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LIMIT THEOREMS FOR ADDITIVE FUNCTIONALS OF A MARKOV CHAIN

M. JARA, T.KOMOROWSKI, AND S. OLLA

ABSTRACT. Consider a Markov chain $\{X_n\}_{n \geq 0}$ with an ergodic probability measure π . Let Ψ a function on the state space of the chain, with α -tails with respect to π , $\alpha \in (0, 2)$. We find sufficient conditions on the probability transition to prove convergence in law of $N^{1/\alpha} \sum_n^N \Psi(X_n)$ to a α -stable law. A “martingale approximation” approach and “coupling” approach give two different sets of conditions. We extend these results to continuous time Markov jump processes X_t , whose skeleton chain satisfies our assumptions. If waiting time between jumps has finite expectation, we prove convergence of $N^{-1/\alpha} \int_0^{Nt} V(X_s) ds$ to a stable process. The result is applied to show that an appropriately scaled limit of solutions of a linear Boltzman equation is a solution of the fractional diffusion equation.

1. INTRODUCTION

Superdiffusive transport of energy is generically observed in a certain class of one dimensional systems. This can be seen numerically in chains of anharmonic oscillators of the Fermi-Pasta-Ulam type and experimentally in carbon nanotubes (see [21] for a physical review). The nature of the stochastic processes describing these emerging macroscopic behaviors is a subject of a vivid debate in the physical literature and remarkably few mathematical results are present for deterministic microscopic models.

The macroscopic behavior of the energy in a chain of harmonic oscillators with the Hamiltonian dynamics perturbed by stochastic terms conserving energy and momentum has been studied in [2]. The density of energy distribution over spatial and momentum variables, obtained there in a proper kinetic limit, satisfies *a linear phonon Boltzmann equation*

$$\partial_t u(t, x, k) + \omega'(k) \partial_x u(t, x, k) = \int R(k, k') (u(t, x, k') - u(t, x, k)) dk'. \quad (1.1)$$

As we have already mentioned $u(t, x, k)$ is the density at time t of energy of waves of Fourier's mode $k \in [0, 1]$, and the velocity $\omega'(k)$ is the derivative of the dispersion relation of the lattice.

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We remark at this point that equation (1.1) appears also as a limit of scaled wave, or Schrödinger equations in a random medium with fast oscillating coefficients and initial data. It is sometimes called in that context *the radiative transport equation*, see e.g. [1, 10, 12, 22, 28], or monography [13] for more details on this subject.

Since the kernel $R(k, k')$ appearing in (1.1) is positive, this has an easy probabilistic interpretation as a forward equation for the evolution of the density of a Markov process $(Y(t), K(t))$ on $\mathbb{R} \times [0, 1]$. In fact here $K(t)$ is an autonomous jump process on $[0, 1]$ with jump rate $R(k, k')$, and $Y(t) = \int_0^t \omega'(K(s)) ds$ is an additive functional of $K(t)$. The conservation of the momentum in the microscopic model imposes a very slow jump rate for small k : $R(k, k') \sim k^2$ as $k \sim 0$. Since the velocity $\omega'(k)$ remains of order 1, the behavior of $Y(t)$ is superdiffusive.

The above example has motivated us to study the following general question. Consider a Markov chain $\{X_n, n \geq 0\}$ taking values in a general Polish metric space (E, d) . Suppose that π is a stationary and ergodic, probability, Borel measure for this chain. Consider a function $\Psi : E \rightarrow \mathbb{R}$ and $S_N := \sum_{n=0}^{N-1} \Psi(X_n)$. If Ψ is centered with respect to π , and possesses a second moment one expects that the central limit theorem holds for $N^{-1/2} S_N$, as $N \rightarrow +\infty$. This, of course requires some assumptions on the rate of the decay of correlation of the chain, as well as hypotheses about its dynamics. If Ψ has the infinite second moment and its tails satisfy a power law then one expects, again under some assumption on the transition probabilities, convergence of the laws of $N^{-1/\alpha} S_N$, for an appropriate α , to the corresponding stable law.

In 1937 W. Doeblin himself looked at this natural question in the seminal article [7]. In the final lines of this paper he has observed that the method of dividing the sum into independent blocks, used in the paper to show the central limit theorem for countable Markov chains, can be used also in the infinite variance situation. A more complete proof, along Doeblin's idea, can be found in an early paper of S. Nagaev [25], assuming a strong *Doeblin's condition*.

Starting from the early sixties, another approach, more analytical, has been developed for proving central limit theorems for Markov chains, based on a martingale approximation of the additive functional. By solving (or by approximating the solution) of the Poisson equation $(I - P)u = \Psi$, where P is the transition probability matrix, one can decompose the sum S_N into a martingale plus a negligible term, thus reducing the problem to a central limit theorem for martingales. If P has a spectral gap, this was exploited by Gordin (see [15, 16]). In the following decades, much progress has been achieved using this approach. It has found applications in stochastic homogenization, random walks in random environments and interacting particle systems (i.e. infinite dimensional problems, where renewal arguments cannot be applied), culminating in the seminal paper of Kipnis and Varadhan [19], where reversibility of the chain is exploited in an optimal way (see also [5, 14, 6]). For non reversible chains there are still open problems, see [23] and the review paper [26] for a more detailed list.

As far as we know, the martingale approximation approach has not been developed in the case of convergence to stable laws of functionals of Markov chains, even though

corresponding theorems for martingales convergence have been available for a while (cf. e.g. [9, 3]). The present article is a first step in this direction.

More precisely, we are concerned with the limiting behavior of functionals formed over functions Ψ with heavy tails that satisfy the power law decay, i.e. $\pi(\Psi > \lambda) \sim c_*^+ \lambda^{-\alpha}$ and $\pi(\Psi < -\lambda) \sim c_*^- \lambda^{-\alpha}$ for $\lambda \gg 1$ with $\alpha \in (0, 2)$. We prove sufficient conditions under which the laws of the functionals of the form $N^{-1/\alpha} S_N$ converge weakly to α -stable laws, as $N \rightarrow +\infty$. Theorem 2.3 is proven by martingale approximation, under a spectral gap condition.

We also give a proof by a more *classical* renewal method based on a coupling technique, inspired by [4]. The coupling argument gives a simpler proof, but under more restrictive assumptions on the form of the probability transition (cf. Condition 2.4). We point out, however, that such hypotheses are of local nature, in the sense that they involve only the behavior of the process around the singularity. In particular, the spectral gap condition (which is a global condition) can be relaxed in this coupling approach, to a moment bound for some regeneration times associated to the process (cf. Theorem 2.6).

Next, we apply these results to a continuous time Markov jump process $\{X_t, t \geq 0\}$ whose skeleton chain satisfies the assumptions made in the respective parts of Theorem 2.3. We prove that in case the mean waiting time $t(x)$ has a finite moment with respect to the invariant measure π and the tails of $V(x)t(x)$ obey the power laws, as above, then finite dimensional distributions of the scaled functional of the form $N^{-1/\alpha} \int_0^{Nt} V(X_s) ds$ converge to the respective finite dimensional distribution of a stable process, see Theorem 2.7.

Finally, these results are applied to deal with the limiting behavior of the solution $u(t, x, k)$ of the linear Boltzmann equation (1.1) in the spatial dimension $d = 1$. We prove that the long time, large scale limit of solutions of such an equation tends to the solution of the fractional heat equation

$$\partial_t \bar{u}(t, x) = -(-\partial_x^2)^{3/4} \bar{u}(t, x),$$

corresponding to a stable process with exponent $\alpha = 3/2$. Both approaches (i.e. martingale approximation and coupling) apply to this example.

Note added to the second version: After completing the first version of the present paper [17], we have received a preprint by Mellet et al. [24] that contains a completely analytical proof of the convergence of the solution of a linear Boltzmann equation to a fractional diffusion. The conditions assumed in [24] imply the same spectral gap condition as in our Theorem 2.3, consequently the corresponding result in [24] is related to our Theorem 2.7.

2. PRELIMINARIES AND STATEMENTS OF THE MAIN RESULTS

2.1. Some preliminaries on stable laws. In this paper we shall consider three types of stable laws. When $\alpha \in (0, 1)$ we say that X is distributed according to a stable law of type I if its characteristic function is of the form $\mathbb{E} e^{i\xi X} = e^{\psi(\xi)}$, where the Levy exponent equals

$$\psi(\xi) := \alpha \int_{\mathbb{R}} (e^{i\lambda\xi} - 1) |\lambda|^{-1-\alpha} c_*(\lambda) d\lambda \tag{2.1}$$

and

$$c_*(\lambda) := \begin{cases} c_*^-, & \text{when } \lambda < 0, \\ c_*^+, & \text{when } \lambda > 0, \end{cases} \quad (2.2)$$

where $c_*^-, c_*^+ \geq 0$ and $c_*^- + c_*^+ > 0$. The stable law is of type *II* if $\alpha \in (1, 2)$ and its Levy exponent equals

$$\psi(\xi) := \alpha \int_{\mathbb{R}} (e^{i\lambda\xi} - 1 - i\lambda\xi) |\lambda|^{-1-\alpha} c_*(\lambda) d\lambda. \quad (2.3)$$

Finally, the stable law is of type *III* is $\alpha = 1$ and its Levy exponent equals

$$\psi(\xi) := \int_{\mathbb{R}} (e^{i\xi\lambda} - 1 - i\xi\lambda 1_{[-1,1]}(\lambda)) |\lambda|^{-2} c_*(\lambda) d\lambda. \quad (2.4)$$

We say that $\{Z(t), t \geq 0\}$ is a stable process of type *I* (resp. *II*, or *III*) if $Z(0) = 0$ and it is a process with independent increments such that $Z(1)$ is distributed according to a stable law of type *I* (resp. *II*, or *III*).

2.2. A Markov chain. Let (E, d) be a Polish metric space, \mathcal{E} its Borel σ -algebra. Assume that $\{X_n, n \geq 0\}$ is a Markov chain with the state space E and π - the law of X_0 - is an *invariant* and *ergodic* measure for the chain. Denote by P the transition operator corresponding to the chain. Since π is invariant it can be defined, as a positivity preserving linear contraction, on any $L^p(\pi)$ space for $p \in [1, +\infty]$.

Suppose that $\Psi : E \rightarrow \mathbb{R}$ is Borel measurable such that there exist $\alpha \in (0, 2)$ and two constants c_*^+, c_*^- satisfying

$$\begin{aligned} \lim_{\lambda \rightarrow +\infty} \lambda^\alpha \pi(\Psi \geq \lambda) &= c_*^+, \\ \lim_{\lambda \rightarrow +\infty} \lambda^\alpha \pi(\Psi \leq -\lambda) &= c_*^-. \end{aligned} \quad (2.5)$$

The above assumption guarantees that $\Psi \in L^\beta(\pi)$ for any $\beta < \alpha$.

In the case $\alpha \in (1, 2)$ we will always assume that $\int \Psi d\pi = 0$. We are interested in the asymptotic behavior of $S_N := \sum_{n=1}^N \Psi(X_n)$. We are looking for sufficient conditions on the chain, which guarantee that the laws of $N^{-1/\alpha} S_N$ converge to a α -stable law, as $N \rightarrow +\infty$.

We present two different approaches (by martingale approximation and by coupling) with two separate set of conditions.

2.3. The martingale approach result. We suppose that the chain satisfies:

Condition 2.1. *Spectral gap condition:*

$$\sup[\|Pf\|_{L^2(\pi)} : f \perp 1, \|f\|_{L^2(\pi)} = 1] = a < 1. \quad (2.6)$$

Since P is also a contraction in $L^1(\pi)$ and $L^\infty(\pi)$ we conclude, via Riesz-Thorin interpolation theorem, that for any $p \in [1, +\infty)$:

$$\|Pf\|_{L^p(\pi)} \leq a^{|2/p-1|} \|f\|_{L^p(\pi)}, \quad (2.7)$$

for all $f \in L^p(\pi)$, such that $\int f d\pi = 0$.

