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► **To cite this version:**

| Julien Brémont. Self-similar measures and the Rajchman property. 2020. hal-02306859v7

**HAL Id: hal-02306859**

**<https://hal-upec-upem.archives-ouvertes.fr/hal-02306859v7>**

Preprint submitted on 6 Apr 2020

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# SELF-SIMILAR MEASURES AND THE RAJCHMAN PROPERTY

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## Abstract

For Bernoulli convolutions, the convergence to zero of the Fourier transform at infinity was characterized by successive works of Erdős [4] and Salem [17]. We provide a quasi-complete extension of these results for general self-similar measures on the real line.

## 1 Introduction

*Rajchman measures.* In the present article we consider the question of extending some classical results concerning Bernoulli convolutions to a more general context of self-similar measures. For a Borel probability measure  $\mu$  on  $\mathbb{R}$ , define its Fourier transform as :

$$\hat{\mu}(t) = \int_{\mathbb{R}} e^{2i\pi tx} d\mu(x), \quad t \in \mathbb{R}.$$

We say that  $\mu$  is Rajchman, whenever  $\hat{\mu}(t) \rightarrow 0$ , as  $t \rightarrow +\infty$ . When  $\mu$  is a Borel probability measure on the torus  $\mathbb{T} = \mathbb{R}/\mathbb{Z}$ , we introduce its Fourier coefficients, defined as :

$$\hat{\mu}(n) = \int_{\mathbb{T}} e^{2i\pi nx} d\mu(x), \quad n \in \mathbb{Z}.$$

In this study, starting from a Borel probability measure  $\mu$  on  $\mathbb{R}$ , Borel probability measures on  $\mathbb{T}$  will naturally appear, quantifying the non-Rajchman character of  $\mu$ .

For a Borel probability measure  $\mu$  on  $\mathbb{R}$ , the Rajchman property holds for example if  $\mu$  has a density with respect to Lebesgue measure  $\mathcal{L}_{\mathbb{R}}$ , by the Riemann-Lebesgue lemma. The situation can be more subtle and for instance there exist Cantor sets of zero Lebesgue measure and even of zero Hausdorff dimension which support a Rajchman measure; cf Menshov [13], Bluhm [2]. Questions on the Rajchman property of a measure naturally arise in Harmonic Analysis, for example when studying sets of multiplicity for trigonometric series; cf Lyons [12] or Zygmund [28]. We shall say a word on this topic at the end of the article. A classical counter-example is the uniform measure  $\mu$  on the standard middle-third Cantor set, which is a continuous singular measure, not Rajchman (due to  $\hat{\mu}(3n) = \hat{\mu}(n)$ ,  $n \in \mathbb{Z}$ ). As in this last example, the obstructions for a measure to be Rajchman are often seen to be of arithmetical nature. The present work goes in this direction.

As it concerns  $t \rightarrow +\infty$ , the Rajchman character of a measure  $\mu$  on  $\mathbb{R}$  is an information of local regularity. As is well-known, it says for example that  $\mu$  has no atom; if ever the convergence to zero is fast enough, then  $\mu$  has a density; etc. Stricto sensu, the Rajchman character can be reformulated as an equidistribution property modulo 1. Since  $\hat{\mu}(t) \rightarrow 0$  is equivalent to  $\hat{\mu}(mt) \rightarrow 0$  for any integer  $m \neq 0$ , if  $X$  is a real random variable with law  $\mu$ , then  $\mu$  is Rajchman if and only if the law of  $tX \pmod{1}$  converges, as  $t \rightarrow +\infty$ , to Lebesgue measure  $\mathcal{L}_{\mathbb{T}}$  on  $\mathbb{T}$ .

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AMS 2010 subject classifications : 11K16, 37A45, 42A38, 42A61, 60K20.

Key words and phrases : Rajchman measure, self-similar measure, Pisot number, Plastic number.

*Self-similar measures.* Let us now recall standard notions on self-similar measures on the real line  $\mathbb{R}$ , with a probabilistic point of view. We write  $\mathcal{L}(X)$  for the law of a real random variable  $X$ . Let  $N \geq 0$  and real affine maps  $\varphi_k(x) = r_k x + b_k$ , with  $r_k > 0$ , for  $0 \leq k \leq N$ , and at least one  $r_k < 1$ . We call (C) the condition that the  $(\varphi_k)_{0 \leq k \leq N}$  are all strict contractions, in other words :

$$(C) : \quad 0 < r_k < 1, \text{ for all } 0 \leq k \leq N.$$

Introduce the vectors  $r = (r_k)_{0 \leq k \leq N}$  and  $b = (b_k)_{0 \leq k \leq N}$ . Notice for what follows that for  $n \geq 0$ , a composition  $\varphi_{k_{n-1}} \circ \dots \circ \varphi_{k_0}$  has the explicit form :

$$\varphi_{k_{n-1}} \circ \dots \circ \varphi_{k_0}(x) = r_{k_{n-1}} \dots r_{k_0} x + \sum_{l=0}^{n-1} b_{k_l} r_{k_{n-1}} \dots r_{k_{l+1}}.$$

Consider the open convex set  $\mathcal{C}_N = \{p = (p_0, \dots, p_N) \mid \forall j, p_j > 0, \sum_j p_j = 1\}$  and its closure  $\bar{\mathcal{C}}_N$ . Define  $\mathcal{D}_N(r) = \{p \in \bar{\mathcal{C}}_N \mid \sum_{0 \leq j \leq N} p_j \log r_j < 0\}$ . This is a non-empty open subset of  $\bar{\mathcal{C}}_N$ , for the relative topology. Notice that  $\mathcal{D}_N(r) = \bar{\mathcal{C}}_N$ , when condition (C) holds.

Fixing a probability vector  $p \in \mathcal{D}_N(r)$ , we now compose the contractions at random, independently, according to  $p$ . Precisely, let  $X_0$  be any real random variable and  $(\varepsilon_n)_{n \geq 0}$  be independent and identically distributed random variables (*i.i.d.*), independent from  $X_0$ , and with law  $p$ , in other words  $\mathbb{P}(\varepsilon_0 = k) = p_k, 0 \leq k \leq N$ . We consider the Markov chain  $(X_n)_{n \geq 0}$  on  $\mathbb{R}$  defined by :

$$X_n = \varphi_{\varepsilon_{n-1}} \circ \dots \circ \varphi_{\varepsilon_0}(X_0), \quad n \geq 0.$$

The condition  $p \in \mathcal{D}_N(r)$  is a hypothesis of contraction on average, rewritten as  $\mathbb{E}(\log r_{\varepsilon_0}) < 0$ . Classically, it implies that  $(X_n)_{n \geq 0}$  has a unique stationary (time invariant) measure, written as  $\nu$ . This follows for example from the fact that  $\mathcal{L}(X_n) = \mathcal{L}(Y_n)$ , where :

$$Y_n := \varphi_{\varepsilon_0} \circ \dots \circ \varphi_{\varepsilon_{n-1}}(X_0) = r_{\varepsilon_0} \dots r_{\varepsilon_{n-1}} X_0 + \sum_{l=0}^{n-1} b_{\varepsilon_l} r_{\varepsilon_0} \dots r_{\varepsilon_{l-1}}.$$

As a standard fact,  $(Y_n)$  is more stable than  $(X_n)$ . Using the Law of Large Numbers, we obtain  $n^{-1} \log(r_{\varepsilon_0} \dots r_{\varepsilon_{n-1}}) \rightarrow \mathbb{E}(\log r_{\varepsilon_0}) < 0$ , a.s., as  $n \rightarrow +\infty$ , so  $Y_n$  converges a.s., as  $n \rightarrow +\infty$ , to :

$$X := \sum_{l \geq 0} b_{\varepsilon_l} r_{\varepsilon_0} \dots r_{\varepsilon_{l-1}}.$$

Setting  $\nu = \mathcal{L}(X)$ , we obtain that  $\mathcal{L}(X_n)$  weakly converges to  $\nu$ . By construction, we have  $\mathcal{L}(X_{n+1}) = \sum_{0 \leq j \leq N} p_j \mathcal{L}(X_n) \circ \varphi_j^{-1}$ . Taking the limit as  $n \rightarrow +\infty$ , the measure  $\nu$  verifies :

$$\nu = \sum_{0 \leq j \leq N} p_j \nu \circ \varphi_j^{-1}. \quad (1)$$

The previous convergence implies that the solution of this “stable fixed point equation” is unique among Borel probability measures. Also,  $\nu$  has to be of pure type, i.e. either purely atomic or absolutely continuous with respect to Lebesgue measure  $\mathcal{L}_{\mathbb{R}}$  or else singular continuous, since each term in its Radon-Nikodym decomposition with respect to  $\mathcal{L}_{\mathbb{R}}$  verifies (1). A few remarks :

*i)* If  $p \in \mathcal{C}_N$ , the measure  $\nu$  is purely atomic if and only if the  $\varphi_j$  have a common fixed point  $c$ , in which case  $\nu$  is the Dirac mass at  $c$ . Indeed, consider the necessity and suppose that  $\nu$  has an atom. Let  $a > 0$  be the maximal mass of an atom and  $E$  the finite set of points having mass  $a$ . Fixing any  $c \in E$ , the relation  $\nu(\{c\}) = \sum_j p_j \nu(\{\varphi_j^{-1}(c)\})$  furnishes  $\varphi_j^{-1}(c) \in E, 0 \leq j \leq N$ . Hence  $\varphi_j^{-n}(c) \in E, n \geq 0$ , for all  $j$ . If  $\varphi_j \neq id$ , then  $\varphi_j^{-1}(c) = c$ , the set  $\{\varphi_j^{-n}(c), n \geq 0\}$  being infinite otherwise. If  $\varphi_j = id$ , it fixes all points.

*ii)* The equation for a potential density  $f$  of  $\nu$  with respect to  $\mathcal{L}_{\mathbb{R}}$ , coming from (1) is :

$$f = \sum_{0 \leq j \leq N} p_j r_j^{-1} f \circ \varphi_j^{-1}.$$

This is essentially an “unstable fixed point equation”, difficult to solve directly. It can be equivalently reformulated into the fact that  $((r_{\varepsilon_{n-1}}^{-1} \cdots r_{\varepsilon_0}^{-1})f \circ \varphi_{\varepsilon_{n-1}}^{-1} \cdots \circ \varphi_{\varepsilon_0}^{-1}(x))_{n \geq 0}$  is a non-negative martingale (for its natural filtration), for Lebesgue a.-e.  $x \in \mathbb{R}$ . When  $f$  exists and is bounded, then  $p_j \leq r_j$  for all  $j$ , because  $p_j r_j^{-1} \|f\|_\infty = \|p_j r_j^{-1} f \circ \varphi_j^{-1}\|_\infty \leq \|f\|_\infty$  and  $\|f\|_\infty \neq 0$ .

iii) Let  $f(x) = ax + b$  be an affine map, with  $a \neq 0$ . With the same  $p \in \mathcal{D}_N(r)$ , consider the conjugate system  $(\psi_j)_{0 \leq j \leq N}$ , with  $\psi_j(x) = f \circ \varphi_j \circ f^{-1}(x) = r_j x + b(1 - r_j) + ab_j$ . It has an invariant measure  $w = \mathcal{L}(aX + b)$  verifying the relation  $\hat{w}(t) = \hat{\nu}(at)e^{2i\pi tb}$ ,  $t \in \mathbb{R}$ . In particular  $\nu$  is Rajchman if and only if  $w$  is Rajchman.

iv) When supposing condition (C), some self-similar set  $F$  can be introduced, where  $F \subset \mathbb{R}$  is the unique non-empty compact set verifying the self-similarity relation  $F = \cup_{0 \leq k \leq N} \varphi_k(F)$ . See for example Hutchinson [7] for general properties of such sets. Introducing  $\mathbb{N} = \{0, 1, \dots\}$  and the compact  $S = \{0, \dots, N\}^{\mathbb{N}}$ , condition (C) implies that  $F$  is a continuous (and even Hölderian) image of  $S$ , in other words we have the following description :

$$F = \left\{ \sum_{l \geq 0} b_{x_l} r_{x_0} \cdots r_{x_{l-1}}, (x_0, x_1, \dots) \in S \right\}.$$

Whereas in the general case a self-similar invariant measure can have  $\mathbb{R}$  as topological support, under condition (C) the compact self-similar set  $F$  exists and supports any self-similar measure.

*Background and content of the article.* Back to the general case, we assume in the sequel that the  $(\varphi_j)_{0 \leq j \leq N}$  do not have a common fixed point; in particular  $N \geq 1$ . A difficult problem is to characterize the absolute continuity of  $\nu$  in terms of the parameters  $r$ ,  $b$  and  $p$ . An example with a long and well-known history is that of Bernoulli convolutions, corresponding to  $N = 1$ , the affine contractions  $\varphi_0(x) = \lambda x - 1$ ,  $\varphi_1(x) = \lambda x + 1$ ,  $0 < \lambda < 1$ , and the probability vector  $p = (1/2, 1/2)$ . Notice that when the  $r_i$  are equal (to some real in  $(0, 1)$ ), the situation is a little simplified, as  $\nu$  is an infinite convolution (this is not true in general). Although we discuss below some works in this context, we will not present here the vast subject of Bernoulli convolutions, addressing the reader to detailed surveys, Peres-Schlag-Solomyak [15] or Solomyak [21].

For general self-similar measures, an important aspect of the problem, that we shall not enter, and an active line of research, concerns the Hausdorff dimension of the measure  $\nu$ , cf the fundamental work of Hochman [6] for example. In a large generality, cf for example Falconer [5] and more recently Jaroszewska and Rams [9], there is an “entropy/Lyapunov exponent” upper-bound :

$$\text{Dim}_{\mathcal{H}}(\nu) \leq \min\{1, s(p, r)\}, \text{ where } s(p, r) := \frac{-\sum_{i=0}^N p_i \log p_i}{-\sum_{i=0}^N p_i \log r_i}.$$

The quantity  $s(p, r)$  is called the singularity dimension of the measure and can be  $> 1$ . The equality  $\text{Dim}_{\mathcal{H}}(\nu) = 1$  does not mean that  $\nu$  is absolutely continuous, but the inequality  $s(p, r) < 1$  implies that  $\nu$  is singular. The interesting domain of parameters for the question of the absolute continuity of the invariant measure therefore corresponds to  $s(p, r) \geq 1$ .

We focus in this work on another fundamental tool, the Fourier transform  $\hat{\nu}$ . If  $\nu$  is not Rajchman, the Riemann-Lebesgue lemma implies that  $\nu$  is singular. This property was used by Erdős [4] in the context of Bernoulli convolutions. Erdős proved that if  $1/2 < \lambda < 1$  is such that  $1/\lambda$  is a Pisot number, then  $\nu$  is not Rajchman. The reciprocal statement was next shown by Salem [17]. As a result, for Bernoulli convolutions the Rajchman property always holds, except for a very particular set of parameters. Some works have next focused on the decay on average of the Fourier transform for general self-similar measures (supposing condition (C)), cf Strichartz [24, 25], Tsuji [26]. In the same context, the non-Rajchman character was recently shown to hold for only a very small set of parameters. Li and Sahlsten [11] showed that  $\nu$  is Rajchman when some  $\log r_i / \log r_j$  is irrational, with moreover some logarithmic decay of  $\hat{\nu}$  at infinity, under a Diophantine condition. Next Solomyak [22] proved that outside a set of  $r$  of zero-Hausdorff dimension,  $\hat{\nu}$  even has a power decay at infinity.

