

A FAMILY OF NATURAL EQUILIBRIUM MEASURES FOR SINAI BILLIARD FLOWS

JÉRÔME CARRAND

ABSTRACT. The Sinai billiard flow on the two-torus, i.e., the periodic Lorentz gaz, is a continuous flow, but it is not everywhere differentiable. Assuming finite horizon, we relate the equilibrium states of the flow with those of the Sinai billiard map T – which is a discontinuous map. We propose a definition for the topological pressure $P_*(T, g)$ associated to a potential g . We prove that for any piecewise Hölder potential g satisfying a mild assumption, $P_*(T, g)$ is equal to the definitions of Bowen using spanning or separating sets. We give sufficient conditions under which a potential gives rise to equilibrium states for the Sinai billiard map. We prove that in this case the equilibrium state μ_g is unique, Bernoulli, adapted and gives positive measure to all nonempty open sets. For this, we make use of a well chosen transfer operator acting on anisotropic Banach spaces, and construct the measure by pairing its maximal eigenvectors. Last, we prove that the flow invariant probability measure $\bar{\mu}_g$, obtained by taking the product of μ_g with the Lebesgue measure along orbits, is Bernoulli and flow adapted. We give examples of billiard tables for which there exists an open set of potentials satisfying those sufficient conditions.

1. INTRODUCTION

1.1. Billiards and equilibrium states. In this work, we are concerned with a class of dynamics with singularities: the dispersing billiards introduced by Sinai [30] on the two-torus. A Sinai billiard on the torus is the periodic case of the planar Lorentz gaz (1905) model for the motion of a single dilute electron in a metal. The scatterers (corresponding to atoms of the metals) are assumed to be strictly convex (but not necessarily discs). Such billiards have become fundamental models in mathematical physics.

To be more precise, a Sinai billiard table Q on the two-torus \mathbb{T}^2 is a set $Q = \mathbb{T}^2 \setminus B$ with $B = \sqcup_{i=1}^D B_i$ for some finite number $D \geq 1$ of pairwise disjoint closed domains B_i , called scatterers, with C^3 boundaries having strictly positive curvature – in particular, the scatterers are strictly convex. The billiard flow ϕ_t is the motion of a point particle travelling at unit speed in Q with specular reflections off the boundary of the scatterers. Identifying outgoing collisions with incoming ones in the phase space, the billiard flow is continuous. However, the grazing collisions – those tangential to scatterers – give rise to singularities in the derivative [13]. The Sinai billiard map T – also called collision map – is the return map of the single

Date: August 25, 2022.

JC is grateful to ITS–ETH Zurich for their invitation in May 2022. Thanks to Viviane Baladi, Mark Demers and Alexey Korepanov for useful discussions and comments. Research supported by the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 787304).

point particle to the scatterers. Because of the grazing collisions, the Sinai billiard map is a discontinuous map.

Sinai billiard maps and flows both preserve smooth invariant probability measures, respectively μ_{SRB} and $\tilde{\mu}_{\text{SRB}}$, which have been extensively studied: (T, μ_{SRB}) and $(\phi_t, \tilde{\mu}_{\text{SRB}})$ are uniformly hyperbolic, ergodic, K-mixing [30, 9, 31], and Bernoulli [20, 15]. The measure μ_{SRB} is T -adapted [24] in the sense of the integrability condition:

$$\int |\log d(x, \mathcal{S}_{\pm 1})| d\mu_{\text{SRB}} < \infty,$$

where $\mathcal{S}_{\pm 1}$ is the singularity set for $T^{\pm 1}$. Both systems enjoy exponential decay of correlations [33, 18]. Since the billiard has many periodic orbits, it thus has many other ergodic invariant measures, but until very recently most of the results apply to perturbations of μ_{SRB} [12, 17].

In the case of an Anosov flow, it is known since the work of Bowen [7] that the Kolmogorov-Sinai entropy is upper-semicontinuous, which guarantees the existence of measures of maximal entropy, or more generally, of equilibrium states. Because of the singularities, billiard flows are not Anosov and therefore methods used in the context of Anosov flows cannot be applied easily. The upper-semicontinuity of the entropy is not known at the moment, and, more generally, the existence of equilibrium states has to be treated one potential at the time.

In a recent paper, Baladi and Demers [3] proved, under a mild technical assumption and assuming finite horizon, that there exists a unique measure of maximal entropy μ_* for the billiard map, and that μ_* is Bernoulli, T -adapted, charges all nonempty open sets and does not have atoms. Their construction of this measure relies on the use of a transfer operator acting on anisotropic Banach spaces, similar to those used by [18] in order to study μ_{SRB} . Combining their work with those of Lima-Matheus [25] and Buzzi [11], Baladi and Demers proved that there exists a positive constant C such that

$$(1.1) \quad Ce^{h_* m} \leq \#\text{Fix } T^m, \quad \forall m \geq 1,$$

where $\#\text{Fix } T^m$ denotes the number of fixed points of T^m , and h_* is the topological entropy of the map T from [3]. Baladi and Demers also give a condition under which μ_* and μ_{SRB} coincide.

In a subsequent paper, Baladi and Demers [4] constructed a family of equilibrium states μ_t for T associated to the family of geometric potentials $-t \log J^u T$, where $J^u T$ is the unstable Jacobian of T and $t \in (0, t_*)$ for some $t_* > 1$. In the case $t = 1$, $\mu_t = \mu_{\text{SRB}}$. The construction again relies on the use of a family of transfer operators \mathcal{L}_t acting on anisotropic Banach spaces. For each $t \in (0, t_*)$, they proved that μ_t is the unique equilibrium state associated with the potential $-t \log J^u T$, that μ_t is mixing, T -adapted, has full support and does not have atoms. Baladi and Demers also showed that each transfer operator \mathcal{L}_t has a spectral gap, from which they deduced the exponential rate of mixing for each measure μ_t , for C^1 observables.

Even more recently, Demers and Korepanov [16] proved a polynomial decay of correlations for the measure μ_* for Hölder observables.

In this paper, we give a sufficient condition under which a piecewise Hölder potential g admits equilibrium states for T . Under this assumption, we prove that the equilibrium state is in fact unique, Bernoulli, T -adapted and charges all nonempty open sets. We prove that its lift into a flow invariant measure is Bernoulli and flow-adapted. We also identify the potential

$g = -h_{\text{top}}(\phi_1)\tau$ to be such that its corresponding equilibrium states for T – whenever they exist – are in bijection with measures of maximal entropy of the billiard flow.

Notice that the geometric potentials $-t \log J^u T$ are not piecewise Hölder, and thus the work of Baladi and Demers [4] on those potentials is distinct from ours.

1.2. Statement of main results – Organization of the paper. Since transfer operator techniques are simpler to implement for maps than for flows, we will be concerned with the associated billiard map $T : M \rightarrow M$ defined to be the first collision map on the boundary of Q , where $M = \partial Q \times [-\pi/2, \pi/2]$. We assume as in [33, 3], that the billiard table Q has *finite horizon*, in the sense that the billiard flow does not have any trajectories making only tangential collisions – in particular, this implies that the return time function τ to a scatterers is bounded.

The first step is to find a suitable notion of topological pressure $P_*(T, g)$ for the discontinuous map T and a potential $g : M \rightarrow \mathbb{R}$. In order to define it, we introduce as in [3], the following increasing family of partition of M . Let \mathcal{P} be the partition into maximal connected sets on which both T and T^{-1} are continuous, and let $\mathcal{P}_{-k}^n = \bigvee_{i=-k}^n T^{-i}\mathcal{P}$. Then the sequence $\sum_{P \in \mathcal{P}_0^n} \sup_P e^{S_n g}$ is submultiplicative, where $S_n g = \frac{1}{n} \sum_{i=0}^{n-1} g \circ T^i$ is the Birkhoff sum of g . We can thus define the topological pressure by

Definition 1.1. $P_*(T, g) := \lim_{n \rightarrow +\infty} \frac{1}{n} \log \sum_{P \in \mathcal{P}_0^n} \sup_P e^{S_n g}$

Section 2 is dedicated to the study of this quantity. In particular, we prove (Proposition 2.2) that whenever the potential g is smooth enough – piecewise Hölder – and $P_*(T, g) - \sup g > 0$ then $P_*(T, g)$ coincides with both Bowen’s definitions using spanning sets and separating sets. We also prove (Lemma 2.4) that for each T -invariant measure μ , we have $P_*(T, g) \geq h_\mu(T) + \int g d\mu$. Finally, we show that if $g = -h_{\text{top}}(\phi_1)\tau$ admits an equilibrium state μ_g , then the measure $\bar{\mu}_g = (\int \tau d\mu_g)^{-1} \mu_g \otimes \lambda$ is a measure of maximal entropy for the billiard flow, seen as a suspension flow over T , where λ is the Lebesgue measure in the flow direction.

To state our existence results (in Section 6), we need to quantify the recurrence to the singular set. Fix an angle φ_0 close to $\pi/2$ and $n_0 \in \mathbb{N}$. We say that a collision is φ_0 -grazing if its angle with the normal is larger than φ_0 in absolute value. Let $s_0 = s_0(\varphi_0, n_0) \in (0, 1]$ denote the smallest number such that

(1.2) any orbit of length n_0 has at most $s_0 n_0$ collisions which are φ_0 -grazing.

Due to the finite horizon condition, we can choose φ_0 and n_0 such that $s_0 < 1$. We refer to [3, §2.4] for further discussion on this quantity. From [13], $\Lambda = 1 + \kappa_{\min} \tau_{\min} > 1$ is the expanding factor in the hyperbolicity of T , where κ_{\min} is the minimal curvature of the scatterers and τ_{\min} is the minimum of the return time function τ . Define $\mathcal{S}_0 = \{(r, \varphi) \in M \mid |\varphi| = \pi/2\}$ the set of grazing collisions, and $\mathcal{S}_{\pm n} = \bigcup_{i=0}^n T^{\mp i} \mathcal{S}_0$ the singular set of $T^{\pm n}$. Call $\mathcal{N}_\varepsilon(\cdot)$ the ε -neighbourhood of a set. Then

Theorem 1.2. *If g is a bounded, piecewise Hölder potential such that $P_*(T, g) - \sup g > s_0 \log 2$ and $\log \Lambda > \sup g - \inf g$, then there exists a probability measure μ_g such that*

(i) μ_g is T -invariant, T -adapted and for all $k \in \mathbb{Z}$, exists $C_k > 0$ such that $\mu_g(\mathcal{N}_\varepsilon(\mathcal{S}_k)) \leq C_k |\log \varepsilon|^{-\gamma}$.

- (ii) μ_g the unique equilibrium state of T under g : that is $P_*(T, g) = h_{\mu_g}(T) + \int g d\mu_g$ and $P_*(T, g) > h_\mu(T) + \int g d\mu$ for all $\mu \neq \mu_g$.
- (iii) μ_g is Bernoulli¹ and charges all nonempty open sets.

If the assumption $\log \Lambda > \sup g - \inf g$ is weakened into the condition SSP.1 (as defined above Lemma 3.2), then item (i) still holds. If the assumption $\log \Lambda > \sup g - \inf g$ is weakened into the condition SSP.2 (as defined above Corollary 3.4), then items (i), (ii) and (iii) hold.

The above theorem will follow from Proposition 6.1, Lemma 6.2, Corollary 6.14, and Propositions 6.18, 6.15, 6.10. Furthermore, assuming the sparse recurrence to singularities condition from [3], we provide in Remark 3.9 an open set of potentials, each having SSP.1 and SSP.2.

The tool used to construct the measure μ_g is a transfer operator \mathcal{L}_g with $\mathcal{L}_g f = (f e^g / J^s T) \circ T^{-1}$, similar to the one used in [3] corresponding to the case $g \equiv 0$. This operator and the anisotropic Banach spaces on which it acts are defined in details in Section 4. Section 3 contains key combinatorial growth lemmas, controlling the growth in weighted complexity of the iterates of a stable curve. These lemmas will be crucial since the quantity they control appears in the norms of the iterates of \mathcal{L}_g . In Section 5, we prove a (degenerated) “Lasota–Yorke” type inequality (Proposition 5.1) – giving an upper bound on the spectral radius of \mathcal{L}_g – as well as a lower bound on the spectral radius (Theorem 5.3).

Section 6 is devoted to the construction and the properties of the measure μ_g . From the estimates on the norms from the previous section, we are able to construct left and right maximal eigenvectors ($\tilde{\nu}$ and ν) for \mathcal{L}_g . We construct the measure μ_g by pairing these eigenvectors. We then prove the estimates on the measure of a neighbourhood of the singular sets (Lemma 6.2). Section 6.3 contains the key result of the absolute continuity of the stable and unstable foliations with respect to μ_g , as well as the proof that μ_g has total support – this is done by exploiting the ν -almost everywhere positive length of unstable manifolds from Section 6.2. In Section 6.4, we show that μ_g is ergodic, from which we bootstrap to K-mixing using Hopf–argument. Adapting [15] with modifications from [3], we deduce from the hyperbolicity and the K-mixing that μ_g is Bernoulli. Still in Section 6.4, we give an upper-bound on the measure of weighted Bowen balls, from which we deduce, using the Shannon–MacMillan–Breiman theorem, that μ_g is an equilibrium state for T under the potential g (Corollary 6.14). Finally, the Section 6.5 is dedicated to the uniqueness of the equilibrium state μ_g .

In Section 7, we prove using arguments from [13] that $(\phi_t, \bar{\mu}_g)$ is K-mixing (Proposition 7.1), and again, using the hyperbolicity of the billiard flow, we adapt [15] in order to prove that $(\phi_t, \bar{\mu}_g)$ is Bernoulli (Proposition 7.2). Finally, we prove that $\bar{\mu}_g$ is flow adapted in the sense of the integrability condition formulated in Proposition 7.4. We summarize this results about the billiard flow in the following theorem.

Theorem 1.3. *Let g be a potential satisfying the assumptions from Theorem 1.2, and let $\bar{\mu}_g := (\int \tau d\mu_g)^{-1} \mu_g \otimes \lambda$. Then $\bar{\mu}_g$ is a ϕ_t -invariant Borel probability measure that is an equilibrium states for any potential \tilde{g} such that $g = \lambda(\tilde{g}) - P(\phi_1, \tilde{g})\tau$, where $\lambda(\tilde{g})(x) = \int_0^{\tau(x)} \tilde{g}(\phi_t(x)) dt$. Furthermore, $\bar{\mu}_g$ is flow adapted and $(\phi_t, \bar{\mu}_g)$ is Bernoulli.*

In a work in preparation with Baladi and Demers [2], we bootstrap from the results of the present paper to show that if $h_{\text{top}}(\phi_1)\tau_{\min} > s_0 \log 2$ then the potential $-h_{\text{top}}(\phi_1)\tau$ satisfies

¹Recall that Bernoulli implies K-mixing, which implies strong mixing, which implies ergodic.

the sufficient assumptions SSP.1 and SSP.2 in our Theorem 1.2, thus constructing a measure of maximal entropy for the billiard flow. This is done by studying the family of potentials $-t\tau$ and proving that the maximal value t_∞ of t such that $-t'\tau$ has SSP.1 and SSP.2 for all $0 \leq t' \leq t$, satisfies $t_\infty > h_{\text{top}}(\phi_1)$. Indeed, recalling Remark 3.9 and Corollary 2.6, for every small enough $|t|$, $-t\tau$ has SSP.1 and SSP.2, and the case $t = h_{\text{top}}(\phi_1)$ corresponds to measures of maximal entropy for the billiard flow.

2. TOPOLOGICAL PRESSURE, VARIATIONAL PRINCIPLE AND ABRAMOV FORMULA

In this section, we formulate definitions of topological pressure for the billiard map, and prove that – under some conditions – they are equivalent. Using a classical estimate, we then prove one direction of the variational principle. Finally, making use of the Abramov formula, we relate equilibrium states of T with the ones of the billiard flow. More specifically, we identified the potential for T which is related to – up to existence – the measures of maximal entropy of ϕ_t .

We first introduce notation: Adopting the standard coordinates $x = (r, \varphi)$ on each connected component M_i of

$$M := \partial Q \times \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] = \bigsqcup_{i=1}^D \partial B_i \times \left[-\frac{\pi}{2}, \frac{\pi}{2}\right],$$

where r denotes arclength along ∂B_i , φ is the angle the post-collisional trajectory makes with the normal to ∂B_i and $M_i = \partial B_i \times \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$. In these coordinates, the collision map $T : M \rightarrow M$ preserve a smooth invariant probability measure μ_{SRB} given by $d\mu_{\text{SRB}} = (2|\partial Q|)^{-1} \cos \varphi \, dr d\varphi$.

We now define the sets where T and its iterates are discontinuous. Let $\mathcal{S}_0 := \{(r, \varphi) \in M \mid |\varphi| = \pi/2\}$ denote the set of grazing collisions. For each nonzero $n \in \mathbb{N}$, let

$$\mathcal{S}_{\pm n} := \bigcup_{i=0}^n T^{\mp i} \mathcal{S}_0,$$

denote the singularity set for $T^{\pm n}$. It would be natural to study the map T restricted to the invariant set $M \setminus \bigcup_{n \in \mathbb{Z}} \mathcal{S}_n$ where T is continuous, however the set of curves $\bigcup_{n \in \mathbb{Z}} \mathcal{S}_n$ is dense in M [13, Lemma 4.55]. We thus introduce the classical family of partitions of M as follows.

For $k, n \geq 0$, let \mathcal{M}_{-k}^n denote the partition of $M \setminus (\mathcal{S}_{-k} \cup \mathcal{S}_n)$ into its maximal connected components. Note that all elements of \mathcal{M}_{-k}^n are open sets on which T^i is continuous, for all $-k \leq i \leq n$. Since the thermodynamic sums over elements of \mathcal{M}_0^n of a potential g will play a key role in the estimates on the norms of the iterates of the transfer operator \mathcal{L}_g in Section 5, it should be natural – by analogy to the case of continuous maps – to define the topological pressure from these sums.

Another natural family of partitions is given as follows. Let \mathcal{P} denote the partition of M into maximal connected components on which both T and T^{-1} are continuous. Define $\mathcal{P}_{-k}^n = \bigvee_{i=-k}^n T^{-i} \mathcal{P}$ and remark that T^i is continuous on every element of \mathcal{P}_{-k}^n , for all $-k \leq i \leq n$.

The interior of each element of \mathcal{P} corresponds to precisely one element of \mathcal{M}_{-1}^1 , but its refinements \mathcal{P}_{-k}^n may also contain some isolated points – this happens if three or more scatterers have a common grazing collision. These partitions already appeared in the work of Baladi and

Demers, where they proved [3, Lemma 3.2] that the number of isolated points in \mathcal{P}_{-k}^n grows linearly in $n + k$.

Finally, denote $\mathring{\mathcal{P}}_{-k}^n$ the collection of interior of elements of \mathcal{P}_{-k}^n . In [3, Lemma 3.3], Baladi and Demers proved that $\mathring{\mathcal{P}}_{-k}^n = \mathcal{M}_{-k-1}^{n+1}$, for all $n, k \geq 0$. It should be natural that the topological pressures obtained from these three families of partitions coincide. This is the content of Theorem 2.1.

In order to formulate the result on the equivalence between definitions of topological pressure for T , we need to be more specific about the definition of *piecewise* Hölder.

We say that a function g is (\mathcal{P}, α) -Hölder, $0 < \alpha < 1$, if g is α -Hölder continuous on each element of the partition \mathcal{P} . We define the C^α norm $|g|_{C^\alpha}$ of g to be the maximum, over all connected components U of the domain of continuity of g , of the usual C^α norm $|g|_{C^\alpha(U)}$, that is

$$|g|_{C^\alpha} = \max\{|g|_{C^0(U)} + H_U^\alpha(g) \mid U \text{ connected set on which } g \text{ is continuous}\},$$

where

$$H_U^\alpha(g) = \sup_{x, y \in U} \frac{|g(x) - g(y)|}{d(x, y)^\alpha}.$$

Similarly, we say that a function g is \mathcal{P} -continuous if g is bounded and continuous on each element of the partition \mathcal{P} . We define the C^0 norm $|g|_{C^0}$ to be the maximum over all connected components U of the domain of continuity of g , of the usual C^0 norm, that is

$$|g|_{C^0} = \max\{|g|_{C^0(U)} \mid U \text{ connected set on which } g \text{ is continuous}\}.$$

Theorem 2.1. *Let $g : M \rightarrow \mathbb{R}$ be a potential bounded from above. Then*

$$\lim_{n \rightarrow +\infty} \frac{1}{n} \log \sum_{A \in \mathcal{P}_0^n} \sup_{x \in A} e^{(S_n g)(x)} =: P_*(T, g)$$

exists and is called the pressure of g . Moreover, the map $g \mapsto P_(T, g)$ is convex.*

When g is \mathcal{P} -continuous and $P_(T, g) - \sup g > 0$, the following limits exist and are equal to $P_*(T, g)$.*

$$\begin{aligned} (i) \quad & \lim_{n \rightarrow +\infty} \frac{1}{n} \log \sum_{A \in \mathcal{P}_0^n} \sup_{x \in A} e^{(S_n g)(x)}, \\ (ii) \quad & \lim_{n \rightarrow +\infty} \frac{1}{n} \log \sum_{A \in \mathcal{M}_0^n} \sup_{x \in A} e^{(S_n g)(x)}. \end{aligned}$$

Furthermore, when g is also (\mathcal{P}, α) -Hölder continuous, then the following limits are equal to $P_(T, g)$.*

$$\begin{aligned} (iii) \quad & \lim_{n \rightarrow +\infty} \frac{1}{n} \log \sum_{A \in \mathcal{P}_0^n} \inf_{x \in A} e^{(S_n g)(x)}, \\ (iv) \quad & \lim_{n \rightarrow +\infty} \frac{1}{n} \log \sum_{A \in \mathcal{P}_0^n} \inf_{x \in A} e^{(S_n g)(x)}, \\ (v) \quad & \lim_{n \rightarrow +\infty} \frac{1}{n} \log \sum_{A \in \mathcal{M}_0^n} \inf_{x \in A} e^{(S_n g)(x)}, \end{aligned}$$

Finally, the sequence $n \mapsto \log \sum_{A \in \mathcal{M}_0^n} \sup_{x \in A} e^{S_{n-1}g(x)}$ is subadditive.

Proposition 2.2. *Let g be a \mathcal{P} -continuous potential. Let $P_{\text{span}}(T, g)$ and $P_{\text{sep}}(T, g)$ be the pressure obtained using Bowen's definition with, respectively, spanning sets and separating sets. Then $P_{\text{span}}(T, g) \leq P_*(T, g)$ and $P_{\text{sep}}(T, g) \leq P_*(T, g)$. When $P_*(T, g) - \sup g > 0$, then $P_*(T, g) = P_{\text{sep}}(T, g)$. Furthermore, when $P_*(T, g) - \sup g > 0$ and g is (\mathcal{P}, α) -Hölder, $P_*(T, g) = P_{\text{span}}(T, g)$.*

The proof of the last three forms of $P_*(T, g)$ in Theorem 2.1 relies crucially on the following lemma.

Lemma 2.3. *For every (\mathcal{P}, α) -Hölder continuous potential g there exists a constant C such that for all $n \geq 1$ and all $P \in \mathcal{P}_0^n$,*

$$\sup_P e^{S_n g} \leq C \inf_P e^{S_n g}.$$

The estimate still holds, for the same constant C , when \mathcal{P}_0^n is replaced by \mathcal{P}_{-l}^n , $\dot{\mathcal{P}}_{-l}^n$ or \mathcal{M}_{-l}^n , for any fixed $l \geq 0$.

Proof. Let d_n denote the Bowen distance, that is the dynamical distance given by

$$d_n(x, y) = \max_{0 \leq i \leq n} d(T^i x, T^i y),$$

where $d(x, y)$ is the Euclidean metric on each M_i , with $d(x, y) = 10D \max_i \text{diam}(M_i)$ if x and y belong to different M_i (this definition ensure we have a compact set). Let $\varepsilon_0 > 0$ be as in [3, eq (3.3)], that is: if $d_n(x, y) < \varepsilon_0$ then x and y lie in the same element of \mathcal{M}_0^n . Therefore, by the uniform hyperbolicity of T , if $d(T^i(x), T^i(y)) \leq \varepsilon_0/2$ for all $|i| \leq n$ then $d(x, y) \leq \Lambda^{-n} \varepsilon_0/2$.

For all integer m and all potential g , define its variation by

$$\text{Var}_m(g, T, \varepsilon) := \sup\{|g(x) - g(y)| \mid d(T^j x, T^j y) \leq \varepsilon, |j| \leq m\}.$$

When g is (\mathcal{P}, α) -Hölder, we get that $\text{Var}_m(g, T, \frac{\varepsilon_0}{2}) \leq C(\frac{\varepsilon_0}{2} \Lambda^{-n})^\alpha$. Therefore

$$\sum_{m \geq 0} \text{Var}_m(g, T, \frac{\varepsilon_0}{2}) =: K < \infty.$$

By uniform hyperbolicity of T , there exists k_ε such that $\text{diam}(\mathcal{M}_{-k_\varepsilon}^{n+1}) < \varepsilon_0/2$ for all $n \geq k_\varepsilon$. It then follows from the proof of [3, Lemma 3.5] that if x and y lie in the same element of $\mathcal{P}_{-k_\varepsilon}^{k_\varepsilon+n}$, then $d_n(x, y) \leq \varepsilon_0/2$, for all $n \geq 0$.

Let $P \in \mathcal{P}_{-k_\varepsilon}^{k_\varepsilon+n}$ and let $x, y \in P$. Let $0 \leq k \leq n$. Then for all $|j| < m_k := \min(k, n - k)$, $d(T^j(T^k x), T^j(T^k y)) < \varepsilon_0/2$ and so $|g(T^k x) - g(T^k y)| \leq \text{Var}_{m_k}(g, T, \frac{\varepsilon_0}{2})$. Therefore

$$|S_n g(x) - S_n g(y)| \leq 2 \sum_{m=0}^{\lfloor \frac{n}{2} \rfloor + 1} \text{Var}_m(g, T, \frac{\varepsilon_0}{2}) \leq 2K < \infty.$$

Now, let $P \in \mathcal{P}_0^n$ for some $n \geq 2k_\varepsilon$. Notice that $\mathcal{P}_0^n = \bigvee_{i=k_\varepsilon}^{n-k_\varepsilon} T^{-i} \mathcal{P}_{-k_\varepsilon}^{k_\varepsilon}$, in other words for all l such that $k_\varepsilon \leq l \leq n - k_\varepsilon$, $T^l P$ is included in an element of $\mathcal{P}_{-k_\varepsilon}^{k_\varepsilon}$. Finally, by decomposing each orbit into three parts, we get that for all $x, y \in P$,

$$\begin{aligned} e^{S_n g(x) - S_n g(y)} &= e^{S_{k_\varepsilon} g(x) - S_{k_\varepsilon} g(y)} e^{S_{n-2k_\varepsilon} g(T^{k_\varepsilon} x) - S_{n-2k_\varepsilon} g(T^{k_\varepsilon} y)} e^{S_{k_\varepsilon} g(T^{n-k_\varepsilon} x) - S_{k_\varepsilon} g(T^{n-k_\varepsilon} y)} \\ &\leq e^{2k_\varepsilon(\sup g - \inf g)} e^{2K}. \end{aligned}$$

The claim holds for $n \geq 2k_\varepsilon$ by taking the sup over x and the inf over y in P . Since there are only finitely many values of n to correct for, by taking a larger constant, the claimed estimate holds for all $n \geq 1$.

Fix some $l \geq 0$. Since an element $P \in \mathcal{P}_{-l}^n$ is contained in a unique element $\tilde{P} \in \mathcal{P}_0^n$, we get that

$$\sup_P e^{S_n g} \leq \sup_{\tilde{P}} e^{S_n g} \leq C \inf_{\tilde{P}} e^{S_n g} \leq C \inf_P e^{S_n g}.$$

Now, assume that $\tilde{P} \neq \emptyset$. Then, by the continuity of $S_n g$ on P , the estimate also holds when the sup and the inf are taken over \tilde{P} . In other words, the claim is true for all $P \in \mathring{\mathcal{P}}_l^n$.

Since by [3, Lemma 3.3], $\mathring{\mathcal{P}}_{-l}^n = \mathcal{M}_{-l-1}^{n+1}$, the claim is true for all $P \in \mathcal{M}_{-l}^n$, for fixed $l \geq 1$. We finish the proof with the case $P \in \mathcal{M}_0^n$. Remark that letting $A \in \mathcal{M}_{-1}^n$, then $T^{-1}A \in \mathcal{M}_0^{n+1}$. Therefore

$$\begin{aligned} e^{-\sup g} \sup_{T^{-1}A} e^{S_{n+1}g} &\leq \sup_{T^{-1}A} e^{S_{n+1}g-g} = \sup_A e^{S_n g} \leq C \inf_A e^{S_n g} = C \inf_{T^{-1}A} e^{S_{n+1}g-g} \\ &\leq 2C e^{-\inf g} \inf_{T^{-1}A} e^{S_{n+1}g}. \end{aligned}$$

Only in this last case, we need to replace C by $2C e^{\sup g - \inf g} \geq C$. \square

Proof of Theorem 2.1. Let $p_n = \sum_{A \in \mathcal{P}_0^n} \sup_{x \in A} e^{(S_n g)(x)}$. Then, for $k \geq n$,

$$p_{n+k} = \sum_{B \cap C \in \mathcal{P}_0^n \vee T^{-n} \mathcal{P}_0^k} \sup_{x \in B \cap C} e^{(S_n g)(x) + (S_k g)(T^n x)} \leq p_n p_k.$$

Therefore $(\log p_n)_n$ is a sub-additive sequence. It is then classical that $\frac{1}{n} \log p_n$ converges to $\inf_{n \geq 1} \frac{1}{n} \log p_n$, hence $P_*(T, g)$ exists. We now prove the statement about convexity. Let g_1 and g_2 be two potentials bounded from above and $p \in [0, 1]$. For all $n \geq 1$ and all $A \in \mathcal{P}_0^n$, there exists $x_A \in A$ such that

$$e^{p(S_n g_1)(x_A) + (1-p)(S_n g_2)(x_A)} \geq \frac{9}{10} \sup_{x \in A} e^{p(S_n g_1)(x) + (1-p)(S_n g_2)(x)}.$$

Therefore, by Hölder's inequality,

$$\begin{aligned} \sum_{A \in \mathcal{P}_0^n} \sup_{x \in A} e^{p(S_n g_1)(x) + (1-p)(S_n g_2)(x)} &\leq \frac{10}{9} \sum_{A \in \mathcal{P}_0^n} e^{p(S_n g_1)(x_A) + (1-p)(S_n g_2)(x_A)} \\ &\leq \frac{10}{9} \left(\sum_{A \in \mathcal{P}_0^n} e^{S_n g_1(x_A)} \right)^p \left(\sum_{A \in \mathcal{P}_0^n} e^{S_n g_2(x_A)} \right)^{1-p} \\ &\leq \frac{10}{9} \left(\sum_{A \in \mathcal{P}_0^n} \sup_{x \in A} e^{S_n g_1(x)} \right)^p \left(\sum_{A \in \mathcal{P}_0^n} \sup_{x \in A} e^{S_n g_2(x)} \right)^{1-p}. \end{aligned}$$

Taking the appropriate limits, we get that $P_*(T, p g_1 + (1-p) g_2) \leq p P_*(T, g_1) + (1-p) P_*(T, g_2)$, hence the claimed convexity.

For (i), consider $\tilde{p}_n = \sum_{A \in \mathring{\mathcal{P}}_0^n} \sup_{x \in A} e^{(S_n g)(x)}$. Notice that

$$\mathcal{P}_0^n = \{A \in \mathcal{P}_0^n \mid \mathring{A} \neq \emptyset\} \sqcup \{A \in \mathcal{P}_0^n \mid \mathring{A} = \emptyset\}.$$

Now, Baladi and Demers proved in [3, Lemma 3.2] that the cardinality of the second term in the right hand side grows at most linearly. Hence

$$\sum_{\substack{A \in \mathcal{P}_0^n \\ \dot{A} = \emptyset}} \sup_{x \in A} e^{(S_n g)(x)} \leq C n e^{n \sup g}.$$

By the smoothness of g ,

$$\sum_{\substack{A \in \mathcal{P}_0^n \\ \dot{A} \neq \emptyset}} \sup_{x \in A} e^{(S_n g)(x)} = \sum_{A \in \mathring{\mathcal{P}}_0^n} \sup_{x \in A} e^{(S_n g)(x)}.$$

Thanks to the assumption $P_*(T, g) - \sup g > 0$, the sum over elements $A \in \mathcal{P}_0^n$ with $\dot{A} \neq \emptyset$ dominates the sum over A with $\dot{A} = \emptyset$. Thus $(\frac{1}{n} \log \tilde{p}_n)_n$ converges to the same limit as $(\frac{1}{n} \log p_n)_n$ does.

For (ii), we use [3, Lemma 3.3] that $\mathring{\mathcal{P}}_0^n = \mathcal{M}_{-1}^{n+1}$. Hence

$$\sum_{A \in \mathcal{M}_0^{n+1}} \sup_{x \in A} e^{(S_{n+1} g)(x)} \leq \sum_{A \in \mathcal{M}_{-1}^{n+1}} \sup_{x \in A} e^{(S_{n+1} g)(x)} \leq \sum_{A \in \mathring{\mathcal{P}}_0^n} \sup_{x \in A} e^{(S_n g)(x)} \sup_{x \in M} e^{g(x)}.$$

Furthermore, since $\mathcal{M}_{-1}^{n+1} = \mathcal{M}_0^{n+1} \vee \mathcal{M}_{-1}^0$, each element of \mathcal{M}_0^{n+1} contains at most $\#\mathcal{M}_{-1}^0$ elements of \mathcal{M}_{-1}^{n+1} . Hence

$$\sum_{A \in \mathcal{M}_0^{n+1}} \sup_{x \in A} e^{(S_{n+1} g)(x)} \geq \frac{1}{\#\mathcal{M}_{-1}^0} \sum_{A \in \mathring{\mathcal{P}}_0^n} \sup_{x \in A} e^{(S_n g)(x)} \inf_{x \in M} e^{g(x)}.$$

Point (iii) (resp. (iv), (v)) follows directly from the definition of $P_*(T, g)$ (resp. from point (i), (ii)) and from Lemma 2.3 since

$$\inf_A e^{S_n g} \leq \sup_A e^{S_n g} \leq C \inf_A e^{S_n g},$$

for all A in \mathcal{P}_0^n (resp. $\mathring{\mathcal{P}}_0^n, \mathcal{M}_0^n$). For the final claim, we prove that $\log \sum_{P \in \mathring{\mathcal{P}}_0^n} \sup_P e^{S_n g}$ is

subadditive. Take P a nonempty element of $\mathring{\mathcal{P}}_1^{n+m}$. It is the interior of an intersection of elements of the form $T^{-j} A_j$ for some $A_j \in \mathcal{P}$, for $j = 1, \dots, n+m$. This is equal to the intersection of the interiors of $T^{-j} A_j$. But since P is nonempty, none of the $T^{-j} A_j$ has empty interior, and so none of the A_j has empty interior. Thus the interiors of A_j are in $\mathring{\mathcal{P}}$. Now, splitting the intersection of the first n sets from the last m , we see that the intersection of the first n sets forms an element of $\mathring{\mathcal{P}}_1^n$. For the last m sets, we can factor out T^{-n} at the price of making the set slightly bigger:

$$\text{int}(T^{-n-j} A_{-n-j}) \subset T^{-n}(\text{int}(T^{-j}(A_{-n-j}))), \quad 1 \leq j \leq m$$

where int denotes the interior of a set. Thus

$$\sum_{P \in \mathring{\mathcal{P}}_1^{n+m}} \sup_P e^{S_{n+m} g} \leq \sum_{\substack{A_{-j} \in \mathring{\mathcal{P}} \\ 1 \leq j \leq n+m}} \sup \{ e^{S_n g + S_m g \circ T^n}(x) \mid x \in \bigcap_{j=1}^n T^{-j} A_{-j} \cap T^{-n} \bigcap_{j=1}^m T^{-j} A_{-n-j} \}$$

$$\begin{aligned}
&\leq \sum_{\substack{A_{-j} \in \mathring{\mathcal{P}} \\ 1 \leq j \leq n}} \sup\{e^{S_n g}(x) \mid x \in \bigcap_{j=1}^n T^{-j} A_{-j}\} \sum_{\substack{A_{-j} \in \mathring{\mathcal{P}} \\ 1 \leq j \leq m}} \sup\{e^{S_m g}(x) \mid x \in \bigcap_{j=1}^m T^{-j} A_{-j}\} \\
&\leq \sum_{P \in \mathring{\mathcal{P}}_1^n} \sup_P e^{S_n g} \sum_{P \in \mathring{\mathcal{P}}_1^m} \sup_P e^{S_m g}
\end{aligned}$$

Taking logs, the sequence is subadditive. And then so is the sequence with \mathcal{M}_0^n in place of $\mathring{\mathcal{P}}_1^{n-1}$. \square

Proof of Proposition 2.2. We first prove the claim about separating sets. Let $\varepsilon > 0$ and let k_ε be large enough so that $\text{diam}^s(\mathcal{M}_{-k_\varepsilon-1}^0) \leq C\Lambda^{-k_\varepsilon} < c_1\varepsilon$ for some constant c_1 to be defined later. Therefore $\text{diam}^u(\mathcal{M}_{-k_\varepsilon-1}^{n+1}) \leq C\Lambda^{-k_\varepsilon} < c_1\varepsilon$ for all $n \geq k_\varepsilon$. By the uniform transversality between the stable and the unstable cones, we can choose c_1 such that $\text{diam}(\mathcal{M}_{-k_\varepsilon-1}^{n+1}) < \varepsilon$ for all $n \geq k_\varepsilon$.

Let E be (n, ε) -separated, for some $n \geq k_\varepsilon$. It is shown in the proof of [3, Lemma 3.4] that if $x, y \in E$ are distinct, then they cannot be contained in the same element of $\mathcal{P}_{-k_\varepsilon}^{k_\varepsilon+n}$. Thus

$$\begin{aligned}
\sum_{x \in E} e^{S_n g(x)} &\leq \sum_{A \in \mathcal{P}_{-k_\varepsilon}^{k_\varepsilon+n}} |e^{S_n g}|_{C^0(A)} = \sum_{A \in \mathcal{P}_0^{2k_\varepsilon+n}} |e^{S_n g \circ T^{-k_\varepsilon}}|_{C^0(A)} \\
&\leq e^{k_\varepsilon(\sup g - 2 \inf g)} \sum_{A \in \mathcal{P}_0^{2k_\varepsilon+n}} |e^{S_{2k_\varepsilon+n} g}|_{C^0(A)}.
\end{aligned}$$

Therefore

$$\lim_{n \rightarrow \infty} \frac{1}{n} \log \sup\left\{ \sum_{x \in E} e^{S_n g(x)} \mid E \text{ is } (n, \varepsilon)\text{-separated} \right\} \leq P_*(T, g) \quad , \text{ for all } \varepsilon > 0.$$

Taking the limit $\varepsilon \rightarrow 0$, we get $P_{\text{sep}}(T, g) \leq P_*(T, g)$.

For the reverse inequality, assume that g is such that $P_*(T, g) - \sup g > 0$. From the proof of [3, Lemma 3.4], there exists $\varepsilon_0 > 0$ such that for all $\varepsilon < \varepsilon_0$, any set E which contains only one point per element of \mathcal{M}_0^n is (n, ε) -separated. For all $A \in \mathcal{M}_0^n$, there exist $x \in A$ such that $e^{S_n g(x)} \geq \frac{9}{10} \sup_A e^{S_n g}$. Let E be the collection of such x . Thus

$$\sum_{x \in E} e^{S_n g(x)} \geq \frac{9}{10} \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)}.$$

Therefore,

$$\lim_{n \rightarrow \infty} \frac{1}{n} \log \sup\left\{ \sum_{x \in E} e^{S_n g(x)} \mid E \text{ is } (n, \varepsilon)\text{-separated} \right\} \leq P_*(T, g), \quad \text{for all } 0 < \varepsilon < \varepsilon_0.$$

Taking the limit $\varepsilon \rightarrow 0$, we get $P_{\text{sep}}(T, g) \geq P_*(T, g)$, thus the claimed equality.

