\epsilon_1}{2}w\sqrt{e(u)}\sqrt{(1-\rho)x(w,u)}\right)\\
&\quad + e^{-\delta\frac{\epsilon_1}{4}w\sqrt{e(u)}\sqrt{(1-\rho)x(w,u)}} + \mathbb{P}\left(|\mathcal{N}| > \frac{\epsilon_1}{2}\sqrt{w\sqrt{e(u)}}\right).
\end{aligned}$$

□

LEMMA 5.3. *We have*

$$\begin{aligned}
&\int_M^{c\sqrt{e(u)}} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\frac{x(w,u)}{\sqrt{x(0,u)}}\right) \mathrm{d}w\\
&= \int_M^{c\sqrt{e(u)}} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) \mathrm{d}w + R(u,M),
\end{aligned}$$

*where*

$$R(u,M) \lesssim \frac{C_M}{\sqrt{e(u)}}$$

*and* $C_M \to 0$ *as* $M \to \infty$.

PROOF. By substitution we get that

$$\int_M^{c\sqrt{e(u)}} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\frac{x(w,u)}{\sqrt{x(0,u)}}\right) \mathrm{d}w$$

(5.2)
$$= \int_{\frac{M}{1+M\frac{1-\rho}{\sqrt{e(u)}}}}^{\frac{c\sqrt{e(u)}}{1+c(1-\rho)}} \frac{1}{1-w\frac{1-\rho}{\sqrt{e(u)}}} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) \mathrm{d}w$$

(5.3)
$$+ \frac{1-\rho}{\sqrt{e(u)}} \int_{\frac{M}{1+M\frac{1-\rho}{\sqrt{e(u)}}}}^{\frac{c\sqrt{e(u)}}{1+c(1-\rho)}} \frac{w}{\left(1-w\frac{1-\rho}{\sqrt{e(u)}}\right)^2}$$

$$\times \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) \mathrm{d}w$$

(5.3) can be bounded by

$$\frac{1-\rho}{\sqrt{e(u)}}(1+c(1-\rho))^2 \times \int_{\frac{M}{1+M\frac{1-\rho}{\sqrt{e(u)}}}}^{\infty} w\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) \mathrm{d}w \sim \frac{c_M}{\sqrt{e(u)}}.$$

where $c_M \to 0$ as $M \to \infty$. For (5.2) we have

$$\int_{\frac{M}{1+M\frac{1-\rho}{\sqrt{e(u)}}}}^{\frac{c\sqrt{e(u)}}{1+c(1-\rho)}} \frac{1}{1-w\frac{1-\rho}{\sqrt{e(u)}}}\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) \mathrm{d}w$$

(5.4)

$$= \int_{\frac{M}{1+M\frac{1-\rho}{\sqrt{e(u)}}}}^{\frac{c\sqrt{e(u)}}{1+c(1-\rho)}} \frac{1-\rho}{\sqrt{e(u)}}\frac{w}{1-w\frac{1-\rho}{\sqrt{e(u)}}}\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) \mathrm{d}w$$

(5.5)

$$+ \int_{\frac{M}{1+M\frac{1-\rho}{\sqrt{e(u)}}}}^{\frac{c\sqrt{e(u)}}{1+c(1-\rho)}} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) \mathrm{d}w.$$

Here (5.4) can be bounded similar to (5.3). The integral (5.5) split into

$$\int_M^{c\sqrt{e(u)}} + \int_{\frac{M}{1+M\frac{1-\rho}{\sqrt{e(u)}}}}^{M} - \int_{\frac{c\sqrt{e(u)}}{1+c(1-\rho)}}^{c\sqrt{e(u)}} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) \mathrm{d}w.$$

where the last integral can be bounded as in (5.9) below. Further

$$\int_{\frac{M}{1+M\frac{1-\rho}{\sqrt{e(u)}}}}^{M} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) \mathrm{d}w$$

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$$\leq \frac{1}{\sqrt{e(u)}} \frac{M^2(1-\rho)}{1+M\frac{1-\rho}{\sqrt{e(u)}}} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > \frac{M\sqrt{x(0,u)}}{1+M\frac{1-\rho}{\sqrt{e(u)}}}\right)$$
$$\sim \frac{M^2(1-\rho)}{\sqrt{e(u)}} \left(1-\Phi\left(\frac{M\sqrt{x(1-\rho)}}{\sqrt{\lambda\mathbb{E}\left[E^2\right]}}\right)\right).$$

□

Lemmas 5.1, 5.2 and 5.3 consider the positive part of

$$\mathcal{N}_u + \frac{h\left(x(-w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}}.$$

We now provide the similar Lemmas for the negative part. We will skip the proofs since they are obvious modifications of the proofs of Lemmas 5.1, 5.2 and 5.3.

LEMMA 5.4. *For every $c>0$,*

$$\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(-w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}} \leq -w\sqrt{x(-w,u)}\right)$$
$$= \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} \leq -w\sqrt{x(0,u)}\right)$$
$$- w^2\sqrt{x(1-\rho)}\frac{(1-\rho)}{\sqrt{e(u)}} f_{0,\infty}(-w\sqrt{x(1-\rho)})$$
$$+ \frac{w(1-\rho)}{2\sqrt{e(u)}}\mathbb{E}\left[\widehat{Z}_u^2\right] f'_{0,\infty}\left(-w\sqrt{x(1-\rho)}\right) + o\left(\frac{1}{\sqrt{e(u)}}\right)$$

*uniformly in $w<M$, where $x(w,u)$ is defined by (5.1) and $f_\infty$ is the density of a normal distribution with mean 0 and variance $\lambda\mathbb{E}[E^2]$.*

LEMMA 5.5. *For every $c>0$*

$$\left|\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(-w,u)e(u)\right)}{\sqrt{x(-w,u)e(u)}} \leq -w\sqrt{x(-w,u)}\right)\right.$$
$$\left. -\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} \leq -w\frac{x(-w,u)}{\sqrt{x(0,u)}}\right)\right|$$
$$\leq \frac{C_1}{w^2\sqrt{e(u)}} + C_2 w\sqrt{e(u)}\mathbb{P}\left(E > \frac{\epsilon_1}{2} w\sqrt{e(u)}\sqrt{(1-\rho)x(w,u)}\right) + o\left(\frac{1}{e(u)}\right)$$

*uniformly in $M\leq w<c\sqrt{e(u)}$, where $x(w,u)$ is defined by (5.1).*

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LEMMA 5.6. *We have*

$$\int_M^{c\sqrt{e(u)}} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} \le -w\frac{x(-w,u)}{\sqrt{x(0,u)}}\right) \mathrm{d}w$$
$$= \int_M^{c\sqrt{e(u)}} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} \le -w\sqrt{x(0,u)}\right) \mathrm{d}w + R(u,M),$$

*where*

$$R(u,M) \lesssim \frac{C_M}{\sqrt{e(u)}}$$

*and* $C_M \to 0$ *as* $M \to \infty$.

LEMMA 5.7. *We have*

$$\int_0^{c\sqrt{xe(u)}} \mathbb{P}\left(\mathcal{N}_u + \frac{h(xe(u))}{\sqrt{xe(u)}} \le -w\right) - \mathbb{P}\left(\mathcal{N}_u + \frac{h(xe(u))}{\sqrt{xe(u)}} > w\right) \mathrm{d}w$$
$$= o\left(\frac{1}{\sqrt{e(u)}}\right).$$

PROOF. Denote with $\widehat{\chi}_u$ the characteristic function of $\mathcal{N}_u + h(xe(u))/\sqrt{xe(u)}$. From the Gil-Pelaez inversion formula we get that (c.f. [14, 21])

$$\int_0^{c\sqrt{xe(u)}} \mathbb{P}\left(\mathcal{N}_u + \frac{h(xe(u))}{\sqrt{xe(u)}} > w\right) - \mathbb{P}\left(\mathcal{N}_u + \frac{h(xe(u))}{\sqrt{xe(u)}} \le w\right) \mathrm{d}w$$
$$= \int_0^{c\sqrt{xe(u)}} \frac{1}{\pi}\int_0^\infty \frac{1}{s}\mathrm{Im}\left(\mathrm{e}^{-\iota ws}\widehat{\chi}_u(s)\right)\mathrm{d}s + \frac{1}{\pi}\int_0^\infty \frac{1}{s}\mathrm{Im}\left(\mathrm{e}^{\iota ws}\widehat{\chi}_u(s)\right)\mathrm{d}s\mathrm{d}w$$
$$= \int_0^{c\sqrt{xe(u)}} \frac{2}{\pi}\int_0^\infty \frac{\cos(ws)}{s}\mathrm{Im}(\widehat{\chi}_u(s))\mathrm{d}s\mathrm{d}w$$
$$= \frac{2}{\pi}\int_0^{\epsilon\sqrt{xe(u)}} \frac{\sin(c\sqrt{x(e(u))}s)}{s^2}\mathrm{Im}(\widehat{\chi}_u(s))\mathrm{d}s$$
$$+ \frac{2}{\pi}\int_{\epsilon\sqrt{xe(u)}}^\infty \frac{\sin(c\sqrt{x(e(u))}s)}{s^2}\mathrm{Im}(\widehat{\chi}_u(s))\mathrm{d}s$$
$$= I_1(u) + I_2(u),$$

where $\epsilon$ is chosen such that for $|s| < \epsilon$, $-\mathrm{Re}(\chi_E''(s)) \ge \delta_1$ for some $\delta_1 > 0$. Since there exists a $\delta > 0$ such that for all $|s| > \epsilon$, $\mathrm{Re}(1 - \chi_E(s)) \ge \delta$ ($E_i$ is non lattice). We get for $s > \epsilon\sqrt{xe(u)}$

$$|\mathrm{Im}(\widehat{\chi}_u(s))| \le \mathrm{e}^{-\frac{s^2\sigma_u^2}{2}}\mathrm{e}^{-\delta\lambda xe(u)}.$$

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and hence $I_2(u)$ goes to 0 faster than any power of $e(u)$. Denote with

$$A_1(s,u) = \lambda x e(u) \int_0^\infty \cos\left(\frac{st}{\sqrt{xe(u)}}\right) - 1 \, \mathrm{d}F_E(t),$$
$$A_2(s,u) = \lambda\sqrt{xe(u)} \int_0^\infty \sqrt{xe(u)} \sin\left(\frac{st}{\sqrt{xe(u)}}\right) - st \, \mathrm{d}F_E(t)$$

To get a bound for $I_1(u)$ we get from Lemma A.1 that we have to study the derivative of

$$\frac{1}{s^2}\mathrm{Im}(\chi_u(s)) = \frac{1}{s^2}\mathrm{e}^{-\frac{s^2\sigma_u^2}{2}} \sin\left(A_2(s,u)\right)\mathrm{e}^{A_1(s,u)}$$

which is the sum of $D_1$, $D_2$ and $D_3$ given by

$$D_1 = \frac{\sigma_u^2}{s}\mathrm{e}^{-\frac{s^2\sigma_u^2}{2}} \sin\left(A_2(s,u)\right)\mathrm{e}^{A_1(s,u)}$$
$$D_2 = \frac{1}{s^2}\mathrm{e}^{-\frac{s^2\sigma_u^2}{2}} \sin\left(A_2(s,u)\right)\mathrm{e}^{A_1(s,u)}$$
$$\times \left(\lambda x e(u) \int_0^\infty \frac{-t}{\sqrt{xe(u)}} \sin\left(\frac{st}{\sqrt{xe(u)}}\right) \, \mathrm{d}F_E(t)\right)$$
$$D_3 = \frac{1}{s^2}\mathrm{e}^{-\frac{s^2\sigma_u^2}{2}}\mathrm{e}^{A_1(s,u)}$$
$$\times \left\{ \cos\left(A_2(s,u)\right)\left(\lambda\sqrt{xe(u)} \int_0^\infty t\left(\cos\left(\frac{st}{\sqrt{xe(u)}}\right) - 1\right) \, \mathrm{d}F_E(t)\right)\right.$$
$$\left. - \frac{2}{s}\sin\left(A_2(s,u)\right)\right\}$$

