

# GOOD BANACH SPACES FOR PIECEWISE HYPERBOLIC MAPS VIA INTERPOLATION

VIVIANE BALADI AND SÉBASTIEN GOUËZEL

ABSTRACT. We introduce a weak transversality condition for piecewise  $C^{1+\alpha}$  and piecewise hyperbolic maps which admit a  $C^{1+\alpha}$  stable distribution. We show good bounds on the essential spectral radius of the associated transfer operators acting on classical anisotropic Sobolev spaces of Triebel-Lizorkin type. In many cases, we obtain a spectral gap from which we deduce the existence of finitely many physical measures with basin of total measure. The analysis relies on standard techniques (in particular complex interpolation) and applies also to piecewise expanding maps and to Anosov diffeomorphisms, giving a unifying picture of several previous results.

Proving the existence of physical measures and studying their statistical properties is an important task in dynamical systems. In this paper, we shall be concerned with maps with singularities (that is, discontinuities in the map or its derivatives). We shall assume that the map is piecewise smooth relative to a finite partition, and the most challenging case is when this partition does not have a Markov-type property.

For one-dimensional piecewise expanding maps, the space of functions of bounded variation has proved a very powerful tool, since the transfer operator acting on it has a spectral gap. This readily implies the existence of finitely many physical measures whose basins have full measure, as well as numerous other consequences. This functional approach has been extended to higher dimensional piecewise expanding maps, under stronger assumptions (the counter-examples of Tsujii [28] and Buzzi [10] show that *some* additional assumption is necessary), by considering various functional spaces (see the work of Keller, Góra–Boyarski, Saussol, Buzzi, Tsujii, Cowieson [21, 17, 23, 9, 29, 15]). On the other hand, a more elementary approach, involving a more detailed study of the dynamics and how sets are cut by the discontinuities, was developed by Young and Chernov [32, 13], culminating in the article of Buzzi–Maume [11] where the existence of physical measures (or more generally equilibrium measures) was proved under very weak additional assumptions.

For piecewise hyperbolic maps, finding good functional spaces on which the transfer operator has a spectral gap is a more complicated task, and the story went in the other direction, with the elementary (but very involved) arguments of Chernov and Young [12, 32, 13] coming first. Indeed, even for *smooth* hyperbolic dynamics, good spaces of distributions were only introduced a few years ago by Gouëzel–Liverani and Baladi–Tsujii [18, 5, 19, 6], following the pioneering work of Blank–Keller–Liverani [7]. These spaces cannot be used for piecewise hyperbolic

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systems because they are not invariant under multiplication by the characteristic function of a set with smooth boundary. Only very recently, a good functional space was constructed by Demers and Liverani [16], for two-dimensional piecewise hyperbolic maps. However, the arguments in this last paper are close in spirit to the previous ones [32, 13], in the sense that pieces of stable or unstable manifolds are iterated by the dynamics, and the way they are cut by the discontinuities has to be studied in a very careful way. In particular, to ensure sufficiently precise control, an essential assumption in [32, 13, 16] is transversality between stable or unstable manifolds and discontinuity hypersurfaces.

In this paper, we show that, under mild additional assumptions, the transfer operator of piecewise hyperbolic maps in arbitrary dimensions has a spectral gap on classical functional spaces  $\mathcal{H}_p^{t,t-}$ , for suitable indices  $t_- < 0 < t$  and  $1 < p < \infty$ . These spaces are anisotropic Sobolev spaces in the Triebel-Lizorkin class [31, 25]. Moreover, we are able to replace the strong transversality assumption from [32, 13, 16] with a much weaker one, formulated in terms of the geometry of stable manifolds and discontinuity hypersurfaces: for instance, we allow discontinuity sets coinciding with pieces of stable manifolds. Of course, this implicitly assumes the existence of stable manifolds, and this may be the main current restriction of our approach: we require stable manifolds to exist everywhere, and to depend in a piecewise  $C^{1+\alpha}$  way on the point for some  $\alpha > 0$ . (See also Remarks 2 and 8.)

The main novelty in this work is that, as in [23, 15], we do not need to study precisely the dynamics. In particular, we do not iterate single stable or unstable manifolds (contrary to [32, 13, 16]), and we do not need to match nearby stable or unstable manifolds. Indeed, everything comes from the functional analytic framework. This makes it possible to get a short self-contained proof working in any dimension and with very weak transversality assumptions.

Our spaces  $\mathcal{H}_p^{t,t-}$  (or more precisely their  $\tilde{\mathcal{H}}_p^{t_+,t}$  version, see Remark 8) are the same the first named author considered in [4] (with the notation  $W^{t,t_+,p}$ ) to study smooth hyperbolic maps. The main new observation that we shall use is (Lemma 20) that these spaces are stable under multiplication by characteristic functions of nice sets, if the smoothness indices in the definition of the space are small enough with respect to the integrability index ( $0 < t < 1/p$  and  $0 > t_- > -1 + 1/p$ ). This property is well known (see the thesis [24] of Strichartz, and also [22, §4.6.3]) for classical Sobolev spaces where  $t_- = 0$ , and we will exploit some ideas in [24] to prove that it extends to our spaces. For this, we use complex interpolation arguments to extend easily to our spaces estimates that are straightforward for the standard Sobolev spaces. Interpolation also makes it possible to generalize the basic estimates in [4] to arbitrary differentiability (see Appendix A). Another helpful technical ingredient is the use of a “zooming” norm (43) (based on a rather standard localization principle) which allows us to go further than [4], which only dealt with specific transfer operators.

We do not believe that our upper bounds on the essential spectral radius are also lower bounds in general. However, we note that for a (non necessarily Markov) piecewise linear map of the unit square given by a hyperbolic matrix  $A$  of maximal eigenvalue  $\lambda > 1$  (see Subsection 2.2), we find for each  $\epsilon > 0$  a space on which the essential spectral radius of the ordinary (Perron-Frobenius) transfer operator is  $\leq \lambda^{-1/2+\epsilon}$ . This is sharper than the results in [16], and may well be the optimal bound (in the strong sense of meromorphic extensions of the corresponding zeta

function or essential decorrelation rate [14]). We refer also to Subsection 2.2 for examples of conservative and dissipative (sloppy) baker maps to which our results apply.

Our proof extends the results of [4] to  $C^{1+\alpha}$  Anosov diffeomorphisms with  $C^{1+\alpha}$  stable and/or unstable distributions, and general  $C^\alpha$  weights (see Remark 24). Let us also mention that our results apply to piecewise expanding and piecewise  $C^{1+\alpha}$  maps for  $0 < \alpha < 1$  (without transversality assumptions, but under the hypothesis that the dynamical complexity does not grow too fast), giving yet another functional space on which the results of Saussol and Cowieson [23, 15], e.g., hold. This space is simply the usual Sobolev space  $\mathcal{H}_p^t$  for  $1 < p < \infty$  and  $0 < t < \min(1/p, \alpha)$ . Hence, introducing exotic spaces to study piecewise expanding maps is not necessary. This remark seems to be new even for one-dimensional piecewise expanding maps. (For *smooth* expanding maps in arbitrary dimensions, the transfer operator was studied on Sobolev spaces in [3].)

The paper is organized as follows. Section 1 contains the definitions (Definition 1) of the dynamics  $T$  considered (in particular, the condition on the stable foliation) and the spaces (Definition 7)  $\mathcal{H}_p^{t,t-}$ , as well as our weak transversality condition (Definition 4), and our main result. This main result, Theorem 9, gives a bound on the essential spectral radius of the transfer operator acting on  $\mathcal{H}_p^{t,t-}$ . We give in Corollary 10 the consequences of our main result on the existence of finitely many physical measures with total ergodic basin (based on a key result given in Appendix B), as well as variants of this main result under assumptions on the unstable foliation. Section 2 is devoted to a discussion of several examples, illustrating our conditions. In Section 3, we recall various classical results in functional analysis. Section 4 is the heart of the paper: it contains the basic bounds (multiplication by a function, composition by a smooth map preserving the stable foliation, multiplication by the characteristic function of a nice set) which lead to Lasota-Yorke type inequalities. In Section 5, we exploit these bounds, using a new “zooming” trick made possible by the localization property of our spaces, to prove Theorem 9.

## 1. STATEMENTS

Notations: if  $B$  is a Banach space, we denote the norm of an element  $f$  of  $B$  by  $\|f\|_B$ . In this paper, a function defined on a closed subset of a manifold is said to be  $C^k$  or  $C^\infty$  if it admits an extension to a neighborhood of this closed subset, which is  $C^k$  or  $C^\infty$  in the usual sense.

**1.1. The setting.** Let  $X$  be a riemannian manifold of dimension  $d$ , and let  $X_0$  be a compact subset of  $X$ . Let also  $0 \leq d_s \leq d$  and  $\alpha > 0$ . We call  $C^1$  hypersurface with boundary a codimension-one  $C^1$  submanifold of  $X$  with boundary. For a closed subset  $K$  of  $X_0$  we shall consider *integrable  $C^{1+\alpha}$  distributions* of  $d_s$ -dimensional subspaces  $E^s$  on  $K$ . By definition, this means that for each  $x$  in a neighborhood of  $K$ ,  $E^s(x)$  is a  $d_s$ -dimensional vector subspace of the tangent space  $\mathcal{T}_x X$ , the map  $x \mapsto E^s(x)$  is  $C^{1+\alpha}$  and, for any  $x \in K$ , there exists a unique submanifold of dimension  $d_s$  containing  $x$ , defined on a neighborhood of  $x$ , and everywhere tangent to  $E^s$ . We will denote this local submanifold by  $W_{loc}^s(x)$ , and by  $W_\epsilon^s(x)$  we will mean the ball of size  $\epsilon$  around  $x$  in this submanifold.

**Definition 1** (Piecewise hyperbolic maps with stable distribution). *For  $\alpha > 0$ , we say that a map  $T : X_0 \rightarrow X_0$  is a piecewise  $C^{1+\alpha}$  hyperbolic map with smooth stable distribution if*

- *There exists an integrable  $C^{1+\alpha}$  distribution of  $d_s$ -dimensional subspaces  $E^s$  on a neighborhood of  $X_0$ .*
- *There exists a finite number of disjoint open subsets  $O_1, \dots, O_I$  of  $X_0$ , covering Lebesgue-almost all  $X_0$ , whose boundaries are unions of finitely many compact  $C^1$  hypersurfaces with boundary.*
- *For  $1 \leq i \leq I$ , there exists a  $C^{1+\alpha}$  map  $T_i$  defined on a neighborhood of  $\overline{O_i}$ , which is a diffeomorphism onto its image, such that  $T$  coincides with  $T_i$  on  $O_i$ .*
- *For any  $x \in \overline{O_i}$ , there exists  $\lambda_s(x) < 1$  such that, for any  $v \in E^s(x)$ ,  $DT_i(x)v \in E^s(T_i x)$  and  $|DT_i(x)v| \leq \lambda_s(x)|v|$ .*
- *There exists a family of cones  $C^u(x)$ , depending continuously on  $x \in X_0$ , with  $C^u(x) + E^s(x) = T_x X$ , such that, for any  $x \in \overline{O_i}$ ,  $DT_i(x)C^u(x) \subset C^u(T_i x)$ , and there exists  $\lambda_u(x) > 1$  such that  $|DT_i(x)v| \geq \lambda_u(x)|v|$  for any  $v \in C^u(x)$ .*

See Remark 8 and Subsection 1.4 regarding the replacement of  $E^s$  by  $E^u$  and  $C^u$  by  $C^s$  in the above definition.

Note that we do not assume that  $T$  is continuous or injective on  $X_0$ .

When  $d_s = 0$ , the map  $T$  is piecewise expanding. When  $d_u = 0$ , it is piecewise contracting (we shall see that our results are not very useful in this case). In the intermediate case, there are at the same time contracted and expanded directions. We will denote by  $\lambda_{s,n}(x) < 1$  and  $\lambda_{u,n}(x) > 1$  the weakest contraction and expansion constants of  $T^n$  at  $x$ .

**Remark 2.** The requirement that  $E^s$  is defined everywhere and  $C^{1+\alpha}$  is extremely strong. It is possible to weaken it slightly, by requiring only that  $E^s$  is  $C^{1+\alpha}$  on each set  $O_i$ . Indeed, our proofs still work under this weaker assumption (one should just slightly modify the definition of the Banach space we use). It is also possible to apply directly our results to this more general setting, by working on a different manifold, as follows. Assume that  $T$  is a piecewise hyperbolic map for which  $E^s$  is  $C^{1+\alpha}$  on each set  $O_i$ , but not globally. Start from the disjoint union of the sets  $\overline{O_i}$ , and glue them together at all the points  $x \in \overline{O_i} \cap \overline{O_j}$  such that  $E^s$  is  $C^{1+\alpha}$  on a neighborhood of  $x$ . Then  $T$  induces a piecewise hyperbolic map on this new manifold, for which the stable distribution is globally  $C^{1+\alpha}$ . Indeed, since  $T$  is  $C^{1+\alpha}$  on each set  $O_i$ , the set  $T(O_i)$  intersects the boundaries of the sets  $O_j$  only at places where  $E^s$  is  $C^{1+\alpha}$ . Hence, the places in the original manifold where  $\overline{O_i}$  and  $\overline{O_j}$  are cut apart are not an obstruction to extending  $T$  to the new manifold. The assumption on the  $C^u$  can be similarly weakened.

In order to define our weak transversality condition on the boundaries of the sets  $O_i$ , we shall use the following notion.

**Definition 3** ( $L$ -generic vector in  $E^s$ ). *Let  $K \subset X_0$  be a compact hypersurface with boundary and let  $L \in \mathbb{Z}_+$ . For  $x \in K \setminus \partial K$ , we say that a vector  $a \in E^s(x)$  is  $L$ -generic with respect to  $K$  if, for any  $C^1$  vector field  $v$  defined on a neighborhood of  $x$ , with  $v(x) = a$  and  $v(y) \in E^s(y)$  for any  $y$ , there exists a smaller neighborhood of  $x$  in which the intersection of Lebesgue almost every integral line of  $v$  with  $K$  has at most  $L$  points.*

**Definition 4** (Weak transversality condition for  $E^s$ ). *Let  $T : X_0 \rightarrow X_0$  be a piecewise hyperbolic map with smooth stable distribution. We say that  $T$  satisfies the weak transversality condition if there exists  $L > 0$  such that, for any  $K \subset \bigcup_{i=1}^I \partial O_i$  which is hypersurface with boundary, there exists a larger hypersurface with boundary  $K'$  (containing  $K$  in its interior) such that, for any  $x \in K' \setminus \partial K'$ , the set of tangent vectors at  $x$  that are  $L$ -generic with respect to  $K'$  has full Lebesgue measure in  $E^s(x)$ .<sup>1</sup>*

The small enlargement  $K'$  of  $K$  is simply a technical point in the definition, to avoid problems at the boundary of  $K$ .

If the boundary of each  $O_i$  is a finite union of smooth hypersurfaces  $K_{i1}, \dots, K_{ik_i}$ , each of which is transversal to the stable direction (in the sense that  $E^s(x)$  is never contained in  $\mathcal{T}_x K_{ij}$ ), then  $T$  satisfies the weak transversality condition. However, the converse does not hold. For instance, we have the following result:

**Proposition 5.** *Assume that  $d_s = 1$  (so that the stable manifolds are curves), and that  $T$  is a piecewise hyperbolic map with smooth stable distribution. Then  $T$  satisfies the weak transversality condition if there exists  $\epsilon > 0$  such that*

$$(1) \quad \sup_{1 \leq i \leq I} \|\text{Card}(W_\epsilon^s(x) \cap \partial O_i)\|_{L_\infty(\text{Leb})} < \infty.$$

Hence, tangencies to the boundaries of the  $O_i$ 's are allowed, and even flat tangencies or pieces of the boundary coinciding with  $W^s$ . The only problematic situation is when a boundary oscillates around the stable manifold, cutting it into infinitely many small pieces.

To get a result on the physical measures of finitely differentiable maps  $T$ , it is necessary to add *some* assumption on the asymptotic dynamical complexity, already for piecewise expanding maps in dimension two or higher (see [23], [11], [15], [28] and [10]). We shall use the following way to quantify the complexity.

Let  $\mathbf{i} = (i_0, \dots, i_{n-1}) \in \{1, \dots, I\}^n$ . We define inductively sets  $O_{\mathbf{i}}$  by  $O_{(i_0)} = O_{i_0}$ , and

$$(2) \quad O_{(i_0, \dots, i_{n-1})} = \{x \in O_{i_0} \mid T_{i_0} x \in O_{(i_1, \dots, i_{n-1})}\}.$$

Let also  $T_{\mathbf{i}} = T_{i_{n-1}} \circ \dots \circ T_{i_0}$ , it is defined on a neighborhood of  $O_{\mathbf{i}}$ .

We define the complexity at the beginning

$$(3) \quad D_n^b = \max_{x \in X_0} \text{Card}\{\mathbf{i} = (i_0, \dots, i_{n-1}) \mid x \in \overline{O_{\mathbf{i}}}\},$$

and the complexity at the end

$$(4) \quad D_n^e = \max_{x \in X_0} \text{Card}\{\mathbf{i} = (i_0, \dots, i_{n-1}) \mid x \in \overline{T^n(O_{\mathbf{i}})}\}.$$

**1.2. The main spectral result.** We shall use spaces  $\mathcal{H}_p^{t, t-}$  which were first introduced in a dynamical setting in [4] (the local version of these spaces belongs to the Triebel-Lizorkin class, see [31], [2], [25] for earlier mentions of these spaces in functional analysis). Section 4 is devoted to a precise study of these spaces, and the statements in the following definition are justified there.

Let  $\mathcal{F}$  denote the Fourier transform in  $\mathbb{R}^d$ . We will write a point  $z \in \mathbb{R}^d$  as  $z = (x, y)$  where  $x = (z_1, \dots, z_{d_u})$  and  $y = (z_{d_u+1}, \dots, z_d)$ . In the same way, an

<sup>1</sup>We could replace “full Lebesgue measure” in this definition by “generic in the sense of Baire” (i.e., contains a countable intersection of dense open sets), all the following results would hold true as well, with the same proofs.

element  $\zeta$  of the dual space of  $\mathbb{R}^d$  will be written as  $\zeta = (\xi, \eta)$ . The subspaces  $\{x\} \times \mathbb{R}^{d_s}$  of  $\mathbb{R}^d$  will sometimes be referred to as the “stable leaves” in  $\mathbb{R}^d$ . We say that a diffeomorphism sends stable leaves to stable leaves if its derivative has this property.