We now prove the claim concerning spanning sets. Let $\varepsilon > 0$ and let k_ε be such that $\text{diam}(\mathcal{M}_{-k_\varepsilon-1}^{n+1}) < \varepsilon$ for all $n \geq k_\varepsilon$. Let F be a set containing one point in each element of

$\mathcal{P}_{-k_\varepsilon}^{n+1}$. From the proof of [3, Lemma 3.5], F is (n, ε) -spanning. Since

$$\sum_{x \in F} e^{S_n g(x)} \leq e^{k_\varepsilon(\sup g - 2 \inf g)} \sum_{A \in \mathcal{P}_0^{2k_\varepsilon + n}} |e^{S_{2k_\varepsilon + n} g}|_{C^0(A)}$$

we get that

$$\lim_{n \rightarrow \infty} \frac{1}{n} \log \inf \left\{ \sum_{x \in F} e^{S_n g(x)} \mid F \text{ is } (n, \varepsilon)\text{-spanning} \right\} \leq P_*(T, g), \quad \text{for all } \varepsilon > 0.$$

Taking the limit $\varepsilon \rightarrow 0$, we get $P_{\text{span}}(T, g) \leq P_*(T, g)$.

For the reverse inequality, assume that g is a (\mathcal{P}, α) -Hölder potential such that $P_*(T, g) - \sup g > 0$. Let $\varepsilon < \varepsilon_0$ and let F be a (n, ε) -spanning set. By the proof of [3, Lemma 3.5], each element of \mathcal{M}_0^n contains at least one element of F . Thus

$$\sum_{x \in F} e^{S_n g(x)} \geq \sum_{A \in \mathcal{M}_0^n} \inf_A e^{S_n g}.$$

Taking the appropriate limits, we get that $P_{\text{span}}(T, g) \geq P_*(T, g)$, thus the claimed equality. \square

2.1. Easy Direction of the Variational Principle for the Pressure. Recall that given a T -invariant probability measure μ and a finite measurable partition \mathcal{A} of M , the entropy of \mathcal{A} with respect to μ is defined by $H_\mu(\mathcal{A}) = -\sum_{A \in \mathcal{A}} \mu(A) \log \mu(A)$, and the entropy of T with respect to \mathcal{A} is $h_\mu(T, \mathcal{A}) = \lim_{n \rightarrow \infty} \frac{1}{n} H_\mu \left(\bigvee_{i=0}^{n-1} T^{-i} \mathcal{A} \right)$.

Lemma 2.4. *Let $\varphi : M \rightarrow \mathbb{R}$ be a measurable function. Then*

$$P_*(T, \varphi) \geq P(T, \varphi) := \sup \{ h_\mu(T) + \int \varphi d\mu \mid \mu \text{ is a } T\text{-invariant Borel probability measure} \}$$

Proof. Let μ be a T -invariant probability measure on M . Notice that \mathcal{P} is a generator for T since $\bigvee_{i=-\infty}^{\infty} T^{-i} \mathcal{P}$ separates points in M . Thus $h_\mu(T) = h_\mu(T, \mathcal{P})$ (see for example [32, Theorem 4.17]). Then,

$$\begin{aligned} h_\mu(T) + \int \varphi d\mu &= \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{A \in \mathcal{P}_0^n} \left(-\mu(A) \log \mu(A) + \int_A S_n \varphi d\mu \right) \\ &\leq \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{A \in \mathcal{P}_0^n} \mu(A) (\sup_A (S_n \varphi) - \log \mu(A)) \\ &\leq \lim_{n \rightarrow \infty} \frac{1}{n} \log \sum_{A \in \mathcal{P}_0^n} \sup_A e^{S_n \varphi} \leq P_*(T, \varphi) \end{aligned}$$

where we used [32, Lemma 9.9] for the second inequality. \square

2.2. Abramov Formula and Choice of the Potential g . In order to obtain the existence of MME for the billiard flow, we make use of the Abramov formula to relate equilibrium measure for T and some potential g , to the MME of the flow. First, we need the following lemma.

Lemma 2.5. *Let φ be a bounded non-negative measurable function such that $\varphi_0 := \sup \{ \int \varphi d\mu \mid T_* \mu = \mu \} > 0$. Then, there exists a unique real number c_φ such that $P(T, -c_\varphi \varphi) = 0$.*

Proof. We first prove that the function $t \mapsto P(T, t\varphi)$ is increasing. Let $\varepsilon > 0$ and $t_1 < t_2$. There exists a T -invariant probability measure μ_1 such that

$$P(T, t_1\varphi) \leq h_{\mu_1}(T) + t_1 \int \varphi d\mu_1 + \varepsilon \leq P(T, t_2\varphi) - (t_2 - t_1)\varphi_0 + \varepsilon.$$

By this computation, we also get that $\lim_{t \rightarrow \pm\infty} P(T, t\varphi) = \pm\infty$.

Now we prove that $t \mapsto P(T, t\varphi)$ is continuous. Let $\varepsilon > 0$ and $t \in \mathbb{R}$. By the previous computation, we get that $\varepsilon\varphi_0 \leq P(T, (t+\varepsilon)\varphi) - P(T, t\varphi)$. Let μ_2 be such that $P(T, (t+\varepsilon)\varphi) \leq h_{\mu_2}(T) + (t+\varepsilon) \int \varphi d\mu_2 + \varepsilon$. Thus

$$P(T, (t+\varepsilon)\varphi) - P(T, t\varphi) \leq \varepsilon(1 + \sup \varphi).$$

Therefore $t \mapsto P(T, t\varphi)$ is strictly increasing and continuous, so it must vanish at exactly one point, noted $-c_\varphi$. \square

We can now use this lemma with the Abramov formula to get the following

Corollary 2.6. *Equilibrium measures of T under the potential $-h_{\text{top}}(\phi_1)\tau$ and MME of the billiard flow (seen as a suspension flow) are in one-to-one correspondence through the bijection $\mu \mapsto \mu_\tau := \frac{1}{\mu(\tau)}\mu \otimes \lambda$, where λ is the Lebesgue measure.*

Proof. Let c be the constant given by Lemma 2.5 such that $0 = P(T, -c\tau)$. Then, for every equilibrium state m of T under the potential $-c\tau$, we get

$$0 = h_m(T) - c \int \tau dm \geq h_\mu(T) - c \int \tau d\mu,$$

for all T -invariant measure μ . Thus

$$c = \frac{h_m(T)}{\int \tau dm} \geq \frac{h_\mu(T)}{\int \tau d\mu}.$$

Now, by the Abramov formula, $c = h_{m_\tau}(\phi_1) \geq h_{\mu_\tau}(\phi_1)$. In other words, m_τ is a MME for the billiard flow. Furthermore, since ϕ_1 is a continuous map of a compact metric space, by [32, Theorem 8.6], we get that $h_{\text{top}}(\phi_1) = \sup\{h_\mu(\phi_1) \mid (\phi_1)_*\mu = \mu\}$. Thus $c = h_{\text{top}}(\phi_1)$.

To prove that the function is onto, we use that any ϕ_t -invariant probability measure μ_τ must be of the form $\frac{1}{\mu(\tau)}\mu \otimes \lambda$, for some T -invariant probability measure μ . Thus, reversing the above computations, we get that if μ_τ is a MME, then μ is an equilibrium state for T under the potential $-h_{\text{top}}(\phi_1)\tau$. \square

Therefore, proving the existence and uniqueness of a MME for the billiard flow is equivalent to proving the existence and uniqueness of equilibrium states of T under the potential $g = -h_{\text{top}}(\phi_1)\tau$. Notice that in the second case, g is $(\mathcal{P}, \frac{1}{2})$ -Hölder continuous and the condition $P_*(T, g) - \sup g > 0$ from Theorem 2.1 is realised since $P_*(T, g) - \sup g \geq P(T, -h_{\text{top}}(\phi_1)\tau) + h_{\text{top}}(\phi_1)\tau_{\min} > 0$.

Remark 2.7. Using similar arguments as in Corollary 2.6, we can relate the equilibrium states of ϕ_t under $\tilde{g} : \Omega \rightarrow \mathbb{R}$ to the ones of T under $g = \lambda(\tilde{g}) - P(\phi_1, \tilde{g})\tau$, where $\lambda(\tilde{g}) : M \rightarrow \mathbb{R}$ is given by

$$\lambda(\tilde{g})(x) = \int_0^{\tau(x)} \tilde{g}(\phi_t(x)) dt.$$

3. GROWTH LEMMA AND FRAGMENTATION LEMMAS

This section contains growth lemmas, controlling the growth in complexity of the iterates of a stable curve, with a weight g . We also formulate the precise definitions of the conditions SSP.1 and SSP.2. The first condition will be used to prove the “Lasota–Yorke” bounds on the transfer operator \mathcal{L}_g in Proposition 5.1, as well as the lower bound on the spectral radius in Theorem 5.3, while SSP.2 will be crucial for the absolute continuity (Corollary 6.8) used to prove statistical properties (Propositions 6.12 and 6.15 and to compute the pressure (Corollary 6.14).

In view of deriving Lemma 3.3 from Lemma 3.2, we must work with a class of curves more general than stable manifolds. We first recall that T is uniformly hyperbolic in the sense [13] that the cones

$$(3.1) \quad \begin{aligned} \mathcal{C}^u &:= \{(dr, d\varphi) \in \mathbb{R}^2 \mid \kappa_{\min} \leq d\varphi/dr \leq \kappa_{\max} + 1/\tau_{\min}\}, \\ \mathcal{C}^s &:= \{(dr, d\varphi) \in \mathbb{R}^2 \mid -\kappa_{\min} \geq d\varphi/dr \geq -\kappa_{\max} - 1/\tau_{\min}\}, \end{aligned}$$

are strictly invariant under DT and DT^{-1} , respectively, whenever these derivatives exist. Here κ_{\max} is the maximum curvature of the scatterer boundaries, and κ_{\min} the minimum.

We define a set of cone-stable curves² $\widehat{\mathcal{W}}^s$ whose tangent vectors all lie in the stable cone \mathcal{C}^s for the map, with length at most δ_0 (to be determined latter) and curvature bounded above so that $T^{-1}\widehat{\mathcal{W}}^s \subset \widehat{\mathcal{W}}^s$, up to subdivision of curves. We define a set of cone-unstable curves $\widehat{\mathcal{W}}^u$ similarly. These sets of curves will be relevant since \mathcal{S}_n and \mathcal{S}_{-k} are composed of curves in $\widehat{\mathcal{W}}^s$ and $\widehat{\mathcal{W}}^u$, respectively.

For $\delta \in (0, \delta_0]$ and $W \in \widehat{\mathcal{W}}^s$, let $\mathcal{G}_0^\delta(W) := \{W\}$. For $n \geq 1$, define the δ -scaled subdivision $\mathcal{G}_n^\delta(W)$ inductively as the collection of smooth components of $T^{-1}(W')$ for $W' \in \mathcal{G}_{n-1}^\delta(W)$, where elements longer than δ are subdivided to have length between $\delta/2$ and δ . Thus $\mathcal{G}_n^\delta(W) \subset \widehat{\mathcal{W}}^s$ for each n and $\cup_{U \in \mathcal{G}_n^\delta(W)} U = T^{-n}W$. Moreover, if $W \in \mathcal{W}^s$, then $\mathcal{G}_n^\delta(W) \subset \mathcal{W}^s$.

Denote by $L_n^\delta(W)$ those elements of $\mathcal{G}_n^\delta(W)$ having length at least $\delta/3$, and define $\mathcal{I}_n^\delta(W)$ to comprise those elements $U \in \mathcal{G}_n^\delta(W)$ for which $T^i U$ is contained in an element of $\mathcal{G}_{n-i}^\delta(W) \setminus L_{n-i}^\delta(W)$ for all $0 \leq i \leq n-1$.

A fundamental fact [14, Lemma 5.2] we will use is that the growth in complexity for the billiard is at most linear:

$$(3.2) \quad \exists K > 0 \text{ such that } \forall n \geq 0, \text{ the number of curves in } \mathcal{S}_{\pm n} \text{ that intersect at a single point is at most } Kn.$$

3.1. Growth Lemma.

Lemma 3.1. *For any $m \in \mathbb{N}$, there exists $\delta_0 = \delta_0(m) \in (0, 1)$ such that for all $W \in \widehat{\mathcal{W}}^s$, if $|W| < \delta_0$, then for all $0 \leq l \leq 2m$, $T^{-l}W$ comprises at most $Km + 1$ connected components. Furthermore, for any $\delta \in (0, \delta_0]$, the δ -scaled subdivisions satisfy the following estimates: for all $n \geq 1$, all $\gamma \in [0, \infty)$, all $W \in \widehat{\mathcal{W}}^s$, and all \mathcal{P} -continuous potential g , we have*

$$a) \quad \sum_{W_i \in \mathcal{I}_n^\delta(W)} \left(\frac{\log |W|}{\log |W_i|} \right)^\gamma |e^{S_n g}|_{C^0(W_i)} \leq 2^{((n \vee n_0)s_0 + 1)\gamma + 1} (Km + 1)^{n/m} e^{n \sup g}$$

²The notation \mathcal{W}^s will be used for the stable manifolds. See Subsection 4.2.

$$\text{b)} \quad \sum_{W_i \in \mathcal{G}_n^\delta(W)} \left(\frac{\log |W|}{\log |W_i|} \right)^\gamma |e^{S_n g}|_{C^0(W_i)} \leq \min \left\{ 2C\delta^{-1} 2^{((n \vee n_0)s_0+1)\gamma} \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)}, \right. \\ \left. 2^{2\gamma+1} C\delta^{-1} \sum_{j=1}^n 2^{(j \vee n_0)s_0\gamma} (Km+1)^{j/m} e^{j \sup g} \sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_{n-j} g}|_{C^0(A)} \right\}$$

where $(n \vee n_0) = \max(n, n_0)$.

Moreover, if $|W| \geq \delta/2$, then both factors $2^{(ns_0+1)\gamma}$ can be replaced by 2^γ .

Proof. By [13, Exercise 4.50], there exist constants $\delta_{\text{CM}} > 0$ and $C \geq 1$ such that for all $W \in \widehat{\mathcal{W}}^s$ with $|W| < \delta_{\text{CM}}$, then $|T^{-1}W| \leq C|W|^{1/2}$. Notice also that there exists $\Lambda_1 := \Lambda_1(\varphi_0)$ such that for $W \in \widehat{\mathcal{W}}^s$ with $T^{-1}W \cap \{|\varphi| > \varphi_0\} = \emptyset$, then $|T^{-1}W| \leq \Lambda_1|W|$. We want to iterate these bounds.

Let $\delta \in (0, \delta_{\text{CM}}]$, $W \in \widehat{\mathcal{W}}^s$ with $|W| < \delta$, and $W_i \in \mathcal{I}_n^\delta(W)$. Let $V \subset W$ corresponding to W_i , that is $V = T^n W_i$. Thus, for all $1 \leq j \leq n$, we have $|T^{-j}V| = |T^{n-j}W_i| \leq \delta/3$.

We can decompose $V = \bigsqcup_{i_0 \in I_0} V_{i_0, \text{graz}}^0 \cup \bigsqcup_{j_0 \in J_0} V_{j_0, \text{exp}}^0$ such that: for all $i_0 \in I_0$, $T^{-1}V_{i_0, \text{graz}}^0 \subset \{|\varphi| \geq \varphi_0\}$, and thus $|T^{-1}V_{i_0, \text{graz}}^0| \leq C|V_{i_0, \text{graz}}^0|^{1/2}$, and for all $j_0 \in J_0$, $T^{-1}V_{j_0, \text{exp}}^0 \subset \{|\varphi| < \varphi_0\}$, and thus $|T^{-1}V_{j_0, \text{exp}}^0| \leq \Lambda_1|V_{j_0, \text{exp}}^0|$. We can perform the same decomposition for $V_{i_0, \text{graz}}^0$ or $V_{j_0, \text{exp}}^0$ instead of V :

$$V_{i_0, \text{graz}}^0 = \bigsqcup_{i_1} V_{i_1, \text{graz}}^{1, i_0} \cup \bigsqcup_{j_1} V_{j_1, \text{exp}}^{1, i_0}, \quad V_{j_0, \text{exp}}^0 = \bigsqcup_{i_1} V_{i_1, \text{graz}}^{1, j_0} \cup \bigsqcup_{j_1} V_{j_1, \text{exp}}^{1, j_0}.$$

We can iterate this decomposition until having a decomposition of $T^{-n}V = W_i$. Notice that since the stable curves $T^{-j}V$ have length at most $\delta/3 \leq \delta_{\text{CM}}/3$ and are uniformly transverse to \mathcal{S}_0 , they can cross $\{|\varphi| \geq \varphi_0\}$ at most B times, where $B > 0$ is a constant uniform in W . Thus the number of pieces at each decomposition is bounded by $2B$.

Thus $W_i = T^{-n}V = \bigsqcup_{\substack{* \in \{\text{graz}, \text{exp}\} \\ \alpha_k \in I_k \sqcup J_k}} V_{\alpha_n, *}^{n, \alpha_0, \dots, \alpha_{n-1}}$, where the union is made of at most $(2B)^n$

elements we can estimate the length.

Consider first the case $n \leq n_0$. By definition, s_0 is such that $s_0 = \sup_M \frac{1}{n_0} \sum_{k=0}^{n_0-1} \mathbb{1}_{\{|\varphi| > \varphi_0\}} \circ T^k <$

1. Thus, for each $V_{\alpha_n, *}^{n, \alpha_0, \dots, \alpha_{n-1}}$ there are at most $s_0 n_0$ indices $\alpha_k \in I_k$. Thus $|V_{\alpha_n, *}^{n, \alpha_0, \dots, \alpha_{n-1}}| \leq C^2 \Lambda_1^{n_0} |V|^{2^{-s_0 n_0}}$. Therefore

(3.3)

$$|W_i| = |T^{-n_0}V| \leq (2B)^{n_0} C^2 \Lambda_1^{n_0} |V|^{2^{-s_0 n_0}} \leq \tilde{C} |W|^{2^{-s_0 n_0}}, \quad \forall W_i \in \mathcal{I}_n^\delta(W), \quad n \leq n_0, \quad \delta \leq \delta_{\text{CM}}$$

Now, consider the case $n = kn_0 + l$, for $k \geq 1$ and $0 \leq l < n_0$. By construction, if $W_i \in \mathcal{I}_n^\delta(W)$, then $T^{-l}W_i \subset W_i^0 \in \mathcal{I}_{kn_0}^\delta(W)$ and $T^{-n_0}W_i^j \subset W_i^{j+1} \in \mathcal{I}_{(k-j-1)n_0}^\delta(W)$ for all $0 \leq j \leq k-1$. Thus, we can iterate (3.3):

$$|W_i| \leq \tilde{C} |W_i^0|^{2^{-s_0 n_0}} \leq \tilde{C}^{\sum_{m=0}^j 2^{-ms_0 n_0}} |W_i^j|^{2^{-js_0 n_0}} \leq \tilde{C}^2 |W|^{2^{-(k+1)s_0 n_0}}$$

and so $|W_i| \leq \tilde{C}^2 |W|^{2^{-s_0 n_0}}$ for all $W_i \in \mathcal{I}_n^\delta(W)$, $n \geq n_0$ and all $W \in \widehat{\mathcal{W}}^s$ with $|W| < \delta_{\text{CM}}$.

Therefore, if $\delta \leq \min(\tilde{C}^{-2}, \delta_{\text{CM}})$, we have

$$\left(\frac{\log |W_i|}{\log |W|} \right)^{\bar{\gamma}} \leq \left(2^{s_0 n} \left(1 - \frac{\log \tilde{C}^2}{\log |W_i|} \right) \right)^{\bar{\gamma}} \leq 2^{(ns_0+1)\bar{\gamma}}, \forall W_i \in \mathcal{I}_n^\delta(W),$$

since $|W_i| \leq \delta$.

(a) Let $m \geq 1$ and $W \in \widehat{\mathcal{W}}^s$ with $|W| < \delta \leq \min(\tilde{C}^{-2}, \delta_{\text{CM}})$. First, we want to estimate the number of smooth components of $T^{-l}W$, for $0 \leq l \leq 2m$. The problem is the same as knowing the number of connected components of $W \setminus \mathcal{S}_{-l}$. Now, by (3.2), at most Kl curves in \mathcal{S}_{-l} can intersect at a given point. Since W and \mathcal{S}_{-l} are uniformly transverse, for each $0 \leq l \leq 2m$ there exists $\delta_{(l)}$ such that if $|W| < \delta_{(l)}$ then $W \setminus \mathcal{S}_{-l}$ has at most $Kl+1$ connected components. Let $\delta_0 := \min\{\delta_{(l)} \mid 0 \leq l \leq 2m\}$.

Let $n \geq 1$, $\delta \in (0, \delta_0]$ and $W \in \widehat{\mathcal{W}}^s$ with $|W| < \delta$. We want to estimate $\#\mathcal{I}_n^\delta(W)$. We prove by induction that $\#\mathcal{I}_{jm}^\delta(W) \leq (Km+1)^j$. For $j=1$, this follows from the choice of δ_0 . Since elements of $\mathcal{I}_{(j+1)m}^\delta(W)$ are of the form $V \in \mathcal{I}_m^\delta(W_i)$ for $W_i \in \mathcal{I}_j^\delta(W)$, we have

$$\#\mathcal{I}_{(j+1)m}^\delta(W) \leq (Km+1)\#\mathcal{I}_{jm}^\delta(W) \leq (Km+1)^{j+1}.$$

Now for estimating $\#\mathcal{I}_{jm+l}^\delta(W)$, $0 \leq l < m$, we only need to modify the last step:

$$\#\mathcal{I}_{jm+l}^\delta(W) \leq (K(m+l)+1)\#\mathcal{I}_{(j-1)m}^\delta(W) \leq 2(Km+1)^j.$$

Therefore, $\#\mathcal{I}_n^\delta(W) \leq 2(Km+1)^{n/m}$, for all $n \geq 1$.

Finally, we have that for $n \geq n_0$

$$\sum_{W_i \in \mathcal{I}_n^\delta(W)} \left(\frac{\log |W|}{\log |W_i|} \right)^{\bar{\gamma}} |e^{S_n g}|_{C^0(W_i)} \leq e^{n \sup g} 2^{(ns_0+1)\bar{\gamma}} \#\mathcal{I}_n^\delta(W) \leq 2^{(ns_0+1)\bar{\gamma}+1} (Km+1)^{n/m} e^{n \sup g}$$

(b) Let $\delta \leq \delta_0$, and $W \in \widehat{\mathcal{W}}^s$ with $|W| < \delta$. We start by giving an estimate on $\sum_{W_i \in \mathcal{G}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}$.

Since the border of elements of \mathcal{M}_{-n}^0 is contained in \mathcal{S}_{-l} , by uniform transversality, each element of \mathcal{M}_{-n}^0 is crossed at most one time by W . Thus, each element of \mathcal{M}_0^n is crossed at most one time by $T^{-n}W$. Now, since the diameter of elements of \mathcal{M}_0^n is bounded uniformly in n by some constant C , there can be no more than $2C\delta^{-1}$ elements of $\mathcal{G}_n^\delta(W)$ in a single element of \mathcal{M}_0^n . Thus

$$(3.4) \quad \sum_{W_i \in \mathcal{G}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)} \leq 2C\delta^{-1} \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)}$$

First, in the case $|W| \geq \delta/2$, the estimate

$$\sum_{W_i \in \mathcal{G}_n^\delta(W)} \left(\frac{\log |W|}{\log |W_i|} \right)^{\bar{\gamma}} |e^{S_n g}|_{C^0(W_i)} \leq 2C\delta^{-1} 2^{((n \vee n_0)s_0+1)\bar{\gamma}} \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)},$$

is enough for what we need.

Now, assume that $|W| < \delta/2$. Let $F_1(W)$ denote those $V \in \mathcal{G}_1^\delta(W)$ whose length is at least $\delta/2$. Inductively, define $F_j(W)$, for $2 \leq j \leq n-1$, to contain those $V \in \mathcal{G}_j^\delta(W)$ whose length is at least $\delta/2$, and such that $T^k V$ is contained in an element of $\mathcal{G}_{j-k}^\delta(W) \setminus F_{j-k}(W)$ for any

$1 \leq k \leq j-1$. Thus $F_j(W)$ contains elements of $\mathcal{G}_j^\delta(W)$ that are “long for the first time” at time j .

We group $W_i \in \mathcal{G}_n^\delta(W)$ by its “first long ancestor” as follows. We say W_i has *first long ancestor*³ $V \in F_j(W)$ for $1 \leq j \leq n-1$ if $T^{n-j}W_i \subseteq V$. Note that such a j and V are unique for each W_i if they exist. If no such j and V exist, then W_i has been forever short and so must belong to $\mathcal{I}_n^\delta(W)$. Denote by $A_{n-j}(V)$ the set of $W_i \in \mathcal{G}_n^\delta(W)$ corresponding to one $V \in F_j(W)$, that is

$$A_{n-j}(V) := \{W_i \in \mathcal{G}_n(W) \mid T^{n-j}W_i \subset V\}.$$

By construction, we have the relation

$$\mathcal{G}_n^\delta(W) \setminus \left(\bigsqcup_{j=1}^{n-1} \bigsqcup_{V \in F_j(W)} A_{n-j}(V) \right) = \mathcal{I}_n^\delta(W).$$

Therefore

$$\begin{aligned} & \sum_{W_i \in \mathcal{G}_n^\delta(W)} \left(\frac{\log |W|}{\log |W_i|} \right)^\gamma |e^{S_n g}|_{C^0(W_i)} \\ &= \sum_{j=1}^{n-1} \sum_{V_i \in F_j(W)} \sum_{W_i \in A_{n-j}(V_i)} \left(\frac{\log |W|}{\log |W_i|} \right)^\gamma |e^{S_n g}|_{C^0(W_i)} + \sum_{W_i \in \mathcal{I}_n(W)} \left(\frac{\log |W|}{\log |W_i|} \right)^\gamma |e^{S_n g}|_{C^0(W_i)} \\ &\leq \sum_{j=1}^{n-1} \sum_{V_i \in F_j(W)} \left(\frac{\log |W|}{\log |V_i|} \right)^\gamma |e^{S_j g}|_{C^0(V_i)} \sum_{W_i \in A_{n-j}(V_i)} \left(\frac{\log |V_i|}{\log |W_i|} \right)^\gamma |e^{S_{n-j} g}|_{C^0(W_i)} \\ &\quad + 2^{((n \vee n_0)s_0+1)\gamma} (Km+1)^{n/m} e^{n \sup g} \\ &\leq 2^{\gamma+1} C \delta^{-1} \sum_{j=1}^{n-1} \sum_{V_i \in F_j(W)} \left(\frac{\log |W|}{\log |V_i|} \right)^\gamma |e^{S_j g}|_{C^0(V_i)} \sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_n g}|_{C^0(A)} \\ &\quad + 2^{((n \vee n_0)s_0+1)\gamma} (Km+1)^{n/m} e^{n \sup g} \\ &\leq 2^{2\gamma+1} C \delta^{-1} \sum_{j=1}^n 2^{(j \vee n_0)s_0\gamma} (Km+1)^{j/m} e^{j \sup g} \sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_n g}|_{C^0(A)}. \end{aligned}$$

where we have applied part (a) from time 1 to time j and the first estimate in part (b) from time j to time n , since each $|V_\ell| \geq \delta/2$. \square

3.2. Fragmentation Lemmas. Here, given a potential g , we introduce the conditions of Small Singular Pressure (SSP.1 and SSP.2) which are crucial for the existence and the statistical properties of the equilibrium states μ_g that will be constructed in Section 6. We prove in Lemma 3.2, Corollary 3.4 and Lemma 3.3 that there exist potentials satisfying simultaneously the conditions SSP.1 and SSP.2. These conditions and their consequences will be used in Section 3.3.

³Note that “ancestor” refers to the backwards dynamics mapping W to W_i .

In what follows, we will always assume that the potential g is such that $P_*(T, g) - \sup g > s_0 \log 2$. Thus, there exist m large enough such that

$$\frac{1}{m} \log(Km + 1) < P_*(T, g) - \sup g - s_0 \log 2,$$

and we choose $\delta_0 = \delta_0(m)$ to be the corresponding length scale from Lemma 3.1. Notice that m , and therefore also δ_0 , depend on g .

In order to state the results of this subsection, we give a precise definition of SSP.1. First, we introduce some notations.

Let $L_u^\delta(\mathcal{M}_{-n}^0)$ denote the elements of \mathcal{M}_{-n}^0 whose unstable diameter⁴ is at least $\delta/3$, for some $\delta \in (0, \delta_0]$. Similarly, let $L_s^\delta(\mathcal{M}_0^n)$ denote the elements of \mathcal{M}_0^n whose stable diameter is at least $\delta/3$. Recall that the boundary of the partition formed by \mathcal{M}_n^N is comprised of stable curves belonging to $\mathcal{S}_n = \cup_{j=0}^n T^{-j}(\mathcal{S}_0) \subset \widehat{\mathcal{W}}^s$.

Define

$$\ell_n^s(g, \delta) := \inf \left\{ \sum_{V \in L_n^\delta(W)} |e^{S_n g}|_{C^0(V)} \mid W \in \widehat{\mathcal{W}}^s, \frac{\delta}{3} \leq |W| \leq \delta \right\},$$

and $\ell_n^u(g, \delta)$ similarly using forward images of curves from $\widehat{\mathcal{W}}^u$ and Birkhoff sums with respect to T^{-1} .

A potential g such that $P(T, g) - \sup g > s_0 \log 2$ is said to have ε -SSP.1 (small singular pressure), for some $\varepsilon > 0$, if

(3.5) there exist $\delta = \delta(\varepsilon) \in (0, \delta_0]$ and $n_1 \in \mathbb{N}$ such that

$$\frac{\sum_{W_i \in L_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}}{\sum_{W_i \in \mathcal{G}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}} \geq \frac{1 - 2\varepsilon}{1 - \varepsilon}, \quad \forall n \geq n_1 \quad \forall W \in \widehat{\mathcal{W}}^s \text{ with } |W| \geq \delta/3,$$

(3.6) the sequences $(e^{n \sup g} \ell_n^s(g, \delta)^{-1})_{n \geq n_1}$ and $(e^{n \sup g} \ell_n^u(g, \delta)^{-1})_{n \geq n_1}$ are summable,

and the time reversal of (3.5) holds. By the time reversal of (3.5) we mean the same estimate but where the sets $\mathcal{G}_n^\delta(W)$ and $L_n^\delta(W)$ are defined from $T^n W$ for unstable curves $W \in \widehat{\mathcal{W}}^u$ with $|W| \geq \delta/3$ (instead of from $T^{-n} W$ and $W \in \widehat{\mathcal{W}}^s$), and the Birkhoff sums are defined with respect to T^{-1} (instead of T). Notice that (3.5) (resp. its time reversal) implies that $\ell_n^s(g, \delta)$ (resp. $\ell_n^u(g, \delta)$) is nonzero for all $n \geq n_1$.

A potential is said to have SSP.1 if it has ε -SSP.1 for some $\varepsilon \leq 1/4$.

The following lemma bootstraps from Lemma 3.1 and will be crucial to get the lower bound on the spectral radius:

Lemma 3.2. *If g is a (\mathcal{P}, α) -Hölder potential such that $P(T, g) - \sup g > s_0$ and $\log \Lambda > \sup g - \inf g$, then g satisfies (3.5), as well as its time reversal, for all $\varepsilon > 0$.*

Proof. Fix $\varepsilon > 0$. Choose n_1 so large that $6CC_1^{-1}n_1(Kn_1 + 1)e^{n_1(\sup g - \inf g - \log \Lambda)} < \varepsilon$, where C is the constant from Lemma 2.3 and C_1 is such that $|T^{-n} W| > C_1 \Lambda^n |W|$ whenever $W \in \widehat{\mathcal{W}}^s$.

⁴Recall that the unstable diameter of a set is the length of the longest unstable curve contained in that set.

Next, choose $\delta > 0$ sufficiently small that if $W \in \widehat{\mathcal{W}}^s$ with $|W| < \delta$, then $T^{-n}W$ comprises at most $Kn + 1$ smooth pieces of length at most δ_0 for all $0 \leq n \leq 2n_1$.

Let $W \in \widehat{\mathcal{W}}^s$ with $|W| \geq \delta/3$. We shall prove the following equivalent inequality for $n \geq n_1$:

$$(3.7) \quad \frac{\sum_{W_i \in S_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}}{\sum_{W_i \in \mathcal{G}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}} \leq \frac{\varepsilon}{1 - \varepsilon}.$$

For $n \geq n_1$, write $n = kn_1 + l$ for some $0 \leq l < n_1$. If $k = 1$, the above inequality is clear since $S_{n_1+l}^\delta(W)$ contains at most $K(n_1 + l) + 1$ components by assumption on δ and n_1 , while $|T^{-n_1-l}W| \geq C_1 \Lambda^{n_1+l} |W| \geq C_1 \Lambda^{n_1+l} \delta/3$. Thus $\mathcal{G}_n^\delta(W)$ must contain at least $C_1 \Lambda^{n_1+l}/3$ curves since each has length at most δ . Thus,

$$\frac{\sum_{W_i \in S_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}}{\sum_{W_i \in \mathcal{G}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}} \leq 3 \frac{K(n_1 + l) + 1}{C_1 \Lambda^{n_1+l}} \frac{e^{(n_1+l) \sup g}}{e^{(n_1+l) \inf g}} \leq 6C_1^{-1} (Kn_1 + 1) e^{n_1(\sup g - \inf g - \log \Lambda)} < \varepsilon,$$

where the last inequality holds by choice of n_1 .

For $k > 1$, we split $n = kn_1 + l$, $0 \leq l < n_1$, into $k-1$ blocks of length n_1 and the last block of length $n_1 + l$. We call *age* of the first long ancestor of $V \in \mathcal{G}_n^\delta(W) \setminus \mathcal{I}_n^\delta(W)$ the greatest integer $j < n$ such that $T^{n-j}V$ is contained in an element of $L_j^\delta(W)$ and for all $j < i < n$, $T^{n-i}V$ is contained in an element of $S_i^\delta(W)$.

We group elements of $S_n^\delta(W) \setminus \mathcal{I}_n^\delta(W)$ by their age in $[0, n_1 - 1]$, $[n_1, 2n_1 - 1]$, \dots , $[(k-2)n_1, (k-1)n_1 - 1]$ and $[(k-1)n_1, n-1]$. In other words, we consider the following decomposition

$$(3.8) \quad S_n^\delta(W) = \bigsqcup_{q=0}^{k-2} \left(\bigsqcup_{j=qn_1}^{(q+1)n_1-1} \bigsqcup_{V \in L_j^\delta(W)} \mathcal{I}_{n-j}^\delta(V) \right) \sqcup \left(\bigsqcup_{j=(k-1)n_1}^{n-1} \bigsqcup_{V \in L_j^\delta(W)} \mathcal{I}_{n-j}^\delta(V) \right).$$

We can therefore split the left hand side of (3.7) into two manageable parts. For this, we rely on Lemma 3.1 for $\gamma = 0$ and the fact that

$$\mathcal{G}_n^\delta(W) \supset \bigsqcup_{V \in L_j^\delta(W)} \mathcal{G}_{n-j}^\delta(V), \quad \forall 0 < j < n.$$

Thus, using Lemma 2.3, we have

$$\begin{aligned} \frac{\sum_{q=0}^{k-2} \sum_{j=qn_1}^{(q+1)n_1-1} \sum_{V \in L_j^\delta(W)} \sum_{W_i \in \mathcal{I}_{n-j}^\delta(V)} |e^{S_n g}|_{C^0(W_i)}}{\sum_{W_i \in \mathcal{G}_{kn_1+l}^\delta(W)} |e^{S_n g}|_{C^0(W_i)}} &\leq \sum_{q=0}^{k-2} \sum_{j=qn_1}^{(q+1)n_1-1} \frac{\sum_{V \in L_j^\delta(W)} |e^{S_j g}|_{C^0(V)} \sum_{W_i \in \mathcal{I}_{n-j}^\delta(V)} |e^{S_{n-j} g}|_{C^0(W_i)}}{C^{-1} \sum_{V \in L_j^\delta(W)} |e^{S_j g}|_{C^0(V)} \sum_{W_i \in \mathcal{G}_{n-j}^\delta(V)} e^{(n-j) \inf g}} \\ &\leq \sum_{q=0}^{k-2} 6CC_1^{-1} n_1 (Kn_1 + 1)^{k-q} e^{(k-q)n_1(\sup g - \inf g - \log \Lambda)} \end{aligned}$$

$$\leq \sum_{q=0}^{k-2} \varepsilon^{k-q} = \sum_{q=2}^k \varepsilon^q$$

Similarly, for the second part we have

$$\begin{aligned} \frac{\sum_{j=(k-1)n_1}^{n-1} \sum_{V \in L_j^\delta(W)} \sum_{W_i \in \mathcal{I}_{n-j}^\delta(V)} |e^{S_n g}|_{C^0(W_i)}}{\sum_{W_i \in \mathcal{G}_{kn_1+l}^\delta(W)} |e^{S_n g}|_{C^0(W_i)}} &\leq \sum_{j=(k-1)n_1}^{n-1} \frac{\sum_{V \in L_j^\delta(W)} |e^{S_j g}|_{C^0(V)} \sum_{W_i \in \mathcal{I}_{n-j}^\delta(V)} |e^{S_{n-j} g}|_{C^0(W_i)}}{C^{-1} \sum_{V \in L_j^\delta(W)} |e^{S_j g}|_{C^0(V)} \sum_{W_i \in \mathcal{G}_{n-j}^\delta(V)} e^{(n-j) \inf g}} \\ &\leq 6CC_1^{-1} n_1 (Kn_1 + 1) e^{n_1 (\sup g - \inf g - \log \Lambda)} \leq \varepsilon \end{aligned}$$

Summing these two estimates, we obtain (3.7).

The time reversal is obtained from the same proof by changing the construction of the set $\mathcal{G}_n^\delta(W)$ (and thus $L_n^\delta(W)$, $S_n^\delta(W)$ and $\mathcal{I}_n^\delta(W)$) so that elements of $\mathcal{G}_n^\delta(W)$ are contained in $T^n W$ (instead of $T^{-n}(W)$) for $W \in \widehat{\mathcal{W}}^u$. \square

Notice that if $\varepsilon \leq 1/4$ and $\delta_1 \leq \delta_0$ and n_1 are the corresponding δ and n_1 from the ε -SSP.1 condition, then we have for all $W \in \widehat{\mathcal{W}}^s$ with $|W| \geq \delta_1/3$ and $n \geq n_1$

$$(3.9) \quad \sum_{W_i \in L_n^{\delta_1}(W)} |e^{S_n g}|_{C^0(W_i)} \geq \frac{2}{3} \sum_{W_i \in \mathcal{G}_n^{\delta_1}(W)} |e^{S_n g}|_{C^0(W_i)},$$

In particular, since $\mathcal{G}_n^{\delta_1}(W) = L_n^{\delta_1}(W) \sqcup S_n^{\delta_1}(W)$, we also get that

$$\sum_{W_i \in L_n^{\delta_1}(W)} |e^{S_n g}|_{C^0(W_i)} \geq 2 \sum_{W_i \in S_n^{\delta_1}(W)} |e^{S_n g}|_{C^0(W_i)}.$$

The following lemma will be used to get both lower and upper bounds on the spectral radius via Proposition 3.5:

Lemma 3.3. *Let g be a (\mathcal{P}, α) -Hölder potential such that $P_*(T, g) - \sup g > s_0 \log 2$ and which has SSP.1. Let δ_1 and n_1 be the corresponding parameters associated with SSP.1. Then there exist $C_{n_1} > 0$ and $n_2 \geq n_1$ such that for all $n \geq n_2$,*

$$\begin{aligned} \sum_{A \in L_u^{\delta_1}(\mathcal{M}_{-n}^0)} |e^{S_n^{-1} g}|_{C^0(A)} &\geq C_{n_1} \delta_1 \sum_{A \in \mathcal{M}_{-n}^0} |e^{S_n^{-1} g}|_{C^0(A)}, \\ \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^n)} |e^{S_n g}|_{C^0(A)} &\geq C_{n_1} \delta_1 \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)}. \end{aligned}$$

where $S_n^{-1} g := \sum_{i=0}^n g \circ T^{-i}$.