Note that

$$-\frac{A_1(s,u)}{\lambda x e(u)} = \mathrm{Re}\left(\chi_E\left(\frac{s}{\sqrt{xe(u)}}\right)\right) - 1$$
$$= -\frac{s^2}{2xe(u)}\mathrm{Re}\left(\chi_E''(\xi_{s,u})\right) \geq \delta_1\frac{s^2}{2xe(u)}.$$

Further note that

$$A_2(s,u) = -s^2 \int_0^\infty t^2 \sin\left(\xi_{s,u,t}\right) \mathrm{d}F_E(t), \tag{5.6}$$

where $0 < \xi_{s,u,t} < \frac{st}{\sqrt{xe(u)}}$. Now for $s \leq (xe(u))^{1/4}$ we have that

$$\left|\int_0^\infty t^2 \sin\left(\xi_{s,u,t}\right) \mathrm{d}t\right| = \left|\int_0^{(xe(u))^{1/8}} t^2 \sin\left(\xi_{s,u,t}\right) \mathrm{d}F_E(t)\right|$$

$$
\begin{aligned}
&+\left|\int_{(xe(u))^{1/8}}^{\infty} t^2 \sin\left(\xi_{s,u,t}\right) \mathrm{d}F_E(t)\right| \\
&\leq \int_0^{(xe(u))^{1/8}} t^2 \sin\left((xe(u))^{-1/8}\right) \mathrm{d}F_E(t) \\
&\quad + \int_{(xe(u))^{1/8}}^{\infty} t^2 \mathrm{d}F_E(t) \\
&\leq \sin\left((xe(u))^{-1/8}\right) \mathbb{E}\left[E^2\right] + \int_{(xe(u))^{1/8}}^{\infty} t^2 \mathrm{d}F_E(t) \to 0 \qquad (5.7)
\end{aligned}
$$

as $u \to \infty$. Hence for every $\epsilon_1 > 0$ there exists an $u_0$ such that for $u > u_0$ (note that $|\sin(t)| \leq t$).

$$
|D_1| \leq \begin{cases} \mathbb{E}\left[E^2\right] s \exp(-\frac{\lambda\delta_1 s^2}{2}) & s > (xe(u))^{1/4} \\ \epsilon_1 s \exp(-\frac{\lambda\delta_1 s^2}{2}) & s \leq (xe(u))^{1/4} \end{cases}
$$

$$
|D_2| \leq \begin{cases} s\lambda\mathbb{E}\left[E^2\right]^2 \exp(-\frac{\lambda\delta_1 s^2}{2}) & s > (xe(u))^{1/4} \\ \epsilon_1 s\lambda\mathbb{E}\left[E^2\right] \exp(-\frac{\lambda\delta_1 s^2}{2}) & s \leq (xe(u))^{1/4} \end{cases}.
$$

It follows that

$$
\int_0^{\epsilon\sqrt{xe(u)}} |D_1| + |D_2| \mathrm{d}s = o\left(1\right).
$$

At last we have to bound $\int_0^1 |D_3| \mathrm{d}s + \int_1^{\epsilon\sqrt{xe(u)}} |D_3| \mathrm{d}s$. Since

$$
\lambda\sqrt{xe(u)} \int_0^{\infty} t \left(\cos\left(\frac{st}{\sqrt{xe(u)}}\right) - 1\right) \mathrm{d}F_E(t) = -\lambda s \int_0^{\infty} t^2 \sin(\xi_{s,u,x}) \mathrm{d}s.
$$

We get with the same method as above

$$
\int_1^{\epsilon\sqrt{xe(u)}} |D_3| \mathrm{d}s = o\left(1\right).
$$

For $0 < s < 1$ we get with (5.6) and (5.7) that for large enough $u$

$$
\begin{aligned}
|D_3| &\leq \frac{1}{s^2}\left|\cos\left(A_2(s,u)\right)\left(\lambda\sqrt{xe(u)} \int_0^{\infty} t \left(\cos\left(\frac{st}{\sqrt{xe(u)}}\right) - 1\right) \mathrm{d}F_E(t)\right)\right. \\
&\qquad \left. - \frac{2}{s}\sin\left(A_2(s,u)\right)\right| \\
&= \frac{\lambda\sqrt{xe(u)}}{s^2}\left|\int_0^{\infty} t \left(\cos\left(\frac{st}{\sqrt{xe(u)}}\right) - 1\right) \mathrm{d}F_E(t)\right.
\end{aligned}
$$

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$$
\begin{aligned}
&\quad - \frac{2}{s}\int_0^\infty \sqrt{xe(u)}\sin\left(\frac{st}{\sqrt{xe(u)}}\right) - st\ \mathrm{d}F_E(t)\Bigg| + o(1).\\
&\le 4\frac{\lambda\sqrt{xe(u)}}{s^2}\int_{\frac{1}{s}\sqrt{x(e(u))}}^\infty t\mathrm{d}F_E(t)\\
&\quad + \frac{2\sin(1)-3\cos(1)}{2\sqrt{xe(u)}}\int_0^{\frac{1}{s}\sqrt{x(e(u))}} t^3\mathrm{d}F_E(t) + o(1).
\end{aligned}
$$

It remains to show that $\int_0^1 \mathrm{d}s$ of the last expression is $o(1)$. From Karamata's Theorem it follows that

$$
\begin{aligned}
\int_0^1 4\frac{\lambda\sqrt{xe(u)}}{s^2}\int_{\frac{1}{s}\sqrt{x(e(u))}}^\infty t\mathrm{d}F_E(t)\mathrm{d}s &\sim c\int_0^1 \frac{\lambda xe(u)}{s^3}\overline{F}_E\left(\frac{1}{s}\sqrt{x(e(u))}\right)\mathrm{d}s\\
&= c\int_{\sqrt{xe(u)}}^\infty s\overline{F}_E(s)\,\mathrm{d}s = o(1).
\end{aligned}
$$

If $\mathbb{E}[E^3] < \infty$ then the Lemma follows. If $\mathbb{E}[E^3] = \infty$ and $\alpha \neq 3$ then

$$
\begin{aligned}
&\int_0^1 \frac{1}{\sqrt{xe(u)}}\int_0^{\frac{1}{s}\sqrt{x(e(u))}} t^3\mathrm{d}F_E(t)\mathrm{d}s\\
&\sim c\int_0^1 \frac{\lambda xe(u)}{s^3}\overline{F}_E\left(\frac{1}{s}\sqrt{x(e(u))}\right)\mathrm{d}s = o(1).
\end{aligned}
$$

If $\alpha = 3$ and $\mathbb{E}[E^3] = \infty$ then the integral is asymptotically less as when we replace $t^3$ with $t^{3.5}$ and the Lemma follows with the same argument. □

Proof of Lemma 3.5. First consider $W_u > 1/(1-\epsilon)$. We get from Lemma A.5 that there exists an $\delta > 0$ with

$$
\begin{aligned}
&\mathbb{P}(W_u > 1/(1-\epsilon)) - \mathbb{P}(w((1-\rho)xe(u)W_u) > xe(u), W_u > 1/(1-\epsilon))\\
&= \int_{1/(1-\epsilon)}^\infty \mathbb{P}\left(\frac{h((1-\rho)xe(u)w)}{(1-\rho)xe(u)w} \le \frac{1/w-1}{1-\rho}\right)\mathrm{d}G_u(w)\\
&\le \int_{1/(1-\epsilon)}^\infty \mathbb{P}\left(\frac{h((1-\rho)xe(u)w)}{(1-\rho)xe(u)w} \le -\frac{\epsilon}{1-\rho}\right)\mathrm{d}G_u(w)\\
&\le \int_{1/(1-\epsilon)}^\infty \mathrm{e}^{-\delta e(u)w}\mathrm{d}G_u(w)\\
&= o(e(u)^{-1}). \qquad (5.8)
\end{aligned}
$$

For $W_u < 1/(1+\epsilon)$ we get by [16]

$$
\mathbb{P}(w((1-\rho)xe(u)W_u) > xe(u), W_u < 1/(1+\epsilon))
$$

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$$
\begin{aligned}
&= \int_0^{1/(1+\epsilon)} \mathbb{P}\left(\frac{h((1-\rho)xe(u)w)}{(1-\rho)xe(u)w} > \frac{1/w-1}{1-\rho}\right) \mathrm{d}G_u(w) \\
&\sim \int_0^{1/(1+\epsilon)} \lambda(1-\rho)xe(u)w\mathbb{P}\left(E > (1-w)xe(u)\right) \mathrm{d}G_u(w) \\
&\le \lambda(1-\rho)xe(u)\mathbb{P}\left(E > \frac{\epsilon}{1+\epsilon}xe(u)\right) \int_0^{1/(1+\epsilon)} w\mathrm{d}G_u(w) \\
&= o(e(u)^{-1}). \qquad (5.9)
\end{aligned}
$$

It remains to consider the case $1/(1+\epsilon) < W_u < 1/(1-\epsilon)$.

$$
\begin{aligned}
&\mathbb{P}(w((1-\rho)xe(u)W_u) > xe(u), 1/(1+\epsilon) < W_u < 1/(1-\epsilon)) \\
&= \int_{1/(1+\epsilon)}^{1/(1-\epsilon)} \mathbb{P}\left(\frac{h((1-\rho)xe(u)w)}{(1-\rho)xe(u)w} > \frac{1/w-1}{1-\rho}\right) \mathrm{d}G_u(w) \\
&= \mathbb{P}(1 \le W_u < 1/(1-\epsilon)) \\
&\quad + \int_{1/(1+\epsilon)}^{1} \mathbb{P}\left(\frac{h((1-\rho)xe(u)w)}{(1-\rho)xe(u)w} > \frac{1/w-1}{1-\rho}\right) \mathrm{d}G_u(w) \qquad (5.10) \\
&\quad - \int_{1}^{1/(1-\epsilon)} \mathbb{P}\left(\frac{h((1-\rho)xe(u)w)}{(1-\rho)xe(u)w} \le \frac{1/w-1}{1-\rho}\right) \mathrm{d}G_u(w). \qquad (5.11)
\end{aligned}
$$