The aim of the present article is to study for general self-similar measures the exceptional set of parameters where the Rajchman property is not true, trying to follow the line of [4] and [17]. We essentially show that  $r$  and  $b$  have to be very specific, as for Bernoulli convolutions. We shall first prove a general extension of the result of Salem [17], drastically reducing the set of parameters where the Rajchman property does not hold. Focusing then on this particular case, we provide a general characterization of the Rajchman character. Next, restricting to condition (C), we prove a partial extension of the theorem of Erdős [4]. We finally give some complements, first rather surprising numerical simulations involving the Plastic number, then an application to sets of uniqueness for trigonometric series.

## 2 Statement of the results

Let us place in the general situation considered in the Introduction. Pisot numbers will play a central role in the analysis. Let us introduce a few definitions concerning Algebraic Number Theory; cf for example Samuel [19] for more details.

### Definition 2.1

A Pisot number is a real algebraic integer  $\theta > 1$ , with conjugates (the other roots of its minimal unitary polynomial) of modulus strictly less than 1. Fixing such a  $\theta > 1$ , denote its minimal polynomial as  $Q = X^{s+1} + a_s X^s + \dots + a_0 \in \mathbb{Z}[X]$ , of degree  $s + 1$ , with  $s \geq 0$ . If  $s = 0$ , then  $\theta$  is an integer  $\geq 2$ . The images of  $\mu \in \mathbb{Q}[\theta]$  by the  $s + 1$   $\mathbb{Q}$ -homomorphisms  $\mathbb{Q}[\theta] \rightarrow \mathbb{C}$  are the conjugates of  $\mu$  corresponding to the field  $\mathbb{Q}[\theta]$ , in general denoted by  $\mu = \mu^{(0)}, \mu^{(1)}, \dots, \mu^{(s)}$ .

i) For  $\alpha \in \mathbb{Q}[\theta]$ , the trace  $Tr_\theta(\alpha)$  is the trace of the linear operator  $x \mapsto \alpha x$  of multiplication, considered from  $\mathbb{Q}[\theta]$  to itself. As a general fact,  $Tr_\theta(\alpha) \in \mathbb{Q}$ .

ii) Let  $\mathbb{Z}[\theta] = \mathbb{Z}\theta^0 + \dots + \mathbb{Z}\theta^s$  be the subring generated by  $\theta$  of the ring of algebraic integers of  $\mathbb{Q}[\theta]$ . We write  $\mathcal{D}(\theta)$  for its  $\mathbb{Z}$ -dual (as a  $\mathbb{Z}$ -lattice) :

$$\mathcal{D}(\theta) = \{\alpha \in \mathbb{Q}[\theta], Tr_\theta(\theta^n \alpha) \in \mathbb{Z}, \text{ for } 0 \leq n \leq s\}.$$

It can be shown that  $\mathcal{D}(\theta) = (1/Q'(\theta))\mathbb{Z}[\theta]$ . Classically,  $Tr_\theta(\theta^n \alpha) \in \mathbb{Z}$ , for all  $n \geq 0$ , if this holds for  $0 \leq n \leq s$ . Define :

$$\mathcal{T}(\theta) = \{\alpha \in \mathbb{Q}[\theta], Tr_\theta(\theta^n \alpha) \in \mathbb{Z}, \text{ for large } n \geq 0\} = \cup_{n \geq 0} \theta^{-n} \mathcal{D}(\theta) = \frac{1}{Q'(\theta)} \mathbb{Z}[\theta, 1/\theta],$$

where  $\mathbb{Z}[\theta, 1/\theta]$  is the subring of  $\mathbb{Q}[\theta]$  generated by  $\theta$  and  $1/\theta$ .

*Remark.* — In the context of the previous definition, introduce the integer-valued  $(s + 1) \times (s + 1)$ -companion matrix  $M$  of  $Q$  :

$$M = \begin{pmatrix} 0 & 1 & \dots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ \vdots & \vdots & 0 & 1 \\ -a_0 & \dots & -a_{s-1} & -a_s \end{pmatrix}.$$

One may show that for any  $\mu \in \mathbb{Q}[\theta]$ , setting  $V = (Tr_\theta(\theta^0 \mu), \dots, Tr_\theta(\theta^s \mu))$ , then  $\mu \in \mathcal{T}(\theta)$  if and only if there exists  $n \geq 0$  such that  $VM^n$  has integral entries.

We introduce some families of affine maps, that will play the role of canonical models for the analysis of the Rajchman property.

### Definition 2.2

Let  $N \geq 1$ . A system of real affine maps  $\varphi_k(x) = r_k x + b_k$ , with  $r_k > 0$ , for  $0 \leq k \leq N$ , is in Pisot form, if there exist a Pisot number  $1/\lambda > 1$ , relatively prime integers  $(n_k)_{0 \leq k \leq N}$  and  $\mu_k \in \mathcal{T}(1/\lambda)$ ,  $0 \leq k \leq N$ , such that  $\varphi_j(x) = \lambda^{n_j} x + \mu_j$ , for all  $0 \leq j \leq N$ .

*Remark.* — If a family  $(\varphi_j)_{0 \leq j \leq N}$  is in Pisot form, then the  $(\lambda, (n_j), (\mu_j))$  are uniquely determined. Indeed, if the  $(\lambda', (n'_j), (\mu'_j))$  also convene, it suffices to show that  $\lambda = \lambda'$ . Taking some collection of integers  $(a_j)$  realizing a Bezout relation for the  $(n_j)$ , we have :

$$\lambda = \lambda^{\sum_j a_j n_j} = \lambda'^{\sum_j a_j n'_j} = \lambda'^p,$$

for some  $p \geq 1$ . Idem,  $\lambda' = \lambda^q$ , for some  $q \geq 1$ . Hence  $pq = 1$ , giving  $p = q = 1$  and  $\lambda = \lambda'$ .

As a first result, extending [17], the analysis of the non-Rajchman character of the invariant measure necessitates to consider families in Pisot form.

### Theorem 2.3

Let  $N \geq 1$ ,  $p \in \mathcal{C}_N$  and affine maps  $\varphi_k(x) = r_k x + b_k$ ,  $r_k > 0$ , for  $0 \leq k \leq N$ , with no common fixed point and  $\sum_{0 \leq j \leq N} p_j \log r_j < 0$ . The invariant measure  $\nu$  is not Rajchman if and only if there exists  $f(x) = ax + b$ ,  $a \neq 0$ , such that the conjugate system  $(f \circ \varphi_j \circ f^{-1})_{0 \leq j \leq N}$  is in Pisot form, for some Pisot number  $1/\lambda > 1$ , with invariant measure  $w$  verifying  $\hat{w}(\lambda^{-k}) \xrightarrow[k \rightarrow \infty]{} 0$ .

In particular,  $r_j = \lambda^{n_j}$ , for all  $j$ . Up to an affine change of variables, the non-Rajchman character can thus be read on the sequence  $(\lambda^{-k})$ , as in [4]. In a second step, we provide a general analysis of families in Pisot form.

Fix a Pisot number  $1/\lambda > 1$ ,  $N \geq 1$ , relatively prime integers  $(n_k)_{0 \leq k \leq N}$  and  $(\mu_k)_{0 \leq k \leq N} \in \mathcal{T}(1/\lambda)^{N+1}$ , such that  $\varphi_k(x) = \lambda^{n_k} x + \mu_k$ ,  $0 \leq k \leq N$ . Let  $p \in \mathcal{C}_N$  be such that  $\sum_{0 \leq j \leq N} p_j n_j > 0$  and *i.i.d.* random variables  $(\varepsilon_n)_{n \in \mathbb{Z}}$ , with  $\mathbb{P}(\varepsilon_0 = k) = p_k$ ,  $0 \leq k \leq N$ . We introduce cocycle notations  $S_0 = 0$  and  $S_l = n_{\varepsilon_0} + \dots + n_{\varepsilon_{l-1}}$ ,  $S_{-l} = -n_{\varepsilon_{-l}} - \dots - n_{\varepsilon_{-1}}$ , for  $l \geq 1$ .

An important preliminary remark is that when  $\mu \in \mathcal{T}(1/\lambda)$  and  $k \geq 0$  is large enough, we have :

$$\lambda^{-k} \mu + \sum_{1 \leq j \leq s} \alpha_j^k \mu^{(j)} = Tr_{1/\lambda}(\lambda^{-k} \mu) \in \mathbb{Z},$$

where the  $(\alpha_j)_{0 \leq j \leq s}$  are the conjugates of  $1/\lambda = \alpha_0$  and the  $(\mu^{(j)})_{0 \leq j \leq s}$  that of  $\mu = \mu^{(0)}$ , corresponding to the field  $\mathbb{Q}[\lambda]$ . Since  $|\alpha_j| < 1$ , for  $1 \leq j \leq s$ , and  $(S_l)$  is a.s. transient with a non-zero linear speed to  $-\infty$ , as  $l \rightarrow -\infty$ , this ensures that for any  $k \in \mathbb{Z}$ , the random variable  $\sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+S_l} \pmod{1}$  is a well-defined  $\mathbb{T}$ -valued random variable.

In the sequel we use standard inner products and Euclidean norms on all spaces  $\mathbb{R}^n$ .

### Theorem 2.4

Let  $1/\lambda > 1$  be a Pisot number of degree  $s + 1$ . Let  $N \geq 1$ , relatively prime integers  $(n_k)_{0 \leq k \leq N}$  and  $(\mu_k)_{0 \leq k \leq N} \in \mathcal{T}(1/\lambda)^{N+1}$ , such that  $\varphi_k(x) = \lambda^{n_k} x + \mu_k$ ,  $0 \leq k \leq N$ . Let  $p \in \mathcal{C}_N$  be such that  $\sum_{0 \leq j \leq N} p_j n_j > 0$  and *i.i.d.* random variables  $(\varepsilon_n)_{n \in \mathbb{Z}}$ , with law  $p$ . Let  $(S_l)_{l \in \mathbb{Z}}$  be the cocycle notations associated to the  $(n_{\varepsilon_l})$ . The real random variable  $X = \sum_{l \geq 0} \mu_{\varepsilon_l} \lambda^{S_l}$  has law  $\nu$ .

*i)* Let the  $\mathbb{T}$ -valued random variables  $Z_k = \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+S_l}$ ,  $k \in \mathbb{Z}$ . Then  $\lambda^{-n} X \pmod{1}$  converges, as  $n \rightarrow +\infty$ , to a probability measure  $m$  on  $\mathbb{T}$ , verifying, for all  $f \in C(\mathbb{T}, \mathbb{R})$  and all  $k \in \mathbb{Z}$  :

$$\int_{\mathbb{T}} f(x) dm(x) = \frac{1}{\mathbb{E}(n_{\varepsilon_0})} \sum_{0 \leq r < n^*} \mathbb{E} [f(Z_{k+r}) 1_{S_{-u} < -r, u \geq 1}],$$

where  $n^* = \max_{0 \leq k \leq N} n_k$ . More generally,  $\lambda^{-n}(X, \lambda^{-1}X, \dots, \lambda^{-s}X) \pmod{\mathbb{Z}^{s+1}}$  converges in law, as  $n \rightarrow +\infty$ , to a probability measure  $\mathcal{M}$  on  $\mathbb{T}^{s+1}$ , with one-dimensional marginals  $m$ , verifying :

$$\int_{\mathbb{T}^{s+1}} f(x) d\mathcal{M}(x) = \frac{1}{\mathbb{E}(n_{\varepsilon_0})} \sum_{0 \leq r < n^*} \mathbb{E} [f(Z_{k+r}, Z_{k+r-1}, \dots, Z_{k+r-s}) 1_{S_{-u} < -r, u \geq 1}],$$

for all  $f \in C(\mathbb{T}^{s+1}, \mathbb{R})$  and all  $k \in \mathbb{Z}$ .

*ii)* If the  $(\varphi_k)_{0 \leq k \leq N}$  do not have a common fixed point (*i.e.*  $\nu$  is continuous), denoting by  $Z$  a  $\mathbb{T}^{s+1}$ -valued random variable with law  $\mathcal{M}$ , then for any  $0 \neq n = (n_0, \dots, n_s)^t \in \mathbb{Z}^{s+1}$ ,  $\langle Z, n \rangle$  has a

continuous law; hence  $m$  and  $\mathcal{M}$  are continuous measures. If the  $(\varphi_k)_{0 \leq k \leq N}$  have a common fixed point, there exists a rational number  $p/q$  such that  $m = \delta_{p/q}$  and  $\mathcal{M} = (\delta_{p/q})^{\otimes(s+1)}$ .

iii) Either  $\mathcal{M} \perp \mathcal{L}_{\mathbb{T}^{s+1}}$  or  $\mathcal{M} = \mathcal{L}_{\mathbb{T}^{s+1}}$ . One has  $\mathcal{M} = \mathcal{L}_{\mathbb{T}^{s+1}} \Leftrightarrow \nu$  is Rajchman  $\Leftrightarrow \nu \ll \mathcal{L}_{\mathbb{R}}$ .

As a corollary of the previous theorem,  $\nu$  and  $\mathcal{M}$  are always of the same nature, with respect to the uniform measure of the space they live on. In particular,  $\mathcal{M}$  is also of pure type. We finally consider families in Pisot form, under condition (C).

### Theorem 2.5

Let  $N \geq 1$  and  $\varphi_k(x) = \lambda^{n_k}x + \mu_k$ , for  $0 \leq k \leq N$ , with  $1/\lambda > 1$  a Pisot number, relatively prime integers  $(n_k)_{0 \leq k \leq N}$ , with  $n_k \geq 1$  and  $\mu_k \in \mathcal{T}(1/\lambda)$ , for  $0 \leq k \leq N$ . When  $p \in \mathcal{C}_N$  is fixed, we denote by  $m$  the measure on  $\mathbb{T}$  of Theorem 2.4, i).

i) For any  $p \in \mathcal{C}_N$ , if the invariant measure  $\nu$  is Rajchman, then it has a density, bounded and with compact support, with respect to  $\mathcal{L}_{\mathbb{R}}$ .

ii) There exists  $0 \neq a \in \mathbb{Z}$  such that for any  $k \neq 0$ , for any  $p \in \mathcal{C}_N$  outside finitely many real-analytic graphs of dimension  $\leq N - 1$  (points if  $N = 1$ ), we have  $\hat{m}(ak) \neq 0$ . In this case,  $m \neq \mathcal{L}_{\mathbb{T}}$  and  $\nu$  is not Rajchman.

*Remark.* — Part ii) of Theorem 2.5 relies on an indirect argument, based on the analysis of the regularity of  $\hat{m}(n)$ , for some fixed  $n \in \mathbb{Z}$ , as a function of  $p \in \mathcal{C}_N$ . Arrived at a real-valued real analytic non constant function  $h$  on a open neighborhood  $\mathcal{C}_N^\delta$  of  $\bar{\mathcal{C}}_N$ , we use Lojasiewicz's stratification theorem (cf Krantz-Park [8], theorem 5.2.3), giving the local structure of  $\{p \in \mathcal{C}_N^\delta \mid h(p) = 0\}$ . In an elementary and classical way, using the implicit function theorem, one can show that the previous set is included in a countable union of connected real-analytic graphs of dimension  $N - 1$ . In Theorem 2.5, making  $k$  vary, for all  $p \in \mathcal{C}_N$  outside a countable number of real-analytic graphs of dimension  $\leq N - 1$  (points if  $N = 1$ ),  $\hat{m}(ak) \neq 0$ , for all  $k \in \mathbb{Z}$ . On the existence of singular measures in the non-homogeneous case, we were previously aware of the non-explicit examples, using algebraic curves, of Neunhuserer [14].