**Definition 6** (Local spaces  $H_p^{t, t_-}$ ). *For  $1 < p < \infty$ ,  $t, t_- \in \mathbb{R}$ , we define a space  $H_p^{t, t_-}$  of distributions in  $\mathbb{R}^d$  as the (tempered) distributions  $u$  such that*

$$\mathcal{F}^{-1}((1 + |\xi|^2 + |\eta|^2)^{t/2}(1 + |\eta|^2)^{t_-/2}\mathcal{F}u) \in L_p,$$

with its canonical norm.

We will simply write  $H_p^t$  instead of  $H_p^{t, 0}$ .

If  $t \geq 0$ ,  $t + t_- \leq 0$  and  $t + |t_-| < \alpha < 1$ , we shall see that  $H_p^{t, t_-}$  is invariant under  $C^{1+\alpha}$  diffeomorphisms sending stable leaves to stable leaves (Remark 23). Hence, we can glue such spaces locally together in appropriate coordinate patches, to define a space  $\mathcal{H}_p^{t, t_-}$  of distributions on the manifold:

**Definition 7** (Spaces  $\mathcal{H}_p^{t, t_-}$  of distributions on  $X$ ). *Let  $t \geq 0$ ,  $t + t_- \leq 0$  and  $t + |t_-| < \alpha < 1$ . Fix a finite number of  $C^{1+\alpha}$  charts  $\kappa_1, \dots, \kappa_J$  whose derivatives send  $E^s$  to  $\{0\} \times \mathbb{R}^{d_s}$ , and whose domains of definition cover a compact neighborhood of  $X_0$ , and a partition of unity  $\rho_1, \dots, \rho_J$ , such that the support of  $\rho_j$  is compactly contained in the domain of definition of  $\kappa_j$ , and  $\sum \rho_j = 1$  on  $X_0$ . The space  $\mathcal{H}_p^{t, t_-}$  is then the space of distributions<sup>2</sup>  $u$  supported on  $X_0$  such that  $(\rho_j u) \circ \kappa_j^{-1}$  belongs to  $H_p^{t, t_-}$  for all  $j$ , endowed with the norm*

$$(5) \quad \|u\|_{\mathcal{H}_p^{t, t_-}} = \sum \|(\rho_j u) \circ \kappa_j^{-1}\|_{H_p^{t, t_-}}.$$

Changing the charts and the partition of unity gives an equivalent norm on the same space of distributions by Lemma 19 and Remark 23. To fix ideas, we shall view the charts and partition of unity as fixed.

**Remark 8.** Note that [4] considers a slightly different space, where the stable and unstable direction and the signs of  $t$  and  $t + t_-$  are exchanged. This choice is completely innocent, we also get the same results for the space of [4] (for maps with smooth unstable distribution) in Theorem 12.

Our main result follows (recall the notation (3)–(4)):

**Theorem 9** (Spectral theorem for smooth stable distributions). *Let  $\alpha \in (0, 1]$ . Let  $T$  be a piecewise  $C^{1+\alpha}$  hyperbolic map with smooth stable distribution, satisfying the weak transversality condition. Let  $1 < p < \infty$  and let  $t, t_-$  be so that  $1/p - 1 < t_- < 0 < t < 1/p$ ,  $t + t_- < 0$  and  $t + |t_-| < \alpha$ .*

*Let  $g : X_0 \rightarrow \mathbb{C}$  be a function such that the restriction of  $g$  to any  $O_i$  admits a  $C^\alpha$  extension to  $\overline{O_i}$ . Define an operator  $\mathcal{L}_g$  acting on bounded functions by  $(\mathcal{L}_g u)(x) =$*

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<sup>2</sup>On a manifold, the space of *generalized functions* supported in  $X_0$ , i.e., elements in the dual of the space of smooth densities, and the space of *generalized densities* supported in  $X_0$ , i.e., elements in the dual of the space of smooth functions, are isomorphic if  $X_0$  is compact: taking Lebesgue any smooth riemannian measure then  $f \mapsto f \, d\text{Leb}$  gives an isomorphism. “Distributions supported in  $X_0$ ” (not to be confused with the integrable distributions of subspaces in Definition 1) refers in this paper to generalized functions (this avoids jacobians in the change of variables).

$\sum_{Ty=x} g(y)u(y)$ . Then  $\mathcal{L}_g$  acts continuously on  $\mathcal{H}_p^{t,t-}$ . Moreover, its essential spectral radius is at most

$$(6) \quad \lim_{n \rightarrow \infty} (D_n^b)^{1/(pn)} \cdot (D_n^e)^{(1/n)(1-1/p)} \cdot \left\| |g^{(n)}| \det DT^n |^{1/p} \max(\lambda_{u,n}^{-t}, \lambda_{s,n}^{-(t+t-)}) \right\|_{L_\infty}^{1/n},$$

where  $g^{(n)} = \prod_{j=0}^{n-1} g \circ T^j$ .

When we say that  $\mathcal{L}_g$  acts continuously on  $\mathcal{H}_p^{t,t-}$ , we should be more precise. We mean that, for any  $u \in \mathcal{H}_p^{t,t-} \cap L_\infty(\text{Leb})$ , then  $\mathcal{L}_g u$ , which is defined as a bounded function, still belongs to  $\mathcal{H}_p^{t,t-}$  and satisfies  $\|\mathcal{L}_g u\|_{\mathcal{H}_p^{t,t-}} \leq C \|u\|_{\mathcal{H}_p^{t,t-}}$ . Since the set of bounded functions is dense in  $\mathcal{H}_p^{t,t-}$  (by Lemma 15), the operator  $\mathcal{L}_g$  can therefore be extended to a continuous operator on  $\mathcal{H}_p^{t,t-}$ .

Note that the limit in (6) exists by submultiplicativity. Of course, we can bound  $\lambda_{s,n}$  and  $\lambda_{u,n}^{-1}$  by  $\lambda^n$ , where  $\lambda < 1$  is the weakest rate of contraction/expansion of  $T$ . In some cases, it will be important to use the more precise expression given above (see e.g. Example 3 below).

The restriction  $1/p - 1 < t_- < 0 < t < 1/p$  is exactly designed so that the space  $\mathcal{H}_p^{t,t-}$  is stable under multiplication by characteristic functions of nice sets, see Lemma 20. While this feature will be used in an essential way in the proof, it also implies (see Remark 32 in Appendix B) that Dirac measures (or more generally measures supported on nice hypersurfaces) do not belong to the space  $\mathcal{H}_p^{t,t-}$ .

**1.3. Physical measures.** The physical measures of  $T$  are by definition the probability measures  $\mu$  such that there exists a set  $A$  of positive Lebesgue measure such that, for all  $x \in A$ ,  $1/n \sum_{k=0}^{n-1} \delta_{T^k x}$  converges weakly to  $\mu$ .

The physical measures of  $T$  are often studied through the transfer operator  $\mathcal{L}_{1/|\det DT|}$ . (Note that the dual of  $\mathcal{L}_{1/|\det DT|}$  preserves Lebesgue measure.) Theorem 9 becomes in this setting:

**Corollary 10.** *Under the assumptions of Theorem 9, assume that*

$$(7) \quad \lim_{n \rightarrow \infty} (D_n^b)^{1/(np)} \cdot (D_n^e)^{(1/n)(1-1/p)} \cdot \left\| \max(\lambda_{u,n}^{-t}, \lambda_{s,n}^{-(t+t-)}) |\det DT^n|^{1/p-1} \right\|_{L_\infty}^{1/n} < 1.$$

*Then the essential spectral radius of  $\mathcal{L}_{1/|\det DT|}$  acting on  $\mathcal{H}_p^{t,t-}$  is  $< 1$ .*

Together with classical arguments, this implies the following:

**Theorem 11.** *Under the assumptions of Theorem 9, if (7) holds, then  $T$  has a finite number of physical measures, which are invariant and ergodic, whose basins cover Lebesgue almost all  $X_0$ . Moreover, if  $\mu$  is one of these measures, there exist an integer  $k$  and a decomposition  $\mu = \mu_1 + \dots + \mu_k$  such that  $T$  sends  $\mu_j$  to  $\mu_{j+1}$  for  $j \in \mathbb{Z}/k\mathbb{Z}$ , and the probability measures  $k\mu_j$  are exponentially mixing for  $T^k$  and Hölder test functions.*

The deduction of this theorem from Corollary 10 is essentially folklore, but the proofs of similar results in the literature (e.g. in [7, 16]) rely on some properties of stable manifolds that are not established in our setting. We prove in Appendix B a general theorem (Theorem 30) that guarantees the existence of finitely many physical measures whenever the transfer operator has a spectral gap on a space of distributions, and show (Lemma 31) that this general theorem holds in our setting.

The interest of this argument is that it also applies to non hyperbolic situations, such as (perturbations of the operators in) [30].

The results in this subsection answer the question in [4, Remark 1.1], in a much more general framework.

**1.4. Hyperbolic maps with smooth unstable distribution.** Just like in Definition 1, we can define piecewise  $C^{1+\alpha}$  hyperbolic maps with smooth unstable distribution. Our results also apply to such maps (by the same techniques used to prove Theorem 9), but on the space of distributions  $\tilde{\mathcal{H}}^{t_+, t}$  whose norm is given in charts by  $\|\mathcal{F}^{-1}((1 + |\xi|^2)^{t_+/2}(1 + |\xi|^2 + |\eta|^2)^{t/2}\mathcal{F}u)\|_{L^p}$ . More precisely:

**Theorem 12** (Spectral theorem for smooth unstable distributions). *Let  $\alpha \in (0, 1]$ . Let  $T$  be a piecewise  $C^{1+\alpha}$  hyperbolic map with smooth unstable distribution, satisfying the weak transversality condition with  $E^s$  replaced by  $E^u$ . Let  $1 < p < \infty$  and let  $t_+, t$  be so that  $1/p - 1 < t < 0 < t_+ < 1/p$ ,  $t + t_+ > 0$  and  $|t| + t_+ < \alpha$ .*

*Let  $g : X_0 \rightarrow \mathbb{C}$  be a function such that the restriction of  $g$  to any  $O_i$  admits a  $C^\alpha$  extension to  $\overline{O}_i$ . Define an operator  $\mathcal{L}_g$  acting on bounded functions by  $(\mathcal{L}_g u)(x) = \sum_{Ty=x} g(y)u(y)$ . Then  $\mathcal{L}_g$  acts continuously on  $\tilde{\mathcal{H}}_p^{t_+, t}$ . Moreover, its essential spectral radius is at most*

$$\lim_{n \rightarrow \infty} (D_n^b)^{1/(pn)} \cdot (D_n^e)^{(1/n)(1-1/p)} \cdot \left\| g^{(n)} | \det DT^n |^{1/p} \max(\lambda_{u,n}^{-(t+t_+)}, \lambda_{s,n}^{-t}) \right\|_{L^\infty}^{1/n}.$$

*In particular, if*

$$\lim_{n \rightarrow \infty} (D_n^b)^{1/(np)} \cdot (D_n^e)^{(1/n)(1-1/p)} \cdot \left\| \max(\lambda_{u,n}^{-(t+t_+)}, \lambda_{s,n}^{-t}) | \det DT^n |^{1/p-1} \right\|_{L^\infty}^{1/n} < 1,$$

*then the spectral radius of  $\mathcal{L}_{1/|\det DT|}$  acting on  $\tilde{\mathcal{H}}_p^{t_+, t}$  is  $< 1$ . This implies that  $T$  has a finite number of ergodic physical measures whose basins cover Lebesgue almost all  $X_0$ . Moreover, if  $\mu$  is one of these measures, there exist an integer  $k$  and a decomposition  $\mu = \mu_1 + \dots + \mu_k$  such that  $T$  sends  $\mu_j$  to  $\mu_{j+1}$  for  $j \in \mathbb{Z}/k\mathbb{Z}$ , and the probability measures  $k\mu_j$  are exponentially mixing for  $T^k$  and Hölder test functions.*

We will not give further details on the proof of this theorem, since it follows from the techniques used in the proof of Theorem 9.

Finally, similar results hold for maps that have at the same time smooth stable and unstable distributions (and satisfy the weak transversality condition in both directions), as follows. Let  $\tilde{\mathcal{H}}_p^{t_+, t_-}$  be the space of distributions whose norm is given in charts by  $\|\mathcal{F}^{-1}((1 + |\xi|^2)^{t_+/2}(1 + |\eta|^2)^{t_-/2}\mathcal{F}u)\|_{L^p}$ .

**Theorem 13** (Spectral theorem when both distributions are smooth). *Let  $T$  be a piecewise  $C^{1+\alpha}$  hyperbolic map with smooth stable and unstable distribution, satisfying the weak transversality conditions for  $E^s$  and  $E^u$  for  $\alpha \in (0, 1]$ . Let  $1 < p < \infty$  and let  $t_+, t_-$  be so that  $1/p - 1 < t_- < 0 < t_+ < 1/p$ , and  $|t_-| + t_+ < \alpha$ .*

*Let  $g : X_0 \rightarrow \mathbb{C}$  be a function such that the restriction of  $g$  to any  $O_i$  admits a  $C^\alpha$  extension to  $\overline{O}_i$ . Define an operator  $\mathcal{L}_g$  acting on bounded functions by  $(\mathcal{L}_g u)(x) = \sum_{Ty=x} g(y)u(y)$ . Then  $\mathcal{L}_g$  acts continuously on  $\tilde{\mathcal{H}}_p^{t_+, t_-}$ . Moreover, its essential spectral radius is at most*

$$(8) \quad \lim_{n \rightarrow \infty} (D_n^b)^{1/(pn)} \cdot (D_n^e)^{(1/n)(1-1/p)} \cdot \left\| g^{(n)} | \det DT^n |^{1/p} \max(\lambda_{u,n}^{-t_+}, \lambda_{s,n}^{-t_-}) \right\|_{L^\infty}^{1/n}.$$

The results on physical measures follow analogously. It should be noted that the results of Theorem 13 are stronger than Theorems 9 and 12, since the exponents  $t_+$  and  $t_-$  appear independently in the estimate (8).

Once again, this theorem follows from the techniques we will use to prove Theorem 9.

## 2. EXAMPLES

Let us look at some applications of our results to  $\mathcal{L}_{1/|\det DT|}$ .

### 2.1. General examples.

**Example 1.** On  $[-1, 1] \times \{0, 1\}$ , let  $T(x, j) = (x/2, j)$  if  $x \neq 0$ , and  $T(0, j) = (0, 1 - j)$ . This fits in our framework. Since the complexities  $D_n^b$  and  $D_n^e$  are always equal to 2, Theorem 9 gives the following bound for the essential spectral radius of  $\mathcal{L}_{1/|\det DT|}$  on the classical Sobolev space  $\mathcal{H}_p^{t_-}$ :

$$(9) \quad \lim_{n \rightarrow \infty} \left\| \lambda_{s,n}^{-t_-} |\det DT^n|^{1/p-1} \right\|_{L^\infty}^{1/n} = 2^{t_-+1-1/p}.$$

Since  $t_- < 0$  is restricted by  $t_- > 1/p - 1$ , this bound is  $> 1$ , hence useless. This is not surprising since the physical measure, the Dirac mass at 0, does not belong to  $\mathcal{H}_p^{t_-}$  if  $1/p - 1 < t_- < 0$  (see Remark 32).

This was to be expected since the conclusion of Theorem 11 is false: the map  $T$  has two physical measures, the Dirac masses at  $(0, 0)$  and  $(0, 1)$ , but these measures are not invariant!

It is nevertheless interesting to see where precisely our arguments fail. Let  $\tilde{T}(x, j) = (x/2, j)$ , then the transfer operators associated to  $T$  and  $\tilde{T}$  acting on distributions coincide on  $C^\infty$  functions (since the difference at 0 is not seen by the integration against smooth functions). Since  $\tilde{T}$  is continuous, there is no truncation term in its transfer operator, hence the results of Theorem 9 hold for the full range  $t_- < 0$ , without the restriction  $t_- > 1/p - 1$  (with the same proof). In particular, for  $t_- = -1$  and  $p = 2$ , we get a bound  $1/\sqrt{2}$  for the essential spectral radius of  $\mathcal{L}_{1/|\det DT|}(T) = \mathcal{L}_{1/|\det D\tilde{T}|}(\tilde{T})$  acting on  $\mathcal{H}_2^{-1}$ , and Corollary 10 holds. The problem comes up in the deduction of the properties of physical measures from this bound on the essential spectral radius of  $\mathcal{L}_{1/|\det DT|}$ : we need to check that the physical measures do not give weight to the discontinuities of the map, to apply Theorem 30. This is ensured by Lemma 31 when  $t_- > 1/p - 1$ , but does not hold for  $t_- = -1$  and  $p = 2$ .

**Example 2.** Assume that  $d_s = 0$ , i.e.,  $T$  is piecewise expanding. In this case, we can take  $\lambda_s = 0$ , and the value of  $t_-$  is irrelevant (in fact, the space  $\mathcal{H}_p^{t, t_-}$  does not depend on  $t_-$ , and is the classical Sobolev space  $\mathcal{H}_p^t$ ).

**Proposition.** *If  $T$  is piecewise  $C^2$ , if  $d_s = 0$  and  $\lim \|\lambda_{u,n}^{-1}\|_{L^\infty}^{1/n} \cdot \lim (D_n^b)^{1/n} < 1$ , then there exist  $0 < t < 1/p < 1$  such that the spectral radius of  $\mathcal{L}_{1/|\det DT|}$  acting on  $\mathcal{H}_p^t$  is  $< 1$ . In particular, Theorem 11 applies.*

*Proof.* When  $\epsilon$  tends to 0, the bound on the essential spectral radius of  $\mathcal{L}_{1/|\det DT|}$  acting on  $\mathcal{H}_{(1-\epsilon)^{-1}}^{1-2\epsilon}$ , given by Corollary 10, converges at most to  $\lim_{n \rightarrow \infty} \|\lambda_{u,n}^{-1}\|_{L^\infty}^{1/n} \cdot \lim_{n \rightarrow \infty} (D_n^b)^{1/n}$ . Hence, it is  $< 1$  for small enough  $\epsilon$ .  $\square$

In the proof of the above proposition, we use parameters  $t$  and  $p$  very close to 1, but we are “morally” working with  $\mathcal{H}_1^1$ . This is not surprising since this space is essentially a space of functions with one derivative in  $L_1$ , i.e., a space of functions of bounded variation. It is well known that functions of bounded variation are useful to study piecewise expanding maps, see [15]. This proposition is analogous to results proved in [23, 15] for different Banach spaces.