We start with (5.10). For $\mathcal{N}_u$ normally distributed with mean 0 and variance $\sigma_u^2 = (xe(u))^{-4}$, and $x(w,u)$ as in (5.1) we get from Lemma A.2

$$
\begin{aligned}
&\int_{1/(1+\epsilon)}^{1} \mathbb{P}\left(\frac{h((1-\rho)xe(u)w)}{(1-\rho)xe(u)w} > \frac{1/w-1}{1-\rho}\right) \mathrm{d}G_u(w) \qquad (5.12) \\
&= \frac{1-\rho}{\sqrt{e(u)}} \int_0^{\sqrt{e(u)}\epsilon/(1-\rho)} \mathbb{P}\left(\frac{h\left(x(w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}} > w\sqrt{x(w,u)}\right) \\
&\qquad \times \frac{g_u\left(\frac{1}{1+(1-\rho)\frac{w}{\sqrt{e(u)}}}\right)}{\left(1+(1-\rho)\frac{w}{\sqrt{e(u)}}\right)^2} \mathrm{d}w \\
&= \frac{1-\rho}{\sqrt{e(u)}} \int_0^{\sqrt{e(u)}\epsilon/(1-\rho)} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}} > w\sqrt{x(w,u)}\right) \\
&\quad \times \frac{g_u\left(\frac{1}{1+(1-\rho)\frac{w}{\sqrt{e(u)}}}\right)}{\left(1+(1-\rho)\frac{w}{\sqrt{e(u)}}\right)^2} \mathrm{d}w + o\left(\frac{1}{e(u)}\right)
\end{aligned}
$$

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(5.13)
$$= \frac{1-\rho}{\sqrt{e(u)}} \int_0^{\sqrt{e(u)}\epsilon/(1-\rho)} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}} > w\sqrt{x(w,u)}\right) g_u\left(1\right) \mathrm{d}w$$

(5.14)
$$- \frac{(1-\rho)^2}{e(u)} \int_0^{\sqrt{e(u)}\epsilon/(1-\rho)} w\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}} > w\sqrt{x(w,u)}\right)$$
$$\times \left(\frac{g_u'\left(\frac{1}{1+\xi_{u,w}}\right)}{(1+\xi_{u,w})^4} + 2\frac{g_u\left(\frac{1}{1+\xi_{u,w}}\right)}{(1+\xi_{u,w})^3}\right) \mathrm{d}w + o\left(\frac{1}{e(u)}\right).$$

We have to evaluate the integrals in (5.13) and (5.14) so we split the integrals into $\int_0^M$ and $\int_M^{\sqrt{e(u)}\epsilon/(1-\rho)}$. By Lemma 5.1 we get that

$$\frac{1-\rho}{\sqrt{e(u)}} \int_0^M \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}} > w\sqrt{x(w,u)}\right) g_u\left(1\right) \mathrm{d}w$$
$$= \frac{1-\rho}{\sqrt{e(u)}} \int_0^M \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) g_u\left(1\right) \mathrm{d}w$$
$$+ \frac{(1-\rho)^2}{e(u)} \int_0^M w^2\sqrt{x(1-\rho)} f_{0,\infty}(w\sqrt{x(1-\rho)}) g_u\left(1\right) \mathrm{d}w$$
$$+ \frac{(1-\rho)^2}{2e(u)} \lambda\mathbb{E}\left[E^2\right] \int_0^M w f_{w,\infty}'\left(w\sqrt{x(1-\rho)}\right) g_u\left(1\right) \mathrm{d}w$$
$$+ o(1/e(u)).$$

Note that

$$\lim_{M\to\infty} \int_0^M w^2\sqrt{x(1-\rho)} f_{0,\infty}(w\sqrt{x(1-\rho)}) g_\infty\left(1\right) \mathrm{d}w = \frac{g_\infty(1)\lambda\mathbb{E}\left[E^2\right]}{2x(1-\rho)}$$
$$\lim_{M\to\infty} \int_0^M w f_{w,\infty}'\left(w\sqrt{x(1-\rho}\right) g_\infty\left(1\right) \mathrm{d}w = -\frac{g_\infty(1)}{2x(1-\rho)}.$$
$$\lim_{M\to\infty} \lim_{u\to\infty} \int_0^M w\mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(w,u)e(u)\right)}{\sqrt{x(w,u)e(u)}} > w\sqrt{x(w,u)}\right)$$
$$\times \left(\frac{g_u'\left(\frac{1}{1+\xi_{u,w}}\right)}{(1+\xi_{u,w})^4} + 2\frac{g_u\left(\frac{1}{1+\xi_{u,w}}\right)}{(1+\xi_{u,w})^3}\right) \mathrm{d}w = \frac{\lambda\mathbb{E}\left[E^2\right]}{4x(1-\rho)} \left(g_\infty'(1) + 2g_\infty(1)\right).$$

For the integral $\int_M^{\sqrt{e(u)}\epsilon/(1-\rho)}$ we get from Lemmas 5.2 and 5.3 that there exist a function $R(M,u) \lesssim \frac{C_M}{e(u)}$ and $C_M \to 0$ as $u \to \infty$ such that the sum

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of (5.13) and (5.14) is the same as

$$\frac{1-\rho}{\sqrt{e(u)}}\int_M^{\sqrt{e(u)}\epsilon/(1-\rho)} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right) g_\infty(1)\,\mathrm{d}w + R(M,u).$$

With Lemmas 5.4, 5.5 and 5.6, we can get analogously the asymptotic of (5.11), so that we are left with the integrals

$$\int_0^{\sqrt{e(u)}\epsilon/(1-\rho)} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} > w\sqrt{x(0,u)}\right)\mathrm{d}w - \int_0^{\sqrt{e(u)}\epsilon/(1-\rho)} \mathbb{P}\left(\mathcal{N}_u + \frac{h\left(x(0,u)e(u)\right)}{\sqrt{x(0,u)e(u)}} \le -w\sqrt{x(0,u)}\right)\mathrm{d}w.$$

From Lemma 5.7 we get that the last equation is asymptotically negligibility and hence the Lemma follows. □

**6. Proofs of Lemmas 3.2–3.4 (The asymptotics of the $Z$).** As before, $S_n = \sum_{i=1}^n Y_i$, $M_n = \max_{1\le i\le n} Y_i$, $\widehat{S}_n = \sum_{i=1}^n Z_i$, and with $\widehat{M}_n = \max_{1\le i\le n} Z_i$

Proof of Lemma 3.2. Note that

$$\begin{aligned}&\mathbb{P}(S_n > u, S_{n-1} \le u, \widehat{S}_n > xe(u))\\ &= \sum_{i=1}^n \mathbb{P}(S_n > u, S_{n-1} \le u, \widehat{S}_n > xe(u), M_n = Y_i).\end{aligned}$$

At first we consider $\{M_n = Y_n\}$. We have that

$$\begin{aligned}&\mathbb{P}(S_n > u, S_{n-1} \le u, \widehat{S}_n > xe(u), M_n = Y_n)\\ &= \mathbb{P}(S_n > u, S_{n-1} \le u, \widehat{S}_n > xe(u), M_n = Y_n, S_{n-1} > u/2)\\ &\quad + \mathbb{P}(S_n > u, \widehat{S}_n > xe(u), M_n = Y_n, S_{n-1} \le u/2, \widehat{S}_{n-1} > u/2)\\ &\quad + \mathbb{P}(S_n > u, \widehat{S}_n > xe(u), M_n = Y_n, S_{n-1} \le u/2, \widehat{S}_{n-1} \le u/2).\end{aligned}$$

Since $F$ is regularly varying we get with the Potter bounds and Kesten's inequality that for every $\epsilon > 0$ there exists a $K > 0$ such that

$$\begin{aligned}&\mathbb{P}(S_n > u, S_{n-1} \le u, \widehat{S}_n > xe(u), M_n = Y_n, S_{n-1} > u/2)\\ &\le \mathbb{P}(Y_n > u/n)\mathbb{P}(S_{n-1} > u/2)\end{aligned}$$

$$\leq K(2n)^{\alpha+\epsilon}(1+\epsilon)^n\overline{F}_0(u)^2$$

and

$$\begin{aligned}&\mathbb{P}(S_n > u, S_{n-1} \leq u, \widehat{S}_n > xe(u), M_n = Y_n, \widehat{S}_{n-1} > u/2)\\ &\leq \mathbb{P}(Y_n > u/n)\mathbb{P}(\widehat{S}_{n-1} > xe(u))\\ &\leq K(2n)^{\alpha+\epsilon}(1+\epsilon)^n\overline{F}_0(u)\overline{F}(xe(u)).\end{aligned}$$

We are left with

$$\begin{aligned}&\mathbb{P}(S_n > u, \widehat{S}_n > xe(u), M_n = Y_n, S_{n-1} \leq u/2, \widehat{S}_{n-1} \leq xe(u)/2)\\ &= \int_0^{u/2}\int_0^{\frac{xe(u)}{2}} \overline{F}_0(u - S_{n-1} + xe(u) - \widehat{S}_{n-1})\mathrm{d}S_{n-1}\mathrm{d}\widehat{S}_{n-1}\\ &= \int_0^{u/2}\int_0^{\frac{xe(u)}{2}} \overline{F}_0(u + xe(u))\mathrm{d}S_{n-1}\mathrm{d}\widehat{S}_{n-1}\\ &\quad + \frac{1}{\mu}\int_0^{u/2}\int_0^{\frac{xe(u)}{2}} (S_{n-1} + \widehat{S}_{n-1})\overline{F}(u + xe(u) - \xi_{u,S_{n-1},\widehat{S}_{n-1}})\mathrm{d}S_{n-1}\mathrm{d}\widehat{S}_{n-1},\end{aligned}$$

where $0 < \xi_{u,S_{n-1},\widehat{S}_{n-1}} < S_{n-1} + \widehat{S}_{n-1} < (u + xe(u))/2$ and hence there exists a constant $C$ such that $\overline{F}(u + xe(u) - \xi_{u,S_{n-1},\widehat{S}_{n-1}}) \leq C\overline{F}(u + xe(u))$. It follows by dominated convergence that

$$\begin{aligned}&\frac{1}{\mu}\mathbb{E}\left[S_{n-1} + \widehat{S}_{n-1}\right]\overline{F}(u + xe(u))\\ &\lesssim \frac{1}{\mu}\int_0^{u/2}\int_0^{\frac{xe(u)}{2}} (S_{n-1} + \widehat{S}_{n-1})\overline{F}(u + xe(u) - \xi_{u,S_{n-1},\widehat{S}_{n-1}})\mathrm{d}S_{n-1}\mathrm{d}\widehat{S}_{n-1}\\ &\lesssim \frac{1}{\mu}\mathbb{E}\left[\frac{\overline{F}(u + xe(u) - S_{n-1} - \widehat{S}_{n-1})}{\overline{F}(u + xe(u))}1_{\{S_{n-1}\leq u, \widehat{S}_{n-1}\leq xe(u)\}}\right]\overline{F}(u + xe(u))\\ &\sim \frac{1}{\mu}\mathbb{E}\left[S_{n-1} + \widehat{S}_{n-1}\right]\overline{F}(u + xe(u)).\end{aligned}$$

Note that

$$\begin{aligned}1 - \int_0^{u/2}\int_0^{\frac{xe(u)}{2}} \mathrm{d}S_{n-1}\mathrm{d}\widehat{S}_{n-1} &\leq \mathbb{P}\left(S_{n-1} > u/2\right) + \mathbb{P}\left(\widehat{S}_{n-1} > \frac{xe(u)}{2}\right)\\ &\leq K(1+\epsilon)^n 2^{n+\epsilon}(\overline{F}_0(u) + \overline{F}_0(xe(u))).\end{aligned}$$

It follows that

$$\mathbb{P}(S_n > u, S_{n-1} \leq u, \widehat{S}_n > xe(u), M_n = Y_n)$$

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$$= \mathbb{P}(S_n > u, \widehat{S}_n > xe(u), M_n = Y_n) + \mathcal{O}(\overline{F}_0(u)^2)$$

$$= \overline{F}_0(u + xe(u)) + \frac{1}{\mu}\mathbb{E}\left[S_{n-1} + \widehat{S}_{n-1}\right]\overline{F}(u + xe(u)) + o(\overline{F}(u)). \tag{6.1}$$