Furthermore, if g is a (\mathcal{P}, α) -Hölder potential with $P_*(T, g) - \sup g > s_0 \log 2$ and $\log \Lambda > \sup g - \inf g$, then g has SSP.1.

Proof. We prove the lower bound for $L_s^{\delta_1}(\mathcal{M}_0^n)$. The lower bound for $L_u^{\delta_1}(\mathcal{M}_{-n}^0)$ then follows by time reversal.

First, we need to define sets that will be relevant only here. Let

$$I_s(\mathcal{M}_0^n) := \{A \in \mathcal{M}_0^n \mid \text{diam}^s(A) < \delta_1/3\}$$

be the complement of $L_s^{\delta_1}(\mathcal{M}_0^n)$ in \mathcal{M}_0^n , and

$$I_s(T^{-j}\mathcal{S}_0) := \{\text{unstable curves in } T^{-j}(\mathcal{S}_0) \text{ with length less than } \delta_1/3\}$$

Define also $L_s(T^{-j}\mathcal{S}_0)$ as the complement of $I_s(T^{-j}\mathcal{S}_0)$ in $\mathcal{G}_j^{\delta_1}(\mathcal{S}_0)$.

We will deduce the claim by estimating the sum of norms of $e^{S_{ng}}$ over $I_s(\mathcal{M}_0^n)$ by the one over $L_s^{\delta_1}(\mathcal{M}_0^n)$. To do so, we estimate the sum over $I_s(\mathcal{M}_0^n)$ with the sums over $I_s(T^{-j}\mathcal{S}_0)$. Then, using (3.5) we estimate the sum over $I_s(T^{-j}\mathcal{S}_0)$ with sums over $L_s(T^{-j}\mathcal{S}_0)$. Finally, we estimate sums over $L_s(T^{-j}\mathcal{S}_0)$ with a sum over $L_s^{\delta_1}(\mathcal{M}_0^n)$.

In order to estimate the sum over $I_s(\mathcal{M}_0^n)$, first remark that if $A \in \mathcal{M}_0^n$ then $\partial A \subset \mathcal{S}_n = \bigcup_{j=0}^n T^{-j}\mathcal{S}_0$. Let $A \in I_s(\mathcal{M}_0^n)$. We distinguish two cases:

(a) For some $1 \leq j \leq n$, ∂A contains a point of intersection between two curves of $T^{-j}\mathcal{S}_0$. Since such intersection point is the image by T^{-j+1} of an intersection point between curves of $T^{-1}\mathcal{S}_0$, which are finite, and thank to the linear complexity (3.2), we get that there are at most K_2n elements of $I_s(\mathcal{M}_0^n)$ in this case.

(b) ∂A only contains intersection points between curves belonging to $T^{-j}\mathcal{S}_0$ for different j . Let j_A be the maximal $1 \leq j \leq n$ such that $A \cap T^{-j}\mathcal{S}_0 \neq \emptyset$, and $\gamma \in T^{-j_A}\mathcal{S}_0$ such that $\gamma \cap A \neq \emptyset$. Notice that γ must intersect other curves from ∂A . These curves belong to $T^{-j}\mathcal{S}_0$ for some $j < j_A$. Applying T^j , it appears that γ must terminates at these intersection points, and thus $\gamma \subset \partial A$. Since γ is a stable curve, γ belongs to $I_s(T^{-j_A}\mathcal{S}_0)$ by assumption on A . Finally, such a curve γ belong to at most 2 elements of $I_s(\mathcal{M}_0^n)$.

Therefore

$$(3.10) \quad \sum_{A \in I_s(\mathcal{M}_0^n)} |e^{S_{ng}}|_{C^0(A)} \leq K_2 n e^{n \sup g} + C \sum_{j=1}^n \sum_{W \in I_s(T^{-j}\mathcal{S}_0)} |e^{S_{ng}}|_{C_+^0(W)} + |e^{S_{ng}}|_{C_-^0(W)},$$

where we have extended $e^{S_{ng}}$ by Hölder continuity to W from both sides – and noted $|\cdot|_{C_+^0(W)}$ and $|\cdot|_{C_-^0(W)}$ the corresponding norms – and C is the constant from Lemma 2.3.

In order to use (3.5), we decompose $\mathcal{S}_0 = \bigsqcup_{i=1}^{l_0} U_i$ where each U_i is a connected curve such that $\frac{\delta_1}{3} \leq |T^{-1}U_i| \leq \delta_1$. But first we need to compare the sum indexed by $I_s(T^{-j}\mathcal{S}_0)$ with the one indexed by $I_s(\mathcal{G}_{j-1}^{\delta_1}(U_i))$. Let $W \in I_s(T^{-j}\mathcal{S}_0)$. Thus, each $W \cap T^{-j}U_i$ is a single maximal smooth component of length less than $\delta_1/3$. In other words, $W \cap T^{-j}U_i \in I_s(\mathcal{G}_{j-1}^{\delta_1}(U_i))$. Therefore

$$(3.11) \quad \sum_{W \in I_s(T^{-j}\mathcal{S}_0)} |e^{S_{ng}}|_{C_{\pm}^0(W)} \leq \sum_{i=1}^{l_0} \sum_{W \in I_s(\mathcal{G}_{j-1}^{\delta_1}(U_i))} |e^{S_{ng}}|_{C_{\pm}^0(W)}.$$

Now, using SSP.1 (3.5), in the case $j \geq n_1$, we get that

$$(3.12) \quad \sum_{W \in I_s(\mathcal{G}_{j-1}^{\delta_1}(U_i))} |e^{S_{ng}}|_{C_{\pm}^0(W)} \leq \frac{1}{2} e^{(n-j+1) \sup g} \sum_{W \in I_s(\mathcal{G}_{j-1}^{\delta_1}(U_i))} |e^{S_{j-1}g}|_{C_{\pm}^0(W)}.$$

In order to estimate this last sum with the sum indexed by $L_s(\mathcal{G}_{n-1}^{\delta_1}(T^{-1}U_i))$, notice that

$$L_s(\mathcal{G}_{n-1}^{\delta_1}(T^{-1}U_i)) \supset \bigsqcup_{V \in L_s(\mathcal{G}_{j-1}^{\delta_1}(TU_i))} L_s(\mathcal{G}_{n-j}^{\delta_1}(V)).$$

Thus

$$\begin{aligned} \sum_{W \in L_s(\mathcal{G}_{n-1}^{\delta_1}(T^{-1}U_i))} |e^{S_n g}|_{C_{\pm}^0(W)} &\geq \sum_{W \in L_s(\mathcal{G}_{j-1}^{\delta_1}(T^{-1}U_i))} \sum_{V \in L_s(\mathcal{G}_{n-j}^{\delta_1}(W))} |e^{S_{n-j}g + S_j g \circ T^{n-j}}|_{C_{\pm}^0(V)} \\ &\geq C^{-2} e^{\inf g} \sum_{W \in L_s(\mathcal{G}_{j-1}^{\delta_1}(T^{-1}U_i))} |e^{S_{j-1}g}|_{C_{\pm}^0(W)} \sum_{V \in L_s(\mathcal{G}_{n-j}^{\delta_1}(W))} |e^{S_{n-j}g}|_{C_{\pm}^0(V)} \\ &\geq C^{-2} e^{\inf g} \ell_{n-j}^s(g, \delta_1) \sum_{W \in L_s(\mathcal{G}_{j-1}^{\delta_1}(T^{-1}U_i))} |e^{S_{j-1}g}|_{C_{\pm}^0(W)}, \end{aligned}$$

where we used Lemma 2.3 for the second inequality, and the definition of $\ell_{n-j}^s(g, \delta_1)$ for the third inequality. Notice however that (3.5) ensure that $\ell_{n-j}^s(g, \delta_1) \neq 0$ only for $n-j \geq n_1$. We will treat these troublesome j in a second time. Assume for now that $n_1 \leq j \leq n-n_1$. Combining the above lower bound with (3.11) and (3.12), we get

$$(3.13) \quad \sum_{W \in I_s(T^{-j}\mathcal{S}_0)} |e^{S_n g}|_{C_{\pm}^0(W)} \leq \bar{C} e^{(n-j)\sup g} \ell_{n-j}^s(g, \delta_1)^{-1} \sum_{W \in L_s(T^{-n}\mathcal{S}_0)} |e^{S_n g}|_{C_{\pm}^0(W)}.$$

where we used that $\bigsqcup_{i=1}^{l_0} L_s(\mathcal{G}_{j-1}^{\delta_1}(T^{-1}U_i)) \subset L_s(T^{-j}\mathcal{S}_0)$ – which is true if we choose the δ_1 -scaling $\mathcal{G}_1(T^{-j}\mathcal{S}_0)$ to be adapted with the decomposition $\mathcal{S}_0 = \bigsqcup_i U_i$.

Now, if $n-n_1 \leq j \leq n$, then we obtain from similar computations

$$(3.14) \quad \sum_{W \in I_s(T^{-j}\mathcal{S}_0)} |e^{S_n g}|_{C_{\pm}^0(W)} \leq \frac{1}{2} C^2 e^{\inf g} e^{(n-j+1)\sup g} \ell_{n_1}^s(g, \delta_1)^{-1} \sum_{W \in L_s(T^{-j-n_1}\mathcal{S}_0)} |e^{S_{n_1+j}g}|_{C_{\pm}^0(W)}$$

Finally, we estimate the sum over $L_s(T^{-n}\mathcal{S}_0)$ with the sum over $L_s^{\delta_1}(\mathcal{M}_0^n)$. To do so, we use similar arguments than for the estimate (3.10). Let $W \in L_s(T^{-n}\mathcal{S}_0)$. We distinguish the two following cases:

- (a) W intersects another curve from $T^{-n}\mathcal{S}_0$. There are at most $2K_2$ elements of $L_s(T^{-n}\mathcal{S}_0)$ in this case,
- (b) W does not intersect other curves from $T^{-n}\mathcal{S}_0$. In that case, W must be contained in the boundary of an element of \mathcal{M}_0^n , and thus an element of $L_s^{\delta_1}(\mathcal{M}_0^n)$. Now, there are at most $2C\delta_1^{-1}$ elements of $L_s(T^{-n}\mathcal{S}_0)$ in the boundary of a single element of $L_s^{\delta_1}(\mathcal{M}_0^n)$, where C is a large enough constant depending only on the billiard table.

Thus

$$(3.15) \quad \sum_{W \in L_s(T^{-n}\mathcal{S}_0)} |e^{S_n g}|_{C_{\pm}^0(W)} \leq 2K_2 e^{n\sup g} + C\delta_1^{-1} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^n)} |e^{S_n g}|_{C^0(A)}.$$

Similarly, for all $n - n_1 \leq j \leq n$,

$$(3.16) \quad \sum_{W \in L_s(T^{-n_1-j}S_0)} |e^{S_{n_1+j}g}|_{C_{\pm}^0(W)} \leq 2K_2 e^{(n_1+j)\sup g} + C\delta_1^{-1} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^{n_1+j})} |e^{S_{n_1+j}g}|_{C^0(A)}.$$

Putting together (3.10), (3.13) and (3.15), as well as (3.14) and (3.16), we get

$$\begin{aligned} \sum_{A \in I_s(\mathcal{M}_0^n)} |e^{S_n g}|_{C^0(A)} &\leq K_2 n e^{n \sup g} + C \sum_{j=1}^{n_1-1} \sum_{W \in I_s(T^{-j}S_0)} |e^{S_n g}|_{C_+^0(W)} + |e^{S_n g}|_{C_-^0(W)} \\ &\quad + C \sum_{j=n_1}^{n-n_1} \sum_{W \in I_s(T^{-j}S_0)} |e^{S_n g}|_{C_+^0(W)} + |e^{S_n g}|_{C_-^0(W)} \\ &\quad + C \sum_{j=n-n_1+1}^n \sum_{W \in I_s(T^{-j}S_0)} |e^{S_n g}|_{C_+^0(W)} + |e^{S_n g}|_{C_-^0(W)} \\ &\leq (K_2 n + \bar{C}_{n_1}) e^{n \sup g} + \bar{C} \sum_{j=n_1}^{n-n_1} e^{j \sup g} \ell_j^s(g, \delta_1)^{-1} \sum_{W \in L_s(T^{-n}S_0)} |e^{S_n g}|_{C_+^0(W)} + |e^{S_n g}|_{C_-^0(W)} \\ &\quad + C \sum_{j=n-n_1+1}^n e^{(n-j) \sup g} \ell_{n_1}^s(g, \delta_1)^{-1} \sum_{W \in L_s(T^{-j-n_1}S_0)} |e^{S_{j+n_1}g}|_{C_+^0(W)} + |e^{S_{j+n_1}g}|_{C_-^0(W)} \\ &\leq (K_2 n + \bar{C}_{n_1}) e^{n \sup g} + \tilde{C} n \left(2K_2 e^{n \sup g} + C\delta_1^{-1} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^n)} |e^{S_n g}|_{C^0(A)} \right) \\ &\quad + \sum_{j=n-n_1+1}^n \bar{C}_{n_1} \left(2K_2 e^{(n_1+j) \sup g} + C\delta_1^{-1} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^{j+n_1})} |e^{S_{j+n_1}g}|_{C^0(A)} \right), \end{aligned}$$

where in the last inequality we used (3.6) and the fact that $n - n_1 + 1 \leq j \leq n$ is equivalent to $0 \leq n - j \leq n_1 - 1$, that is, in the second sum over j after the second inequality symbol, the $e^{(n-j)\sup g}$ are uniformly bounded.

We now relate the sum over $L_s^{\delta_1}(\mathcal{M}_0^{j+n_1})$ to the sum over $L_s^{\delta_1}(\mathcal{M}_0^n)$. To do so, notice that if $A \in L_s^{\delta_1}(\mathcal{M}_0^{j+n_1})$, then it contains at most B^{j+n_1-n} elements of $L_s^{\delta_1}(\mathcal{M}_0^n)$, where $B = |\mathcal{P}|$. On the other hand, an element $A' \in L_s^{\delta_1}(\mathcal{M}_0^n)$ is contained in exactly one element of $L_s^{\delta_1}(\mathcal{M}_0^{j+n_1})$. Thus

$$\begin{aligned} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^{j+n_1})} |e^{S_{j+n_1}g}|_{C^0(A)} &= \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^{j+n_1})} \sum_{\substack{A' \in L_s^{\delta_1}(\mathcal{M}_0^n) \\ A \subset A'}} |e^{S_{j+n_1}g}|_{C^0(A)} \\ &\leq \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^{j+n_1})} \sum_{\substack{A' \in L_s^{\delta_1}(\mathcal{M}_0^n) \\ A \subset A'}} e^{n_1 \sup g} |e^{S_j g}|_{C^0(A')} \end{aligned}$$

$$\begin{aligned}
&\leq \sum_{A' \in L_s^{\delta_1}(\mathcal{M}_0^n)} \sum_{\substack{A \in L_s^{\delta_1}(\mathcal{M}_0^{j+n_1}) \\ A \subset A'}} e^{n_1 \sup g} |e^{S_j g}|_{C^0(A')} \\
&\leq B^{j+n_1-n} e^{n_0 \sup g} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^n)} |e^{S_j g}|_{C^0(A)},
\end{aligned}$$

and therefore,

$$\begin{aligned}
\sum_{j=n-n_1+1}^n \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^{j+n_0})} |e^{S_{j+n_1} g}|_{C^0(A)} &\leq \sum_{j=n-n_1+1}^n B^{j+n_1-n} e^{n_1 \sup g} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^n)} |e^{S_j g}|_{C^0(A)} \\
&\leq \sum_{j=n-n_1+1}^n B^{j+n_1-n} e^{n_1 \sup g} e^{(n-j) \inf g} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^n)} |e^{S_n g}|_{C^0(A)} \\
&\leq \bar{C}_{n_1} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^n)} |e^{S_n g}|_{C^0(A)}.
\end{aligned}$$

Using this last estimates, we obtain

$$\sum_{A \in I_s(\mathcal{M}_0^n)} |e^{S_n g}|_{C^0(A)} \leq (K_2 n + \bar{C}_{n_1} + C_{g,\ell} n) e^{n \sup g} + (C_{g,\ell} + \bar{C}_{n_1}) \delta_1^{-1} \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^n)} |e^{S_n g}|_{C^0(A)},$$

where $C_{g,\ell}$ is a constant coming from the summability assumption (3.6), and \bar{C}_{n_1} depends only on n_1 and g .

Finally, since $I_s(\mathcal{M}_0^n) \sqcup L_s^{\delta_1}(\mathcal{M}_0^n) = \mathcal{M}_0^n$, we get that

$$\sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^n)} |e^{S_n g}|_{C^0(A)} \geq \frac{\sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)} - (K_2 n + \bar{C}_{n_1} + C_{g,\ell} n) e^{n \sup g}}{1 + (C_{g,\ell} + \bar{C}_{n_1}) \delta_1^{-1}}.$$

Since $\lim_{n \rightarrow +\infty} \frac{1}{n} \log \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)} = P_*(T, g)$ and by the assumption $P_*(T, g) > \sup g$, there is an integer n_2 such that for all $n \geq n_2$,

$$\sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)} - (K_2 n + \bar{C}_{n_1} + C_{g,\ell} n) e^{n \sup g} \geq \frac{1}{2} \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)}.$$

Thus, there exists $C_{n_1} > 0$ such that for all $n \geq n_2$ the claim holds.

We now prove the second part of Lemma 3.3. Assume that g is a (\mathcal{P}, α) -Hölder potential with $P_*(T, g) - \sup g > s_0 \log 2$ and $\log \Lambda > \sup g - \inf g$. From the convexity of the topological pressure (Theorem 2.1), we get that $t \mapsto P_*(T, tg)$ is a convex function. Thus, the map $t \mapsto P_*(T, t(g - \sup g)) = P_*(T, tg) - t \sup g$ is continuous on $[0, 1]$. Since for all $s < t$ we have

$$\sum_{A \in \mathcal{M}_0^n} |e^{S_n t(g - \sup g)}|_{C^0(A)} \leq e^{n(t-s) \sup(g - \sup g)} \sum_{A \in \mathcal{M}_0^n} |e^{S_n s(g - \sup g)}|_{C^0(A)} = \sum_{A \in \mathcal{M}_0^n} |e^{S_n s(g - \sup g)}|_{C^0(A)},$$

the map is nonincreasing. Thus

$$P_*(T, g) - \sup g = P_*(T, g - \sup g) \leq P_*(T, 0) = h_*,$$

where h_* is the topological entropy from [3]. Therefore we have $h_* > s_0 \log 2$ and estimates from [3] can be used. For all $W \in \widehat{\mathcal{W}}^s$ with $\delta_1 \geq |W| \geq \delta_1/3$ and all $n \geq n_1$,

$$\begin{aligned} \sum_{V \in L_n^{\delta_1}(W)} |e^{S_n g}|_{C^0(V)} &\geq e^{n \inf g} \#L_n^{\delta_1}(W) \geq \frac{2}{3} e^{n \inf g} \#\mathcal{G}_n^{\delta_1}(W) \geq \frac{2}{3} c_0 e^{n \inf g} \#\mathcal{M}_0^n \\ &\geq \frac{2}{3} c_0 e^{n(\inf g + P_*(T, 0))} \end{aligned}$$

where we used [3, Lemma 5.2] for the second inequality, and Propositions 4.6 and 5.5 from [3] in the third inequality⁵.

Thus we get that $\ell_n^s(g, \delta_1) \geq \frac{2}{3} c_0 e^{n(\inf g + P_*(T, 0))}$. Since⁶ $P_*(T, 0) = h_* \geq \log \Lambda$, we then get the summability of the sequence $(e^{n \sup g} \ell_n^s(g, \delta_1)^{-1})_{n \geq n_1}$. The summability of $e^{n \sup g} \ell_n^u(g, \delta_1)^{-1}$ is obtained similarly by considering lower bounds on $\#L_n^{\delta_1}(W)$, also given in [3]. \square

We now introduce the precise definition of SSP.2: A potential g is said to have ε -SSP.2 if it has ε -SSP.1, if there exists $\bar{n}_1 : (0, +\infty) \rightarrow \mathbb{N}$ such that

$$(3.17) \quad \frac{\sum_{W_i \in L_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}}{\sum_{W_i \in \mathcal{G}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}} \geq \frac{1 - 3\varepsilon}{1 - \varepsilon}, \quad \forall W \in \widehat{\mathcal{W}}^s, \forall n \geq \bar{n}_1(|W|),$$

and if the time reversal of (3.17) holds, where δ is the corresponding constant from ε -SSP.1. A potential is said to have SSP.2 if it has ε -SSP.2 for some $\varepsilon \leq 1/4$.

Corollary 3.4. *If g is a (\mathcal{P}, α) -Hölder potential such that $P(T, g) - \sup g > s_0$ and $\log \Lambda > \sup g - \inf g$, then there exists $C_2 > 0$ such that g has ε -SSP.2 for all $\varepsilon > 0$ and $\bar{n}_1(|W|) = C_2 n_1 \frac{|\log(|W|/\delta)|}{|\log \varepsilon|}$, where δ and n_1 are the corresponding constants from Lemma 3.2.*

Proof. From the Lemmas 3.2 and 3.3, such a potential has SSP.1. We thus only prove (3.17).

The proof is essentially the same as the one for Lemma 3.2, except that for curves shorter than $\delta/3$ one must wait $n \lesssim |\log(|W|/\delta)|$ for at least one component of $\mathcal{G}_n^\delta(W)$ to belong to $L_n^\delta(W)$.

More precisely, fix $\varepsilon > 0$ and the corresponding δ and n_1 from Lemma 3.2. Let $W \in \widehat{\mathcal{W}}^s$ with $|W| < \delta/3$ and take $n > n_1$. Decomposing $\mathcal{G}_n^\delta(W)$ and $S_n^\delta(W)$ as in Lemma 3.2, we estimate the second part as before. For the first part, we have to split the sum between $\mathcal{I}_n^\delta(W)$ and the rest, which is estimated as before.

For the first part, concerning $\mathcal{I}_n^\delta(W)$, for δ sufficiently small, notice that since the flow is continuous, either $\#\mathcal{G}_l^\delta(W) \leq Kl + 1$ by (3.2) or at least one element of $\mathcal{G}_l^\delta(W)$ has length at least $\delta/3$. Let n_2 denote the first iterate l at which $\mathcal{G}_l^\delta(W)$ contains at least one element of length more than $\delta/3$. By the complexity estimate (3.2) and the fact that $|T^{-n_2}W| \geq$

⁵We can choose the scale δ_1 from [3] to agree with the one here. The constant c_0 comes from [3, Proposition 5.5] and depends on δ_1 .

⁶ $\log \Lambda$ is a lower bound on the unstable Lyapunov exponent of T . Integrating against μ_{SRB} gives the desired inequality.

$C_1 \Lambda^{n_2} |W|$ by hyperbolicity of T , there exists $\overline{C}_2 > 0$, independent of $W \in \widehat{\mathcal{W}}^s$, such that $n_2 \leq \overline{C}_2 |\log(|W|/\delta)|$.

Now, for $n \geq n_2$,

$$\begin{aligned} \sum_{W_i \in \mathcal{I}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)} &\leq \sum_{W' \in \mathcal{G}_{n_2}^\delta(W)} |e^{S_{n_2} g}|_{C^0(W')} \sum_{W_i \in \mathcal{I}_{n-n_2}^\delta(W')} |e^{S_{n-n_2} g}|_{C^0(W_i)} \\ &\leq K(Kn_2 + 1) e^{n_2 \sup g} \times 2(Kn_1 + 1)^{\frac{n-n_2}{n_1}} e^{(n-n_2) \sup g} \end{aligned}$$

and by hyperbolicity and Lemma 2.3,

$$\begin{aligned} \sum_{W_i \in \mathcal{G}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)} &\geq C^{-1} |e^{S_{n_2} g}|_{C^0(W')} \sum_{W_i \in \mathcal{G}_{n-n_2}^\delta(W')} e^{(n-n_2) \inf g} \\ &\geq \frac{1}{3} C_1 C^{-1} e^{n_2 \inf g} e^{(n-n_2)(\inf g + \log \Lambda)} \end{aligned}$$

where $W' \in \mathcal{G}_{n_2}^\delta(W)$ is such that $|W'| > \delta/3$. Therefore,

$$\begin{aligned} \frac{\sum_{W_i \in \mathcal{I}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}}{\sum_{W_i \in \mathcal{G}_n^\delta(W)} |e^{S_n g}|_{C^0(W_i)}} &\leq 6C_1^{-1} C e^{n_2(\sup g - \inf g)} K(Kn_2 + 1)(Kn_1 + 1)^{\frac{n-n_2}{n_1}} e^{(n-n_2)(\sup g - \inf g - \log \Lambda)} \\ &\leq 2c_0^{-1} C^2 e^{n_2(\sup g - \inf g)} K(Kn_2 + 1) \varepsilon^{n/n_1}. \end{aligned}$$

Since $n_2 \leq \overline{C}_2 |\log(|W|/\delta)|$, we can bound this expression by ε by choosing some $C_2 > 0$ and n large enough so that $n/n_1 \geq C_2 \frac{\log(|W|/\delta)}{\log \varepsilon}$. For such n , the left hand side of (3.7) is bounded by $\varepsilon + \frac{\varepsilon}{1-\varepsilon} \leq \frac{2\varepsilon}{1-\varepsilon}$, which completes the proof of the corollary.

As usual, the time reversal of (3.17) is obtained by performing the same proof, but with the time reversal counterpart of $\mathcal{G}_n^\delta(W)$, for unstable curves W . \square

3.3. Exact Exponential Growth of Thermodynamic Sums – Cantor Rectangles. It follows from the submultiplicativity in the characterisation of $P_*(T, g)$ that

$$e^{nP_*(T, g)} \leq e^{-\inf g} \sum_{A \in \mathcal{M}_0^n} \sup_{x \in A} e^{(S_n g)(x)}$$

for all n . In this subsection, we shall prove a supermultiplicativity statement (Lemma 3.7) from which we deduce the upper bound for $\sum_{A \in \mathcal{M}_0^n} \sup_{x \in A} e^{(S_n g)(x)}$ in Proposition 3.8 giving the upper bound in Proposition 5.1, and ultimately the upper bound on the spectral radius of \mathcal{L}_g on \mathcal{B} .

The following key estimate is a lower bound on the weighted rate of growth of stable curves having a certain length. The proof will crucially use the fact that the SRB measure is mixing in order to bootstrap from SSP.1.

Proposition 3.5. *Let g be a (\mathcal{P}, α) -Hölder potential with $P_*(T, g) - \sup g > s_0 \log 2$ and which has SSP.1. Let δ_1 be the value of δ from the condition SSP.1. Then there exists $c_0 > 0$ such*

that for all $W \in \widehat{W}^s$ with $|W| \geq \delta_1/3$ and $n \geq 1$, we have

$$\sum_{W_i \in \mathcal{G}_n^{\delta_0}(W)} |e^{S_n g}|_{C^0(A)} \geq c_0 \sum_{A \in \mathcal{M}_{-n}^0} |e^{S_n^{-1} g}|_{C^0(A)}.$$

The constant c_0 depends on δ_1 .

The proof relies crucially on the notion of *Cantor rectangles*. We introduce this notion as in [3, Definition 5.7]. Let $W^s(x)$ and $W^u(x)$ denote the maximal smooth components of the local stable and unstable manifolds of $x \in M$.

Definition 3.6. A solid rectangle D in M is a closed connected set whose boundary comprises precisely four nontrivial curves: two stable manifolds and two unstable manifolds. Given a solid rectangle D , the (locally maximal) Cantor rectangle R in D is formed by taking the points in D whose local stable and unstable manifolds completely cross D . Cantor rectangles have a natural product structure: for any $x, y \in R$, then $W^s(x) \cap W^u(y) \in R$. In [13, Section 7.11], Cantor rectangles are proved to be closed, and thus contains their outer boundaries, which are contained in the boundary of D . With a slight abuse, we will call this pairs of stable and unstable manifolds the stable and unstable boundaries of R . In this case, we denote D by $D(R)$ to emphasize that it is the smallest solid rectangle containing R .

Proof. Using [13, Lemma 7.87], we may cover M by Cantor rectangles R_1, \dots, R_k satisfying

$$(3.18) \quad \inf_{x \in R} \frac{m_{W^u}(W^u(x) \cap R)}{m_{W^u}(W^u(x) \cap D(R))} \geq 0.9,$$

whose stable and unstable boundaries have lengths at most $\frac{1}{10}\delta_1$, with the property that any stable curve of length at least $\delta_1/3$ properly crosses at least one of them. A stable curve $W \in \widehat{W}^s$ is said to properly cross R if W crosses both unstable sides of R , W does not cross any stable manifolds $W^s(x) \cap D(R)$ for $x \in R$, and the point $W \cap W^u(x)$ subdivides the curve $W^u(x) \cap D(R)$ in a ratio between 0.1 and 0.9 (i.e. W does not come too close to either stable boundary of R). The cardinality k is fixed, depending only on δ_1 .

Recall that $L_u^{\delta_1}(\mathcal{M}_{-n}^0)$ denotes the elements of \mathcal{M}_{-n}^0 whose unstable diameter is longer than $\delta_1/3$. We claim that for all $n \in \mathbb{N}$, at least one R_i is fully crossed in the unstable direction by a subset \tilde{L} of \mathcal{M}_{-n}^0 such that

$$(3.19) \quad \sum_{A \in \tilde{L}} |e^{S_n^{-1} g}|_{C^0(A)} \geq \frac{1}{k} \sum_{A \in L_u^{\delta_1}(\mathcal{M}_{-n}^0)} |e^{S_n^{-1} g}|_{C^0(A)}.$$

Notice that if $A \in \mathcal{M}_{-n}^0$, then ∂A is comprised of unstable curves belonging to $\cup_{i=1}^n T^i \mathcal{S}_0$, and possibly \mathcal{S}_0 . By definition of unstable manifolds, $T^i \mathcal{S}_0$ cannot intersect the unstable boundaries of the R_i ; thus if $A \cap R_i \neq \emptyset$, then either ∂A terminates inside R_i or A fully crosses R_i . Thus elements of $L_u^{\delta_1}(\mathcal{M}_{-n}^0)$ fully cross at least one R_i and so at least one R_i must be fully crossed by a large fraction \tilde{L} of $L_u^{\delta_1}(\mathcal{M}_{-n}^0)$ in the sense of (3.19), proving the claim.

For each $n \in \mathbb{N}$, denote by i_n the index of a rectangle R_{i_n} which is fully crossed by a large enough subset \tilde{L}_n of $L_u(\mathcal{M}_{-n}^0)$, in the sense of (3.19).

Fix $\delta_* \in (0, \delta_1/10)$ and for $i = 1, \dots, k$, choose a “high density” subset $R_i^* \subset R_i$ satisfying the following conditions: R_i^* has a non-zero Lebesgue measure, and for any unstable manifold

W^u such that $W^u \cap R_i^* \neq \emptyset$ and $|W^u| < \delta_*$, we have $\frac{m_{W^u}(W^u \cap R_i^*)}{|W^u|} \geq 0.9$. (Such a δ_* and R_i^* exist due to the fact that m_{W^u} -almost every $y \in R_i$ is a Lebesgue density point of the set $W^u(y) \cap R_i$ and the unstable foliation is absolutely continuous with respect to μ_{SRB} or, equivalently, Lebesgue.)

Due to the mixing property of μ_{SRB} and the finiteness of the number of rectangle R_i , there exist $\varepsilon > 0$ and $n_3 \in \mathbb{N}$ such that for all $1 \leq i, j \leq k$ and all $n \geq n_3$, $\mu_{\text{SRB}}(R_i^* \cap T^{-n}R_j) \geq \varepsilon$. If necessary, we increase n_3 so that the unstable diameter of the set $T^{-n}R_i$ is less than δ_* for each i , and $n \geq n_3$.

Now let $W \in \widehat{\mathcal{W}}^s$ with $|W| \geq \delta_1/3$ be arbitrary. Let R_j be a Cantor rectangle that is properly crossed by W . Let $n \in \mathbb{N}$ and let i_n be as above. By mixing, $\mu_{\text{SRB}}(R_{i_n}^* \cap T^{-n_3}R_j) \geq \varepsilon$. By [13, Lemma 7.90], there is a component of $T^{-n_3}W$ that fully crosses $R_{i_n}^*$ in the stable direction. Call this component $V \in \mathcal{G}_{n_3}^{\delta_0}(W)$. Thus

$$\begin{aligned} \sum_{W_i \in \mathcal{G}_n^{\delta_0}(V)} |e^{S_n g}|_{C^0(W_i)} &= \sum_{W_i \in \mathcal{G}_n^{\delta_0}(V)} |e^{S_n^{-1} g}|_{C^0(T^n W_i)} \geq \sum_{A \in \tilde{L}_n} \inf_A |e^{S_n^{-1} g}| \geq \sum_{A \in \tilde{L}_n} \sup_A |e^{S_n^{-1} g}| \\ &\geq \frac{1}{k} \sum_{A \in L_u^{\delta_1}(\mathcal{M}_{-n}^0)} |e^{S_n^{-1} g}|_{C^0(A)}. \end{aligned}$$

We now have to relate the lhs to the analogous quantity where V is replaced by W .

$$\begin{aligned} \sum_{W_i \in \mathcal{G}_n^{\delta_0}(W)} |e^{S_n g}|_{C^0(W_i)} &= \sum_{V_j \in \mathcal{G}_{n+n_3}^{\delta_0}(W)} \sum_{\substack{W_i \in \mathcal{G}_n^{\delta_0}(W) \\ T^{n_3} V_j \subset W_i}} \frac{|e^{S_n g}|_{C^0(W_i)}}{\#\{V_j \in \mathcal{G}_{n+n_3}^{\delta_0}(W) \mid T^{n_3} V_j \subset W_i\}} \\ &\geq \sum_{V_j \in \mathcal{G}_{n+n_3}^{\delta_0}(W)} |e^{S_n g \circ T^{n_3}}|_{C^0(V_j)} \sum_{\substack{W_i \in \mathcal{G}_n^{\delta_0}(W) \\ T^{n_3} V_j \subset W_i}} \frac{1}{\#\{V_j \in \mathcal{G}_{n+n_3}^{\delta_0}(W) \mid T^{n_3} V_j \subset W_i\}} \\ &\geq \frac{C\delta_0}{\#\mathcal{M}_0^{n_3}} e^{-n_3 \sup g} \sum_{V_j \in \mathcal{G}_{n+n_3}^{\delta_0}(W)} |e^{S_{n+n_3} g}|_{C^0(V_j)} \geq \frac{C\delta_0}{\#\mathcal{M}_0^{n_3}} e^{-n_3 \sup g} \sum_{V_j \in \mathcal{G}_n^{\delta_0}(V)} |e^{S_{n+n_3} g}|_{C^0(V_j)} \\ &\geq \frac{C\delta_0}{\#\mathcal{M}_0^{n_3}} e^{-n_3(\sup g - \inf g)} \sum_{V_j \in \mathcal{G}_n^{\delta_0}(V)} |e^{S_n g}|_{C^0(V_j)} \geq \frac{1}{k} \frac{C\delta_0}{\#\mathcal{M}_0^{n_3}} e^{-n_3(\sup g - \inf g)} \sum_{A \in L_u^{\delta_1}(\mathcal{M}_{-n}^0)} |e^{S_n^{-1} g}|_{C^0(A)} \\ &\geq C_{n_1} \delta_1 \frac{1}{k} \frac{C\delta_0}{\#\mathcal{M}_0^{n_3}} e^{-n_3(\sup g - \inf g)} \sum_{A \in \mathcal{M}_{-n}^0} |e^{S_n^{-1} g}|_{C^0(A)}, \end{aligned}$$

for all $n \geq \max\{n_2, n_3\}$, where we used Lemma 3.3 for the last inequality. Thus the proposition holds for all $n \geq \max\{n_2, n_3\}$. It extends to all $n \in \mathbb{N}$ since there are finitely many values of n to correct for. \square

Lemma 3.7 (Supermultiplicativity). *There exists a constant c_1 such that for all $n \in \mathbb{N}$, and all $0 < j < n$, we have*

$$\sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)} \geq c_1 \sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_{n-j} g}|_{C^0(A)} \sum_{A \in \mathcal{M}_{-j}^0} |e^{S_j^{-1} g}|_{C^0(A)}.$$

Proof. Fix $n, j \in \mathbb{N}$ with $j < n$. First, notice that

$$\begin{aligned} \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)} &\geq \sum_{A \in \mathcal{M}_0^n} \inf_A e^{(S_{n-j} g + S_j^{-1} g - g) \circ T^j} \geq e^{-\sup g} \sum_{A \in \mathcal{M}_{-j}^{n-j}} \inf_A e^{S_{n-j} g} \inf_A e^{S_j^{-1} g} \\ &\geq e^{-\sup g} \sum_{A \in \mathcal{M}_0^{n-j}} \inf_A e^{S_{n-j} g} \sum_{\substack{B \in \mathcal{M}_{-j}^0 \\ B \cap A \neq \emptyset}} \inf_B e^{S_j^{-1} g} \\ &\geq C^2 e^{-\sup g} \sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_{n-j} g}|_{C^0(A)} \sum_{\substack{B \in \mathcal{M}_{-j}^0 \\ B \cap A \neq \emptyset}} |e^{S_j^{-1} g}|_{C^0(B)} \\ &\geq C^2 e^{-\sup g} \sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_{n-j} g}|_{C^0(A)} \sum_{\substack{B \in \mathcal{M}_{-j}^0 \\ B \cap A \neq \emptyset}} |e^{S_j^{-1} g}|_{C^0(B)}, \end{aligned}$$

where we used Lemma 2.3 twice for the forth inequality.