In addition, we assume that the tails of Ψ under the invariant measure do not differ very much from those with respect to the transition probabilities. Namely, we suppose that:

Condition 2.2. *there exist a measurable family of Borel measures $Q(x, dy)$ and a measurable, non-negative function $p(x, y)$ such that*

$$P(x, dy) = p(x, y)\pi(dy) + Q(x, dy), \quad \text{for all } x \in E, \quad (2.8)$$

$$C(2) := \iint p^2(x, y)\pi(dx)\pi(dy) < +\infty \quad (2.9)$$

and

$$\int Q^2(x, |\Psi| \geq \lambda)\pi(dx) \leq C\pi^2(|\Psi| \geq \lambda), \quad \forall \lambda \geq 0. \quad (2.10)$$

A simple consequence of (2.8) and the fact that π is invariant is that

$$\int p(x, y)\pi(dy) \leq 1 \quad \text{and} \quad \int p(y, x)\pi(dy) \leq 1, \quad \forall x \in E. \quad (2.11)$$

If $\alpha \in (1, 2)$ then, in particular Ψ possesses the first absolute moment.

Theorem 2.3. *We assume here conditions 2.1 - 2.2.*

i) Suppose $\alpha \in (1, 2)$, Ψ is centered. Furthermore, assume that for some $\alpha' > \alpha$ we have

$$\|P\Psi\|_{L^{\alpha'}(\pi)} < +\infty. \quad (2.12)$$

Then, the law of $N^{-1/\alpha}S_N$ converges weakly, as $N \rightarrow +\infty$, to a stable law of type II.

ii) If $\alpha \in (0, 1)$ then, the law of $N^{-1/\alpha}S_N$ converges weakly, as $N \rightarrow +\infty$, to a stable law of type I.

iii) When $\alpha = 1$, assume that for some $\alpha' > 1$ we have

$$\sup_{N \geq 1} \|P\Psi_N\|_{L^{\alpha'}(\pi)} < +\infty, \quad (2.13)$$

where $\Psi_N := \Psi 1[|\Psi| \leq N]$. Let $c_N := \int \Psi_N d\pi$. Then, the law of $N^{-1}(S_N - Nc_N)$ converges weakly, as $N \rightarrow +\infty$, to a stable law of type III.

Remark. A simple calculation shows that in case iii) $c_N = (c + o(1)) \log N$ for some constant c .

2.4. The coupling approach results.

Condition 2.4. *There exists a measurable function $\theta : E \rightarrow [0, 1]$, a probability q and a transition probability $Q_1(x, dy)$, such that*

$$P(x, dy) = \theta(x)q(dy) + (1 - \theta(x))Q_1(x, dy).$$

Furthermore we assume that

$$\bar{\theta} := \int \theta(x)\pi(dx) > 0, \quad (2.14)$$

and that the tails of distribution of Ψ with respect to $Q_1(x, dy)$ are uniformly lighter than its tails with respect to q :

$$\limsup_{\lambda \rightarrow \infty} \sup_{x \in E} \frac{Q_1(x, |\Psi| \geq \lambda)}{q(|\Psi| \geq \lambda)} = 0 \quad (2.15)$$

Clearly, because of (2.15), the function Ψ satisfies condition (2.5) also with respect to the measure q , but with different constants:

$$\begin{aligned} \lim_{\lambda \rightarrow +\infty} \lambda^\alpha q(\Psi > \lambda) &= c_*^+ \bar{\theta}^{-1} \\ \lim_{\lambda \rightarrow +\infty} \lambda^\alpha q(\Psi < -\lambda) &= c_*^- \bar{\theta}^{-1} \end{aligned} \quad (2.16)$$

The purpose of condition 2.4 is that it permits to define a Markov chain $\{(X_n, \delta_n), n \geq 0\}$ on $E \times \{0, 1\}$ such that

$$\begin{aligned} \mathbb{P}(\delta_{n+1} = 0 | X_n = x, \delta_n = \epsilon) &= \theta(x), \\ \mathbb{P}(\delta_{n+1} = 1 | X_n = x, \delta_n = \epsilon) &= 1 - \theta(x), \\ \mathbb{P}(X_{n+1} \in A | \delta_{n+1} = 0, X_n = x, \delta_n = \epsilon) &= q(A), \\ \mathbb{P}(X_{n+1} \in A | \delta_{n+1} = 1, X_n = x, \delta_n = \epsilon) &= Q_1(x, A) \end{aligned} \quad (2.17)$$

for $n \geq 0$. We call this Markov chain the *basic coupling*. It is clear that the marginal chain $\{X_n, n \geq 0\}$ has probability transition P . The dynamics of $\{(X_n, \delta_n), n \geq 0\}$ is easy to understand. When $X_n = x$, we choose X_{n+1} according to the distribution $q(dy)$ with probability $\theta(x)$, and according to the distribution $Q_1(x, dy)$ with probability $1 - \theta(x)$.

Let κ_n be the n -th zero in the sequence $\{\delta_n, n \geq 0\}$. In a more precise way, define $\kappa_0 = 0$ and, for $i \geq 1$,

$$\kappa_i = \inf\{n > \kappa_{i-1}; \delta_n = 0\}.$$

Notice that the sequence $\{\kappa_{i+1} - \kappa_i; i \geq 1\}$ is i.i.d. and $\mathbb{E}(\kappa_{i+1} - \kappa_i) \bar{\theta}^{-1}$. We call the sequence $\{\kappa_n, n \geq 1\}$ the *regeneration times*.

Observe that, for any $i \geq 1$, the distribution of X_{κ_i} is given by $q(dy)$. In particular, X_{κ_i} is independent of $\{X_0, \dots, X_{\kappa_i-1}\}$. Therefore, the blocks

$$\{(X_{\kappa_i}, \delta_{\kappa_i}), \dots, (X_{\kappa_{i+1}-1}, \delta_{\kappa_{i+1}-1})\}$$

are independent. The dynamics for each one of these blocks is easy to understand. Start a Markov chain $\{X_n^1, n \geq 0\}$ with initial distribution $q(dy)$ and transition probability $Q_1(x, dy)$. At each step n , we stop the chain with probability $\theta(X_n^1)$. Each one of the blocks, except for the first one, has a distribution $\{(X_1^1, 0), (X_2^1, 1), \dots, (X_{\kappa}^1, 1)\}$, where κ is the stopping time. The first block is constructed in the same way, but starting from $X_0^1 = X_0$ instead of with the law $q(dy)$. Now we are ready to state our last condition:

Condition 2.5.

$$\sum_{n=1}^{\infty} n^{1+\alpha} \mathbb{P}(\kappa \geq n) < +\infty.$$

Theorem 2.6. *Suppose that $\alpha \in (1, 2)$ and Ψ is centered under π , or $\alpha \in (0, 1)$. Then, under conditions 2.4 and 2.5, the law of $N^{-1/\alpha} S_N$ converges to an α -stable law.*

2.5. An additive functional of a continuous time jump process. Suppose that $\{\tau_n, n \geq 0\}$ is a sequence of i.i.d. random variables, independent of $\mathcal{F} := \sigma(X_0, X_1, \dots)$ and such that τ_0 has exponential distribution with parameter 1. Suppose that $t : E \rightarrow (0, +\infty)$ is a measurable function such that $t(x) \geq t_* > 0, x \in E$. Let

$$t_N := \sum_{n=0}^N t(X_n)\tau_n. \tag{2.18}$$

One can define a compound Poisson process $X_t = X_n, t \in [t_N, t_{N+1})$. It is Markovian, see e.g Section 2 of Appendix 1, pp. 314-321, of [18] with the generator

$$Lf(x) = t^{-1}(x) \int [f(y) - f(x)]P(x, dy), \quad f \in B_b(E). \tag{2.19}$$

Here $B_b(E)$ is the space of bounded and Borel measurable functions on E . Let

$$\bar{t} := \int t d\pi < +\infty. \tag{2.20}$$

Suppose $V : E \rightarrow \mathbb{R}$ is measurable and $\Psi(x) := V(x)t(x)$ satisfies condition (2.5). We shall be concerned with the limit of scaled processes

$$Y_N(t) := \frac{1}{N^{1/\alpha}} \int_0^{Nt} V(X(s))ds, \quad t \geq 0, \tag{2.21}$$

as $N \rightarrow +\infty$. Then, $\bar{t}^{-1}t(x)\pi(dx)$ is an ergodic, invariant probability measure for $\{X_t, t \geq 0\}$. Our result can be formulated as follows.

Theorem 2.7. *i) Suppose that $\alpha \in (1, 2)$ and that the assumptions of either part i) Theorem 2.3, or of Theorem 2.6, hold. Then, the convergence of finite dimensional distributions takes place to a stable process of type II.*

ii) In case $\alpha \in (0, 1)$ we suppose that the assumptions of either part ii) of Theorem 2.3, or of Theorem 2.6 hold. Then, the finite distributions of processes $\{Y_N(t), t \geq 0\}$ converge, as $N \rightarrow +\infty$, to the respective distributions of a stable process of type I.

iii) When $\alpha = 1$ and the assumptions of part iii) of Theorem 2.3 hold the finite distributions of processes $\{Y_N(t) - c_N t, t \geq 0\}$ converge, as $N \rightarrow +\infty$, to the respective distributions of a stable process of type III. Here $c_N := \int_{|\Psi| \leq N} \Psi d\pi$.

3. AN APPLICATION: SUPERDIFFUSION OF ENERGY IN A LATTICE DYNAMICS

In [2] it is proven that the Wigner distribution associated to the energy of a system of interacting oscillators with momentum and energy conserving noise, converges, in an appropriate kinetic limit, to the solution $u(t, x, k)$ of the linear kinetic equation

$$\begin{cases} \partial_t u(t, x, k) + \omega'(k)\partial_x u(t, x, k) = \mathcal{L}u(t, x, k), \\ u(0, x, k) = u_0(x, k), \end{cases} \tag{3.1}$$

where $(t, x, k) \in [0, +\infty) \times \mathbb{R}^d \times \mathbb{T}^d$ and the initial condition $u_0(\cdot, \cdot)$ is a function of class $C^{1,0}(\mathbb{R}^d \times \mathbb{T}^d)$. Here \mathbb{T} is the one dimensional circle, understood as the interval $[-1/2, 1/2]$

with identified endpoints, and \mathbb{T}^d is the d -dimensional torus. The function $\omega(k)$ is the dispersion relation of the lattice and it is assumed that $\omega(-k) = \omega(k)$ and $\omega(k) \sim |k|$ for $|k| \sim 0$ (*acoustic dispersion*). The scattering operator \mathcal{L} , acting in (3.1) on variable k , is usually an integral operator that is a generator of a certain jump process.

In case $d = 1$ the scattering operator is given by

$$\mathcal{L}f(k) = \int_{\mathbb{T}} R(k, k')[f(k') - f(k)]dk', \quad (3.2)$$

with the scattering kernel

$$R(k, k') = \frac{4}{3} [2 \sin^2(2\pi k) \sin^2(\pi k') + 2 \sin^2(2\pi k') \sin^2(\pi k) - \sin^2(2\pi k) \sin^2(2\pi k')] \quad (3.3)$$

We shall assume that the dispersion relation is given by a function $\omega : \mathbb{T} \rightarrow [0, +\infty)$ that satisfies, $\omega \in C^1(\mathbb{T} \setminus \{0\})$ and

$$c_l |\sin(\pi k)| \leq \omega(k) \leq c_u |\sin(\pi k)|, \quad k \in \mathbb{T} \quad (3.4)$$

for some $0 < c_l \leq c_u < +\infty$, while

$$\lim_{k \rightarrow \pm 0} \omega'(k) = \pm c_\omega. \quad (3.5)$$

In the case of a simple one dimensional lattice we have $\omega(k) = c|\sin(\pi k)|$.