Next consider $\{M_n = Y_i\}$ where w.l.o.g we will assume that $i = n-1$. Then we get with the same method that leads to (6.1)

$$\begin{aligned}
&\mathbb{P}(S_n > u, S_{n-1} < u, \widehat{S}_n > xe(u), M_n = Y_{n-1}) \\
&= \mathbb{P}(Y_{n-1} > u - S_{n-2} - Y_n, \widehat{S}_n > xe(u), M_n = Y_{n-1}) \\
&\quad - \mathbb{P}(Y_{n-1} > u - S_{n-2}, \widehat{S}_n > xe(u), M_n = Y_{n-1}) \\
&= \frac{1}{\mu}\mathbb{E}\left[Y_n\right]\overline{F}(u + xe(u)) + o(\overline{F}(u)).
\end{aligned}$$

□

Proof of Lemma 3.3. Note that

$$\begin{aligned}
&\mathbb{P}(S_{n-1} \le u, S_n > u, \widehat{S}_n \le x) \\
&= \int_0^x \int_0^u \mathbb{P}(Y_n > u - S_{n-1}, Z_n \le x - \widehat{S}_{n-1})\mathrm{d}S_{n-1}\mathrm{d}\widehat{S}_{n-1}
\end{aligned}$$

It follows that

$$\begin{aligned}
&\frac{\mathrm{d}\mathbb{P}(S_{n-1} \le u, S_n > u, \widehat{S}_n \le x)}{\mathrm{d}x} \\
&= \mu^{-n} \int_{S_{n-1}<u} \int_{u-S_{n-1}}^{\infty} \int_0^x \int_0^{x-x_1} \cdots \int_0^{x-\sum_{i=1}^{n-1} x_i} \\
&\quad f(x_1 + y_1) \cdots f(x_{n-1} + y_{n-1}) f\left(x - \sum_{i=1}^{n-1} x_i + y_n\right) \mathrm{d}x_1 \cdots \mathrm{d}x_{n-1}\mathrm{d}y_1 \cdots \mathrm{d}y_n
\end{aligned}$$

$$= \mu^{-1}\mathbb{E}\left[\overline{F}\left(u + x - S_{n-1} - \widehat{S}_{n-1}\right), S_{n-1} < u, \widehat{S}_{n-1} < x/2\right] \tag{6.2}$$

$$+ \mu^{-1}\mathbb{E}\left[\overline{F}\left(u + x - S_{n-1} - \widehat{S}_{n-1}\right), S_{n-1} < u, x/2 \le \widehat{S}_{n-1} < x\right]. \tag{6.3}$$

If we choose $x = yu$ for some $y > 0$ then we get with dominated convergence that (6.2) $\sim \overline{F}(u + x)$ further (6.2) $\le c(y)\overline{F}(u + x)$ for some $0 < c(y) < \infty$. To find a bound for (6.3) note that the mean over the region $Z_i > x/4n$ and $Z_j > x/4n$ can be bounded by $\overline{F}_0(x/4n)^2$ (and since $\mathbb{E}[X^2] < \infty$ we get that $\overline{F}_0(x)^2 = o(\overline{F}(x))$. By using the symmetry of the problem in the $Z_i$ we can

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asymptotically bound the mean of (6.3) by

$$\begin{aligned}&\mathbb{E}\Big[\overline{F}\left(u+x-S_{n-1}-\widehat{S}_{n-1}\right),\\&\qquad S_{n-2}>u/4, S_{n-1}<u, x/2\le\widehat{S}_{n-1}<x, \widehat{S}_{n-2}\le x/4\Big]\\&+\mathbb{E}\Big[\overline{F}\left(u+x-S_{n-1}-\widehat{S}_{n-1}\right),\\&\qquad S_{n-2}\le u/4, S_{n-1}<u, x/2\le\widehat{S}_{n-1}<x, \widehat{S}_{n-2}\le x/4\Big].\end{aligned}$$

If $S_{n-2}>u/4$ then one of the $Y_i$ $i\le n-2$ is bigger then $u/(4(n-2))$ and we can bound the corresponding mean by $\overline{F}_0(x/4)\overline{F}_0(u/(4(n-2))$.

It is left to bound the mean when $S_{n-2}\le u/4$. At first we assume that $S_{n-1}<u/2$ then we can use the same method to bound the mean by

$$\begin{aligned}&\mathbb{E}\left[\overline{F}\left(u+x-S_{n-1}-\widehat{S}_{n-1}\right), S_{n-1}\le u/2, x/2\le\widehat{S}_{n-1}<x, \widehat{S}_{n-2}\le x/4\right]\\&\le\mathbb{E}\left[\overline{F}\left(u/2\right), Z_{n-1}>x/4\right]=\overline{F}\left(u/2\right)\overline{F}_0(x/4).\end{aligned}$$

Finally note that

$$\begin{aligned}&\mathbb{E}\Big[\overline{F}\left(u+x-S_{n-1}-\widehat{S}_{n-1}\right),\\&\qquad S_{n-2}\le u/4, u/2<S_{n-1}\le u, x/2\le\widehat{S}_{n-1}<x, \widehat{S}_{n-2}\le x/4\Big]\\&=\mu^{-1}\mathbb{E}\Bigg[\int_{u/2-S_{n-2}}^{u-S_{n-2}}\int_{x/2-\widehat{S}_{n-2}}^{x-\widehat{S}_{n-2}}f(z+y)\\&\qquad\times\overline{F}\left(u+x-S_{n-2}-\widehat{S}_{n-2}-z-y\right)\mathrm{d}z\mathrm{d}y, S_{n-2}\le u/4, \widehat{S}_{n-2}\le x/4\Bigg]\\&=\mu^{-1}\mathbb{E}\Bigg[\int_0^{u/2}\int_0^{x/2}f(u+x-S_{n-2}-\widehat{S}_{n-2}-z-y)\\&\qquad\qquad\times\overline{F}\left(z+y\right)\mathrm{d}z\mathrm{d}y, S_{n-2}\le u/4, \widehat{S}_{n-2}\le x/4\Bigg]\\&\lesssim\mu^{-1}f((u+x)/4)\int_0^{u/2}\overline{F}\left(z+y\right)\mathrm{d}z\mathrm{d}y.\end{aligned}$$

The integral in the last equation is finite since $\mathbb{E}[X^2]<\infty$. □

Proof of Lemma 3.4. We can write

$$\frac{\mathrm{d}^2\mathbb{P}(S_{n-1}\le u, S_n>u, \widehat{S}_n\le x)}{\mathrm{d}x^2}$$

$$= -\mu^{-1}\mathbb{E}\left[f\left(u+x-S_{n-1}-\widehat{S}_{n-1}\right), S_{n-1}\le u, \widehat{S}_{n-1}\le x\right]$$
$$+\mu^{-2}\mathbb{E}\left[\int_0^{u-S_{n-2}} f\left(x-\widehat{S}_{n-2}+y\right)\overline{F}\left(u-S_{n-2}-y\right)\mathrm{d}y,\right.$$
$$\left. S_{n-2}\le u, \widehat{S}_{n-2}\le x\right]$$
$$= I_1 + I_2.$$

We only give a detailed asymptotic analysis for $I_2$ (the asymptotic of $I_1$ can be found analogously). If $S_{n-1}\le u/2$ and $\widehat{S}_{n-2}\le x/2$ then the mean can be asymptotically bounded by $\overline{F}(x/2)\overline{F}(u/2) = o(f(x+u))$. Next we consider the case where $S_{n-1} > u/2$ and only one $Y_i > u/(4n)$.

At first we assume that $S_{n-2}\le u/4$ and $u/2 < S_{n-1}\le u$. Then

$$\mu^{-1}\mathbb{E}\left[\int_{u/2-S_{n-2}}^{u-S_{n-2}} f\left(x-\widehat{S}_{n-2}+y\right)\overline{F}\left(u-S_{n-2}-y\right)\mathrm{d}y,\right.$$
$$\left. S_{n-2}\le u/4, \widehat{S}_{n-2}\le x\right]$$
$$= \mu^{-1}\mathbb{E}\left[\int_0^{u/2} f\left(x+u-\widehat{S}_{n-2}-y-S_{n-2}\right)\overline{F}\left(y\right)\mathrm{d}y,\right.$$
$$\left. S_{n-2}\le u/4, \widehat{S}_{n-2}\le x\right]$$
$$\sim f(x+u)$$

where the last equation follows with dominated convergence. If $Y_{n-1}\le u/(4n)$ then by symmetry it is enough to consider $Y_{n-2} > u/4$. Hence we get

$$\mu^{-2}\mathbb{E}\left[\int_0^{u/4-S_{n-3}}\int_0^{x-\widehat{S}_{n-3}}\int_{u/2-S_{n-3}-y}^{u-S_{n-3}-y} f\left(x-\widehat{S}_{n-3}-z_{n-2}+y\right)\right.$$
$$\times f(x_{n-2}+y_{n-2})\overline{F}\left(u-S_{n-3}-y_{n-2}-y\right)\mathrm{d}y_{n-2}\mathrm{d}z_{n-2}\mathrm{d}y,$$
$$\left. S_{n-3}\le u/4, \widehat{S}_{n-3}\le x\right]$$
$$= \mu^{-2}\mathbb{E}\left[\int_0^{u/4-S_{n-3}}\int_0^{x-\widehat{S}_{n-3}}\int_0^{u/2} f(x_{n-2}+u-S_{n-3}-y_{n-2}-y)\right.$$

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$$\times f\left(x-\widehat{S}_{n-3}-z_{n-2}+y\right)\overline{F}\left(y_{n-2}\right)\mathrm{d}y_{n-2}\mathrm{d}z_{n-2}\mathrm{d}y,$$
$$S_{n-3}\le u/4,\widehat{S}_{n-3}\le x\Bigg].$$

For $\widehat{S}_{n-2}\le x/2$ the above mean is $\mathcal{O}(\overline{F}(x/2)\overline{F}(u/4))=o(f(u+x))$. If $x/2<\widehat{S}_{n-2}<x$ and $Z_i\le x/4n$ for all but one $i\neq n-2$ the above mean is $\mathcal{O}(\overline{F}(x/4x)\overline{F}(u/4))$. If more then two $Z_i>x/4n$ $i\neq n-2$ the above mean is $\mathcal{O}(\overline{F}_0(x/4n)^2\overline{F}(u/4))$. If $Z_{n-2}>x/4n$ and another $Z_i>x/4n$ then the mean is $\mathcal{O}(\overline{F}_0(x/4n)\overline{F}(3u/4))$. Finally if all $Z_i\le x/4n$. then the above integral is asymptotically the same as $f(u+x)$. Similar we can show that when at least two $Y_i>u/4n$ the integral is asymptotically negligibly and hence $I_2\sim\mu^{-1}(n-1)f(u+x)$. With the same method we get that $I_1\sim-\mu^{-1}nf(u+x)$ and hence the Lemma follows. □

## APPENDIX A: SOME AUXILIARY LEMMAS

LEMMA A.1. *Assume that for a function $g_u(x)$ such that $\sup_{x,u}|g_u(x)|<\infty$, there exists a function $h(x)$ with $|g'_u(x)|\le h(x)$ for all $u>0$. Then for every function $a(u)$ we have as $u\to\infty$*

$$\left|\int_0^{a(u)}\sin(ux)g_u(x)\mathrm{d}x\right|\le\frac{1}{u}\int_0^{a(u)}h(x)\mathrm{d}x+o(1).$$