Recall that $L_u^{\delta_1}(\mathcal{M}_{-j}^0)$ denotes the elements of \mathcal{M}_{-j}^0 whose unstable diameter is longer than $\delta_1/3$. Similarly, $L_s^{\delta_1}(\mathcal{M}_0^{n-j})$ denotes those elements of \mathcal{M}_0^{n-j} whose stable diameter is larger than $\delta_1/3$. By Lemma 3.3

$$\sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^{n-j})} |e^{S_{n-j} g}|_{C^0(A)} \geq C_{n_1} \delta_1 \sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_{n-j} g}|_{C^0(A)}, \quad \text{for } n-j \geq n_2.$$

Let $A \in L_s(\mathcal{M}_0^{n-j})$ and let $V_A \in \widehat{\mathcal{W}}^s$ be a stable curve in A with length at least $\delta_1/3$. By Proposition 3.5,

$$\sum_{W_i \in \mathcal{G}_j^{\delta_0}(V_A)} |e^{S_j g}|_{C^0(W_i)} \geq c_0 \sum_{A \in \mathcal{M}_0^j} |e^{S_j^{-1} g}|_{C^0(W_i)}.$$

Each component of $\mathcal{G}_j^{\delta_0}(V_A)$ corresponds to one component of $V \setminus \mathcal{S}_{-j}$ (up to subdivision of long pieces in $\mathcal{G}_j^{\delta_0}(V_A)$). Thus

$$\begin{aligned} \sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_{n-j} g}|_{C^0(A)} \sum_{\substack{B \in \mathcal{M}_{-j}^0 \\ B \cap A \neq \emptyset}} |e^{S_j^{-1} g}|_{C^0(B)} &\geq \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^{n-j})} |e^{S_{n-j} g}|_{C^0(A)} \sum_{W_i \in \mathcal{G}_j^{\delta_0}(V_A)} |e^{S_j^{-1} g}|_{C^0(T^j W_i)} \\ &\geq \sum_{A \in L_s^{\delta_1}(\mathcal{M}_0^{n-j})} |e^{S_{n-j} g}|_{C^0(A)} \sum_{W_i \in \mathcal{G}_j^{\delta_0}(V_A)} |e^{S_j g}|_{C^0(W_i)} \\ &\geq C \sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_{n-j} g}|_{C^0(A)} \sum_{B \in \mathcal{M}_{-j}^0} |e^{S_j g}|_{C^0(B)}, \end{aligned}$$

proving the lemma with $c_1 = c_0 C_{n_1} C^2 \delta_1$ when $n - j \geq n_2$. For $n - j \leq n_2$, since

$$\sum_{A \in \mathcal{M}_0^{n-j}} |e^{S_{n-j-1}g}|_{C^0(A)} \leq \left(\sum_{A \in \mathcal{M}_0^1} |e^g|_{C^0(A)} \right)^{n-j}$$

we obtain the lemma by decreasing c_1 since there are only finitely many values to correct for. \square

Proposition 3.8 (Exact Exponential Growth). *Let g be a (\mathcal{P}, α) -Hölder continuous potential such that $P_*(T, g) - \sup g > 0$ and which has SSP.1. Let c_1 be the constant given by Lemma 3.7. Then for all $n \in \mathbb{N}$, we have*

$$\sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)} \leq \frac{2}{c_1} e^{nP_*(T, g)}.$$

Proof. Let $\psi(n) := e^{-nP_*(T, g)} \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)}$. Suppose there exists $n_1 \in \mathbb{N}$ such that $\psi(n_1) \geq 2/c_1$, where c_1 is the constant from Lemma 3.7. Then

$$\psi(2n_1) \geq c_1 \psi(n_1)^2 = \frac{1}{c_1} (c_1 \psi(n_1))^2.$$

Integrating this bound, we have inductively for any $k \geq 1$,

$$\psi(2^k n_1) \geq \frac{1}{c_1} (c_1 \psi(n_1))^{2^k}.$$

This implies that $\lim_{k \rightarrow +\infty} \frac{1}{2^k n_1} \log \psi(2^k n_1) \geq \frac{1}{n_1} \log 2 > 0$, which contradicts the definition of $\psi(n)$ (since $\lim_{n \rightarrow +\infty} \frac{1}{n} \log \psi(n) = 0$). We conclude that $\psi(n) \leq 2/c_1$ for all $n \geq 1$. \square

Remark 3.9. Notice that for $g = 0$, the condition $P_*(T, g) - \sup g > s_0 \log 2$ becomes $h_* > s_0 \log 2$, where h_* is the topological entropy of T defined in [3]. This is precisely the condition of sparse recurrence to singularities from [3], and as discussed there, we don't know any example of billiard table not satisfying this condition. Notice that by continuity, if $h_* > s_0 \log 2$ holds, then $P_*(T, g) - \sup g > s_0 \log 2$ holds for all g in a neighbourhood of the zero potential. For potential g close enough to 0, we have $\log \Lambda > \sup g - \inf g$. Therefore, by Lemmas 3.2, 3.3 and Corollary 3.4, there exists a neighbourhood of $g = 0$ (in the (\mathcal{P}, α) -Hölder topology) in which every potential has SSP.1 and SSP.2, and thus all the consequent results from the present section also hold.

In particular, for any $t \in \mathbb{R}$ with $|t|$ close enough to zero, the potential $-t\tau$ has SSP.1 and SSP.2.

3.4. Estimates on norms of the potential. In Section 6, we will need similar estimates as in the present section but with the C^0 norm replaced by the C^β norm, $0 < \beta < 1/3$. The following lemma shows that previous estimates are still valid up to a multiplicative constant.

Lemma 3.10. *For every lower-bounded (\mathcal{P}, α) -Hölder continuous potential g , there exists $C > 0$ such that for all $W \in \mathcal{W}^s$, all $n \geq 0$ and all $W_i \in \mathcal{G}_n^\delta(W)$, $|e^{S_n g}|_{C^\alpha(W_i)} \leq C |e^{S_n g}|_{C^0(W_i)}$, where $\delta \in (0, \delta_0]$.*

Proof. Let g be such a potential. Let c be such that $g \geq c$. Let $W_i \in \mathcal{G}_n^\delta(W)$. Then

$$\begin{aligned} H_{W_i}^\alpha(e^{S_n g}) &\leq \sum_{k=0}^{n-1} |e^{-g \circ T^k + S_n g}|_{C^0(W_i)} H_{W_i}^\alpha(g \circ T^k) \\ &\leq |e^{S_n g}|_{C^0(W_i)} \sum_{k=0}^{n-1} e^{-c} C \Lambda^{-\alpha k} |g|_{C^\alpha(M)} \\ &\leq |e^{S_n g}|_{C^0(W_i)} C \frac{1}{1 - \Lambda^\alpha} e^{-c} |g|_{C^\alpha(M)}, \end{aligned}$$

where for the second inequality we adapted the argument from [3, eq (6.2)], so that

$$\frac{g(T^k x) - g(T^k y)}{d_W(T^k x, T^k y)^\alpha} \frac{d_W(T^k x, T^k y)^\alpha}{d_W(x, y)^\alpha} \leq C H_{T^k W_i}^\alpha(g) |J^s T^k|_{C^0(W_i)}^\alpha \leq C \Lambda^{-\alpha k} |g|_{C^\alpha(M)}.$$

□

4. THE BANACH SPACES \mathcal{B} AND \mathcal{B}_w AND THE TRANSFER OPERATORS \mathcal{L}_g

In Section 6, we construct the equilibrium state μ_g for T under the potential g out of left and right eigenvectors, $\tilde{\nu}$ and ν , of a transfer operator \mathcal{L}_g associated with the billiard map and the potential g , acting on suitable Banach spaces \mathcal{B} and \mathcal{B}_w of anisotropic distributions. In this section, we define the Banach spaces \mathcal{B} and \mathcal{B}_w as well as the transfer operator \mathcal{L}_g .

4.1. Motivation and heuristics. The spaces \mathcal{B} and \mathcal{B}_w are the same as in [3], but we recall their construction not only for completeness, but also to introduce notations. The norms we introduce below are defined by integrating along stable manifolds in \mathcal{W}^s . We define precisely the notion of distance $d_{\mathcal{W}^s}(\cdot, \cdot)$ between such curves as well as a distance $d(\cdot, \cdot)$ defined among functions supported on these curves.

In the setup of uniform hyperbolic dynamic, the relevant transfer operator to study equilibrium states associated to a potential g – see for example [1] – can be defined on measurable function f by

$$\mathcal{L}_g f = \left(e^g \frac{f}{J^s T} \right) \circ T^{-1}$$

where $J^s T$ is the stable Jacobian of T . Ignoring first the low regularity of $J^s T$, we see from the hyperbolicity of T that the composition with T^{-1} should increase the regularity of f in the unstable direction, while decreasing the regularity in the stable direction. By integrating along stable manifold against the arclength measure, we hope to recover some regularity along the stable manifold – notice that by a change of variable, $J^s T$ does disappear. Morally, the weak norm $|\cdot|_w$ and the strong stable norm $\|\cdot\|_s$ measure the regularity of the averaged action of \mathcal{L}_g . On the other hand, the strong unstable norm $\|\cdot\|_u$ capture the regularity when passing from a stable manifold to another one. Here, this regularity should be thought as a log-scaled Hölder regularity.

4.2. Definition of the Banach spaces and embeddings into distribution. Let \mathcal{W}^s denote the set of all nontrivial connected subsets W of stable manifolds for T so that W has length at most δ_0 . Such curves have bounded curvature above by fixed constant [13, Prop. 4.29]. Thus $T^{-1}\mathcal{W}^s = \mathcal{W}^s$, up to subdivision of curves. Obviously, $\mathcal{W}^s \subset \widehat{\mathcal{W}}^s$. We define \mathcal{W}^u similarly from unstable manifolds of T .

Given a curve $W \in \mathcal{W}^s$, we denote by m_W the unnormalized Lebesgue (arclength) measure on W , so that $|W| = m_W(W)$. Since the stable cone C^s (3.1) is bounded away from the vertical, we may view each stable manifolds $W \in \mathcal{W}^s$ as the graph of a function $\varphi_W(r)$ of the arclength coordinate r ranging over some interval I_W , that is

$$W = \{G_W(r) := (r, \varphi_W(r)) \mid r \in I_W\}.$$

Given two curves $W_1, W_2 \in \mathcal{W}^s$, we may use this representation to define a “distance”⁷ between them. Define

$$d_{\mathcal{W}^s}(W_1, W_2) = |I_{W_1} \triangle I_{W_2}| + |\varphi_{W_1} - \varphi_{W_2}|_{C^1(I_{W_1} \cap I_{W_2})}$$

if $I_{W_1} \cap I_{W_2} \neq \emptyset$, and $d_{\mathcal{W}^s}(W_1, W_2) = +\infty$ otherwise.

Similarly, given two test functions ψ_1 on W_1 , and ψ_2 on W_2 , we define a distance between them by

$$d(\psi_1, \psi_2) = |\psi_1 \circ G_{W_1} - \psi_2 \circ G_{W_2}|_{C^0(I_{W_1} \cap I_{W_2})},$$

whenever $d_{\mathcal{W}^s}(W_1, W_2)$ is finite, and $d(\psi_1, \psi_2) = +\infty$ otherwise.

We can now introduce the norms used to define the spaces \mathcal{B} and \mathcal{B}_w . These norms will depend on the constants $\epsilon_0 > 0$ and $\delta_0 \in (0, 1)$, as well as on four positive real numbers α , β , γ and ζ so that

$$0 < \beta < \alpha \leq \min\{1/3, \alpha_g\}, \quad 1 < 2^{s_0\gamma} < e^{P_*(T, g) - \sup g}, \quad 0 < \zeta < \gamma$$

where g is a given, bounded (\mathcal{P}, α_g) -Hölder potential such that $P_*(T, g) - \sup g > s_0 \log 2$.

Remark 4.1. The condition $\alpha \leq 1/3$ is needed for [3, Lemma 4.4], which is used to prove the embedding into distributions. The number $1/3$ comes from the regularity of the density function of the conditional measures in the disintegration of μ_{SRB} against the stable foliation. The bound $\alpha \leq \alpha_g$ will make possible to see g as an element of \mathcal{B} . The upper bound on γ arises from the use of the growth lemma 3.1. The dependence on δ_0 comes from the definition of \mathcal{W}^s .

For $f \in C^1(M)$, define the weak norm of f by

$$|f|_w = \sup_{W \in \mathcal{W}^s} \sup_{\substack{\psi \in C^\alpha(W) \\ |\psi|_{C^\alpha(W)} \leq 1}} \int_W f \psi \, dm_W.$$

⁷Actually, $d_{\mathcal{W}^s}$ is not a metric since it does not satisfies the triangle inequality. It is nonetheless sufficient for our purpose to produce a usable notion of a distance between stable manifolds.

Similarly, define the strong stable norm of f by⁸

$$\|f\|_s = \sup_{W \in \mathcal{W}^s} \sup_{\substack{\psi \in C^\beta(W) \\ |\psi|_{C^\beta(W)} \leq |\log |W||^\gamma}} \int_W f \psi \, dm_W,$$

(note that $|f|_w \leq \max\{1, |\log \delta_0|^{-\gamma}\} \|f\|_s$). Finally, for $\varsigma \in (0, \gamma)$, define the strong unstable norm⁹ of f by

$$\|f\|_u = \sup_{\varepsilon \leq \varepsilon_0} \sup_{\substack{W_1, W_2 \in \mathcal{W}^s \\ d_{\mathcal{W}^s}(W_1, W_2) \leq \varepsilon}} \sup_{\substack{\psi_i \in C^\alpha(W_i) \\ |\psi_i|_{C^\alpha(W_i)} \leq 1 \\ d(\psi_1, \psi_2) = 0}} |\log \varepsilon|^\varsigma \left| \int_{W_1} f \psi_1 \, dm_{W_1} - \int_{W_2} f \psi_2 \, dm_{W_2} \right|.$$

In order to use functional analysis results, we need to work with complete spaces. Since $C^1(M)$ is not complete for the norms¹⁰ $|\cdot|_w$ and $\|\cdot\|_s + \|\cdot\|_u$, we will use the corresponding completed spaces.

Definition 4.2 (The Banach spaces). *The space \mathcal{B}_w is the completion of $C^1(M)$ with respect to the weak norm $|\cdot|_w$, while \mathcal{B} is the completion of $C^1(M)$ with respect to the strong norm, $\|\cdot\|_{\mathcal{B}} = \|\cdot\|_s + \|\cdot\|_u$. Notice that since $|\cdot|_w \leq \|\cdot\|_{\mathcal{B}}$, there is a canonical map $\mathcal{B} \rightarrow \mathcal{B}_w$.*

Since the main purpose of the spaces \mathcal{B} and \mathcal{B}_w is to contain left and right eigenvectors of a transfer operator acting on those spaces, a crucial feature of \mathcal{B} and \mathcal{B}_w is that we can see them as subspaces of the distributional space $(C^1(M))^*$. Thanks to this property, we will be able to construct a positive distribution by pairing the left and right eigenvectors, and to extend it into the desired equilibrium measure. In order to state this result, we need to introduce some other spaces, on which the transfer operator will be naturally defined (and then extended to \mathcal{B} and \mathcal{B}_w).

Define the usual homogeneity strips

$$\mathbb{H}_k := \left\{ (r, \varphi) \in M_i \mid \frac{\pi}{2} - \frac{1}{k^2} \leq \varphi \leq \frac{\pi}{2} - \frac{1}{(k+1)^2} \right\}, \quad k \geq k_0,$$

and analogously for $k \leq -k_0$. Define $\mathcal{W}_{\mathbb{H}}^s \subset \mathcal{W}^s$ as the set of stable manifolds $W \in \mathcal{W}^s$ such that $T^n W$ lies in a single homogeneity strip for all $n \geq 0$. We write $\psi \in C^\alpha(\mathcal{W}_{\mathbb{H}}^s)$ if $\psi \in C^\alpha(W)$ for all $W \in \mathcal{W}_{\mathbb{H}}^s$ with uniformly bounded Hölder norm. The norm of ψ in $C^\alpha(\mathcal{W}_{\mathbb{H}}^s)$ is defined to be the sup over all the $C^\alpha(W)$ norms, with W ranging in $\mathcal{W}_{\mathbb{H}}^s$. Similarly, define the space $C_{\cos}^\alpha(\mathcal{W}_{\mathbb{H}}^s)$ containing the functions ψ such that $\psi \cos \varphi \in C^\alpha(\mathcal{W}_{\mathbb{H}}^s)$. The norm of ψ in $C_{\cos}^\alpha(\mathcal{W}_{\mathbb{H}}^s)$ is defined to be the norm of $\psi \cos \varphi$ in $C^\alpha(\mathcal{W}_{\mathbb{H}}^s)$. Clearly, $C^\alpha(\mathcal{W}_{\mathbb{H}}^s) \subset C_{\cos}^\alpha(\mathcal{W}_{\mathbb{H}}^s)$.

The canonical map $\mathcal{B}_w \rightarrow (\mathcal{F})^*$ (for $\mathcal{F} = C^1(M)$, or $\mathcal{F} = C^\alpha(\mathcal{W}_{\mathbb{H}}^s)$) is understood in the following sense: for $f \in \mathcal{B}_w$, there exists $C_f < \infty$ such that letting $f_n \in C^1(M)$ be a sequence

⁸The logarithmic modulus of continuity in $\|f\|_s$ is used to obtain a finite spectral radius.

⁹The logarithmic modulus of continuity appears in $\|f\|_u$ because of the logarithmic modulus of continuity in $\|f\|_s$. Its presence in $\|f\|_u$ causes the loss of the spectral gap.

¹⁰For example, the sequence $\left(\frac{1}{n} \sin 2\pi n^2 \frac{r}{|\Gamma_i|}\right)_n$ is a Cauchy sequence of $C^1(M)$ functions with respect to $|\cdot|_w$, but diverges in the C^1 -norm.

converging to f in the \mathcal{B}_w norm, for every $f \in \mathcal{F}$ the following limit exists

$$f(\psi) := \lim_{n \rightarrow +\infty} \int f_n \psi \, d\mu_{\text{SRB}}$$

and satisfies $|f(\psi)| \leq C_f \|\psi\|_{\mathcal{F}}$.

We summarize the properties of these Banach spaces obtained in [3] in the following proposition.

Proposition 4.3. *The spaces \mathcal{B}_w and \mathcal{B} are such that:*

(i) *The following canonical maps are all continuous*

$$C^1(M) \rightarrow \mathcal{B} \rightarrow \mathcal{B}_w \rightarrow (C^\alpha(\mathcal{W}_{\mathbb{H}}^s))^* \rightarrow (C^1(M))^*,$$

and the first two maps are injective. In particular, we also have the two injective and continuous maps

$$(\mathcal{B}_w)^* \rightarrow \mathcal{B}^* \rightarrow (C^1(M))^*.$$

(ii) *The inclusion map $\mathcal{B} \hookrightarrow \mathcal{B}_w$ is compact.*

Proof. The point (i) is the content of [3, Proposition 4.2]. We detail the proof of the injectivity of the map $\mathcal{B} \rightarrow \mathcal{B}_w$. To do so, we prove that the formula defining $|\cdot|_w$ (respectively $\|\cdot\|_s$ and $\|\cdot\|_u$) can be extended when $f \in \mathcal{B}_w$ (respectively $f \in \mathcal{B}$), and that it coincides with the norm of f .

First, notice that when $f \in C^1(M)$, then for given $W \in \mathcal{W}^s$ and $\psi \in C^\alpha(W)$ we have $\int_W f \psi \, dm_W \leq |f|_w |\psi|_{C^\alpha(W)}$. Thus the map $f \mapsto \int_W f \psi \, dm_W$ can be extended uniquely to \mathcal{B}_w .

Now, let $f \in \mathcal{B}_w$ and $\varepsilon > 0$. Let f_n be a Cauchy sequence of $C^1(M)$ functions converging to f in \mathcal{B}_w . Thus, there exists some n_ε such that for all $n \geq n_\varepsilon$, $|f - f_n|_w \leq \varepsilon$. Let $W \in \mathcal{W}^s$ and $\psi \in C^\alpha(W)$ with $|\psi|_{C^\alpha(W)} \leq 1$. By definition of $|f_n|_w$, for all n , there exist W_n and $\psi_n \in C^\alpha(W_n)$ with $|\psi_n|_{C^\alpha(W_n)} \leq 1$ such that

$$\left| \int_{W_n} f_n \psi_n \, dm_{W_n} - |f_n|_w \right| \leq \varepsilon.$$

Thus, we have

$$\left| \int_{W_n} f \psi_n \, dm_{W_n} - \int_{W_n} f_n \psi_n \, dm_{W_n} \right| \leq |f - f_n|_w |\psi_n|_{C^\alpha(W_n)} \leq \varepsilon, \quad \forall n \geq n_\varepsilon,$$

and so $\left| |f_n|_w - \int_{W_n} f \psi_n \, dm_{W_n} \right| \leq 2\varepsilon$. In particular, we get

$$\sup_{W \in \mathcal{W}^s} \sup_{\substack{\psi \in C^\alpha(W) \\ |\psi|_{C^\alpha(W)} \leq 1}} \int_W f \psi \, dm_W \geq |f|_w.$$

We now prove the reverse inequality. Using the same notations as above, there exist $V \in \mathcal{W}^s$ and $\varphi \in C^\alpha(V)$ with $|\varphi|_{C^\alpha(V)} \leq 1$ such that

$$\left| \int_V f \varphi \, dm_V - \sup_{W \in \mathcal{W}^s} \sup_{\substack{\psi \in C^\alpha(W) \\ |\psi|_{C^\alpha(W)} \leq 1}} \int_W f \psi \, dm_W \right| \leq \varepsilon.$$

Now, since

$$\left| \int_V f_n \varphi \, dm_V - \int_V f \varphi \, dm_V \right| \leq |f - f_n|_w \leq \varepsilon, \quad \forall n \geq n_\varepsilon,$$

we have that $|\sup_{W \in \mathcal{W}^s} \sup_{\substack{\psi \in C^\alpha(W) \\ |\psi|_{C^\alpha(W)} \leq 1}} \int_W f \psi \, dm_W - \int_V f_n \varphi \, dm_V| \leq 2\varepsilon$ for all large enough n .

In particular

$$\sup_{W \in \mathcal{W}^s} \sup_{\substack{\psi \in C^\alpha(W) \\ |\psi|_{C^\alpha(W)} \leq 1}} \int_W f \psi \, dm_W \leq |f_n|_w + 2\varepsilon.$$

Taking the limit in n , we get the claimed inequality.

The corresponding results for $f \in \mathcal{B}$ and norms $\|\cdot\|_s$ and $\|\cdot\|_u$ are obtained similarly, noticing that for all $f \in C^1(M)$,

$$\int_W f \psi \, dm_W \leq \|f\|_s |\psi|_{C^\beta(W)} |\log |W||^{-\gamma} \leq \|f\|_{\mathcal{B}} |\psi|_{C^\beta(W)} |\log |W||^{-\gamma}, \quad \forall W \in \mathcal{W}^s, \forall \psi \in C^\beta(W)$$

Thus the integrals against $C^\beta(W)$ functions in the definition of $\|\cdot\|_s$ makes sense even when $f \in \mathcal{B}$. On the other hand, since $|\cdot|_w \leq \|\cdot\|_{\mathcal{B}}$, the integrals in the definition of $\|\cdot\|_u$ can be extended to $f \in \mathcal{B}$ as in the above case where $f \in \mathcal{B}_w$.

We can now show the injectivity of the canonical map $\mathcal{B} \rightarrow \mathcal{B}_w$. Let $f \in \mathcal{B}$ with $\|f\|_{\mathcal{B}} \neq 0$. If $\|f\|_s \neq 0$, then the fact that $|f|_w \neq 0$ follows from the definition of $C^\beta(W)$ as the closure of $C^1(W)$ in the C^β norm, so that $C^\alpha(W)$ is dense in $C^\beta(W)$. Now, if $\|f\|_u \neq 0$, then by definition of $\|\cdot\|_u$, we can find some $W \in \mathcal{W}^s$ and $\psi \in C^\alpha(W)$ so that $\int_W f \psi \, dm_W > 0$. Thus $|f|_w \neq 0$.

The point (ii) is precisely the content of [3, Proposition 6.1]. \square

4.3. The transfer operators. We may define the transfer operator $\mathcal{L}_g : (C_{\cos}^\alpha(\mathcal{W}_{\mathbb{H}}^s))^* \rightarrow (C^\alpha(\mathcal{W}^s))^*$, for a given weight function g by

$$\mathcal{L}_g f(\psi) = f(e^g \frac{\psi \circ T}{J^s T}), \quad \psi \in C^\alpha(\mathcal{W}^s).$$

This operator is well defined because, if $\psi \in C^\alpha(\mathcal{W}^s)$ then $e^g \psi \circ T \in C^\alpha(\mathcal{W}^s)$. Furthermore, since $J^s T$ and $\cos \varphi$ are $1/3$ -log-Hölder on homogeneous stable manifolds, and $\cos \varphi / J^s T$ is bounded away from 0 and $+\infty$ also on homogeneous stable manifolds, we get that $1/J^s T \in C_{\cos}^\alpha(\mathcal{W}_{\mathbb{H}}^s)$. Thus $e^g \frac{\psi \circ T}{J^s T} \in C_{\cos}^\alpha(\mathcal{W}_{\mathbb{H}}^s)$.

When $f \in C^1(M)$, we identify f with the measure¹¹

$$(4.1) \quad f \mu_{\text{SRB}} \in (C_{\cos}^\alpha(\mathcal{W}_{\mathbb{H}}^s))^*.$$

The measure above is (abusively) still denoted by f . For $f \in C^1(M)$, we have

$$\begin{aligned} \mathcal{L}_g(f \mu_{\text{SRB}})(\psi) &= \int f e^g \frac{\psi \circ T}{J^s T} \, d\mu_{\text{SRB}} = \int \left(e^g \frac{f}{J^s T} \right) \circ T^{-1} \psi \, d\mu_{\text{SRB}} \\ &= \left(\left(e^g \frac{f}{J^s T} \right) \circ T^{-1} \mu_{\text{SRB}} \right) (\psi). \end{aligned}$$

Thus, due to our identification (4.1) we have $\mathcal{L}_g f = (e^g f / J^s T) \circ T^{-1}$, as claimed above.

¹¹To show the claimed inclusion just use that $d\mu_{\text{SRB}} = (2|\partial Q|)^{-1} \cos \varphi \, dr d\varphi$.

Proposition 4.4. *For any fixed (\mathcal{P}, α_g) -Hölder potential g and corresponding spaces \mathcal{B} and \mathcal{B}_w :*

(i) *If $f \in C^1(M)$, then $\mathcal{L}_g(f\mu_{SRB}) \in \mathcal{B}$.*

(ii) *The operators $\mathcal{L}_g : (C^1(M), |\cdot|_w) \rightarrow \mathcal{B}_w$ and $\mathcal{L}_g : (C^1(M), \|\cdot\|_{\mathcal{B}}) \rightarrow \mathcal{B}$ are continuous.*

In particular, \mathcal{L}_g extends uniquely into operators on both \mathcal{B}_w and \mathcal{B} .

Proof. Let $f \in C^1(M)$. Consider first the case $g = 0$. Then, by [4, Lemma 4.3, Remark 4.11], $\mathcal{L}_0 f \in \mathcal{B}$. Now, for $g \not\equiv 0$ a piecewise Hölder potential, we can use [18, Lemma 3.7] to get that $e^g \circ T^{-1} \in \mathcal{B}$ (checking that the absence of homogeneity layers does not affect the computations). Since $\mathcal{L}_g f = e^g \circ T^{-1} \mathcal{L}_0 f$, we get that $\mathcal{L}_g f \in \mathcal{B}$, where \mathcal{B} has been constructed according to g .

Point (ii) follows from Proposition 5.1, in the case $n = 1$. \square

5. NORM ESTIMATES AND SPECTRAL RADIUS

The purpose of this section is to state and prove sharp upper and lower bounds on the norm of the iterated operator \mathcal{L}_g^n , both in \mathcal{B}_w and \mathcal{B} .

Proposition 5.1. *Let g be a (\mathcal{P}, α_g) -Hölder continuous potential. Assume that $P_*(T, g) - \sup g > s_0 \log 2$ and that SSP.1 holds. Then there exist δ_0 and $C > 0$ such that for all $f \in \mathcal{B}$,*

$$(5.1) \quad |\mathcal{L}_g^n f|_w \leq \frac{C}{\delta_0} e^{nP_*(T, g)} |f|_w, \quad \forall n \geq 0;$$

$$(5.2) \quad \|\mathcal{L}_g^n f\|_s \leq \frac{C}{\delta_0} e^{nP_*(T, g)} \|f\|_s, \quad \forall n \geq 0;$$

$$(5.3) \quad \|\mathcal{L}_g^n f\|_u \leq \frac{C}{\delta_0} (\|f\|_u + \|f\|_s) e^{nP_*(T, g)}, \quad \forall n \geq 0.$$

It follows that the spectral radius of \mathcal{L}_g on \mathcal{B} and \mathcal{B}_w is at most $e^{P_(T, g)}$.*

Remark 5.2. It is possible to obtain similar estimates without the assumption SSP.1, however an additional factor $e^{n\varepsilon}$ appears on the right hand sides, for any arbitrary $\varepsilon > 0$. We indicate places in the proof where it happens and how to correct for. The conclusion about the upper bound of the spectral radius still holds. Nonetheless, in order to construct nontrivial maximal eigenvectors, we will need the estimates from Proposition 5.1.

Theorem 5.3. *Let g be a (\mathcal{P}, α_g) -Hölder continuous potential. Assume that $P_*(T, g) - \sup g > s_0 \log 2$ and that SSP.1 holds. Then there exists C such that*

$$\|\mathcal{L}_g^n 1\|_s \geq |\mathcal{L}_g^n 1|_w \geq C \frac{\delta_1}{2} e^{nP_*(T, g)}.$$

Proof of Proposition 5.1. Let δ_0 be the scale associated to g as in the beginning of Section 3.2. The set \mathcal{W}^s is defined with respect to the scale δ_0 .

We start with the weak norm estimate (5.1). Let $f \in C^1(M)$, $W \in \mathcal{W}^s$ and $\psi \in C^\alpha(W)$ be such that $|\psi|_{C^\alpha(W)} \leq 1$. For $n \geq 0$ we use the definition of the weak norm on each $W_i \in \mathcal{G}_n^{\delta_0}(W)$ to estimate

$$\int_W \mathcal{L}_g^n f \psi \, d\mu_W = \sum_{W_i \in \mathcal{G}_n^{\delta_0}(W)} \int_{W_i} f e^{S_n g} \psi \circ T^n \, d\mu_{W_i} \leq |f|_w \sum_{W_i \in \mathcal{G}_n^{\delta_0}(W)} |e^{S_n g}|_{C^\alpha(W_i)} |\psi \circ T^n|_{C^\alpha(W_i)}.$$

Clearly, $\sup |\psi \circ T^n|_{W_i} \leq \sup_W |\psi|$. For $x, y \in W_i$, we have,

$$(5.4) \quad \frac{|\psi(T^n x) - \psi(T^n y)|}{d_W(T^n x, T^n y)^\alpha} \cdot \frac{d_W(T^n x, T^n y)^\alpha}{d_W(x, y)^\alpha} \leq C |\psi|_{C^\alpha(W)} |J^s T^n|_{C^0(W_i)}^\alpha \\ \leq C \Lambda^{-\alpha n} |\psi|_{C^\alpha(W)},$$

so that $H_{W_i}^\alpha(\psi \circ T^n) \leq C \Lambda^{-\alpha n} H_W^\alpha(\psi)$ and thus $|\psi \circ T^n|_{C^\alpha(W_i)} \leq C |\psi|_{C^\alpha(W)}$. By Lemma 3.10, we get

$$\int_W \mathcal{L}_g^n f \psi \, dm_W \leq C |f|_w |\psi|_{C^\alpha(W)} \sum_{W_i \in \mathcal{G}_n^{\delta_0}(W)} |e^{S_n g}|_{C^0(W_i)} \leq \frac{2C}{\delta_0} |f|_w |\psi|_{C^\alpha(W)} \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)}, \\ \leq \frac{2C}{c_1 \delta_0} |f|_w |\psi|_{C^\alpha(W)} e^{nP_*(T, g)},$$

where the second inequality uses that there are no more than $2\delta_0^{-1}$ curves W_i of $\mathcal{G}_n^{\delta_0}(W)$ per element of \mathcal{M}_0^n , and the third inequality uses the Exact Exponential Growth from Proposition 3.8¹².

Now we prove the strong stable norm estimate (5.2). We can choose m so large that $2^{s_0 \gamma} (Km + 1)^{1/m} < e^{P_*(T, g) - \sup g}$. Let $W \in \mathcal{W}^s$, $\psi \in C^\beta(W)$ such that $|\psi|_{C^\beta(W)} \leq |\log |W||^\gamma$. Then, by definition of the strong norm

$$\int_W \mathcal{L}_g^n f \psi \, dm_W = \sum_{W_i \in \mathcal{G}_n^{\delta_0}(W)} \int_{W_i} f \psi \circ T^n e^{S_n g} \, dm_{W_i} \\ \leq \sum_{W_i \in \mathcal{G}_n^{\delta_0}(W)} \|f\|_s |\psi \circ T^n|_{C^\beta(W_i)} |e^{S_n g}|_{C^\beta(W_i)} |\log |W_i||^{-\gamma} \\ \leq C \|f\|_s \sum_{W_i \in \mathcal{G}_n^{\delta_0}(W)} \left(\frac{\log |W|}{\log |W_i|} \right)^\gamma \|e^{S_n g}\|_{C^\beta(W_i)} \\ \leq C \|f\|_s 2^{2\gamma+1} \delta_0^{-1} \sum_{j=1}^n 2^{js_0 \gamma} (Km + 1)^{j/m} e^{j \sup g} \sum_{A \in \mathcal{M}_0^{n-j}} \|e^{S_{n-j} g}\|_{C^0(A)}$$

where for the last line we used Lemma 3.1(b) and Lemma 3.10. Let

$$D_n := C 2^{2\gamma+1} \delta_0^{-1} \sum_{j=1}^n 2^{js_0 \gamma} (Km + 1)^{j/m} e^{j \sup g} \sum_{A \in \mathcal{M}_0^{n-j}} \|e^{S_{n-j} g}\|_{C^0(A)}.$$

¹²without the assumptions SSP.1 and SSP.3, Proposition 3.8 might not hold. Still, for $\varepsilon > 0$ and all $n \geq 1$, $\sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)} \leq C_\varepsilon e^{n(P_*(T, g) + \varepsilon)}$ because of the subadditivity from Theorem 2.1.

From Proposition 3.8, for all $n \geq 1$, $\sum_{A \in \mathcal{M}_0^n} \|e^{S_n g}\|_{C^0(A)} \leq \frac{2}{c_1} e^{nP_*(T,g)}$. Let $\varepsilon_1 = P_*(T, g) - \sup g - \log(2^{s_0 \gamma} (Km + 1)^{1/m})$. Thus¹³,

$$D_n \leq 2^{2\gamma+1} \frac{C}{c_1 \delta_0} \sum_{j=1}^n e^{(P_*(T,g) - \varepsilon_1)j} e^{(n-j)P_*(T,g)} \leq 2^{2\gamma+1} \frac{1}{1 - e^{-\varepsilon_1}} \frac{C}{c_1 \delta_0} e^{nP_*(T,g)}.$$

This conclude the proof of (5.2).

Finally, we now prove the strong unstable norm estimate (5.3). Fix $\tilde{\varepsilon} < \varepsilon_0$, and consider two curves $W^1, W^2 \in \mathcal{W}^s$ with $d_{\mathcal{W}^s}(W^1, W^2) < \tilde{\varepsilon}$.

For $n \geq 1$, we describe how to partition $T^{-n}W^\ell$ into “matched” pieces U_j^ℓ and “unmatched” pieces V_i^ℓ , $\ell = 1, 2$.

Let ω be a connected component of $W^1 \setminus \mathcal{S}_{-n}$. To each point $x \in T^{-n}\omega$, we associate a vertical line segment γ_x of length at most $C\Lambda^{-n}\tilde{\varepsilon}$ such that its image $T^n\gamma_x$, if not cut by a singularity, will have length $C\tilde{\varepsilon}$. By [13, §4.4], all the tangent vectors to $T^i\gamma_x$ lie in the unstable cone $C^u(T^i x)$ for each $i \geq 1$ so that they remain uniformly transverse to the stable cone and enjoy the minimum expansion given by Λ .

Doing this for each connected component of $W^1 \setminus \mathcal{S}_{-n}$, we subdivide $W^1 \setminus \mathcal{S}_{-n}$ into a countable collection of subintervals of points for which $T^n\gamma_x$ intersects $W^2 \setminus \mathcal{S}_{-n}$ and subintervals for which this is not the case. This in turn induces a corresponding partition on $W^2 \setminus \mathcal{S}_{-n}$.

We denote by V_i^ℓ the pieces in $T^{-n}W^\ell$ which are not matched up by this process and note that the images $T^n V_i^\ell$ occur either at the endpoints of W^ℓ or because the vertical segment γ_x has been cut by a singularity. In both cases, the length of the curves $T^n V_i^\ell$ can be at most $C\tilde{\varepsilon}$ due to the uniform transversality of \mathcal{S}_{-n} with the stable cone and of $C^s(x)$ with $C^u(x)$.

In the remaining pieces the foliation $\{T^n\gamma_x\}_{x \in T^{-n}W^1}$ provides a one-to-one correspondence between points in W^1 and W^2 . We further subdivide these pieces in such a way that the lengths of their images under T^{-i} are less than δ_0 for each $0 \leq i \leq n$ and the pieces are pairwise matched by the foliation $\{\gamma_x\}$. We call these matched pieces U_j^ℓ . Since the stable cone is bounded away from the vertical direction, we can adjust the elements of $\mathcal{G}_n^{\delta_0}(W^\ell)$ created by artificial subdivisions due to length so that $U_j^\ell \subset W_i^\ell$ and $V_k^\ell \subset W_{i'}^\ell$ for some $W_i^\ell, W_{i'}^\ell \in \mathcal{G}_n^{\delta_0}(W^\ell)$ for all $j, k \geq 1$ and $\ell = 1, 2$, without changing the bounds on sums over $\mathcal{G}_n^{\delta_0}(W^\ell)$. There is at most one U_j^ℓ and two V_j^ℓ per $W_i^\ell \in \mathcal{G}_n^{\delta_0}(W^\ell)$.

In this way we write $W^\ell = (\cup_j T^n U_j^\ell) \cup (\cup_i T^n V_i^\ell)$. Note that the images $T^n V_i^\ell$ of the unmatched pieces must be short while the images of the matched pieces U_j^ℓ may be long or short.

We have arranged a pairing of the pieces $U_j^\ell = G_{U_j^\ell}(I_j)$, $\ell = 1, 2$, with the property:

$$(5.5) \quad \text{If } U_j^1 = \{(r, \varphi_{U_j^1}(r)) \mid r \in I_j\} \text{ then } U_j^2 = \{(r, \varphi_{U_j^2}(r)) \mid r \in I_j\},$$

so that the point $x = (r, \varphi_{U_j^1}(r))$ is associated with the point $\bar{x} = (r, \varphi_{U_j^2}(r))$ by the vertical segment $\gamma_x \subset \{(r, s)\}_{s \in [-\pi/2, \pi/2]}$, for each $r \in I_j$.

Given ψ_ℓ on W^ℓ with $|\psi_\ell|_{C^\alpha(W^\ell)} \leq 1$ and $d(\psi_1, \psi_2) \leq \tilde{\varepsilon}$, we must estimate

¹³Here, again, conclusion from Proposition 3.8 can be replaced.

(5.6)

$$\left| \int_{W^1} \mathcal{L}_g^n f \psi_1 dm_{W^1} - \int_{W^2} \mathcal{L}_g^n f \psi_2 dm_{W^2} \right| \leq \sum_{l,i} \left| \int_{V_i^l} f \psi_l \circ T^n e^{S_n g} dm \right| \\ + \sum_j \left| \int_{U_j^1} f \psi_1 \circ T^n e^{S_n g} dm - \int_{U_j^2} f \psi_2 \circ T^n e^{S_n g} dm \right|.$$

We first estimate the differences of matched pieces U_j^l . The function $\phi_j = (\psi_1 \circ T^n e^{S_n g}) \circ G_{U_j^1} \circ G_{U_j^2}^{-1}$ is well defined on U_j^2 , and we can estimate each difference by

$$(5.7) \quad \left| \int_{U_j^1} f \psi_1 \circ T^n e^{S_n g} dm - \int_{U_j^2} f \psi_2 \circ T^n e^{S_n g} dm \right| \leq \left| \int_{U_j^1} f \psi_1 \circ T^n e^{S_n g} dm - \int_{U_j^2} f \phi_j dm \right| \\ + \left| \int_{U_j^2} f(\phi_j - \psi_2 \circ T^n e^{S_n g}) dm \right|.$$

We bound the first term in equation (5.7) using the strong unstable norm. We have that $|G_{U_j^1} \circ G_{U_j^2}^{-1}|_{C^1} \leq C_g$, for some $C_g > 0$ due to the fact that each curve U_j^l has uniformly bounded curvature and slopes bounded away from infinity. Thus $|\phi_j|_{C^\alpha(U_j^2)} \leq C C_g |\psi_1|_{C^\alpha(W^1)} |e^{S_n g}|_{C^\alpha(W^1)}$. Moreover, $d(\psi_1 \circ T^n e^{S_n g}, \phi_j) = |\psi_1 \circ T^n e^{S_n g} \circ G_{U_j^1} - \phi_j \circ G_{U_j^2}| = 0$ by definition of ϕ_j . To complete the bound on the first term, we need the following estimate from [18, Lemma 4.2]: There exists $C > 0$, independent of W^1 and W^2 , such that

$$(5.8) \quad d_{\mathcal{W}^s}(U_j^1, U_j^2) \leq C \Lambda^{-n} n \tilde{\varepsilon} =: \varepsilon_1, \quad \forall j.$$

Then we apply the definition of the strong unstable norm with ε_1 instead of $\tilde{\varepsilon}$. Thus,

$$(5.9) \quad \sum_j \left| \int_{U_j^1} f \psi_1 \circ T^n e^{S_n g} dm - \int_{U_j^2} f \phi_j dm \right| \leq 2\delta_0^{-1} C C_g^2 |\log \varepsilon_1|^{-\zeta} \|f\|_u \sum_{A \in \mathcal{M}_0^n} |e^{S_n g}|_{C^0(A)},$$

where we used Lemmas 3.10 and 3.1(b) with $\gamma = 0$ since there is at most one matched piece U_j^1 corresponding to each component $W_i^1 \in \mathcal{G}_n^{\delta_0}(W^1)$ of $T^{-n}W^1$.