**Example 3.** When  $\det DT = 1$  and  $D_n^e, D_n^b$  grow subexponentially fast, then it is clear from Corollary 10 that the essential spectral radius of  $\mathcal{L}_{1/|\det DT|}$  is  $< 1$  on any space  $\mathcal{H}_p^{t, t_-}$  (as soon as  $t > 0$  and  $t + t_- < 0$ ). In some situations, it is possible to weaken (or even remove) the assumption that  $\det DT = 1$ . We get more precise results using Theorem 12, i.e., assuming that the unstable direction is smooth.

**Proposition.** *Let  $T$  be a piecewise  $C^2$  hyperbolic map with smooth unstable distribution satisfying the weak transversality condition, and such that  $D_n^e$  and  $D_n^b$  grow subexponentially. Assume that there exist  $N > 0$  and  $\gamma < 1$  such that  $\lambda_{s, N} \leq \gamma |\det DT^N|$ . Then there exist  $p \in (1, \infty)$  and  $1/p - 1 < t < 0 < t_+ < 1/p$  such that the essential spectral radius of  $\mathcal{L}_{1/|\det DT|}$  acting on  $\tilde{\mathcal{H}}_p^{t_+, t}$  is  $< 1$ . In particular,  $T$  has finitely many physical measures whose basins contain Lebesgue almost every point.*

The assumption  $\lambda_{s, N} \leq \gamma |\det DT^N|$  is a kind of pinching condition. It is satisfied whenever  $d_s = 1$  and  $d_u > 0$ .

*Proof.* We will take  $p$  very close to 1,  $t = 1/p - 1 + \epsilon$  and  $t_+ = 1/p - \epsilon$  for  $\epsilon > 0$  very small.

We have

$$(10) \quad |\det DT^N|^{1/p-1} \lambda_{s, N}^{-t} \leq (\gamma^{-1} \lambda_{s, N})^{1/p-1} \lambda_{s, N}^{-(1/p-1)-\epsilon} = \gamma^{1-1/p} \lambda_{s, N}^{-\epsilon}.$$

Since  $\gamma < 1$ , this quantity is  $< 1$  if  $\epsilon$  is small enough (in terms of  $p$ ).

Moreover,

$$(11) \quad |\det DT^N|^{1/p-1} \lambda_{u, N}^{-(t_++t)} = |\det DT^N|^{1/p-1} \lambda_{u, N}^{1-2/p}.$$

When  $p \rightarrow 1$ , this quantity converges to  $\lambda_{u, N}^{-1} < 1$ .

Hence, it is possible to choose  $p$  and  $\epsilon$  such that

$$(12) \quad \left\| |\det DT^N|^{1/p-1} \max(\lambda_{s, N}^{-t}, \lambda_{u, N}^{-(t_++t)}) \right\|_{L_\infty} < 1.$$

This concludes the proof.  $\square$

**2.2. Piecewise linear maps.** In this paragraph, we describe an explicit class of maps for which the assumptions of the previous theorems are satisfied. Let  $A$  be a  $d \times d$  matrix with no eigenvalue of modulus 1. It acts on  $\mathbb{R}^d$  in a hyperbolic way, with best expansion/contraction constants  $\lambda_u > 1$  and  $\lambda_s < 1$ . Let  $X_0$  be a polyhedral region of  $\mathbb{R}^d$ , and define a map  $T$  on  $X_0$  by cutting it into finitely many polyhedral subregions  $O_1, \dots, O_N$ , applying  $A$  to each of them, and then mapping  $AO_1, \dots, AO_N$  back into  $X_0$  by translations.

Let  $J(n)$  be the covering multiplicity of  $T^n$ , i.e., the maximal number of preimages of a point under  $T^n$ . It is submultiplicative, hence the limit  $J = \lim_{n \rightarrow \infty} J(n)^{1/n}$  exists.

**Proposition 14.** *The map  $T$  is a piecewise hyperbolic map with smooth stable and unstable distributions (given by the eigenspaces of  $A$  corresponding to eigenvalues of modulus  $< 1$ , resp.  $> 1$ ). It satisfies the weak transversality conditions for both stable and unstable distributions. Moreover, if  $J\lambda_s < |\det A|$ , there exist  $1 < p < \infty$ , and  $t_+$ ,  $t_-$  so that  $1/p - 1 < t_- < 0 < t_+ < 1/p$  and such that the essential spectral radius of  $\mathcal{L}_{1/|\det|DT|}$  acting on  $\tilde{\mathcal{H}}_p^{t_+, t_-}$  is  $< 1$ . Therefore,  $T$  satisfies the conclusions of Theorem 11.*

As an example of such a map, one can take  $A = \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix}$ . Cutting the torus  $\mathbb{T}^2$  into finitely many squares, applying  $A$  to each of these squares, and then permuting the images of the squares, one obtains a bijection of the torus (for which  $J = 1$ ). Hence, Proposition 14 applies. The novelty with respect to previous works such as [32, 13, 16] is that the sides of the squares can be taken parallel to the stable or unstable directions.

*Proof of Proposition 14.* The weak transversality conditions are direct consequences of the definitions.

Let  $K$  be the total number of the sides of the polyhedra  $O_i$ . Around any point  $x$ , the boundaries of the sets  $O_{(i_0, \dots, i_{n-1})}$  are preimages of these sides by one of the maps  $A, \dots, A^{n-1}$ , which gives at most  $nK$  possible directions. Hence, the claim p. 105 in [8] gives  $D_n^b \leq 2(nK)^d$ . This quantity grows subexponentially. In the same way,  $D_n^e \leq 2J(n)(nK)^d$ .

By Theorem 13, the essential spectral radius of  $\mathcal{L}_{1/|\det A|}$  acting on  $\tilde{\mathcal{H}}_p^{t_+, t_-}$  (for suitable values of  $p, t_+, t_-$ ) is bounded by  $J^{1-1/p} |\det A|^{1/p-1} \max(\lambda_u^{-t_+}, \lambda_s^{-t_-})$ . Let us take  $t_+ = 1/p - \epsilon$ ,  $t_- = 1/p - 1 + \epsilon$  and  $p$  close to 1. Then  $1/p - 1 < t_- < 0 < t_+ < 1/p$ , hence Theorem 13 applies and yields the following bound for the essential spectral radius:

$$(13) \quad |\det A|^{1/p-1} J^{1-1/p} \max(\lambda_u^{-1/p+\epsilon}, \lambda_s^{1-1/p-\epsilon}).$$

If  $p$  is close to 1 and  $\epsilon$  is small enough, this quantity is  $< 1$  under the assumptions of the proposition. (Note that if  $\det A = J = 1$ , choosing  $p = 1/2$  and  $t_+ = 1/2 - \epsilon$ ,  $t_- = -1/2 + \epsilon$  gives better bounds.)  $\square$

The standard conservative (piecewise affine) baker's map on the unit square is given by  $T(x, y) = (2x, y/2)$  for  $0 \leq x < 1/2$  and  $T(x, y) = (2x - 1, (y + 1)/2)$  for  $1/2 \leq x \leq 1$ . It fits in the model of this subsection, for a diagonal matrix  $A$  with eigenvalues 2 and  $1/2$ . The baker has an obvious Markov partition with two pieces, and can thus be analyzed by a (Lipschitz) symbolic model, which gives an essential decorrelation rate of  $2^{-1/2}$  for Lipschitz observables. (The physical measure is just Lebesgue measure.) The proof of the previous proposition gives a bound  $2^{-1/2+\epsilon}$  for the essential spectral radius of  $\mathcal{L}_{1/|\det A|}$  on  $\tilde{\mathcal{H}}_2^{1/2-\epsilon, -1/2+\epsilon}$  for arbitrarily small  $\epsilon > 0$  (here  $J = 1$ ,  $\det A = 1$ ,  $\lambda_u = 2$  and  $\lambda_s = 1/2$ ). For a dissipative baker  $T(x, y) = (2x, y/3)$  for  $0 \leq x < 1/2$  and  $T(x, y) = (2x - 1, (y + 2)/3)$  for  $1/2 \leq x \leq 1$  ( $\lambda_u = 2$  and  $\lambda_s = 1/3$ ,  $\det A = 2/3$  and  $J = 1$ ), the proof of the above proposition gives a bound  $2^{-1+\epsilon+(\log 3/\log 6)}$  for the essential spectral radius on  $\tilde{\mathcal{H}}_p^{1/p-\epsilon, 1/p-1+\epsilon}$  for  $p = \log 6/\log 3$ . (Note that the dimension of the attractor is strictly between 1 and 2 in this case.) The above two examples are piecewise affine hyperbolic maps with a finite Markov partition. But the following variant, that we shall call a

“sloppy baker,” does not have a finite Markov partition: let  $(a, b)$  be a point in the interior of the unit square and put  $T(x, y) = (2x + a, y/2 + b) \bmod 1$  for  $0 \leq x < 1/2$  and  $T(x, y) = (2x - 1 + a, (y + 1)/2 + b) \bmod 1$  for  $0 \leq x < 1$ . For almost all  $(a, b)$ , the sloppy baker does not have a finite Markov partition. However, our estimate gives the same bound  $2^{-1/2+\epsilon}$  for the essential spectral radius on  $\tilde{\mathcal{H}}_2^{1/2-\epsilon, -1/2+\epsilon}$ . Similarly, one may consider a dissipative sloppy baker, and we recover the same estimates.

### 3. TOOLS OF FUNCTIONAL ANALYSIS

In this section, we recall some classical notions of functional analysis (interpolation theory and properties of Triebel spaces), that will be useful in the next sections to study the space  $H_p^{t, t-}$  and to prove our main result.

**3.1. Complex interpolation.** We first recall some notations and definitions from the classical complex interpolation theory of Lions, Calderón and Krejn (see e.g. [26]). A pair  $(\mathcal{B}_0, \mathcal{B}_1)$  of Banach spaces is called an interpolation couple if they are both continuously embedded in a linear Hausdorff space  $\mathcal{B}$ . For any interpolation couple  $(\mathcal{B}_0, \mathcal{B}_1)$ , we let  $L(\mathcal{B}_0, \mathcal{B}_1)$  be the space of all linear operators  $\mathcal{L}$  mapping  $\mathcal{B}_0 + \mathcal{B}_1$  to itself so that  $\mathcal{L}|_{\mathcal{B}_j}$  is continuous from  $\mathcal{B}_j$  to itself for  $j = 0, 1$ . For an interpolation couple  $(\mathcal{B}_0, \mathcal{B}_1)$  and  $0 < \theta < 1$ , we denote by  $[\mathcal{B}_0, \mathcal{B}_1]_\theta$  the complex interpolation space of parameter  $\theta$ . We recall the definition: set  $S = \{z \in \mathbb{C} \mid 0 < \Re z < 1\}$ , and introduce the normed vector space

$$\begin{aligned} F(\mathcal{B}_0, \mathcal{B}_1) = \{ & f : S \rightarrow \mathcal{B}_0 + \mathcal{B}_1, \text{ analytic, extending continuously to } \overline{S}, \\ & \text{with } \sup_{z \in \overline{S}} \|f(z)\|_{\mathcal{B}_0 + \mathcal{B}_1} < \infty, \text{ and} \\ & t \mapsto f(j + it) \text{ is continuous from } (-\infty, \infty) \text{ to } \mathcal{B}_j, j = 0, 1, \\ & \text{and } \|f\|_{F(\mathcal{B}_0, \mathcal{B}_1)} := \max_{j=0,1} (\sup_t \|f(j + it)\|_{\mathcal{B}_j}) < \infty \}. \end{aligned}$$

Then the complex interpolation space is defined for  $\theta \in (0, 1)$  by

$$(14) \quad [\mathcal{B}_0, \mathcal{B}_1]_\theta := \{u \in \mathcal{B}_0 + \mathcal{B}_1 \mid \exists f \in F(\mathcal{B}_0, \mathcal{B}_1) \text{ with } f(\theta) = u\},$$

normed by

$$(15) \quad \|u\|_{[\mathcal{B}_0, \mathcal{B}_1]_\theta} = \inf_{f(\theta)=u} \|f\|_{F(\mathcal{B}_0, \mathcal{B}_1)}.$$

It is well-known (see e.g. [26, §1.9]) that  $(\mathcal{B}_0, \mathcal{B}_1) \mapsto [\mathcal{B}_0, \mathcal{B}_1]_\theta$  is an exact interpolation functor of type  $\theta$ , in the following sense: for any interpolation couple  $(\mathcal{B}_0, \mathcal{B}_1)$  and every  $\mathcal{L} \in L(\mathcal{B}_0, \mathcal{B}_1)$  we have

$$(16) \quad \|\mathcal{L}\|_{[\mathcal{B}_0, \mathcal{B}_1]_\theta \rightarrow [\mathcal{B}_0, \mathcal{B}_1]_\theta} \leq \|\mathcal{L}\|_{\mathcal{B}_0 \rightarrow \mathcal{B}_0}^{1-\theta} \|\mathcal{L}\|_{\mathcal{B}_1 \rightarrow \mathcal{B}_1}^\theta \quad \forall \theta \in (0, 1).$$

The above bound will be used several times throughout this work.

**3.2. A class of Sobolev-like spaces containing the local spaces  $H_p^{t, t-}$ .** Let  $S$  be the Schwartz space of  $C^\infty$  rapidly decaying functions. Its dual  $S'$  is the space of tempered distributions.

Let  $M$  be the set of functions  $a$  from  $\mathbb{R}^d$  to  $\mathbb{R}_+$  such that there exists  $C > 0$  such that, for all multi-indices  $\gamma = (\gamma_1, \dots, \gamma_d)$  with  $\gamma_j \in \{0, 1\}$ , and all  $\zeta \in \mathbb{R}^d$ ,

$$(17) \quad \left| \prod_{j=1}^d (1 + \zeta_j^2)^{\gamma_j/2} D^\gamma a(\zeta) \right| \leq Ca(\zeta).$$

For  $a \in M$  and  $p \in (1, \infty)$ , let us define a space  $H_p^a$  as the space of all tempered distributions  $u$  such that  $\mathcal{F}^{-1}(a\mathcal{F}u)$  belongs to  $L_p$ , with its canonical norm

$$(18) \quad \|u\|_{H_p^a} = \|\mathcal{F}^{-1}(a\mathcal{F}u)\|_{L_p(\mathbb{R}^d)}.$$

These spaces were introduced and studied by Triebel in [25], in a slightly more general setting involving another parameter  $q$  (under a different form [25, Def. 2.3/4], but Theorem 5.1/2 and Remark 5.1 there shows that it is equivalent to the previous description for  $q = 2$ ).

Among other things, Triebel proved the following results concerning these spaces:

**Lemma 15.** *For any  $a \in M$  and  $1 < p < \infty$ , the space  $S$  is contained in  $H_p^a$ , and dense.*

*Proof.* This is proved in Theorem 3.2/2 and Remark 3.2/2 in [25].  $\square$

For  $t, t_- \in \mathbb{R}$ , the function  $a_{t,t_-}(\xi, \eta) = (1 + |\xi|^2 + |\eta|^2)^{t/2} (1 + |\eta|^2)^{t_-/2}$  belongs to  $M$ . Then  $H_p^{t,t_-}$  from Definition 6 is just  $H_p^{a_{t,t_-}}$ , and the previous lemma says that  $S$  is dense in  $H_p^{t,t_-}$ .

**Proposition 16** (Interpolation). *For any  $a_0, a_1 \in M$ ,  $p_0, p_1 \in (1, \infty)$  and  $\theta \in (0, 1)$ , the interpolation space  $[H_{p_0}^{a_0}, H_{p_1}^{a_1}]_\theta$  is equal to  $H_p^a$  for  $a = a_0^{1-\theta} a_1^\theta$  and  $1/p = (1-\theta)/p_0 + \theta/p_1$ .*

*Proof.* This is [25, Theorem 4.2/2].  $\square$

We will also use the following straightforward lemma. (Note that if  $a \in M$  then  $1/a \in M$ , see e.g. [25, Lemma 2.1/1]).

**Lemma 17** (Duality). *For any  $a \in M$  and  $1 < p < \infty$ , the dual of the space  $H_p^a$  is  $H_{p'}^{1/a}$  for  $1/p + 1/p' = 1$ .*

**3.3. Multiplier theorems.** In order to understand the spaces  $H_p^a$ , an essential tool is provided by Fourier multiplier theorems. The following Marcinkiewicz multiplier theorem (see e.g. [25, Theorem 2.4/2]) will be sufficient for our purposes.

**Theorem 18.** *Let  $b \in C^d(\mathbb{R}^d)$  satisfy  $|\zeta^\gamma D^\gamma b(\zeta)| \leq B$  for all multi-indices  $\gamma = (\gamma_1, \dots, \gamma_d)$  with  $\gamma_j \in \{0, 1\}$ , and all  $\zeta \in \mathbb{R}^d$ . Then, for all  $p \in (1, \infty)$ , there exists a constant  $C(p, d)$  such that, for any  $u \in L_p$ ,*

$$(19) \quad \|\mathcal{F}^{-1}(b\mathcal{F}u)\|_{L_p} \leq CB \|u\|_{L_p}.$$

#### 4. TOWARDS LASOTA-YORKE BOUNDS ON THE LOCAL SPACE $H_p^{t,t_-}$

Aiming at the proof of Theorem 9 on transfer operators, we describe in Subsections 4.1 and 4.2 how the local spaces  $H_p^{t,t_-}$ , which are the building blocks of our spaces of distributions, behave under multiplication by a smooth function or by the characteristic function of a nice set, as well as under composition with a smooth map preserving the stable leaves. Then, in Subsection 4.3, we state and prove a

localization principle on  $H_p^{t,t_-}$  that we were not able to find in the literature and which plays a key part in the “zooming” procedure in the proof of Theorem 9. Note for further use that since  $X_0$  is compact, [4, Lemma 2.2] (e.g.) gives that the inclusion  $\mathcal{H}_p^{t,t_-} \subset \mathcal{H}_p^{t',t'_-}$  for  $t' \leq t$  and  $t'_- \leq t_-$  is compact if  $t' < t$ .

To study  $H_p^{t,t_-}$ , we will mainly study  $H_p^{t,0}$  and  $H_p^{0,t_-}$  and use interpolation (via Proposition 16). It is therefore useful to recall some classical properties of these spaces.