The total scattering cross section is given by

$$R(k) = \int_{\mathbb{T}} R(k, k')dk' = \frac{4}{3} \sin^2(\pi k) (1 + 2 \cos^2(\pi k)) \quad (3.6)$$

We define $t(k) := R(k)^{-1}$, since these are the expected waiting times of the scattering process.

Let $\{X_n, n \geq 0\}$ be a Markov chain on \mathbb{T} whose transition probability equals

$$P(k, dk') := t(k)R(k, k')dk'.$$

Suppose that $\{\tau_n, n \geq 0\}$ is an i.i.d. sequence of random variables such that τ_0 is exponentially distributed with intensity 1. Let $t_n := t(X_n)\tau_n$, $n \geq 0$. One can represent then the solution of (3.1) with the formula

$$u(t, x, k) = \mathbb{E}u_0(x(t), k(t)), \quad (3.7)$$

where

$$\begin{aligned} x(t) &= x + \int_0^t \omega'(k(s))ds, \\ k(t) &= X_n, \quad t \in [t_n, t_{n+1}) \end{aligned}$$

and $k(0) = X_0 = k$. We shall be concerned in determining the weak limit of the finite dimensional distribution of the scaled process $\{N^{-1/\alpha}x(Nt), t \geq 0\}$, as $N \rightarrow +\infty$, for an appropriate scaling exponent α .

It is straightforward to verify that

$$\pi(dk) = \frac{t^{-1}(k)}{\bar{R}} dk = \frac{R(k)}{\bar{R}} dk \quad (3.8)$$

where $\bar{R} := \int_{\mathbb{T}} R(k) dk$ is a stationary and reversible measure for the chain. Then, $P(k, dk') = p(k, k')\pi(dk')$, where

$$p(k, k') = \bar{R} t(k)R(k, k')t(k').$$

and, after straightforward calculations, we obtain

$$\begin{aligned} p(k, k') &= 6[\cos^2(\pi k) + \cos^2(\pi k') - 2\cos^2(\pi k)\cos^2(\pi k')] \\ &\quad \times [(1 + 2\cos^2(\pi k))(1 + 2\cos^2(\pi k'))]^{-1} \\ &= 6\{[|\cos(\pi k)| - |\cos(\pi k')|]^2 + 2|\cos(\pi k)\cos(\pi k')|[1 - |\cos(\pi k)\cos(\pi k')|]\} \\ &\quad \times [(1 + 2\cos^2(\pi k))(1 + 2\cos^2(\pi k'))]^{-1}. \end{aligned} \quad (3.9)$$

We apply Theorem 2.7 and probabilistic representation (3.7) to describe the asymptotic behavior for long times and large spatial scales of solutions of the kinetic equation (3.1). The result is contained in the following.

Theorem 3.1. *The finite dimensional distributions of scaled processes $\{N^{-2/3}x(Nt), t \geq 0\}$ converge weakly to those of a stable process of type II. In addition, for any $t > 0$, $x \in \mathbb{R}$ we have*

$$\lim_{N \rightarrow +\infty} \int_{\mathbb{T}} |u(Nt, N^{2/3}x, k) - \bar{u}(t, x)|^2 dk = 0, \quad (3.10)$$

where $u(t, x, k)$ satisfies (3.1) with the initial condition $u_0(N^{-2/3}x, k)$, such that u_0 is compactly supported, and $\bar{u}(t, x)$ is the solution of

$$\begin{cases} \partial_t \bar{u}(t, x) = -(-\partial_x^2)^{3/4} \bar{u}(t, x), \\ \bar{u}(0, x) = \int_{\mathbb{T}} u_0(x, k) dk. \end{cases} \quad (3.11)$$

Proof. We start verifying the hypotheses of Theorem 2.7 finding the tails of

$$\Psi(k) = \omega'(k)t(k) \quad (3.12)$$

under measure π . Since $\omega'(k)$ is both bounded and bounded away from zero the tails of $\Psi(k)$, under π , are the same as those of $t(k)$. Note that

$$\pi(k : t(k) \geq \lambda) = C_R \lambda^{-3/2} (1 + O(1)) \quad \text{for } \lambda \gg 1 \quad (3.13)$$

and some $C_R > 0$. This verifies (2.5) with $\alpha = 3/2$. Since the density of π with respect to the Lebesgue measure is even and Ψ is odd, it has a null π -average.

Verification of hypotheses of part i) of Theorem 2.3. Note that we can decompose $P(k, dk')$ as in (2.8) with $p(k, k')$ given by (3.9) and $Q(k, dk') \equiv 0$. Since $p(k, k')$ is bounded, conditions 2.2 and (2.12) are obviously satisfied. Operator P is a contraction on $L^2(\pi)$ and, by the Hilbert-Schmidt theorem, see e.g. Theorem 4, p. 247 of [20], is symmetric and compact. In consequence, its spectrum is contained in $[-1, 1]$ and is discrete, except for a possible accumulation point at 0.

Lemma 3.2. *Point 1 is a simple eigenvalue of both P and P^2 .*

Proof. Suppose

$$Pf = f. \quad (3.14)$$

We claim that f is either everywhere positive, or everywhere negative. Let f^+, f^- be the positive and negative parts of f . Suppose also that f^+ is non zero on a set of positive π measure. Then $f = f^+ - f^-$ and $Pf = Pf^+ - Pf^-$. Thus $f^+ = (Pf)^+ \leq Pf^+$. Yet

$$\int f^+ d\pi \leq \int Pf^+ d\pi = \int f^+ d\pi,$$

thus $Pf^+ = f^+$. Likewise, $Pf^- = f^-$. Since for each k we have $p(k, k') > 0$, except for a set of k' of measure π zero, we conclude that $f^+ > 0$ π a.e., hence $f^- \equiv 0$.

Now, we know that $P1 = 1$. We claim that any other $f \not\equiv 0$ that satisfies (3.14) belongs to $\text{span}\{1\}$. Otherwise $f - c1$ for some c would suffer change of sign. But this contradicts our conclusion reached above so the lemma holds for P . The argument for P^2 is analogous. \square

As a corollary of the above lemma we conclude that condition 2.1 holds. Applying part i) of Theorem 2.7 to $N^{-2/3} \int_0^{Nt} \omega'(k(s)) ds$ we conclude that its finite dimensional distributions converge in law to an α -stable Levy process for $\alpha = 3/2$.

We use the above result to prove (3.10). To abbreviate the notation denote $Y_N(t) := x + N^{-2/3} \int_0^{Nt} \omega'(k(s)) ds$. Using probabilistic representation for a solution of (3.1) we can write

$$\begin{aligned} u(Nt, N^{3/2}x, k) &= \mathbb{E}_k u_0(Y_N(t), k(Nt)) \\ &= \sum_{\eta \in \mathbb{Z}} \int_{\mathbb{R}} \hat{u}_0(\xi, \eta) \mathbb{E}_k \exp\{i\xi Y_N(t) + i\eta k(Nt)\} d\xi. \end{aligned} \quad (3.15)$$

Here $\hat{u}_0(\xi, \eta)$ is the Fourier transform of $u(x, k)$ and \mathbb{E}_k is the expectation with respect to the path measure corresponding to the momentum process $\{k(t), t \geq 0\}$ that satisfies $k(0) = k$. Since the dynamics of the momentum process is reversible with respect to the normalized Lebesgue measure m on the torus and 0 is a simple eigenvalue for the generator \mathcal{L} we have $\|P^t f\|_{L^2(m)} \rightarrow 0$, as $t \rightarrow +\infty$, provided $\int_{\mathbb{T}} f dk = 0$. Suppose that $\{a_N, N \geq 1\}$ is an increasing sequence of positive numbers tending to infinity and such that $a_N N^{-3/2} \rightarrow 0$. A simple calculation shows that for any $\xi, \eta \in \mathbb{R}$ and $e_\xi(x) := e^{ix\xi}$ we have

$$|\mathbb{E}_k[e_\xi(Y_N(t))e_\eta(k(Nt))] - \mathbb{E}_k[e_\xi(Y_N(t - ta_N/N))e_\eta(k(Nt))]| \rightarrow 0, \quad \text{as } N \rightarrow +\infty. \quad (3.16)$$

Using Markov property we can write that the second term under the absolute value in the formula above equals

$$\mathbb{E}_k[e_\xi(Y_N(t - ta_N/N))P^{a_N t} e_\eta(k((N - a_N)t))].$$

Let $\tilde{e}_\eta(k) := e_\eta(k) - \bar{e}_\eta$, where $\bar{e}_\eta := \int_{\mathbb{T}} e_\eta(k) dk$. By Cauchy-Schwartz inequality we obtain

$$\begin{aligned} & \left| \mathbb{E}_k [e_\xi(Y_N(t - ta_N/N))] P^{a_N t} e_\eta(k((N - a_N)t)) - \mathbb{E}_k e_\xi(Y_N(t - ta_N/N)) \bar{e}_\eta \right| \\ & \leq \left\{ \mathbb{E}_k \left| P^{a_N t} \tilde{e}_\eta(k((N - a_N)t)) \right|^2 \right\}^{1/2}. \end{aligned} \quad (3.17)$$

The right hand side of (3.17) tends to 0 in the L^2 sense with respect to $k \in \mathbb{T}$, as $N \rightarrow +\infty$.

From (3.17) we conclude that

$$\begin{aligned} & \left| \sum_{\eta \in \mathbb{Z}} \int_{\mathbb{R}} \int_{\mathbb{T}} \hat{u}_0(\xi, \eta) \mathbb{E}_k [e_\xi(Y_N(t - ta_N/N))] P^{a_N t} e_\eta(k((N - a_N)t)) d\xi dk \right. \\ & \left. - \sum_{\eta \in \mathbb{Z}} \int_{\mathbb{R}} \int_{\mathbb{T}} \hat{u}_0(\xi, \eta) \mathbb{E}_k e_\xi(Y_N(t - ta_N/N)) \bar{e}_\eta d\xi dk \right| \rightarrow 0, \end{aligned} \quad (3.18)$$

as $N \rightarrow +\infty$. Combining this with (3.16) we conclude the proof of the theorem. \square

Verification of hypotheses of Theorem 2.6. Here we show the convergence of $N^{-3/2}x(Nt)$ by using the coupling approach of section 4. Define the functions

$$\begin{aligned} q_0(k) &:= \sin^2(2\pi k) = 4[\sin^2(\pi k) - \sin^4(\pi k)], \\ q_1(k) &:= \frac{4}{3} \sin^4(\pi k), \end{aligned}$$

which are densities with respect to the Lebesgue measure in \mathbb{T} . A simple computation shows that $R(k, k') = 2^{-4}[q_0(k)q_1(k') + q_1(k)q_0(k')]$ and therefore $R(k) = 2^{-4}[q_0(k) + q_1(k)]$. The transition probability $P(k, dk')$ can be written as

$$P(k, dk') = \frac{q_1(k)}{q_0(k) + q_1(k)} q_0(k') dk' + \frac{q_0(k)}{q_0(k) + q_1(k)} q_1(k') dk'.$$

In particular, in the notation of section 4, this model satisfies condition 2.4 with $q(dk') = q_0(k') dk'$, $\theta = q_1/(q_0 + q_1)$ and $Q_1(k, dk') = q_1(k') dk'$. Notice that the behavior around 0 of π and q is the same. Hence, $q(\Psi(k) \geq \lambda) \sim c\lambda^{-3/2}$ for $\lambda \gg 1$. We conclude therefore that the function $\Psi(k)$, given by (3.12), satisfies (2.16). Observe furthermore that Q_1 does not depend on k and that $Q_1(k', t(k) \geq \lambda) \sim c\lambda^{-5/2}$ for $\lambda \gg 1$. Due to this last observation, condition (2.15) is satisfied.