It remains to estimate the second term using the strong stable norm.

$$\left| \int_{U_j^2} f(\phi_j - \psi_2 \circ T^n e^{S_n g}) dm \right| \leq \|f\|_s |\log |U_j^2||^{-\gamma} |\phi_j - \psi_2 \circ T^n e^{S_n g}|_{C^\beta(U_j^2)}.$$

In order to estimate this last C^β -norm, we use that $|G_{U_j^2}|_{C^1} \leq C_g$ and $|G_{U_j^2}^{-1}|_{C^1} \leq C_g$.

$$\begin{aligned}
|\phi_j - \psi_2 \circ T^n e^{S_{ng}}|_{C^\beta(U_j^2)} &\leq C|(\psi_1 \circ T^n e^{S_{ng}}) \circ G_{U_j^1} - (\psi_2 \circ T^n e^{S_{ng}}) \circ G_{U_j^2}|_{C^\beta(I_j)} \\
&\leq C|(\psi_1 \circ T^n \circ G_{U_j^1} - \psi_2 \circ T^n \circ G_{U_j^2})(e^{S_{ng}} \circ G_{U_j^1}) \\
&\quad + (\psi_2 \circ T^n \circ G_{U_j^2})(e^{S_{ng}} \circ G_{U_j^1} - e^{S_{ng}} \circ G_{U_j^2})|_{C^\beta(I_j)} \\
(5.10) \quad &\leq C|(\psi_1 \circ T^n \circ G_{U_j^1} - \psi_2 \circ T^n \circ G_{U_j^2})|_{C^\beta(I_j)} |e^{S_{ng}}|_{C^0(U_j^1)} \\
&\quad + C|\psi_2|_{C^0(U_j^2)} |e^{S_{ng}} \circ G_{U_j^1} - e^{S_{ng}} \circ G_{U_j^2}|_{C^\beta(I_j)}.
\end{aligned}$$

It follows from [18, Lemma 4.4] that

$$|\psi_1 \circ T^n \circ G_{U_j^1} - \psi_2 \circ T^n \circ G_{U_j^2}|_{C^\beta(I_j)} \leq C\tilde{\varepsilon}^{\alpha-\beta}.$$

Now, we need to estimate $|e^{S_{ng}} \circ G_{U_j^1} - e^{S_{ng}} \circ G_{U_j^2}|_{C^\beta(I_j)}$. Since $d(T^i(G_{U_j^1}(r)), T^i(G_{U_j^2}(r))) \leq C\Lambda^{-(n-i)}\tilde{\varepsilon}$ for all $r \in I_j$ and $0 \leq i \leq n$, we get

$$\begin{aligned}
|e^{S_{ng}} \circ G_{U_j^1}(r) - e^{S_{ng}} \circ G_{U_j^2}(r)| &= e^{S_{ng}(G_{U_j^1}(r))} |1 - e^{S_{ng}(G_{U_j^2}(r)) - S_{ng}(G_{U_j^1}(r))}| \\
(5.11) \quad &\leq 2|e^{S_{ng}}|_{C^0(U_j^1)} |S_{ng}(G_{U_j^2}(r)) - S_{ng}(G_{U_j^1}(r))| \\
&\leq 2C \frac{\Lambda^{\alpha_g}}{\Lambda^{\alpha_g} - 1} |g|_{C^{\alpha_g}} (C\tilde{\varepsilon})^{\alpha_g} |e^{S_{ng}}|_{C^0(U_j^1)}
\end{aligned}$$

We estimate the β -Hölder constant in two ways. First, using (5.11) twice, we have for all $r, s \in I_j$ that

$$|e^{S_{ng}} \circ G_{U_j^1}(r) - e^{S_{ng}} \circ G_{U_j^2}(r) - e^{S_{ng}} \circ G_{U_j^1}(s) + e^{S_{ng}} \circ G_{U_j^2}(s)| \leq C\tilde{\varepsilon}^{\alpha_g} |e^{S_{ng}}|_{C^0(U_j^1)}.$$

On the other hand, using that $G_{U_j^\ell}(r)$ and $G_{U_j^\ell}(s)$ lie on the same stable curve,

$$\begin{aligned}
|e^{S_{ng}} \circ G_{U_j^1}(r) - e^{S_{ng}} \circ G_{U_j^2}(r) - e^{S_{ng}} \circ G_{U_j^1}(s) + e^{S_{ng}} \circ G_{U_j^2}(s)| \\
&\leq |e^{S_{ng}} \circ G_{U_j^1}(r) - e^{S_{ng}} \circ G_{U_j^1}(s) + e^{S_{ng}} \circ G_{U_j^2}(s) - e^{S_{ng}} \circ G_{U_j^2}(r)| \\
&\leq |e^{S_{ng}}|_{C^{\alpha_g}(U_j^1)} d(G_{U_j^1}(r), G_{U_j^1}(s))^{\alpha_g} + |e^{S_{ng}}|_{C^{\alpha_g}(U_j^2)} d(G_{U_j^2}(r), G_{U_j^2}(s))^{\alpha_g} \\
&\leq C|e^{S_{ng}}|_{C^0(U_j^1)} |r - s|^{\alpha_g}.
\end{aligned}$$

Thus, this quantity is bounded by the min of the two estimates. This min is maximal when the two upperbounds are equal, that is when $\tilde{\varepsilon} = C|r - s|$. Therefore, the β -Hölder constant satisfies

$$H_{I_j}^\beta(e^{S_{ng}} \circ G_{U_j^1} - e^{S_{ng}} \circ G_{U_j^2}) \leq C\tilde{\varepsilon}^{\alpha_g-\beta} |e^{S_{ng}}|_{C^0(U_j^1)}$$

We therefore have proved that

$$|e^{S_{ng}} \circ G_{U_j^1} - e^{S_{ng}} \circ G_{U_j^2}|_{C^\beta(I_j)} \leq C\tilde{\varepsilon}^{\alpha_g-\beta} |e^{S_{ng}}|_{C^0(U_j^1)}.$$

Combining the above estimates inside (5.10), we finally have

$$|\phi_j - \psi_2 \circ T^n e^{S_{ng}}|_{C^\beta(U_j^2)} \leq C\tilde{\varepsilon}^{\alpha-\beta} |e^{S_{ng}}|_{C^0(U_j^1)},$$

Summing over j yields

$$\sum_j \left| \int_{U_j^2} f(\phi_j - \psi_2 \circ T^n e^{S_{ng}}) dm \right| \leq C |\log \delta_0|^{-\gamma} \|f\|_s \tilde{\varepsilon}^{\alpha-\beta} 2\delta_0^{-1} \sum_{A \in \mathcal{M}_0^n} |e^{S_{ng}}|_{C^0(A)},$$

where we used Lemma 3.1(b) with $\gamma = 0$ since there is at most one matched piece U_j^l corresponding to each component $W_i^l \in \mathcal{G}_n^{\delta_0}(W^l)$ of $T^{-n}W^l$. Since $\delta_0 < 1$ is fixed, this completes the estimate on the second term of the matched pieces (originating from (5.6)).

We now turn to the estimate of the first sum in (5.6) concerning the unmatched pieces.

We say an unmatched curve V_i^1 is created at time j , $1 \leq j \leq n$, if j is the first time that $T^{n-j}V_i^1$ is not part of a matched element of $\mathcal{G}_j^{\delta_0}(W^1)$. Indeed, there may be several curves V_i^1 (in principle exponentially many in $n - j$) such that $T^{n-j}V_i^1$ belongs to the same unmatched element of $\mathcal{G}_j^{\delta_0}(W^1)$. Define

$$A_{j,k} = \{i \mid V_i^1 \text{ is created at time } j$$

$$\text{and } T^{n-j}V_i^1 \text{ belongs to the unmatched curve } W_k^1 \subset T^{-j}W^1\}.$$

Due to the uniform hyperbolicity of T , and, again, uniform transversality of \mathcal{S}_{-n} with the stable cone and of $C^s(x)$ with $C^u(x)$, we have $|W_k^1| \leq C\Lambda^{-j}\tilde{\varepsilon}$.

Recall that from Lemma 3.1(a) for $\bar{\gamma} = 0$, if for a certain time q , every element of $\mathcal{G}_q^{\delta_0}(W_k^1)$ have length less than $\delta_0/3$ – that is, if $\mathcal{G}_q^{\delta_0}(W_k^1) = \mathcal{I}_q^{\delta_0}(W_k^1)$ – then we have the subexponential growth

$$(5.12) \quad \sum_{V \in \mathcal{G}_q^{\delta_0}(W_k^1)} |e^{S_{qg}}|_{C^0(V)} \leq 2(Km + 1)^{q/m} e^{q \sup g}.$$

We would like to establish a lower bound on the value of q as a function of j .

More precisely, we want to find $q(j)$, as large as possible, so that

- (a) $\mathcal{G}_{q(j)}^{\delta_0}(W_k^1) = \mathcal{I}_{q(j)}^{\delta_0}(W_k^1)$;
- (b) $\frac{|\log |V||^{-\gamma}}{|\log \tilde{\varepsilon}|^{-\varsigma}} \leq 1$, for all $V \in \mathcal{I}_{q(j)}^{\delta_0}(W_k^1)$.

This is the content of the next two lemmas.

Lemma 5.4. *If $W \in \widehat{\mathcal{W}}^s$ is such that $\tilde{C}^2|W|^{2^{-kn_0s_0}} < \delta_0/3$ for some $k \geq 1$, where \tilde{C} is the constant from (3.3). Then $\mathcal{G}_{kn_0}^{\delta_0}(W) = \mathcal{I}_{kn_0}^{\delta_0}(W)$, and for all $1 \leq l \leq k$, and all $W_i \in \mathcal{G}_{ln_0}^{\delta_0}(W)$, $|W_i| \leq \tilde{C}^2|W|^{2^{-ln_0s_0}}$.*

Proof. We prove the lemma by induction on k . We start with the case $k = 1$. Let $1 \leq l \leq n_0$ and $W_i \in \mathcal{G}_l^{\delta_0}(W)$. Denote $V = T^l W_i \subset W$. Then, for all $0 \leq j \leq l$, $|T^j W_i| \leq \delta_0$. Decomposing $T^{-l}V = W_i$ as in the beginning of the proof of Lemma 3.1, we get that $|W_i| \leq \tilde{C}|W|^{2^{-n_0s_0}}$, which is less than $\delta_0/3$ by assumption. Thus, $\mathcal{G}_l^{\delta_0}(W) = \mathcal{I}_l^{\delta_0}(W)$ for each $0 \leq l \leq n_0$. Therefore $\mathcal{G}_{n_0}^{\delta_0}(W) = \mathcal{G}_{n_0}^{\delta_0}(W)$, with the claimed estimate.

Consider now the case $k > 1$. Notice that, by construction, we have

$$\mathcal{G}_{(k+1)n_0}^{\delta_0}(W) = \bigcup_{W_i \in \mathcal{G}_{kn_0}^{\delta_0}(W)} \mathcal{G}_{n_0}^{\delta_0}(W).$$

Thus, we can apply the same method to estimate the length of an element $W_i \in \mathcal{G}_{kn_0+l}^{\delta_0}(W)$ from the length of its *parent* in $\mathcal{G}_{kn_0}^{\delta_0}(W)$, iterating the estimates in the same fashion as for (3.3). \square

Lemma 5.5. *The above conditions (a) and (b) are satisfied for $q(j) := \frac{\gamma-\zeta \log(j-j_0)}{\gamma s_0 \log 2} - 1$, for all $j \geq j_1$, where $j_1 > j_0 \geq 0$ are constants (uniform in $\tilde{\varepsilon}$ and W_k^1). For $j < j_1$, set $q(j) = 0$.*

Proof. Since $|W_k^1| \leq C\tilde{\varepsilon}\Lambda^{-j}$ and using Lemma 5.5, the condition (a) will be satisfied whenever $\tilde{C}^2(C\tilde{\varepsilon}\Lambda^{-j})^{2^{-q}s_0} \leq \delta_0/3$.

Let j_0 be such that $C\Lambda^{-j_0} < 1$. Then (a) is satisfied whenever $\tilde{C}^2\Lambda^{-(j-j_0)2^{-q}} \leq \delta_0/3$, that is

$$(5.13) \quad q \leq \frac{\log(j-j_0)}{s_0 \log 2} - C_2, \text{ with } C_2 := \frac{1}{s_0 \log 2} \log \frac{\log \frac{3\tilde{C}^2}{\delta_0}}{\log \Lambda}.$$

Note that C_2 is uniform, and that the right-hand-side of (5.13) is larger than $q(j)$ for all j large enough, say $j \geq j_1$.

Using the estimate from Lemma 5.5, condition (b) is satisfied whenever $|\log \tilde{C}^2(C\tilde{\varepsilon}\Lambda^{-j})^{2^{-q}}|^\gamma > |\log \tilde{\varepsilon}|^\zeta$. Now, we have that

$$|\log \tilde{C}^2(C\tilde{\varepsilon}\Lambda^{-j})^{2^{-q}}| = |\log \tilde{C}^2 + 2^{-q} \log(C\tilde{\varepsilon}\Lambda^{-j})| > \frac{1}{2} |2^{-q} \log(C\tilde{\varepsilon}\Lambda^{-j})|,$$

whenever

$$(5.14) \quad q+1 \leq \frac{\log(j-j_0)}{s_0 \log 2} + C_3, \text{ with } C_3 = \frac{1}{s_0 \log 2} \log \frac{\log \Lambda}{\log \tilde{C}^2}$$

Note that C_3 is uniform, and that the right-hand-side of (5.14) is larger than $q(j)$ for all j large enough, say $j \geq j_1$ (up to increasing the value of j_1).

We thus have to prove that $|\log C\tilde{\varepsilon}\Lambda^{-j}|^\gamma > 2^{(q+1)\gamma} |\log \tilde{\varepsilon}|^\zeta$ (which implies (b)). Notice that, from the definition of $q(j)$, we have $2^{(q(j)+1)\gamma} \leq (j-j_0)^{\gamma-\zeta}$. We distinguish two cases.

Assume first that $(j-j_0) \log \Lambda \geq \log \tilde{\varepsilon}$. Therefore

$$\begin{aligned} 2^{(q(j)+1)\gamma} |\log \tilde{\varepsilon}|^\zeta &\leq (j-j_0)^{\gamma-\zeta} |\log \tilde{\varepsilon}|^\zeta \leq (j-j_0)^\gamma (\log \Lambda)^\zeta \leq ((j-j_0) \log \Lambda)^\gamma \\ &\leq ((j-j_0) \log \Lambda + |\log \tilde{\varepsilon}| + |\log C\Lambda^{-j_0}|)^\gamma \\ &\leq |-(j-j_0) \log \Lambda + \log \tilde{\varepsilon} + \log C\Lambda^{-j_0}|^\gamma \\ &\leq |\log C\tilde{\varepsilon}\Lambda^{-j}|^\gamma. \end{aligned}$$

On the other hand, if $(j-j_0) \log \Lambda \leq \log \tilde{\varepsilon}$, then

$$\begin{aligned} 2^{(q(j)+1)\gamma} |\log \tilde{\varepsilon}|^\zeta &\leq (j-j_0)^{\gamma-\zeta} |\log \tilde{\varepsilon}|^\zeta \leq \frac{|\log \tilde{\varepsilon}|^{\gamma-\zeta}}{(\log \Lambda)^{\gamma-\zeta}} |\log \tilde{\varepsilon}|^\zeta \leq |\log \tilde{\varepsilon}|^\gamma \\ &\leq ((j-j_0) \log \Lambda + |\log \tilde{\varepsilon}| + |\log C\Lambda^{-j_0}|)^\gamma \\ &\leq |-(j-j_0) \log \Lambda + \log \tilde{\varepsilon} + \log C\Lambda^{-j_0}|^\gamma \\ &\leq |\log C\tilde{\varepsilon}\Lambda^{-j}|^\gamma. \end{aligned}$$

Thus, the choice $q(j)$ satisfies (a) and (b) for all $j \geq j_1$. \square

We next estimate¹⁴ over the unmatched pieces V_i^l in (5.6), using the strong stable norm. Since cases $l = 1$ and $l = 2$ are similar here, we only deal with the case $l = 1$.

$$\begin{aligned}
& \sum_{V_i^1} \left| \int_{V_i^1} f \psi_1 \circ T^n e^{S_n g} dm_{V_i^1} \right| = \sum_{j=1}^n \sum_k \sum_{i \in A_{j,k}} \left| \int_{T^{n-j} V_i^1} (\mathcal{L}_g^{n-j} f) \psi_1 \circ T^j e^{S_j g} \right| \\
& \leq \sum_{j=1}^n \sum_k \sum_{V_l \in \mathcal{G}_{q(j)}^{\delta_0}(W_k^1)} \left| \int_{V_l} (\mathcal{L}_g^{n-j-q(j)} f) \psi_1 \circ T^{j+q(j)} e^{S_{j+q(j)} g} \right| \\
& \leq \sum_{j=1}^n \sum_k \sum_{V_l \in \mathcal{G}_{q(j)}^{\delta_0}(W_k^1)} \|\mathcal{L}_g^{n-j-q(j)} f\|_s C |\log |V_l||^{-\gamma} |\psi_1 \circ T^{j+q(j)}|_{C^\beta(V_l)} |e^{S_{j+q(j)} g}|_{C^\beta(V_l)} \\
& \leq C \|f\|_s \sum_{j=1}^n \frac{C}{c_1 \delta_0} e^{(n-j-q(j))P_*(T,g)} |\log \tilde{\varepsilon}|^{-\zeta} \sum_k \sum_{V_l \in \mathcal{G}_{q(j)}^{\delta_0}(W_k^1)} |e^{S_{j+q(j)} g}|_{C^\beta(V_l)} \\
& \leq \frac{C}{c_1 \delta_0} \|f\|_s \sum_{j=1}^n e^{(n-j-q(j))P_*(T,g)} |\log \tilde{\varepsilon}|^{-\zeta} \sum_{W_k^1 \subset T^{-j} W^1} \sum_{V_l \in \mathcal{G}_{q(j)}^{\delta_0}(W_k^1)} |e^{S_j g \circ T^{q(j)} + S_{q(j)} g}|_{C^\beta(V_l)} \\
& \leq \frac{C}{c_1 \delta_0} \|f\|_s \sum_{j=1}^n e^{(n-j-q(j))P_*(T,g)} |\log \tilde{\varepsilon}|^{-\zeta} \sum_{W_k^1 \subset T^{-j} W^1} |e^{S_j g}|_{C^0(W_k^1)} \sum_{V_l \in \mathcal{G}_{q(j)}^{\delta_0}(W_k^1)} |e^{S_{q(j)} g}|_{C^0(V_l)} \\
& \leq \frac{C}{c_1 \delta_0} \|f\|_s \sum_{j=1}^n e^{(n-j-q(j))P_*(T,g)} |\log \tilde{\varepsilon}|^{-\zeta} \frac{4C}{c_1 \delta_0} e^{jP_*(T,g)} e^{q(j) \sup g} (Km+1)^{q(j)/m} \\
& \leq \frac{C}{(c_1 \delta_0)^2} \|f\|_s |\log \tilde{\varepsilon}|^{-\zeta} e^{nP_*(T,g)} \sum_{j=1}^n e^{-q(j)(P_*(T,g) - \sup g - \frac{1}{m} \log(Km+1))}.
\end{aligned}$$

Now, for $\tilde{\varepsilon} > 0$, fixed, since we assume that $P_*(T, g) - \sup g > s_0 \log 2$, we can chose m large enough and ζ small enough such that $\varepsilon_1 := P_*(T, g) - \sup g - \frac{1}{m} \log(Km+1) - \frac{\gamma}{\gamma-\zeta} s_0 \log 2 > 0$. By definition of $q(j)$, we obtain that

$$\sum_{j=j_1}^n e^{-q(j)(P_*(T,g) - \sup g - \frac{1}{m} \log(Km+1))} = \sum_{j=j_1}^n e^{-\frac{(\gamma-\zeta) \log(j-j_0)}{\gamma s_0 \log 2} (\varepsilon_1 + \frac{\gamma}{\gamma-\zeta} s_0 \log 2)} = \sum_{j=j_1}^n (j-j_0)^{-1 - \frac{\gamma-\zeta}{\gamma s_0 \log 2} \varepsilon_1},$$

is bounded. The bound (5.3) then follows by combining all the above estimates into (5.6) and taking the appropriate suprema. \square

Remark 5.6. In the case $g = -h_{\text{top}}(\phi_1)\tau$, the assumption $P_*(T, g) - \sup g > s_0 \log 2$ in Proposition 5.1 is implied by the condition $h_{\text{top}}(\phi_1)\tau_{\min} > s_0 \log 2$, which is itself implied by $\tau_{\min} h_{\mu_{\text{SRB}}}(T)/\mu_{\text{SRB}}(\tau) > s_0 \log 2$ thanks to the Abramov formula. This latter condition appears to be satisfied for billiards studied by Baras and Gaspard [22] and by Garrido [21], as long as τ_{\min} is *not too small*.

¹⁴For the 4th and 6th inequalities, we use Proposition 3.8. Here again, $P_*(T, g)$ can be replaced by $P_*(T, g) + \varepsilon$ up to a larger multiplicative constant.

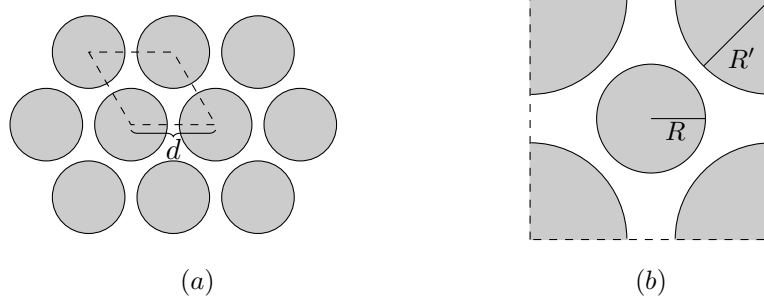


FIGURE 1. (a) The Sinai billiard on a triangular lattice studied in [22] with angle $\pi/3$, scatterer of radius 1, and distance d between the centers of adjacent scatterers. (b) The Sinai billiard on a square lattice with scatterers of radius $R < R'$ studied in [21]. The boundary of a single cell is indicated by dashed lines in both tables.

Indeed, Garrido [21] studied the Sinai billiard corresponding to the periodic Lorentz gas with two scatterers of radius $R < R'$ on the unit square lattice (Figure 1(b)). Setting $R' = 0.4$, Garrido computed $h_{\mu_{\text{SRB}}}(T)$ and $\mu_{\text{SRB}}(\tau)$ for about 20 values of R ranging from $R = 0.1$ (when the horizon becomes infinite) to $R = \frac{\sqrt{2}}{2} - 0.4$ (when the scatterers touch: $\tau_{\min} = 0$). According to [3, § 2.4], in those examples we can always find φ_0 and n_0 such that $s_0 \leq \frac{1}{2}$. Furthermore, $\tau_{\min} = \frac{\sqrt{2}}{2} - 0.4 - R$. Now, for $R = 0.1^+$, we find that

$$\tau_{\min} h_{\mu_{\text{SRB}}}(T) / \mu_{\text{SRB}}(\tau) \geq (\frac{\sqrt{2}}{2} - 0.5) \frac{1.7}{0.5} \geq 0.7 > \frac{1}{2} \log 2 \geq s_0 \log 2,$$

and for $R = 0.2$, we find that

$$\tau_{\min} h_{\mu_{\text{SRB}}}(T) / \mu_{\text{SRB}}(\tau) \geq (\frac{\sqrt{2}}{2} - 0.6) \frac{1.4}{0.3} \geq 0.48 > \frac{1}{2} \log 2 \geq s_0 \log 2.$$

Since for $R \in (0.1, 0.2]$, $R \mapsto \tau_{\min}(R)$ is a linear function, and according to Garrido Figures 6 and 8, $R \mapsto \mu_{\text{SRB}}(\tau)(R)$ is well approximated by an affine function and $R \mapsto h_{\mu_{\text{SRB}}}(T)(R)$ is lower bounded by an affine function joining the values at $R = 0.1$ and 0.2 , it appears that the condition $\tau_{\min} h_{\mu_{\text{SRB}}}(T) / \mu_{\text{SRB}}(\tau) > s_0 \log 2$ is satisfied for all $R \in (0.1, 0.2]$.

Baras and Gaspard studied the Sinai billiard corresponding to the Lorentz gas with disks of radius 1 centered in a triangular lattice (Figure 1(a)). The distance d between points on the lattice is varied from $d = 2$ (when the scatterers touch: $\tau_{\min} = 0$) to $d = 4/\sqrt{3}$ (when the horizon becomes infinite). We have that $\tau_{\min} = d - 2$ and, still according to [3, § 2.4], in those examples we can always find φ_0 and n_0 such that $s_0 \leq \frac{1}{2}$. The computed values are the average Lyapunov exponent of the billiard flows given in [22], provide a lower bound directly on $h_{\mu_{\text{SRB}}}(T) / \mu_{\text{SRB}}(\tau)$. For $d = 0.2$, we find

$$\tau_{\min} h_{\mu_{\text{SRB}}}(T) / \mu_{\text{SRB}}(\tau) \geq (\frac{4}{\sqrt{3}} - 2) 1.8 \geq 0.55 > \frac{1}{2} \log 2 \geq s_0 \log 2.$$

The condition $h_{\text{top}}(\phi_1)\tau_{\min} > s_0 \log 2$ is a little bit more restrictive than the one used by Baladi and Demers in [3] since, by the Abramov formula, $h_* = h_{\text{top}}(\phi_1)\mu_*(\tau) \geq h_{\text{top}}(\phi_1)\tau_{\min}$. (Also, we do not know any example of billiard for which the condition $h_* > s_0 \log 2$ is not satisfied.)

We now turn to the condition SSP.1. Unfortunately, we don't know any billiard table such that the potential $g = -h_{\text{top}}(\phi_1)\tau$ satisfies a *simple* condition implying SSP.1. By *simple*, we mean a sufficient condition that does not involve topological entropies, since they are notoriously hard to estimate numerically. First, recall from Lemmas 3.2 and 3.3 that $\log \Lambda > h_{\text{top}}(\phi_1)(\tau_{\max} - \tau_{\min})$ implies SSP.1. Remark that since g and $\frac{1}{n}S_n g$ are cohomologous, they would give rise to the same equilibrium states. It is then advantageous to work with the Birkhoff average instead of g because $\max \frac{1}{n}S_n g \leq \tau_{\max}$ and $\min \frac{1}{n}S_n g = \tau_{\min}$ (notice that τ_{\min} is achieved on an orbit of period 2). Now, taking advantage of the Abramov formula and of the variational principle, we get that $\max \frac{1}{n}S_n g < 2\tau_{\min}$ implies $h_* > h_{\text{top}}(\phi_1)(\max \frac{1}{n}S_n g - \tau_{\min})$ (recall that $h_* > \log \Lambda$ is the topological entropy of T , as defined in [3]). The condition $\max \frac{1}{n}S_n g < 2\tau_{\min}$ involves quantity that are easy to estimate numerically, however, we don't know any billiard table satisfying this condition.

We now deduce the bounds of Theorem 5.3 from the rate of growth of stable curves proved in Proposition 3.5.

Proof of Theorem 5.3. To prove this lower bound on $|\mathcal{L}_g^n 1|_w$, recall the choice of $\delta_1 > 0$ from Lemma 3.2 for $\varepsilon = 1/4$. Let $w \in \mathcal{W}^s$ with $|W| \geq \delta_1/3$ and set the test function $\psi \equiv 1$. For $n \geq n_1$,

$$\int_W \mathcal{L}_g^n 1 dm_W = \sum_{W_i \in \mathcal{G}_n^{\delta_1}(W)} \int_{W_i} e^{S_n g} dm_{W_i} \geq \sum_{W_i \in \mathcal{G}_n^{\delta_1}(W)} \frac{\delta_1}{2} \inf_{W_i} e^{S_n g} \geq \frac{\delta_1}{2} C^{-1} \sum_{W_i \in \mathcal{G}_n^{\delta_1}(W)} \sup_{W_i} e^{S_n g},$$

where we used Lemma 2.3 for the second inequality, since for each $W_i \in \mathcal{G}_n^{\delta_1}(W)$ there exists $A \in \mathcal{M}_0^n$ such that $W_i \subset A$ and

$$\sup_{W_i} e^{S_n g} \leq \sup_A e^{S_n g} \leq C \inf_A e^{S_n g} \leq C \inf_{W_i} e^{S_n g}.$$

We can now use Proposition 3.5 to get

$$(5.15) \quad \int_W \mathcal{L}_g^n 1 dm_W \geq \frac{\delta_1}{2C} c_0 \sum_{A \in \mathcal{M}_{-n}^0} |e^{S_n^{-1} g}|_{C^0(A)} \geq \frac{\delta_1}{2C} c_0 e^{nP_*(T,g)}.$$

Thus

$$\|\mathcal{L}_g^n 1\|_s \geq |\mathcal{L}_g^n 1|_w \geq \frac{\delta_1}{2} c_0 e^{nP_*(T,g)}.$$

Letting n tend to infinity, one obtains $\lim_{n \rightarrow \infty} \|\mathcal{L}_g^n 1\|_{\mathcal{B}}^{1/n} \geq e^{P_*(T,g)}$. \square

6. THE MEASURE μ_g

This section is devoted to the construction, the properties and the uniqueness of an equilibrium state μ_g for T , associated to a potential g .

We will assume throughout that g is a (\mathcal{P}, α_g) -Hölder potential such that $P_*(T, g) - \sup g > s_0 \log 2$ and that the conditions SSP.1 and SSP.2 are satisfied.

6.1. Construction of the measure μ_g – Measure of Singular Sets. In this section, we construct a T -invariant probability measure μ_g on M by combining in (6.1) a maximal eigenvector of \mathcal{L}_g on \mathcal{B} and a maximal eigenvector of its dual, obtained in Proposition 6.1. In addition, the information on these left and right eigenvectors will give Lemma 6.2 and Corollary 6.3, which imply that μ_g is T -adapted.

We first show that such maximal eigenvectors exist and are in fact nonnegative Radon measures – that is, elements of the dual of $C^0(M)$.

Proposition 6.1. *If g is a (\mathcal{P}, α_g) -Hölder continuous potential such that $P_*(T, g) - \sup g > s_0 \log 2$ and $\log \Lambda > \sup g - \inf g$, then there exist $\nu \in \mathcal{B}_w$ and $\tilde{\nu} \in \mathcal{B}_w^*$ such that $\mathcal{L}_g \nu = e^{P_*(T, g)} \nu$ and $\mathcal{L}_g^* \tilde{\nu} = e^{P_*(T, g)} \tilde{\nu}$. In addition, ν and $\tilde{\nu}$ take nonnegative values on nonnegative C^1 functions on M and are thus nonnegative Radon measures. Finally, $\tilde{\nu}(\nu) \neq 0$ and $\|\nu\|_u \leq \bar{C}$.*

It is easy to see that $|f\varphi|_w \leq |\varphi|_{C^1} |f|_w$ (use $|\varphi\psi|_{C^\alpha(W)} \leq |\varphi|_{C^1} |\psi|_{C^\alpha(W)}$). Clearly, if $f \in C^1$ and $\varphi \in C^1$ then $f\varphi \in C^1$. Therefore, if $P_*(T, g) - \sup g > s_0 \log 2$ and all three SSP condition are satisfied, a bounded linear map μ_g from $C^1(M)$ to \mathbb{C} can be defined by taking ν and $\tilde{\nu}$ from Proposition 6.1 and setting

$$(6.1) \quad \mu_g(\varphi) = \frac{\tilde{\nu}(\varphi\nu)}{\tilde{\nu}(\nu)}.$$

This map is nonnegative for all nonnegative φ and thus defines a nonnegative measure $\mu_g \in (C^0(M))^*$, with $\mu_g(1) = 1$. Clearly, μ_g is a T invariant probability measure since for every $\varphi \in C^1$ we have

$$\tilde{\nu}(\varphi\nu) = e^{-P_*(T, g)} \tilde{\nu}(\varphi \mathcal{L}_g(\nu)) = e^{-P_*(T, g)} \tilde{\nu}(\mathcal{L}_g((\varphi \circ T)\nu)) = \tilde{\nu}((\varphi \circ T)\nu) = \tilde{\nu}(\nu) \mu_g(\varphi \circ T).$$

Proof. Let 1 denote the constant function equal to 1 on M . We will take this as a seed in our construction of a maximal eigenvector. By Theorem 5.3, we see that $\|\mathcal{L}_g^n 1\|_{\mathcal{B}} \geq \|\mathcal{L}_g^n 1\|_s \geq \|\mathcal{L}_g^n 1\|_w \geq C e^{nP_*(T, g)}$. Now consider

$$(6.2) \quad \nu_n := \frac{1}{n} \sum_{k=0}^{n-1} e^{-kP_*(T, g)} \mathcal{L}_g^k 1, \quad n \geq 1.$$

By construction, the ν_n are nonnegative, and thus Radon measures. By Proposition 5.1, they satisfy $\nu_n \leq \bar{C}$, so using the relative compactness of \mathcal{B} in \mathcal{B}_w ([3, Proposition 6.1]), we extract a subsequence (n_j) such that $\lim_j \nu_{n_j} = \nu$ is a nonnegative Radon measure, and the convergence is in \mathcal{B}_w . Since \mathcal{L}_g is continuous on \mathcal{B}_w , we may write,

$$\begin{aligned} \mathcal{L}_g \nu &= \lim_{j \rightarrow \infty} \frac{1}{n_j} \sum_{k=0}^{n_j-1} e^{-kP_*(T, g)} \mathcal{L}_g^{k+1} 1 \\ &= \lim_{j \rightarrow \infty} \frac{e^{P_*(T, g)}}{n_j} \sum_{k=0}^{n_j-1} e^{-kP_*(T, g)} \mathcal{L}_g^k 1 - \frac{1}{n_j} e^{P_*(T, g)} 1 + \frac{1}{n_j} e^{(n_j-1)P_*(T, g)} \mathcal{L}_g^{n_j} 1 \\ &= e^{P_*(T, g)} \nu, \end{aligned}$$

where we used that the second and third terms go to 0 (in the \mathcal{B} -norm). We thus obtain a nonnegative measure $\nu \in \mathcal{B}_w$ such that $\mathcal{L}_g \nu = e^{P_*(T, g)} \nu$.

Although ν is not a priori an element of \mathcal{B} , it does inherit bounds on the unstable norm from the sequence ν_n . The convergence of (ν_{n_j}) to ν in \mathcal{B}_w implies that

$$\lim_{j \rightarrow \infty} \sup_{W \in \mathcal{W}^s} \sup_{\substack{\psi \in C^\alpha(W) \\ |\psi|_{C^\alpha(W)}}} \left(\int_W \nu \psi \, dm_W - \int_W \nu_{n_j} \psi \, dm_W \right) = 0$$

Since $\|\nu_{n_j}\|_u \leq \bar{C}$, it follows that $\|\nu\|_u \leq \bar{C}$, as claimed.

Next, recalling the bound $|\int f d\mu_{\text{SRB}}| \leq \hat{C}|f|_w$ from [3, Proposition 4.2], setting $d\mu_{\text{SRB}} \in (\mathcal{B}_w)^*$ to be the functional defined on $C^1(M) \subset \mathcal{B}_w$ by $d\mu_{\text{SRB}}(f) = \int f d\mu_{\text{SRB}}$ and extended by density, we define

$$(6.3) \quad \tilde{\nu}_n := \frac{1}{n} \sum_{k=0}^{n-1} e^{-kP_*(T,g)} (\mathcal{L}_g^*)^k (d\mu_{\text{SRB}}).$$

Then, we have $|\tilde{\nu}_n(f)| \leq C|f|_w$ for all n and all $f \in \mathcal{B}_w$. So $\tilde{\nu}_n$ is bounded in $(\mathcal{B}_w)^* \subset \mathcal{B}^*$. By compactness of the embedding ([3, Proposition 6.1]), we can find a subsequence $\tilde{\nu}_{\tilde{n}_j}$ converging to $\tilde{\nu} \in \mathcal{B}^*$. By the argument above, we have $\mathcal{L}_g^* \tilde{\nu} = e^{P_*(T,g)} \tilde{\nu}$.

We next check that $\tilde{\nu}$, which in principle lies in the dual of \mathcal{B} , is in fact an element of $(\mathcal{B}_w)^*$. For this, it suffices to find $\tilde{C} < \infty$ so that for any $f \in \mathcal{B}$ we have

$$(6.4) \quad \tilde{\nu}(f) \leq \tilde{C}|f|_w.$$

Now, for $f \in \mathcal{B}$ and any $n_j \geq 1$, we have

$$|\tilde{\nu}(f)| \leq |(\tilde{\nu}_{n_j} - \tilde{\nu})(f)| + |\tilde{\nu}_{n_j}(f)| \leq |(\tilde{\nu}_{n_j} - \tilde{\nu})(f)| + |f|_w.$$

Since $\tilde{\nu}_{n_j} \rightarrow \tilde{\nu}$ in \mathcal{B}^* , we conclude $|\tilde{\nu}(f)| \leq |f|_w$ for all $f \in \mathcal{B}$. Since \mathcal{B} is dense in \mathcal{B}_w , by [29, Thm I.7] $\tilde{\nu}$ extends uniquely to a bounded linear functional on \mathcal{B}_w satisfying (6.4). It only remains to prove that $\tilde{\nu}(\nu) > 0$.

Let (n_j) (resp. (\tilde{n}_j)) denote the subsequence such that $\nu = \lim_j \nu_{n_j}$ (resp. $\tilde{\nu} = \lim_j \tilde{\nu}_{\tilde{n}_j}$). Since $\tilde{\nu}$ is continuous on \mathcal{B}_w , we have on the one hand

$$\tilde{\nu}(\nu) = \lim_{j \rightarrow \infty} \tilde{\nu}(\nu_{n_j}) = \lim_{j \rightarrow \infty} \frac{1}{n_j} \sum_{k=0}^{n_j-1} e^{-kP_*(T,g)} \tilde{\nu}(\mathcal{L}_g^k 1) = \lim_{j \rightarrow \infty} \frac{1}{n_j} \sum_{k=0}^{n_j-1} \tilde{\nu}(1) = \tilde{\nu}(1),$$

where we have used that $\tilde{\nu}$ is an eigenvector of \mathcal{L}_g^* . On the other hand,

$$\tilde{\nu}(1) = \lim_{j \rightarrow \infty} \frac{1}{\tilde{n}_j} \sum_{k=0}^{\tilde{n}_j-1} e^{-kP_*(T,g)} (\mathcal{L}_g^*)^k d\mu_{\text{SRB}}(1) = \lim_{j \rightarrow \infty} \frac{1}{\tilde{n}_j} \sum_{k=0}^{\tilde{n}_j-1} e^{-kP_*(T,g)} \int \mathcal{L}_g^k 1 \, d\mu_{\text{SRB}}.$$

Next, we disintegrate $d\mu_{\text{SRB}}$ as in the proof of [3, Lemma 4.4] into conditional measure $\mu_{\text{SRB}}^{W_\xi}$ on maximal homogeneous stable manifolds $W_\xi \in \mathcal{W}_{\mathbb{H}}^s$ and a factor measure $d\hat{\mu}_{\text{SRB}}(\xi)$ on the index set Ξ of stable manifolds. Recall that $\mu_{\text{SRB}}^{W_\xi} = |W_\xi|^{-1} \rho_\xi dm_W$, where ρ_ξ is uniformly log-Hölder continuous so that

$$0 < c_\rho \leq \inf_{\xi \in \Xi} \inf_{W_\xi} \rho_\xi \leq \sup_{\xi \in \Xi} |\rho_\xi|_{C^\alpha(W_\xi)} \leq C_\rho < \infty.$$

Let Ξ^{δ_1} denote those $\xi \in \Xi$ such that $|W_\xi| \geq \delta_1/3$ and note that $\hat{\mu}_{\text{SRB}}(\Xi^{\delta_1}) > 0$. Then, disintegrating as usual, we get by (5.15) for $k \geq n_1$,

$$\begin{aligned} \int \mathcal{L}_g^k 1 d\mu_{\text{SRB}} &= \int_{\Xi} \int_{W_\xi} \mathcal{L}_g^k 1 \rho_\xi |W_\xi|^{-1} dm_{W_\xi} d\hat{\mu}_{\text{SRB}}(\xi) \\ &= \int_{\Xi^{\delta_1}} \int_{W_\xi} \mathcal{L}_g^k 1 dm_{W_\xi} c_\rho 3\delta_1^{-1} d\hat{\mu}_{\text{SRB}}(\xi) \geq c_\rho \frac{2c_0}{3} e^{kP_*(T,g)} \hat{\mu}_{\text{SRB}}(\Xi^{\delta_1}) > 0. \end{aligned}$$

Thus $\tilde{\nu}(\nu) = \tilde{\nu}(1) \geq c_\rho \frac{2c_0}{3} \hat{\mu}_{\text{SRB}}(\Xi^{\delta_1}) > 0$ as required. \square

Lemma 6.2. *For any $\gamma > 0$ such that $2^{s_0\gamma} < e^{P_*(T,g) - \sup g}$ and any $k \in \mathbb{Z}$ there exists $C_k > 0$ such that*

$$(6.5) \quad \mu_g(\mathcal{N}_\varepsilon(\mathcal{S}_k)) \leq C_k |\log \varepsilon|^{-\gamma}, \quad \forall \varepsilon > 0.$$

In particular, for any $p > 1/\gamma$ (one can choose $p < 1$ for $\gamma > 1$), $\eta > 0$, and $k \in \mathbb{Z}$, for μ_g -almost every $x \in M$, there exists $C > 0$ such that

$$(6.6) \quad d(T^n x, \mathcal{S}_k) \geq C e^{-\eta n^p}, \quad \forall n \geq 0.$$

Proof. First, for each $k \geq 0$, we claim that there exists $C_k > 0$ such that for all $\varepsilon > 0$,

$$(6.7) \quad |\nu(\mathcal{N}_\varepsilon(\mathcal{S}_k))| \leq C |1_{k,\varepsilon} \nu|_w \leq C_k |\log \varepsilon|^{-\gamma}.$$

The proof of the first inequality in (6.7) is formally the same as in the proof of [3, Lemma 7.3].