When  $t \geq 0$ , the space  $H_p^t$  is the classical Sobolev space. By [24, Theorem I.4.1], it satisfies a Fubini property: if  $u$  is a function on  $\mathbb{R}^d$ , define a function  $u_j$  on  $\mathbb{R}^{d-1}$  as follows:  $u_j(x_1, \dots, x_{j-1}, x_{j+1}, \dots, x_d)$  is the  $H_p^t(\mathbb{R})$ -norm of the restriction of  $u$  to the line  $\{(x_1, \dots, x_{j-1}, x, x_{j+1}, \dots, x_d) \mid x \in \mathbb{R}\}$ . Then  $u$  belongs to  $H_p^t(\mathbb{R}^d)$  if and only if each  $u_j$  belongs to  $L_p(\mathbb{R}^{d-1})$ , and the norms  $\|u\|_{H_p^t}$  and  $\sum_{j=1}^d \|u_j\|_{L_p}$  are equivalent. (This is true for any set of coordinates, but for simplicity we shall use a fixed system of coordinates.) This makes it often possible to study only the one-dimensional situation, and extend it readily to  $d$  dimensions.

For  $t_- > 0$ , the space  $H_p^{0,t_-}$  also has a Fubini-type property: the norm  $\|u\|_{H_p^{0,t_-}}$  is equivalent to  $\sum_{j=d_u+1}^d \|u_j\|_{L_p}$  where  $u_j$  is the  $H_p^{t_-}(\mathbb{R})$ -norm of a restriction of  $u$  as above (the proof of [24, Theorem I.4.1] directly applies, we may take any coordinates on  $\mathbb{R}^d$  which preserve the stable leaves of the original coordinate system used to define  $H_p^{0,t_-}$ , for simplicity we shall fix this original coordinate system). In particular, the study of  $H_p^{0,t_-}$  reduces to the study of the usual Sobolev space in one dimension.

Finally, for  $t_- \in \mathbb{R}$ , the space  $H_p^{0,t_-}$  also has a slightly different Fubini-type property. Let  $u$  be a function on  $\mathbb{R}^d$ , and define a function  $v$  on  $\mathbb{R}^{d_u}$  as follows:  $v(x)$  is the  $H_p^{t_-}(\mathbb{R}^{d_s})$ -norm of the restriction of  $u$  to  $\{x\} \times \mathbb{R}^{d_s}$ . Then  $\|u\|_{H_p^{0,t_-}(\mathbb{R}^d)} = \|v\|_{L_p(\mathbb{R}^{d_u})}$ : this follows from the fact that the function  $(1+|\eta|^2)^{t_-/2}$  does not depend on the variable  $\xi$ , which makes it possible to integrate away the variable  $x$  using the Fourier inversion formula (see [24, p. 1045] for details).

We will refer to these properties respectively as the one-dimensional and the  $d_s$ -dimensional Fubini properties of  $H_p^{0,t_-}$ .

#### 4.1. Multiplication by functions.

**Lemma 19.** *Let  $t > 0$ ,  $t_- < 0$  and  $\alpha > 0$  be real numbers with  $t + |t_-| < \alpha$ . For any  $p \in (1, \infty)$ , there exists a constant  $C_\#$  such that for any  $C^\alpha$  function  $g : \mathbb{R}^d \rightarrow \mathbb{C}$ , for any distribution  $u \in H_p^{t,t_-}$ , the distribution  $gu$  also belongs to  $H_p^{t,t_-}$  and satisfies*

$$\|g \cdot u\|_{H_p^{t,t_-}} \leq C_\# \|g\|_{C^\alpha} \|u\|_{H_p^{t,t_-}} .$$

The assertion  $gu \in H_p^{t,t_-}$  should be interpreted as explained after Theorem 9.

*Proof.* Let  $t^0 = t + |t_-|$ ,  $t_-^0 = -t^0$  and  $\theta = t/t^0$ , so that  $(t, t_-) = (\theta t^0, (1-\theta)t_-^0)$  and  $\max(t^0, |t_-^0|) < \alpha$ . We will write  $H_p^{t,t_-}$  as an interpolation space with parameter  $\theta$  between  $H_p^{t^0}$  and  $H_p^{0,t_-^0}$ , thereby reducing the proof to the study of  $H_p^{t^0}$  and  $H_p^{0,t_-^0}$ .

First, since  $H_p^{t^0}$  is the classical Sobolev space, [27, Corollary 4.2.2] shows that

$$(20) \quad \|gu\|_{H_p^{t^0}} \leq C_\# \|g\|_{C^\alpha} \|u\|_{H_p^{t^0}} ,$$

where  $C_{\#}$  depends only on  $t^0$  and  $\alpha$ , whenever  $|t^0| < \alpha$ .

Together with the  $d_s$ -dimensional Fubini-type property of  $H_p^{0,t_-^0}$ , this readily implies

$$(21) \quad \|gu\|_{H_p^{0,t_-^0}} \leq C_{\#} \|g\|_{C^\alpha} \|u\|_{H_p^{0,t_-^0}}$$

whenever  $|t_-^0| < \alpha$ .

Interpolating between (20) and (21) via Proposition 16, we get the conclusion of the lemma.  $\square$

The following extension of a classical result of Strichartz is the key to our results:

**Lemma 20.** *Let  $1 < p < \infty$  and  $1/p - 1 < t_- \leq 0 \leq t < 1/p$ . There exists a constant  $C_{\#}$  satisfying the following property. Let  $O$  be a set in  $\mathbb{R}^d$  whose intersection with almost every line parallel to a coordinate axis has at most  $N$  connected components. Then, for any  $u \in H_p^{t,t_-}$ , the distribution  $1_O u$  also belongs to  $H_p^{t,t_-}$ , and satisfies*

$$(22) \quad \|1_O u\|_{H_p^{t,t_-}} \leq C_{\#} N \|u\|_{H_p^{t,t_-}} .$$

*Proof.* If  $t_- = 0$  and  $t \in [0, 1/p)$  then our claim is just Strichartz' result [24, Cor II.4.2] on generalized Sobolev spaces (noting that [24, Cor II.3.7] gives the estimate  $C_{\#} N$ ). (See also [22, §4.6.3] for alternative sufficient conditions on  $O$  and  $p$ ,  $t$  ensuring that  $1_O$  is a multiplier of  $H_p^{t,0}$ .)

Assume now that  $t = 0$  and  $t_- \in (0, 1/p)$ . Then the one-dimensional Fubini-type argument of Strichartz [24, Thm I.4.1] applies, and allows us to generalize [24, Cor II.4.2] to give the claim. If  $t = 0$  and  $t_- \in (1/p - 1, 0)$ , the result follows by duality.

Interpolating via Proposition 16, the set of parameters  $(1/p, t, t_-)$  for which the conclusion of the lemma holds is convex. It therefore contains the convex hull of  $\{(1/p, t, 0) \mid 0 \leq t < 1/p\}$  and  $\{(1/p, 0, t_-) \mid 1/p - 1 < t_- \leq 0\}$ , which coincides with the set  $\{(1/p, t, t_-) \mid 1/p - 1 < t_- \leq 0 \leq t < 1/p\}$ .  $\square$

**4.2. Composition with smooth maps preserving the stable leaves.** In this paragraph, we study the behavior of  $H_p^{t,t_-}$  under the composition with smooth maps preserving the stable leaves.

Let us start with a very rough and easy to prove lemma.

**Lemma 21.** *Let  $1 < p < \infty$ , and  $t, t_-$  be real numbers with  $|t| + |t_-| \leq 1$ . There exists a constant  $C_{\#}$  such that, for any invertible matrix  $A$  on  $\mathbb{R}^d$ , sending  $\{0\} \times \mathbb{R}^{d_s}$  to itself, and for any  $u \in H_p^{t,t_-}$ ,*

$$(23) \quad \|u \circ A\|_{H_p^{t,t_-}} \leq C_{\#} |\det A|^{-1/p} \max(\|A\|, \|A^{-1}\|) \|u\|_{H_p^{t,t_-}} .$$

*Proof.* By [22, Proposition 2.1.2 (iv)+(vii)], the  $H_p^1$ -norm is equivalent to the norm  $\|u\|_{L_p} + \|Du\|_{L_p}$ . Hence,  $\|u \circ A\|_{H_p^{1,0}} \leq C_{\#} |\det A|^{-1/p} \max(\|A\|, \|A^{-1}\|) \|u\|_{\mathcal{H}_p^{1,0}}$ . Similarly,  $\| |\det A|^{-1} u \circ A^{-1} \|_{H_{p'}^{0,1}} \leq C_{\#} |\det A|^{-1+1/p'} \max(\|A\|, \|A^{-1}\|) \|u\|_{H_{p'}^{0,1}}$ , by a  $d_s$ -dimensional Fubini-type argument. Since the adjoint of  $u \mapsto \det A^{-1} u \circ A^{-1}$  is  $u \mapsto u \circ A$ , the general case follows by duality (Lemma 17) and interpolation (Proposition 16).  $\square$

**Lemma 22.** *Let  $\alpha \in (0, 1)$ , let  $F : \mathbb{R}^d \rightarrow \mathbb{R}^d$  be a  $C^{1+\alpha}$  diffeomorphism sending stable leaves to stable leaves, and let  $A$  be a matrix such that, for all  $z \in \mathbb{R}^d$ ,  $\|A^{-1} \circ DF(z)\| \leq 2$  and  $\|DF(z)^{-1} \circ A\| \leq 2$ .*

*Assume moreover that  $A$  can be written as  $M_0^{-1} \begin{pmatrix} A^u & 0 \\ 0 & A^s \end{pmatrix} M_1$ , where  $M_0$  and  $M_1$  are matrices sending stable leaves to stable leaves, and  $\mu_u := \|A^u\| \leq 1$ ,  $\mu_s := \|(A^s)^{-1}\|^{-1} \geq 1$ .<sup>3</sup>*

*Then, for all  $t > 0$  and  $t_- < 0$  with  $t + |t_-| < \alpha$  and  $t + t_- < 0$ , for all  $p \in (1, \infty)$ , there exists a constant  $C_\#$  depending only on  $\max(\|M_0\|, \|M_0^{-1}\|, \|M_1\|, \|M_1^{-1}\|)$  and  $t, t_-, p$ , and a constant  $C(A, F)$  such that, for all  $u \in H_p^{t, t_-}$ ,*

$$\|u \circ F\|_{H_p^{t, t_-}} \leq C_\# \|\det A / \det DF\|_{C^\alpha} |\det A|^{-1/p} \max(\mu_u^t, \mu_s^{t+t_-}) \|u\|_{H_p^{t, t_-}} + C \|u\|_{H_p^{0, t_-}}.$$

In the applications to transfer operators,  $F$  will be the local *inverse* of some iterate  $T^n$  of a piecewise hyperbolic map. Since  $T^n$  is contracting along  $E^s$  and expanding along  $E^u$ , the map  $F$  will therefore satisfy the assumptions of the lemma regarding  $\mu_s$  and  $\mu_u$ .

*Proof of Lemma 22.* We will write  $u \circ F = u \circ A \circ A^{-1} \circ F$ . Hence, we need to study the composition with  $A$  and  $A^{-1} \circ F$ . We claim that

$$(24) \quad \|u \circ A\|_{H_p^{t, t_-}} \leq |\det A|^{-1/p} C_\# \max(\mu_u^t, \mu_s^{t+t_-}) \|u\|_{H_p^{t, t_-}} + C \|u\|_{H_p^{0, t_-}}$$

and

$$(25) \quad \|u \circ A^{-1} \circ F\|_{H_p^{t, t_-}} \leq C_\# \|\det A / \det DF\|_{C^\alpha} \|u\|_{H_p^{t, t_-}}.$$

Together, these equations prove the lemma.

*First step.* Let us prove (24). This is a special case of [4, Lemma 2.10] (replacing  $(0, t_-)$  by  $(t - 1/2, t_-)$ ). We will give the proof for the convenience of the reader, since it is at the same time very simple and at the heart of our argument. Lemma 21 deals with the composition with  $M_0^{-1}$  and  $M_1$ , hence we can assume that  $M_0 = M_1 = \text{Id}$ .

We want to estimate  $\|u \circ A\|_{H_p^{t, t_-}} = \|\mathcal{F}^{-1}(a_{t, t_-} \mathcal{F}(u \circ A))\|_{L_p}$ . A change of variables readily gives  $\mathcal{F}^{-1}(a_{t, t_-} \mathcal{F}(u \circ A)) = \mathcal{F}^{-1}(a_{t, t_-} \circ {}^t A \cdot \mathcal{F}u) \circ A$ . Hence, we have to show that

$$(26) \quad \|\mathcal{F}^{-1}(a_{t, t_-} \circ {}^t A \cdot \mathcal{F}u)\|_{L_p} \leq C_\# \max(\mu_u^t, \mu_s^{t+t_-}) \|u\|_{H_p^{t, t_-}} + C \|u\|_{H_p^{0, t_-}}.$$

Write  ${}^t A = \begin{pmatrix} U & 0 \\ 0 & S \end{pmatrix}$  with  $|U\xi| \leq \mu_u |\xi|$  and  $|S\eta| \geq \mu_s |\eta|$  by definition of  $\mu_u, \mu_s$ .

Let

$$(27) \quad b(\xi, \eta) = a_{t, t_-} \circ {}^t A(\xi, \eta) = (1 + |U\xi|^2 + |S\eta|^2)^{t/2} (1 + |S\eta|^2)^{t_-/2}.$$

Let us prove that, if  $C$  is large enough, we have

$$(28) \quad b \leq C_\# \max(\mu_u^t, \mu_s^{t+t_-}) a_{t, t_-} + C a_{0, t_-}.$$

<sup>3</sup>The matrix norms are the operator norms with respect to the usual euclidean metric on  $\mathbb{R}^d$ , so that the norm of a matrix equals the norm of its transpose.

If we can prove this equation together with the corresponding estimates for the successive derivatives of  $b$ , then Theorem 18 applied to

$$b/(C_{\#} \max(\mu_u^t, \mu_s^{t+t_-}) a_{t,t_-} + C a_{0,t_-})$$

gives

$$(29) \quad \|\mathcal{F}^{-1}(b\mathcal{F}u)\|_{L_p} \leq C_{\#} \|\mathcal{F}^{-1}((C_{\#} \max(\mu_u^t, \mu_s^{t+t_-}) a_{t,t_-} + C a_{0,t_-}) \mathcal{F}u)\|_{L_p},$$

which yields (26).

Let us now prove (28) (the proof for the derivatives of  $b$  is similar). We will freely use the following trivial inequalities: for  $x \geq 1$  and  $\lambda \geq 1$ ,

$$(30) \quad \frac{1}{\lambda}(1 + \lambda x) \leq 1 + x \leq \frac{2}{\lambda}(1 + \lambda x).$$

Assume first  $|U\xi|^2 \leq |S\eta|^2$  and  $|S\eta|^2 \geq 1$ . Then, since  $t > 0$  and  $t + t_- < 0$ ,

$$\begin{aligned} b(\xi, \eta) &\leq (1 + 2|S\eta|^2)^{t/2} (1 + |S\eta|^2)^{t_-/2} \leq 2^{t/2} (1 + |S\eta|^2)^{t/2} (1 + |S\eta|^2)^{t_-/2} \\ &\leq 2^{t/2} (1 + \mu_s^2 |\eta|^2)^{(t+t_-)/2} \leq 2^{t/2} (\mu_s^2/2)^{(t+t_-)/2} (1 + |\eta|^2)^{(t+t_-)/2} \\ &\leq 2^{-t_-/2} \mu_s^{(t+t_-)} a_{t,t_-}(\xi, \eta). \end{aligned}$$

If  $|U\xi|^2 \geq |S\eta|^2$  and  $|U\xi|^2 \geq 1$ , then

$$\begin{aligned} b(\xi, \eta) &\leq (1 + 2|U\xi|^2)^{t/2} (1 + |S\eta|^2)^{t_-/2} \leq 2^{t/2} (1 + |U\xi|^2)^{t/2} (1 + \mu_s^2 |\eta|^2)^{t_-/2} \\ &\leq 2^{t/2} (1 + \mu_u^2 |\xi|^2)^{t/2} (1 + |\eta|^2)^{t_-/2} \leq 2^{t/2} (2\mu_u^2)^{t/2} (1 + |\xi|^2)^{t/2} (1 + |\eta|^2)^{t_-/2} \\ &\leq 2^t \mu_u^t a_{t,t_-}(\xi, \eta). \end{aligned}$$

In the remaining case,  $\xi$  and  $\eta$  are uniformly bounded, and (28) follows by choosing  $C$  large enough. This concludes the proof of (24).

*Second step.* Let us now prove (25). We will write  $\tilde{F} = A^{-1} \circ F$ . As in the proof of Lemmas 19, 20, and 21, we will study simpler spaces before concluding by interpolation. We thus write  $(t, t_-) = (\theta t^0, (1 - \theta)t_-^0)$  for some  $0 < \theta < 1$  and  $t^0, -t_-^0 \in (0, \alpha)$ .