*Remark.* — It would be important to determine all the exceptional parameters where  $\nu$  has a density. Let us give some examples where the exceptional set is non-empty :

1) Let  $1/\lambda = N \geq 1$  and  $\varphi_k(x) = (x + k)/(N + 1)$ , with  $p_k = 1/(N + 1)$ , for  $0 \leq k \leq N$ ; then  $\nu$  is Lebesgue measure on  $[0, 1]$ .

2) Take for  $1/\lambda > 1$  the Plastic number, i.e. the real root of  $X^3 - X - 1$ . This is the smallest Pisot number; cf Siegel [20]. Let  $N = 1$  and  $\varphi_0(x) = \lambda^2x$ ,  $\varphi_1(x) = \lambda^3x + 1$ . One verifies that the similarity dimension is  $< 1$  for all  $p \in \mathcal{C}_1$ , except for  $p = (\lambda^2, \lambda^3)$ , where it equals one. Hence the invariant measure  $\nu$  is singular for  $p \in \mathcal{C}_1$  with  $p \neq (\lambda^2, \lambda^3)$ . Another way, if  $\nu$  has a density, then it has to be bounded by Theorem 2.5, so  $p_0 \leq \lambda^2$  and  $p_1 \leq \lambda^3$ , using the remark in the Introduction. Since  $\lambda^2 + \lambda^3 = 1$ , we have  $p_0 = \lambda^2$  and  $p_1 = \lambda^3$ . As a result, when  $p = (p_0, p_1) \neq (\lambda^2, \lambda^3)$  and  $p_0 > 0$ ,  $p_1 > 0$ , then  $\nu$  is continuous singular and not Rajchman. When  $p = (\lambda^2, \lambda^3)$ , set  $I = [0, 1 + \lambda]$  and notice that  $\varphi_0(I) = [0, 1]$ ,  $\varphi_1(I) = [1, 1 + \lambda]$ . Hence, Lebesgue a.-e. :

$$1_I = 1_{\varphi_0(I)} + 1_{\varphi_1(I)} = p_0\lambda^{-2}1_{\varphi_0(I)} + p_1\lambda^{-3}1_{\varphi_1(I)},$$

meaning that  $\nu = \frac{1}{1+\lambda}\mathcal{L}_I$ . Taking for  $1/\lambda$  the supergolden ratio (the real root of  $X^3 - X^2 - 1$ ; the fourth Pisot number), one gets the same situation with the system  $(\lambda x + 1, \lambda^3x)$ , the exceptional parameters being then  $(\lambda, \lambda^3)$ , giving for  $\nu$  the uniform probability measure on  $[0, \lambda^{-3}]$ . With  $N = 1$  and  $1/\lambda$  the Plastic number, we will show in the last section that for  $\varphi_0(x) = \lambda x$  and  $\varphi_1(x) = \lambda^2x + 1$ , then  $\nu$  is singular and not Rajchman, for all  $p \in \mathcal{C}_1$ .

3) When  $1/\lambda > 1$  is the Plastic number,  $N = 2$ ,  $\varphi_0(x) = \lambda^2x$ ,  $\varphi_1(x) = \lambda^3x + 1$ ,  $\varphi_2(x) = \lambda^3x + 1$  and  $p_0 = \lambda^2$ ,  $p_1 = \lambda^3\alpha$ ,  $p_2 = \lambda^3(1 - \alpha)$ , then  $\nu = \frac{1}{1+\lambda}\mathcal{L}_{[0, 1+\lambda]}$ , for all  $0 < \alpha < 1$ . This is an example, a little degenerated, of a one-dimensional real analytic graph where  $\nu$  has a density.

In the context of Theorem 2.5, it would be interesting to find more developed examples, when overlaps occur, where  $\nu$  has a density. This could be delicate, as the probability vector  $p$  may have to be chosen in accordance with the polynomial equations verified by  $\lambda$ .

### 3 Proof of Theorem 2.3

For the sequel, introduce *i.i.d.* random variables  $(\varepsilon_n)_{n \geq 0}$  with law  $p$ , to which  $\mathbb{P}$  and  $\mathbb{E}$  refer. Recall that  $\nu$  is the law of the random variable  $\sum_{l \geq 0} b_{\varepsilon_l} r_{\varepsilon_0} \cdots r_{\varepsilon_{l-1}}$ . Without loss of generality, we also assume that  $0 < r_0 \leq r_1 \leq \cdots \leq r_N$ , with necessarily  $r_0 < 1$ .

*Step 1.* We prove that if  $\log r_i / \log r_j \notin \mathbb{Q}$ , for some  $0 \leq i \neq j \leq N$ , then  $\nu$  is Rajchman, as shown in [11], under condition (C). We simplify their proof.

For  $n \geq 1$ , consider the random walk  $S_n = -\log r_{\varepsilon_0} - \cdots - \log r_{\varepsilon_{n-1}}$ , with  $S_0 = 0$ . For a real  $s \geq 0$ , introduce the finite stopping time  $\tau_s = \min\{n \geq 0, S_n > s\}$  and write  $\mathcal{T}_s$  for the corresponding sub- $\sigma$ -algebra of the underlying  $\sigma$ -algebra. Taking  $\alpha > 0$  and  $s \geq 0$  :

$$\begin{aligned} \hat{\nu}(\alpha e^s) &= \mathbb{E} \left( e^{2\pi i \alpha e^s \sum_{l \geq 0} b_{\varepsilon_l} e^{-S_l}} \right) \\ &= \mathbb{E} \left( e^{2\pi i \alpha e^s \sum_{0 \leq l < \tau_s} b_{\varepsilon_l} e^{-S_l}} e^{2\pi i \alpha e^{-S_{\tau_s} + s} \sum_{l \geq \tau_s} b_{\varepsilon_l} e^{-S_l + S_{\tau_s}}} \right). \end{aligned}$$

In the expectation, the first exponential term is  $\mathcal{T}_s$ -measurable. Also, the conditional expectation of the second exponential term with respect to  $\mathcal{T}_s$  is just  $\hat{\nu}(\alpha e^{-S_{\tau_s} + s})$ , as a consequence of the strong Markov property. It follows that :

$$\hat{\nu}(\alpha e^s) = \mathbb{E} \left( \hat{\nu}(\alpha e^{-S_{\tau_s} + s}) e^{2\pi i \alpha e^s \sum_{0 \leq l < \tau_s} b_{\varepsilon_l} e^{-S_l}} \right).$$

This gives  $|\hat{\nu}(\alpha e^s)| \leq \mathbb{E} (|\hat{\nu}(\alpha e^{-S_{\tau_s} + s})|)$ , so by the Cauchy-Schwarz inequality and a safe Fubini theorem consecutively :

$$\begin{aligned} |\hat{\nu}(\alpha e^s)|^2 &\leq \mathbb{E} (|\hat{\nu}(\alpha e^{-S_{\tau_s} + s})|^2) = \mathbb{E} \left( \int_{\mathbb{R}^2} e^{2\pi i \alpha e^{-S_{\tau_s} + s} (x-y)} d\nu(x) d\nu(y) \right) \\ &= \int_{\mathbb{R}^2} \mathbb{E} \left( e^{2\pi i \alpha e^{-S_{\tau_s} + s} (x-y)} \right) d\nu(x) d\nu(y). \end{aligned}$$

Let  $Y := -\log r_{\varepsilon_0}$ . As the law of  $Y$  is non-lattice (since some  $\log r_i / \log r_j \notin \mathbb{Q}$  and  $p_k > 0$  for all  $0 \leq k \leq N$ ) and with  $0 < \mathbb{E}(Y) < \infty$ , it is a well-known consequence of the Blackwell theorem on the law of the overshoot that (see for instance Woodrooffe [27], chap. 2, thm 2.3), that :

$$\mathbb{E}(g(S_{\tau_s} - s)) \rightarrow \frac{1}{\mathbb{E}(S_{\tau_0})} \int_0^{+\infty} g(x) \mathbb{P}(S_{\tau_0} > x) dx, \text{ as } s \rightarrow +\infty,$$

for any Riemann-integrable  $g$  on  $\mathbb{R}_+$ . Here, all  $S_{\tau_s} - s, s \geq 0$ , (in particular  $S_{\tau_0}$ ) have support in some  $[0, A]$ . Thus, also,  $\mathbb{P}(S_{\tau_0} > x) = 0$  for large  $x > 0$ . By dominated convergence, for any  $\alpha > 0$  :

$$\limsup_{t \rightarrow +\infty} |\hat{\nu}(t)|^2 \leq \frac{1}{\mathbb{E}(S_{\tau_0})} \int_{\mathbb{R}^2} \left| \int_0^{+\infty} e^{2\pi i \alpha e^{-u} (x-y)} \mathbb{P}(S_{\tau_0} > u) du \right| d\nu(x) d\nu(y).$$

The inside term (in the modulus) is uniformly bounded with respect to  $(x, y) \in \mathbb{R}^2$ . We shall use dominated convergence once more, this time with  $\alpha \rightarrow +\infty$ . It is sufficient to show that for  $\nu^{\otimes 2}$ -almost every  $(x, y)$ , the inside term goes to zero. Since  $\nu$  is non-atomic,  $\nu^{\otimes 2}$ -almost-surely,  $x \neq y$ . If for example  $x > y$  :

$$\int_0^{+\infty} e^{2\pi i \alpha e^{-u} (x-y)} \mathbb{P}(S_{\tau_0} > u) du = \int_0^{x-y} e^{2\pi i \alpha t} \mathbb{P}(S_{\tau_0} > \log((x-y)/t)) \frac{dt}{t},$$

making the change of variable  $t = e^{-u} (x-y)$ . The last integral now converges to 0, as  $\alpha \rightarrow +\infty$ , by the Riemann-Lebesgue lemma. Hence,  $\lim_{t \rightarrow +\infty} \hat{\nu}(t) = 0$ . This ends the proof of this step.



*Step 2.* Assuming  $\nu$  not Rajchman, from *Step 1*,  $\log r_i / \log r_j \in \mathbb{Q}$ , for all  $(i, j)$ . Hence  $r_j = r_0^{p_j/q_j}$ , with integers  $p_j \in \mathbb{Z}$ ,  $q_j \geq 1$ , for  $1 \leq j \leq N$ . Let :

$$n_0 = \prod_{1 \leq l \leq N} q_l \geq 1 \text{ and } n_j = p_j \prod_{1 \leq l \leq N, l \neq j} q_l \in \mathbb{Z}, \quad 1 \leq j \leq N.$$

Recall that  $0 < r_0 < 1$ . Setting  $\lambda = r_0^{1/n_0} \in (0, 1)$ , one has  $r_j = \lambda^{n_j}$ ,  $0 \leq j \leq N$ . Up to taking some positive integral power of  $\lambda$ , one can assume that  $\gcd(n_0, \dots, n_N) = 1$ . Recall in passing that the set of Pisot numbers is stable under positive integral powers. The condition  $\mathbb{E}(\log r_{\varepsilon_0}) < 0$  rewrites into  $\mathbb{E}(n_{\varepsilon_0}) > 0$  and we have  $n_N \leq \dots \leq n_0$ , with  $n_0 \geq 1$ .

Using now some sub-harmonicity, one can reinforce the assumption that  $\hat{\nu}(t)$  is not converging to 0, as  $t \rightarrow +\infty$ .

**Lemma 3.1**

*There exists  $1 \leq \alpha \leq 1/\lambda$  and  $c > 0$  such that  $\hat{\nu}(\alpha\lambda^{-k}) = c_k e^{2i\pi\theta_k}$ , written in polar form, verifies  $c_k \rightarrow c$ , as  $k \rightarrow +\infty$ .*

*Proof of the lemma :*

Let us write this time  $S_n = n_{\varepsilon_0} + \dots + n_{\varepsilon_{n-1}}$ , for  $n \geq 1$ , with  $S_0 = 0$ . Since  $\mathbb{E}(n_{\varepsilon_0}) > 0$ ,  $(S_n)$  is transient to  $+\infty$ . Introduce the random ladder epochs  $0 = \sigma_0 < \sigma_1 < \dots$ , where inductively  $\sigma_{k+1}$  is the first time  $n \geq 0$  with  $S_n > S_{\sigma_k}$ . Let  $S'_k = S_{\sigma_k}$ . The  $(S'_k - S'_{k-1})_{k \geq 1}$  are *i.i.d.* random variables with law  $\mathcal{L}(S_{\tau_0})$  and support in  $\{1, \dots, n_0\}$ . Since  $\gcd(n_0, \dots, n_N) = 1$ , the support of the law of  $S_{\tau_0}$  generates  $\mathbb{Z}$  as an additive group (cf for example Woodroffe [27], thm 2.3, second part). For an integer  $u \geq 1$  large enough, we can fix integers  $r \geq 1$  and  $s \geq 1$  such that the support of the law of  $S'_r$  contains  $u$  and that of  $S'_s$  contains  $u + 1$ , both supports being included in some  $\{1, \dots, M\}$ , with therefore  $1 \leq u \leq u + 1 \leq M$ . Proceeding as in *Step 1*, for any  $t \in \mathbb{R}$  :

$$\hat{\nu}(t) = \mathbb{E} \left( e^{2\pi i t \sum_{l \geq 0} b_{\varepsilon_l} \lambda^{S_l}} \right) = \mathbb{E} \left( \hat{\nu}(t \lambda^{S'_r}) e^{2\pi i t \sum_{0 \leq l < \sigma_r} b_{\varepsilon_l} \lambda^{S_l}} \right).$$

Doing the same thing with  $S'_s$  and taking modulus gives :

$$|\hat{\nu}(t)| \leq \mathbb{E} \left( |\hat{\nu}(t \lambda^{S'_r})| \right) \text{ and } |\hat{\nu}(t)| \leq \mathbb{E} \left( |\hat{\nu}(t \lambda^{S'_s})| \right). \quad (2)$$

In particular,  $|\hat{\nu}(t)| \leq \max_{1 \leq l \leq M} |\hat{\nu}(\lambda^l t)|$ . We now set :

$$V_\alpha(k) := \max_{k \leq l < k+M} |\hat{\nu}(\alpha \lambda^l)|, \quad k \in \mathbb{Z}, \quad \alpha > 0.$$

The previous remarks imply that  $V_\alpha(k) \leq V_\alpha(k + 1)$ ,  $k \in \mathbb{Z}$ ,  $\alpha > 0$ .

Since  $\nu$  is not Rajchman,  $|\hat{\nu}(t_l)| \geq c' > 0$ , along some sequence  $t_l \rightarrow +\infty$ . Write  $t_l = \alpha_l \lambda^{-k_l}$ , with  $1 \leq \alpha_l \leq 1/\lambda$  and  $k_l \rightarrow +\infty$ . Up to taking a subsequence,  $\alpha_l \rightarrow \alpha \in [1, 1/\lambda]$ . Fixing  $k \in \mathbb{Z}$  :

$$c' \leq V_{\alpha_l}(-k_l) \leq V_{\alpha_l}(-k),$$

as soon as  $l$  is large enough. By continuity, letting  $l \rightarrow +\infty$ , we get  $c' \leq V_\alpha(-k)$ ,  $k \in \mathbb{Z}$ . As  $k \mapsto V_\alpha(-k)$  is non-increasing,  $V_\alpha(-k) \rightarrow c \geq c'$ , as  $k \rightarrow +\infty$ . We now show that necessarily  $|\hat{\nu}(\alpha \lambda^{-k})| \rightarrow c$ , as  $k \rightarrow +\infty$ .