We are only left to check condition 2.5. But this one is also simple, once we observe that the sequence $\{\delta_n, n \geq 0\}$ is a Markov chain with transition probabilities

$$\begin{aligned} P(\delta_{n+1} = 1 | \delta_n = 0) &= P(\delta_{n+1} = 0 | \delta_n = 1) \\ &= \int_{-1}^1 \frac{q_0(k)q_1(k)dk}{q_0(k) + q_1(k)} \\ P(\delta_{n+1} = 1 | \delta_n = 1) &= \int_{-1/2}^{1/2} \frac{q_1^2(k)dk}{q_0(k) + q_1(k)} \\ P(\delta_{n+1} = 0 | \delta_n = 0) &= \int_{-1/2}^{1/2} \frac{q_0^2(k)dk}{q_0(k) + q_1(k)}. \end{aligned}$$

We conclude that the regeneration time κ satisfies $\mathbb{E}[\exp\{\gamma\kappa\}] < +\infty$ for γ small enough, and therefore condition 2.5 holds.

4. PROOF OF THEOREM 2.6 BY COUPLING

Because of its simplicity, we present first the proof of Theorem 2.6, based on the basic coupling. This coupling permits to decompose the initial Markov chain into independent blocks. Let us define

$$\varphi_i = \sum_{j=\kappa_i}^{\kappa_{i+1}-1} \Psi(X_j),$$

$$\mathcal{M}(N) = \sup\{i \geq 0; \kappa_i \leq N\}.$$

Note that $\mathcal{M}(N) < +\infty$ a.s. An alternative way of defining $\mathcal{M}(N)$ is demanding the inequality $\kappa_{\mathcal{M}(N)} \leq N < \kappa_{\mathcal{M}(N)+1}$ to be satisfied. Then, we have

$$S_N = \sum_{i=0}^{\mathcal{M}(N)} \varphi_i + R_N, \tag{4.1}$$

where

$$R_N := \sum_{j=\kappa_{\mathcal{M}(N)+1}}^N \Psi(X_j).$$

In (4.1) we have decomposed S_N into a random sum of i.i.d. random variables $\{\varphi_i, i \geq 1\}$ and two boundary terms: φ_0 and R_N . Notice also that $\kappa_N - \kappa_1$ is a sum of i.i.d. random variables. Consequently, the law of large numbers gives

$$\frac{\kappa_N}{N} \rightarrow \bar{\kappa} = \mathbb{E}(\kappa_2 - \kappa_1), \quad \text{and} \quad \frac{\mathcal{M}(N)}{N} \rightarrow \bar{\kappa}^{-1} = \bar{\theta}, \tag{4.2}$$

a.s., as $N \rightarrow +\infty$.

Observe also that when $\alpha \in (1, 2)$ and Ψ is centered, random variable φ_1 also has to be centered. Indeed, by the ergodic theorem we have that a.s.

$$0 = \lim_{N \rightarrow +\infty} \frac{S_N}{N} = \lim_{N \rightarrow +\infty} \frac{1}{\mathcal{M}(N)} \sum_{i=1}^{\kappa \mathcal{M}(N)} \varphi_i \times \frac{\mathcal{M}(N)}{N} = \mathbb{E} \varphi_1 \bar{\theta},$$

which proves that

$$\mathbb{E} \varphi_1 = 0. \quad (4.3)$$

The idea now is that under conditions 2.4 – 2.5, the random variable φ_i is equal to $\Psi(X_{\kappa_i})$ plus a term with lighter tails. Before stating this result, we need a simple lemma:

Lemma 4.1. *Let ζ be a random variable such that*

$$\lim_{x \rightarrow \infty} x^\alpha \mathbb{P}(\zeta > x) = c^+, \quad \lim_{x \rightarrow \infty} x^\alpha \mathbb{P}(\zeta < -x) = c^-.$$

Let ξ be such that $\lim_{x \rightarrow \infty} \mathbb{P}(|\xi| > x) / \mathbb{P}(|\zeta| > x) = 0$. Then,

$$\lim_{x \rightarrow \infty} x^\alpha \mathbb{P}(\zeta + \xi > x) = c^+, \quad \lim_{x \rightarrow \infty} x^\alpha \mathbb{P}(\zeta + \xi < -x) = c^-.$$

Proof. Without loss of generality, we just consider the first limit, the second one follows considering $-\zeta, -\xi$. We will prove that the $\liminf_{x \rightarrow \infty}$ of the previous expression is bigger than c_+ and the \limsup is smaller than c_+ . We start with the upper bound: for any $\epsilon > 0$,

$$\begin{aligned} x^\alpha \mathbb{P}(\zeta + \xi > x) &\leq x^\alpha \mathbb{P}(\zeta > (1 - \epsilon)x) + x^\alpha \mathbb{P}(\xi > \epsilon x) = \\ &\leq \frac{c_+}{(1 - \epsilon)^\alpha} + \frac{\mathbb{P}(|\xi| > \epsilon x) c_+}{\mathbb{P}(\zeta > \epsilon x) \epsilon^\alpha}. \end{aligned}$$

Now take above the limit as $x \rightarrow +\infty$ to get

$$\limsup_{x \rightarrow +\infty} x^\alpha \mathbb{P}(\zeta + \xi > x) \leq \frac{c_+}{(1 - \epsilon)^\alpha}.$$

Since ϵ is arbitrary, we have proved the upper bound. The lower bound is very similar:

$$\begin{aligned} \mathbb{P}(\zeta + \xi > x) &= \mathbb{P}(\zeta + \xi > x, \xi > -\epsilon x) + \mathbb{P}(\zeta + \xi > x, \xi \leq -\epsilon x) \\ &\geq \mathbb{P}(\zeta > (1 + \epsilon)x, \xi > -\epsilon x) = \\ &\geq \mathbb{P}(\zeta > (1 + \epsilon)x) - \mathbb{P}(\zeta > (1 + \epsilon)x, \xi \leq -\epsilon x) \\ &\geq \mathbb{P}(\zeta > (1 + \epsilon)x) - \mathbb{P}(\xi < -\epsilon x). \end{aligned}$$

Starting from this last expression, the same computations done for the upper bound show that

$$\liminf_{x \rightarrow +\infty} x^\alpha \mathbb{P}(\zeta + \xi > x) \geq \frac{c_+}{(1 + \epsilon)^\alpha}.$$

Since $\epsilon > 0$ is arbitrary, the lemma is proved. \square

Lemma 4.2. *Let Ψ satisfy (2.5) with constants c_*^+, c_*^- together with conditions 2.4 - 2.5. Then, the law of each φ_i satisfies*

$$\begin{aligned} \lim_{\lambda \rightarrow +\infty} \lambda^\alpha \mathbb{P}(\varphi_i > \lambda) &= c_*^+ \bar{\theta}^{-1}, \\ \lim_{\lambda \rightarrow +\infty} \lambda^\alpha \mathbb{P}(\varphi_i < -\lambda) &= c_*^- \bar{\theta}^{-1}. \end{aligned} \tag{4.4}$$

Proof. The idea of the proof is simple. Random variable φ_i is the sum of a random variable with an α -tail, $\Psi(X_{\kappa_i})$, and a finite (but random) number of random variables with lighter tails ($\Psi(X_{\kappa_i+1}), \dots, \Psi(X_{\kappa_{i+1}-1})$). By condition 2.5, the random number can be efficiently controlled. To simplify the notation, assume that X_0 is distributed according to q , so the first block is also distributed like the other ones. Then,

$$\begin{aligned} \mathbb{P}\left(\sum_{j=1}^{\kappa_1-1} \Psi(X_j) \geq t\right) &= \sum_{n=1}^{\infty} \mathbb{P}\left(\sum_{j=1}^{n-1} \Psi(X_j) \geq t, \kappa_1 = n\right) \\ &\leq \sum_{n=1}^{\infty} \mathbb{P}\left(\sum_{j=1}^{n-1} \Psi(X_j) \geq t, \kappa_1 \geq n\right) \\ &\leq \sum_{n=1}^{\infty} \mathbb{P}\left(\sum_{j=1}^{n-1} \Psi(X_j) \geq t \mid \kappa_1 \geq n\right) \mathbb{P}(\kappa_1 \geq n) \\ &\leq \sum_{n=1}^{\infty} \sum_{j=1}^{n-1} \mathbb{P}(\Psi(X_j) \geq t/(n-1) \mid \kappa_1 \geq n) \mathbb{P}(\kappa_1 \geq n) \\ &\leq \sum_{n=1}^{\infty} \sum_{j=1}^{n-1} \mathbb{P}(\Psi(X_j) \geq t/(n-1) \mid \delta_j = 1) \mathbb{P}(\kappa_1 \geq n) \\ &\leq \sum_{n=1}^{\infty} \frac{g(t/n)n^{1+\alpha}}{t^\alpha} \mathbb{P}(\kappa_1 \geq n) \end{aligned}$$

for some bounded function $g(x)$ that goes to 0 as $x \rightarrow \infty$. We have used the Markov property in the third line and condition (2.16) in the last line. We conclude that this last term is $o(t^{-\alpha})$ by invoking Fatou's lemma and condition 2.5. The negative tails are treated in the same way. Therefore, $\varphi_0 - \Psi(X_0)$ has lighter tails than $\Psi(X_0)$ itself. By lemma 4.1, the sum of a random variable satisfying condition (2.16) and a random variable with lighter tails also satisfies condition (2.16) for the same constants $c^+ \bar{\theta}^{-1}, c^- \bar{\theta}^{-1}$. \square

At this point we are only left to recall the classical limit theorem for i.i.d. random variables. It follows that there exist

$$\begin{aligned} N^{-1/\alpha} S_N &= \left(\frac{\mathcal{M}(N)}{N} \right)^{1/\alpha} \frac{1}{\mathcal{M}(N)^{1/\alpha}} \sum_{i=0}^{\mathcal{M}(N)} \varphi_i + \frac{1}{N^{1/\alpha}} \sum_{j=\kappa_{\mathcal{M}(N)}+1}^N \Psi(X_j) \\ &= \left(\frac{\mathcal{M}(N)}{N\bar{\theta}} \right)^{1/\alpha} \frac{1}{\mathcal{M}(N)^{1/\alpha}} \sum_{i=0}^{\mathcal{M}(N)} \bar{\theta}^{1/\alpha} \varphi_i + \frac{1}{N^{1/\alpha}} \sum_{j=\kappa_{\mathcal{M}(N)}+1}^N \Psi(X_j) \end{aligned}$$

Recall (4.2), and notice that, by (4.4),

$$\begin{aligned} \lim_{\lambda \rightarrow +\infty} \lambda^\alpha \mathbb{P}(\bar{\theta}^{1/\alpha} \varphi_i > \lambda) &= c_*^+, \\ \lim_{\lambda \rightarrow +\infty} \lambda^\alpha \mathbb{P}(\bar{\theta}^{1/\alpha} \varphi_i < -\lambda) &= c_*^-. \end{aligned}$$

Let $C_* := (c_*^- + c_*^+) \bar{\theta}^{-1}$. By virtue of the stable limit theorem for i.i.d. random variables, see e.g. [8] Theorem 7.7 p. 153, we know that for $c_N := N \mathbb{E}[\varphi_1, |\varphi_1| \leq (C_* N)^{1/\alpha}]$ such that the laws of $N^{-1/\alpha} \left(\sum_{i=0}^N \bar{\theta}^{1/\alpha} \varphi_i - c_N \right)$ converge to an α -stable law. When $\alpha < 1$ constants $c_N \sim c N^{1/\alpha}$ and they can be discarded. Observe however that since $\mathbb{E}\varphi_1 = 0$, cf. (4.3), for $\alpha \in (1, 2)$ we have

$$\begin{aligned} c_N &= -N \mathbb{E}[\varphi_1, |\varphi_1| > (C_* N)^{1/\alpha}] = N \int_{(C_* N)^{1/\alpha}}^{+\infty} [\mathbb{P}[\varphi_1 < -\lambda] - \mathbb{P}[\varphi_1 > \lambda]] d\lambda \\ &= \bar{\theta}^{-1} N \int_{(C_* N)^{1/\alpha}}^{+\infty} (c_*^- - c_*^+) \frac{d\lambda}{\lambda^\alpha} = C(1 + o(1)) N^{1/\alpha} \end{aligned}$$

for some constant C . The constants c_N can again be discarded. We conclude therefore that the laws of

$$\mathcal{K}_N := N^{-1/\alpha} \left(\sum_{i=0}^N \bar{\theta}^{1/\alpha} \varphi_i \right)$$

weakly converge to some α -stable law ν_* . Since $\mathcal{L}_N := \bar{\theta}^{-1/\alpha} N^{-1} \mathcal{M}(N)$ converges a.s. to 1, the joint law of $(\mathcal{K}_N, \mathcal{L}_N)$ converges to $\nu_* \otimes \delta_1$, as $N \rightarrow +\infty$. According to Skorochod's representation theorem there exists a probability space and random variables $(\bar{\mathcal{K}}_N, \bar{\mathcal{L}}_N)$ such that $(\bar{\mathcal{K}}_N, \bar{\mathcal{L}}_N) \stackrel{d}{=} (\mathcal{K}_N, \mathcal{L}_N)$ for each N and $(\bar{\mathcal{K}}_N, \bar{\mathcal{L}}_N) \rightarrow (Y_*, 1)$ a.s.. The above in particular implies that $\bar{\mathcal{K}}_{N\bar{\mathcal{L}}_N}$ converges a.s. to Y_* . Since $\bar{\mathcal{K}}_{N\bar{\mathcal{L}}_N} \stackrel{d}{=} \mathcal{K}_{N\mathcal{L}_N}$ we conclude the convergence of the laws of $\mathcal{K}_{N\mathcal{L}_N}$ to ν_* .