By [22, Proposition 2.1.2 (iv)+(vii)], the  $H_p^1$ -norm is equivalent to the norm  $\|u\|_{L_p} + \|Du\|_{L_p}$ . Since the derivative of  $\tilde{F}$  has norm everywhere bounded by 2 and  $|\det D\tilde{F}| \leq 2^d$  by assumption, we get after a change of variables  $\|u \circ \tilde{F}\|_{H_p^1} \leq C_{\#} \|u\|_{H_p^1}$ . Since  $\|u \circ \tilde{F}\|_{L_p} \leq C_{\#} \|u\|_{L_p}$ , the interpolation inequality (16) gives

$$(31) \quad \|u \circ \tilde{F}\|_{H_p^{0,t_-}} \leq C_{\#} \|u\|_{H_p^{t^0}}.$$

Applying the same argument via Fubini to  $\tilde{F}^{-1}$  on each leaf of the vertical direction, we also have  $\|u \circ \tilde{F}^{-1}\|_{H_p^{0,1}} \leq C_{\#} \|u\|_{H_p^{0,1}}$ . The adjoint of the composition by  $\tilde{F}^{-1}$  is given by  $\mathcal{P}(u) = \det D\tilde{F} \cdot u \circ \tilde{F}$ . Hence, duality yields  $\|\mathcal{P}u\|_{H_p^{0,-1}} \leq C_{\#} \|u\|_{H_p^{0,-1}}$ . Since  $\mathcal{P}$  is bounded by  $C_{\#}$  on  $L_p$ , we get by interpolation

$$(32) \quad \|\det D\tilde{F} \cdot u \circ \tilde{F}\|_{H_p^{0,t_-}} \leq C_{\#} \|u\|_{H_p^{0,t^0}}.$$

Together with (21), we obtain

$$(33) \quad \begin{aligned} \left\| u \circ \tilde{F} \right\|_{H_p^{0,t_0}} &\leq C_{\#} \left\| 1/\det D\tilde{F} \right\|_{C^\alpha} \left\| \det D\tilde{F} \cdot u \circ \tilde{F} \right\|_{H_p^{0,t_0}} \\ &\leq C_{\#} \left\| 1/\det D\tilde{F} \right\|_{C^\alpha} \|u\|_{H_p^{0,t_0}}. \end{aligned}$$

Interpolating between (31) and (33), we get

$$(34) \quad \left\| u \circ \tilde{F} \right\|_{H_p^{t,t_-}} \leq C_{\#} \left\| 1/\det D\tilde{F} \right\|_{C^\alpha}^{1-\theta} \|u\|_{H_p^{t,t_-}}.$$

Finally,  $1/\det D\tilde{F} = \det A/\det DF$  is bounded from below, and (25) follows.  $\square$

**Remark 23** (Invariance). The arguments in the second step of the proof of Lemma 22 (with  $A = \text{Id}$ ) also imply that, whenever  $t > 0$  and  $t_- < 0$  satisfy  $t + |t_-| < \alpha$ , then the space  $H_p^{t,t_-}$  is invariant under the composition with  $C^{1+\alpha}$  diffeomorphisms of  $\mathbb{R}^d$  sending stable leaves to stable leaves.

**Remark 24** (Extending [4] to  $C^{1+\alpha}$  Anosov diffeomorphisms). If  $0 < \alpha < 1$  we can apply Lemma 22. If  $\alpha \geq 1$  and  $t > 0$ ,  $t + t_- < 0$  satisfy  $t + |t_-| < \alpha$ , letting  $m$  be the smallest integer  $\geq t + |t_-|$ , [22, Proposition 2.1.2 (iv)+(vii)], implies that the  $H_p^m$ -norm is equivalent to the norm  $\sum_{|\gamma| \leq m} \|\partial^\gamma u\|_{L_p}$ . Thus, replacing the matrix  $A$  in Lemma 22 by a  $C^\infty$  diffeomorphism  $A$  preserving stable leaves, with least expansion  $\mu_s \geq 1$  on the verticals, and whose inverse preserves horizontal cones with least expansion  $\mu_s^{-1} \geq 1$ , and such that  $\|DA^{-1} \circ DF\|_{C^{m-1}} \leq 2$  and  $\|DF^{-1} \circ DA\|_{C^{m-1}} \leq 2$ , we get, by applying [4, Lemma 2.10] to prove the analogue of (24), that

$$\begin{aligned} \|u \circ F\|_{H_p^{t,t_-}} &\leq C_{\#} \|\det DA/\det DF\|_{C^\alpha} |\det DA|^{-1/p} \max(\mu_u^t, \mu_s^{t+t_-}) \|u\|_{H_p^{t,t_-}} \\ &\quad + C \|u\|_{H_p^{t-1/2,t_-}}. \end{aligned}$$

The proof of Theorem 9 then applies to any  $C^{1+\alpha}$  Anosov diffeomorphism  $T$  with  $C^{1+\alpha}$  stable distribution, and to any  $C^\alpha$  weight  $g$ , with  $\alpha > 0$ .

### 4.3. Localization.

**Lemma 25** (Localization principle). *Let  $\eta : \mathbb{R}^d \rightarrow [0, 1]$  be a  $C^\infty$  function with compact support and write  $\eta_m(x) = \eta(x + m)$ . For any  $p \in (1, \infty)$  and  $t, t_- \in \mathbb{R}$ , there exists  $C_{\#} > 0$  so that for each  $u \in H_p^{t,t_-}$*

$$(35) \quad \left( \sum_{m \in \mathbb{Z}^d} \|\eta_m u\|_{H_p^{t,t_-}}^p \right)^{1/p} \leq C_{\#} \|u\|_{H_p^{t,t_-}}.$$

**Remark 26.** If, in addition to the assumptions of Lemma 25, one supposes that  $\sum_{m \in \mathbb{Z}^d} \eta_m(x) = 1$  for all  $x$ , then one can show that there is  $C_{\#}$  so that for each  $u$  such that  $\eta_m u \in H_p^{t,t_-}$  for all  $m$  we have

$$\|u\|_{H_p^{t,t_-}} \leq C_{\#} \left( \sum_{m \in \mathbb{Z}^d} \|\eta_m u\|_{H_p^{t,t_-}}^p \right)^{1/p}.$$

(We shall not need the above bound.)

*Proof of Lemma 25.* For  $t_- = 0$  and arbitrary  $t$ , Lemma 25 is a result of Triebel [27, Theorem 2.4.7] based on a Paley-Littlewood-type decomposition. Moreover, the constant  $C_\#$  depends only on the size of the support of  $\eta$ , and its  $C^k$ -norm for some large enough  $k$ .

To handle  $t_- \in \mathbb{R}$ , we will (again) start from the result for the classical Sobolev space and use Fubini and interpolation, as follows.

Let us prove the lemma for  $t = 0$  and  $t_- \in \mathbb{R}$ , using a  $d_s$ -dimensional Fubini argument. We have

$$(36) \quad \sum_{m \in \mathbb{Z}^d} \|\eta_m u\|_{H_p^{0,t_-}(\mathbb{R}^d)}^p = \sum_{m \in \mathbb{Z}^d} \int_{x \in \mathbb{R}^{d_u}} \|\eta_m u\|_{H_p^{t_-}(\{x\} \times \mathbb{R}^{d_s})}^p dx.$$

For each  $x \in \mathbb{R}^{d_u}$ , the values of  $m \in \mathbb{Z}^d$  for which the restriction of  $\eta_m u$  to  $\{x\} \times \mathbb{R}^{d_s}$  is nonzero are contained in a set  $M(x) \times \mathbb{Z}^{d_s}$ , where  $\text{Card } M(x)$  is bounded independently of  $x$ . Using the result of Triebel for the Sobolev space  $H_p^{t_-}(\mathbb{R}^{d_s})$ , we get

$$(37) \quad \sum_{m \in \mathbb{Z}^d} \|\eta_m u\|_{H_p^{t_-}(\{x\} \times \mathbb{R}^{d_s})}^p \leq C_\# \|u\|_{H_p^{t_-}(\{x\} \times \mathbb{R}^{d_s})}^p.$$

Integrating over  $x \in \mathbb{R}^{d_u}$  and using the Fubini equality

$$(38) \quad \int_{x \in \mathbb{R}^{d_u}} \|u\|_{H_p^{t_-}(\{x\} \times \mathbb{R}^{d_s})}^p dx = \|u\|_{H_p^{0,t_-}}^p,$$

we obtain the lemma for  $t = 0$  and  $t_- \in \mathbb{R}$ .

Consider the map  $u \mapsto (\eta_m u)_{m \in \mathbb{Z}^d}$ . We have shown that it sends continuously  $H_p^t$  to  $\ell_p(H_p^t)$  and  $H_p^{0,t_-}$  to  $\ell_p(H_p^{0,t_-})$ . By interpolation, for any  $\theta \in (0, 1)$ , it sends  $[H_p^t, H_p^{0,t_-}]_\theta$  to  $[\ell_p(H_p^t), \ell_p(H_p^{0,t_-})]_\theta$ . By Proposition 16, the first space is  $H_p^{(1-\theta)t, \theta t_-}$  while, by [26, Theorem 1.18.1] and again Proposition 16, the second space is  $\ell_p(H_p^{(1-\theta)t, \theta t_-})$ . This proves the lemma.  $\square$

## 5. PROOF OF THE MAIN THEOREM

In this section, we prove Theorem 9. Let us fix once and for all a piecewise  $C^{1+\alpha}$  hyperbolic map  $T$  and a  $C^\alpha$  function  $g$ , satisfying the assumptions of this theorem. We will denote by  $C_\#$  constants that depend only on  $p, t, t_-$  and  $T$ .

We recall that the norm on  $\mathcal{H}_p^{t,t_-}$  has been defined in (5) using a partition of unity  $\rho_1, \dots, \rho_J$  and charts  $\kappa_1, \dots, \kappa_J$  subordinated to this partition of unity.

In the following arguments, when working on a set  $\overline{O}_i$  or in a neighborhood of this set (with  $\mathbf{i}$  of length  $n$ ), then  $T^n$  will implicitly mean  $T_i$ . In the same way,  $g^{(n)}$  will rather be a smooth extension of  $g^{(n)}|_{O_i}$  to a neighborhood of  $\overline{O}_i$ . This should not cause any confusion.

To study  $\mathcal{L}_g^n$ , we will need, in addition to the estimates from Section 4, to iterate the inverse branches  $T_i^{-1}$ , to truncate the functions and to use partitions of unity. To do this, we will use the three following lemmas.

**Lemma 27.** *There exists a constant  $C_\#$  such that, for any  $n$  and  $\mathbf{i} = (i_0, \dots, i_{n-1})$ , for any  $x \in \overline{O}_i$ , for any  $j, k \in [1, J]$  such that  $x \in \text{supp } \rho_j$  and  $y = T_i x \in \text{supp } \rho_k$ , there exists a neighborhood  $O$  of  $y$  and a  $C^{1+\alpha}$  diffeomorphism  $F$  of  $\mathbb{R}^d$ , coinciding*

with  $\kappa_j \circ T_{\mathbf{i}}^{-1} \circ \kappa_k^{-1}$  on  $\kappa_k(O)$ , and satisfying the assumptions of Lemma 22 with  $\mu_u \leq C_{\#} \lambda_{u,n}^{-1}(x)$  and  $\mu_s \geq C_{\#}^{-1} \lambda_{s,n}^{-1}(x)$ , and

$$\max(\|M_0\|, \|M_0^{-1}\|, \|M_1\|, \|M_1^{-1}\|) \leq C_{\#}.$$

*Proof.* Let  $F_0 = \kappa_j \circ T_{\mathbf{i}}^{-1} \circ \kappa_k^{-1}$ , it is defined on a neighborhood of  $\kappa_k(y)$ . Moreover, let  $P$  be a  $d_u$ -dimensional subspace of the unstable cone at  $x$ , and let  $M_0, M_1$  be invertible matrices (with bounded norms) sending respectively  $D\kappa_j(x)P$  and  $D\kappa_k(y)DT_{\mathbf{i}}(x)P$  to  $\mathbb{R}^{d_u} \times \{0\}$ , and stable leaves to stable leaves. Such matrices exist since the unstable cone is uniformly bounded away from the stable direction.

Let  $A = DF_0(\kappa_k(y))$ , then  $M_0 A M_1^{-1}$  sends  $\mathbb{R}^{d_u} \times \{0\}$  to itself, and  $\{0\} \times \mathbb{R}^{d_s}$  to itself, i.e., it is block-diagonal. Hence, the matrix  $A$  satisfies the assumptions of Lemma 22. Let  $F$  be a  $C^{1+\alpha}$  diffeomorphism of  $\mathbb{R}^d$  coinciding with  $F_0$  on a neighborhood of  $\kappa_k(y)$  and such that  $DF(z)$  is everywhere close to  $A$ . Up to taking a smaller neighborhood  $O$  of  $y$  (depending on  $n$ ), the claims of Lemma 27 hold for  $F$ .  $\square$

**Lemma 28.** *There exists  $C_{\#}$  such that, for any  $n$ , for any  $\mathbf{i} = (i_0, \dots, i_{n-1})$ , for any  $x \in \overline{O_{\mathbf{i}}}$ , for any  $j$  such that  $x \in \text{supp } \rho_j$ , there exists a neighborhood  $O'$  of  $x$  and a matrix  $M$  sending stable leaves to stable leaves, with*

$$\max(\|M\|, \|M^{-1}\|) \leq C_{\#},$$

*such that the intersection of  $M\kappa_j(O' \cap O_{\mathbf{i}})$  intersects almost any line parallel to a coordinate axis along at most  $C_{\#}n$  connected components.*

*Proof.* Let  $L$  be as in Definition 4. Fix  $\mathbf{i} = (i_0, \dots, i_{n-1})$  and  $x \in \overline{O_{\mathbf{i}}}$ . Let  $a_1, \dots, a_d$  be a basis of  $\mathcal{T}_x X$ , which is close to an orthonormal basis, such that its last  $d_s$  vectors form a basis of  $E^s(x)$ . We can ensure that, for any  $\ell < n$ ,  $DT^{\ell}(x)a_k$  is  $L$ -generic with respect to  $\partial O_{i_j}$ , for  $d_u < k \leq d$ . This is indeed a consequence of the definition of weak transversality. Moving slightly the vectors  $a_k$  for  $1 \leq k \leq d_u$ , we can also ensure that  $DT^{\ell}(x)a_k$  is transversal to the hypersurfaces defining  $\partial O_{i_j}$  at  $T^{\ell}x$  for any  $\ell < n$ .

Let  $b_k = D\kappa_j(x) \cdot a_k$ , so that  $b_1, \dots, b_d$  is a basis of  $\mathbb{R}^d$ . Multiplying  $a_k$  by a scalar, we can ensure that  $b_k$  has norm 1. If  $O'$  is a small enough neighborhood of  $x$ , then  $\kappa_{\ell}(O' \cap O_{\mathbf{i}})$  intersects almost any line oriented by one of the vectors  $b_k$ ,  $d_u < k \leq d$ , along at most  $nL$  connected components, by definition of  $L$ -genericity. Moreover, it intersects any line oriented by one of the vectors  $b_k$ ,  $1 \leq k \leq d_u$ , along at most one connected component by construction.

Let  $M$  be the matrix sending  $b_1, \dots, b_d$  to the canonical basis of  $\mathbb{R}^d$ , it satisfies the requirements of the lemma.  $\square$

The following lemma on partitions of unity is similar to [5, Lemma 7.1].

**Lemma 29.** *Let  $t$  and  $t_-$  be arbitrary real numbers. There exists a constant  $C_{\#}$  such that, for any distributions  $v_1, \dots, v_l$  with compact support in  $\mathbb{R}^d$ , belonging to  $H_p^{t, t_-}$ , there exists a constant  $C$  with*

$$(39) \quad \left\| \sum_{i=1}^l v_i \right\|_{H_p^{t, t_-}}^p \leq C_{\#} m^{p-1} \sum_{i=1}^l \|v_i\|_{H_p^{t, t_-}}^p + C \sum_{i=1}^l \|v_i\|_{H_p^{t-1, t_-}}^p,$$

where  $m$  is the intersection multiplicity of the supports of the  $v_i$ 's, i.e.,  $m = \sup_{x \in \mathbb{R}^d} \text{Card}\{i \mid x \in \text{supp}(v_i)\}$ .

*Proof.* Let  $A$  be the operator acting on distributions by  $Av = \mathcal{F}^{-1}((1 + |\xi|^2 + |\eta|^2)^{t/2}(1 + |\eta|^2)^{t-/2}\mathcal{F}v)$ , so that  $\|v\|_{\mathcal{H}_p^{t,t-}} = \|Av\|_{L_p}$ .

[4, Lemma 2.7] shows that, for any distribution  $v$  with compact support  $K$  and any neighborhood  $K'$  of this support, there exist  $C > 0$  and a function  $\Psi : \mathbb{R}^d \rightarrow [0, 1]$  equal to 1 on  $K$  and vanishing on the complement of  $K'$ , with

$$(40) \quad \|\Psi Av - Av\|_{L_p} \leq C \|v\|_{H_p^{t-1,t-}}.$$

Let  $v_1, \dots, v_l$  be distributions with compact supports whose intersection multiplicity is  $m$ . Choose neighborhoods  $K'_1, \dots, K'_l$  of the supports of the  $v_i$ s whose intersection multiplicity is also  $m$ , and functions  $\Psi_1, \dots, \Psi_l$  as above. Then

$$(41) \quad \left\| \sum_i v_i \right\|_{H_p^{t,t-}}^p = \left\| \sum_i Av_i \right\|_{L_p}^p \leq \left\| \sum_i \Psi_i Av_i \right\|_{L_p}^p + C \sum_i \|v_i\|_{H_p^{t-1,t-}}^p.$$

By convexity, the inequality  $(x_1 + \dots + x_m)^p \leq m^{p-1} \sum x_i^p$  holds for any nonnegative numbers  $x_1, \dots, x_m$ . Since the multiplicity of the  $K'_i$ s is at most  $m$ , this yields

$$(42) \quad \left| \sum_i \Psi_i Av_i \right|^p \leq m^{p-1} \sum_i |Av_i|^p.$$

Integrating this inequality and using (41), we get the lemma.  $\square$

*Proof of Theorem 9.* Let  $p, t$  and  $t_-$  be as in the assumptions of the theorem. Let  $n > 0$ , and let  $r_n > 1$  (the precise value of  $r_n$  will be chosen later). We define a dilation  $R_n$  on  $\mathbb{R}^d$  by  $R_n(z) = r_n z$ . Let  $\|u\|_n$  be another norm on  $\mathcal{H}_p^{t,t-}$ , given by

$$(43) \quad \|u\|_n = \sum \|(\rho_j u) \circ \kappa_j^{-1} \circ R_n^{-1}\|_{H_p^{t,t-}}.$$

The norm  $\|u\|_n$  is of course equivalent to the usual norm on  $\mathcal{H}_p^{t,t-}$ , but we look at the space  $X_0$  at a smaller scale. Functions are much more flatter at this new scale, so that estimates involving their  $C^\alpha$  norm, such as Lemma 19 or Lemma 22, will not cause problems. This will also enable us to use partitions of unity with very small supports without spoiling the estimates. The use of this ‘‘zooming’’ norm is similar to the good choice of  $\epsilon_0$  in [23], or the use of weighted norms in [16].