We now prove the second inequality in (6.7). Let $W \in \mathcal{W}^s$ and $\psi \in C^\alpha(W)$ with $|\psi|_{C^\alpha(W)} \leq 1$. Due to the uniform transversality of curves in \mathcal{S}_{-k} with the stable cone, the intersection $W \cap \mathcal{N}_\varepsilon(\mathcal{S}_{-k})$ can be expressed as a finite union with cardinality bounded by a constant A_k (depending only on \mathcal{S}_{-k}) of stable manifolds $W_i \in \mathcal{W}^s$, of lengths at most $C\varepsilon$. Therefore, for any $f \in C^1(M)$,

$$\int_{W_\xi} f 1_{k,\varepsilon} \psi dm_W = \sum_i \int_{W_i} f \psi dm_{W_i} \leq \sum_i |f|_w |\psi|_{C^\alpha(W_i)} \leq C A_k |f|_w.$$

It follows that $|1_{k,\varepsilon} f|_w \leq A_k |f|_w$ for all $f \in \mathcal{B}_w$. Similarly, we have $|1_{k,\varepsilon} f|_w \leq A_k \|f\|_s |\log \varepsilon|^{-\gamma}$ for all $f \in \mathcal{B}$. Now, recalling ν_n , we estimate,

$$|1_{k,\varepsilon} \nu|_w \leq |1_{k,\varepsilon}(\nu - \nu_n)|_w + |1_{k,\varepsilon} \nu_n|_w \leq A_k |\nu - \nu_n|_w + C'_k |\log \varepsilon|^{-\gamma} \|\nu_n\|_{\mathcal{B}}.$$

Since $\|\nu_n\|_{\mathcal{B}} \leq \overline{C}$ for all $n \geq 1$, we take the limit as $n \rightarrow \infty$ to conclude that $|1_{k,\varepsilon} \nu|_w \leq C_k |\log \varepsilon|^{-\gamma}$, concluding the proof of (6.7).

Next, applying (6.4), we have

$$\tilde{\nu}(\nu) \mu_g(\mathcal{N}_\varepsilon(\mathcal{S}_{-k})) = \tilde{\nu}(1_{k,\varepsilon} \nu) \leq \tilde{C} |1_{k,\varepsilon} \nu|_w \leq \tilde{C} C_k |\log \varepsilon|^{-\gamma} \quad \forall k \geq 0.$$

To obtain the analogous bound for $\mathcal{N}_\varepsilon(\mathcal{S}_k)$, for $k > 0$, we use the invariance of μ_g . It follows from [13, Exercice 4.50] that $T(\mathcal{N}_\varepsilon(\mathcal{S}_1)) \subset \mathcal{N}_{C\varepsilon^{1/2}}(\mathcal{S}_{-1})$. Thus,

$$\mu_g(\mathcal{N}_\varepsilon(\mathcal{S}_1)) \leq \mu_g(\mathcal{N}_{C\varepsilon^{1/2}}(\mathcal{S}_{-1})) \leq C_1 |\log C\varepsilon^{1/2}|^{-\gamma} \leq C'_1 |\log \varepsilon|^{-\gamma}.$$

The estimate for $\mathcal{N}_\varepsilon(\mathcal{S}_k)$, for $k \geq 2$, follows similarly since $T^k \mathcal{S}_k = \mathcal{S}_{-k}$.

Finally, fix $\eta > 0$, $k \in \mathbb{Z}$ and $p > 1/\gamma$. Since

$$(6.8) \quad \sum_{n \geq 0} \mu_g(\mathcal{N}_{e^{-\eta n^p}}(\mathcal{S}_k)) \leq \tilde{C} C_k \eta^{-\gamma} \sum_{n \geq 1} n^{-p\gamma} < \infty,$$

by the Borel–Cantelli Lemma, μ_g -almost every $x \in M$ visits $\mathcal{N}_{e^{-\eta n^p}}(\mathcal{S}_k)$ only finitely many times, and the last part of the lemma follows. \square

Corollary 6.3. *a) For any $\gamma > 0$ so that $P_*(T, g) - \sup g > \gamma s_0 \log 2$ and any C^1 curve S uniformly transverse to the stable cone, there exists $C > 0$ such that $\nu(\mathcal{N}_\varepsilon(S)) \leq C |\log \varepsilon|^{-\gamma}$ and $\mu_g(\mathcal{N}_\varepsilon(S)) \leq C |\log \varepsilon|^{-\gamma}$ for all $\varepsilon > 0$.
b) The measures ν and μ_g have no atoms, and $\mu_g(W) = 0$ for all $W \in \mathcal{W}^s$ and $W \in \mathcal{W}^u$.
c) The measure μ_g is adapted: $\int |\log d(x, \mathcal{S}_{\pm 1})| d\mu_g < \infty$.
d) μ_g -almost every point in M has a stable and unstable manifold of positive length.*

Proof. The proof is identical to the one of [3, Corollary 7.4], where μ_* should be replaced by μ_g . \square

6.2. ν -Almost Everywhere Positive Length of Unstable Manifolds. In this section, we establish almost everywhere positive length of unstable manifolds in the sense of the measure ν – the maximal eigenvector of \mathcal{L}_g in \mathcal{B}_w , extended into a measure since it is nonnegative distribution. To do so, we will view elements of \mathcal{B}_w as *leafwise measure* (Definition 6.4). Indeed, in Lemma 6.6, we make a connection between the disintegration of ν as a measure, and the family of leafwise measures on the set of stable manifolds \mathcal{W}^s .

Definition 6.4 (Leafwise distribution and leafwise measure). *For $f \in C^1(M)$ and $W \in \mathcal{W}^s$, the map defined on $C^\alpha(W)$ by*

$$\psi \mapsto \int_W f \psi d\mathbf{m}_W,$$

can be viewed as a distribution of order α on W . Since $|\int_W f \psi d\mathbf{m}_W| \leq \|f\|_W \|\psi\|_{C^\alpha(W)}$, we can extend the map sending $f \in C^1(M)$ to this distribution of order α , to $f \in \mathcal{B}_w$. We denote this extension by $\int_W f \psi d\mathbf{m}_W$ or $\int_W \psi f$, and we call the corresponding family of distributions $(f, W)_{W \in \mathcal{W}^s}$ the leafwise distribution associated to $f \in \mathcal{B}_w$.

Note that if $\int_W f \psi d\mathbf{m}_W \geq 0$ for all $\psi \geq 0$, then the leafwise distribution on W can be extended into a bounded linear functional on $C^0(W)$, or in other words, a Radon measure. If this holds for all $W \in \mathcal{W}^s$, the leafwise distribution is called a leafwise measure.

Lemma 6.5 (Almost Everywhere Positive Length of Unstable Manifolds, for ν). *For ν -almost every $x \in M$ the stable and unstable manifolds have positive length. Moreover, viewing ν as a leafwise measure, for every $W \in \mathcal{W}^s$, ν -almost every $x \in W$ has an unstable manifold of positive length.*

Lemma 6.6. *Let ν^{W_ξ} and $\hat{\nu}$ denote the conditional measures and factor measure obtained by disintegrating ν on the set of homogeneous stable manifolds $W_\xi \in \mathcal{W}_{\mathbb{H}}^s$, $\xi \in \Xi$. Then for any $\psi \in C^\alpha(M)$,*

$$\int_{W_\xi} \psi d\nu^{W_\xi} = \frac{\int_{W_\xi} \psi \rho_\xi \nu}{\int_{W_\xi} \rho_\xi \nu} \quad \forall \xi \in \Xi, \text{ and } d\hat{\nu}(\xi) = |W_\xi|^{-1} \left(\int_{W_\xi} \rho_\xi \nu \right) d\hat{\mu}_{SRB}(\xi).$$

Moreover, viewed as a leafwise measure, $\nu(W) > 0$ for all $W \in \mathcal{W}^s$.

Proof. First, we establish the following claim: For $W \in \mathcal{W}^s$, we let $n_2 \leq \bar{C}_2 |\log(|W|/\delta)|$ be the constant from the proof of Corollary 3.4 (This is the first time l such that $\mathcal{G}_l^{\delta_1}(W)$ has at least one element of length at least $\delta_1/3$.) Then there exists $\bar{C} > 0$ such that for all $W \in \mathcal{W}^s$,

$$(6.9) \quad \int_W \nu \geq \bar{C} |W|^{(P_*(T,g) - \sup g) \bar{C}_2}.$$

Indeed, recalling (6.2) and using Theorem 5.3, we have for $\bar{C} = \frac{c_0}{2C} \delta_1^{1-(P_*(T,g) - \inf g) \bar{C}_2}$,

$$\begin{aligned} \int_W \nu &= \lim_{n_j} \frac{1}{n_j} \sum_{k=0}^{n_j-1} e^{-kP_*(T,g)} \int_W \mathcal{L}_g^k 1 \, dm_W \\ &\geq \lim_{n_j} \frac{1}{n_j} \sum_{k=n_2}^{n_j-1} e^{-kP_*(T,g)} \sum_{W_i \in \mathcal{G}_{n_2}^{\delta_1}(W)} \int_{W_i} e^{S_{n_2} g} \mathcal{L}_g^{k-n_2} 1 \, dm_{W_i} \\ &\geq \lim_{n_j} \frac{1}{n_j} \sum_{k=n_2}^{n_j-1} e^{-kP_*(T,g)} e^{n_2 \inf g} \frac{\delta_1}{2C} c_0 e^{P_*(T,g)(k-n_2)} \\ &\geq \frac{\delta_1}{2C} c_0 e^{-n_2(P_*(T,g) - \inf g)} \geq \bar{C} |W|^{(P_*(T,g) - \sup g) \bar{C}_2}. \end{aligned}$$

This proves the last statement of the lemma.

Next, for any $f \in C^1(M)$, according to our convention, we view f as an element of \mathcal{B}_w by considering it as a measure integrated against μ_{SRB} . Now let $(\nu_{n_j})_j$ be the sequence of functions defined by (6.2) such that $|\nu_{n_j} - \nu|_w \rightarrow 0$. For any $\psi \in C^\alpha(M)$, we have

$$\begin{aligned} \nu_{n_j}(\psi) &= \int_M \nu_{n_j} \psi \, d\mu_{\text{SRB}} = \int_{\Xi} \int_{W_\xi} \nu_{n_j} \psi \rho_\xi \, dm_{W_\xi} |W_\xi|^{-1} \, d\hat{\mu}_{\text{SRB}}(\xi) \\ &= \int_{\Xi} \frac{\int_{W_\xi} \nu_{n_j} \psi \rho_\xi \, dm_{W_\xi}}{\int_{W_\xi} \nu_{n_j} \rho_\xi \, dm_{W_\xi}} \, d(\hat{\mu}_{\text{SRB}})_{n_j}(\xi) \end{aligned}$$

where $d(\hat{\mu}_{\text{SRB}})_{n_j}(\xi) = |W_\xi|^{-1} \int_{W_\xi} \nu_{n_j} \rho_\xi \, dm_{W_\xi} \, d\hat{\mu}_{\text{SRB}}(\xi)$. By definition of convergences in \mathcal{B}_w since $\psi, \rho_\xi \in C^\alpha(W_\xi)$, the ratio of integrals converges (uniformly in ξ) to $\int_{W_\xi} \psi \rho_\xi \nu / \int_{W_\xi} \rho_\xi \nu$, and the factor measure converges to $|W_\xi|^{-1} \int_{W_\xi} \rho_\xi \, d\nu \, d\hat{\mu}_{\text{SRB}}(\xi)$. Note that since ρ_ξ is uniformly log-Hölder, and due to (6.9), we have $\int_{W_\xi} \rho_\xi \nu > 0$ with lower bound depending only on the length of W_ξ . Finally, by [3, Proposition 4.2] and [3, Lemma 4.4], we have $\nu_{n_j}(\psi)$ converging to $\nu(\psi)$. Disintegrating ν according the statement of the lemma yields to the claimed identifications. \square

Proof of Lemma 6.5. The statement about stable manifolds of positive length follows from the characterization of $\hat{\nu}$ in Lemma 6.6, since the set of points with stable manifolds of zero length has zero $\hat{\mu}_{\text{SRB}}$ -measure [13].

We fix $W \in \mathcal{W}^s$ and prove the statement about ν as a leafwise measure. This will imply the statement regarding unstable manifolds for the measure ν by Lemma 6.6.

Fix $\varepsilon > 0$ and $\hat{\Lambda} \in (1, \Lambda)$, and define $O = \cup_{n \geq 1} O_n$, where

$$O_n := \{x \in W \mid n = \min\{j \geq 1 \mid d_u(T^{-j}x, \mathcal{S}_1) < \varepsilon C_e \hat{\Lambda}^{-j}\}\},$$

and d_u denotes distance restricted to the unstable cone. By [13, Lemma 4.67], any $x \in W \setminus \mathcal{O}$ has an unstable manifold of length at least 2ε . We now estimate $\nu(O) = \sum_{n \geq 1} \nu(O_n)$, where equality holds since the O_n are disjoint. Since each O_n is a finite union of open subcurves of W , we have

$$(6.10) \quad \int_W \mathbb{1}_{O_n} \nu = \lim_{j \rightarrow \infty} \int_W \mathbb{1}_{O_n} \nu_{n_j} = \lim_{j \rightarrow \infty} \frac{1}{n_j} \sum_{k=0}^{n_j-1} e^{kP_*(T,g)} \int_W \mathbb{1}_{O_n} \mathcal{L}_g^k 1 \, dm_W.$$

We give estimates in two cases.

Case I: $k < n$. Write $\int_{W \cap O_n} \mathcal{L}_g^k 1 \, dm_W = \sum_{W_i \in \mathcal{G}_k^{\delta_0}(W)} \int_{W_i \cap T^{-k}O_n} e^{S_{kg}} \, dm_{W_i}$.

If $x \in T^{-k}O_n$, then $y = T^{-n+k}x$ satisfies $d_u(y, \mathcal{S}_1) < \varepsilon C_e \hat{\Lambda}^{-n}$ and thus we have $d_u(Ty, \mathcal{S}_{-1}) \leq C\varepsilon^{1/2} \hat{\Lambda}^{-n/2}$. Due to the uniform transversality of stable and unstable cones, as well as the fact that elements of \mathcal{S}_{-1} are uniformly transverse to the stable cone, we have $d_s(Ty, \mathcal{S}_{-1}) \leq C\varepsilon^{1/2} \hat{\Lambda}^{-n/2}$ as well, with possibly a larger constant C .

Let $r_{-j}^s(x)$ denote the distance from $T^{-j}x$ to the nearest endpoint of $W^s(T^{-j}x)$, where $W^s(T^{-j}x)$ is the maximal local stable manifold containing $T^{-j}x$. From the above analysis, we see that $W_i \cap T^{-k}O_n \subseteq \{x \in W_i : r_{-n+k+1}^s(x) \leq C\varepsilon^{1/2} \hat{\Lambda}^{-n/2}\}$. The time reversal of the growth lemma [13, Thm 5.52] gives $m_{W_i}(r_{-n+k+1}^s(x) \leq C\varepsilon^{1/2} \hat{\Lambda}^{-n/2}) \leq C'\varepsilon^{1/2} \hat{\Lambda}^{-n/2}$ for a constant C' that is uniform in n and k . Thus, using Theorem 3.8, we find

$$\int_{W \cap O_n} \mathcal{L}_g^k 1 \, dm_W \leq C'\varepsilon^{1/2} \hat{\Lambda}^{-n/2} \sum_{W_i \in \mathcal{G}_k^{\delta_0}(W)} |e^{S_{kg}}|_{C^0(W_i)} \leq C e^{kP_*(T,g)} \varepsilon^{1/2} \hat{\Lambda}^{-n/2}.$$

Case II: $k \geq n$. Using the same observation as in Case I, if $x \in T^{-n+1}O_n$, then x satisfies $d_s(x, \mathcal{S}_{-1}) \leq C\varepsilon^{1/2} \hat{\Lambda}^{-n/2}$. We change variables to estimate the integral precisely at time $-n+1$, and then use Theorem 5.3 and Proposition 3.8,

$$\begin{aligned} \int_{W \cap O_n} \mathcal{L}^k 1 \, dm_W &= \sum_{W_i \in \mathcal{G}_{n-1}^{\delta_0}(W)} \int_{W_i \cap T^{-n+1}O_n} e^{S_{n-1g}} \mathcal{L}_g^{k-n+1} 1 \, dm_{W_i} \\ &\leq \sum_{W_i \in \mathcal{G}_{n-1}^{\delta_0}(W)} \int_{W_i \cap (r_1^s \leq C\varepsilon^{1/2} \hat{\Lambda}^{-n/2})} e^{S_{n-1g}} \mathcal{L}_g^{k-n+1} 1 \, dm_{W_i} \\ &\leq \sum_{W_i \in \mathcal{G}_{n-1}^{\delta_0}(W)} |\log |W_i \cap (r_1^s \leq C\varepsilon^{1/2} \hat{\Lambda}^{-n/2})||^{-\gamma} |e^{S_{n-1g}}|_{C^\beta(W_i)} \|\mathcal{L}^{k-n+1} 1\|_s \\ &\leq \sum_{W_i \in \mathcal{G}_{n-1}^{\delta_0}(W)} |\log(C\varepsilon^{1/2} \hat{\Lambda}^{-n/2})|^{-\gamma} C |e^{S_{n-1g}}|_{C^0(W_i)} e^{(k-n+1)P_*(T,g)} \leq |\log(C\varepsilon^{1/2} \hat{\Lambda}^{-n/2})|^{-\gamma} C e^{kP_*(T,g)}. \end{aligned}$$

Using the estimates of Cases I and II in (6.10) and using the weaker bound, we see that,

$$\int_W \mathbb{1}_{O_n} \nu_{n_j} \leq C |\log(C\varepsilon^{1/2} \hat{\Lambda}^{-n/2})|^{-\gamma}.$$

Summing over n , we have, $\int_W 1_O \nu_{n_j} \leq C' |\log \varepsilon|^{1-\gamma}$, uniformly in j . Since ν_{n_j} converges to ν in the weak norm, this bound carries over to ν . Since $\varepsilon > 0$ was arbitrary and $\gamma > 1$, this implies $\nu(O) = 0$, completing the proof of the lemma. \square

6.3. Absolute Continuity of μ_g – Full Support. In this subsection, we will assume that $\gamma > 1$, which is possible since $P_*(T, g) - \sup g > s_0 \log 2$. In the next subsection, we prove that μ_g is Bernoulli. This proof relies on showing first that μ_g is K-mixing. As a first step, we will prove that μ_g is ergodic, using a Hopf-type argument. This will require the absolute continuity of the stable and the unstable foliations for μ_g , which will be deduce from SSP.2 and the following absolute continuity for ν :

Proposition 6.7. *Let R be a Cantor rectangle. Fix $W^0 \in \mathcal{W}^s(R)$ and for $W \in \mathcal{W}^s(R)$, let Θ_W denote the holonomy map from $W^0 \cap R$ to $W \cap R$ along unstable manifolds in $\mathcal{W}^u(R)$. Then for any (P, α_g) -Hölder potential with $P_*(T, g) - \sup g > s_0 \log 2$ and having SSP.1, Θ_W is absolutely continuous with respect to the leafwise measure ν .*

Proof. Since by Lemma 6.5 unstable manifolds comprise a set of full ν -measure, it suffices to fix a set $E \subset W^0 \cap R$ with ν -measure zero, and prove that the ν -measure of $\Theta_W(E) \subset W$ is also zero.

Since ν is a regular measure on W^0 , for $\varepsilon > 0$, there exists an open set $O_\varepsilon \subset W^0$, $O_\varepsilon \supset E$, such that $\nu(O_\varepsilon) \leq \varepsilon$. Indeed, since W^0 is compact, we may choose O_ε to be a finite union of intervals. Let ψ_ε be a smooth function which is 1 on O_ε and 0 outside of an ε -neighbourhood of O_ε . We may choose ψ_ε so that $\int_{W^0} \psi_\varepsilon \nu < 2\varepsilon$.

Using (5.4), we choose $n = n(\varepsilon)$ such that $|\psi_\varepsilon \circ T^n|_{C^1(T^{-n}W^0)} \leq 1$ and $\Lambda^{-n} \leq \varepsilon$. Following the procedure described in the proof of the estimate on the unstable norm in Proposition 5.1, we subdivide $T^{-n}W^0$ and $T^{-n}W$ into matched pieces U_j^0 , U_j and unmatched pieces V_i^0 , V_i . With this construction, none of the unmatched pieces $T^n V_i^0$ intersect an unstable manifold in $\mathcal{W}^u(R)$ since unstable manifolds are not cut under T^{-n} .

Indeed, on matched pieces, we may choose a foliation $\Gamma_j = \{\gamma_x\}_{x \in U_j^0}$ such that:

- i) $T^n \Gamma_j$ contains all unstable manifolds in $\mathcal{W}^u(R)$ that intersect $T^n U_j^0$;
- ii) between unstable manifolds in $\Gamma_j \cap T^{-n}(\mathcal{W}^u(R))$, we interpolate via unstable curves;
- iii) the resulting holonomy Θ_j from $T^n U_j^0$ to $T^n U_j$ has uniformly bounded Jacobian¹⁵ with respect to arc-length, with bound depending on the unstable diameter of $D(R)$, by [5, Lemmas 6.6, 6.8];
- iv) pushing forward Γ_j to $T^n \Gamma_j$ in $D(R)$, we interpolate in the gaps using unstable curves; call $\bar{\Gamma}$ the resulting foliation of $D(R)$;
- v) the associated holonomy map $\bar{\Theta}_W$ extends Θ_W and has uniformly bounded Jacobian, again by [5, Lemmas 6.6 and 6.8].

Using the map $\bar{\Theta}_W$, we define $\tilde{\psi}_\varepsilon = \psi_\varepsilon \circ \bar{\Theta}_W^{-1}$, and note that $|\tilde{\psi}_\varepsilon|_{C^1(W)} \leq C |\psi_\varepsilon|_{C^1(W^0)}$, where we write $C^1(W)$ for the set of Lipschitz functions on W , i.e., C^α with $\alpha = 1$.

Next, we modify ψ_ε and $\tilde{\psi}_\varepsilon$ as follows: We set them equal to 0 on the images of unmatched pieces, $T^n V_i^0$ and $T^n V_i$, respectively. Since these curves do not intersect unstable manifolds

¹⁵Indeed, [5] shows the Jacobian is Hölder continuous, but we shall not need this here.

in $\mathcal{W}^u(R)$, we still have $\psi_\varepsilon = 1$ on E and $\tilde{\psi}_\varepsilon = 1$ on $\Theta_W(E)$. Moreover, the set of points on which $\psi_\varepsilon > 0$ (resp. $\tilde{\psi}_\varepsilon > 0$) is a finite union of open intervals that cover E (resp. $\Theta_W(E)$).

Since $\int_{W^0} \psi_\varepsilon \nu < 2\varepsilon$, in order to estimate $\int_W \tilde{\psi}_\varepsilon \nu$, we estimate the following difference, using matched pieces

(6.11)

$$\begin{aligned} \int_{W^0} \psi_\varepsilon \nu - \int_W \tilde{\psi}_\varepsilon \nu &= e^{-nP_*(T,g)} \left(\int_{W^0} \psi_\varepsilon \mathcal{L}^n \nu - \int_W \tilde{\psi}_\varepsilon \mathcal{L}^n \nu \right) \\ &= e^{-nP_*(T,g)} \sum_j \int_{U_j^0} \psi_\varepsilon \circ T^n e^{S_{ng}} \nu - \int_{U_j} \phi_j \nu + \int_{U_j} (\phi_j - \tilde{\psi}_\varepsilon \circ T^n e^{S_{ng}}) \nu, \end{aligned}$$

where $\phi_j = (\psi_\varepsilon \circ T^n e^{S_{ng}}) \circ G_{U_j^0} \circ G_{U_j}^{-1}$, and $G_{U_j^0}$ and G_{U_j} represent the functions defining U_j^0 and U_j , respectively, defined as in (5.5). Next, since $d(\psi_\varepsilon \circ T^n e^{S_{ng}}, \phi_j) = 0$ by construction, and using (5.8) and the assumption that $\Lambda^{-n} \leq \varepsilon$, we have by (5.9),

$$(6.12) \quad e^{-nP_*(T,g)} \left| \sum_j \int_{U_j^0} \psi_\varepsilon \circ T^n \nu - \int_{U_j} \phi_j \nu \right| \leq C |\log \varepsilon|^{-\varsigma} \|\nu\|_u.$$

It remains to estimate the last term in (6.11). This we do using the weak norm,

$$(6.13) \quad \int_{U_j} (\phi_j - \tilde{\psi}_\varepsilon \circ T^n e^{S_{ng}}) \nu \leq |\phi_j - \tilde{\psi}_\varepsilon \circ T^n e^{S_{ng}}|_{C^\alpha(U_j)} |\nu|_w.$$

By (5.10), we have

$$|\phi_j - \tilde{\psi}_\varepsilon \circ T^n e^{S_{ng}}|_{C^\alpha(U_j)} \leq C |(\psi_\varepsilon \circ T^n e^{S_{ng}}) \circ G_{U_j^0} - (\tilde{\psi}_\varepsilon \circ T^n e^{S_{ng}}) \circ G_{U_j}|_{C^\alpha(I_j)},$$

where I_j is the common r -interval on which $G_{U_j^0}$ and G_{U_j} are defined.

Fix $r \in I_j$, and let $x = G_{U_j^0}(r) \in U_j$ and $\bar{x} = G_{U_j}(r)$. Since U_j^0 and U_j are matched, there exists $y \in U_j^0$ and an unstable curve $\gamma_y \in \Gamma_j$ such that $\gamma_y \cap U_j = \bar{x}$. By definition of $\tilde{\psi}_\varepsilon$, we have $\tilde{\psi}_\varepsilon \circ T^n(\bar{x}) = \psi_\varepsilon \circ T^n(y)$. Thus,

$$\begin{aligned} &|(\psi_\varepsilon \circ T^n e^{S_{ng}}) \circ G_{U_j^0}(r) - (\tilde{\psi}_\varepsilon \circ T^n e^{S_{ng}}) \circ G_{U_j}(r)| \\ &\leq |\psi_\varepsilon \circ T^n(x) - \tilde{\psi}_\varepsilon \circ T^n(\bar{x})| e^{S_{ng}(x)} + |\tilde{\psi}_\varepsilon \circ T^n(\bar{x})| |e^{S_{ng}(x)} - e^{S_{ng}(\bar{x})}| \\ &\leq (|\psi_\varepsilon \circ T^n(x) - \psi_\varepsilon \circ T^n(y)| + |\psi_\varepsilon \circ T^n(y) - \tilde{\psi}_\varepsilon \circ T^n(\bar{x})|) e^{n \sup g} + |e^{S_{ng}(x)} - e^{S_{ng}(\bar{x})}| \\ &\leq \left(|\psi_\varepsilon \circ T^n|_{C^1(U_j^0)} d(x, y) + |g|_{C^{\alpha_g}} \frac{\Lambda^{\alpha_g}}{\Lambda^{\alpha_g} - 1} (C\varepsilon)^{\alpha_g} \right) e^{n \sup g} \\ &\leq (C\Lambda^{-n} + C\varepsilon^{\alpha_g}) e^{n \sup g} \leq C(\varepsilon + \varepsilon^{\alpha_g}) e^{n \sup g}, \end{aligned}$$

where we have used the fact that $d(x, y) \leq C\Lambda^{-n}$ due to the uniform transversality of stable and unstable curves. We also used the fact that, by definition, the vertical segment γ_x connecting x to \bar{x} is such that $|T^n \gamma_x| < C\varepsilon$. Since each $T^i \gamma_x$ lies in the extended unstable cone, for all $0 \leq i \leq n$, we get that $d(T^i(x), T^i(\bar{x})) \leq C\Lambda^{-(n-i)}\varepsilon$, hence the bound

$$|e^{S_{ng}(x)} - e^{S_{ng}(\bar{x})}| \leq |e^{S_{ng}(x)}| \cdot |1 - e^{S_{ng}(\bar{x}) - S_{ng}(x)}| \leq 2e^{n \sup g} |S_{ng}(\bar{x}) - S_{ng}(x)|$$

$$\leq \frac{\Lambda^{\alpha_g}}{\Lambda^{\alpha_g} - 1} (C\varepsilon)^{\bar{\alpha}} |g|_{C^{\alpha_g}} e^{n \sup g}$$

where we used that $|1 - e^x| \leq 2|x|$ when x is near 0.

Now given $r, s \in I_j$, we have on the one hand,

$$|(\psi_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j^0}(r) - (\tilde{\psi}_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j}(r) - (\psi_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j^0}(s) + (\tilde{\psi}_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j}(s)| \leq 2C\varepsilon^{\bar{\alpha}} e^{n \sup g},$$

while on the other hand,

$$\begin{aligned} & |(\psi_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j^0}(r) - (\tilde{\psi}_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j}(r) - (\psi_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j^0}(s) + (\tilde{\psi}_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j}(s)| \\ &= |(\psi_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j^0}(r) - (\psi_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j^0}(s) - ((\tilde{\psi}_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j}(r) - (\tilde{\psi}_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j}(s))| \\ &\leq |\psi_\varepsilon|_{C^0(W^0)} |e^{S_n g}|_{C^{\alpha_g}} d(G_{U_j^0}(r), G_{U_j^0}(s))^{\alpha_g} + |\psi_\varepsilon \circ T^n|_{C^1(W^0)} d(G_{U_j^0}(r), G_{U_j^0}(s)) |e^{S_n g}|_{C^0} \\ &\quad + |\tilde{\psi}_\varepsilon|_{C^0(W)} |e^{S_n g}|_{C^{\alpha_g}} d(G_{U_j^0}(r), G_{U_j^0}(s))^{\alpha_g} + |\tilde{\psi}_\varepsilon \circ T^n|_{C^1(W)} d(G_{U_j^0}(r), G_{U_j^0}(s)) |e^{S_n g}|_{C^0} \\ &\leq (C|r-s| + C'|r-s|^{\alpha_g}) e^{n \sup g} \leq C|r-s|^{\alpha_g} e^{n \sup g}, \end{aligned}$$

where we have used Lemma 3.10 and the fact that $G_{U_j^0}^{-1}$ and $G_{U_j}^{-1}$ have bounded derivatives since the stable cone is bounded away from the vertical.

The difference between evaluation at r and s is bounded by the minimum of these two expressions. This is greatest when the two are equal, i.e., when $|r-s| = C\varepsilon$. Thus $H^\alpha((\psi_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j^0} - (\tilde{\psi}_\varepsilon \circ T^n e^{S_n g}) \circ G_{U_j}) \leq C\varepsilon^{\alpha_g - \alpha} e^{n \sup g}$, and so $|\phi_j - \tilde{\psi}_\varepsilon \circ T^n e^{S_n g}|_{C^\alpha(U_j)} \leq C\varepsilon^{\alpha_g - \alpha} e^{n \sup g}$. Putting this estimate together with (6.12) and (6.13) in (6.11), we conclude,

$$(6.14) \quad \left| \int_{W^0} \psi_\varepsilon \nu - \int_W \tilde{\psi}_\varepsilon \nu \right| \leq C |\log \varepsilon|^{-\varsigma} \|\nu\|_u + C\varepsilon^{\alpha_g - \alpha} |\nu|_w e^{-n(P_*(T,g) - \sup g)}.$$

Now since $\int_{W^0} \psi_\varepsilon \nu \leq 2\varepsilon$, we have

$$(6.15) \quad \int_W \tilde{\psi}_\varepsilon \nu \leq C' |\log \varepsilon|^{-\varsigma},$$

where C' depends on ν . Since $\tilde{\psi}_\varepsilon = 1$ on $\Theta_W(E)$ and $\tilde{\psi}_\varepsilon > 0$ on an open set containing $\Theta_W(E)$ for every $\varepsilon > 0$, we have $\nu(\Theta_W(E)) = 0$, as required. \square

Corollary 6.8 (Absolute Continuity of μ_g with Respect to Unstable Foliations). *Let R be a Cantor rectangle with $\mu_g(R) > 0$. Fix $W^0 \in \mathcal{W}^s(R)$ and for $W \in \mathcal{W}^s(R)$, let Θ_W denote the holonomy map from $W^0 \cap R$ to $W \cap R$ along unstable manifolds in $\mathcal{W}^u(R)$. Then Θ_W is absolutely continuous with respect to the measure μ_g .*

In order to deduce the corollary from the Proposition 6.7, we introduce the set M^{reg} , as in [3], of regular points and a countable cover of this set by Cantor rectangles. The set M^{reg} is defined by

$$M^{\text{reg}} = \{x \in M \mid d(x, \partial W^s(x)) > 0, d(x, \partial W^u(x)) > 0\}.$$

At each $x \in M^{\text{reg}}$, we can apply [13, Prop 7.81] and construct a closed locally maximal Cantor rectangle R_x containing x , which is the direct product of local stable and unstable manifolds. Furthermore, by trimming the sides, we may arrange it so that $\frac{1}{2} \text{diam}^s(R_x) \leq \text{diam}^u(R_x) \leq 2 \text{diam}^s(R_x)$.

Lemma 6.9 (Countable Cover of M^{reg} by Cantor Rectangle). *There exists a countable set $\{x_j\}_{j \in \mathbb{N}} \subset M^{\text{reg}}$, such that $\cup_j R_{x_j} = M^{\text{reg}}$ and each $R_j := R_{x_j}$ satisfies (3.18).*

Proof. This lemma is exactly the content of [3, Lemma 7.10]. \square

Let $\{R_j \mid j \in \mathbb{N}\}$ be the family of Cantor rectangles constructed in Lemma 6.9, discarding the ones with zero μ_g -measure. Then $\mu_g(\cup_j R_j) = \mu_g(M^{\text{reg}}) = 1$, by Corollary 6.3(d). In the rest of the paper, we shall work with this countable collection of rectangles.

Given a Cantor rectangle R , define $\mathcal{W}^s(R)$ to be the set of stable manifolds that completely cross $D(R)$, and similarly for $\mathcal{W}^u(R)$.

Proof of Corollary 6.8. In order to prove absolute continuity of the unstable foliation with respect to μ_g , we will show that the conditional measures μ_g^W of μ_g are equivalent to ν on μ_g -almost every $W \in \mathcal{W}^s(R)$.

Fix a Cantor rectangle R satisfying (3.18) with $\mu_g(R) > 0$, and W^0 as in the statement of the corollary. Let $E \subset W^0 \cap R$ satisfy $\nu(E) = 0$, for the leafwise measure ν .

For any $W \in \mathcal{W}^s(R)$, we have the holonomy map $\Theta_W : W^0 \cap R \rightarrow W \cap R$ as in the proof of Proposition 6.7. For $\varepsilon > 0$, we approximate E , choose n and construct a foliation $\bar{\Gamma}$ of the solid rectangle $D(R)$ as before. Define ψ_ε and use the foliation $\bar{\Gamma}$ to define $\tilde{\psi}_\varepsilon$ on $D(R)$. We have $\tilde{\psi}_\varepsilon = 1$ on $\bar{E} = \cup_{x \in E} \bar{\gamma}_x$, where $\bar{\gamma}_x$ is the element of $\bar{\Gamma}$ containing x . We extend $\tilde{\psi}_\varepsilon$ to M by setting it equal to 0 on $M \setminus D(R)$.

It follows from the proof of Proposition 6.7, in particular (6.15), that $\tilde{\psi}_\varepsilon \nu \in \mathcal{B}_w$, and $|\tilde{\psi}_\varepsilon \nu|_w \leq C' |\log \varepsilon|^{-\varsigma}$. Now,

$$\begin{aligned}
 \tilde{\nu}(\nu) \mu_g(\tilde{\psi}_\varepsilon) &= \tilde{\nu}(\tilde{\psi}_\varepsilon \nu) = \lim_{j \rightarrow \infty} \frac{1}{n_j} \sum_{k=0}^{n_j-1} e^{-kP_*(T,g)} (\mathcal{L}_g^*)^k d\mu_{\text{SRB}}(\tilde{\psi}_\varepsilon \nu) \\
 (6.16) \quad &= \lim_{j \rightarrow \infty} \frac{1}{n_j} \sum_{k=0}^{n_j-1} e^{-kP_*(T,g)} \mu_{\text{SRB}}(\mathcal{L}_g^k(\tilde{\psi}_\varepsilon \nu)).
 \end{aligned}$$

For each k , using the disintegration of μ_{SRB} as in the proof of Lemma 6.6 with the same notation as there, we estimate,

$$\begin{aligned}
 \mu_{\text{SRB}}(\mathcal{L}_g^k(\tilde{\psi}_\varepsilon \nu)) &= \int_{\Xi} \int_{W_\xi} \mathcal{L}_g^k(\tilde{\psi}_\varepsilon \nu) \rho_\xi dm_{W_\xi} |W_\xi|^{-1} d\hat{\mu}_{\text{SRB}}(\xi) \\
 &\leq C \int_{\Xi} |\mathcal{L}_g^k(\tilde{\psi}_\varepsilon \nu)|_w |W_\xi|^{-1} d\hat{\mu}_{\text{SRB}}(\xi) \\
 &\leq C e^{kP_*(T,g)} |\tilde{\psi}_\varepsilon \nu|_w \leq C e^{kP_*(T,g)} |\log \varepsilon|^{-\varsigma},
 \end{aligned}$$

where we have used (5.1) in the last line. Thus $\mu_g(\tilde{\psi}_\varepsilon) \leq C |\log \varepsilon|^{-\varsigma}$, for each $\varepsilon > 0$, so that $\mu_g(\bar{E}) = 0$.

Disintegrating μ_g into conditional measures $\mu_g^{W_\xi}$ on $W_\xi \in \mathcal{W}^s$ and a factor measure $d\hat{\mu}_g(\xi)$ on the index set Ξ_R of stable manifolds in $\mathcal{W}^s(R)$, it follows that $\mu_g^{W_\xi}(\bar{E}) = 0$ for $\hat{\mu}_g$ -almost every $\xi \in \Xi_R$. Since E was arbitrary, the conditional measures of μ_g on $\mathcal{W}^s(R)$ are absolutely continuous with respect to the leafwise measure ν .