PROOF. The Lemma follows by partial integration:

$$\int_0^{a(u)}\sin(ux)g_u(x)\mathrm{d}x=\frac{1}{u}g_u(0)-\frac{\cos(ua(u))}{u}g_u(a(u))+\frac{1}{u}\int_0^{a(u)}\cos(ux)g'_u(x)\mathrm{d}x.$$

□

LEMMA A.2. *Assume that $E$ is non lattice and that $\mathbb{E}[E^2]<\infty$ and $h(z)=\sum_{i=1}^{N(z)}E_i-\lambda z\mathbb{E}[E]$ and $\mathcal{N}_u$ a normal random variable with mean zero and variance $\sigma_u^2\sim e(u)^{-k}$ for some $c>0$, $k>0$. Then the random variable $\mathcal{N}_u+h(xe(u))/\sqrt{xe(u)}$ has a differentiable density $f_u$. Further, if $a,b$ are arbitrary but fixed, it holds uniformly for $w$ and $0<a<x<b<\infty$ that*

$$\lim_{u\to\infty}f_u(w)=\frac{\exp\left(-\frac{w^2}{\lambda\mathbb{E}[E^2]}\right)}{\sqrt{2\pi\lambda\mathbb{E}\left[E^2\right]}},\quad\lim_{u\to\infty}f'_u(w)=\frac{-2w\exp\left(-\frac{w^2}{\lambda\mathbb{E}[E^2]}\right)}{\sqrt{2\pi(\lambda\mathbb{E}\left[E^2\right])^3}}.$$

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*If further $k \geq 4$ then*

$$\left| \mathbb{P}\left( \mathcal{N}_u + \frac{h(xe(u))}{\sqrt{xe(u)}} > w \right) - \mathbb{P}\left( \frac{h(xe(u))}{\sqrt{xe(u)}} > w \right) \right| = o\left( \frac{1}{e(u)} \right).$$

PROOF. Denote with $\chi_E(s)$ the characteristic function of $E$ and with $\sigma^2 = \lambda \mathbb{E}[E^2]$. Note that the Fourier transform of $f'_u(w) - f'_{N(0,\sigma^2)}(w)$ is

$$is\left( \mathrm{e}^{-\frac{\sigma_u^2 s^2}{2}} \mathrm{e}^{\lambda x e(u)\left(\chi_E\left(s/\sqrt{xe(u)}\right)-1\right) - i\sqrt{xe(u)}\lambda \mathbb{E}[E]s} - \mathrm{e}^{-\frac{\sigma^2 s^2}{2}} \right)$$

and hence

$$\begin{aligned} &|f'_u(w) - f'_{N(0,\sigma^2)}(w)| \\ &\leq \int_{-\infty}^{\infty} |s| \left| \mathrm{e}^{-\frac{\sigma_u^2 s^2}{2}} \mathrm{e}^{\lambda x e(u)\left(\chi_E\left(s/\sqrt{xe(u)}\right)-1\right) - i\sqrt{xe(u)}\lambda \mathbb{E}[E]s} - \mathrm{e}^{-\frac{\sigma^2 s^2}{2}} \right| \mathrm{d}s. \end{aligned}$$

Choose an $\epsilon > 0$ such that for $|x| \leq \epsilon$, $\mathrm{Re}(\chi''_E(x))$ is bounded away from 0. Since there exists a $\delta > 0$ such that for all $|s| > \epsilon$, $\mathrm{Re}(1 - \chi_E(s)) \geq \delta$ ($E$ is non lattice).

$$\begin{aligned} &\int_{\epsilon\sqrt{xe(u)}}^{\infty} |s| \left| \mathrm{e}^{-\frac{\sigma_u^2 s^2}{2}} \mathrm{e}^{\lambda x e(u)\left(\chi_E\left(s/\sqrt{xe(u)}\right)-1\right) - i\sqrt{xe(u)}\lambda \mathbb{E}[E]s} - \mathrm{e}^{-\frac{\sigma^2 s^2}{2}} \right| \mathrm{d}s \\ &\leq \mathrm{e}^{-\delta \lambda x e(u)} \int_{\epsilon\sqrt{xe(u)}}^{\infty} s \mathrm{e}^{-\frac{\sigma_u^2 s^2}{2}} \mathrm{d}s + \int_{\epsilon\sqrt{xe(u)}}^{\infty} s \mathrm{e}^{-s^2} \mathrm{d}s \\ &\leq \frac{1}{\sigma_u^2} \mathrm{e}^{-\delta \lambda x e(u)} \int_0^{\infty} s \mathrm{e}^{-\frac{s^2}{2}} \mathrm{d}s + \int_{\epsilon\sqrt{xe(u)}}^{\infty} s \mathrm{e}^{-s^2} \mathrm{d}s \to 0 \end{aligned}$$

as $u \to \infty$. With the same arguments

$$\int_{-\infty}^{-\epsilon\sqrt{xe(u)}} |s| \left| \mathrm{e}^{-\frac{\sigma_u^2 s^2}{2}} \mathrm{e}^{\lambda x e(u)\left(\chi_E\left(s/\sqrt{xe(u)}\right)-1\right) - i\sqrt{xe(u)}\lambda \mathbb{E}[E]s} - \mathrm{e}^{-\frac{\sigma^2 s^2}{2}} \right| \mathrm{d}s \to 0.$$

Further for a $\xi_{u,s}$ bounded away from 0 and $\xi_{u,s} \to \mathbb{E}[E^2]$ for fixed $s$ as $u \to \infty$

$$\begin{aligned} &\int_{-\epsilon\sqrt{xe(u)}}^{\epsilon\sqrt{xe(u)}} |s| \left| \mathrm{e}^{-\frac{\sigma_u^2 s^2}{2}} \mathrm{e}^{\lambda x e(u)\left(\chi_E\left(s/\sqrt{xe(u)}\right)-1\right) - i\sqrt{xe(u)}\lambda \mathbb{E}[E]s} - \mathrm{e}^{-\frac{\sigma^2 s^2}{2}} \right| \mathrm{d}s \\ &= \int_{-\epsilon\sqrt{xe(u)}}^{\epsilon\sqrt{xe(u)}} |s| \left| \mathrm{e}^{-\frac{\sigma_u^2 s^2}{2}} \mathrm{e}^{-\lambda \xi_{s,u} s^2/2} - \mathrm{e}^{-\frac{\sigma^2 s^2}{2}} \right| \mathrm{d}s. \end{aligned}$$

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By dominated convergence we get that the last integral tends to 0 as $u \to \infty$. Since the estimate of $|f_u(w) - f_{N(0,\sigma^2)}(w)|$ works with exactly the same arguments we leave it to the reader.

Denote with $\chi_u$ the characteristic function of $h(xe(u))/\sqrt{xe(u)}$. Since we can find an $m$ such that $f_u(w) \leq m$ for all $w$ and $u$ we get by Lemma XVI.4 2 of [13] that

$$\begin{aligned}
&\left|\mathbb{P}\left(\mathcal{N}_u + \frac{h(xe(u))}{\sqrt{xe(u)}} > w\right) - \mathbb{P}\left(\frac{h(xe(u))}{\sqrt{xe(u)}} > w\right)\right| \\
&\leq \frac{1}{\pi}\int_{-T}^{T}\left|\frac{\left(1 - \mathrm{e}^{-\frac{s^2\sigma_u^2}{2}}\right)\chi_u(s)}{s}\right|\mathrm{d}s + \frac{24m}{\pi T} \leq \frac{1}{\pi}\int_{-T}^{T}\left|\frac{s\sigma_u^2}{2}\right|\mathrm{d}s + \frac{24m}{\pi T} \\
&= \frac{\sigma_u^2 T^2}{2\pi} + \frac{24m}{\pi T}.
\end{aligned}$$

For $T = e(u)^{1+\epsilon}$ for some $0 < \epsilon < 1/2$ and $\sigma_u^2 \leq e(u)^{-4}$ we get that

$$\left|\mathbb{P}\left(\mathcal{N}_u + \frac{h(xe(u))}{\sqrt{xe(u)}} > w\right) - \mathbb{P}\left(\frac{h(xe(u))}{\sqrt{xe(u)}} > w\right)\right| \leq \frac{e(u)^{-2+2\epsilon}}{2\pi} + \frac{24m}{\pi e(u)^{1+\epsilon}}.$$

□

LEMMA A.3. *Let $h(z) = \sum_{i=1}^{N(z)} E_i - \lambda z\mathbb{E}[E_i]$ and let $\mathcal{N}_u$ be a normal random variable with mean zero and variance $\sigma^2 \sim e(u)^{-k}$ for some $c > 0$, $k > 0$. Then the random variable $\mathcal{N}_u + h(xe(u))/\sqrt{xe(u)}$ has a differentiable density $f_u$. Further, if $a, b$ are arbitrary but fixed it holds uniformly for $w$ and $0 < a < x < b < \infty$ that*

$$w^3 f_u'(w) \text{ and } w^2 f_u(w)$$

*are bounded for $w > w_0 > 0$ and all $u > u_0$ where $u_0$ is choosen such that $xe(u) > 1$.*

PROOF. Denote with $\widehat{F}_E(s) = \mathbb{E}[\mathrm{e}^{-sE_i}]$ and with

$$A(s,u) = \lambda\sqrt{xe(u)}\widehat{F}_E'\left(s/\sqrt{xe(u)}\right) + \sqrt{xe(u)}\lambda\mathbb{E}\left[E\right].$$

Note that the (bilateral) Laplace transform of transform of $w^3 f_u'(w)$ is given by

$$\widehat{L}_{w^3 f_u'}(s) = \frac{\mathrm{d}}{\mathrm{d}s^3}\left(s\mathrm{e}^{\frac{\sigma_u^2 s^2}{2}}\mathrm{e}^{\lambda xe(u)\left(\widehat{F}_E\left(s/\sqrt{xe(u)}\right)-1\right)+\sqrt{xe(u)}\lambda\mathbb{E}[E]s}\right)$$

$$= \mathrm{e}^{\frac{\sigma_u^2 s^2}{2}} \mathrm{e}^{\lambda x e(u)\left(\widehat{F}_E\left(s/\sqrt{xe(u)}\right)-1\right)+\sqrt{xe(u)}\lambda\mathbb{E}[E]s}$$
$$\times \Bigg\{ \left(sA(s,u)+\sigma_u^2 s^2\right)^2 \left(1+sA(s,u)+\sigma_u^2 s^2\right)$$
$$+ \left(sA(s,u)+\sigma_u^2 s^2\right)\left(A(s,u)+2\sigma_u^2 s+\lambda s\widehat{F}_E''\left(s/\sqrt{xe(u)}\right)\right)$$
$$+ \left(1+2sA(s,u)+2\sigma_u^2 s^2\right)\left(A(s,u)+2\sigma_u^2 s+\lambda s\widehat{F}_E''\left(s/\sqrt{xe(u)}\right)\right)$$
$$+ \left(\lambda\widehat{F}_E''\left(s/\sqrt{xe(u)}\right)+2\sigma_u^2+\lambda\frac{s}{\sqrt{xe(u)}}\widehat{F}_E'''\left(s/\sqrt{xe(u)}\right)\right)\Bigg\}.$$

Note that for every $w > w_0$ and $0 < \epsilon < 1$

$$w^3 f_u'(w) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \mathrm{e}^{w(\epsilon/w+\iota s)}\widehat{L}_{w^3 f_u'}(\epsilon/w+\iota s)\mathrm{d}s.$$