We will prove that, if  $n$  is fixed and  $r_n$  is large enough, then

$$(44) \quad \|\mathcal{L}_g^n u\|_n^p \leq C \|u\|_{\mathcal{H}_p^{0,t-}}^p + C_\# n^p D_n^b (D_n^e)^{p-1} \left\| |\det DT^n| \max(\lambda_{u,n}^{-(t+t-)}, \lambda_{s,n}^{-t-})^p |g^{(n)}|^p \right\|_{L_\infty} \|u\|_n^p.$$

The injection of  $\mathcal{H}_p^{t,t-}$  into  $\mathcal{H}_p^{0,t-}$  is compact. Hence, by Hennion’s theorem [20], the essential spectral radius of  $\mathcal{L}_g^n$  acting on  $\mathcal{H}_p^{t,t-}$  (for either  $\|u\|_{\mathcal{H}_p^{t,t-}}$  or  $\|u\|_n$ , since these norms are equivalent) is at most

$$(45) \quad \left[ C_\# n^p D_n^b (D_n^e)^{p-1} \left\| |\det DT^n| \max(\lambda_{u,n}^{-(t+t-)}, \lambda_{s,n}^{-t-})^p |g^{(n)}|^p \right\|_{L_\infty} \right]^{1/p}.$$

Taking the power  $1/n$  and letting  $n$  tend to  $\infty$ , we obtain Theorem 9 since the quantity  $(C_\# n^p)^{1/pn}$  converges to 1 (here, it is essential that  $C_\#$  does not depend on  $n$ ).

It remains to prove (44), for large enough  $r_n$ . The estimate will be subdivided into three steps:

- (1) Decomposing  $u$  into a sum of distributions  $v_{j,m}$  with small supports and well controlled  $\|\cdot\|_n$  norms.
- (2) Estimating each term  $(1_{O_i} g^{(n)} v_{j,m}) \circ T_{\mathbf{i}}^{-1}$ , for  $\mathbf{i}$  of length  $n$ .
- (3) Adding all terms to obtain  $\mathcal{L}_g^n u$ .

*First step.* For  $1 \leq j \leq J$  and  $m \in \mathbb{Z}^d$ , let  $\tilde{v}_{j,m} = \eta_m \cdot (\rho_j u) \circ \kappa_j^{-1} \circ R_n^{-1}$ , where  $\eta_m(x) = \eta(x+m)$ , with  $\eta : \mathbb{R}^d \rightarrow [0, 1]$  a compactly supported  $C^\infty$  function so that  $\sum_{m \in \mathbb{Z}^d} \eta_m = 1$ . Since the intersection multiplicity of the supports of the functions  $\eta_m$  is bounded, this is also the case for the  $\tilde{v}_{j,m}$ . Moreover, if  $j$  is fixed, we get using Lemma 25

$$(46) \quad \begin{aligned} \sum_{m \in \mathbb{Z}^d} \|\tilde{v}_{j,m}\|_{H_p^{t,t-}}^p &= \sum_{m \in \mathbb{Z}^d} \|\eta_m \cdot (\rho_j u) \circ \kappa_j^{-1} \circ R_n^{-1}\|_{H_p^{t,t-}}^p \\ &\leq C_{\#} \|(\rho_j u) \circ \kappa_j^{-1} \circ R_n^{-1}\|_{H_p^{t,t-}}^p \leq C_{\#} \|u\|_n^p. \end{aligned}$$

Since  $R_n$  expands the distances by a factor  $r_n$  while the size of the supports of the functions  $\eta_m$  is uniformly bounded, the supports of the distributions

$$v_{j,m} = \tilde{v}_{j,m} \circ R_n \circ \kappa_j = \eta_m \circ R_n \circ \kappa_j \cdot (\rho_j u)$$

are arbitrarily small if  $r_n$  is large enough. Finally

$$(47) \quad u = \sum_j \rho_j u = \sum_{j,m} v_{j,m}.$$

*Second step.* Fix  $j, k \in \{1, \dots, J\}$ ,  $m \in \mathbb{Z}^d$  and  $\mathbf{i} = (i_0, \dots, i_{n-1})$ . We will prove that

$$(48) \quad \begin{aligned} \left\| (\rho_k(g^{(n)} 1_{O_i} v_{j,m}) \circ T_{\mathbf{i}}^{-1}) \circ \kappa_k^{-1} \circ R_n^{-1} \right\|_{H_p^{t,t-}} &\leq C \|u\|_{\mathcal{H}_p^{0,t-}} \\ &+ C_{\#} n \left\| |\det DT^n|^{1/p} g^{(n)} \max(\lambda_{u,n}^{-t}, \lambda_{s,n}^{-(t+t-)}) \right\|_{L^\infty} \|\tilde{v}_{j,m}\|_{H_p^{t,t-}}. \end{aligned}$$

First, if the support of  $v_{j,m}$  is small enough (which can be ensured by taking  $r_n$  large enough), there exists a neighborhood  $O$  of this support and a matrix  $M$  satisfying the conclusion of Lemma 28: this follows from Lemma 28 and the compactness of  $X_0$ . Therefore, the intersection of  $R_n(M(\kappa_j(O \cap O_i)))$  with almost any line parallel to a coordinate axis contains at most  $C_{\#} n$  connected components. Hence, Lemma 20 implies that the multiplication by  $1_{O \cap O_i} \circ \kappa_j^{-1} \circ M^{-1} \circ R_n^{-1}$  sends  $H_p^{t,t-}$  into itself, with a norm bounded by  $C_{\#} n$ . Using the fact that  $M$  and  $R_n$  commute, the properties of  $M$ , and Lemma 21, we get

$$(49) \quad \|1_{O_i} \circ \kappa_j^{-1} \circ R_n^{-1} \cdot \tilde{v}_{j,m}\|_{H_p^{t,t-}} \leq C_{\#} n \|\tilde{v}_{j,m}\|_{H_p^{t,t-}}.$$

(Recall that  $v_{j,m}$  is supported inside  $O$ .) Next, let

$$\tilde{v}_{j,k,m} = ((\rho_k \circ T_{\mathbf{i}}) 1_{O_i}) \circ \kappa_j^{-1} \circ R_n^{-1} \cdot \tilde{v}_{j,m}$$

(we suppress  $\mathbf{i}$  from the notation for simplicity). Let also  $\chi$  be a  $C^\infty$  function supported in the neighborhood  $O$  of the support of  $v_{j,m}$  with  $\chi \equiv 1$  on this support. Up to taking larger  $r_n$  we may ensure that  $\|(\chi(\rho_k \circ T_{\mathbf{i}})) \circ \kappa_j^{-1} \circ R_n^{-1}\|_{C^\alpha} \leq C_{\#}$ . Then Lemma 19 and (49) imply

$$(50) \quad \|\tilde{v}_{j,k,m}\|_{H_p^{t,t-}} \leq C_{\#} n \|\tilde{v}_{j,m}\|_{H_p^{t,t-}}$$

In addition, we have

$$(51) \quad ((\rho_k \circ T_{\mathbf{i}})1_{O_{\mathbf{i}}}v_{j,m}) \circ T_{\mathbf{i}}^{-1} \circ \kappa_k^{-1} \circ R_n^{-1} = \tilde{v}_{j,k,m} \circ R_n \circ \kappa_j \circ T_{\mathbf{i}}^{-1} \circ \kappa_k^{-1} \circ R_n^{-1} \\ = \tilde{v}_{j,k,m} \circ R_n \circ F \circ R_n^{-1},$$

where  $F$  is given by Lemma 27 (we use the fact that the support of  $v_{j,m} \circ T_{\mathbf{i}}^{-1}$  is contained in a very small neighborhood  $O'$  if  $r_n$  is large enough, and again the compactness of  $X_0$ ). The diffeomorphism  $F$  satisfies the assumptions of Lemma 22. Since the dilations  $R_n$  commute with any matrix, this is also the case of the diffeomorphism  $G = R_n \circ F \circ R_n^{-1}$ . Applying Lemma 22 to  $G$ , we get (for some point  $x$  in the support of  $v_{j,m}$ , and some matrix  $A$  of the form  $DF(R_n^{-1}(z))$  for some  $z$ )

$$(52) \quad \|\tilde{v}_{j,k,m} \circ R_n \circ F \circ R_n^{-1}\|_{H_p^{t,t-}} \leq C \|u\|_{\mathcal{H}_p^{0,t-}} \\ + C_{\#} \left\| \frac{\det A}{\det DG} \right\|_{C^\alpha} |\det A|^{-1/p} \max(\lambda_{u,n}(x)^{-t}, \lambda_{s,n}(x)^{-(t+t-)}) \|\tilde{v}_{j,k,m}\|_{H_p^{t,t-}}.$$

The factor  $\det A$  is close to  $\det DT_{\mathbf{i}}(x)^{-1}$ . Moreover,  $\det DG = (\det DF) \circ R_n^{-1}$ . By choosing  $r_n$  large enough, we can make sure that the  $C^\alpha$  norm of  $\det DG$  is controlled by its sup norm, to ensure that  $\|\det A / \det DG\|_{C^\alpha}$  is uniformly bounded.

Let  $\chi'$  be a  $C^\infty$  function supported in  $O'$  with  $\chi' \equiv 1$  on the support of  $v_{j,m} \circ T_{\mathbf{i}}^{-1}$ . For  $\delta > 0$ , we can ensure by increasing  $r_n$  that the  $C^\alpha$  norm of  $(\chi' g^{(n)}) \circ T_{\mathbf{i}}^{-1} \circ \kappa_k^{-1} \circ R_n^{-1}$  is bounded by  $|g^{(n)}(x)| + \delta$  for some  $x$  in the support of  $v_{j,m}$ . Choosing  $\delta > 0$  small enough, we deduce from (52), Lemma 19 and (50)

$$\left\| (\rho_k(g^{(n)}1_{O_{\mathbf{i}}}v_{j,m}) \circ T_{\mathbf{i}}^{-1}) \circ \kappa_k^{-1} \circ R_n^{-1} \right\|_{H_p^{t,t-}} \leq C \|u\|_{\mathcal{H}_p^{0,t-}} \\ + C_{\#} n \left\| |\det DT^n|^{1/p} g^{(n)} \max(\lambda_{u,n}^{-t}, \lambda_{s,n}^{-(t+t-)}) \right\|_{L^\infty} \|\tilde{v}_{j,m}\|_{H_p^{t,t-}}.$$

This proves (48).

*Third step.* We have  $\mathcal{L}_g^n u = \sum_{j,m} \sum_{\mathbf{i}} (1_{O_{\mathbf{i}}}g^{(n)}v_{j,m}) \circ T_{\mathbf{i}}^{-1}$ . (Note that only finitely many terms in this sum are nonzero by compactness of the support of each  $\rho_j$ .) We claim that the intersection multiplicity of the supports of the functions  $(1_{O_{\mathbf{i}}}g^{(n)}v_{j,m}) \circ T_{\mathbf{i}}^{-1}$  is bounded by  $C_{\#} D_n^e$ . Indeed, this follows from the fact that any point  $x \in X_0$  belongs to at most  $D_n^e$  sets  $\overline{T_{\mathbf{i}}(O_{\mathbf{i}})}$ , and that the intersection multiplicity of the supports of the functions  $v_{j,m}$  is bounded.

To estimate  $\|\mathcal{L}_g^n u\|_n$ , we have to bound each term  $\|(\rho_k \mathcal{L}_g^n u) \circ \kappa_k^{-1} \circ R_n^{-1}\|_{H_p^{t,t-}}$ , for  $1 \leq k \leq J$ . Let us fix such a  $k$ . By Lemma 29, we have

$$\|(\rho_k \mathcal{L}_g^n u) \circ \kappa_k^{-1} \circ R_n^{-1}\|_{H_p^{t,t-}}^p \leq C \|u\|_{\mathcal{H}_p^{0,t-}}^p \\ + C_{\#} (C_{\#} D_n^e)^{p-1} \sum_{j,m,\mathbf{i}} \left\| (\rho_k(1_{O_{\mathbf{i}}}g^{(n)}v_{j,m}) \circ T_{\mathbf{i}}^{-1}) \circ \kappa_k^{-1} \circ R_n^{-1} \right\|_{H_p^{t,t-}}^p.$$

We can bound each term in the sum using (48) and the convexity inequality  $(a+b)^p \leq 2^{p-1}(a^p + b^p)$ . Moreover, for any  $(j,m)$ , the number of parameters  $\mathbf{i}$  for which the corresponding term is nonzero is bounded by the number of sets  $\overline{O_{\mathbf{i}}}$  intersecting the support of  $v_{j,m}$ . Choosing  $r_n$  large enough, we can ensure that the supports of the  $v_{j,m}$  are small enough so that this number is bounded by  $D_n^b$ . Together with (46), this concludes the proof of (44), and of Theorem 9.  $\square$

## APPENDIX A. CORRIGENDUM TO [4, Lemma 2.8] – ABOUT INTERPOLATION

The statement of [4, Lemma 2.8] should be replaced by<sup>4</sup>: letting  $n = \lceil t \rceil + \lceil t_- \rceil + d + 4$ , if  $g$  is  $C^n$ , then

$$(53) \quad \|gu\|_{\mathcal{H}_p^{t,t_-}} \leq C_{\#} \|g\|_{C^{n-1}(C_s^1)} \|u\|_{\mathcal{H}_p^{t,t_-}} + C \|u\|_{\mathcal{H}_p^{t-1,t_-}},$$

where  $\|g\|_{C^{n-1}(C_s^1)}$  is the maximum between  $\|g\|_{L^\infty}$  and the  $C^{n-1}$  norm of the first derivatives of  $g$  along  $E^s$ . It was mistakenly claimed in [4, Lemma 2.8] that it is enough to take  $n = 3$ . The sentence ‘‘This can be shown by a straightforward...oscillatory integral argument’’ in the proof there should be replaced by ‘‘This can be shown by integrating by parts  $\lceil p \rceil + \lceil q \rceil + d + 1$  times in total with respect to  $(u, v)$ , noting that

$$\begin{aligned} (1 + |\eta - s\theta|^2 + |\xi - s\omega|^2)^{p/2} (1 + |\xi - s\omega|^2)^{q/2} (1 + |\eta|^2 + |\xi|^2)^{-p/2} (1 + |\xi|^2)^{-q/2} \\ \leq 16(1 + |s\omega|^2)^{|q|/2} (1 + |s\theta|^2 + |s\omega|^2)^{|p|/2}. \end{aligned}$$

Since  $\partial^{\gamma''+\gamma'} h$  has been differentiated up to 3 times including  $|\gamma'| \in \{1, 2\}$  times along  $x$ -directions, we get at most  $\lceil p \rceil + \lceil q \rceil + d + 4$  derivatives in total.’’ In particular [4, Lemma 2.8] only holds if  $g$  is sufficiently differentiable.

We derive via interpolation in Lemma 19 a simpler Leibniz-type bound which takes the place of [4, Lemma 2.8] and is valid for  $g \in C^\alpha$  for any  $\alpha > 0$ . The ‘‘zooming’’ norm (43) then allows us to replace  $\|g\|_{C^\alpha}$  by a sup-norm type estimate for arbitrary  $g$ .

The interpolation estimates also yield a chain-rule-type bound (Lemma 22 and Remark 24) which extends [4, Lemma 2.10] to arbitrary differentiability: the proof of [4, Lemma 2.10] uses that  $T$  is  $C^\infty$  implicitly in several places (when referring to arguments of [1]), although a modification of this proof along the lines given above gives the claim for  $C^k$  dynamics, with  $k(d)$  large if  $d$  is large.

## APPENDIX B. PROPERTIES OF PHYSICAL MEASURES

In this section, we prove Theorem 11. In fact, we will prove a more general result in a more abstract context. Let  $X$  be a manifold,  $X_0$  a compact subset of  $X$  with positive Lebesgue measure, and  $T : X_0 \rightarrow X_0$  a transformation for which Lebesgue measure is nonsingular. We will denote in this appendix by  $\mathcal{L}$  the corresponding transfer operator, defined by duality on  $L_1(\text{Leb})$  by  $\int_{X_0} \mathcal{L}f \cdot g \, d\text{Leb} = \int_{X_0} f \cdot g \circ T \, d\text{Leb}$ .

**Theorem 30.** *Let  $H$  be a Banach space of distributions supported on  $X_0$ . Assume that*

- (1) *There exist  $\alpha > 0$  and  $C > 0$  such that, for any  $u \in H$  and  $f \in C^\alpha(X)$ , then  $fu \in H$  and  $\|fu\|_H \leq C \|f\|_{C^\alpha} \|u\|_H$ .*
- (2) *The space  $H \cap L_\infty(\text{Leb})$  is dense in  $H$ .*
- (3) *The transfer operator  $\mathcal{L}$  associated to  $T$  sends continuously  $H \cap L_\infty(\text{Leb})$  into itself, hence it admits a continuous extension to  $H$  (still denoted by  $\mathcal{L}$ ). We assume that the essential spectral radius of this extension is  $< 1$ .*
- (4) *There exist  $f_0 \in H \cap L_\infty(\text{Leb})$  taking its values in  $[0, 1]$  and  $N_0 > 0$  such that, for any  $\phi \in L_\infty(\text{Leb})$ , then  $f_0 = 1$  on the support of  $\mathcal{L}^{N_0}\phi$ .*

<sup>4</sup>This has no consequences on the other claims in [4].

- (5) For any  $u \in H$  which is a limit of nonnegative functions  $u_n \in H \cap L_\infty(\text{Leb})$  and for which there exists a measure  $\mu_u$  such that<sup>5</sup>  $\langle u, g \, d\text{Leb} \rangle = \int g \, d\mu_u$  for any  $C^\infty$  function  $g$ , then the measure  $\mu_u$  gives zero mass to the discontinuity set of  $T$ .

Then there exist a finite number of probability measures  $\mu_1, \dots, \mu_l$  which are  $T$ -invariant and ergodic, and disjoint sets  $A_1, \dots, A_l$  such that  $\mu_i(A_i) = 1$ ,  $\text{Leb}(A_i) > 0$ ,  $\text{Leb}(X_0 \setminus \bigcup_{i=1}^l A_i) = 0$  and, for every  $x \in A_i$  and every function  $f \in \overline{C^0(X_0) \cap H}$  (the closure of  $C^0(X_0) \cap H$  in  $C^0(X_0)$ ), then  $\frac{1}{n} \sum_{j=0}^{n-1} f(T^j x) \rightarrow \int f \, d\mu_i$ .

Moreover, for every  $i$ , there exist an integer  $k_i$  and a decomposition  $\mu_i = \mu_{i,1} + \dots + \mu_{i,k_i}$  such that  $T$  sends  $\mu_{i,j}$  to  $\mu_{i,j+1}$  for  $j \in \mathbb{Z}/k_i\mathbb{Z}$ , and the probability measures  $k_i \mu_{i,j}$  are exponentially mixing for  $T^{k_i}$  and  $C^\alpha$  test functions.