To show that in fact μ_g^W is equivalent to ν , suppose now that $E \subset W^0$ has $\nu(E) > 0$. For any $\varepsilon > 0$ such that $C'|\log \varepsilon|^{-\varsigma} < \nu(E)/2$, where C' is from (6.15), choose $\psi_\varepsilon \in C^1(W^0)$ such that $\nu(|\psi_\varepsilon - 1_E|) < \varepsilon$, where 1_E is the indicator function of the set E . As above, we extend ψ_ε to a function $\tilde{\psi}_\varepsilon$ on $D(R)$ via the foliation $\bar{\Gamma}$, and then to M by setting $\tilde{\psi}_\varepsilon = 0$ on $M \setminus D(R)$.

We have $\tilde{\psi}_\varepsilon \nu \in \mathcal{B}_w$ and by (6.14)

$$(6.17) \quad \nu(\tilde{\psi}_\varepsilon 1_W) \geq \nu(\psi_\varepsilon 1_{W^0}) - C'|\log \varepsilon|^{-\varsigma}, \quad \text{for all } W \in \mathcal{W}^s(R).$$

Now following (6.16) and disintegrating μ_{SRB} as usual, we obtain,

$$(6.18) \quad \begin{aligned} \mu_g(\tilde{\psi}_\varepsilon) &= \lim_n \frac{1}{n} \sum_{k=0}^{n-1} e^{-kP_*(T,g)} \int_{\Xi} \int_{W_\xi} \mathcal{L}_g^k(\tilde{\psi}_\varepsilon \nu) \rho_\xi \, dm_{W_\xi} \, d\hat{\mu}_{\text{SRB}}(\xi) \\ &= \lim_n \frac{1}{n} \sum_{k=0}^{n-1} e^{-kP_*(T,g)} \int_{\Xi} \left(\sum_{W_{\xi,i} \in \mathcal{G}_k^{\delta_1}(W_\xi)} \int_{W_{\xi,i}} \tilde{\psi}_\varepsilon \rho_\xi \circ T^k e^{S_k g} \nu \right) d\hat{\mu}_{\text{SRB}}(\xi). \end{aligned}$$

To estimate this last expression, we estimate the thermodynamic sum over the curves $W_{\xi,i}$ which properly cross the rectangle R .

By SSP.2 and the choice of δ_1 in (3.9), there exists k_0 , depending only on the minimum length of $W \in \mathcal{W}^s(R)$, such that

$$\sum_{W_i \in L_k^{\delta_1}(W_\xi)} |e^{S_k g}|_{C^0(W_i)} \geq \frac{1}{3} \sum_{W_i \in \mathcal{G}_k^{\delta_1}(W_\xi)} |e^{S_k g}|_{C^0(W_i)}, \quad \text{for all } k \geq k_0.$$

By choice of our covering $\{R_i\}$ from Lemma 6.9, all $W_{\xi,j} \in L_k^{\delta_1}(W_\xi)$ properly cross one of finitely many R_i . By the topological mixing property of T , there exists n_0 , depending only on the length scale δ_1 , such that some smooth component of $T^{-n_0} W_{\xi,j}$ properly crosses R . Thus, letting $\mathcal{C}_k(W_\xi)$ denote those $W_{\xi,i} \in \mathcal{G}_k^{\delta_1}(W_\xi)$ which properly cross R , we have

$$\begin{aligned} \sum_{W_i \in \mathcal{C}_{k+n_0}(W_\xi)} |e^{S_k g}|_{C^0(W_i)} &\geq \sum_{W_{\xi,i} \in L_k^{\delta_1}(W_\xi)} \sum_{\tilde{W} \subset \mathcal{G}_{n_0}^{\delta_1}(W_{\xi,i}) \cap \mathcal{C}_{k+n_0}(W_\xi)} e^{n_0 \inf g} |e^{S_k g}|_{C^0(W_{\xi,i})} \\ &\geq e^{n_0 \inf g} \sum_{W_{\xi,i} \in L_k^{\delta_1}(W_\xi)} |e^{S_k g}|_{C^0(W_{\xi,i})} \\ &\geq \frac{1}{3} e^{n_0 \inf g} \sum_{W_{\xi,i} \in \mathcal{G}_k^{\delta_1}(W_\xi)} |e^{S_k g}|_{C^0(W_{\xi,i})} \geq \frac{1}{3} c e^{n_0 \inf g} e^{kP_*(T,g)}, \end{aligned}$$

for all $k \geq k_0$, where $c > 0$ depends on c_0 from Proposition 3.5 as well as the minimum length of $W \in \mathcal{W}^s(R)$.

Using this lower bound on the sum together with (6.17) yields,

$$\mu_g(\tilde{\psi}_\varepsilon) \geq \frac{1}{3} c e^{-n_0 P_*(T,g)} (\nu(\psi_\varepsilon) - C'|\log \varepsilon|^{-\varsigma}) \geq C''(\nu(E) - |\log \varepsilon|^{-\varsigma}).$$

Taking $\varepsilon \rightarrow 0$, we have $\mu_g(\bar{E}) \geq C''\nu(E)$, and so $\mu_g^W(\bar{E}) > 0$ for almost every $W \in \mathcal{W}^s(R)$. \square

Proposition 6.10 (Full Support). *We have $\mu_g(O) > 0$ for any open set O .*

Proof. The proof is the same as the one of [3, Proposition 7.11], replacing μ_* by μ_g . \square

6.4. Bernoulli property of μ_g and Variational Principle. In this section, we use the absolute continuity results on the holonomy map from Section 6.3 to establish that μ_g is K-mixing. We also prove an upper bound on the μ_g -measure of weighted dynamical Bowen balls. Using these estimates, we are able to prove that μ_g is an equilibrium state for T under the potential g – that is, μ_g realizes the sup in the definition of $P(T, g)$ – and μ_g satisfies the variational principle: $P_*(T, g) = P(T, g)$. Finally, using again the absolute continuity along side with Cantor rectangles and the bound (6.5) on the neighbourhoods of the singular sets, we can bootstrap from the K-mixing to prove that μ_g is Bernoulli.

Lemma 6.11 (Single Ergodic Component). *If R is a Cantor rectangle with $\mu_g(R) > 0$, then the set of stable manifolds $\mathcal{W}^s(R)$ belongs to a single ergodic component of μ_g .*

Proof. Replacing μ_* by μ_g , the proof of the analogous result [3, Lemma 7.15] can be applied verbatim. The proof there follows the Hopf strategy. \square

Proposition 6.12. *For all (\mathcal{P}, α_g) -Hölder potential g such that $P_*(T, g) - \sup g > s_0 \log 2$ and having SSP.1 and SSP.2, (T, μ_g) is K-mixing.*

Proof. Replacing μ_* by μ_g , the proof of the analogous result [3, Proposition 7.16] can be applied verbatim. We outline the steps of the proof.

First, Baladi and Demers show that (T^n, μ_*) is ergodic for all $n \geq 1$. To do so, they use the topological mixing of T to prove that any two Cantor rectangle belong to the same ergodic component of T^n .

Then, they prove that T is K-mixing. To do so, they construct a measurable partition out of the stable and unstable manifolds, that is finer than the Pinsker partition $\pi(T)$. Using the covering of M^{reg} by Cantor rectangles $\{R_i\}$, and the absolute continuity of the holonomy map, they prove that each R_i belongs to a single component of $\pi(T)$. From this, they deduce that $\pi(T)$ contains finitely many elements on which T acts by permutation. Since $\pi(T)$ is T -invariant and (T^n, μ_*) is ergodic for all $n \geq 1$, $\pi(T)$ must be trivial. \square

Proposition 6.13 (Upper Bounds on Weighted Dynamical Balls). *Assume that $P_*(T, g) - \sup g > s_0 \log 2$ and that SSP.1 holds. There exists $A < \infty$ such that for all $\varepsilon > 0$ sufficiently small, $x \in M$, and $n \geq 1$, the measure μ_g constructed in (6.1) satisfies*

$$\mu_g(e^{-S_n^{-1}g} \mathbb{1}_{B_n(x, \varepsilon)}) \leq A e^{-nP_*(T, g)}.$$

Proof. The inequality follows from the beginning of the proof of [3, Proposition 7.12], where μ_* , \mathcal{L} and h_* should be replaced by respectively μ_g , \mathcal{L}_g and $P_*(T, g)$. \square

Corollary 6.14. *For all (\mathcal{P}, α_g) -Hölder potential g such that $P_*(T, g) - \sup g > s_0 \log 2$ and having SSP.1 and SSP.2, the measure μ_g is an equilibrium state of T under the potential g : we have $P_*(T, g) = h_{\mu_g}(T) + \int g d\mu_g$.*

Proof. For all $x \in M$, let $\mathcal{P}_0^n(x)$ denotes the element of \mathcal{P}_0^n containing x . By the Shannon–MacMillan–Breiman theorem, we have

$$-\lim_{n \rightarrow \infty} \frac{1}{n} \log \mu_g(\mathcal{P}_0^n(x)) = h_{\mu_g}(\mathcal{P}, T) = h_{\mu_g}(T) \quad \text{for } \mu_g\text{-a.e. } x \in M,$$

where the last equality follows from the Kolmogorov–Sinai theorem (because T is expansive [3, Lemma 3.4]). Furthermore, since by Proposition 6.12 μ_g is ergodic, then $\frac{1}{n} \log e^{-S_n^{-1}g}$

converges to $-\mu_g(g)$ as n goes to infinity. Thus

$$(6.19) \quad -\lim_{n \rightarrow \infty} \frac{1}{n} \log \left(e^{-S_n^{-1}g(x)} \mu_g(\mathcal{P}_0^n(x)) \right) = h_{\mu_g}(T) + \int g d\mu_g \quad \text{for } \mu_g\text{-a.e. } x \in M.$$

Now, by Lemma 2.3, there exists a constant C such that for all $x \in M$ and all $y, z \in \mathcal{P}_0^n(x)$, we have $|S_n^{-1}g(y) - S_n^{-1}g(z)| \leq C$. Thus

$$e^{-C} \leq \frac{\mu_g \left(e^{-S_n^{-1}g} \mathbb{1}_{\mathcal{P}_0^n(x)} \right)}{e^{-S_n^{-1}g(x)} \mu_g(\mathcal{P}_0^n(x))} \leq e^C,$$

and so we can replace $e^{-S_n^{-1}g(x)} \mu_g(\mathcal{P}_0^n(x))$ in (6.19) by $\mu_g \left(e^{-S_n^{-1}g} \mathbb{1}_{\mathcal{P}_0^n(x)} \right)$.

Now, we want to replace $\mathcal{P}_0^n(x)$ with a dynamical ball and use Proposition 6.13. To do so, recall that for all $\varepsilon < \varepsilon_0$, the dynamical ball $B_n(x, \varepsilon)$ is included in a single element of \mathcal{M}_0^n , which is itself included in at most C elements of \mathcal{P}_0^n , for some C independent of x . Thus,

$$-\liminf_{n \rightarrow \infty} \frac{1}{n} \log \mu_g \left(e^{-S_n^{-1}g} \mathbb{1}_{B_n(x, \varepsilon)} \right) \leq h_{\mu_g}(T) + \int g d\mu_g,$$

On the other hand, for ε small enough, we get by Proposition 6.13,

$$-\liminf_{n \rightarrow \infty} \frac{1}{n} \log \mu_g \left(e^{-S_n^{-1}g} \mathbb{1}_{B_n(x, \varepsilon)} \right) \geq P_*(T, g).$$

Combining these last two inequalities, we get $h_{\mu_g}(T) + \int g d\mu_g \geq P_*(T, g)$, which ends the proof. \square

Proposition 6.15. *Under the assumptions of Proposition 6.12, (T, μ_g) is Bernoulli.*

Proof. The proof follows the arguments in Section 5 and 6 in [15], relying on the notion vwB partition introduced by Ornstein in [27]. Actually, we can apply the same modifications as in the proof of the analogous result [3, Proposition 7.19], replacing μ_* by μ_g . \square

6.5. Uniqueness of the equilibrium state. This subsection is devoted to the uniqueness of the equilibrium state μ_g (Proposition 6.18). The proof relies on exploiting the fact that while the lower bound on weighted Bowen balls (or thermodynamic sum over elements of \mathcal{M}_{-n}^0) cannot be improved for μ_g -almost every x , yet if one fixes n , most elements of \mathcal{M}_{-n}^0 (in the sense of thermodynamic sums) should either have unstable diameter of a fixed length, or have previously been contained in an element of \mathcal{M}_{-j}^0 with this property, for some $j < n$ (Lemma 6.16). Such elements collectively satisfy stronger lower bounds on their measure, when weighted accordingly (Lemma 6.17). Since we have established good control of the sums over \mathcal{M}_{-n}^0 and \mathcal{M}_0^0 in Section 3, we will work with these partitions instead of Bowen balls.

Recalling (3.2), choose m_1 large enough so that $(Km_1 + 1)^{1/m_1} < e^{\frac{1}{4}(P_*(T, g) - \sup g)}$. Now, choose $\delta_2 > 0$ sufficiently small that for all $n, k \in \mathbb{N}$, if $A \in \mathcal{M}_{-n}^k$ is such that

$$\max\{\text{diam}^u(A), \text{diam}^s(A)\} \leq \delta_2,$$

then $A \setminus \mathcal{S}_{\pm m_1}$ consists of at most $Km_1 + 1$ connected components.

For $n \geq 1$, define

$$B_{-2n}^0 := \{A \in \mathcal{M}_{-2n}^0 \mid \forall 0 \leq j \leq n/2,$$

$$T^{-j}A \subset E \in \mathcal{M}_{-n+j}^0 \text{ such that } \text{diam}^u(E) < \delta_2\},$$

and its time reversal

$$B_0^{2n} := \{A \in \mathcal{M}_0^{2n} \mid \forall 0 \leq j \leq n/2, \\ T^j A \subset E \in \mathcal{M}_0^{n-j} \text{ such that } \text{diam}^s(E) < \delta_2\}.$$

Next, set $B_{2n} = \{A \in \mathcal{M}_{-2n}^0 \mid \text{either } A \in B_{-2n}^0 \text{ or } T^{-2n} A \in B_0^{2n}\}$. Define $G_{2n} = \mathcal{M}_{-2n}^0 \setminus B_{2n}$.

Our first lemma shows that the thermodynamic sum over elements of B_{2n} is small relative to the one over elements of \mathcal{M}_{-2n}^0 , for large n . Let $n_1 \geq 2m_1$ be chosen so that for all $A \in \mathcal{M}_{-n}^0$, $\text{diam}^s(A) \leq C\Lambda^{-n} \leq \delta_2$ for all $n \geq n_1$.

Lemma 6.16. *There exists $C > 0$ such that for all $n \geq n_1$,*

$$\sum_{A \in B_{2n}} |e^{S_{2n}^{-1}g}|_{C^0(A)} \leq C e^{\frac{3}{2}nP_*(T,g)} e^{\frac{1}{2}n \sup g} (Km_1 + 1)^{\frac{n}{m_1} + 1} \leq C e^{\frac{7}{4}nP_*(T,g) + \frac{1}{4}n \sup g}.$$

Notice that since $P_*(T, g) - \sup g > 0$, we have that $\frac{7}{4}P_*(T, g) + \frac{1}{4} \sup g < 2P_*(T, g)$.

Proof. Let $n \geq n_1$ and $A \in B_{-2n}^0 \subset \mathcal{M}_{-2n}^0$. For all $0 \leq j \leq \lfloor n/2 \rfloor$, call $A_j \in \mathcal{M}_{-\lfloor 3n/2 \rfloor - j}^0$ the unique element containing $T^{-\lfloor n/2 \rfloor + j} A$. By definition of B_{-2n}^0 , we have that $\text{diam}^u(A_j) \leq \delta_2$, meanwhile $\text{diam}^s(A_j) \leq \delta_2$ by choice of n_1 .

By choice of δ_2 , we have that A_0 is the union of at most $Km_1 + 1$ elements of $\mathcal{M}_{-\lfloor 3n/2 \rfloor}^{m_1}$. Thus the number of connected components of $T^{m_1} A_0$ is at most $Km_1 + 1$. Notice that this fact not only applies to A_0 , but also to $A_{m_1}, \dots, A_{lm_1}, A_{\lfloor n/2 \rfloor}$, where $\lfloor n/2 \rfloor = lm_1 + i$, $0 \leq i < m_1$. Thus, we get

$$\#\{A' \in B_{2n}^0 \mid T^{\lfloor n/2 \rfloor} A' \subset A_0\} \leq (Km_1 + 1)^{l+1} \leq (Km_1 + 1)^{\frac{n}{m_1} + 1}.$$

We are now able to estimate the thermodynamic sum over B_{-2n}^0 :

$$\begin{aligned} \sum_{A \in B_{-2n}^0} |e^{S_{2n}^{-1}g}|_{C^0(A)} &= \sum_{A_0 \in \mathcal{M}_{-\lfloor 3n/2 \rfloor}^0} \sum_{\substack{A' \in B_{-2n}^0 \\ T^{-\lfloor n/2 \rfloor} A' \subset A_0}} |e^{S_{2n}^{-1}g}|_{C^0(A')} = \sum_{A_0} \sum_{A'} \left| e^{S_{\lfloor 3n/2 \rfloor}^{-1}g \circ T^{\lfloor n/2 \rfloor} + S_{\lfloor n/2 \rfloor}^{-1}g} \right|_{C^0(A')} \\ &\leq \sum_{A_0} \left| e^{S_{\lfloor 3n/2 \rfloor}^{-1}g} \right|_{C^0(A_0)} \sum_{A'} \left| e^{S_{\lfloor n/2 \rfloor}^{-1}g} \right|_{C^0(A')} \\ &\leq e^{\frac{1}{2}n \sup g} (Km_1 + 1)^{\frac{n}{m_1} + 1} \sum_{A_0} \left| e^{S_{\lfloor 3n/2 \rfloor}^{-1}g} \right|_{C^0(A_0)} \\ &\leq C e^{\frac{7}{4}nP_*(T,g) + \frac{1}{4}n \sup g}. \end{aligned}$$

Now, notice that B_0^{2n} is the time reversal of B_{-2n}^0 , thus

$$\sum_{A \in B_0^{2n}} |e^{S_{2n}g}|_{C^0(A)} \leq C e^{\frac{7}{4}nP_*(T^{-1},g) + \frac{1}{2}n \sup g} = C e^{\frac{7}{4}nP_*(T,g) + \frac{1}{4}n \sup g}.$$

Hence

$$\sum_{A \in B_0^{2n}} |e^{S_{2n}^{-1}g}|_{C^0(T^{-2n}A)} = \sum_{A \in B_0^{2n}} |e^{S_{2n}g}|_{C^0(A)} \leq C e^{\frac{7}{4}nP_*(T,g) + \frac{1}{4}n \sup g}.$$

Finally, we get

$$\sum_{A \in B_{2n}} |e^{S_{2n}^{-1}g}|_{C^0(A)} \leq 2C e^{\frac{7}{4}nP_*(T,g) + \frac{1}{4}n \sup g}.$$

□

Next, the following lemma establishes the importance of long pieces in providing good lower bounds on the measure of weighted elements of the partition.

Lemma 6.17. *There exists $C_{\delta_2} > 0$ such that for all $j \geq 1$ and all $A \in \mathcal{M}_{-j}^0$ such that $\text{diam}^u(A) \geq \delta_2$ and $\text{diam}^s(T^{-j}A) \geq \delta_2$, we have*

$$\mu_g(e^{-S_j^{-1}g} \mathbb{1}_A) \geq C_{\delta_2} e^{-jP_*(T,g)}.$$

Proof. Let R_1, \dots, R_k be Cantor rectangles such that $\mu_g(R_i) > 0$ for all $1 \leq i \leq k$, and such that any unstable or stable curve of length more than δ_2 crosses at least one of them. Note $\mathcal{R}_{\delta_2} = \{R_1, \dots, R_k\}$ this family.

Let $j > 0$ and $A \in \mathcal{M}_{-j}^0$ such that $\text{diam}^u(A) \geq \delta_2$ and $\text{diam}^s(T^{-j}A) \geq \delta_2$. By choice of \mathcal{R}_{δ_2} , A crosses some rectangle R_i and $T^{-j}A$ also crosses some rectangle $R_{i'}$. Note Ξ_i the index set for the family of stable manifolds W_ξ of R_i . For $\xi \in \Xi_i$, let $W_{\xi,A} := W_\xi \cap A$. Since $T^{-j}A$ properly crosses $R_{i'}$ in the stable direction, and that T^{-j} is smooth on A , it follows that $T^{-j}W_{\xi,A}$ is a single curve containing a stable manifold of $R_{i'}$.

Let l_{δ_2} denote the length of the smallest stable manifold among the one in the family of Cantor rectangles \mathcal{R}_{δ_2} . Thus, for all $\xi \in \Xi_i$

$$\int_{W_{\xi,A}} e^{-S_j^{-1}g} \nu = e^{-jP_*(T,g)} \int_{T^{-j}W_{\xi,A}} \nu \geq e^{-jP_*(T,g)} \bar{C} l_{\delta_2}^{\bar{C}_2(P_*(T,g) - \sup g)}.$$

Finally, let $D(R_i)$ be the smallest solid rectangle containing R_i . Since μ_g^W and ν are equivalent on μ_g -a.e. $W \in \widehat{\mathcal{W}}^s$, we get

$$\begin{aligned} \mu_g(e^{-S_j^{-1}g} \mathbb{1}_A) &\geq \mu_g(e^{-S_j^{-1}g} \mathbb{1}_{A \cap D(R_i)}) \geq \int_{\Xi_i} \mu_g^{W_\xi}(e^{-S_j^{-1}g} \mathbb{1}_A) d\hat{\mu}_g(\xi) \\ &\geq C \int_{\Xi_i} \nu(e^{-S_j^{-1}g} \mathbb{1}_{A \cap W_\xi}) d\hat{\mu}_g(\xi) \geq C'_{\delta_2} \hat{\mu}_g(\Xi_i) e^{-jP_*(T,g)}. \end{aligned}$$

Since the family \mathcal{R}_{δ_2} is finite, this proves the lemma. □

Proposition 6.18. *If g is a (\mathcal{P}, α_g) -Hölder potential with $P_*(T, g) - \sup g > s_0 \log 2$, having SSP.1 and SSP.2, then the measure μ_g is the unique equilibrium state for T under the potential g .*

Proof. Usually, given a known equilibrium state (thus ergodic) μ_g , in order to prove uniqueness it suffices to check that for all T -invariant measure μ singular with respect to μ_g , we have $h_\mu(T) + \mu(g) < h_{\mu_g}(T) + \mu_g(g)$ – see for example [23, Section 20.3]. This is the strategy we adopt.

Let μ be a T -invariant Borel probability measure, singular with respect to μ_g , that is there exists a Borel set $F \subset M$ with $T^{-1}F = F$ and $\mu_g(F) = 0$ but $\mu(F) = 1$.

For each $n \in \mathbb{N}$, we consider the partition \mathcal{Q}_n of maximal connected components of M on which T^{-n} is continuous. By [3, Lemma 3.2 and 3.3], \mathcal{Q}_n is \mathcal{M}_{-n}^0 plus isolated points whose

cardinality grows at most linearly with n . Thus $G_{2n} \subset \mathcal{Q}_{2n}$ for each n . Define $\tilde{B}_{2n} = \mathcal{Q}_{2n} \setminus G_{2n}$. The set \tilde{B}_{2n} contains B_{2n} plus isolated points, and so its associated thermodynamic sum is bounded by the expression in Lemma 6.16 plus $\#\{\text{isolated points}\}e^{2n \sup g}$. Since $P_*(T, g) - \sup g > 0$, we have that $\frac{7}{4}P_*(T, g) + \frac{1}{4}\sup g > 2\sup g$, and thus the contribution of isolated points is small compared with the one of B_{2n} .

By uniform hyperbolicity of T , the diameters of the elements of $T^{\lfloor n/2 \rfloor} \mathcal{Q}_n$ tend to zero as n goes to infinity. This implies the following fact.

Sublemma 6.19. *For each $n \geq n_1$, there exists a finite union \mathcal{C}_n of elements of \mathcal{Q}_n such that*

$$\lim_{n \rightarrow +\infty} (\mu + \mu_g)(F \triangle T^{\lfloor n/2 \rfloor} \mathcal{C}_n) = 0.$$

Proof. The proof is essentially the same as [3, Sublemma 7.24] where the role of μ_* is played by μ_g . Since notations are introduced in this proof, we write it down for completeness and latter use.

Let $\bar{\mu} = \mu + \mu_g$ and $\tilde{\mathcal{Q}}_n = T^{-\lfloor n/2 \rfloor} \mathcal{Q}_n$. For $\delta > 0$, by regularity of Radon measures, pick compact sets $K_1 \subset F$ and $K_2 \subset M \setminus F$ such that $\max\{\bar{\mu}(F \setminus K_1), \bar{\mu}((M \setminus F) \setminus K_2)\} < \delta$. Since K_1 and K_2 are disjoint and compact, we have $\eta = \eta_\delta := d(K_1, K_2) > 0$. If $\text{diam}(\tilde{Q}) < \eta/2$, then either $\tilde{Q} \cap K_1 = \emptyset$ or $\tilde{Q} \cap K_2 = \emptyset$. Let n_δ be large enough so that the diameter of \tilde{Q}_k is smaller than $\eta_\delta/2$ for all $k \geq n_\delta$. Fix $n = 2n_\delta$ and set $\tilde{\mathcal{C}}_n$ to be the union of $\tilde{Q} \in \tilde{\mathcal{Q}}_n$ such that $\tilde{Q} \cap K_1 \neq \emptyset$. By construction, $K_1 \subset \tilde{\mathcal{C}}_n$ and $\tilde{\mathcal{C}}_n \cap K_2 = \emptyset$. Hence $\bar{\mu}(F \triangle \tilde{\mathcal{C}}_n) \leq \delta + \bar{\mu}(K_1 \triangle \tilde{\mathcal{C}}_n) \leq \delta + \bar{\mu}(M \setminus (K_1 \cup K_2)) \leq 3\delta$. Defining $\mathcal{C}_n = T^{\lfloor n/2 \rfloor} \tilde{\mathcal{C}}_n$ completes the proof. \square

Remark that since $T^{-1}F = F$, it follows that $(\mu + \mu_g)(\mathcal{C}_n \triangle F)$ also tends to zero as $n \rightarrow +\infty$. Since \mathcal{Q}_{2n} is generating for T^{2n} , we have

$$h_\mu(T^{2n}) = h_\mu(T^{2n}, \mathcal{Q}_{2n}) \leq H_\mu(\mathcal{Q}_{2n}) = - \sum_{Q \in \mathcal{Q}_{2n}} \mu(Q) \log \mu(Q).$$

Thus,

$$\begin{aligned} 2nP_\mu(T, g) &= 2nh_\mu(T) + 2n\mu(g) = h_\mu(T^{2n}) + \mu(S_{2n}^{-1}g) \leq H_\mu(\mathcal{Q}_{2n}) + \mu(S_{2n}^{-1}g) \\ &\leq \sum_{Q \in \mathcal{Q}_{2n}} \mu(Q) (-\log \mu(Q) + S_{2n}^{-1}g(x_Q) + C_g), \end{aligned}$$

where $x_Q \in Q$ and C_g is the constant from Lemma 2.3.

Now, we want to distinguish elements of \mathcal{Q}_{2n} . From the proof of Sublemma 6.19, for each n , there exists a compact set $K_1(n)$ that defines $\tilde{\mathcal{C}}_n = T^{-\lfloor n/2 \rfloor} \mathcal{C}_n$, and satisfying $(\mu + \mu_g)(\cup_n K_1(n)) = (\mu + \mu_g)(F)$. We group elements $Q \in \mathcal{Q}_{2n} \subset \mathcal{Q}_n$ according to whether $T^{-n}Q \subset \tilde{\mathcal{C}}_n$ or $T^{-n}Q \cap \tilde{\mathcal{C}}_n = \emptyset$. This dichotomy is well defined because if Q is not an isolated point, and if $T^{-n}Q \cap \tilde{\mathcal{C}}_n \neq \emptyset$, then $T^{-n}Q \in \mathcal{M}_{-n}^n$ is contained in an element of $\mathcal{M}_{-\lfloor n/2 \rfloor}^{\lfloor n/2 \rfloor}$ that intersect $K_1(n)$. Thus $Q \subset T^n \tilde{\mathcal{C}}_n = T^{\lceil n/2 \rceil} \mathcal{C}_n$ – the case where Q is an isolated point is obvious. Therefore,

$$2nP_\mu(T, g)$$

$$\leq C_g + \sum_{Q \subset T^n \tilde{\mathcal{C}}_n} \mu(Q) (-\log \mu(Q) + S_{2n}^{-1}g(x_Q)) + \sum_{Q \in \mathcal{Q}_{2n} \setminus T^n \tilde{\mathcal{C}}_n} \mu(Q) (-\log \mu(Q) + S_{2n}^{-1}g(x_Q))$$

$$\leq C_g + \frac{2}{e} + \mu(T^n \tilde{\mathcal{C}}_n) \log \left(\sum_{Q \subset T^n \tilde{\mathcal{C}}_n} e^{S_{2n}^{-1} g(x_Q)} \right) + \mu(M \setminus T^n \tilde{\mathcal{C}}_n) \log \left(\sum_{Q \in \mathcal{Q}_{2n} \setminus T^n \tilde{\mathcal{C}}_n} e^{S_{2n}^{-1} g(x_Q)} \right)$$

where we used in the last line that the convexity of $x \log x$ implies that for all $p_j > 0$ with $\sum_{j=1}^N p_j \leq 1$, and all $a_j \in \mathbb{R}$, we have (see [23, (20.3.5)])

$$\sum_{j=1}^N p_j (-\log p_j + a_j) \leq \frac{1}{e} + \sum_{j=1}^N p_j \log \sum_{i=1}^N e^{a_i}.$$

Then, since $-2nP_{\mu_g} = (\mu(T^n \tilde{\mathcal{C}}_{2n}) + \mu(M \setminus T^n \tilde{\mathcal{C}}_{2n}))e^{-2nP_*(T,g)}$, we write for $n \geq n_1$

(6.20)

$$\begin{aligned} & 2n(P_\mu(T, g) - P_{\mu_g}(T, g)) - \frac{2}{e} - C_g \\ & \leq \mu(T^{-n} \tilde{\mathcal{C}}_n) \log \left(\sum_{Q \subset T^n \tilde{\mathcal{C}}_n} e^{S_{2n}^{-1} g(x_Q) - 2nP_*(T,g)} \right) + \mu(M \setminus T^{-n} \tilde{\mathcal{C}}_n) \log \left(\sum_{Q \in \mathcal{Q}_{2n} \setminus T^n \tilde{\mathcal{C}}_n} e^{S_{2n}^{-1} g(x_Q) - 2nP_*(T,g)} \right) \\ & \leq \mu(\mathcal{C}_n) \log \left(\sum_{\substack{Q \subset T^n \tilde{\mathcal{C}}_n \\ Q \in G_{2n}}} e^{S_{2n}^{-1} g(x_Q) - 2nP_*(T,g)} + \sum_{\substack{Q \subset T^n \tilde{\mathcal{C}}_n \\ Q \in \tilde{B}_{2n}}} e^{S_{2n}^{-1} g(x_Q) - 2nP_*(T,g)} \right) \\ & \quad + \mu(M \setminus \mathcal{C}_{2n}) \log \left(\sum_{Q \in G_{2n} \setminus T^n \tilde{\mathcal{C}}_n} e^{S_{2n}^{-1} g(x_Q) - 2nP_*(T,g)} + \sum_{Q \in \tilde{B}_{2n} \setminus T^n \tilde{\mathcal{C}}_n} e^{S_{2n}^{-1} g(x_Q) - 2nP_*(T,g)} \right) \end{aligned}$$

where we used that $\mathcal{Q}_{2n} = G_{2n} \sqcup \tilde{B}_{2n}$. By Lemma 6.16 (and the remark concerning the contribution of isolated points), both sums over elements of \tilde{B}_{2n} are bounded by $Ce^{-\frac{1}{4}n(P_*(T,g) - \sup g)}$.

It remains to estimate both sums over elements of G_{2n} . To do so, we want use Lemma 6.17, that is for each $Q \in G_{2n}$, we want to assign a set \bar{E} satisfying the assumptions of the lemma. Let $Q \in G_{2n}$. Thus $Q \notin B_{-2n}^0$, and so there exists $0 \leq j \leq \lfloor n/2 \rfloor$ such that $T^{-j}Q \subset E_j \in \mathcal{M}_{2n+j}^0$ with $\text{diam}^u(E_j) \geq \delta_2$. Also, since $T^{-2n}Q \notin B_0^{2n}$, there exists $0 \leq k \leq \lfloor n/2 \rfloor$ such that $T^{-2n+k}Q \subset \tilde{E}_k \in \mathcal{M}_0^{2n-k}$ with $\text{diam}^s(\tilde{E}_k) \geq \delta_2$. Thus, both $\tilde{E}_k \in \mathcal{M}_0^{2n-k}$ and $T^{-2n+j+k}E_j \in \mathcal{M}_{-k}^{2n-j-k}$ contain $T^{-2n+k}Q$. In particular, there exists $\tilde{E} \in \mathcal{M}_0^{2n-j-k}$ containing both \tilde{E}_k and $T^{-2n+j+k}E_j$. Let $\bar{E} = T^{2n-j-k}\tilde{E} \in \mathcal{M}_{-2n+j+k}^0$. Notice that by construction $E_j \subset \bar{E}$ and $\tilde{E}_k \subset T^{-2n+j+k}\bar{E}$, therefore \bar{E} satisfies $\text{diam}^u(\bar{E}) \geq \delta_2$ and $\text{diam}^s(T^{-2n+j+k}\bar{E}) \geq \delta_2$, the assumption from Lemma 6.17. Thus,

$$\mu_g(e^{-S_{2n-j-k}^{-1}g} \mathbb{1}_{\bar{E}}) \geq C_{\delta_2} e^{-(2n-j-k)P_*(T,g)}.$$

We call (\bar{E}, j, k) an *admissible triple* for $Q \in G_{2n}$ if $0 \leq j, k \leq \lfloor n/2 \rfloor$ and $\bar{E} \in \mathcal{M}_{-2n+j+k}^0$, with $T^{-j}Q \in \bar{E}$ and $\min\{\text{diam}^u(\bar{E}), \text{diam}^s(T^{-2n+j+k}\bar{E})\} \geq \delta_2$. By the above construction, such admissible triples always exist, but there may be many associated to a given $Q \in G_{2n}$.

However, we can define the unique *maximal triple* for Q by taking first the maximum j , and then the maximum k over all admissible triples for Q .

Let \mathcal{E}_{2n} be the set of maximal triples obtained in this way from elements of G_{2n} . For $(\bar{E}, j, k) \in \mathcal{E}_{2n}$, let $\mathcal{A}_M(\bar{E}, j, k)$ denote the set of $Q \in G_{2n}$ for which the maximal triple is (\bar{E}, j, k) . The importance of the set \mathcal{E}_{2n} lies in [3, Sublemma 7.25], which we state, and prove, as follows for completeness.

Sublemma 6.20. *Suppose that $(\bar{E}_1, j_1, k_2), (\bar{E}_2, j_2, k_2) \in \mathcal{E}_{2n}$ with $j_2 \geq j_1$ and $(\bar{E}_1, j_1, k_2) \neq (\bar{E}_2, j_2, k_2)$. Then $T^{-(j_2-j_1)}\bar{E}_1 \cap \bar{E}_2 = \emptyset$.*

Proof. By contradiction, let $(\bar{E}_1, j_1, k_2), (\bar{E}_2, j_2, k_2) \in \mathcal{E}_{2n}$ with $j_2 \geq j_1$, $(\bar{E}_1, j_1, k_2) \neq (\bar{E}_2, j_2, k_2)$ and $T^{-(j_2-j_1)}\bar{E}_1 \cap \bar{E}_2 \neq \emptyset$. Notice that $T^{-(j_2-j_1)}\bar{E}_1 \in \mathcal{M}_{-2n+j_2+k_1}^{j_2-j_1}$ while $\bar{E}_2 \in \mathcal{M}_{-2n+j_2+k_2}^0$.

Consider first the case $k_1 \leq k_2$. Therefore $T^{-(j_2-j_1)}\bar{E}_1 \subset \bar{E}_2$. In particular, any element $Q \in \mathcal{A}_M(\bar{E}_1, j_1, k_1)$ satisfies $T^{-j_2}Q \subset \bar{E}_2$, and so $Q \in \mathcal{A}_M(\bar{E}_2, j_2, k_2)$, a contradiction.

Consider now the case $k_1 > k_2$. Therefore $T^{-(j_2-j_1)}\bar{E}_1$ and \bar{E}_2 are both contained in an element $\bar{E}' \in \mathcal{M}_{-2n+j_2+k_1}^0$. Since $\bar{E}_2 \subset \bar{E}'$, we have that $\text{diam}^u(\bar{E}') \geq \delta_2$. Also, since $T^{-2n+j_1+k_1}\bar{E}_1 \subset T^{-2n+j_2+k_1}\bar{E}'$, we have that $\text{diam}^s(T^{-2n+j_2+k_1}\bar{E}') \geq \delta_2$. Note that if $Q \in \mathcal{A}_M(\bar{E}_1, j_1, k_1) \cup \mathcal{A}_M(\bar{E}_2, j_2, k_2)$, then (\bar{E}', j_2, k_1) is an admissible triple for Q . Thus, if $j_1 = j_2$, then $\bar{E}' = \bar{E}_1$. For $Q \in \mathcal{A}_M(\bar{E}_2, j_2, k_2)$, then $Q \subset \bar{E}_1$ and so (\bar{E}_1, j_1, k_1) is an admissible triple for Q , which contradicts the maximality of (\bar{E}_2, j_2, k_2) since $k_1 > k_2$. Similarly, if $j_2 > j_1$, then for $Q \in \mathcal{A}_M(\bar{E}_1, j_1, k_1)$, the triple (\bar{E}', j_2, k_1) is admissible for Q , which contradicts the maximality of (\bar{E}_1, j_1, k_1) . \square

We now prove that if $T^n\tilde{\mathcal{C}}_n \cap \mathcal{A}_M(\bar{E}, j, k) \neq \emptyset$, then $\mathcal{A}_M(\bar{E}, j, k) \subset T^n\tilde{\mathcal{C}}_n$ and $\bar{E} \subset T^{n-j}\tilde{\mathcal{C}}_n$. Let $Q \in \mathcal{A}_M(\bar{E}, j, k)$ be such that $Q \cap T^n\tilde{\mathcal{C}}_n \neq \emptyset$. Then, by definition of (\bar{E}, j, k) , $T^{-n}Q \subset T^{-n+j}\bar{E} \in \mathcal{M}_{-n+k}^{n-j}$. Since $0 \leq j, k \leq \lfloor n/2 \rfloor$, there exists $E' \in \mathcal{M}_{-\lfloor n/2 \rfloor}^{\lfloor n/2 \rfloor}$ such that $T^{-n+j}\bar{E} \subset E'$. In particular, we have $E' \in \tilde{\mathcal{Q}}_n$ and $E' \cap \tilde{\mathcal{C}}_n \neq \emptyset$. Thus, by construction of $\tilde{\mathcal{C}}_n$, we have $\tilde{\mathcal{C}}_n \supset E' \supset T^{-n+j}\bar{E} \supset T^{-n}Q$. In particular, we get $Q \subset T^n\tilde{\mathcal{C}}_n$, and thus $\mathcal{A}_M(\bar{E}, j, k) \subset T^n\tilde{\mathcal{C}}_n$. We also get $\bar{E} \subset T^{n-j}\tilde{\mathcal{C}}_n$.