If this were not true, there would exist  $\varepsilon > 0$  and  $(m_k) \rightarrow +\infty$ , with  $|\hat{\nu}(\alpha \lambda^{-m_k})| \leq c - \varepsilon$ . Using  $V_\alpha(-k) \rightarrow c$  and  $|\hat{\nu}(\alpha \lambda^{-m_k})| \leq c - \varepsilon$ , as  $k \rightarrow +\infty$ , consider (2) with  $r$  and  $t = \alpha \lambda^{-m_k - u}$  and next with  $s$  and  $t = \alpha \lambda^{-m_k - u - 1}$ . Since  $u$  is in the support of the law of  $S'_r$  and  $u + 1$  is in the support of the law of  $S'_s$ , we obtain the existence of some  $c_1 < c$  such that for  $k$  large enough :

$$\max\{|\hat{\nu}(\alpha \lambda^{-m_k - u})|, |\hat{\nu}(\alpha \lambda^{-m_k - u - 1})|\} \leq c_1 < c.$$

Again via (2), with successively  $r$  and  $t = \alpha \lambda^{-m_k - 2u}$ , next  $r$  and  $t = \alpha \lambda^{-m_k - 2u - 1}$  and finally  $s$  and  $t = \alpha \lambda^{-m_k - 2u - 2}$ , still using that  $u$  is in the support of the law of  $S'_r$  and  $u + 1$  in the support of the law of  $S'_s$ , we get some  $c_2 < c$  such that for  $k$  large enough :

$$\max\{|\hat{\nu}(\alpha\lambda^{-m_k-2u})|, |\hat{\nu}(\alpha\lambda^{-m_k-2u-1})|, |\hat{\nu}(\alpha\lambda^{-m_k-2u-2})|\} \leq c_2 < c.$$

Etc, for some  $c_{M-1} < c$  and  $k$  large enough :

$$\max\{|\hat{\nu}(\alpha\lambda^{-m_k-(M-1)u})|, \dots, |\hat{\nu}(\alpha\lambda^{-m_k-(M-1)u-(M-1)})|\} \leq c_{M-1} < c.$$

This contradicts the fact that  $V_\alpha(-k) \rightarrow c$ , as  $k \rightarrow \infty$ . We conclude that  $|\hat{\nu}(\alpha\lambda^{-k})| \rightarrow c$ , as  $k \rightarrow \infty$ , and this ends the proof of the lemma.  $\square$

*Step 3.* We complete the proof of Theorem 2.3. In this part, introduce the notation  $\|x\| = \text{dist}(x, \mathbb{Z})$ , for  $x \in \mathbb{R}$ . Let us consider any  $1 \leq \alpha \leq 1/\lambda$ , with  $\hat{\nu}(\alpha\lambda^{-k}) = c_k e^{2i\pi\theta_k}$ , verifying  $c_k \rightarrow c > 0$ , as  $k \rightarrow +\infty$ . We start from the relation :

$$\hat{\nu}(\alpha\lambda^{-k}) = \sum_{0 \leq j \leq N} p_j e^{2i\pi\alpha\lambda^{-k}b_j} \hat{\nu}(\alpha\lambda^{-k+n_j}),$$

obtained by conditioning with respect to the value of  $\varepsilon_0$ . This furnishes for  $k \geq 0$  :

$$c_k = \sum_{0 \leq j \leq N} p_j e^{2i\pi(\alpha\lambda^{-k}b_j + \theta_{k-n_j} - \theta_k)} c_{k-n_j}.$$

We rewrite this as :

$$\sum_{0 \leq j \leq N} p_j \left[ e^{2i\pi(\alpha\lambda^{-k}b_j + \theta_{k-n_j} - \theta_k)} - 1 \right] c_{k-n_j} = c_k - \sum_{0 \leq j \leq N} p_j c_{k-n_j} = \sum_{0 \leq j \leq N} p_j (c_k - c_{k-n_j}).$$

Let  $K > 0$  be such that  $c_{k-n_j} \geq c/2 > 0$ , for  $k \geq K$  and all  $0 \leq j \leq N$ . For  $L > n^*$ , where  $n^* = \max_{0 \leq j \leq N} |n_j|$ , we sum the previous equality on  $K \leq k \leq K+L$  :

$$\sum_{0 \leq j \leq N} p_j \sum_{k=K}^{K+L} c_{k-n_j} \left[ e^{2i\pi(\alpha\lambda^{-k}b_j + \theta_{k-n_j} - \theta_k)} - 1 \right] = \sum_{0 \leq j \leq N} p_j \left( \sum_{k=K}^{K+L} c_k - \sum_{k=K-n_j}^{K+L-n_j} c_k \right).$$

Observe that the right-hand side involves a telescopic sum and is bounded by  $2n^*$  (using that  $|c_k| \leq 1$ ), uniformly in  $K$  and  $L$ . In the left hand-hand side, we take the real part and use that  $1 - \cos(2\pi x) = 2(\sin \pi x)^2$ , which, as is well-known, has the same order as  $\|x\|^2$ . We obtain, for some constant  $C$ , that for  $K$  and  $L$  large enough :

$$\frac{c}{2} \sum_{0 \leq j \leq N} p_j \sum_{k=K}^{K+L} \|\alpha\lambda^{-k}b_j + \theta_{k-n_j} - \theta_k\|^2 \leq C.$$

Introducing the constants  $p_* = \min_{0 \leq j \leq N} p_j > 0$  and  $C' = 2C/(cp_*)$ , we get that for all  $0 \leq j \leq N$  and  $K, L$  large enough :

$$\sum_{k=K}^{K+L} \|\alpha\lambda^{-k}b_j + \theta_{k-n_j} - \theta_k\|^2 \leq C'. \quad (3)$$

In the sequel, we distinguish two cases : there is a non-zero translation (case 1) or not (case 2).

- *Case 1.* For any non-zero-translation  $\varphi_j(x) = x + b_j$ , we have  $n_j = 0$  and  $b_j \neq 0$ . Then (3) gives that for  $K, L$  large enough :

$$\sum_{k=K}^{K+L} \|\alpha\lambda^{-k}b_j\|^2 \leq C'.$$

This implies that  $(\|\alpha b_j \lambda^{-k}\|)_{k \geq 0} \in \mathcal{I}^2(\mathbb{N})$ . By a classical theorem of Pisot, cf Cassels [3], chap. 8, Theorems I and II, we obtain that  $1/\lambda$  is a Pisot number and  $b_j = (1/\alpha)\mu_j$ , with  $\mu_j \in \mathcal{T}(1/\lambda)$ . Consider now the non-translations  $\varphi_j(x) = \lambda^{n_j}x + b_j$ ,  $n_j \neq 0$ . By (3), for any  $r \geq 0$  and  $K, L$  large enough (depending on  $r$ ) :

$$\sum_{k=K}^{K+L} \|\alpha \lambda^{-k+r n_j} b_j + \theta_{k-(r+1)n_j} - \theta_{k-r n_j}\|^2 \leq C'.$$

Fixing  $l_j \geq 1$  and summing over  $0 \leq r \leq l_j - 1$ , making use of the triangular inequality and of  $(x_1 + \dots + x_n)^2 \leq n(x_1^2 + \dots + x_n^2)$ , we obtain, for  $K, L$  large enough (depending on  $l_j$ ) :

$$\sum_{k=K}^{K+L} \left\| \alpha \lambda^{-k} b_j \left( \frac{1 - \lambda^{l_j n_j}}{1 - \lambda^{n_j}} \right) + \theta_{k-l_j n_j} - \theta_k \right\|^2 \leq l_j C'. \quad (4)$$

Changing  $k$  into  $k + l_j n_j$ , we obtain, for  $K, L$  large enough (depending on  $l_j$ ) :

$$\sum_{k=K}^{K+L} \left\| \alpha \lambda^{-k} b_j \left( \frac{1 - \lambda^{-l_j n_j}}{1 - \lambda^{n_j}} \right) + \theta_{k+l_j n_j} - \theta_k \right\|^2 \leq l_j C'. \quad (5)$$

Let  $1 = \sum_{0 \leq j \leq N} l_j n_j$  be a Bezout relation and  $J \subset \{0, \dots, N\}$  be the subset where  $l_j n_j \neq 0$ , equipped with its natural order. Using successively for  $j \in J$  either (4) or (5), according to the sign of  $l_j$ , we obtain with :

$$b = \sum_{j \in J} b_j \lambda^{\sum_{k \in J, k < j} l_k n_k} \left( \frac{1 - \lambda^{l_j n_j}}{1 - \lambda^{n_j}} \right), \quad (6)$$

the following relation, for a new constant  $C'$  and all  $K, L$  large enough :

$$\sum_{k=K}^{K+L} \|\alpha \lambda^{-k} b + \theta_{k-1} - \theta_k\|^2 \leq C'.$$

Now, for any  $n_j \neq 0$ , whatever the sign of  $n_j$  is, we arrive at, for some constant  $C'$  and all  $K, L$  large enough :

$$\sum_{k=K}^{K+L} \left\| \alpha \lambda^{-k} b \left( \frac{1 - \lambda^{n_j}}{1 - \lambda} \right) + \theta_{k-n_j} - \theta_k \right\|^2 \leq C'.$$

Set  $b' = b/(1 - \lambda)$ . Hence, for any  $0 \leq j \leq N$  with  $n_j \neq 0$ , for some new constant  $C'$  and all  $K, L$  large enough, using (3) :

$$\sum_{k=K}^{K+L} \|\alpha \lambda^{-k} (b_j - b'(1 - \lambda^{n_j}))\|^2 \leq C'.$$

Let  $0 \leq j \leq N$ , with  $n_j \neq 0$ . If  $b_j \neq b'(1 - \lambda^{n_j})$ , then we deduce again that  $1/\lambda$  is a Pisot number and  $b_j = b'(1 - \lambda^{n_j}) + (1/\alpha)\mu_j$ , with  $\mu_j \in \mathcal{T}(1/\lambda)$ . The other case is  $b_j = b'(1 - \lambda^{n_j})$ . In any case, we obtain that for all  $0 \leq j \leq N$  :

$$\varphi_j(x) = b' + \lambda^{n_j}(x - b') + (1/\alpha)\mu_j, \quad (7)$$

for some  $\mu_j \in \mathcal{T}(1/\lambda)$ . Finally, remark that (7) says that the  $(\varphi_j)_{0 \leq j \leq N}$  are conjugated with the  $(\psi_j)_{0 \leq j \leq N}$ , where  $\psi_j(x) = \lambda^{n_j}x + \mu_j$ ; precisely  $\varphi_j = f \circ \psi_j \circ f^{-1}$ , with  $f(x) = x/\alpha + b'$ .

- *Case 2.* Any  $\varphi_j$  with  $n_j = 0$  is the identity. The conclusion is the same, because there now necessarily exists some  $0 \leq j \leq N$  with  $n_j \neq 0$  and  $b_j \neq b'(1 - \lambda^{n_j})$ , otherwise  $b'$  is a common fixed point for all  $(\varphi_j)_{0 \leq j \leq N}$ .

This ends the proof of the theorem. □

## 4 Proof of Theorem 2.4

Let  $N \geq 1$  and affine maps  $\varphi_k(x) = \lambda^{n_k}x + \mu_k$ , for  $0 \leq k \leq N$ , with  $1/\lambda > 1$  a Pisot number, relatively prime integers  $(n_k)_{0 \leq k \leq N}$  and  $\mu_k \in \mathcal{T}(1/\lambda)$ , for  $0 \leq k \leq N$ . Let  $p \in \mathcal{C}_N$  and denote by  $(\varepsilon_n)_{n \in \mathbb{Z}}$  *i.i.d.* random variables with law  $p$ , to which the probability  $\mathbb{P}$  and the expectation  $\mathbb{E}$  refer. We suppose that  $\mathbb{E}(n_{\varepsilon_0}) > 0$ . Without loss of generality,  $n_N \leq \dots \leq n_0$ . Thus  $n_0 \geq 1$ . For general background on Markov chains, cf Spitzer [23].

Recall the cocycle notations introduced before the statement of the theorem and denote by  $\theta$  the formal shift such that  $\theta \varepsilon_l = \varepsilon_{l+1}$ ,  $l \in \mathbb{Z}$ . We have for all  $k$  and  $l$  in  $\mathbb{Z}$  :

$$S_{k+l} = S_k + \theta^k S_l.$$

Then  $\nu$  is the law of  $X = \sum_{l \geq 0} \mu_{\varepsilon_l} \lambda^{S_l}$ . We write  $Q \in \mathbb{Z}[X]$  for the minimal polynomial of  $1/\lambda$ , of degree  $s+1$ , with roots  $\alpha_0 = 1/\lambda, \alpha_1, \dots, \alpha_s$ , where  $|\alpha_k| < 1$ , for  $1 \leq k \leq s$ . The case  $s = 0$  corresponds to  $1/\lambda$  an integer  $\geq 2$  (using then usual conventions regarding sums or products). Recall that for any  $k \in \mathbb{Z}$ ,  $\sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+S_l} \pmod{1}$  is a well-defined  $\mathbb{T}$ -valued random variable.

*Step 1.* In order to prove the convergence in law of  $(\lambda^{-n}X, \lambda^{-n-1}X, \dots, \lambda^{-n-s}X) \pmod{\mathbb{Z}^{s+1}}$ , as  $n \rightarrow +\infty$ , it is enough to prove, for any  $(m_0, \dots, m_s) \in \mathbb{Z}^{s+1}$ , the convergence of :

$$\mathbb{E} \left( e^{2i\pi \sum_{0 \leq u \leq s} m_u \lambda^{-n-u} X} \right) = \mathbb{E} \left( e^{2i\pi \sum_{l \geq 0} (\alpha_{\mu_{\varepsilon_l}}) \lambda^{-n+S_l}} \right),$$

with  $\alpha = \sum_{0 \leq u \leq s} m_u \lambda^{-u}$ . Notice that  $\alpha \mu_j \in \mathcal{T}(1/\lambda)$ , for  $0 \leq j \leq N$ . We make the proof when  $\alpha = 1$ , the one for  $\alpha$  being obtained by changing  $(\mu_j)$  into  $(\alpha \mu_j)$ .

Since  $\sum_{l < 0} \mu_{\varepsilon_l} \lambda^{-n+S_l} \pmod{1}$  converges a.s. to 0 in  $\mathbb{T}$ , as  $n \rightarrow +\infty$ , it is enough to consider expectations with  $\sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{-n+S_l} \pmod{1}$  in the exponential. Let  $k \in \mathbb{Z}$  be a fixed integer. Looking at  $(S_l)_{l \in \mathbb{Z}}$  and the first  $q \in \mathbb{Z}$  such that  $S_q \geq n$ , we have :

$$\begin{aligned} \mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k-n+S_l}} \right) &= \sum_{0 \leq r < n_0} \sum_{q \in \mathbb{Z}} \mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{(k-n+S_q)+(S_l-S_q)}} \mathbf{1}_{S_{q-u} < n, u \geq 1, S_q = n+r} \right) \\ &= \sum_{0 \leq r < n_0} \sum_{q \in \mathbb{Z}} \mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+\theta^q S_{l-q}}} \mathbf{1}_{\theta^q S_{-u} < -r, u \geq 1, \theta^q S_{-q} = -n-r} \right) \\ &= \sum_{0 \leq r < n_0} \sum_{q \in \mathbb{Z}} \mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_{l-q}} \lambda^{k+r+S_{l-q}}} \mathbf{1}_{S_{-u} < -r, u \geq 1, S_{-q} = -n-r} \right) \\ &= \sum_{0 \leq r < n_0} \sum_{q \in \mathbb{Z}} \mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \mathbf{1}_{S_{-u} < -r, u \geq 1, S_{-q} = -n-r} \right). \end{aligned}$$

For each  $0 \leq r < n_0$ , we can move the sum  $\sum_{q \in \mathbb{Z}}$  inside the expectation, using the theorem of Fubini, if we for example show the finiteness of :

$$\sum_{q \in \mathbb{Z}} \mathbb{E} ( \mathbf{1}_{S_{-q} = -n-r} ) = \mathbb{E} \left( \sum_{q \geq 0} \mathbf{1}_{S_{-q} = -n-r} \right) + \mathbb{E} \left( \sum_{q \geq 1} \mathbf{1}_{S_q = -n-r} \right).$$

This is true, since, as soon as  $n$  is larger than some constant (because of the missing term for  $q = 0$  in the second sum), this equals  $G^-(0, -n-r) + G^+(0, -n-r) < +\infty$ , where  $G^-(x, y)$  and  $G^+(x, y)$  are the Green functions, finite for every integers  $x$  and  $y$ , respectively associated to the *i.i.d.* transient random walks  $(S_{-q})_{q \geq 0}$  and  $(S_q)_{q \geq 0}$ . Let  $\sigma_k^+$ , for  $k \in \mathbb{Z}$ , be the first time  $\geq 0$  when  $(S_q)_{q \geq 0}$  touches  $k$ . We have  $G^+(x, y) = \mathbb{P}_0(\sigma_{y-x}^+ < \infty)G^+(0, 0)$ . With some symmetric quantities, one has  $G^-(x, y) = \mathbb{P}_0(\sigma_{y-x}^- < \infty)G^-(0, 0)$ .