5. THE PROOF OF THEOREM 2.3 BY MARTINGALE APPROXIMATION

Below we formulate stable limits law that shall be crucial during the course of the proof of the theorems. Their proofs are contained in Section 4 of [9].

Suppose that $\{Z_n : n \geq 1\}$ is a stationary sequence that is adapted with respect to the filtration $\{\mathcal{G}_n : n \geq 0\}$ and such that for any f bounded and measurable $\{\mathbb{E}[f(Z_n) | \mathcal{G}_{n-1}] : n \geq 1\}$

is also stationary. We assume furthermore that there exist $\alpha \in (0, 2)$ and $c_*^+, c_*^- \geq 0$ such that $c_*^+ + c_*^- > 0$ and

$$\begin{aligned} \mathbb{P}[Z_1 > \lambda] &= \lambda^{-\alpha}(c_*^+ + o(1)), \quad \text{as } \lambda \rightarrow +\infty, \\ \mathbb{P}[Z_1 < -\lambda] &= \lambda^{-\alpha}(c_*^- + o(1)), \quad \text{as } \lambda \rightarrow +\infty. \end{aligned} \quad (5.1)$$

In addition, for any $g \in C_0^\infty(\mathbb{R} \setminus \{0\})$ we have

$$\lim_{N \rightarrow +\infty} \mathbb{E} \left[\sum_{n=1}^{\lfloor Nt \rfloor} \mathbb{E} \left[g \left(\frac{Z_n}{N^{1/\alpha}} \right) \mid \mathcal{G}_{n-1} \right] - \alpha t \int_{\mathbb{R}} g(\lambda) \frac{c_*(\lambda) d\lambda}{|\lambda|^{1+\alpha}} \right] = 0 \quad (5.2)$$

and

$$\lim_{N \rightarrow +\infty} N \mathbb{E} \left\{ \mathbb{E} \left[g \left(\frac{Z_1}{N^{1/\alpha}} \right) \mid \mathcal{G}_0 \right] \right\}^2 = 0. \quad (5.3)$$

Here $c_*(\cdot)$ appearing in (5.2) is given by (2.2). Let $M_N := \sum_{n=1}^N Z_n$, $N \geq 1$ and $M_0 := 0$.

When $\alpha = 1$ we shall also consider an array $\{Z_n^{(N)} : n \geq 1\}$, $N \geq 1$ of stationary sequences adapted with respect to the filtration $\{\mathcal{G}_n : n \geq 0\}$. Assume furthermore that for each $N \geq 1$ and any f bounded and measurable sequence $\{\mathbb{E}[f(Z_n^{(N)}) \mid \mathcal{G}_{n-1}] : n \geq 1\}$ is stationary. We suppose that there exist non-negative c_*^+, c_*^- such that $c_*^+ + c_*^- > 0$ and

$$\lim_{\lambda \rightarrow +\infty} \sup_{N \geq 1} [|\lambda \mathbb{P}[Z_1^{(N)} > \lambda] - c_*^+| + |\lambda \mathbb{P}[Z_1^{(N)} < -\lambda] - c_*^-|] = 0. \quad (5.4)$$

Let

$$\tilde{M}_N := \sum_{n=1}^N \{Z_n^{(N)} - \mathbb{E}[Z_n^{(N)} \mathbf{1}_{\{|Z_n^{(N)}| \leq N\}} \mid \mathcal{G}_{n-1}]\}, \quad N \geq 1$$

and $\tilde{M}_0 := 0$.

Theorem 5.1. *i) Suppose that $\alpha \in (1, 2)$, conditions (5.1)-(5.3) hold and*

$$\mathbb{E}[Z_n \mid \mathcal{G}_{n-1}] = 0 \quad \text{for } n \geq 1, \quad (5.5)$$

Then, $N^{-1/\alpha} M_{[N]} \Rightarrow Z(\cdot)$, as $N \rightarrow +\infty$, weakly in $D[0, +\infty)$, where $\{Z(t), t \geq 0\}$ is an α -stable process of type II.

ii) Suppose that $\alpha \in (0, 1)$ and conditions (5.1)-(5.3) hold. Then, $N^{-1/\alpha} M_{[N]} \Rightarrow Z(\cdot)$, as $N \rightarrow +\infty$, weakly in $D[0, +\infty)$, where $\{Z(t), t \geq 0\}$ is an α -stable process of type I.

iii) For $\alpha = 1$ assume (5.2)-(5.3) with $Z_n^{(N)}$ replacing Z_n and (5.4). Then, $N^{-1} \tilde{M}_{[N]} \Rightarrow Z(\cdot)$, as $N \rightarrow +\infty$, weakly in $D[0, +\infty)$ to a Levy process $\{Z(t), t \geq 0\}$ of type III.

The proof of part i) of Theorem 2.3. Let $\chi \in L^\beta(\pi)$, $\beta \in (1, \alpha)$ be the unique, zero mean, solution of the equation

$$\chi - P\chi = \Psi. \quad (5.6)$$

Since $\Psi \in L^\beta(\pi)$ for $\beta \in (0, \alpha)$ is of zero mean, the solution to (5.6) exists in $L^\beta(\pi)$ and is given by $\chi = \sum_{n \geq 0} P^n \Psi$. This follows from the fact that $\|P^n \Psi\|_{L^\beta} \leq a^{2/\alpha-1} \|\Psi\|_{L^\beta}$, $n \geq 0$, (see (2.7)) so the series defining χ geometrically converges. Uniqueness follows from the

spectral gap. Note also that from (2.12) it follows that in fact $P\chi = (I - P)^{-1}(P\Psi) \in L^{\alpha'}(\pi)$. Thus, in particular

$$\pi(|P\chi| > \lambda) \leq \frac{\|P\chi\|_{L^{\alpha'}(\pi)}^{\alpha'}}{\lambda^{\alpha'}}. \quad (5.7)$$

and consequently χ satisfies the same tail condition as Ψ (cf. (2.5)).

Then, by using (5.6), we can write

$$S_N = \sum_{n=1}^N \Psi(X_n) = \sum_{n=1}^N Z_n + P\chi(X_0) - P\chi(X_N) \quad (5.8)$$

with $Z_n = \chi(X_n) - P\chi(X_{n-1})$. According to part i) of Theorem 5.1, we only need to demonstrate the following.

Proposition 5.2. *For any $g \in C_0^\infty(\mathbb{R} \setminus \{0\})$*

$$\lim_{N \rightarrow +\infty} \mathbb{E} \left| \sum_{n=1}^N \mathbb{E} \left[g \left(\frac{Z_n}{N^{1/\alpha}} \right) \middle| \mathcal{G}_{n-1} \right] - \int_{\mathbb{R}} g(\lambda) \frac{c_*(\lambda) d\lambda}{|\lambda|^{1+\alpha}} \right| = 0 \quad (5.9)$$

and

$$\lim_{N \rightarrow +\infty} N \mathbb{E} \left\{ \mathbb{E} \left[g \left(\frac{Z_1}{N^{1/\alpha}} \right) \middle| \mathcal{G}_0 \right] \right\}^2 = 0. \quad (5.10)$$

More explicitly we have

$$E \left[g \left(\frac{Z_n}{N^{1/\alpha}} \right) \middle| \mathcal{G}_{n-1} \right] = \int g(N^{-1/\alpha}[\chi(y) - P\chi(X_{n-1})]) P(X_{n-1}, dy)$$

and using stationarity of π we can bound the left hand side of (5.9) by

$$\begin{aligned} & \mathbb{E} \left| \sum_{n=1}^N \int \left[g(N^{-1/\alpha}[\chi(y) - P\chi(X_{n-1})]) - g \left(\frac{\chi(y)}{N^{1/\alpha}} \right) \right] P(X_{n-1}, dy) \right| \\ & + \mathbb{E} \left| \sum_{n=1}^N \int g \left(\frac{\chi(y)}{N^{1/\alpha}} \right) P(X_{n-1}, dy) - N \int g \left(\frac{\chi(y)}{N^{1/\alpha}} \right) \pi(dy) \right| \\ & + \left| N \int g \left(\frac{\chi(y)}{N^{1/\alpha}} \right) \pi(dy) - \alpha \int_{\mathbb{R}} g(\lambda) \frac{c_*(\lambda) d\lambda}{|\lambda|^{1+\alpha}} \right| \end{aligned} \quad (5.11)$$

so (5.9) is a consequence of the following three lemmas, each taking care of the respective term of (5.11):

Lemma 5.3.

$$\lim_{N \rightarrow \infty} N \iint |g(N^{-1/\alpha}[\chi(y) - P\chi(x)]) - g(N^{-1/\alpha}\chi(y))| P(x, dy) \pi(dx) = 0 \quad (5.12)$$

Lemma 5.4.

$$\mathbb{E} \left| \sum_{n=1}^N \mathbb{E} [g(N^{-1/\alpha} \chi(X_n)) \mid \mathcal{G}_{n-1}] - N \int g(N^{-1/\alpha} \chi(y)) \pi(dy) \right| = 0. \quad (5.13)$$

Lemma 5.5.

$$\lim_{N \rightarrow \infty} \left| N \int g(N^{-1/\alpha} \chi(y)) \pi(dy) - \alpha \int_{\mathbb{R}} g(\lambda) \frac{c_*(\lambda) d\lambda}{|\lambda|^{1+\alpha}} \right| = 0, \quad (5.14)$$

where $c_*(\cdot)$ is given by (2.2).