Since

$$A(s,u) = \lambda\sqrt{xe(u)}\widehat{F}_E'\left(s/\sqrt{xe(u)}\right)+\sqrt{xe(u)}\lambda\mathbb{E}\left[E\right] = \lambda s\widehat{F}_E''\left(\xi_{s,u}\right)$$

$|\widehat{F}_E''(s)| \le \mathbb{E}[E^2]$ and $s\widehat{F}_E'''(s)$ is bounded (see Lemma A.4 below) for $|s| < 1$, we get that for $|s| < 1$ the term in the curly brackets can be bounded by a polynomial in $|s|$. Hence the Lemma follows analogously to the proof of A.2. □

LEMMA A.4. *Under Assumption 3.1* $s\widehat{F}_E'''(s)$ *is uniformly bounded for* $s \to 0$

PROOF. Note that

$$E \stackrel{d}{=} X + \sum_{i=1}^{N(X)} E_i$$

and hence

$$\widehat{F}_E(s) = \mathbb{E}\left[\mathrm{e}^{-sX+\lambda X(\widehat{F}_E(s)-1)}\right] = \widehat{F}(s-\lambda(\widehat{F}_E(s)-1))$$

Since for $\mathrm{Re}(s) > 0$, $|\widehat{F}_E(s)| < 1$ and hence $\mathrm{Re}(s-\lambda(\widehat{F}_E(s)-1)) > 0$ hence the above formula is valid for all $\mathrm{Re}(s) > 0$. Hence both sides are infinitely often differentiable for all $\mathrm{Re}(s) > 0$ and we have

$$\widehat{F}_E'(s) = \frac{\widehat{F}'\left(s-\lambda(\widehat{F}_E(s)-1)\right)}{1+\lambda\widehat{F}'\left(s-\lambda(\widehat{F}_E(s)-1)\right)},$$

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$$\widehat{F}_E''(s) = \frac{\widehat{F}''\left(s-\lambda(\widehat{F}_E(s)-1)\right)\left(1-\lambda\widehat{F}_E'(s)\right)^2}{1+\lambda\widehat{F}'\left(s-\lambda(\widehat{F}_E(s)-1)\right)},$$

$$\begin{aligned}\widehat{F}_E'''(s) = {} & \frac{\widehat{F}'''\left(s-\lambda(\widehat{F}_E(s)-1)\right)\left(1-\lambda\widehat{F}_E'(s)\right)^3}{1+\lambda\widehat{F}'\left(s-\lambda(\widehat{F}_E(s)-1)\right)} \\ & - \frac{2\lambda\widehat{F}_E''(s)F''\left(s-\lambda(\widehat{F}_E(s)-1)\right)\left(1-\lambda\widehat{F}_E'(s)\right)}{1+\lambda\widehat{F}'\left(s-\lambda(\widehat{F}_E(s)-1)\right)} \\ & - \frac{\lambda\widehat{F}_E''(s)F''\left(s-\lambda(\widehat{F}_E(s)-1)\right)\left(1-\lambda\widehat{F}_E'(s)\right)}{1+\lambda\widehat{F}'\left(s-\lambda(\widehat{F}_E(s)-1)\right)}.\end{aligned}$$

Since $\lambda\mathbb{E}[X] < 1$ we have that

$$\sup_{\mathrm{Re}(s)\geq 0}\left|\lambda\widehat{F}'\left(s-\lambda(\widehat{F}_E(s)-1)\right)\right| < 1$$

and hence $\widehat{F}_E'(s)$ is bounded for all $\mathrm{Re}(s) > 0$ and since $\mathbb{E}[X^2] < \infty$ also $\widehat{F}_E''(s)$ is bounded. Finally we get that $s\widehat{F}_E'''(s)$ is bounded Since $s\widehat{F}'''(s)$ is bounded and

$$s-\lambda(\overline{F}_E(s)-1) = s-\lambda(\widehat{F}_E(s)-1) = s(1-\lambda\widehat{F}_E'(s))+\frac{s^2}{2}\widehat{F}_E''(\xi_s) = \mathcal{O}(s). \quad \square$$

LEMMA A.5. *Let $E_i$ be iid with $\mathbb{E}[E] < \infty$ and $N(t)$ a Poisson process with intensity $\lambda$ independent of the $E_i$. Then there exists constants $C_1$, $C_2$ and $\delta > 0$ such that uniformly in $x > \epsilon t$*

$$\mathbb{P}\left(\left|\sum_{1=1}^{N(t)} E_i - \lambda t\mathbb{E}\left[E\right]\right| > x\right) \leq C_1 t\mathbb{P}(E > x) + e^{-\delta\left(x-\frac{\epsilon}{2}t\right)}.$$

PROOF. In [16] it is proved that

$$\mathbb{P}\left(\sum_{1=1}^{N(t)} E_i - \lambda t\mathbb{E}\left[E\right] > x\right) \leq C_1 t\mathbb{P}(E > x)$$

uniformly for $x > \epsilon t$. We can find a $\delta > 0$ such that for all $t > 0$

$$\mathbb{E}\left[\exp\left(-\delta\left(\sum_{1=1}^{N(t)} E_i - t\left(\lambda\mathbb{E}\left[E\right]+\frac{\epsilon}{2}\right)\right)\right)\right] \leq 1.$$

The Lemma follows by the Chernoff bound. $\square$

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We often used the following Lemma without further mentioning. Since we don't have a reference by hand we give for completeness a proof.

LEMMA A.6. *Let $L(x)$ be slowly varying and*

$$\int_0^\infty \frac{1}{x} L(x)\mathrm{d}x < \infty,$$

*then* $\lim_{x\to\infty} L(x) = 0$

PROOF. Assume that the Lemma is not true, i.e. there exists a series of points $x_n$ with $x_n \to \infty$ and $L(x_n) > \delta$. W.l.o.g. assume that

$$\inf_{1\le t\le 2} \frac{L(tx_n)}{L(x_n)} > 1/2.$$

Then

$$\int_{x_n}^{2x_n} \frac{1}{x} L(x)\mathrm{d}x \ge \frac{\delta}{2} \int_{x_n}^{2x_n} \frac{1}{x}\mathrm{d}x = \frac{\delta \log(2)}{2},$$

which contradicts the conditions of the Lemma. □

## APPENDIX B: AN ALTERNATIVE WAY OF PROOF

In this appendix we want to derive an alternative way to evaluate the error term in the asymptotic of $\mathbb{P}(\tau(u) \le xe(u))$. We will do this under the following assumptions

ASSUMPTION B.1. Assume that $\overline{F}$ is regularly varying with index $\alpha > 2$ and has a regularly varying density $f$ with regularly varying derivative.

REMARK B.1. Note that Assumptions B.1 is stronger than Assumptions 3.1 in the two following ways. First we assume that $\alpha > 2$ instead of $\mathbb{E}[X^2] < \infty$. Second we assume that $f$ has a regularly varying derivative instead of there exists an $M > 0$ with $|s\widehat{F}'''(s)| < M$ for $\mathrm{Re}(s) > 0$ and $|s| < 1$.

We will proof the following theorem

THEOREM B.1. *Under Assumption B.1*

$$\begin{aligned}
&\mathbb{P}(\tau(u) \le xe(u)) \\
&= \frac{\rho}{1-\rho}\left(\overline{F}_0(u) - \overline{F}_0(u + x(1-\rho)e(u))\right) \\
&\quad + \frac{\lambda^2 \mathbb{E}\left[X_1^2\right] \overline{F}(u)}{(1-\rho)^2} - \frac{\alpha\lambda^2 \mathbb{E}\left[X_1^2\right] \overline{F}(u) x(1+(1-\rho)x)^{-\alpha-1}}{2(1-\rho)}
\end{aligned}$$

$$- \frac{\lambda^2 \mathbb{E}\left[X_1^2\right] \overline{F}(u)(1+(1-\rho)x)^{-\alpha}}{(1-\rho)^2} + o(\overline{F}(x)).$$

We will postpone the proof after some auxiliary results.

The idea of the proof is to replace the original continuous process with a discrete process therefore denote with

$$X_1^\epsilon = \frac{\sum_{i=1}^{N_\epsilon} X_i - \rho\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}}$$

and with $F_\epsilon(x) = \mathbb{P}(X_1^\epsilon \le x)$.

At first we note that

LEMMA B.2. *Assume that $\overline{F}(x)$ has an eventually differentiable density $f(x)$ and that $-f'(x)$ is regularly varying with index $-\alpha-2$ then for every fixed $\epsilon$*

$$\begin{aligned}\overline{F}_\epsilon(x) = {} & \epsilon\lambda\overline{F}\left(x\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right) + (\epsilon\lambda)^2\mathbb{E}\left[X_1\right] f\left(x\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right) \\ & - (1+o(1))\frac{1}{2}\left((\epsilon\lambda)^2\mathbb{E}\left[X_1^2\right] + (\epsilon\lambda)^3\mathbb{E}\left[X_1\right]\right) \\ & \times \mathbb{E}\left[X_1\right] f'\left(x\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right).\end{aligned}$$

PROOF. At first note that

$$\overline{F}_\epsilon(x) = \mathbb{P}\left(\sum_{i=1}^{N_\epsilon} X_i > x\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right).$$

With the results of [6] we get that

$$\begin{aligned}\mathbb{P}\left(\sum_{i=1}^{N_\epsilon} X_i > x\right) = {} & \mathbb{E}\left[N_\epsilon\right]\overline{F}\left(x\right) + (1+o(1))\mathbb{E}\left[N_\epsilon(N_\epsilon-1)\right]\mathbb{E}\left[X_1\right] f\left(x\right) \\ & - (1+o(1))\frac{1}{2}\mathbb{E}\left[N_\epsilon(N_\epsilon-1)(N_\epsilon-2)\right]\mathbb{E}\left[X_1\right] f'\left(x\right)\end{aligned}$$

□

LEMMA B.3. *For $u-x>x_0$ and $|\xi_x| \le x$, $|\widehat{\xi}_x| \le x$*

$$\begin{aligned}\overline{F}_\epsilon(u-x) = {} & \epsilon\lambda\overline{F}\left(u\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right) \\ & + \epsilon\lambda\left(\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}x - \epsilon\lambda\mathbb{E}\left[X_1\right]\right) f\left(u\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\end{aligned}$$

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$$
\begin{aligned}
&- \frac{x^2}{2}(\epsilon\lambda)^2\mathbb{E}\left[X^2\right] f'\left((u-\xi_x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&- x(\epsilon\lambda)^2\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}\mathbb{E}\left[X_1\right] f'\left((u-\widehat{\xi}_x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&- (1+o(1))\frac{1}{2}\left((\epsilon\lambda)^2\mathbb{E}\left[X_1^2\right]+(\epsilon\lambda)^3\mathbb{E}\left[X_1\right]\right)\\
&\quad\times\mathbb{E}\left[X_1\right] f'\left((u-x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right).
\end{aligned}
$$