The proof will also describe a direct relationship between the eigenfunctions of  $\mathcal{L}$  for eigenvalues of modulus 1, and the physical measures of  $T$ . The first part of the proof is directly borrowed from [7].

The first, second and fourth conditions say that the space  $H$  is sufficiently large. They are satisfied in the setting of this paper (taking  $f_0 = 1_{X_0}$ , which belongs to  $\mathcal{H}_p^{t,t^-}$ ), but also in the case of an attractor, when  $T(X_0)$  is contained in the interior of  $X_0$  (the function  $f_0$  can be taken  $C^\infty$ , compactly supported in the interior of  $X_0$ , equal to 1 on  $T(X_0)$ ).

The fifth condition is necessary, as shown by Example 1 in Section 2: taking for  $H$  the space of distributions in the Sobolev space  $H_2^{-1}$  supported in  $[-1, 1] \times \{0, 1\}$ , then all the assumptions of the theorem but the fifth one are satisfied, and the conclusion of the theorem does not hold.

*Proof.* Let us first prove the existence of  $C > 0$  such that, for any  $n \in \mathbb{N}$ ,

$$(54) \quad \|\mathcal{L}^n\|_{H \rightarrow H} \leq C.$$

Otherwise,  $\mathcal{L}$  has an eigenvalue of modulus  $> 1$ , or a nontrivial Jordan block for an eigenvalue of modulus 1. Let  $\lambda$  be an eigenvalue of  $\mathcal{L}$  of maximal modulus, with a Jordan block of maximal size  $d$ . Since  $L_\infty \cap H$  is dense in  $H$ , its image under the eigenprojections is dense in the eigenspaces, which are finite dimensional. Hence, it coincides with the full eigenspaces. Therefore, there exists a bounded function  $f$  such that  $n^{-d} \sum_{i=0}^{n-1} \lambda^{-i} \mathcal{L}^i f$  converges to a nonzero limit  $u$ . For any  $C^\infty$  function  $g$ ,

$$\langle u, g \, d\text{Leb} \rangle = \lim_{n \rightarrow \infty} \frac{1}{n^d} \sum_{i=0}^{n-1} \lambda^{-i} \langle \mathcal{L}^i f, g \, d\text{Leb} \rangle = \lim_{n \rightarrow \infty} \frac{1}{n^d} \sum_{i=0}^{n-1} \lambda^{-i} \int f \cdot g \circ T^i \, d\text{Leb}.$$

If  $|\lambda| > 1$  or  $d \geq 2$ , this quantity converges to 0 when  $n \rightarrow \infty$  since  $\int f \cdot g \circ T^i \, d\text{Leb}$  is uniformly bounded. This contradicts the fact that  $u$  is nonzero, and proves (54).

For  $|\lambda| = 1$ , let  $E_\lambda$  denote the corresponding eigenspace, and  $\Pi_\lambda : H \rightarrow E_\lambda$  the corresponding eigenprojection. It is given by

$$(55) \quad \Pi_\lambda f = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=0}^{n-1} \lambda^{-i} \mathcal{L}^i f,$$

<sup>5</sup>We write  $\langle u, g \, d\text{Leb} \rangle$  and not  $\langle u, g \rangle$ , in accordance with the convention stated in the footnote page 6, viewing distributions as generalized functions which can only be integrated against smooth densities.

where the convergence holds in  $H$ . Since  $L_\infty(\text{Leb}) \cap H$  is dense in  $H$ ,  $E_\lambda = \Pi_\lambda(L_\infty(\text{Leb}) \cap H)$ . For any  $f \in L_\infty(\text{Leb}) \cap H$  and  $g \in C^\infty$ ,

$$(56) \quad |\langle \Pi_\lambda f, g \, d\text{Leb} \rangle| \leq \lim \frac{1}{n} \sum_{i=0}^{n-1} \left| \int f \cdot g \circ T^i \, d\text{Leb} \right| \leq C \|f\|_{L_\infty} \|g\|_{C^0}.$$

By Riesz representation theorem on the compact space  $X_0$ , this implies that, for any  $u \in E_\lambda$ , there exists a finite measure  $\mu_u$  on  $X_0$  such that  $\langle u, g \, d\text{Leb} \rangle = \int g \, d\mu_u$ . Moreover, for  $i \geq N_0$  and  $g \geq 0$ ,

$$\begin{aligned} \left| \int f \cdot g \circ T^i \, d\text{Leb} \right| &= \left| \int \mathcal{L}^{N_0} f \cdot g \circ T^{i-N_0} \, d\text{Leb} \right| = \left| \int \mathcal{L}^{N_0} f \cdot f_0 \cdot g \circ T^{i-N_0} \, d\text{Leb} \right| \\ &\leq C \int f_0 \cdot g \circ T^{i-N_0} \, d\text{Leb} = C \int \mathcal{L}^{i-N_0} f_0 \cdot g \, d\text{Leb}. \end{aligned}$$

Averaging and taking the limit, we obtain

$$(57) \quad \left| \int g \, d\mu_{\Pi_\lambda f} \right| \leq C \int g \, d\mu_{\Pi_1 f_0}.$$

This means that the measures  $\mu_u$  are all absolutely continuous with respect to the reference measure  $\mu := \mu_{\Pi_1 f_0}$ , with bounded density.

Let us show that the measure  $\mu$  is invariant. This is formally trivial from the computation

$$\int g \, d\mu = \langle \Pi_1 f_0, g \, d\text{Leb} \rangle = \langle \mathcal{L} \Pi_1 f_0, g \, d\text{Leb} \rangle = \langle \Pi_1 f_0, g \circ T \, d\text{Leb} \rangle = \int g \circ T \, d\mu.$$

However, this argument is not correct since  $\langle \Pi_1 f_0, g \circ T \, d\text{Leb} \rangle$  is not well defined since  $g$  is not smooth. More importantly, even if we could define it, the equality between  $\langle \Pi_1 f_0, g \circ T \, d\text{Leb} \rangle$  and  $\int g \circ T \, d\mu$  would not be trivial since the relationship between  $\Pi_1 f_0$  and  $d\mu$  is established only for continuous functions.

The rigorous proof relies on the fifth assumption of the theorem. By definition, if  $g$  is  $C^\infty$ , then  $\int g \, d\mu = \lim \int g \, d\left(\frac{1}{n} \sum_{i=0}^{n-1} T_*^i(f_0 \, \text{Leb})\right)$ . By density, this equality extends to  $C^0$  functions, hence  $\mu$  is the weak limit of the sequence of measures  $\frac{1}{n} \sum_{i=0}^{n-1} T_*^i(f_0 \, \text{Leb})$ . In turn, for any function  $h$  whose discontinuity set has zero measure for  $\mu$ ,

$$(58) \quad \int h \, d\mu = \lim \int h \, d\left(\frac{1}{n} \sum_{i=0}^{n-1} T_*^i(f_0 \, \text{Leb})\right).$$

If  $g$  is a continuous function, then  $g \circ T$  is continuous except on the discontinuity set of  $T$ . The fifth assumption of the theorem shows that this set has zero measure for  $\mu$ . Hence, (58) applies to  $g \circ T$ . It also applies to  $g$ . Since the right hand side for  $g$  and  $g \circ T$  coincide up to  $O(1/n)$ , this yields  $\int g \circ T \, d\mu = \int g \, d\mu$  and concludes the proof of the invariance of  $\mu$ .

In the following, we shall encounter several instances of similar equations that are formally trivial but need a rigorous justification. Let us give a last justification of this type, and leave the remaining ones to the reader. We claim that, if  $\phi \in C^\alpha$  and  $g \in C^\infty$ ,

$$(59) \quad \langle \mathcal{L}^i(\phi \Pi_1 f_0), g \, d\text{Leb} \rangle = \int \phi \cdot g \circ T^i \, d\mu.$$

Indeed,  $\mathcal{L}^i(\phi \Pi_1 f_0)$  is the limit in  $H$  of  $\mathcal{L}^i(\phi \frac{1}{n} \sum_{j=0}^{n-1} \mathcal{L}^j f_0)$ , hence

$$\begin{aligned} \langle \mathcal{L}^i(\phi \Pi_1 f_0), g \, d\text{Leb} \rangle &= \lim \frac{1}{n} \sum_{j=0}^{n-1} \langle \mathcal{L}^i(\phi \mathcal{L}^j f_0), g \, d\text{Leb} \rangle \\ &= \lim \frac{1}{n} \sum_{j=0}^{n-1} \int \phi \mathcal{L}^j f_0 \cdot g \circ T^i \, d\text{Leb} \\ &= \lim \int \phi \cdot g \circ T^i \, d \left( \frac{1}{n} \sum_{j=0}^{n-1} T_*^j(f_0 \text{Leb}) \right). \end{aligned}$$

The measure  $\mu$  gives zero mass to the discontinuities of  $g \circ T^i$  (since it is invariant and gives zero mass to the discontinuities of  $T$ ). Hence, (58) holds for  $\phi \cdot g \circ T^i$ . This concludes the proof of (59).

For any  $u \in E_\lambda$ , write  $\mu_u = \phi_u \mu$  where  $\phi_u \in L_\infty(\mu)$  is defined  $\mu$ -almost everywhere. The equation  $\mathcal{L}u = \lambda u$  translates into  $T_*(\phi_u \mu) = \lambda \phi_u \mu$ . Hence, since  $\mu$  is invariant,

$$\begin{aligned} \int |\phi_u \circ T - \lambda^{-1} \phi_u|^2 \, d\mu &= \int |\phi_u|^2 \circ T \, d\mu + \int |\phi_u|^2 - 2\Re \int \overline{\phi_u} \circ T \lambda^{-1} \phi_u \, d\mu \\ &= 2 \int |\phi_u|^2 \, d\mu - 2\Re \int \lambda^{-1} \overline{\phi_u} \, dT_*(\phi_u \mu) = 0. \end{aligned}$$

Let  $F_\lambda = \{\phi \in L_\infty(\mu) \mid \phi \circ T = \lambda^{-1} \phi\}$  (this is a space of equivalence classes of functions), then the map  $\Phi_\lambda : u \mapsto \phi_u$  sends (injectively)  $E_\lambda$  to  $F_\lambda$ . Let us show that it is also surjective.

Let  $\phi \in F_\lambda$ . By Lusin's theorem, there exists a sequence of  $C^\alpha$  functions  $\phi_p$  with  $\|\phi - \phi_p\|_{L^1(\mu)} \leq 1/p$ . Let  $u_p = \Pi_\lambda(\phi_p \Pi_1 f_0)$ , and let  $\mu_p = \mu_{u_p}$ . Let us prove that the total mass of the measure  $\phi d\mu - d\mu_p$  converges to 0. If  $g$  is a  $C^\infty$  function,

$$\begin{aligned} \int g \, d\mu_p &= \langle u_p, g \, d\text{Leb} \rangle = \lim \frac{1}{n} \sum_{i=0}^{n-1} \lambda^{-i} \langle \mathcal{L}^i(\phi_p \Pi_1 f_0), g \, d\text{Leb} \rangle \\ &= \lim \frac{1}{n} \sum_{i=0}^{n-1} \lambda^{-i} \int \phi_p \cdot g \circ T^i \, d\mu, \end{aligned}$$

by (59). On the other hand, for any  $n$ , since  $\mu$  is invariant and  $\phi \circ T = \lambda^{-1} \phi$ ,

$$\int g \phi \, d\mu = \frac{1}{n} \sum_{i=0}^{n-1} \int g \circ T^i \phi \circ T^i \, d\mu = \frac{1}{n} \sum_{i=0}^{n-1} \lambda^{-i} \int g \circ T^i \phi \, d\mu.$$

Subtracting the two previous equations, we get

$$(60) \quad \left| \int g \phi \, d\mu - \int g \, d\mu_p \right| \leq \|\phi - \phi_p\|_{L^1(\mu)} \|g\|_{C^0},$$

which proves that the total mass of  $\phi d\mu - d\mu_p$  converges to 0.

The sequence  $u_p$  belongs to the finite dimensional space  $E_\lambda$ , and the elements of  $E_\lambda$  are separated by the linear forms given by the integration along  $C^\infty$  densities (since  $H$  is a space of distributions). Since  $\langle u_p, g \, d\text{Leb} \rangle$  converges for any  $g$ , the sequence  $u_p$  is therefore converging to a limit  $u_\infty$ . By construction,  $\Phi_\lambda(u_\infty) = \phi$ . This concludes the proof of the surjectivity of  $\Phi_\lambda$ .

The eigenvalues of  $\mathcal{L}$  of modulus 1 are exactly the  $\lambda$  such that  $F_\lambda$  is not reduced to 0. This set is a group, since  $\phi_\lambda \phi_{\lambda'} \in F_{\lambda\lambda'}$  whenever  $\phi_\lambda \in F_\lambda$  and  $\phi_{\lambda'} \in F_{\lambda'}$ . Since  $\mathcal{L}$  only has a finite number of eigenvalues of modulus 1, this implies that these eigenvalues are roots of unity. In particular, there exists  $N > 0$  such that  $\lambda^N = 1$  for any eigenvalue  $\lambda$ .

Let us now assume that 1 is the only eigenvalue of  $\mathcal{L}$  of modulus 1 (in the general case, this will be true for  $\mathcal{L}^N$ , so we will be able to deduce the general case from this particular case). Under this assumption, for any  $u \in H$ ,  $\mathcal{L}^n u$  converges to  $\Pi_1 u$ .

Consider the subset of  $F_1$  given by the nonnegative functions with integral 1. It is a convex cone in  $F_1$ , whose extremal points are of the form  $1_B$  for some minimal invariant set  $B$ . Such extremal points are automatically linearly independent. Since  $F_1$  is finite-dimensional, there is only a finite number of them, say  $1_{B_1}, \dots, 1_{B_l}$ , and a function belongs to  $F_1$  if and only if it can be written as  $\phi = \sum \alpha_i 1_{B_i}$  for some scalars  $\alpha_1, \dots, \alpha_l$ . The decomposition of the function  $1 \in F_1$  is given by  $1 = \sum 1_{B_i}$ , hence the sets  $B_i$  cover the whole space up to a set of zero measure for  $\mu$ . Moreover, since  $B_i$  is minimal, the measure  $\mu_i := \frac{1_{B_i} \mu}{\mu(B_i)}$  is an invariant ergodic probability measure.

Let  $u_i = \Phi_1^{-1}(1_{B_i}) \in H$ , then any element of  $E_1$  is a linear combination of the  $u_i$ . In particular, this applies to  $\Pi_1(fu_i)$  for any  $f \in C^\alpha$ . Let us show that

$$(61) \quad \Pi_1(fu_i) = \left( \int f \, d\mu_i \right) u_i.$$

We can write  $\Pi_1(fu_i) = \sum a_{ij}(f)u_j$ . Let us fix once and for all  $l$  sequences of  $C^\alpha$  functions  $\phi_{j,p}$  taking values in  $[0, 1]$  and such that  $\phi_{j,p}$  converges in  $L_1(\mu)$  to  $1_{B_j}$ . Since  $\langle u_j, \phi_{j',p} \, d\text{Leb} \rangle = \int_{B_j} \phi_{j',p} \, d\mu \rightarrow \delta_{jj'} \mu(B_j)$ , we have  $a_{ij}(f) = \frac{1}{\mu(B_j)} \lim_{p \rightarrow \infty} \langle \Pi_1(fu_i), \phi_{j,p} \, d\text{Leb} \rangle$ . Moreover, if  $p$  is fixed,

$$\begin{aligned} \langle \Pi_1(fu_i), \phi_{j,p} \, d\text{Leb} \rangle &= \lim_{n \rightarrow \infty} \langle \mathcal{L}^n(fu_i), \phi_{j,p} \, d\text{Leb} \rangle \\ &= \lim_{n \rightarrow \infty} \int_{B_i} f \phi_{j,p} \circ T^n \, d\mu. \end{aligned}$$

Writing  $\phi_{j,p} \circ T^n = 1_{B_j} \circ T^n + (\phi_{j,p} - 1_{B_j}) \circ T^n$  and using  $1_{B_j} \circ T^n = 1_{B_j}$  and  $\|(\phi_{j,p} - 1_{B_j}) \circ T^n\|_{L_1(\mu)} = \|\phi_{j,p} - 1_{B_j}\|_{L_1(\mu)} \rightarrow_{p \rightarrow \infty} 0$ , we obtain (61).

This enables us to deduce that each measure  $\mu_i$  is exponentially mixing, as follows. Let  $\delta < 1$  be such that  $\|\mathcal{L}^n - \Pi_1\|_{H \rightarrow H} = O(\delta^n)$ . Then, if  $f, g$  are  $C^\alpha$  functions,

$$\begin{aligned} \int f \cdot g \circ T^n \, d\mu_i &= \frac{1}{\mu(B_i)} \langle \mathcal{L}^n(fu_i), g \, d\text{Leb} \rangle = \frac{1}{\mu(B_i)} \langle \Pi_1(fu_i), g \, d\text{Leb} \rangle + O(\delta^n) \\ &= \left( \int f \, d\mu_i \right) \frac{1}{\mu(B_i)} \langle u_i, g \, d\text{Leb} \rangle + O(\delta^n) \\ &= \left( \int f \, d\mu_i \right) \left( \int g \, d\mu_i \right) + O(\delta^n). \end{aligned}$$

We now turn to the relationships between Lebesgue measure and the measures  $\mu_i$ . For any function  $f \in L_\infty(\text{Leb}) \cap H$ , let us write

$$(62) \quad \Pi_1(f) = \sum_{i=1}^l b_i(f) u_i.$$

We will need to describe the coefficients  $b_i(f)$ . Let  $n_p$  be a sequence tending fast enough to  $\infty$  so that  $\|\mathcal{L}^{n_p} - \Pi_1\|_{H \rightarrow H} \|\phi_{i,p}\|_{C^\alpha} \rightarrow_{p \rightarrow \infty} 0$ . If  $f$  belongs to  $L_\infty(\text{Leb}) \cap H$ ,

$$\begin{aligned} \int f \cdot \phi_{i,p} \circ T^{n_p} \, d\text{Leb} &= \langle \mathcal{L}^{n_p} f, \phi_{i,p} \, d\text{Leb} \rangle \\ &= \langle \phi_{i,p}(\mathcal{L}^{n_p} - \Pi_1)f, d\text{Leb} \rangle + \langle \Pi_1 f, \phi_{i,p} \, d\text{Leb} \rangle \\ &= o(1) + \sum_{j=1}^l b_j(f) \int_{B_j} \phi_{i,p} \, d\mu = o(1) + b_i(f) \mu(B_i). \end{aligned}$$

More generally,  $\int f \cdot \left( \frac{1}{n_p} \sum_{n=n_p}^{2n_p-1} \phi_{i,p} \circ T^n \right) d\text{Leb} \rightarrow \mu(B_i) b_i(f)$ . The sequence  $\frac{1}{n_p} \sum_{n=n_p}^{2n_p-1} \phi_{i,p} \circ T^n$  is bounded in  $L^2(\text{Leb})$ , and asymptotically invariant. Let  $h_i : X \rightarrow [0, 1]$  be one of its weak limits. It satisfies

$$(63) \quad b_i(f) = \frac{1}{\mu(B_i)} \int f h_i \, d\text{Leb},$$

and  $h_i \circ T = h_i$ . Since  $b_i(f_0) = 1$ , we have  $\int h_i f_0 \, d\text{Leb} = \mu(B_i)$ .