Proof of Lemma 5.3. Suppose that $\text{supp } g \subset [-M, M] \setminus [-m, m]$ for some $0 < m < M < +\infty$ and $\theta > 0$. Denote

$$A_{N,\theta} = \{(x, y) : |\chi(y) - \theta P\chi(x)| > N^{1/\alpha} m\}$$

The left hand side of (5.12) can be bounded from above by

$$\begin{aligned} N^{1-1/\alpha} \int_0^1 d\theta \iint |g'(N^{-1/\alpha} [\chi(y) - \theta P\chi(x)]) P\chi(x)| P(x, dy) \pi(dx) \\ \leq CN^{1-1/\alpha} \int_0^1 d\theta \iint_{A_{N,\theta}} |P\chi(x)| P(x, dy) \pi(dx) \\ \leq CN^{1-1/\alpha} \int_0^1 d\theta \left(\iint_{A_{N,\theta}} P(x, dy) \pi(dx) \right)^{1-1/\alpha'} \|P\chi\|_{L^{\alpha'}} \end{aligned}$$

From the tail behavior of χ and of $P\chi$, see (5.7) and the remark below that estimate, it is easy to see that for any $\theta \in [0, 1]$

$$\begin{aligned} \iint_{A_{N,\theta}} P(x, dy) \pi(dx) &\leq \mathbb{P}[|\chi(X_1)| \geq (mN^{1/\alpha})/2] + \mathbb{P}[|P\chi(X_0)| \geq (mN^{1/\alpha})/2] \\ &\leq C[(Nm^\alpha)^{-1} + (Nm^\alpha)^{-\alpha'/\alpha}] = \frac{C}{N}(1 + o(1)), \end{aligned}$$

as $N \gg 1$. Since $\alpha' > \alpha$ we obtain (5.12). \square

Proof of Lemma 5.4. To simplify the notation we assume that $\text{supp } g \subset [m, M]$ for $0 < m < M < +\infty$. Denote $B_{N,\lambda} = \{y : \chi(y) \geq N^{1/\alpha} \lambda\}$. We can rewrite the left hand side of (5.13) as

$$\mathbb{E} \left| \int_0^\infty g'(\lambda) \sum_{n=1}^N G_N(X_{n-1}, \lambda) d\lambda \right| \quad (5.15)$$

where

$$G_N(x, \lambda) = P(x, B_{N,\lambda}) - \pi(B_{N,\lambda}).$$

Notice that $\int G_N(y, \lambda) \pi(dy) = 0$ and

$$\begin{aligned} & \int G_N^2(y, \lambda) \pi(dy) = \int P^2(y, B_{N,\lambda}) \pi(dy) - \pi^2(B_{N,\lambda}) \\ & \leq 2 \int \left(\int_{B_{N,\lambda}} p(x, y) \pi(dx) \right)^2 \pi(dy) + 2 \int Q^2(x, B_{N,\lambda}) \pi(dy) - \pi^2(B_{N,\lambda}) \end{aligned} \quad (5.16)$$

To estimate the first term on the utmost right hand side we use Cauchy Schwartz inequality, while for the second one we apply condition (2.10). For $\lambda \geq m$ we can bound the expression on the right hand side of (5.16) by

$$\begin{aligned} & \frac{1}{2} \pi(B_{N,m}) \int \int_{B_{N,m}} p^2(x, y) \pi(dx) \pi(dy) + C \pi^2(B_{N,m}) \\ & \leq \frac{1}{N} o(1), \quad \text{as } N \rightarrow \infty, \end{aligned} \quad (5.17)$$

by virtue of (2.9) and the remark after (5.7). Thus, we have shown that

$$N \sup_{\lambda \geq m} \int G_N^2(y, \lambda) \pi(dy) \rightarrow 0, \quad (5.18)$$

as $N \rightarrow \infty$. We will show now that (5.18) and the spectral gap together imply that

$$\sup_{\lambda \geq m} \mathbb{E} \left| \sum_{n=1}^N G_N(X_{n-1}, \lambda) \right|^2 \rightarrow 0, \quad (5.19)$$

as $N \rightarrow \infty$. Since $\text{supp } g' \subset [m, M]$ expression in (5.15) can be then estimated by

$$\sup_{\lambda \geq m} \mathbb{E} \left| \sum_{n=1}^N G_N(X_{n-1}, \lambda) \right| \times \int_0^\infty |g'(\lambda)| d\lambda \rightarrow 0,$$

as $N \rightarrow +\infty$ and the conclusion of the lemma follows.

To prove (5.19) let $u_N(\cdot, \lambda) = (I - P)^{-1} G_N(\cdot, \lambda)$. By the spectral gap condition (2.7) we have

$$\int u_N^2(y, \lambda) \pi(dy) \leq \frac{1}{1-a} \int G_N^2(y, \lambda) \pi(dy) \quad (5.20)$$

We can rewrite then

$$\sum_{n=1}^N G_N(X_{n-1}, \lambda) = u_N(X_0) - u_N(X_N) + \sum_{n=1}^{N-1} U_n,$$

where $U_n = u_N(X_n) - P u_N(X_{n-1})$, $n \geq 1$ is a stationary sequence of martingale differences with respect to the natural filtration corresponding to $\{X_n, n \geq 0\}$. Consequently,

$$\mathbb{E} \left| \sum_{n=1}^N G_N(X_{n-1}, \lambda) \right|^2 \leq CN \int u_N^2(y, \lambda) \pi(dy) \rightarrow 0$$

and (5.19) follows from (5.18) and (5.20). \square

Proof of Lemma 5.5. To avoid long notation we again assume that $\text{supp } g \subset [m, M]$ for $0 < m < M < +\infty$. The proof in case $g \subset [-M, -m]$ is virtually the same. Note that

$$\begin{aligned} & N \int g \left(\frac{\chi(y)}{N^{1/\alpha}} \right) \pi(dy) \\ &= N \int \int_0^{+\infty} N^{-1/\alpha} g' \left(\frac{\lambda}{N^{1/\alpha}} \right) 1_{[0, \chi(y)]}(\lambda) \pi(dy) d\lambda \\ &= N \int_0^{+\infty} N^{-1/\alpha} g' \left(\frac{\lambda}{N^{1/\alpha}} \right) \pi(\chi > \lambda) d\lambda \\ &= N \int_0^{+\infty} g'(\lambda) \pi(\chi \geq N^{1/\alpha} \lambda) d\lambda. \end{aligned}$$

Thanks to (2.5) the last expression tends however, as $N \rightarrow +\infty$, to

$$\int_0^{+\infty} g'(\lambda) \frac{c_*^+ d\lambda}{\lambda^\alpha} = \alpha \int_{\mathbb{R}} g(\lambda) \frac{c_*(\lambda) d\lambda}{|\lambda|^{\alpha+1}}.$$

□

The proof of Proposition 5.2. We have already shown (5.9), so only (5.10) requires a proof. Suppose that $\text{supp } g \subset [m, M]$ for some $0 < m < M$. We can write

$$\begin{aligned} & \mathbb{E} \left[g \left(\frac{Z_1}{N^{1/\alpha}} \right) \mid \mathcal{G}_0 \right] \\ &= \int g(N^{-1/\alpha} \Psi(y)) p(X_0, y) \pi(dy) \\ &+ N^{-1/\alpha} \int \int_0^1 h(X_0, y) g'(N^{-1/\alpha} (\Psi(y) + \theta h(X_0, y))) p(X_0, y) \pi(dy) d\theta, \end{aligned} \tag{5.21}$$

where $h(x, y) := P\chi(y) - P\chi(x)$. Denote by K_1 and K_2 the first and the second terms appearing on the right hand side above. By Cauchy-Schwartz inequality

$$\begin{aligned} \mathbb{E} K_2^2 &\leq \frac{\|g'\|_\infty^2}{N^{2\alpha}} \left[\mathbb{E} \left(\int |P\chi(y)| p(X_0, y) \pi(dy) \right)^2 \right. \\ &\quad \left. + \mathbb{E} \left(\int |P\chi(X_0)| p(X_0, y) \pi(dy) \right)^2 \right] \\ &\leq \frac{2\|g'\|_\infty^2 \|P\chi\|_{L^2(\pi)}^2}{N^{2/\alpha}}. \end{aligned} \tag{5.22}$$

Hence, $\lim_{N \rightarrow +\infty} N \mathbb{E} K_2^2 = 0$.

On the other hand,

$$K_1 \leq \|g\|_\infty \int p(X_0, y) 1_{[|\Psi(y)| > mN^{1/\alpha}/2]} \pi(dy) \tag{5.23}$$

and in consequence, by Jensen's inequality,

$$\begin{aligned} (\mathbb{E}K_1^2)^{1/2} &\leq \|g\|_\infty \int (\mathbb{E}p^2(X_0, y))^{1/2} 1[|\Psi(y)| > aN^{1/\alpha}/2] \pi(dy) \\ &\leq \|g\|_\infty \left[\int \int p^2(x, y) 1[|\Psi(y)| > aN^{1/\alpha}/2] \pi(dx) \pi(dy) \right]^{1/2} \\ &\quad \times \pi^{1/2}[|\Psi| > aN^{1/\alpha}/2]. \end{aligned}$$

Thus, we have shown that

$$\begin{aligned} N\mathbb{E}K_1^2 &\leq N\pi[|\Psi| > aN^{1/\alpha}/2] \\ &\quad \times \int \int p^2(x, y) 1[|\Psi(y)| > aN^{1/\alpha}/2] \pi(dx) \pi(dy) \rightarrow 0. \end{aligned} \tag{5.24}$$

Condition (5.10) is then a consequence of (5.22) and (5.24). \square

The proof of part ii) of Theorem 2.3. The proof of this part relies on part ii) of Theorem 5.1. The following analogue of Proposition 5.2 can be established.

Proposition 5.6. *Suppose that $\alpha \in (0, 1)$. Then, for any $g \in C_0^\infty(\mathbb{R} \setminus \{0\})$*

$$\lim_{N \rightarrow +\infty} \mathbb{E} \left| \sum_{n=1}^N \mathbb{E} \left[g \left(\frac{\Psi(X_n)}{N^{1/\alpha}} \right) \mid \mathcal{G}_{n-1} \right] - \int_{\mathbb{R}} g(\lambda) \frac{C_*(\lambda) d\lambda}{|\lambda|^{1+\alpha}} \right| = 0 \tag{5.25}$$

and

$$\lim_{N \rightarrow +\infty} N\mathbb{E} \left\{ \mathbb{E} \left[g \left(\frac{\Psi(X_1)}{N^{1/\alpha}} \right) \mid \mathcal{G}_0 \right] \right\}^2 = 0. \tag{5.26}$$

Proof. The proof of this proposition is a simplified version of the argument used in the proof of Proposition 5.2. The expression in (5.25) can be estimated by

$$\begin{aligned} \mathbb{E} \left| \sum_{n=1}^N \int g \left(\frac{\Psi(y)}{N^{1/\alpha}} \right) P(X_{n-1}, dy) - N \int g \left(\frac{\Psi(y)}{N^{1/\alpha}} \right) \pi(dy) \right| \\ + \left| N \int g \left(\frac{\Psi(y)}{N^{1/\alpha}} \right) \pi(dy) - \alpha \int_{\mathbb{R}} g(\lambda) \frac{c_*(\lambda) d\lambda}{|\lambda|^{1+\alpha}} \right| \end{aligned} \tag{5.27}$$

The proof that both the terms of the sum above vanish goes along the lines of the proofs of Lemmas 5.4 and 5.5. We can repeat word by word the argument used there, replacing this time χ by Ψ . As for the proof of (5.26) it is identical with the respective part of the proof of (5.10) (the one concerning term K_1). \square

The proof of part iii) of Theorem 2.3. Recall that $\Psi_N := \Psi 1[|\Psi| \leq N]$. Let χ_N be the unique, zero mean, solution of the equation

$$\chi_N - P\chi_N = \Psi_N - c_N. \quad (5.28)$$

We can write then

$$S_N - Nc_N = \sum_{n=1}^N (\Psi(X_n) - c_N) = \sum_{n=1}^N Z_n^{(N)} + P\chi_N(X_0) - P\chi_N(X_N), \quad (5.29)$$

with

$$Z_n^{(N)} = \chi_N(X_n) - P\chi_N(X_{n-1}) + \Psi(X_n)1[|\Psi(X_n)| > N].$$

We verify first assumptions (5.2), (5.3) and (5.4).