PROOF. From Lemma B.2 and a Taylor expansion we get that

$$
\begin{aligned}
\overline{F}_\epsilon(u-x) &= \epsilon\lambda\overline{F}\left((u-x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad+(\epsilon\lambda)^2\mathbb{E}\left[X_1\right] f\left((u-x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad-(1+o(1))\frac{1}{2}\left((\epsilon\lambda)^2\mathbb{E}\left[X_1^2\right]+(\epsilon\lambda)^3\mathbb{E}\left[X_1\right]\right)\\
&\quad\times\mathbb{E}\left[X_1\right] f'\left((u-x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&= \epsilon\lambda\overline{F}\left(u\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad+\epsilon\lambda\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}x\overline{F}\left(u\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad-(\epsilon\lambda)^2\mathbb{E}\left[X^2\right]\frac{x}{2}f'\left((u-\xi_x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad+(\epsilon\lambda)^2\mathbb{E}\left[X_1\right] f\left(u\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad-(\epsilon\lambda)^2\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}\mathbb{E}\left[X_1\right]xf'\left((u-\widehat{\xi}_x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad-(1+o(1))\frac{1}{2}\left((\epsilon\lambda)^2\mathbb{E}\left[X_1^2\right]+(\epsilon\lambda)^3\mathbb{E}\left[X_1\right]\right)\\
&\quad\times\mathbb{E}\left[X_1\right] f'\left((u-x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right).
\end{aligned}
$$

□

Next we adapt Theorem 6 of [10] to our situation. The difference is that we replace $F_\epsilon$ with $F$ and do not assume uniformity in $n$. We will denote with

$$
a=\frac{(1-\rho)\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}}\quad\text{and}\quad S_m(a)=\sup_{0\le j\le m}\left(\sum_{i=1}^{j}X_i^\epsilon-aj\right)
$$

$$
S_n=\sum_{i=1}^{n}X_i^\epsilon\quad\text{and}\quad\overline{S}_m^{(j)}=0\vee\sup_{j<i\le m+j}\left(\sum_{k=1}^{i}(X_k^\epsilon-a)\right)
$$

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LEMMA B.4. *Denote with* $n = \lfloor \frac{xe(u)}{\epsilon} \rfloor$, *then we have*

$$\begin{aligned}
&\mathbb{P}\left(\inf_{1\le m\le n}\sum_{i=1}^{m} X_i^{\epsilon} - \frac{(1-\rho)m\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}} > \frac{u}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}}\right)\\
&= \epsilon\lambda\sum_{j=1}^{n}\overline{F}\left(u+(1-\rho)\epsilon j+\epsilon\rho\right)\\
&\quad+\epsilon\lambda\sum_{j=1}^{n}\left(\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}\left(\mathbb{E}\left[S_{n-j}(a)\right]\right)-\epsilon\lambda\mathbb{E}\left[X_1\right]\right)f\left(u+(1-\rho)\epsilon j+\epsilon\rho\right)\\
&\quad-(1+o_{\epsilon}(1))(\epsilon\lambda)^2\sum_{j=1}^{n}\frac{(j-1)\mathbb{E}\left[X^2\right]}{2}f'\left(u+(1-\rho)\epsilon j+\epsilon\rho\right)\\
&\quad+o(\overline{F}(u)).
\end{aligned}$$

PROOF. Denote with

$$B_j = \left\{|S_{j-1}| < \epsilon u, \overline{S}_{n-j}^{(j)} < \epsilon u\right\}$$

From Lemma 3 and 4 of [10] we get that

$$\begin{aligned}
&\mathbb{P}\left(\sup_{1\le m\le n}\sum_{i=1}^{m} X_i^{\epsilon} - am > u\right)\\
&\quad=\sum_{j=1}^{n}\mathbb{E}\left[\overline{F}_{\epsilon}\left(u+aj-S_{j-1}-\overline{S}_{n-j}^{(j)}\right),B_j\right]+o(\overline{F}_{\epsilon}(u)).
\end{aligned}$$

Note that

$$\begin{aligned}
&\mathbb{E}\left[\overline{F}_{\epsilon}\left(u+aj-S_{j-1}-\overline{S}_{n-j}^{(j)}\right),B_j\right]\\
&=\mathbb{E}\Bigg[\epsilon\lambda\overline{F}\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad+\epsilon\lambda\left(\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}\left(S_{j-1}+\overline{S}_{n-j}^{(j)}\right)-\epsilon\lambda\mathbb{E}\left[X_1\right]\right)\\
&\qquad\times f\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad-\frac{\left(S_{j-1}+\overline{S}_{n-j}^{(j)}\right)^2}{2}(\epsilon\lambda)^2\mathbb{E}\left[X^2\right]f'\left((u+aj-\xi_x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad-\left(S_{j-1}+\overline{S}_{n-j}^{(j)}\right)(\epsilon\lambda)^2\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}\mathbb{E}\left[X_1\right]
\end{aligned}$$

$$\times f'\left((u+aj-\widehat{\xi}_x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)$$
$$-(1+o(1))\frac{1}{2}\left((\epsilon\lambda)^2\mathbb{E}\left[X_1^2\right]+(\epsilon\lambda)^3\mathbb{E}\left[X_1\right]\right)$$
$$\times\mathbb{E}\left[X_1\right]f'\left(\left(u+aj-\left(S_{j-1}+\overline{S}_{n-j}^{(j)}\right)\right)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right),B_j\Bigg].$$

Since by assumption $n\approx u$ we get that (uniformly in $j$)

$$\mathbb{P}(|S_{j-1}|>\epsilon u)\sim(j-1)\overline{F}(u)\le n\overline{F}(u)\quad\text{and}$$
$$\mathbb{P}(\overline{S}_{n-j}^{(j)}>\epsilon u)\le\mathbb{P}(\overline{S}_{\infty}^{(j)}>\epsilon u)\approx u\overline{F}(u).$$

It follows that

$$\begin{aligned}\mathbb{E}\left[1,B_j^c\right]&\le\mathbb{P}(|S_{j-1}|>\epsilon u)+\mathbb{P}(\overline{S}_{n-j}^{(j)}>\epsilon u)=\mathcal{O}(u\overline{F}(u))\\ |\mathbb{E}\left[S_{j-1},B_j^c\right]|&\le\mathbb{E}\left[|S_{j-1}|1_{\{|S_{j-1}|>\epsilon u\}}\right]+n\mathbb{E}\left[|X^{\epsilon}|\right]\mathbb{P}(\overline{S}_{n-j}^{(j)}>\epsilon u)\\ &=\mathcal{O}(u^2\overline{F}(u))\\ \mathbb{E}\left[S_{n-j}^{(j)},B_j^c\right]&\le\mathbb{E}\left[S_{n-j}^{(j)}1_{\left\{S_{n-j}^{(j)}>\epsilon u\right\}}\right]+\mathbb{E}\left[S_{n-j}^{(j)}\right]\mathbb{P}(S_{n-j}>\epsilon u)\\ &=\mathcal{O}(u^2\overline{F}(u))\end{aligned}$$

and finally

$$\begin{aligned}&\mathbb{E}\left[(S_{j-1}+S_{n-j}^{(j)})^2,B_j\right]\\ &=\mathbb{E}\left[S_{j-1}^2,B_j\right]+2\mathbb{E}\left[S_{j-1}S_{n-j}^{(j)},B_j\right]+\mathbb{E}\left[\left(S_{n-j}^{(j)}\right)^2,B_j\right]\\ &=(j-1)+\mathbb{E}\left[\left(S_{n-j}^{(j)}\right)^2,B_j\right]+\mathbb{E}\left[S_{j-1}^2,B_j^c\right]+2\mathbb{E}\left[S_{j-1}S_{n-j}^{(j)},B_j^c\right]\\ &=(j-1)+\mathbb{E}\left[(S_{n-j}^{(j)})^2,B_j\right]+\mathcal{O}\left(u^3\overline{F}(u)\right)).\end{aligned}$$

If $\alpha>3$ then $\mathbb{E}[(S_{n-j}^{(j)})^2,B_j]=\mathbb{E}[(S_{n-j}^{(j)})^2]+\mathcal{O}(u^3\overline{F}(u)))$ and if $2<\alpha<3$ then $\mathbb{E}[(S_{n-j}^{(j)})^2,B_j]\le\mathbb{E}[(S_{n-j}^{(j)})^2,S_{n-j}^{(j)}\le\epsilon u]=\mathcal{O}(u^3\overline{F}(u)))$.

It follows that

$$\begin{aligned}&\mathbb{E}\left[\epsilon\lambda\overline{F}\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right),B_j\right]\\ &=\epsilon\lambda\overline{F}\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)+\mathcal{O}(u\overline{F}(u)^2)\end{aligned}$$

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$$
\begin{aligned}
&\mathbb{E}\Bigg[\epsilon\lambda\left(\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}\left(S_{j-1}+\overline{S}^{(j)}_{n-j}\right)-\epsilon\lambda\mathbb{E}\left[X_1\right]\right)\\
&\qquad\qquad\times f\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right),B_j\Bigg]\\
&=\epsilon\lambda\left(\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}\left(\mathbb{E}\left[S_{n-j}(a)\right]\right)-\epsilon\lambda\mathbb{E}\left[X_1\right]\right)f\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad+\mathcal{O}(u^2\overline{F}(u)f(u)).
\end{aligned}
$$

Further note that for $C_{j,\alpha}=\mathbb{E}[S_{n-j}(a)^2 1_{\{\alpha>3\}}]$

$$
\begin{aligned}
&\mathbb{E}\left[\frac{\left(S_{j-1}+\overline{S}^{(j)}_{n-j}\right)^2}{2}(\epsilon\lambda)^2\mathbb{E}\left[X^2\right]f'\left((u+aj-\xi_x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right),B_j\right]\\
&=(1+o_\epsilon(1))\\
&\quad\times\mathbb{E}\left[\frac{\left(S_{j-1}+\overline{S}^{(j)}_{n-j}\right)^2}{2}(\epsilon\lambda)^2\mathbb{E}\left[X^2\right]f'\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right),B_j\right]\\
&=(1+o_\epsilon(1))\frac{(j-1)+C_{j,\alpha}}{2}(\epsilon\lambda)^2\mathbb{E}\left[X^2\right]f'\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad+\mathcal{O}(u^3\overline{F}(u)f'(u))
\end{aligned}
$$

and finally note that there exists constants $c_1,c_2$ such that

$$
\begin{aligned}
&\Bigg|\mathbb{E}\Bigg[\left(S_{j-1}+\overline{S}^{(j)}_{n-j}\right)(\epsilon\lambda)^2\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}\mathbb{E}\left[X_1\right]f'\left((u+aj-\widehat{\xi}_x)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad+(1+o(1))\frac{1}{2}\left((\epsilon\lambda)^2\mathbb{E}\left[X_1^2\right]+(\epsilon\lambda)^3\mathbb{E}\left[X_1\right]\right)\\
&\qquad\times\mathbb{E}\left[X_1\right]f'\left(\left(u+aj-\left(S_{j-1}+\overline{S}^{(j)}_{n-j}\right)\right)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right),B_j\Bigg]\Bigg|\\
&\le c_1 j\epsilon^{5/2}f'\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)+c_2\epsilon^2 f'\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&=o_\epsilon(1)(j-1)f'\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\\
&\quad+\mathcal{O}\left(f'\left((u+aj)\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}+\epsilon\rho\right)\right),
\end{aligned}
$$

which proofs the Lemma. □

Next we give some auxiliary results concerning the approximations of certain sums.