We therefore obtain :

$$\mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k-n+S_l}} \right) = \sum_{0 \leq r < n_0} \mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, u \geq 1} \left( \sum_{q \in \mathbb{Z}} 1_{S_{-q} = -n-r} \right) \right).$$

Let us now fix  $0 \leq r < n_0$  and consider the corresponding term of the right-hand side. First of all, for  $n > 0$  larger than some constant :

$$\mathbb{E} \left( \sum_{q < 0} 1_{S_{-q} = -n-r} \right) = \mathbb{P}_0(\sigma_{-n-r}^+ < \infty) G^+(0, 0) \rightarrow 0, \quad (8)$$

as  $n \rightarrow +\infty$ , since  $(S_q)_{q \geq 0}$  is transient to the right. We thus only need to consider :

$$T(-n) := \mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, u \geq 1} N(-n-r) \right),$$

where we set  $N(-k-r) = \sum_{q \geq 0} 1_{S_{-q} = -n-r}$ . Consider an integer  $M_0$ , that we will let tend to  $+\infty$  at the end. The difference of  $T(-n)$  with the following expression :

$$\mathbb{E} \left( e^{2i\pi \sum_{l \geq -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, 1 \leq u \leq M_0} N(-n-r) \right)$$

is bounded by  $A + B$ , where, first :

$$\begin{aligned} A &= \mathbb{E} \left[ \left| e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} - e^{2i\pi \sum_{l \geq -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \right| N(-n-r) \right] \\ &= \mathbb{E} \left[ \left| 1 - e^{2i\pi \sum_{l < -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \right| N(-n-r) \right] \\ &\leq \left( \mathbb{E} \left[ \left| 1 - e^{2i\pi \sum_{l < -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \right|^2 \right] \right)^{1/2} (\mathbb{E}(N(-n-r)^2))^{1/2} \\ &\leq \left( \mathbb{E} \left[ \left| 1 - e^{2i\pi \sum_{l < -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \right|^2 \right] \right)^{1/2} (\mathbb{E}(N(0)^2))^{1/2}, \end{aligned}$$

because  $N(-n-r)$  is stochastically dominated by  $N(0)$ . Notice that  $N(0)$  is square integrable, as it has exponential tail. The first term on the right-hand side also goes to 0, as  $M_0 \rightarrow +\infty$ , by dominated convergence. The other term  $B$  is :

$$\begin{aligned} B &= \mathbb{E} \left( 1_{S_{-u} < -r, 1 \leq u \leq M_0, \exists v > M_0, S_{-v} \geq -r} N(-n-r) \right) \\ &\leq \mathbb{P}(\exists v > M_0, S_{-v} \geq -r)^{1/2} (\mathbb{E}(N(-n-r)^2))^{1/2} \\ &\leq \mathbb{P}(\exists v > M_0, S_{-v} \geq -r)^{1/2} (\mathbb{E}(N(0)^2))^{1/2}, \end{aligned}$$

as before. The first term on the right-hand side goes to 0, as  $M_0 \rightarrow +\infty$ , since  $(S_{-v})$  is transient to  $-\infty$ , as  $v \rightarrow +\infty$ . As a result :

$$T(-n) = \mathbb{E} \left( e^{2i\pi \sum_{l \geq -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, 1 \leq u \leq M_0} N(-n-r) \right) + o_{M_0}(1),$$

where  $o_{M_0}(1)$  goes to 0, as  $M_0 \rightarrow +\infty$ , uniformly in  $n$ . Now, when  $n > 0$  is large enough,  $N(-k-r) = \sum_{q \geq 0} 1_{S_{-q} = -n-r} = \sum_{q \geq M_0} 1_{S_{-q} = -n-r}$ , for all  $\omega$ . Taking inside the expectation the conditional expectation with respect to the  $\sigma$ -algebra generated by the  $(\varepsilon_l)_{l \geq -M_0}$ , we obtain :

$$T(-n) = \mathbb{E} \left( e^{2i\pi \sum_{l \geq -M_0} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, 1 \leq u \leq M_0} G^-(S_{-M_0}, -n-r) \right) + o_{M_0}(1).$$

Now, things are simpler because  $G^-(S_{-M_0}, -n-r)$  is bounded by the constant  $G^-(0,0)$ . Hence, for some new  $o_{M_0}(1)$ , with the same properties :

$$T(-n) = \mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, u \geq 1} G^-(S_{-M_0}, -n-r) \right) + o_{M_0}(1).$$

Since  $G^-(S_{-M_0}, -n-r) \rightarrow 1/\mathbb{E}(n_{\varepsilon_0})$ , as  $n \rightarrow \infty$ , by renewal theory (since the  $(n_j)$  are relatively prime and  $p_j > 0$ , for all  $0 \leq j \leq N$ ; cf Woodrooffe [27], chap. 2, thm 2.1), staying bounded by  $G^-(0,0)$ , we get by dominated convergence and next  $M_0 \rightarrow +\infty$  :

$$\lim_{n \rightarrow +\infty} T(-n) = \frac{1}{\mathbb{E}(n_{\varepsilon_0})} \mathbb{E} \left( e^{2i\pi \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} 1_{S_{-u} < -r, u \geq 1} \right).$$

From the initial expression, the limit, if existing, had to be independent on the parameter  $k$ . So this gives the announced convergence and invariance, hence proving item *i*) in Theorem 2.4.

*Step 2.* In the proof of Theorem 2.4, we now consider *ii*) and suppose that  $\nu$  is continuous. We first show that  $m$  is a continuous measure. For a continuous  $f : \mathbb{T} \rightarrow \mathbb{R}^+$  and any  $k \in \mathbb{R}$ , we have :

$$\int_{\mathbb{T}} f(x) dm(x) \leq \frac{1}{\mathbb{E}(n_{\varepsilon_0})} \sum_{0 \leq r < n^*} \mathbb{E}[f(Z_{k+r})].$$

Now  $Z_k = \sum_{l < 0} \mu_{\varepsilon_l} \lambda^{k+S_l} + \lambda^k X \pmod{1}$ . Since  $\mathcal{L}(\lambda^k X)$  on  $\mathbb{R}$  is continuous,  $\mathcal{L}(\lambda^k X \pmod{1})$  on  $\mathbb{T}$  is continuous. Since  $\sum_{l < 0} \mu_{\varepsilon_l} \lambda^{k+S_l} \pmod{1}$  and  $\lambda^k X \pmod{1}$  are independent random variables, for any  $k \in \mathbb{Z}$ , the law of  $Z_k$  on  $\mathbb{T}$  is continuous. Thus  $m$  is a continuous measure (hence  $\mathcal{M}$ ).

More generally, if  $0 \neq n = (n_0, \dots, n_s)^t \in \mathbb{Z}^{s+1}$  and if  $Z$  is random variable with law  $\mathcal{M}$ , then the law of  $\langle Z, n \rangle$  on  $\mathbb{T}$  is  $m_\alpha$ , measure corresponding to  $m$  when replacing the  $(\mu_j)$  by  $(\alpha \mu_j)$ , thus the  $(\varphi_j)$  by the  $(\psi_j)$ , with  $\psi_j(x) = \lambda^{n_j} x + \alpha \mu_j$ , where  $\alpha = \sum_{0 \leq u \leq s} n_u \lambda^{-u}$ . Since  $\alpha \neq 0$ , because  $(\lambda^{-u})_{0 \leq u \leq s}$  is a basis of  $\mathbb{Q}[\lambda]$  over  $\mathbb{Q}$ , the  $(\psi_j)$  do not have a common fixed point and thus  $m_\alpha$  is continuous, by the previous reasoning.

Suppose now that the  $(\varphi_j)$  have a common fixed point  $c$ . Hence  $\mu_j = c(1 - \lambda^{n_j})$ ,  $0 \leq j \leq N$ , and  $\nu = \delta_c$ . Necessarily  $c \in \mathbb{Q}[\lambda]$ , since the  $n_j$  are not all zero. We shall show that  $\lambda^{-n} c \pmod{1}$  converges to a rational number in  $\mathbb{T}$ , as  $n \rightarrow +\infty$ . First of all, for  $n$  large enough, for all  $0 \leq j \leq N$  :

$$Tr_{1/\lambda}(c\lambda^{-n}) - Tr_{1/\lambda}(c\lambda^{-n+n_j}) = Tr_{1/\lambda}(\lambda^{-n} \mu_j) \in \mathbb{Z}.$$

Hence, for any fixed sequence  $(k_j)_{0 \leq j \leq N}$ , for  $n$  large enough, for all  $0 \leq j \leq N$  :

$$Tr_{1/\lambda}(c\lambda^{-n}) - Tr_{1/\lambda}(c\lambda^{-n+k_j n_j}) \in \mathbb{Z}.$$

Supposing that  $\sum_{0 \leq j \leq N} k_j n_j = 1$ , using the previous expression successively  $n$  replaced by  $n, n - k_0 n_0, \dots, n - \sum_{0 \leq j \leq N-1} k_j n_j$ , respectively with  $j = 0, j = 1, \dots, j = N$ , and finally adding the results, we obtain that for some large  $K > 0$ , for all  $n > K$  :

$$Tr_{1/\lambda}(c\lambda^{-n}) - Tr_{1/\lambda}(c\lambda^{-n+1}) \in \mathbb{Z}.$$

Let  $Tr_{1/\lambda}(c\lambda^{-K}) = p/q$ . For  $n > K$ , there exists an integer  $l_n$  such that  $Tr_{1/\lambda}(c\lambda^{-n}) = p/q + l_n$ . As a result, denoting by  $c = c_0, c_1, \dots, c_s$  the conjugates of  $c$  corresponding to  $\mathbb{Q}[\lambda]$ , we get :

$$c\lambda^{-n} = p/q + l_n - \sum_{1 \leq j \leq N} c_j \alpha_j^n.$$

Consequently  $\lambda^{-n} c \pmod{1}$  converges to  $p/q$  in  $\mathbb{T}$ , as announced.

Consider *iii*). We prove that when  $\nu$  is Rajchman, then  $\mathcal{M} = \mathcal{L}_{\mathbb{T}^{s+1}}$ . Fix any  $0 \neq (n_0, \dots, n_s)^t \in \mathbb{Z}^{s+1}$  and set  $\beta = \sum_{0 \leq u \leq s} n_u \lambda^{-u}$ . Again  $\beta \neq 0$ . We have :

$$\sum_{0 \leq u \leq s} n_u (\lambda^{-n-u} X) = \beta \lambda^{-n} X.$$

Since  $\nu$  is Rajchman,  $\mathbb{E}(e^{2i\pi\beta\lambda^{-n}X}) \rightarrow 0$ , as  $n \rightarrow +\infty$ . As a result, the Fourier coefficient of  $\mathcal{M}$  corresponding to  $(n_0, \dots, n_s)$  is zero. Hence  $\mathcal{M} = \mathcal{L}_{\mathbb{T}^{s+1}}$ . Also  $m = \mathcal{L}_{\mathbb{T}}$ .

To complete the proof of *iii*), we show that  $\nu \perp \mathcal{L}_{\mathbb{R}}$  implies  $\mathcal{M} \perp \mathcal{L}_{\mathbb{T}^{s+1}}$ . Recall that  $Z_k = \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+S_l} \pmod{1}$ . For any  $f \in C(\mathbb{T}^{s+1}, \mathbb{R})$  and  $k \in \mathbb{Z}$ :

$$\frac{1}{\mathbb{E}(n_{\varepsilon_0})} \sum_{0 \leq r < n^*} \mathbb{E} [f(Z_{-k+r}, Z_{-k+r-1}, \dots, Z_{-k+r-s}) 1_{S_{-v} < -r, v \geq 1}] = \int_{\mathbb{T}^{s+1}} f(x) d\mathcal{M}(x),$$

with  $n^* = \max_{0 \leq j \leq N} n_j$ . We now fix  $k \geq n^*$  so that  $Tr_{1/\lambda}(\lambda^{-l} \mu_j) \in \mathbb{Z}$ ,  $0 \leq j \leq N$ ,  $l \geq k - n^*$ .

For  $0 \leq j \leq N$ , denote by  $(\mu_j^{(t)})_{0 \leq t \leq s}$  the conjugates of  $\mu_j = \mu_j^{(0)}$  corresponding to the field  $\mathbb{Q}[\lambda]$ . Let  $0 \leq r < n^*$ . Taking any  $0 \leq u \leq s$  and  $l < 0$ , we have:

$$\mu_{\varepsilon_l} \lambda^{-u-k+r+S_l} = Tr_{1/\lambda}(\mu_{\varepsilon_l} \lambda^{-u-k+r+S_l}) - \sum_{1 \leq t \leq s} \mu_{\varepsilon_l}^{(t)} \alpha_t^{u+k-r-S_l}.$$

The role of the indicator function is now fundamental. On the event  $\{S_{-v} < -r, v \geq 1\}$ , we have  $Tr_{1/\lambda}(\mu_{\varepsilon_l} \lambda^{-u-k+r+S_l}) \in \mathbb{Z}$ , by our choice of  $k$ . As a result, introducing the *real* random variables:

$$Y_u^{(r)} = \lambda^{-u} \sum_{l \geq 0} \mu_{\varepsilon_l} \lambda^{-k+r+S_l} - \sum_{1 \leq t \leq s} \alpha_t^{u+k-r} \sum_{l < 0} \mu_{\varepsilon_l}^{(t)} \alpha_t^{-S_l},$$

together with  $Y^{(r)} = (Y_0^{(r)}, \dots, Y_s^{(r)})$ , we obtain that for any  $f \in C(\mathbb{T}^{s+1}, \mathbb{R})$ :

$$\frac{1}{\mathbb{E}(n_{\varepsilon_0})} \sum_{0 \leq r < n^*} \mathbb{E} [f(Y^{(r)}) 1_{S_{-v} < -r, v \geq 1}] = \int_{\mathbb{T}^{s+1}} f(x) d\mathcal{M}(x). \quad (9)$$

Hence, for any  $f \in C(\mathbb{T}^{s+1}, \mathbb{R}^+)$ :

$$\int_{\mathbb{T}^{s+1}} f(x) d\mathcal{M}(x) \leq \frac{1}{\mathbb{E}(n_{\varepsilon_0})} \sum_{0 \leq r < n^*} \mathbb{E} [f(Y^{(r)})]. \quad (10)$$

Fix any  $0 \leq r < n^*$  and let  $X_0 = \sum_{l \geq 0} \mu_{\varepsilon_l} \lambda^{-k+r+S_l}$  and for  $1 \leq j \leq s$ ,  $X_j = -\sum_{l < 0} \mu_{\varepsilon_l}^{(j)} \alpha_j^{k-r-S_l}$ . By definition,  $(Y^{(r)})^t = V(X_0, \dots, X_s)^t$ , where  $V$  is the Vandermonde matrix:

$$V = \begin{pmatrix} 1 & 1 & \dots & 1 \\ \lambda^{-1} & \alpha_1 & \dots & \alpha_s \\ \vdots & \vdots & \vdots & \vdots \\ \lambda^{-s} & \alpha_1^s & \dots & \alpha_s^s \end{pmatrix}.$$

The matrix  $V$  is invertible (as the roots of the minimal polynomial  $Q$  of  $1/\lambda$  are simple). By Cramer's formula:

$$X_0 = \sum_{0 \leq i \leq s} \gamma_i Y_i^{(r)},$$

with  $\gamma_i = \det(V^{(i)})/\det(V)$ , where  $V^{(i)}$  is obtained from  $V$  by replacing the first column by  $e_i$ , denoting by  $(e_i)_{0 \leq i \leq s}$  the canonical basis of  $\mathbb{R}^{s+1}$ .