Condition (5.4) is an obvious consequence of the fact that

$$Z_n^{(N)} = P\chi_N(X_n) - P\chi_N(X_{n-1}) + \Psi(X_n) - c_N \quad (5.30)$$

and assumption (2.13). To verify the remaining hypotheses suppose that $\text{supp } g \subset (m, M)$ and $m < 1 < M$. Let us fix $\delta > 0$, to be further chosen later on, such that $m < 1 - \delta < 1 + \delta < M$. We can write then $g = g_1 + g_2 + g_3$, where each $g_i \in C^\infty(\mathbb{R})$, $\|g_i\|_\infty \leq \|g\|_\infty$ and the supports of g_1, g_2, g_3 are correspondingly contained in $(m, 1 - \delta)$, $(1 - \delta, 1 + \delta)$, $(1 + \delta, M)$. We prove (5.2) and (5.3) for each of the functions g_i -s separately. Note that

$$\mathbb{E} \left[g_i \left(\frac{Z_n^{(N)}}{N} \right) \middle| \mathcal{G}_{n-1} \right] = \int g_i (w^{(N)}(X_{n-1}, y)) P(X_{n-1}, dy),$$

where

$$w^{(N)}(x, y) := N^{-1}\Psi(y)1[|\Psi(y)| > N] + N^{-1}[\chi_N(y) - P\chi_N(x)].$$

For $i = 1$ and $i = 3$ we essentially estimate in the same way as in parts i) and ii) of the proof of the theorem respectively. We shall only consider here the case $i = 2$.

Note that then $w^{(N)}(x, y) = w_1^{(N)}(x, y)$, where

$$w_\theta^{(N)}(x, y) = N^{-1}[\Psi(y) - c_N] + N^{-1}\theta R_N(x, y), \quad (5.31)$$

with $R_N(x, y) := P\chi_N(y) - P\chi_N(x)$. However,

$$g_2 (w^{(N)}(X_{n-1}, y)) = g_2 (N^{-1}(\Psi(y) - c_N)) + N^{-1}R_N(X_{n-1}, y) \int_0^1 g_2' (w_\theta^{(N)}(X_{n-1}, y)) d\theta$$

and

$$\begin{aligned} & \mathbb{E} \left| \sum_{n=1}^N \int g_2 (w^{(N)}(X_{n-1}, y)) P(X_{n-1}, dy) \right| \\ & \leq \mathbb{E} \left| \sum_{n=1}^N \int g_2 (N^{-1}(\Psi(y) - c_N)) P(X_{n-1}, dy) \right| \\ & \quad + \int \int \int_0^1 |g_2' (w_\theta^{(N)}(x, y)) R_N(x, y)| P(x, dy) \pi(dy) d\theta. \end{aligned}$$

Denote the first and the second term on the right hand side by $J_1^{(N)}$ and $J_2^{(N)}$ respectively. Term $J_1^{(N)}$ can be now estimated as in the proof of part ii) of the theorem. We conclude then, using the arguments contained in the proofs of Lemmas 5.4 and 5.5 that

$$\limsup_{N \rightarrow +\infty} J_1^{(N)} \leq \|g\|_\infty \int_{1-\delta}^{1+\delta} \frac{d\lambda}{\lambda^2}.$$

On the other hand, to estimate $\lim_{N \rightarrow +\infty} J_2^{(N)} = 0$, since $g'_2 \left(w_\theta^{(N)}(x, y) \right) \rightarrow 0$ in measure $P(x, dy)\pi(dy)d\theta$ and the passage to the limit under the integral can be substantiated thanks to (2.13).

Choosing now sufficiently small $\delta > 0$ we can argue that the calculation of the limit can be reduced to the cases considered for g_1 and g_3 and the condition (5.2) can be established for $Z_n^{(N)}$. The proof of (5.3) can be repeated from the argument for part i) of the theorem.

Finally, we show that

$$\lim_{N \rightarrow +\infty} \frac{1}{N} \mathbb{E} \left| \sum_{n=1}^N \mathbb{E}[Z_n^{(N)} 1[|Z_n^{(N)}| \leq N] | \mathcal{G}_{n-1}] \right| = 0. \quad (5.32)$$

Denote the expression under the limit by $L^{(N)}$. Let $\Delta > 1$. We can write $L^{(N)} = L_1^{(N)} + L_2^{(N)} + L_3^{(N)}$ depending on whether $|\Psi(X_n)| > \Delta N$, $|\Psi(X_n)| \in (\Delta^{-1}N, \Delta N]$, or $|\Psi(X_n)| \leq (\Delta)^{-1}N$. Then,

$$L_1^{(N)} \leq \sum_{n=1}^N \mathbb{P}[|\Psi(X_n)| > \Delta N, |Z_n^{(N)}| \leq N] = N \mathbb{P}[|\Psi(X_1)| > \Delta N, |Z_1^{(N)}| \leq N]$$

From formula (5.30) for $Z_n^{(N)}$ we conclude that the event under the conditional probability can take place only when $|P\chi_N(X_n)|$, or $|P\chi_N(X_{n-1})| > N(\Delta - 1)/3$ for those N , for which $c_N/N \leq (\Delta - 1)/3$. Using this observation, (2.13) and Chebyshev's inequality one can easily see that

$$L_1^{(N)} \leq 2N[N(\Delta - 1)/3]^{-\alpha'} \|P\chi_N\|_{L^{\alpha'}(\pi)}^{\alpha'} \rightarrow 0,$$

as $N \rightarrow +\infty$. To deal with $L_2^{(N)}$ consider a non-negative $g \in C^\infty(\mathbb{R})$ such that $\|g\|_\infty \leq 1$, $[\Delta^{-1}, \Delta] \subset \text{supp } g \subset [\Delta_1^{-1}, \Delta_1]$ for some $\Delta_1 > \Delta$. Repeating the foregoing argument for g_2 we conclude that

$$\limsup_{N \rightarrow +\infty} L_2^{(N)} \leq \|g\|_\infty \int_{\Delta_1^{-1}}^{\Delta_1} \frac{d\lambda}{\lambda^2},$$

which can be made as small as we wish by choosing Δ_1 sufficiently close to 1. As for $L_3^{(N)}$, note that it equals

$$L_3^{(N)} = \frac{1}{N} \mathbb{E} \left| \sum_{n=1}^N \mathbb{E}[M_n^{(N)} 1[|M_n^{(N)}| \leq N, |\Psi(X_n)| \leq (\Delta)^{-1}N] | \mathcal{G}_{n-1}] \right|, \quad (5.33)$$

where

$$M_n^{(N)} := \chi_N(X_n) - P\chi_N(X_{n-1}) = \Psi_N(X_n) - c_N + P\chi_N(X_n) - P\chi_N(X_{n-1}). \quad (5.34)$$

Thanks to the fact that $M_n^{(N)}$ are martingale differences, the expression in (5.33) can be written as $L_3^{(N)} = -(L_{31}^{(N)} + L_{32}^{(N)} + L_{33}^{(N)})$, where $L_{3i}^{(N)}$ correspond to taking the conditional expectation over the events A_i for $i = 1, 2, 3$ given by

$$\begin{aligned} A_1 &:= [|M_n^{(N)}| > N, |\Psi(X_n)| \leq (\Delta)^{-1}N], \\ A_2 &:= [|M_n^{(N)}| > N, |\Psi(X_n)| > (\Delta)^{-1}N], \\ A_3 &:= [|M_n^{(N)}| \leq N, |\Psi(X_n)| > (\Delta)^{-1}N]. \end{aligned}$$

To estimate $L_{3i}^{(N)}$, $i = 1, 2$ we note from (5.34) that $|M_n^{(N)}| > N$ only when $\Psi_N(X_n) = \Psi(X_n)$ and $|\Psi(X_n)| \leq N$, or $P\chi_N(X_{n-1}), P\chi_N(X_n)$ are greater than cN for some $c > 0$. In the latter two cases we can estimate similarly to $L_1^{(N)}$. In the first one however we end up with the limit

$$\begin{aligned} &\limsup_{N \rightarrow +\infty} \frac{1}{N} \mathbb{E} \sum_{n=1}^N \mathbb{E} [(|\Psi_N(X_n)| + |c_N| \\ &\quad + |P\chi_N(X_n)| + |P\chi_N(X_{n-1})|), N \geq |\Psi(X_n)| > \Delta^{-1}N \mid \mathcal{G}_{n-1}] \\ &\leq \limsup_{N \rightarrow +\infty} N(1 + |c_N|/N)\pi[N \geq |\Psi| > (\Delta)^{-1}N] + \\ &\quad + \limsup_{N \rightarrow +\infty} \int (I + P)|P\chi_N| 1[N \geq |\Psi| > (\Delta)^{-1}N]d\pi \end{aligned}$$

The second term on the utmost right hand side vanishes thanks to (2.13). The first one can be estimated as in the proof of Lemma 5.5 and we obtain that it is smaller than $C \int_{\Delta^{-1}}^1 \lambda^{-2}d\lambda$, which can be made as small as we wish upon choosing Δ sufficiently close to 1. We can estimate therefore

$$\begin{aligned} &\limsup_{N \rightarrow +\infty} L_{33}^{(N)} \\ &\leq \limsup_{N \rightarrow +\infty} \frac{1}{N} \mathbb{E} \sum_{n=1}^N \mathbb{E} [(|\Psi_N(X_n)| + |c_N|), N \geq |\Psi(X_n)| > \Delta^{-1}N \mid \mathcal{G}_{n-1}] \\ &\quad + \limsup_{N \rightarrow +\infty} \frac{1}{N} \mathbb{E} \sum_{n=1}^N \mathbb{E} [(|P\chi_N(X_n)| + |P\chi_N(X_{n-1})|), |\Psi(X_n)| > \Delta^{-1}N \mid \mathcal{G}_{n-1}] \\ &= \limsup_{N \rightarrow +\infty} N\pi[N \geq |\Psi| > (\Delta)^{-1}N] + \limsup_{N \rightarrow +\infty} \int (I + P)|P\chi_N| 1[|\Psi| > (\Delta)^{-1}N]d\pi \\ &\leq C \int_{\Delta^{-1}}^1 \frac{d\lambda}{\lambda^2}, \end{aligned}$$

which again can be made arbitrarily small.

6. THE PROOF OF THEOREM 2.7

Suppose that we are given a sequence of i.i.d. nonnegative random variables $\{\rho_n, n \geq 0\}$ independent of $\{X_n, n \geq 0\}$ and such that $A_\alpha := \int_0^{+\infty} \rho^\alpha \varphi(d\rho) < +\infty$, where $\varphi(\cdot)$ is the distribuant of ρ_0 and $\alpha \in (0, 2)$. We consider a slightly more general situation than the one presented in Theorem 2.3 by allowing

$$S_N(t) := \sum_{n=0}^{[Nt]} \Psi(X_n) \rho_n. \tag{6.1}$$

Observe that, if π is the law of X_n , observable Ψ satisfies the tail conditions (2.5), and ρ_n is independent of X_n , then

$$\lambda^\alpha \mathbb{P}(\Psi(X_0) \rho_0 > \lambda) = \int_0^\infty \lambda^\alpha \pi(\Psi > \lambda \rho^{-1}) \varphi(d\rho) \xrightarrow{\lambda \rightarrow +\infty} c_*^+ A_\alpha$$

Define also

$$C_N := \int_{|\Psi| \leq N} \Psi d\pi \mathbb{E} \rho_0. \tag{6.2}$$

Consider then the Markov chain $\{(X_n, \rho_n), n \geq 0\}$ on $E \times \mathbb{R}_+$. This Markov chain satisfies all conditions used in the previous sections, with stationary ergodic measure given by $\pi(dy) \otimes \varphi(d\rho)$. Then, with the same arguments as used in section 5 we get:

Theorem 6.1. *i) Under the assumptions of the respective part i), or ii) of Theorem 2.3 we have $N^{-1/\alpha} S_N(\cdot) \xrightarrow{f.d.} Z(\cdot)$, as $N \rightarrow +\infty$, where $\{Z(t), t \geq 0\}$ is an α -stable process of type either type I, or II with the parameters of the corresponding Levy measure, cf (2.2), given by*

$$C_*(\lambda) := \begin{cases} \alpha A_\alpha c_*^-, & \text{when } \lambda < 0, \\ \alpha A_\alpha c_*^+, & \text{when } \lambda > 0. \end{cases} \tag{6.3}$$

Here $\xrightarrow{f.d.}$ denotes the convergence in the sense of finite dimensional distributions.

ii) In addition, under the assumptions of part iii) of Theorem 2.3 finite dimensional distributions of $N^{-1} S_N(t) - C_N t$ converge weakly to those of $\{Z(t), t \geq 0\}$ a stable process of type III. Here C_N is given by (6.2).