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LEMMA B.5.

$$\epsilon\lambda \sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor} \overline{F}\left(u + \epsilon\rho + \epsilon(1-\rho)i\right)$$
$$= \lambda \int_0^{xe(u)} \overline{F}(u + \epsilon\rho + (1-\rho)t)\mathrm{d}t$$
$$- (1 + o(1))\epsilon\lambda \sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor} \frac{\epsilon(1-\rho)}{2} f\left(u + \epsilon\rho + \epsilon(1-\rho)i\right) + o_\epsilon(1)\overline{F}(u).$$

PROOF. Using that $\overline{F}$ is regularly varying and $f$ is long tailed we get:

$$\lambda \int_0^{xe(u)} \overline{F}(u + \epsilon\rho + (1-\rho)t)\mathrm{d}t = \epsilon\lambda \int_0^{xe(u)/\epsilon} \overline{F}(u + \epsilon\rho + \epsilon(1-\rho)t)\mathrm{d}t$$
$$= \epsilon\lambda \int_{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor}^{xe(u)/\epsilon} \overline{F}(u + \epsilon\rho + \epsilon(1-\rho)t)\mathrm{d}t$$
$$+ \epsilon\lambda \sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor} \int_{i-1}^{i} \overline{F}\left(u + \epsilon\rho + \epsilon(1-\rho)t\right)\mathrm{d}t$$
$$= o_\epsilon(1)\overline{F}(u) + \epsilon\lambda \sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor} \overline{F}\left(u + \epsilon\rho + \epsilon(1-\rho)i\right)$$
$$+ \epsilon\lambda \sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor} \int_{i-1}^{i} (i-t)\epsilon(1-\rho) f\left(u + \epsilon\rho + \epsilon(1-\rho)(i-\xi_t)\right)\mathrm{d}t$$
$$= \epsilon\lambda \sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor} \overline{F}\left(u + \epsilon\rho + \epsilon(1-\rho)i\right)$$
$$+ (1 + o(1))\epsilon\lambda \sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor} \frac{\epsilon(1-\rho)}{2} f\left(u + \epsilon\rho + \epsilon(1-\rho)i\right) + o_\epsilon(1)\overline{F}(u).$$

□

LEMMA B.6. *Let $s_n$ be some constant with $\lim_{n\to\infty} s_n = s_\infty$ then*

$$\epsilon\lambda \sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor} s_{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor - i} f\left(u + \epsilon\rho + \epsilon(1-\rho)i\right)$$

$$\sim \frac{\lambda s_\infty}{1-\rho}\left(\overline{F}(u)-\overline{F}(u+(1-\rho)xe(u)\right).$$

PROOF. Since

$$\sum_{i=1}^{\sqrt{\left\lfloor \frac{xe(u)}{\epsilon}\right\rfloor}} s_{\left\lfloor \frac{xe(u)}{\epsilon}\right\rfloor -i} f\left(u+\epsilon\rho+\epsilon(1-\rho)i\right)$$
$$\leq \sup_{j\leq\sqrt{\left\lfloor \frac{xe(u)}{\epsilon}\right\rfloor}} s_j \sqrt{\left\lfloor \frac{xe(u)}{\epsilon}\right\rfloor} f(u) = o(\overline{F}(u)),$$

we can w.l.o.g. replace $s_{\lfloor \frac{xe(u)}{\epsilon}\rfloor -i}$ with $s_\infty$. As in the proof of Lemma B.5 we get from the long tailed property of $f$ that

$$\lambda\int_0^{xe(u)} f(u+\epsilon\rho+(1-\rho)t)\mathrm{d}t = \epsilon\lambda\int_0^{xe(u)/\epsilon} f(u+\epsilon\rho+\epsilon(1-\rho)t)\mathrm{d}t$$
$$= \mathcal{O}(f(u)) + \epsilon\lambda\sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon}\right\rfloor}\int_{i-1}^{i} f\left(u+\epsilon\rho+\epsilon(1-\rho)t\right)\mathrm{d}t$$
$$\sim \epsilon\lambda\sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon}\right\rfloor} f\left(u+\epsilon\rho+\epsilon(1-\rho)i\right) \qquad \square$$

LEMMA B.7.

$$\epsilon^2\sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon}\right\rfloor}(j-1)f'\left(u+\epsilon\rho+\epsilon(1-\rho)i\right)$$
$$\sim \frac{xe(u)f(u+(1-\rho)xe(u))}{1-\rho} - \frac{1}{(1-\rho)^2}\left(\overline{F}(u)-\overline{F}(u+(1-\rho)xe(u))\right)$$

PROOF.

$$\int_0^{xe(u)} tf'(u+\epsilon\rho+(1-\rho)t)\mathrm{d}t = \epsilon^2\int_0^{xe(u)/\epsilon} tf'(u+\epsilon\rho+\epsilon(1-\rho)t)\mathrm{d}t$$
$$= \mathcal{O}(f'(u)) + \epsilon^2\sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon}\right\rfloor}\int_{i-1}^{i} tf\left(u+\epsilon\rho+\epsilon(1-\rho)t\right)\mathrm{d}t$$
$$\sim \epsilon^2\sum_{i=1}^{\left\lfloor \frac{xe(u)}{\epsilon}\right\rfloor}(i-1)f'\left(u+\epsilon\rho+\epsilon(1-\rho)i\right) \qquad \square$$

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LEMMA B.8. *Denote with* $s^\epsilon_\infty \lim_{m\to\infty}\mathbb{E}[S_m(a)]$ *(if the limit does not exists we interprate* $s^\epsilon_\infty$ *as the possible limit points) then*

$$\lim_{\epsilon\to 0}\sqrt{\epsilon}s^\epsilon_\infty = \frac{\rho\mu_2}{2\mu(1-\rho)\sqrt{\lambda\mathbb{E}\left[X^2\right]}}$$

PROOF. Since

$$\sup_{0\le t\le \epsilon m}\frac{\sum_{i=1}^{N_t}X_i - t}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}} - \frac{\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}} \le \sup_{0\le j\le m}\left(\sum_{i=1}^{j}X^\epsilon_i - aj\right) \le \sup_{0\le t\le \epsilon m}\frac{\sum_{i=1}^{N_t}X_i - t}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}}$$

we get that

$$\lim_{\epsilon\to 0}\sqrt{\epsilon}s^\epsilon_\infty = \mathbb{E}\left[\sup_{t\ge 0}\frac{\sum_{i=1}^{N_t}X_i - t}{\sqrt{\lambda\mathbb{E}\left[X^2\right]}}\right] = \frac{\rho\mu_2}{2\mu(1-\rho)\sqrt{\lambda\mathbb{E}\left[X^2\right]}}. \qquad \square$$

We are now ready to proof Theorem B.1

PROOF OF THEOREM B.1. We have that

$$\mathbb{P}\left(\inf_{1\le m\le\left\lfloor\frac{xe(u)}{\epsilon}\right\rfloor}\sum_{i=1}^{m}X^\epsilon_i - \frac{(1-\rho)m\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}} > \frac{u}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}}\right) \le \mathbb{P}(\tau(u)\le xe(u))$$
$$\le \mathbb{P}\left(\inf_{1\le m\le\left\lceil\frac{xe(u)}{\epsilon}\right\rceil}\sum_{i=1}^{m}X^\epsilon_i - \frac{(1-\rho)m\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}} > \frac{u-\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}}\right).$$

By Lemma B.4 we get that

$$\mathbb{P}\left(\inf_{1\le m\le\left\lfloor\frac{xe(u)}{\epsilon}\right\rfloor}\sum_{i=1}^{m}X^\epsilon_i - \frac{(1-\rho)m\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}} > \frac{u}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}}\right)$$
$$= \epsilon\lambda\sum_{j=1}^{\left\lfloor\frac{xe(u)}{\epsilon}\right\rfloor}\overline{F}\left(u+(1-\rho)\epsilon j+\epsilon\rho\right)$$
$$+\epsilon\lambda\sum_{j=1}^{\left\lfloor\frac{xe(u)}{\epsilon}\right\rfloor}\left(\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}\left(\mathbb{E}\left[S_{\left\lfloor\frac{xe(u)}{\epsilon}\right\rfloor-j}(a)\right]\right) - \epsilon\lambda\mathbb{E}\left[X_1\right]\right)$$
$$\times f\left(u+(1-\rho)\epsilon j+\epsilon\rho\right)$$

$$- (1+o_\epsilon(1))(\epsilon\lambda)^2 \sum_{j=1}^{\left\lfloor \frac{xe(u)}{\epsilon} \right\rfloor} \frac{(j-1)\mathbb{E}\left[X^2\right]}{2} f'\left(u+(1-\rho)\epsilon j+\epsilon\rho\right)$$
$$+ o(\overline{F}(u))$$

Applying Lemmas B.8, B.5, B.6 and B.7 it follows that the last equation is equivalent to

$$\begin{aligned}
&= \lambda \int_0^{xe(u)} \overline{F}(u+\epsilon\rho+(1-\rho)t)\mathrm{d}t \\
&\quad - (1+o(1))\frac{\lambda\epsilon}{2}\left(\overline{F}(u)-\overline{F}(u+(1-\rho)xe(u)\right) \\
&\quad + \frac{\lambda\left((1+o_\epsilon(1))\frac{\rho\mu_2}{2\mu(1-\rho)}-\epsilon\lambda\mathbb{E}\left[X_1\right]\right)}{1-\rho}\left(\overline{F}(u)-\overline{F}(u+(1-\rho)xe(u)\right) \\
&\quad - (1+o_\epsilon(1))\frac{\lambda^2\mathbb{E}\left[X^2\right]}{2}\frac{xe(u)f(u+(1-\rho)xe(u))}{1-\rho} \\
&\quad + (1+o_\epsilon(1))\frac{\lambda^2\mathbb{E}\left[X^2\right]}{2}\frac{1}{(1-\rho)^2}\left(\overline{F}(u)-\overline{F}(u+(1-\rho)xe(u))\right) \\
&\quad + o_\epsilon(1)\overline{F}(u)+o(\overline{F}(u)) \\
&= \lambda\int_0^{xe(u)}\overline{F}(u+(1-\rho)t)\mathrm{d}t + \frac{\lambda^2\mathbb{E}\left[X_1^2\right]}{(1-\rho)^2}\left(\overline{F}(u)-\overline{F}(u+(1-\rho)xe(u)\right) \\
&\quad - \frac{\lambda^2\mathbb{E}\left[X^2\right]}{2(1-\rho)}xe(u)f(u+(1-\rho)xe(u))+o_\epsilon(1)\overline{F}(u)+o(\overline{F}(u)).
\end{aligned}$$

Replacing $u$ with $u-\epsilon$ and using a Taylor argument it follows that

$$\begin{aligned}
&\mathbb{P}\left(\inf_{1\le m\le\left\lceil\frac{xe(u)}{\epsilon}\right\rceil}\sum_{i=1}^m X_i^\epsilon - \frac{(1-\rho)m\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}} > \frac{u-\epsilon}{\sqrt{\lambda\epsilon\mathbb{E}\left[X^2\right]}}\right) \\
&= \lambda\int_0^{xe(u)}\overline{F}(u+(1-\rho)t)\mathrm{d}t + \frac{\lambda^2\mathbb{E}\left[X_1^2\right]}{(1-\rho)^2}\left(\overline{F}(u)-\overline{F}(u+(1-\rho)xe(u)\right) \\
&\quad - \frac{\lambda^2\mathbb{E}\left[X^2\right]}{2(1-\rho)}xe(u)f(u+(1-\rho)xe(u))+o_\epsilon(1)\overline{F}(u)+o(\overline{F}(u)).
\end{aligned}$$

Letting $\epsilon\to 0$ the Lemma follows. □

**Acknowledgements.** We would like to thank the referee for a very careful reading of a very technical manuscript and Jens Ledet Jensen for pointing out the proof of Lemma A.1.

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