Let us now compute  $\int h_i h_j f_0 \, d\text{Leb}$ . We have

$$\begin{aligned} \mu(B_j) b_j(\phi_{i,p} \mathcal{L}^n f_0) &= \int \phi_{i,p} \mathcal{L}^n f_0 h_j \, d\text{Leb} = \int f_0 \phi_{i,p} \circ T^n h_j \circ T^n \, d\text{Leb} \\ &= \int \phi_{i,p} \circ T^n h_j f_0 \, d\text{Leb}. \end{aligned}$$

Taking the average and the weak-limit, we obtain

$$(64) \quad \int h_i h_j f_0 \, d\text{Leb} = \mu(B_j) \lim_{p \rightarrow \infty} \frac{1}{n_p} \sum_{n=n_p}^{2n_p-1} b_j(\phi_{i,p} \mathcal{L}^n f_0).$$

Moreover, if  $n \geq n_p$ ,

$$(65) \quad \phi_{i,p} \mathcal{L}^n f_0 = \phi_{i,p}(\mathcal{L}^n - \Pi_1) f_0 + \phi_{i,p} \Pi_1 f_0.$$

The first term converges to 0 in  $H$ , and the computation made in (60) shows that  $\Pi_1(\phi_{i,p} \Pi_1 f_0)$  converges to  $u_i$ . This implies that  $b_j(\phi_{i,p} \mathcal{L}^n f_0)$  converges to  $\delta_{ij}$ . This yields

$$(66) \quad \int h_i h_j f_0 \, d\text{Leb} = \mu(B_j) \delta_{ij}.$$

Let  $X_1 = \{x \mid f_0(x) > 0\}$ . Taking  $i = j$ , we get  $\int h_i^2 f_0 \, d\text{Leb} = \mu(B_i) = \int h_i f_0 \, d\text{Leb}$ . Since  $h_i$  takes its values in  $[0, 1]$ , this shows that there exists a subset  $C_i^0$  of  $X_1$  such that  $h_i 1_{X_1} = 1_{C_i^0}$ , with  $\int_{C_i^0} f_0 \, d\text{Leb} = \mu(B_i)$ . Moreover, (66) shows that  $\text{Leb}(C_i^0 \cap C_j^0) = 0$  if  $i \neq j$ . Let  $C_i = T^{-N_0} C_i^0$ , then these sets are disjoint. For any function  $f \in L_\infty(\text{Leb}) \cap H$ , since  $\mathcal{L}^{N_0} f$  is supported in  $X_1$ ,

$$\begin{aligned} b_i(f) &= b_i(\mathcal{L}^{N_0} f) = \frac{1}{\mu(B_i)} \int \mathcal{L}^{N_0} f h_i \, d\text{Leb} = \frac{1}{\mu(B_i)} \int \mathcal{L}^{N_0} f \cdot 1_{C_i^0} \, d\text{Leb} \\ &= \frac{1}{\mu(B_i)} \int f \cdot 1_{C_i^0} \circ T^{N_0} \, d\text{Leb} = \frac{1}{\mu(B_i)} \int_{C_i} f \, d\text{Leb}. \end{aligned}$$

Moreover, since  $\mathcal{L}^{N_0}1$  is supported on the sets  $C_i^0$ ,

$$\begin{aligned}\text{Leb}(X_0) &= \int 1 \, d\text{Leb} = \int \mathcal{L}^{N_0}1 \, d\text{Leb} = \int \mathcal{L}^{N_0}1 \cdot 1_{\bigcup C_i^0} \, d\text{Leb} \\ &= \int 1_{\bigcup C_i^0} \circ T^{N_0} \, d\text{Leb} = \int 1_{\bigcup C_i} \, d\text{Leb}.\end{aligned}$$

This shows that the sets  $C_i$  form a partition of the space modulo a set of zero Lebesgue measure. We have proved that

$$(67) \quad \Pi_1(f) = \sum_{i=1}^l \frac{\int_{C_i} f \, d\text{Leb}}{\mu(B_i)} u_i.$$

Let us now turn to the convergence of  $\frac{1}{n} \sum_{j=0}^{n-1} f \circ T^j$ , for  $f \in L_\infty(\text{Leb}) \cap H$ . Let  $S_n f = \sum_{j=0}^{n-1} f \circ T^j$ , we will estimate  $\int |S_n f/n - S_m f/m|^2 f_0 \, d\text{Leb}$ . For  $i, j \geq 0$ , we have

$$\begin{aligned}\int f \circ T^i \cdot f \circ T^{i+j} f_0 \, d\text{Leb} &= \int f \mathcal{L}^i(f_0) \cdot f \circ T^j \, d\text{Leb} \\ &= \int \mathcal{L}^j(f \mathcal{L}^i f_0) f \, d\text{Leb} = \langle \mathcal{L}^j(f \mathcal{L}^i f_0), f \rangle \\ &= \langle \mathcal{L}^j(f \Pi_1 f_0), f \rangle + O(\delta^i) = \langle \Pi_1(f \Pi_1 f_0), f \rangle + O(\delta^i) + O(\delta^j),\end{aligned}$$

where  $\delta < 1$  is given by the spectral gap of the operator  $\mathcal{L}$ . Hence, for  $n, m > 0$ ,

$$\begin{aligned}\int S_n f \cdot S_m f f_0 \, d\text{Leb} &= nm \langle \Pi_1(f \Pi_1 f_0), f \rangle + \sum_{\substack{0 \leq i \leq n-1 \\ 0 \leq j \leq m-1-i}} O(\delta^i) + O(\delta^j) + \sum_{\substack{0 \leq i \leq m-1 \\ 0 < j \leq n-1-i}} O(\delta^i) + O(\delta^j) \\ &= nm \langle \Pi_1(f \Pi_1 f_0), f \rangle + O(n) + O(m).\end{aligned}$$

Expanding the square in  $|S_n f/n - S_m f/m|^2$ , we get using the previous equation

$$\begin{aligned}\int |S_n f/n - S_m f/m|^2 f_0 \, d\text{Leb} &= \frac{1}{n^2} \int S_n f \cdot S_n f f_0 \, d\text{Leb} + \frac{1}{m^2} \int S_m f \cdot S_m f f_0 \, d\text{Leb} - \frac{2}{nm} \int S_n f \cdot S_m f f_0 \, d\text{Leb} \\ &= O(1/n) + O(1/m).\end{aligned}$$

The functions  $g_p = S_{p^4} f/p^4$  therefore satisfy  $\|g_{p+1} - g_p\|_{L_2(f_0 \, d\text{Leb})} = O(1/p^2)$ , which is summable. This implies that  $g_p$  converges in  $L_2(f_0 \, d\text{Leb})$  and almost everywhere for this measure. For a general  $n \in \mathbb{N}$ , let  $p$  be such that  $p^4 \leq n < (p+1)^4$ , then  $S_n f/n - S_{p^4} f/p^4$  is uniformly small if  $n$  is large. Hence,  $S_n f/n$  converges almost everywhere and in  $L_2(f_0 \, d\text{Leb})$ , to a function  $\phi_f \in L_2(f_0 \, d\text{Leb})$ .

Let us now identify the function  $\phi_f$ . For any smooth function  $\phi$ ,

$$\begin{aligned} \int \phi \cdot f \circ T^n f_0 \, d\text{Leb} &= \langle \mathcal{L}^n(\phi f_0), f \, d\text{Leb} \rangle \\ &\rightarrow \langle \Pi_1(\phi f_0), f \, d\text{Leb} \rangle = \sum_{i=1}^l b_i(\phi f_0) \int_{B_i} f \, d\mu \\ &= \sum_{i=1}^l \frac{\int_{C_i} \phi f_0 \, d\text{Leb}}{\mu(B_i)} \int_{B_i} f \, d\mu = \int \left( \sum_{i=1}^l 1_{C_i} \frac{\int_{B_i} f \, d\mu}{\mu(B_i)} \right) \phi f_0 \, d\text{Leb}. \end{aligned}$$

This shows that, with respect to the measure  $f_0 \, d\text{Leb}$ , the sequence of functions  $f \circ T^n$  converges weakly to the function  $\tilde{\phi}_f := \sum_{i=1}^l 1_{C_i} (\int f \, d\mu_i)$ . In turn,  $S_n f/n$  converges weakly to  $\tilde{\phi}_f$ . However,  $S_n f/n$  converges strongly to  $\phi_f$ , hence  $\phi_f = \tilde{\phi}_f$  almost everywhere for  $f_0 \, d\text{Leb}$ , and in particular on almost all  $\bigcup_{i=1}^l C_i^0$ .

Let  $A_i^f$  be the set of points for which  $S_n f/n$  converges to  $\int f \, d\mu_i$ . We have shown that  $A_i^f$  contains a full Lebesgue measure subset of  $C_i^0$ . However,  $A_i^f$  is  $T$ -invariant, hence it contains a full Lebesgue measure subset of  $C_i$ . Since the sets  $C_i$  cover Lebesgue almost all the space,  $\text{Leb}(X \setminus \bigcup_{i=1}^l A_i^f) = 0$ . By the Birkhoff ergodic theorem,  $A_i^f$  is also a full  $\mu$  measure subset of  $B_i$ . Let  $f_n$  be a countable sequence of functions in  $C^0(X_0) \cap H$ , which is  $C^0$ -dense in  $\overline{C^0(X_0) \cap H}$ , and set  $A_i = \bigcap_{n \in \mathbb{N}} A_i^{f_n}$ . These sets satisfy the conclusion of the theorem.

This concludes the proof of the theorem when 1 is the only eigenvalue of modulus 1 of  $\mathcal{L}$ . If  $\mathcal{L}$  has other eigenvalues of modulus 1, let  $N$  be such that  $\lambda^N = 1$  for all these eigenvalues  $\lambda$ . The above result applies to  $T^N$ , and gives sets  $A_1, \dots, A_l$  and probability measures  $\mu_1, \dots, \mu_l$ . The map  $T$  induces a permutation of the sets  $A_i$  (modulo sets of 0 measure for  $\mu$ ), say  $T(A_i) = A_{\sigma(i)} \pmod 0$  for some permutation  $\sigma$  of  $\{1, \dots, l\}$ . For any orbit  $(i_1, \dots, i_k)$  of  $\sigma$ , the measure  $\frac{1}{k}(\mu_{i_1} + \dots + \mu_{i_k})$  is  $T$ -invariant, and its basin of attraction contains  $\bigcap_{j=0}^{N-1} T^{-j}(A_{i_1} \cup \dots \cup A_{i_k})$ . These measures are the measures of the statement of the theorem, and their properties readily follow from the corresponding properties for  $T^N$ .  $\square$

To deduce Theorem 11 from Theorem 30, we just have to check the fifth condition of Theorem 30 since the other ones are trivially satisfied. Working locally in a chart, it is sufficient to prove the following lemma:

**Lemma 31.** *Let  $K$  be a compact smooth hypersurface with boundary in  $\mathbb{R}^d$ , whose intersection with almost every line parallel to a coordinate axis has at most  $L < \infty$  points. Let  $1/p - 1 < t_- \leq 0 \leq t < 1/p$ , and let  $u \in H_p^{t, t_-}$  be such that*

- *there exists a sequence of nonnegative functions  $u_n \in H_p^{t, t_-} \cap L_\infty(\text{Leb})$  converging in  $H_p^{t, t_-}$  to  $u$ .*
- *there exists a measure  $\mu$  with  $\langle u, g \, d\text{Leb} \rangle = \int g \, d\mu$  for any  $C^\infty$  function  $g$ .*
- *The support of  $u$  does not intersect  $\partial K$ .*

Then  $\mu(K) = 0$ .

*Proof.* Let us first prove that there exists a sequence of neighborhoods  $K_n$  of  $K \cap \text{supp } u$ , whose intersection with almost every line parallel to a coordinate axis has at most  $L' < \infty$  connected components, and with  $\text{Leb}(K_n) \rightarrow 0$ .

Working locally, we can assume that  $K$  is transversal to a coordinate direction, say the last one. Hence, we can assume that  $u$  is supported in  $[-1/2, 1/2]^{d-1} \times \mathbb{R}$ ,

and that  $K$  can be written as the graph of a smooth function  $f$ ,

$$(68) \quad K = \{(x_1, \dots, x_{d-1}, f(x_1, \dots, x_{d-1})) \mid (x_1, \dots, x_{d-1}) \in [-1, 1]^{d-1}\}.$$

Let  $K_n = \{(x_1, \dots, x_{d-1}, f(x_1, \dots, x_{d-1}) + y) \mid (x_1, \dots, x_{d-1}) \in [-1, 1]^{d-1}, |y| < 1/n\}$ . It is a neighborhood of  $K \cap \text{supp } u$ . It intersects any line parallel to the last coordinate axis along one connected component. Consider now another coordinate axis, say the first one. Fix  $(x_2, \dots, x_{d-1})$ . Then the boundary of  $K_n \cap (\mathbb{R} \times \{(x_2, \dots, x_{d-1})\} \times \mathbb{R})$  is formed of two vertical segments and two translates of the graph of the function  $x \mapsto f(x, x_2, \dots, x_d)$ . For almost every  $(x_2, \dots, x_d)$ , this graph intersects almost every horizontal line along at most  $L$  points. Hence, the intersection of almost every horizontal line with the boundary of  $K_n \cap (\mathbb{R} \times \{(x_2, \dots, x_{d-1})\} \times \mathbb{R})$  has at most  $2L + 2$  points. In particular,  $K_n$  intersects almost every horizontal line along at most  $2L + 1$  connected components. This concludes the construction of  $K_n$ .

By Lemma 20, there exists a constant  $C$  such that, for any  $n \in \mathbb{N}$ , the multiplication by  $1_{K_n}$  sends  $H_p^{t, t_-}$  into itself, with a norm bounded by  $C$ . In particular,  $1_{K_n}$  belongs to  $H_p^{t, t_-}$  and is bounded in this space.

Let us show that  $1_{K_n}$  tends to 0 in  $H_p^{t, t_-}$ . Let  $t' \in (t, 1/p)$ . Then  $1_{K_n}$  is also bounded in  $H_p^{t', t_-}$  by the same argument. Since the injection of  $H_p^{t', t_-}$  in  $H_p^{t, t_-}$  is compact, the sequence  $1_{K_n}$  is therefore relatively compact in  $H_p^{t, t_-}$ . Let  $v$  be one of its cluster values. For any smooth function  $g$ ,

$$(69) \quad \langle v, g \, d\text{Leb} \rangle = \lim \langle 1_{K_n}, g \, d\text{Leb} \rangle = \lim \int 1_{K_n} g \, d\text{Leb} = 0,$$

since  $\text{Leb}(K_n)$  tends to 0. Hence,  $v$  is the zero distribution. The sequence  $1_{K_n}$  is relatively compact in  $H_p^{t, t_-}$  and its only cluster value is zero, hence it converges to 0.

Let us now show that, for any  $v \in H_p^{t, t_-}$ ,

$$(70) \quad \|1_{K_n} v\|_{H_p^{t, t_-}} \rightarrow 0.$$

Choose a  $C^\infty$  function  $\phi$  with  $\|v - \phi\|_{H_p^{t, t_-}} \leq \epsilon$ , then

$$\begin{aligned} \|1_{K_n} v\|_{H_p^{t, t_-}} &\leq \|1_{K_n}(v - \phi)\|_{H_p^{t, t_-}} + \|1_{K_n} \phi\|_{H_p^{t, t_-}} \\ &\leq C \|v - \phi\|_{H_p^{t, t_-}} + \|\phi\|_{C^1} \|1_{K_n}\|_{H_p^{t, t_-}} \leq C\epsilon + o(1). \end{aligned}$$

This proves (70).

Let  $g$  be a  $C^\infty$  function supported in  $K_n$ , taking its values in  $[0, 1]$ , equal to 1 on  $K$ . We claim that

$$(71) \quad \int g \, d\mu \leq \langle 1_{K_n} u, d\text{Leb} \rangle.$$

Indeed, write  $u = \lim u_m$  where  $u_m$  is a nonnegative function belonging to  $L_\infty(\text{Leb}) \cap H_p^{t, t_-}$ . Then  $\langle u_m, g \, d\text{Leb} \rangle = \int g u_m \, d\text{Leb} \leq \int 1_{K_n} u_m \, d\text{Leb} = \langle 1_{K_n} u_m, d\text{Leb} \rangle$ . Taking the limit over  $m$ , we get (71).

We can now conclude the proof: by (71), we have  $\mu(K) \leq C \|1_{K_n} u\|_{H_p^{t, t_-}}$ . This quantity converges to 0 by (70).  $\square$

**Remark 32.** The proof of the previous lemma implies that Dirac masses cannot belong to  $H_p^{t, t_-}$  if  $1/p - 1 < t_- \leq 0 \leq t < 1/p$ : assume for a contradiction that

$\delta_0$ , the Dirac mass at 0, belongs to  $H_p^{t,t-}$ . Take  $K_n$  the ball of radius  $1/n$  centered at 0. Then  $\delta_0 = 1_{K_n} \delta_0$  for each  $n$ , but  $1_{K_n} \delta_0$  tends to zero in  $H_p^{t,t-}$  as  $n \rightarrow \infty$ , a contradiction.

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D.M.A., UMR 8553, ÉCOLE NORMALE SUPÉRIEURE, 75005 PARIS, FRANCE  
*E-mail address:* `viviane.baladi@ens.fr`

IRMAR, UNIVERSITÉ DE RENNES 1, 35042 RENNES, FRANCE  
*E-mail address:* `sebastien.gouezel@univ-rennes1.fr`