Notice that each  $\gamma_i$  is real (first,  $1/\lambda$  is a real root of  $Q$ . Next, regrouping the other roots in conjugate pairs, when conjugating  $\gamma_i$ , one gets permutations in the numerator  $\det(V^{(i)})$  and the denominator  $\det(V)$ , the same ones, so  $\bar{\gamma}_i = \gamma_i$ ). As  $V$  is invertible,  $\gamma := (\gamma_i)_{0 \leq i \leq s} \neq 0$ .

We have  $X_0 = \langle Y^{(r)}, \gamma \rangle$ . Since  $\nu$  is singular, we also have  $\mathcal{L}(X_0) \perp \mathcal{L}_{\mathbb{R}}$ . As  $\gamma \neq 0$ , we get that  $\mathcal{L}(Y^{(r)}) \perp \mathcal{L}_{\mathbb{R}^{s+1}}$ . Hence  $\mathcal{L}(Y^{(r)} \bmod \mathbb{Z}^{s+1}) \perp \mathcal{L}_{\mathbb{T}^{s+1}}$ . By (10), we obtain  $\mathcal{M} \perp \mathcal{L}_{\mathbb{T}^{s+1}}$ , as desired.

Finally, suppose that condition (C) holds and that  $\nu$  has a density. Thus  $\mathcal{M} = \mathcal{L}_{\mathbb{T}^{s+1}}$ . The event  $\{S_{-v} < 0, v \geq 1\}$  has probability one. Looking at (9), at  $r = 0$ , we get that  $Y^{(0)} \bmod \mathbb{Z}^{s+1}$  has a density with respect to  $\mathcal{L}_{\mathbb{T}^{s+1}}$ , bounded by  $\mathbb{E}(n_{\varepsilon_0})$ . Hence  $Y^{(0)}$  has a density with respect to  $\mathcal{L}_{\mathbb{R}^{s+1}}$ , also bounded by  $\mathbb{E}(n_{\varepsilon_0})$ . Under condition (C), the random variable  $Y^{(0)}$  is trivially bounded, thus its density is bounded and with compact support in  $\mathbb{R}^{s+1}$ . Hence this is also the case of  $X_0 = \langle Y^{(0)}, \gamma \rangle$ , taking  $r = 0$  above. Thus this is also true for  $X$ , showing Theorem 2.5 *i*).  $\square$

## 5 Proof of Theorem 2.5

Assume now that condition (C) holds. Precisely, let  $N \geq 1$  and affine contractions  $\varphi_k(x) = \lambda^{n_k}x + \mu_k$ , for  $0 \leq k \leq N$ , with  $1/\lambda > 1$  a Pisot number, relatively prime integers  $(n_k)_{0 \leq k \leq N}$ , with  $n_k \geq 1$  and  $\mu_k \in \mathcal{T}(1/\lambda)$ , for  $0 \leq k \leq N$ . We shall suppose that  $n_0 \geq \dots \geq n_N \geq 1$ .

*Step 1.* Considering  $p \in \mathcal{C}_N$ , denote by  $(\varepsilon_n)_{n \in \mathbb{Z}}$  a sequence of *i.i.d.* random variables with law  $p$ . We fix an integer  $n \neq 0$ , whose exact value will be precised at the end. We focus on the Fourier coefficient  $\hat{m}(n)$  of the measure  $m$  appearing in Theorem 2.4 *i*). Removing the normalizing constant  $\mathbb{E}(n_{\varepsilon_0})$  and observing that it has a simplified expression under condition (C), we introduce the following quantity, which is a constant multiple of it :

$$\Delta_p = \Delta_p(k) = \sum_{0 \leq r < n_0} \mathbb{E} \left( e^{2i\pi n \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \mathbf{1}_{n_{\varepsilon_{-1}} > r} \right),$$

which is independent of  $k \in \mathbb{Z}$  and where we mark the dependence in  $p \in \mathcal{C}_N$ . We now focus on the regularity of  $p \mapsto \Delta_p$  on  $\mathcal{C}_N$ . For any  $k \in \mathbb{Z}$ , observe first that  $\Delta_p(k)$  is well-defined, with the same formula as above, on the closure  $\bar{\mathcal{C}}_N$ . Fixing  $k \in \mathbb{Z}$ , the map  $p \mapsto \Delta_p(k)$  is continuous on  $\bar{\mathcal{C}}_N$ , as this function is the uniform limit on  $\bar{\mathcal{C}}_N$ , as  $L \rightarrow +\infty$ , of the continuous maps :

$$p \mapsto \sum_{0 \leq r < n_0} \mathbb{E} \left( e^{2i\pi n \sum_{-L \leq l \leq L} \mu_{\varepsilon_l} \lambda^{k+r+S_l}} \mathbf{1}_{n_{\varepsilon_{-1}} > r} \right).$$

It thus follows that  $p \mapsto \Delta_p(k) = \Delta_p$  is well-defined on  $\bar{\mathcal{C}}_N$ , is continuous and independent on  $k$ . We shall now prove using standard methods that it is in fact real-analytic in a classical sense, precised below. Let us take  $k = 0$  and fix  $0 \leq r < n_0$ . Using independence, write :

$$\mathbb{E} \left( e^{2i\pi n \sum_{l \in \mathbb{Z}} \mu_{\varepsilon_l} \lambda^{r+S_l}} \mathbf{1}_{n_{\varepsilon_{-1}} > r} \right) = \mathbb{E} \left( e^{2i\pi n \sum_{l \geq 0} \mu_{\varepsilon_l} \lambda^{r+S_l}} \right) \mathbb{E} \left( e^{2i\pi n \sum_{l \leq -1} \mu_{\varepsilon_l} \lambda^{r+S_l}} \mathbf{1}_{n_{\varepsilon_{-1}} > r} \right).$$

Let us call  $F(p)$  and  $G(p)$  respectively the terms appearing in the right-hand side. We shall show that both functions are real-analytic functions of  $p$ . This property will be inherited by  $p \mapsto \Delta_p$ . We treat the case of  $p \mapsto F(p)$ , the case of  $G(p)$  needing only to rewrite first the  $\mu_{\varepsilon_l} \lambda^{r+S_l}$ , appearing in the definition of  $G(p)$  and as soon as  $l < 0$  is large enough (depending only the  $(\mu_j)_{0 \leq j \leq N}$ , since  $n_k \geq 1$ , for all  $k$ ), as  $-\sum_{1 \leq j \leq s} \alpha_j^{-r-S_l} \mu_{\varepsilon_l}^{(j)}$ , quantity equal to  $\mu_{\varepsilon_l} \lambda^{r+S_l}$  in  $\mathbb{T}$ , where the  $(\mu_k^{(j)})_{1 \leq j \leq s}$  are the conjugates of  $\mu_k$  corresponding to the field  $\mathbb{Q}[\lambda]$ .

Fix now  $p \in \bar{\mathcal{C}}_N$ . Let  $\mathbb{N} = \{0, 1, \dots\}$  and the symbolic space  $S = \{0, \dots, N\}^{\mathbb{N}}$ , equipped with the left shift  $\sigma$ . For  $x = (x_0, x_1, \dots) \in S$ , we define :

$$g(x) = e^{2i\pi n \left( \sum_{l \geq 0} \mu_{x_l} \lambda^{r+n_{x_0}+\dots+n_{x_{l-1}}} \right)}.$$

Introducing the product measure  $\mu_p = \left( \sum_{0 \leq j \leq N} p_j \delta_j \right)^{\otimes \mathbb{N}}$  on  $S$ , we can write :

$$F(p) = \int_S g \, d\mu_p.$$



Denote by  $C(S)$  the space of continuous functions  $f : S \rightarrow \mathbb{C}$  and introduce the operator  $P_p : C(S) \rightarrow C(S)$  defined by :

$$P_p(f)(x) = \sum_{0 \leq j \leq N} p_j f((j, x)), \quad x \in S,$$

where  $(j, x) \in S$  is the word obtained by the left concatenation of the symbol  $j$  to  $x$ . The operator  $P_p$  is Markovian, i.e.  $f \geq 0 \Rightarrow P_p(f) \geq 0$  and verifies  $P_p \mathbf{1} = \mathbf{1}$ , where  $\mathbf{1}(x) = 1$ ,  $x \in S$ . The measure  $\mu_p$  has the invariance property  $\int_S P_p(f) d\mu_p = \int_S f d\mu_p$ ,  $f \in C(S)$ . For  $f \in C(S)$  and  $k \geq 0$ , introduce the variation :

$$\text{Var}_k(f) = \sup\{|f(x) - f(y)|, (x, y) \in S^2, x_i = y_i, 0 \leq i < k\}.$$

For any  $0 < \alpha < 1$ , let  $|f|_\alpha = \sup\{\alpha^{-k} \text{Var}_k(f), k \geq 0\}$ , as well as  $\|f\|_\alpha = |f|_\alpha + \|f\|_\infty$ . We denote by  $\mathcal{F}_\alpha$  the complex Banach space of functions  $f$  on  $S$  such that  $\|f\|_\alpha < \infty$ . Any  $\mathcal{F}_\alpha$  is preserved by  $P_p$ . Observe now that  $g \in \mathcal{F}_\alpha$  for  $\lambda \leq \alpha < 1$ . We fix  $\alpha = \lambda$ .

As a classical fact from Spectral Theory, cf for example Baladi [1], the operator  $P_p : \mathcal{F}_\lambda \rightarrow \mathcal{F}_\lambda$  satisfies a Perron-Frobenius theorem. Let us show this elementarily. For  $f \in \mathcal{F}_\lambda$ , we have :

$$P_p^n f(x) = \sum_{0 \leq j_1, \dots, j_n \leq N} p_{j_1} \cdots p_{j_n} f((j_1, \dots, j_n, x)).$$

This furnishes  $\text{Var}_k(P_p^n f - \mathbf{1} \int_S f d\mu_p) = \text{Var}_k(P_p^n f) \leq \text{Var}_{k+n}(f)$ , therefore :

$$\left| P_p^n(f) - \mathbf{1} \int_S f d\mu_p \right|_\lambda \leq \lambda^n |f|_\lambda.$$

In a similar way, we can write :

$$\begin{aligned} (P_p^n f - \mathbf{1} \int_S f d\mu_p)(x) &= P_p^n(f)(x) - \mathbf{1}(x) \int_S P_p^n(f) d\mu_p \\ &= \sum_{0 \leq j_1, \dots, j_n \leq N} p_{j_1} \cdots p_{j_n} \int_S (f((j_1, \dots, j_n, x)) - f((j_1, \dots, j_n, y))) d\mu_p(y). \end{aligned}$$

Consequently,  $\|P_p^n f - \mathbf{1} \int_S f d\mu_p\|_\infty \leq \text{Var}_n(f) \leq \lambda^n |f|_\lambda$ . Putting things together, finally :

$$\|P_p^n(f - \mathbf{1} \int_S f d\mu_p)\|_\lambda \leq 2\lambda^n \|f\|_\lambda.$$

This shows that 1 is a simple eigenvalue 1 and that the rest of the spectrum of  $P_p$  is contained in the closed disk of radius  $\lambda < 1$ . Remark that this holds uniformly on  $p \in \bar{\mathcal{C}}_N$ .

Fix some circle  $\Gamma$  centered at 1 and with radius  $0 < r < 1 - \lambda$ . By standard functional holomorphic calculus, cf Kato [10], for any  $p \in \bar{\mathcal{C}}_N$ , the following operator, involving the resolvent, is a continuous (Riesz) projector on  $\text{Vect}(\mathbf{1})$  :

$$\Pi_p = \int_\Gamma (zI - P_p)^{-1} dz. \quad (11)$$

Moreover  $\Pi_p(\mathcal{F}_\lambda)$  and  $(I - \Pi_p)(\mathcal{F}_\lambda)$  are closed  $P_p$ -invariant subspaces, with  $\mathcal{F}_\lambda = \Pi_p(\mathcal{F}_\lambda) \oplus (I - \Pi_p)(\mathcal{F}_\lambda)$ , and in restriction to  $(I - \Pi_p)(\mathcal{F}_\lambda)$ , the spectral radius of  $P_p$  is less than  $\lambda$ .

Recall that  $N \geq 1$ . We view a function of  $p \in \bar{\mathcal{C}}_N$  in terms of the first  $N$  variables  $(p_0, \dots, p_{N-1}) \in \mathbb{R}^N$ . Let  $\eta' = (\eta_0, \dots, \eta_{N-1})$  and  $\eta = (\eta_0, \dots, \eta_{N-1}, -(\eta_0 + \dots + \eta_{N-1}))$ . For any  $p \in \bar{\mathcal{C}}_N$  and  $\eta'$ , even if  $p + \eta \notin \bar{\mathcal{C}}_N$ , we can define the continuous operator  $P_{p+\eta} : \mathcal{F}_\lambda \rightarrow \mathcal{F}_\lambda$ . It verifies :

$$P_{p+\eta} = P_p + \sum_{0 \leq j \leq N-1} \eta_j Q_j,$$

where  $Q_j(f)(x) = f(j, x) - f(N, x)$ . Denote by  $B_N(0, \delta)$  the open Euclidean ball in  $\mathbb{R}^N$  of radius  $\delta$ . Let  $\lambda < \lambda' < 1 - r$ . For any  $p$  in  $\bar{C}_N$ , there exists  $\delta > 0$  such that when  $\eta' \in B_N(0, \delta)$ , then  $\mathbf{1}$  is still a simple eigenfunction of  $P_{p+\eta}$ , with  $P_{p+\eta}\mathbf{1} = \mathbf{1}$ , the rest of the spectrum of  $P_{p+\eta}$  being contained in the disk of radius  $\lambda'$  and  $\Pi_{p+\eta}$ , also defined by (11), is a continuous projector on  $\text{Vect}(\mathbf{1})$ ; this follows from the implicit function theorem, cf Rosenbloom [16], Kato [10]. By compacity of  $\bar{C}_N$  and  $\Gamma$ ,  $\delta > 0$  can be chosen uniformly on  $p \in \bar{C}_N$ . This defines the open  $\delta$ -neighborhood  $C_N^\delta$  of  $\bar{C}_N$ .