Remark. The results of the first part of the above theorem follow under the conditions of Theorem 2.6, by using the coupling argument of Section 4.

Let us consider now the process $Y_N(t)$ defined by (2.21). We only show that one dimensional distributions of $Y_N(t)$ converge weakly to the respective distribution of a suitable stable process $\{Z(t), t \geq 0\}$. The proof of convergence of finite dimensional distributions can be done in the same way.

Given $t > 0$ define $n(t)$ as the positive integer, such that

$$t_{n(t)} \leq t < t_{n(t)+1},$$

where t_N is given by (2.18). Let

$$s(t) := t/\bar{t},$$

$$B_N(t) := N^{-1/\alpha} \sum_{k=0}^{[Nt]} \Psi(X_k) \tau_k, \quad t \geq 0,$$

where, as we recall, $\Psi(x) := V(x)t(x)$, $x \in E$ and $\{\tau_k, k \geq 0\}$ is a sequence of i.i.d. variables distributed according to an exponential distribution with parameter 1. Using the ergodic theorem one can easily conclude that

$$s_N(t) := \frac{n(Nt)}{N} \rightarrow s(t), \quad \text{as } N \rightarrow +\infty \quad (6.4)$$

a.s. uniformly on intervals of the form $[t_0, T]$, where $0 < t_0 < T$. We have

$$Y_N(t) = \frac{1}{N^{1/\alpha}} \sum_{k=0}^{n(Nt)-1} \Psi(X_k) \tau_k + \frac{Nt - t_{n(Nt)}}{N^{1/\alpha}} V(X_k).$$

Note that

$$\frac{1}{N^{1/\alpha}} \sum_{k=0}^{n(Nt)} \Psi(X_k) \tau_k = B_N(s_N(t)).$$

Lemma 6.2. *For any $t > 0$ and $\varepsilon > 0$ fixed we have*

$$\lim_{N \rightarrow +\infty} \mathbb{P}[|Y_N(t) - B_N(s_N(t))| > \varepsilon] = 0. \quad (6.5)$$

Proof. Let $\sigma > 0$ be arbitrary. We can write that

$$\begin{aligned} \mathbb{P}[|Y_N(t) - B_N(s_N(t))| > \varepsilon] &\leq \mathbb{P}[|s_N(t) - s(t)| > \sigma] \\ &+ \mathbb{P}[|s_N(t) - s(t)| \leq \sigma, |Y_N(t) - B_N(s_N(t))| > \varepsilon]. \end{aligned} \quad (6.6)$$

The second term on the right hand side can be estimated from above by

$$\begin{aligned} &\mathbb{P}[|s_N(t) - s(t)| \leq \sigma, N^{-1/\alpha} |\Psi(X_{n(Nt)})| \tau_{n(Nt)} > \varepsilon] \\ &\leq \mathbb{P}[\sup\{|\Psi(X_k)| \tau_k : k \in [(s(t) - \sigma)N, (s(t) + \sigma)N]\} > N^{1/\alpha} \varepsilon]. \end{aligned}$$

Using stationarity of $\{|\Psi(X_k)| \tau_k, k \geq 0\}$ the term on the right hand side equals

$$\begin{aligned} &\mathbb{P}[\sup\{|\Psi(X_k)| \tau_k : k \in [0, 2\sigma N]\} > N^{1/\alpha} \varepsilon] \\ &\leq 2\sigma N \int_0^{+\infty} e^{-\tau} \pi[|\Psi(x)| \geq \tau^{-1} N^{1/\alpha} \varepsilon] d\tau \leq \frac{C\sigma}{\varepsilon^\alpha} \end{aligned}$$

for some constant $C > 0$, by virtue of (2.5). From (6.6) we obtain therefore

$$\limsup_{N \rightarrow +\infty} \mathbb{P}[|Y_N(t) - B_N(s_N(t))| > \varepsilon] \leq \frac{C\sigma}{\varepsilon^\alpha}$$

for an arbitrary $\sigma > 0$, which in turn implies (6.5). \square

It suffices therefore to prove that the laws of $B_N(s_N(t))$ converge, as $N \rightarrow +\infty$, to the law of the respective stable process. According to Skorochod's embedding theorem one can find pairs of random elements $(\tilde{B}_N(\cdot), \tilde{s}_N(t))$, $N \geq 1$, with values in $D[0, +\infty) \times [0, +\infty)$, such that the law of each pair is identical with that of $(B_N(\cdot), s_N(t))$ and $(\tilde{B}_N(\cdot), \tilde{s}_N(t))$ converges a.s., as $N \rightarrow +\infty$, in the Skorochod topology to $(Z(\cdot), s(t))$. Here, $\{Z(t), t \geq 0\}$ is the stable process, as in Theorem 6.1. According to Proposition 3.5.3 p. 119 of [11] the above means that for each $T > 0$ there exist a sequence of increasing homeomorphisms $\lambda_N : [0, T] \rightarrow [0, T]$ such that

$$\lim_{N \rightarrow +\infty} \gamma(\lambda_N) = 0, \tag{6.7}$$

where

$$\gamma(\lambda_N) := \sup_{0 < s < t < T} \left| \log \frac{\lambda_N(t) - \lambda_N(s)}{t - s} \right| = 0,$$

and

$$\sup_{t \in [0, T]} |\tilde{B}_N \circ \lambda_N(t) - Z(t)| = 0. \tag{6.8}$$

As a consequence of (6.7) we have of course that

$$\lim_{N \rightarrow +\infty} \sup_{t \in [0, T]} |\lambda_N(t) - t| = 0. \tag{6.9}$$

Note that the law of each $B_N(s_N(t))$ is identical with that of $\tilde{B}_N(\tilde{s}_N(t))$. We also have

$$\begin{aligned} |\tilde{B}_N(\tilde{s}_N(t)) - Z(s(t))| &\leq |\tilde{B}_N(\tilde{s}_N(t)) - Z \circ \lambda_N^{-1}(\tilde{s}_N(t))| \\ &+ |Z \circ \lambda_N^{-1}(\tilde{s}_N(t)) - Z(s(t))|. \end{aligned}$$

The right hand side however vanishes a.s., as $N \rightarrow +\infty$, thanks to (6.8), (6.9) and the fact that for each fixed $s > 0$ one has $\mathbb{P}[Z(s-) = Z(s)] = 1$, see e.g. Theorem 11.1, p. 59 of [27]. The above allows us to conclude that $|\tilde{B}_N(\tilde{s}_N(t)) - Z(s(t))| \rightarrow 0$ a.s., as $N \rightarrow +\infty$, thus the assertions of Theorem 2.7 follow.

REFERENCES

- [1] G. Bal, G. Papanicolaou and L. Ryzhik, *Radiative transport limit for the random Schroedinger equation*, Nonlinearity, **15**, 2002, 513-529.
- [2] Basile, G., Olla, S., Spohn, H., *Energy transport in stochastically perturbed lattice dynamics*, to appear in Arch. Rat. Mech., <http://arxiv.org/abs/0805.3012v1>.
- [3] Brown, B. M., Eagleson, G. K., *Martingale convergence to infinite divisible laws with finite variance*, TAMS, **162**, 449-453, (1971).
- [4] Csáki, E. and Csörge, M.: *On additive functionals of Markov chains*, Journal of Theoretical Probability, Vol. 8, No. 4, 1995.
- [5] De Masi, A. and Ferrari, P. A. and Goldstein, S. and Wick, W. D., *An invariance principle for reversible Markov processes. Applications to random motions in random environments*, J. Statist. Phys., **55**, (1989), 787-855.
- [6] Derriennic, Y., Lin, M., *The central limit theorem for Markov chains started at a point*, Probab. Theory Related Fields, **125**, (2003), 73-76.
- [7] Doeblin, W., *Sur deux problèmes de M. Kolmogoroff concernant les chanes dénombrables*, Bull. Soc. Math. France, **66**, (1938) 210-220.

- [8] Durrett, R., *Probability. Theory and examples, 2-nd ed*, Wadsworth Publ. Inc. (1996).
- [9] Durrett, R., Resnick, S., *Functional limit theorems for dependent variables*, Ann. of Prob. **6**, 829-846, (1978).
- [10] L. Erdős and H.T. Yau, *Linear Boltzmann equation as the weak coupling limit of a random Schrödinger Equation*, Comm. Pure Appl. Math., **53**, 2000, 667–735.
- [11] Ethier, S. N., Kurtz, T. G., *Markov processes. Characterization and convergence* Wiley & Sons, (1986).
- [12] Fannjiang, A., *White-Noise and Geometrical Optics Limits of Wigner-Moyal Equation for Wave Beams in Turbulent Media*. Communications in Mathematical Physics. 254:2 (2005), pp. 289-322.
- [13] Fouque, J. P. Garnier, J., Papanicolaou, G., Solna, K., *Wave Propagation and Time Reversal in Randomly Layered Media*, (2007) Springer.
- [14] Goldstein, S., *Antisymmetric functionals of reversible Markov processes*, Ann. Inst. H. Poincaré Probab. Statist., **31**, (1995), 177–190,
- [15] Gordin, M. I., *The central limit theorem for stationary processes*, Dokl. Akad. Nauk SSSR, **188**, 739–741, 1969.
- [16] Gordin, M. I., Lifsic, B. A., *Central limit theorem for stationary Markov Processes*, Soviet Math. Dokl. **19**, no. 2, 392-394, (1978).
- [17] Jara, M, Komorowski, T., Olla, S., *Limit theorems for additive functionals of a Markov Chain*, version 1 (1-sept.-2008), arXiv:0809.0177v1.
- [18] Kipnis, C., Landim, C., *Scaling limit of Interacting Particle Systems*, Spinger-Verlag, (1999)
- [19] Kipnis, C. and Varadhan, S. R. S., *Central limit theorem for additive functionals of reversible Markov processes and applications to simple exclusions*, Comm. Math. Phys., **104**, 1986, pp 1–19.
- [20] Lax, P., *Functional analysis*, Wiley & Sons, (2002)
- [21] S. Lepri, R. Livi, A. Politi, *Thermal Conduction in classical low-dimensional lattices*, Phys. Rep. **377**, 1-80 (2003).
- [22] J. Lukkarinen and H. Spohn, *Kinetic limit for wave propagation in a random medium*. Arch. Ration. Mech. Anal. **183**, 2007, 93–162.
- [23] Maxwell, M. and Woodroffe, M., *Central limit theorems for additive functionals of Markov chains*, Ann. Probab., **28**, (2000), pp 713–724.
- [24] A. Mellet, S. Mischler, C. Mouhot, *Fractional diffusion limit for collisional kinetic equations*, arXiv:0809.2455.
- [25] Nagaev, S., *Some limit theorems for stationary Markov chains*, Theory Probab. Appl., 1957, 2, No 4, 378-406.
- [26] S. Olla, *Central limit theorems for tagged particles and diffusions in random environment*, Notes of the course given at *Etats de la recherche: Milieux Aleatoires*, 23-25 November 2000, Panorama et Syntheses 12, SMF (2001).
- [27] Sato, K., (1999), *Levy Processes and Infinite Divisible Distributions*. Cambridge Univ. Press.
- [28] Spohn, H., (1977), *Derivation of the transport equation for electrons moving through random impurities*, Journ. Stat. Phys., **17**, 385-412.

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