When  $p \in \bar{C}_N$ , we have  $\int_S f d\mu_p = 0$  when  $f \in (I - \Pi_p)(\mathcal{F}_\lambda)$ . Thus for any  $f \in \mathcal{F}_\lambda$  :

$$\Pi_p(f) = \left( \int_S f d\mu_p \right) \mathbf{1}.$$

Applying this to the function  $g$  of interest to us, we obtain that when  $p \in \bar{C}_N$  :

$$F(p)\mathbf{1} = \int_\Gamma (zI - P_p)^{-1}(g) dz.$$

The function  $F$  is extended to  $C_N^\delta$  by the previous formula. Recall the following definition :

**Definition 5.1**

A function  $h : C_N^\delta \rightarrow \mathbb{C}$ , seen as a function of  $(p_0, \dots, p_{N-1})$ , admits a development in series around  $p \in C_N^\delta$ , if there exists  $\varepsilon > 0$  such that for  $\eta' = (\eta_0, \dots, \eta_{N-1}) \in B_N(0, \varepsilon)$  and writing  $\eta = (\eta', -(\eta_0 + \dots + \eta_{N-1}))$ , then  $h(p + \eta)$  is given by an absolutely converging series :

$$h(p + \eta) = \sum_{l_0 \geq 0, \dots, l_{N-1} \geq 0} A_{l_0, \dots, l_{N-1}} \eta_0^{l_0} \cdots \eta_{N-1}^{l_{N-1}}.$$

A function is real-analytic in  $C_N^\delta$  if it admits a development in series around all  $p \in C_N^\delta$ .

Let us now check that  $p \mapsto F(p)$  is real-analytic on  $C_N^\delta$ . Let  $p \in C_N^\delta$ . For  $z \in \Gamma$  and  $\eta'$  small enough, we can write :

$$\begin{aligned} (zI - P_{p+\eta})^{-1} &= \left( I - (zI - P_p)^{-1} \sum_{0 \leq j \leq N-1} \eta_j Q_j \right)^{-1} (zI - P_p)^{-1} \\ &= \sum_{n \geq 0} \sum_{0 \leq j_1, \dots, j_n \leq N-1} \eta_{j_1} \cdots \eta_{j_n} (zI - P_p)^{-1} Q_{j_1} \cdots (zI - P_p)^{-1} Q_{j_n} (zI - P_p)^{-1}. \end{aligned}$$

This is clearly absolutely convergent in the Banach operator algebra, for small enough  $\eta'$ , uniformly in  $z \in \Gamma$ . We rewrite it as :

$$(zI - P_{p+\eta})^{-1} = \sum_{l_0 \geq 0, \dots, l_{N-1} \geq 0} B_{l_0, \dots, l_{N-1}}(z) \eta_0^{l_0} \cdots \eta_{N-1}^{l_{N-1}},$$

converging for the operator norm, uniformly in  $z \in \Gamma$ . This leads to :

$$F(p + \eta)\mathbf{1} = \int_\Gamma (zI - P_{p+\eta})^{-1}(g) dz = \sum_{l_0 \geq 0, \dots, l_{N-1} \geq 0} \eta_0^{l_0} \cdots \eta_{N-1}^{l_{N-1}} \int_\Gamma B_{l_0, \dots, l_{N-1}}(z)(g) dz.$$

Applying this equality at some particular  $x \in S$ , we obtain the desired development in series around  $p$ . This completes this step.

*Step 2.* Maybe restricting  $\delta > 0$ , we get that  $p \mapsto \Delta_p$  is real-analytic on  $C_N^\delta$ . We shall show that if  $n \neq 0$  has been appropriately chosen at the beginning, then  $\Delta_p$  is not zero at some extremal points of  $\bar{C}_N$ . If  $\Delta_p$  has a zero on  $\bar{C}_N$ , then  $p \mapsto \text{Re}(\Delta_p)$  or  $p \mapsto \text{Im}(\Delta_p)$  is non-constant on  $C_N^\delta$ .

Now if  $h : \mathcal{C}_N^\delta \rightarrow \mathbb{R}$  is real-analytic and non-constant, by Lojasiewicz's stratification theorem (cf [8], theorem 5.2.3) the real-analytic set  $\{p \in \mathcal{C}_N^\delta \mid h(p) = 0\}$  is locally a finite union of real-analytic graphs of dimension  $\leq N - 1$  (points if  $N = 1$ ). By compactness of  $\bar{\mathcal{C}}_N$ , the set  $\{p \in \bar{\mathcal{C}}_N \mid h(p) = 0\}$  is included in a finite union of real-analytic graphs of dimension  $\leq N - 1$ .

For the sequel, we write  $x \equiv y$  for equality of  $x$  and  $y$  in  $\mathbb{T}$ .

**Lemma 5.2**

Let  $d \geq 1$  and  $\mu \in \mathcal{T}(1/\lambda)$ . The series  $\sum_{l \in \mathbb{Z}} \mu \lambda^{ld} \pmod{1}$ , well-defined as an element of  $\mathbb{T}$ , equals a rational number modulo 1.

*Proof of the lemma :*

Let  $l_0 \geq 1$  be such that  $Tr_{1/\lambda}(\lambda^{-l_0} \mu) \in \mathbb{Z}$ , for  $l > l_0$ . Denote by  $(\mu^{(j)})_{0 \leq j \leq s}$  the conjugates of  $\mu$ , with  $\mu^{(0)} = \mu$ , and  $\alpha_1, \dots, \alpha_s$  that of  $\alpha_0 = 1/\lambda$ . We have the following equalities on the torus :

$$\begin{aligned} \sum_{l \in \mathbb{Z}} \mu \lambda^{ld} &\equiv \frac{\mu \lambda^{-l_0 d}}{1 - \lambda^d} + \sum_{l > l_0} \mu \lambda^{-ld} \equiv \frac{\mu \lambda^{-l_0 d}}{1 - \lambda^d} - \sum_{1 \leq i \leq s} \mu^{(i)} \sum_{l > l_0} \alpha_i^{ld} \equiv \frac{\mu \lambda^{-l_0 d}}{1 - \lambda^d} - \sum_{1 \leq i \leq s} \mu^{(i)} \frac{\alpha_i^{(l_0+1)d}}{1 - \alpha_i^d} \\ &\equiv - \left( \frac{\mu \lambda^{-(l_0+1)d}}{1 - \lambda^{-d}} + \sum_{1 \leq i \leq s} \mu^{(i)} \frac{\alpha_i^{(l_0+1)d}}{1 - \alpha_i^d} \right) = -Tr_{1/\lambda} \left( \frac{\mu \lambda^{-(l_0+1)d}}{1 - \lambda^{-d}} \right) \in \mathbb{Q}. \end{aligned}$$

□

We conclude the argument. Fixing  $0 \leq j \leq N$  and  $p^j = (0, \dots, 0, 1, 0, \dots, 0)$ , where the 1 is at place  $j$ , we have for  $k \in \mathbb{Z}$ , recalling that  $1 \leq n_j \leq n_0$  :

$$\Delta_{p^j} = \Delta_{p^j}(k) = \sum_{0 \leq r < n_0} e^{2i\pi n \sum_{l \in \mathbb{Z}} \mu_j \lambda^{k+r+ln_j}} 1_{n_j > r} = \sum_{0 \leq r < n_j} e^{2i\pi n \sum_{l \in \mathbb{Z}} \mu_j \lambda^{k+r+ln_j}}.$$

Notice that the invariance with respect to  $k$  is now obvious, as we sum over  $r$  on a full period of length  $n_j$ . Now, taking  $k = 0$ , we have :

$$\Delta_{p^j} = \sum_{0 \leq r < n_j} e^{2i\pi n(A_{j,r}/B_{j,r})},$$

for rational numbers  $A_{j,r}/B_{j,r}$ , making use of the previous lemma, since  $\lambda^r \mu_j \in \mathcal{T}(1/\lambda)$ , for any  $r$ . If for example  $n$  is a multiple of  $B_{j,r}$  for any  $0 \leq r < n_j$ , we get  $\Delta_{p^j} = n_j \geq 1$ , which gives what was desired. This ends the proof of the theorem.

□

*Remark.* — In the general case, without condition (C), the method seems to reach some limit. Considering the regularity of  $p \mapsto F(p)$  on  $\mathcal{D}_N((\lambda^{n_k})_{0 \leq k \leq N})$ , it is not difficult to show continuity, using some standard coupling argument. The real-analytic character, if ever true, a priori requires more work. Still setting  $S = \{0, \dots, N\}^{\mathbb{N}}$  and  $\mu_p = (\sum_{0 \leq j \leq N} p_j \delta_j)^{\otimes \mathbb{N}}$  on  $S$ , we again have :

$$F(p) = \int_S g \, d\mu_p,$$

with  $g(x) = e^{2i\pi n (\sum_{l \geq 0} \mu_{x_l} \lambda^{r+n_{x_0} + \dots + n_{x_l-1})}$ , but this function is not continuous on  $S$  and in fact only defined  $\mu_p$ -almost-everywhere.

## 6 Complements

### 6.1 A numerical example

Considering an example as simple as possible which is not homogeneous, take  $N = 1$  and the two contractions  $\varphi_0(x) = \lambda x$ ,  $\varphi_1(x) = \lambda^2 x + 1$ , where  $1/\lambda > 1$  is a Pisot number, with probability vector  $p = (p_0, p_1)$ . Then  $n_0 = 1$ ,  $n_1 = 2$  and  $\nu$  is the law of  $\sum_{l \geq 0} \varepsilon_l \lambda^{n_{\varepsilon_0} + \dots + n_{\varepsilon_{l-1}}}$ , with  $(\varepsilon_n)_{n \geq 0}$  *i.i.d.*, with common law  $\text{Ber}(p_1)$ , i.e.  $\mathbb{P}(\varepsilon_0 = 1) = p_1$  and  $\mathbb{P}(\varepsilon_0 = 0) = 1 - p_1$ . We shall take  $0 \leq p_1 \leq 1$  as parameter for simulations. Notice that  $\mathbb{E}(n_{\varepsilon_0}) = p_0 + 2p_1 = 1 + p_1$ ,

Taking  $n = 1$ ,  $k \in \mathbb{Z}$  and  $r \in \{0, 1\}$ , let us define :

$$F_p(k) = \mathbb{E} \left( e^{2i\pi \lambda^k \sum_{l \geq 0} \varepsilon_l \lambda^{n_{\varepsilon_0} + \dots + n_{\varepsilon_{l-1}}}} \right), \quad G_p(k, r) = \mathbb{E} \left( e^{2i\pi \sum_{l \geq 0} \varepsilon_l \lambda^{k - (n_{\varepsilon_0} + \dots + n_{\varepsilon_l})}} 1_{n_{\varepsilon_0} > r} \right),$$

leading to  $\Delta_p = F_p(k)G_p(k, 0) + F_p(k+1)G_p(k+1, 1)$ , for all  $k \in \mathbb{Z}$ . Writing  $m_p$  in place of  $m$  for the measure on  $\mathbb{T}$  in Theorem 2.4 *i)* (defined when  $0 < p_1 < 1$ ), we get  $\hat{m}_p(1) = \Delta_p / (1 + p_1)$ . Let us first discuss the choice of probability vector  $p = (1 - p_1, p_1)$  and Pisot number  $1/\lambda$ .

A degenerated example (the invariant measure being automatically singular) is for instance given by  $\lambda = (3 - \sqrt{5})/2 < 1/2$ . Nevertheless, it is interesting to notice that  $\lambda^{-n} \equiv -\lambda^n$ ,  $n \geq 0$ . Taking  $p_1 = 1/2$ , one can check that  $\Delta_p = |F_p(1)|^2 + |F_p(2)|^2/2$ . Necessarily  $\Delta_p > 0$ . Indeed,  $k \mapsto F_p(k)$  verifying a linear recurrence of order two, the equality  $\Delta_p = 0$  would give  $F_p(k) = 0$  for all  $k$ , but  $F_p(k) \rightarrow 1$ , as  $k \rightarrow +\infty$ . Notice that  $(3 - \sqrt{5})/2$  is the largest  $\lambda$  with this property (it has to be a root of some  $X^2 - aX + 1$ , for some integer  $a \geq 0$ ). Mention that in general  $\Delta_p$  is not real; cf the pictures below.

To study an interesting example, we take into account the similarity dimension  $s(p, r)$ , rewritten here as  $s(p, \lambda)$  :

$$s(p, \lambda) := \frac{(1 - p_1) \ln(1 - p_1) + p_1 \ln p_1}{(1 - p_1) \ln \lambda + p_1 \ln(\lambda^2)}.$$

The condition  $s(p, \lambda) \geq 1$  is equivalent to  $(1 - p_1) \ln(1 - p_1) + p_1 \ln p_1 - (1 + p_1) \ln \lambda \leq 0$ . As a function of  $p_1$ , the left-hand side has a minimum value  $-\ln(\lambda + \lambda^2)$ , attained at  $p_1 = \lambda/(1 + \lambda)$ . As a first attempt, taking for  $1/\lambda$  the golden mean  $(\sqrt{5} + 1)/2 = 1,618\dots$  appears in fact not to be a good idea, as in this case  $\lambda + \lambda^2 = 1$ , giving  $s(p, \lambda) \leq 1$ .

We instead take (as in the Introduction) for  $1/\lambda$  the Plastic number, i.e. the unique real root of  $X^3 - X - 1$ . Approximately,  $1/\lambda = 1.324718\dots$ . For this  $\lambda$  :

$$s(p, \lambda) > 1 \iff 0,203\dots < p_0 < 0,907\dots$$

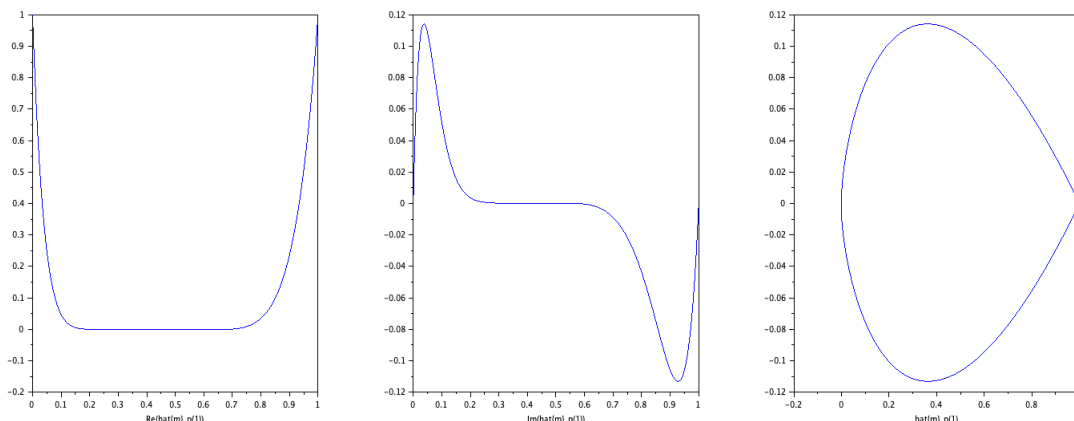
The other roots of  $X^3 - X - 1 = 0$  are conjugate numbers  $\rho e^{\pm i\theta}$ . From the relations  $1/\lambda + 2\rho \cos \theta = 0$  and  $(1/\lambda)\rho^2 = 1$ , we deduce  $\rho = \sqrt{\lambda}$  and  $\cos \theta = -1/(2\lambda^{3/2})$ , thus  $\theta = \pm 2.43\dots$  rad. For computations, the relations  $\lambda^{-n} + \rho^n e^{in\theta} + \rho^n e^{-in\theta} \in \mathbb{Z}$ ,  $n \geq 0$ , furnish  $\lambda^{-n} \equiv -2(\sqrt{\lambda})^n \cos(n\theta)$ .

Let us finally compute the extreme values of  $p_1 \mapsto \hat{m}_p(1)$ , abusively written as  $\hat{m}_{(1,0)}(1)$  and  $\hat{m}_{(0,1)}(1)$ , since  $m_p$  has only been defined for  $0 < p_1 < 1$ . We first observe that  $\hat{m}_{(1,0)}(1) = \Delta_{(1,0)} = F_{(1,0)}(0)G_{(1,0)}(0, 0) = 1$ . At the other extremity :

$$\begin{aligned} \Delta_{(0,1)} &= F_{(0,1)}(0)G_{(0,1)}(0, 0) + F_{(0,1)}(1)G_{(0,1)}(1, 1) \\ &= e^{2i\pi \sum_{l \geq 0} \lambda^{2l}} e^{2i\pi \sum_{l \geq 0} \lambda^{-2(l+1)}} + e^{2i\pi \lambda \sum_{l \geq 0} \lambda^{2l}} e^{2i\pi \sum_{l \geq 0} \lambda^{1-2(l+1)}} \\ &= e^{2i\pi \left( \frac{1}{1-\lambda^2} - 2 \sum_{l \geq 0} (\sqrt{\lambda})^{2l} \cos(2l\theta) \right)} + e^{2i\pi \left( \frac{\lambda}{1-\lambda^2} - 2 \sum_{l \geq 0} (\sqrt{\lambda})^{2l+1} \cos((2l+1)\theta) \right)} \\ &= e^{2i\pi \left( \frac{1}{1-\lambda^2} - 2 \text{Re} \left( \frac{\lambda e^{2i\theta}}{1-\lambda e^{2i\theta}} \right) \right)} + e^{2i\pi \left( \frac{\lambda}{1-\lambda^2} - 2 \text{Re} \left( \frac{\sqrt{\lambda} e^{i\theta}}{1-\lambda e^{2i\theta}} \right) \right)}. \end{aligned}$$

A not difficult computation, shortened by the observation that  $(1 - \lambda e^{2i\theta})(1 - \lambda e^{-2i\theta}) = 1/\lambda$ , shows that the arguments in the exponential terms (after the  $2i\pi$ ) are respectively equal to 3 and 0, leading to  $\Delta_{(0,1)} = 2$  and therefore  $\hat{m}_{(0,1)}(1) = 1$ .

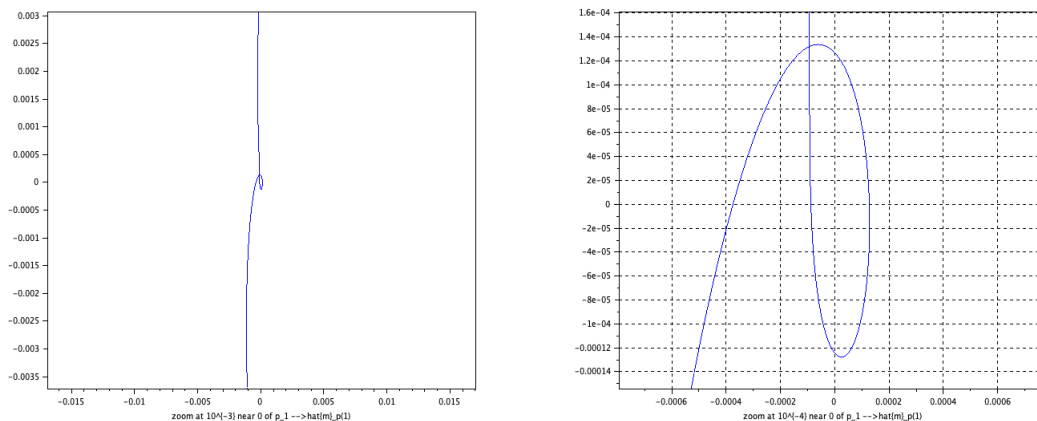
Recalling that  $p = (1 - p_1, p_1)$ , below are respectively drawn the real-analytic maps  $p_1 \mapsto \text{Re}(\hat{m}_p(1))$ ,  $p_1 \mapsto \text{Im}(\hat{m}_p(1))$  and the parametric curve  $p_1 \mapsto \hat{m}_p(1)$ ,  $0 \leq p_1 \leq 1$ .



The first two pictures indicate that  $p_1 \mapsto \hat{m}_p(1)$  spends a rather long time near 0, with  $\text{Re}(\hat{m}_p(1))$  and  $\text{Im}(\hat{m}_p(1))$  both around  $10^{-4}$ . Let us precise here that one can exploit the product form (given by the exponential) inside the expectation appearing in  $F_p(k)$  and  $G_p(k, r)$  and make a deterministic numerical computation of  $\hat{m}_p(1)$ , with nearly an arbitrary precision, based on a dynamical programming (using a binomial tree). For example, one can obtain the rather remarkable value :

$$\hat{m}_{(1/2, 1/2)}(1) = 0,0001186\dots + i0,0000327\dots,$$

where all digits are exact. In this case,  $s((1/2, 1/2), \lambda) = 1,64\dots > 1$ . The above pictures were drawn with 1000 points, each one determined with a sufficient precision. This allows to safely zoom on the neighbourhood of 0 of  $p_1 \mapsto \hat{m}_p(1)$ , the interesting region. We obtain the following surprising pictures, the one on the right-hand side containing around 500 points :



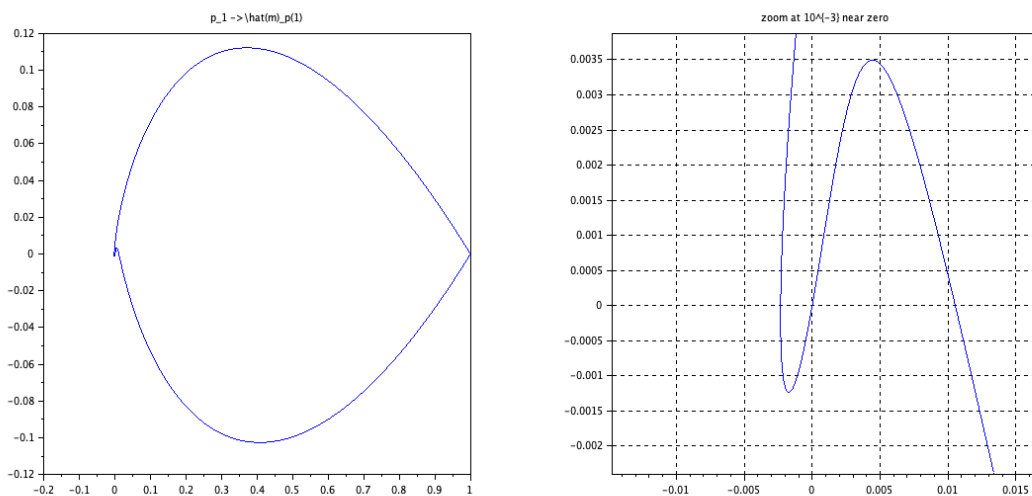
There are probably profound reasons behind these pictures, that would in particular clarify the condition of non-nullity of the Fourier coefficient  $\hat{m}_p(1)$  and more generally of  $\hat{m}_p(n)$ ,  $n \in \mathbb{Z}$ . Further investigations are necessary, but we can conclude that the curve  $p_1 \mapsto \hat{m}_p(1)$  is rather convincingly not touching 0. It may certainly be possible to build a rigorous numerical proof of this fact, but this is not the purpose of the present paper. Being confident in this, we state :

### Numerical Theorem 6.1

Let  $N = 1$ ,  $0 < \lambda < 1$ , with  $1/\lambda > 1$  the Plastic number, and  $\varphi_0(x) = \lambda x$ ,  $\varphi_1(x) = \lambda^2 x + 1$ . Then for all  $p \in \mathcal{C}_1$ , the invariant measure  $\nu$  is continuous singular and not Rajchman.

*Remark.* — For the same system, but taking for  $1/\lambda$  the supergolden ratio, i.e. the fourth Pisot number (the real root of  $X^3 - X^2 - 1$ ), one essentially gets the same pictures.

Still taking for  $1/\lambda$  the Plastic number, but for the system  $\varphi_0(x) = \lambda^2 x$  and  $\varphi_1(x) = \lambda^3 x + 1$ , mentioned in Section 2, recall that the invariant measure  $\nu$  is continuous singular and not Rajchman for all  $p \in \mathcal{C}_1$ , except when  $p = (\lambda^2, \lambda^3)$ , in which case  $\nu = \frac{1}{1+\lambda} \mathcal{L}_{[0,1+\lambda]}$ . We have drawn below the real analytic curve  $p_1 \mapsto \hat{m}_p(1)$ , with next a zoom at  $10^{-3}$  near the origin. This is also interesting, since this time the curve is not self-intersecting, being almost linear near zero and passing at zero exactly for the sole parameter  $p_1 = \lambda^3$ .



## 6.2 Applications to sets of uniqueness for trigonometric series

Let  $N \geq 1$  and for  $0 \leq k \leq N$  affine contractions  $\varphi_k(x) = r_k x + b_k$ , with reals  $(r_k)$  and  $(b_k)$ , with  $0 < r_k < 1$  for all  $k$  (i.e. condition (C) holds). As a general fact, Theorem 2.3 has some consequences in terms of sets of multiplicity for trigonometric series, cf for example Salem [18] or Zygmund [28] for details. As in the introduction, let  $F \subset \mathbb{R}$  be the unique non-empty compact set, verifying the self-similarity relation  $F = \cup_{0 \leq k \leq N} \varphi_k(F)$ . With  $\mathbb{N} = \{0, 1, \dots\}$  and  $S = \{0, \dots, N\}^{\mathbb{N}}$ , recall that :

$$F = \left\{ \sum_{l \geq 0} b_{x_l} r_{x_0} \cdots r_{x_{l-1}}, (x_0, x_1, \dots) \in S \right\}.$$

Let us place on the torus  $\mathbb{T}$  and consider trigonometric series. Recall that a subset  $E$  of  $\mathbb{T}$  is a set of uniqueness ( $U$ -set), if whenever a trigonometric series  $\sum_{n \geq 0} (a_n \cos(2\pi x) + b_n \sin(2\pi x))$ , with complex numbers  $(a_n)$  and  $(b_n)$ , converges to 0 for all  $x \notin E$ , then  $a_n = b_n = 0$  for all  $n \geq 0$ . Otherwise  $E$  is said of multiplicity ( $M$ -set).

### Theorem 6.1

Let  $N \geq 1$  and for  $0 \leq k \leq N$  affine contractions  $\varphi_k(x) = r_k x + b_k$ , where  $0 < r_k < 1$ , with no common fixed point. Suppose that the system  $(\varphi_k)_{0 \leq k \leq N}$  is not conjugated to a family in Pisot form. Then  $F \bmod 1 \subset \mathbb{T}$  is a  $M$ -set.

*Proof of the theorem :*

Taking any  $p \in \mathcal{C}_N$  gives a Rajchman invariant probability measure  $\nu$  supported by  $F \subset \mathbb{R}$ . Hence  $F \bmod 1 \subset \mathbb{T}$  supports the probability measure  $\tilde{\nu}$ , image of  $\nu$  under the projection  $x \mapsto x \bmod 1$ , from  $\mathbb{R}$  to  $\mathbb{T}$ . The measure  $\tilde{\nu}$  is thus a Rajchman measure on  $\mathbb{T}$ , so, cf Salem [18] (chap. V),  $F \bmod 1$  is a  $M$ -set. □

The analysis in the other direction is in general more delicate. We shall simply apply existing results. For the following statement, fixing  $0 < \lambda < 1$  and integers  $n_k \geq 1$ , for  $0 \leq k \leq N$ , notice that for any  $(x_0, x_1, \dots) \in S$  we have  $\sum_{l \geq 0} \lambda^{n_{x_0} + \dots + n_{x_{l-1}}} (1 - \lambda^{n_{x_l}}) = 1$ .

**Theorem 6.2**

Let  $N \geq 1$  and suppose that the  $(\varphi_k)$  are affine contractions of the form  $\varphi_k(x) = \lambda^{n_k} x + b_k$ , with  $b_k = \lambda a_k + c(1 - \lambda^{n_k})$ , for some  $0 < \lambda < 1$  with  $1/\lambda$  a Pisot number  $> N + 2$ , relatively prime positive integers  $n_k \geq 1$ ,  $0 \leq a_k \in \mathbb{Q}[\lambda]$  and real numbers  $b \geq 0$  and  $c$ . Then the non-empty compact self-similar set  $F = \cup_{0 \leq k \leq N} \varphi_k(F) \subset \mathbb{R}$  can be written as  $F = bG + c$ , where  $G$  is the compact set :

$$G = \left\{ \sum_{l \geq 0} a_{x_l} \lambda^{n_{x_0} + \dots + n_{x_{l-1}}}, (x_0, x_1, \dots) \in S \right\}.$$

Assume that  $bG \subset [0, 1)$ , so that  $bG$  and  $F$  can be seen as subsets of  $\mathbb{T}$ . Then  $F$  is  $U$ -set.

*Proof of the theorem :*

Up to replacing  $b$  and the  $(a_k)$  respectively by  $br$  and  $(a_k/r)$ , for some  $r > 1$  in  $\mathbb{Q}$ , we may assume that  $0 \leq a_k < 1/(1 - \lambda)$ , for all  $0 \leq k \leq N$ . Then :

$$G \subset H := \left\{ \sum_{l \geq 0} \eta_l \lambda^l, \eta_l \in \{0, a_0, \dots, a_N\}, l \geq 0 \right\} \subset [0, 1).$$

Since  $1/\lambda > N + 2$  is a Pisot number and all  $a_0, \dots, a_N$  are in  $\mathbb{Q}[\lambda]$ , it follows from the Salem-Zygmund theorem, cf Salem [18], chap. VII, paragraph 3, on perfect homogeneous sets, that  $H$  is a perfect  $U$ -set. Mention that in this theorem, one also assumes that  $\max_{0 \leq k \leq N} a_k = 1/(1 - \lambda)$  and that successive  $a_u < a_v$  in  $[0, 1)$  verify  $a_v - a_u \geq \lambda$ . These conditions serve to give a geometrical description of the perfect homogeneous set  $H$  in terms of dissection, without overlaps. They are in fact not used in the proof, where only the above description of  $H$  is important (one can indeed start reading Salem [18], chap. VII, paragraph 3, directly from line 9 of the proof).

As a subset of a  $U$ -set,  $G$  is also a  $U$ -set. This is also the case of  $bG$ , by hypothesis a subset of  $[0, 1)$ , using Zygmund, Vol. I, chap. IX, Theorem 6.18 (the proof, not obvious, is in Vol. II, chap. XVI, 10.25, and relies on Fourier integrals). Hence,  $F = bG + c$  is also a  $U$ -set, as any translate on  $\mathbb{T}$  of a  $U$ -set is a  $U$ -set. This ends the proof of the theorem. □

*Remark.* — As a general fact, the hypothesis  $1/\lambda > N + 2$  ensures that  $H$  and  $F$  have zero Lebesgue measure, which is a necessary condition for a set to be a  $U$ -set. If overlaps happen in  $H$ , it would be interesting to consider extensions of the previous theorem, when the above condition on  $\lambda$  not necessarily holds.

*Acknowledgments.* We thank B. Kloeckner for initial discussions on this topic, J. Printems for his very precious help in the numerical part of the last section and K. Conrad for several enlightening discussions concerning Algebraic Number Theory questions. We also are grateful to P. Varju for pointing out an error in a first version of Theorem 2.5.

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