On the other hand, we prove that if $T^n\tilde{\mathcal{C}}_n \cap \mathcal{A}_M(\bar{E}, j, k) = \emptyset$, then $\mathcal{A}_M(\bar{E}, j, k) \subset M \setminus T^n\tilde{\mathcal{C}}_n$ and $T^{-n+j}\bar{E} \subset M \setminus \tilde{\mathcal{C}}_n$. Let $Q \in \mathcal{A}_M(\bar{E}, j, k)$. Then, by assumption, $T^{-n}Q \cap \tilde{\mathcal{C}}_n = \emptyset$. As above, there exists $E' \in \mathcal{M}_{-\lfloor n/2 \rfloor}^{\lfloor n/2 \rfloor}$ containing both $T^{-n}Q$ and $T^{-n+j}\bar{E}$. In particular, $E' \in \tilde{\mathcal{Q}}_n$ and $E' \cap \tilde{\mathcal{C}}_n = \emptyset$. By construction of $\tilde{\mathcal{C}}_n$, we get that $E' \in M \setminus \tilde{\mathcal{C}}_n$. Thus $Q \in M \setminus T^n\tilde{\mathcal{C}}_n$, and so $\mathcal{A}_M(\bar{E}, j, k) \subset M \setminus T^n\tilde{\mathcal{C}}_n$. Also, $T^{-n+j}\bar{E} \subset M \setminus \tilde{\mathcal{C}}_n$.

The only last step we have to do before estimating the sums over G_{2n} is to prove that for each $(\bar{E}, j, k) \in \mathcal{E}_{2n}$, we have

$$(6.21) \quad \sum_{Q \in \mathcal{A}_M(\bar{E}, j, k)} |e^{S_{2n}^{-1}g}|_{C^0(Q)} \leq C e^{(j+k)P_*(T, g)} |e^{S_{2n-j-k}^{-1}g}|_{C^0(\bar{E})}$$

where $C > 0$ is a constant depending only on the potential g . To do so, notice that if $Q \in \mathcal{A}_M(\bar{E}, j, k)$, then by construction, $T^{-j}Q \subset \bar{E}$. Thus $T^{-n}Q \in \mathcal{M}_{-n}^n$ is a subset of $T^{-(n-j)}\bar{E} \in \mathcal{M}_{-n+k}^{n-j}$. Decomposing $T^{-n}Q = Q_- \cap Q_+$ with $Q_- \in \mathcal{M}_{-n}^0$ and $Q_+ \in \mathcal{M}_0^n$, and $T^{-(n-j)}\bar{E} = E_- \cap E_+$ with $E_- \in \mathcal{M}_{-n+k}^0$ and $E_+ \in \mathcal{M}_0^{n-j}$, we see that $Q_- \subset E_-$ and $Q_+ \subset E_+$. Thus

$$\begin{aligned}
\sum_{Q \in \mathcal{A}_M(\bar{E}, j, k)} |e^{S_{2n}^{-1}g}|_{C^0(Q)} &= \sum_{Q \in \mathcal{A}_M(\bar{E}, j, k)} |e^{S_{2n}^{-1}g \circ T^n}|_{C^0(T^{-n}Q)} \leq \sum_{\substack{Q_- \in \mathcal{M}_{-n}^0 \\ Q_- \subset E_-}} \sum_{\substack{Q_+ \in \mathcal{M}_0^n \\ Q_+ \subset E_+}} |e^{S_n^{-1}g + S_n g \circ T}|_{C^0(Q_- \cap Q_+)} \\
&\leq \sum_{\substack{Q_- \in \mathcal{M}_{-n}^0 \\ Q_- \subset E_-}} |e^{S_n^{-1}g}|_{C^0(Q_-)} \sum_{\substack{Q_+ \in \mathcal{M}_0^n \\ Q_+ \subset E_+}} |e^{S_n g \circ T}|_{C^0(Q_+)} \\
&\leq \sum_{\substack{Q_- \in \mathcal{M}_{-n}^0 \\ Q_- \subset E_-}} |e^{S_n^{-1}g \circ T^{n-k}}|_{C^0(T^{-n+k}Q_-)} \sum_{\substack{Q_+ \in \mathcal{M}_0^n \\ Q_+ \subset E_+}} |e^{S_n g \circ T \circ T^{-(n-j)}}|_{C^0(T^{n-j}Q_+)}
\end{aligned}$$

Now, notice that $T^{-n+k}Q_- \in \mathcal{M}_{-k}^{n-k}$ is a subset of $T^{-n+k}E_- \in \mathcal{M}_0^{n-k}$. Thus $T^{-n+k}Q_-$ must be of the form $\tilde{Q}_- \cap T^{-n+k}E_-$ for some $\tilde{Q}_- \in \mathcal{M}_{-k}^0$. Similarly, $T^{n-j}Q_+$ must be of the form $\tilde{Q}_+ \cap T^{n-j}E_+$ for some $\tilde{Q}_+ \in \mathcal{M}_0^j$. Thus

$$\begin{aligned}
\sum_{Q \in \mathcal{A}_M(\bar{E}, j, k)} |e^{S_{2n}^{-1}g}|_{C^0(Q)} &\leq \sum_{\tilde{Q}_- \in \mathcal{M}_{-k}^0} |e^{S_n^{-1}g \circ T^{n-k}}|_{C^0(\tilde{Q}_- \cap T^{-n+k}E_-)} \sum_{\tilde{Q}_+ \in \mathcal{M}_0^j} |e^{S_n g \circ T \circ T^{-(n-j)}}|_{C^0(\tilde{Q}_+ \cap T^{n-j}E_+)} \\
&\leq \sum_{\tilde{Q}_- \in \mathcal{M}_{-k}^0} |e^{S_k^{-1}g}|_{C^0(\tilde{Q}_-)} |e^{S_{2n-j-k}g - S_{n-j}^{-1}g}|_{C^0(T^{n-j}E_-)} \sum_{\tilde{Q}_+ \in \mathcal{M}_0^j} |e^{S_j g \circ T}|_{C^0(\tilde{Q}_+)} |e^{S_{n-j}^{-1}g}|_{C^0(T^{n-j}E_+)}.
\end{aligned}$$

Now, using Lemma 2.3, the supermultiplicativity from Lemma 3.7 and the exact exponential growth from Proposition 3.8, we get the upper bound (6.21) with $C = 2C_g e^{\sup g - \inf g}$.

We can now estimate the sums over elements of G_{2n} .

$$\begin{aligned}
\sum_{\substack{Q \in G_{2n} \\ Q \subset T^n \tilde{\mathcal{C}}_n}} e^{S_{2n}^{-1}g(x_Q) - 2nP_*(T, g)} &\leq \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset T^{n-j} \tilde{\mathcal{C}}_n}} \sum_{Q \in \mathcal{A}_M(\bar{E}, j, k)} e^{S_{2n}^{-1}g(x_Q) - 2nP_*(T, g)} \\
&\leq \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset T^{n-j} \tilde{\mathcal{C}}_n}} C e^{-(2n-j-k)P_*(T, g)} |e^{S_{2n-j-k}^{-1}g}|_{C^0(\bar{E})} \\
&\leq \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset T^{n-j} \tilde{\mathcal{C}}_n}} C C_{\delta_2}^{-1} \mu_g(e^{-S_{2n-j-k}^{-1}g} \mathbb{1}_{\bar{E}}) |e^{S_{2n-j-k}^{-1}g}|_{C^0(\bar{E})} \\
&\leq C C_{\delta_2}^{-1} C_g \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset T^{n-j} \tilde{\mathcal{C}}_n}} \mu_g(\bar{E}) \leq C C_{\delta_2}^{-1} C_g \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset T^{n-j} \tilde{\mathcal{C}}_n}} \mu_g(T^{-n+j} \bar{E}) \\
&\leq C' \mu_g(\tilde{\mathcal{C}}_n)
\end{aligned}$$

where $C' = C C_{\delta_2}^{-1} C_g$.

Similarly,

$$\sum_{Q \in G_{2n} \setminus T^n \tilde{\mathcal{C}}_n} e^{S_{2n}^{-1}g(x_Q) - 2nP_*(T, g)} \leq \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset M \setminus T^{n-j} \tilde{\mathcal{C}}_n}} \sum_{Q \in \mathcal{A}_M(\bar{E}, j, k)} e^{S_{2n}^{-1}g(x_Q) - 2nP_*(T, g)}$$

$$\begin{aligned}
&\leq \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset M \setminus T^{n-j} \tilde{\mathcal{C}}_n}} C e^{-(2n-j-k)P_*(T, g)} |e^{S_{2n-j-k}^{-1}g}|_{C^0(\bar{E})} \\
&\leq \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset M \setminus T^{n-j} \tilde{\mathcal{C}}_n}} C C_{\delta_2}^{-1} \mu_g(e^{-S_{2n-j-k}^{-1}g} \mathbb{1}_{\bar{E}}) |e^{S_{2n-j-k}^{-1}g}|_{C^0(\bar{E})} \\
&\leq C C_{\delta_2}^{-1} C_g \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset M \setminus T^{n-j} \tilde{\mathcal{C}}_n}} \mu_g(\bar{E}) \leq C C_{\delta_2}^{-1} C_g \sum_{\substack{(\bar{E}, j, k) \in \mathcal{E}_{2n} \\ \bar{E} \subset M \setminus T^{n-j} \tilde{\mathcal{C}}_n}} \mu_g(T^{-n+j} \bar{E}) \\
&\leq C' \mu_g(M \setminus \tilde{\mathcal{C}}_n)
\end{aligned}$$

Putting these bounds together allows us to complete our estimate of (6.20),

$$\begin{aligned}
2n(P_\mu(T, g) - P_{\mu_g}(T, g)) - \frac{2}{e} - C_g &\leq \mu(\mathcal{C}_n) \log \left(C' \mu_g(\mathcal{C}_n) + C e^{-\frac{1}{4}n(P_*(T, g) - \sup g)} \right) \\
&\quad + \mu(M \setminus \mathcal{C}_n) \log \left(C' \mu_g(M \setminus \mathcal{C}_n) + C e^{-\frac{1}{4}n(P_*(T, g) - \sup g)} \right).
\end{aligned}$$

Since $\mu(\mathcal{C}_n)$ tends to 1 as $n \rightarrow +\infty$, while $\mu_g(\mathcal{C}_n)$ tends to 0 as $n \rightarrow +\infty$, the limit of the right-hand side tends to $-\infty$. This yields a contradiction unless $P_\mu(T, g) < P_{\mu_g}(T, g)$. \square

7. THE BILLIARD FLOW

Throughout this section, we see the billiard flow ϕ_t as the vertical flow in the space

$$\tilde{\Omega} = \{(x, t) \in M \times \mathbb{R} \mid 0 \leq t \leq \tau(x)\} / \sim,$$

where the equivalence relation is defined by $(x, \tau(x)) \sim (T(x), 0)$. In other words, we see ϕ_t as the suspension flow over T under the return time τ . Furthermore, transporting the Euclidean metric on $\mathcal{Q} \times \mathbb{S}^1$ onto $\tilde{\Omega}$, the flow ϕ_t is uniformly hyperbolic.

Proposition 7.1. *Let g be a (\mathcal{P}, α_g) -Hölder potential such that $P_*(T, g) - \sup g > s_0 \log 2$, with SSP.1 and SSP.2. Let $\bar{\mu}_g = (\mu_g(\tau))^{-1} \mu_g \otimes \lambda$, where λ is the Lebesgue measure. Then $(\phi_t, \bar{\mu}_g)$ is a K-system.*

Proof. The ergodicity of $(\phi_t, \bar{\mu}_g)$ follows directly from the ergodicity of (T, μ_g) proved in Proposition 6.12.

To prove the K-mixing, we follow closely the method used in Sections 6.9, 6.10 and 6.11 from [13]. In fact, replacing μ and μ_Ω with μ_g and $\bar{\mu}_g$ throughout these sections, we only have to check that [13, Exercise 6.35] is still true in order to apply verbatim the arguments. This is what we prove here.

To do so, we first need to recall some of the construction done in [13, Section 6.9]. If x_1 and x_3 are two nearby points in M such that

$$(7.1) \quad \{x_2\} := W^u(x_1) \cap W^s(x_3) \neq \emptyset, \quad \{x_4\} := W^s(x_1) \cap W^u(x_3) \neq \emptyset,$$

we then construct the 4-loop $Y_1, Y_2, Y_3, Y_4, Y_5 \in \Omega$ as follow. Let $Y_1 = X_1 = (x_1, t)$ and $X_3 = (x_3, t)$. Define

$$Y_2 = W^u(Y_1) \cap W_{loc}^{ws}(X_3), \quad Y_3 = W^s(Y_2) \cap W_{loc}^{wu}(X_3),$$

$$Y_4 = W^u(Y_3) \cap W_{loc}^{ws}(X_1), \quad Y_5 = W^s(Y_4) \cap W_{loc}^{wu}(X_1),$$

where W^u and W^s are unstable and stable manifolds for the flow, and W_{loc}^{wu} and W_{loc}^{ws} are local weak unstable and local weak stable manifolds for the flow. We always assume that this construction stays under the ceiling function τ . Actually, as proven in [13, Lemma 6.40] there exists σ such that $Y_5 = \phi_\sigma(Y_1)$, with $|\sigma| = \mu_{\text{SRB}}(K)$ where K is the rectangle in M with corners x_1, x_2, x_3, x_4 . Thus the 4-loops are always open.

For $x \in M$, let $\mathcal{L}_x = \{\phi_t(x) \mid 0 < t < \tau(x)\}$. Then the partition $\{\mathcal{L}_x \mid x \in M\}$ of $\tilde{\Omega}$ is measurable and the conditional measures of $\bar{\mu}_g$ on \mathcal{L}_x are uniform. Call λ_x the Lebesgue probability measure on \mathcal{L}_x . Let $D \subset \Omega$ be such that $\bar{\mu}_g(D) = 1$ and let $E_1 = \{x \in M \mid \lambda_x(\mathcal{L}_x \setminus D) = 0\}$. Clearly, $\mu_g(E_1) = 1$.

We call a point $x_1 \in E_1$ *rich* if for any $\varepsilon > 0$ there exists another point $x_3 \in E_1$ such that $0 < d(x_1, x_3) < \varepsilon$ and (7.1) holds with x_2 and $x_4 \in E_1$. Denote $E_2 \subset E_1$ the set of rich points.

The analogous of [13, Exercise 6.35] is to prove that $\mu_g(E_2) = 1$. Let $\{R_j\}_{j \geq 1}$ be the cover of M^{reg} into Cantor rectangles (discarding the ones with zero μ_g -measure). Let R be one of those Cantor rectangle and denote μ_R the conditional measure of μ_g on R . It is enough to prove that $\mu_R(E_2) = 1$. Since $\mu_g(E_1) = 1$ we have that $\mu_R(E_1) = 1$. Furthermore, since the partition of R into stable manifolds is measurable, we can disintegrate μ_R with respect to this partition, with conditional measure μ_s^W on $W \in R \cap \mathcal{W}^s$. It follows that for μ_R -a.e. point $x \in E_1 \cap R$, if $W = W(x) \in \mathcal{W}^s$ contains x then $\mu_s^W(W \cap E_1) = 1$. Similarly, for μ_R -a.e. point $x \in E_1 \cap R$, if $W = W(x) \in \mathcal{W}^u$ contains x then $\mu_u^W(W \cap E_1) = 1$, where μ_u^W is the conditional measure on W in the disintegration of μ_R with respect to the measurable partition $R \cap \mathcal{W}^u$ of R . Then $\mu_R(E_R) = 1$, where E_R denotes the set of points x in R such that both stable and unstable conditional measure on leaves containing x give measure 1 to E_1 .

Let $E_2^R \subset E_2$ be the set of rich points x_1 such that x_3 belongs to $R \cap E_1$ (and therefore x_2 and x_4 also belong to $R \cap E_1$ by the properties of a Cantor rectangle). By contradiction, assume that $\mu_R(E_2^R) \neq 1$. Define the sets

$$C_2^R = \{x_1 \in E_1 \cap R \mid \exists \varepsilon > 0, \forall x_3 \in E_1 \cap R, \text{ if } 0 < d(x_1, x_3) < \varepsilon \text{ then } x_2 \notin E_1 \cap R\},$$

$$C_4^R = \{x_1 \in E_1 \cap R \mid \exists \varepsilon > 0, \forall x_3 \in E_1 \cap R, \text{ if } 0 < d(x_1, x_3) < \varepsilon \text{ then } x_4 \notin E_1 \cap R\}.$$

Note that we don't have to introduce in these definitions the condition (7.1) since it is automatically satisfied by the construction of Cantor rectangles. Thus, we have $(E_1 \cap R) \setminus E_2^R = C_2^R \cup C_4^R$, so that $\mu_R(C_2^R \cup C_4^R) > 0$. Assume first that $\mu_R(C_2^R) > 0$. Define the family of sets

$$C_{2,n}^R = \{x_1 \in C_2^R \mid \varepsilon \geq \frac{1}{n}\}.$$

Since $\bigcup_{n \geq 1} C_{2,n}^R = C_2^R$ is an increasing union, there is some n such that $\mu_R(C_{2,n}^R) > 0$. Let $x_1 \in C_{2,n}^R \cap E_R$ and $W \in \mathcal{W}^u$ be such that $x_1 \in W$. Let $x_3 \in E_1 \cap R \cap E_R$ be such that $0 < d(x_1, x_3) < \frac{1}{n}$. Let $W_0 \in \mathcal{W}^u$ be the unstable manifold containing x_3 . By construction of E_R , we have $\mu_u^{W_0}(W_0 \cap E_1) = 1$, and since $\mu_u^{W_0}$ have support W_0 (otherwise, μ_g would not have total support because of the absolute continuity of the holonomy), in fact we have that

$$\mu_u^{W_0}(W_0 \cap E_1 \cap B(x_1, \frac{1}{n})) > 0.$$

Thus $\mu_u^W(\Theta_W(W_0 \cap E_1 \cap B(x_1, \frac{1}{n}))) > 0$. Now, if $\tilde{x}_3 \in W_0 \cap E_1 \cap B(x_1, \frac{1}{n})$, then $\tilde{x}_2 \notin E_1$. In other words, $E_1 \cap \Theta_W(W_0 \cap E_1 \cap B(x_1, \frac{1}{n})) = \emptyset$. Since $x_1 \in E_R$, we have that $\mu_u^W(W \cap E_1) = 1$,

so that $\mu_u^W(\Theta_W(W_0 \cap E_1 \cap B(x_1, \frac{1}{n}))) = 0$, a contradiction. Thus $E_R \cap C_{2,n}^R = \emptyset$, so that $\mu_R(C_2^R) = 0$. We proceed similarly, exchanging the role of \mathcal{W}^s and \mathcal{W}^u , in order to prove that $\mu_R(C_4^R) = 0$. Finally, we get that $\mu_R(E_2^R) = 1$, the contradiction closing the proof. \square

Proposition 7.2. *Under the assumptions of Proposition 7.1, $(\phi_t, \bar{\mu}_g)$ is Bernoulli.*

Proof. The idea of the proof is to bootstrap from the K-mixing following the techniques of [15] with modifications similar to those in [3, Proposition 7.19]. The proof in [15] proceeds in two steps.

Step 1. Construction of δ -regular coverings. Given $\delta > 0$, the idea is to cover $\tilde{\Omega}$, up to a set of $\bar{\mu}_g$ -measure at most δ , by small Cantor boxes – essentially a set of the form Cantor rectangle times interval – such that $\bar{\mu}_g$ restricted to each Cantor box is arbitrarily close to a product measure. The basis of the boxes will be very similar to the covering $\{R_i\}_{i \in \mathbb{N}}$ from Lemma 6.9, however, some adjustments must be made in order to guarantee uniform properties of the Jacobian of the relevant holonomy map.

Above a Cantor rectangle R with $\mu_g(R) > 0$, we construct a Cantor box B following the construction of P -sets from [28, Section 3]. Let W_1^s and W_2^s be the stable sides of the smallest solid rectangle $D(R)$ containing R . Let W be a stable manifold for ϕ_t projecting on W_1^s through the map $P_- : (x, t) \in \Omega \mapsto x \in M$ if $t < \tau(x)$, and being such that $W \subset \tilde{\Omega}_0 := \{(x, t) \mid 0 < t < \tau(x)\}$. Consider the set $W_R \subset W$ of points $(x, t) \in W$ such that $x \in R$. Let t_0 be small enough so that $S = \bigcup_{t=0}^{t_0} \phi_t(W_R) \subset \Omega_0$. Now, B_0 is obtained by moving S along the unstable manifolds of ϕ_t to another surface of that type, spanned by W_2^s . That is, for each $(x, t) \in S$, take the unstable manifold $W(x, t)$ of ϕ_t passing by (x, t) , and projecting on the unstable manifold for T passing by $x \in R$. Let $B_0 = \bigcup_{(x,t) \in S} W(x, t)$ and let $B \subset B_0$ be the set of points $(x, t) \in B_0$ such that $x \in R$. Notice that, up to subdividing R into smaller rectangle taking a smaller t_0 , we can assume that $B \subset \tilde{\Omega}_0$. Thus, by construction, the set B has the property that for all $x, y \in B$, the local unstable manifold of x and the local weakly stable manifold of y intersect each other at a single point which lies in B . This is the crucial property of what Ornstein and Weiss, in [28], called a *rectangle*.

Since $\mu_g(R) > 0$, we have $\bar{\mu}_g(B) = t_0 \mu_g(R) > 0$, so that the conditional measure $\bar{\mu}_B$ of $\bar{\mu}_g$ restricted to B makes sense. Now, we want to equip B with a product measure, absolutely continuous with respect to $\bar{\mu}_B$. We proceed as follows. Since the partition of B into unstable manifolds is measurable, we can disintegrate $\bar{\mu}_B$ into conditional measures $\bar{\mu}^{W_\xi}$, on $W_\xi \cap B$ with $\xi \in Z_\phi$, and a factor measure $\hat{\mu}$ on the set Z_ϕ parametrizing the unstable manifolds of B . Fix a point $z \in B$, and consider B as the product of $W^u(z) \cap B$ with $W^{ws}(z) \cap B$, where $W^u(z)$ is the local unstable manifold of z and $W^{ws}(z)$ is the local weak stable manifold of z . Define $\bar{\mu}_B^p = \bar{\mu}^{W^u(z)} \otimes \hat{\mu}$, and note that we can view $\hat{\mu}$ as inducing a measure on $W^{ws}(z)$. We still have to prove that $\bar{\mu}_B^p \ll \bar{\mu}_B$.

Similarly, let μ_R be the conditional measure of μ_g restricted to R . Since the partition into unstable manifolds W_ξ , $\xi \in Z$, is measurable, we can disintegrate μ_R into the conditional measures μ^W on $W \cap R$ and a factor measure $\hat{\mu}$ on Z . We want to relate the disintegration $\bar{\mu}_B$ with the one of μ_R . Notice that we can view Z_ϕ as the set $Z \times [0, t_0]$, where Z parametrizes the set of unstable manifolds of R through the map associating $\xi_\phi \in Z_\phi$ with the pair (ξ, t) where $\xi \in Z$ is such that $P_-(W_{\xi_\phi}) = W_\xi \subset D(R)$ and t is the value in the definition of S where W_{ξ_ϕ}

and S intersect. Considering sets $A \subset B$ of the form $A = P_-(A) \times [t_-, t_+]$, we get that

$$\int_{\xi_\phi \in Z_\phi} \bar{\mu}^{W_{\xi_\phi}}(A) d\hat{\mu}(\xi_\phi) = \bar{\mu}_B(A) = \int_{t_-}^{t_+} \mu_R(P_-(A)) dt = \int_{t_-}^{t_+} \int_{\xi \in Z} \mu^{W_\xi}(P_-(A)) d\hat{\mu}(\xi) dt.$$

Thus, we can identify $\bar{\mu}^{W_{\xi_\phi}}$ with $\mu^{P_-(W_{\xi_\phi})}$, and $d\hat{\mu}$ with $d\hat{\mu}dt$. From this identification, we deduce that the projection map $P_{W,-}$ from some W to $P_-(W)$, and its inverse are absolutely continuous. The absolute continuity of the holonomy map $\bar{\Theta}_W$ between unstable manifolds W_0 and W in B thus follows directly from the absolute continuity of the holonomy map between unstable manifolds in R since $\bar{\Theta}_W = P_{W,-}^{-1} \circ \theta_{P_-(W)} \circ P_{W,-}$. This implies that $\bar{\mu}_B^p$ is absolutely continuous with respect to $\bar{\mu}_B$, and thus, also with respect to $\bar{\mu}_g$. The following definition is taken from [15].

Definition 7.3. For $\delta > 0$, a δ -regular covering of Ω is a finite collection of disjoint Cantor boxes \mathfrak{B} for which¹⁶,

- a) $\bar{\mu}_g(\bigcup_{B \in \mathfrak{B}} B) \geq 1 - \delta$.
- b) Every $B \in \mathfrak{B}$ satisfies $\left| \frac{\bar{\mu}_B^p(B)}{\bar{\mu}_g(B)} - 1 \right| < \delta$. Moreover, there exists $G \subset B$, with $\bar{\mu}_g(G) > (1 - \delta)\bar{\mu}_g(B)$, such that $\left| \frac{d\bar{\mu}_B^p}{d\bar{\mu}_g}(x) - 1 \right| < \delta$ for all $x \in G$.

By [15, Lemma 5.1], such coverings exist for any $\delta > 0$, and for Cantor boxes arbitrarily small. The proof essentially uses the covering of M^{reg} from Lemma 6.9 to build Cantor boxes, up to finite subdivision of the covering to ensure a). To get b), subdivide the boxes into smaller ones on which the Jacobian of the holonomy map between unstable manifolds is nearly 1. This argument relies on Lusin's theorem and goes through in our setting with no changes.

Step 2. Proof that $\bar{\alpha}_i$ is vwb. First, define $\bar{\alpha}_i$ to be the partition of $\tilde{\Omega}$ into sets of the form $\tilde{\Omega}_0 \cap (A \times [\frac{l}{2^i}, \frac{l+1}{2^i}))$, where $A \in \mathcal{M}_{-1}^1$ and $l \in \mathbb{N}$. Then $\bar{\alpha}_0 \leq \bar{\alpha}_1 \leq \bar{\alpha}_2 \leq \dots$ is such that $\bigvee_{i=1}^\infty \bigvee_{n=-\infty}^{+\infty} \phi_n \bar{\alpha}_i$ generates the whole σ -algebra on $\tilde{\Omega}$. Using Theorems 4.1 and 4.2 from [15], we only need to prove that each partition $\bar{\alpha}_i$ is vwb in order to prove that $(\phi_t, \bar{\mu}_g)$ is Bernoulli.

Using \mathcal{M}_{-1}^1 as the basis elements of $\bar{\alpha}_i$ allows us to apply the bounds (6.5) directly since $\partial \mathcal{M}_{-1}^1 = \mathcal{S}_1 \cup \mathcal{S}_{-1}$. We can now apply the same arguments as in [15, Section 6.2] with the modifications described in the second part of the proof of [3, Proposition 7.19]. Actually, the only place where we need to be careful is [3, Eq. (7.33)] because of our additional horizontal cuttings. We finish the proof by dealing with this equation. We first have to recall some notations from [3] first.

Fix some $i \in \mathbb{N}$, and let $\bar{\alpha} = \bar{\alpha}_i$. Let $\varepsilon > 0$ and define $\delta = e^{-(\varepsilon/C')^{2/(1-\gamma)}}$ (recalling that $\gamma > 1$), where $C' > 0$ is the constant from (7.2) below.

Let $\mathfrak{B} = \{B_1, B_2, \dots, B_k\}$ be a δ -regular cover of $\tilde{\Omega}$ such that the diameter of the B_i are less than δ . Define the partition $\pi = \{B_0, B_1, B_2, \dots, B_k\}$, where $B_0 = \Omega \setminus \bigcup_{i=1}^k B_i$. For each $i \geq 1$, let $G_i \subset B_i$ denote the set identified in Definition 7.3(b). Since $(\phi_{-1}, \bar{\mu}_g)$ is K-mixing, there exists an even number $N = 2m$, such that for any integers N_0, N_1 such that $N < N_0 < N_1$,

¹⁶The corresponding definition in [15] has a third condition, but it is satisfied in our setting since the stable and unstable manifolds are one-dimensional and have bounded curvature.

δ -almost every atom A of $\bigvee_{N_0-m}^{N_1-m} \phi_{-i}\bar{\alpha}$, satisfies

$$\left| \frac{\bar{\mu}_g(B|A)}{\bar{\mu}_g(B)} - 1 \right| < \delta, \quad \text{for all } B \in \pi,$$

where $\bar{\mu}_g(\cdot|A)$ is the measure $\bar{\mu}_g$ conditioned to A . Now let m, N_0, N_1 be given as above and define $\omega = \bigvee_{N_0-m}^{N_1-m} \phi_{-i}\bar{\alpha}$. Since the estimates on the $\bar{\mu}_g$ -measure of the bad sets \hat{F}_1 and \hat{F}_2 do not change, we skip them and define directly the set \hat{F}_3 . Define F_3 to be the set of all points $x \in \Omega \setminus B_0$ such that $W^s(x)$ intersects the boundary of the element $\omega(x)$ before it fully crosses the rectangle $\pi(x)$. Thus, if $x \in F_3$, there exists a subcurve of $W^s(x)$ connecting x to the boundary of $(\phi_{-i}\bar{\alpha})(x)$ for some $i \in [N_0 - m, N_1 - m]$. Then since $\pi(x)$ has diameter less than δ , $\phi_i(x)$ lies within a distance $C\tilde{\Lambda}^{-i}\delta$ of the boundary of $\bar{\alpha}$ – where \tilde{C}_1 and $\tilde{\Lambda} > 1$ come from the hyperbolicity of the billiard flow. Using the bound (6.5), the total measure of such points must add up to at most

$$(7.2) \quad \sum_{i=N_0-m}^{N_1-m} \left(\frac{C}{|\log(\tilde{C}_1\tilde{\Lambda}^{-i}\delta)|^\gamma} + C_{\bar{\alpha}}\tilde{C}_1\tilde{\Lambda}^{-i}\delta \right) \leq C'_1|\log \delta|^{1-\gamma} + C'_2\delta \leq C'|\log \delta|^{1-\gamma},$$

for some $C' > 0$. Letting \hat{F}_3 denote the union of atoms $A \in \omega$ such that $\bar{\mu}_g(F_3|A) > |\log \delta|^{\frac{1-\gamma}{2}}$, it follows that $\bar{\mu}_g(F_3) \leq C'|\log \delta|^{\frac{1-\gamma}{2}}$. This is at most ε by choice of δ .

The same precaution allows us to get the same bound on $\bar{\mu}_g(\hat{F}_4)$ as in [3].

Finally, the bad set to be avoided in the construction of the joining is $B_0 \cup (\cup_{i=1}^4 \hat{F}_i)$. Its measure is less than $c\varepsilon$ by choice of δ . From this point, once the measure of the bad set is controlled, the rest of the proof in Section 6.3 of [15] can be repeated verbatim. This proves that $\bar{\alpha}$ is vwB. \square

Proposition 7.4. *Under the assumptions of Proposition 7.1, the measure $\bar{\mu}_g$ is flow adapted.*

Proof. Let $\Omega = \{(x, y, \theta) \in Q \times \mathbb{S}^1\} \subset \mathbb{T}^3$ denote the phase space for the billiard flow Φ_t with the usual Euclidean metric denoted by d_Ω . Let ν_g be the flow invariant measure obtained as the image of $\bar{\mu}_g$ by the conjugacy map between Ω and $\tilde{\Omega}$. Let

$$\mathcal{S}_0^- = \{\Phi_{-t}(z) \in \Omega \mid z \in \mathcal{S}_0 \text{ and } t \leq \tau(T^{-1}z)\}$$

denote the flow surface obtained by flowing \mathcal{S}_0 backward until its first collision under the inverse flow. Similarly, let

$$\mathcal{S}_0^+ = \{\Phi_t(z) \in \Omega \mid z \in \mathcal{S}_0 \text{ and } t \leq \tau(z)\}$$

denote the forward flow of \mathcal{S}_0 until its first collision. To show that the measure ν_t is flow-adapted, it suffices to show that $\int_\Omega |\log d_\Omega(x, \mathcal{S}_0^\pm)| d\nu_g(x) < \infty$. For then this implies that $\log \|D\Phi_t\|$ is integrable for each $t \in [-\tau_{\min}, \tau_{\min}]$ and then by subadditivity for each $t \in \mathbb{R}$.

Let $P^\pm(\cdot)$ denote the projection under the forward (backward) flow of a subset of Ω until first collision. Let $N_\varepsilon^M(\cdot)$ denote the ε -neighborhood of a set in M in the Euclidean metric d_M and let $N_\varepsilon^\Omega(\cdot)$ denote the ε -neighborhood of a set in Ω in the metric d_Ω . It follows from [13, Exercise 3.15], that there exists $C > 0$ such that for any $\varepsilon > 0$,

$$(7.3) \quad P^-(N_\varepsilon^\Omega(\mathcal{S}_0^-)) \subset N_{C\varepsilon^{1/2}}^M(\mathcal{S}_1) \quad \text{and similarly} \quad P^+(N_\varepsilon^\Omega(\mathcal{S}_0^+)) \subset N_{C\varepsilon^{1/2}}^M(\mathcal{S}_{-1})$$

From (6.5), there exist $C_g > 0$ and $\gamma > 1$ such that

$$(7.4) \quad \mu_g(N_\varepsilon^M(\mathcal{S}_{\pm 1})) \leq C_g |\log \varepsilon|^{-\gamma} \quad \text{for all } \varepsilon > 0.$$

Putting together (7.3) and (7.4) yields

$$(7.5) \quad \nu_g(N_\varepsilon^\Omega(\mathcal{S}_0^-)) \leq \tau_{\max} C_g |\log C \varepsilon^{1/2}|^{-\gamma} \leq C' \tau_{\max} |\log \varepsilon|^{-\gamma}.$$

For $p > 1$ to be chosen below, define for $n \geq 1$, $A_n = N_{e^{-np}}^\Omega(\mathcal{S}_0^-) \setminus N_{e^{-(n+1)p}}^\Omega(\mathcal{S}_0^-)$. If $x \in A_n$, then $|\log d_\Omega(x, \mathcal{S}_0^-)| \leq (n+1)^p$. Thus we estimate using (7.5),

$$\begin{aligned} \int_\Omega |\log d_\Omega(x, \mathcal{S}_0^-)| d\nu_g &\leq 1 + \log \text{diam}(\Omega) + \sum_{n \geq 1} \int_{A_n} |\log d_\Omega(x, \mathcal{S}_0^-)| d\nu_g \\ &\leq 1 + \log \text{diam}(\Omega) + \sum_{n \geq 1} (n+1)^p C' \tau_{\max} n^{-\gamma p}, \end{aligned}$$

and the series converges as long as $p > 1/(\gamma - 1)$. A similar argument shows that $\log d_\Omega(x, \mathcal{S}_0^+)$ is ν_g integrable so that ν_g is flow adapted. \square

APPENDIX A. MOTIVATIONS FROM UNIFORM HYPERBOLIC DYNAMICS

We start this note by presenting the usual method the existence of measures of maximal entropy is proved in the case of uniform hyperbolicity. First, we consider a hyperbolic transformation of a compact set, and then the case of an Anosov flow.

A.1. Hyperbolic maps. Let X be a compact Riemannian manifold and let $T : X \rightarrow X$ be a C^r diffeomorphism. Assume that T is uniformly hyperbolic, that is

$$\begin{aligned} &\exists \lambda > 1, \exists C > 0, \exists E^s, E^u \subset TX \text{ such that} \\ (i) &TX = E^s \oplus E^u, DT(E^s) \subset E^s, DT^{-1}(E^u) \subset E^u, \\ (ii) &\|D_x T^n v_s\| \leq C \lambda^{-n} \|v_s\|, \quad \forall n \geq 0, \forall v_s \in E_x^s \subset T_x X, \\ (iii) &\|D_x T^{-n} v_u\| \leq C \lambda^{-n} \|v_u\|, \quad \forall n \geq 0, \forall v_u \in E_x^u \subset T_x X. \end{aligned}$$

One fundamental theorem about hyperbolic dynamic is the Hadamard–Perron Theorem [23, Theorem 6.2.8] which states that there exists two unique families of C^r manifolds, $\{W_m^+\}_{m \in \mathbb{Z}}$ and $\{W_m^-\}_{m \in \mathbb{Z}}$, everywhere tangent respectively to E^s and to E^u , obtained as the graph of some functions, and satisfying some stability and contraction properties. A key tool in the proof is the construction of families of stable and unstable cones.

As a consequence [23, Corollary 6.4.10], all such diffeomorphisms are expansive, that is

$$(A.1) \quad \exists \delta > 0, \forall x, y \in X, [d(T^n(x), T^n(y)) < \delta, \forall n \in \mathbb{Z}] \Rightarrow x = y.$$

From the expansive property, it follows from [32, Theorem 8.2] that the metric entropy $\mu \mapsto h_\mu(T)$ is upper semi-continuous, hence the existence of equilibrium states for every continuous potential – and in particular existence of measures of maximal entropy for the zero potential. In the proof of [32, Theorem 8.2], expansiveness is only use to get the equality $h_\mu(T) = h_\mu(T, \mathcal{A})$ for partition \mathcal{A} with $\text{diam}(\mathcal{A}) < \delta$ (the expansivity constant of T) and any T -invariant measure μ .

As proved by Bowen [6, Theorem 3.5], the expansiveness assumption of [32, Theorem 8.2] can be weakened to *entropy-expansiveness* (the proof remains unchanged). This weakening will be relevant in the case of Anosov flows.

A.2. Anosov flows. Let X be a compact manifold and $\phi = \{\phi^t\} : \mathbb{R} \times X \rightarrow X$ be a smooth flow. Assume that ϕ is an Anosov flow, that is

$$\begin{aligned} & \exists \lambda > 1, \exists C > 0, \exists E^s, E^u, E^c \subset TX \text{ such that} \\ (i) & TX = E^c \oplus E^s \oplus E^u, \\ (ii) & D\phi^t(E^{s/u}) = E^{s/u}, \dim E_x^c = 1, \left. \frac{d}{dt} \right|_{t=0} \phi^t(x) \in E_x^c \setminus \{0\}, \\ (iii) & \|D_x \phi^t|_{E_x^s}\| \leq C\lambda^{-t}, \|D_x \phi^t|_{E_x^u}\| \leq C\lambda^{-t}, \forall t \geq 0. \end{aligned}$$

In [7, Proposition 1.6], Bowen proves that an Anosov flow is *flow expansive* (in the sense of Bowen–Walters), that is – as defined in [8] in the case of a fixed-point free flow,

$$(A.2) \quad \begin{aligned} & \forall \varepsilon > 0, \exists \delta > 0, \forall x, y \in X, \forall h \in \mathcal{C}^0(\mathbb{R}) \text{ with } h(0) = 0, \\ & [d(\phi^t(x), \phi^{h(t)}(y)) < \delta, \forall t \in \mathbb{R} \Rightarrow y \in \phi^{[-\varepsilon, \varepsilon]}(x)]. \end{aligned}$$

The key ingredient of the proof is the local product structure for hyperbolic flows. From (A.2), it is easy to see, for $h = id$, that an Anosov flow satisfies the following weaker property

$$(A.3) \quad \begin{aligned} & \exists \varepsilon > 0, \exists s > 0, \forall x \in X, \\ & \Gamma_\varepsilon(x) := \{y \in X \mid \forall t \in \mathbb{R}, d(\phi^t(x), \phi^t(y)) < \varepsilon\} \subset \phi^{[-s, s]}(x). \end{aligned}$$

Bowen proved [6, Example 1.6] that (A.3) is a sufficient condition so that every time ϕ^t of the flow is entropy-expansive. Therefore the map $\mu \in \mathcal{M}_X(\phi^1) \mapsto h_\mu(\phi^1)$ is upper semi-continuous, and so is its restriction to $\mathcal{M}_X(\phi) \subset \mathcal{M}_X(\phi^1)$. Hence, Anosov flows have equilibrium states for every continuous potential, and in particular for the zero potential, measures of maximal entropy.

APPENDIX B. OBSTRUCTIONS FOR THE BILLIARD FLOW

In the previous section, in both situations, proofs of existence of MME use some sort of expansiveness. However, the existence of a local product structure is a key ingredient in order to establish the expansivity property: it gives a scale used as the δ in (A.1) and the ε in (A.3). Furthermore, the uniform contraction of stable (resp. unstable) manifolds for large positive (resp. negative) times is used, and not some estimates of their lengths in negative (resp. positive) times (such as fragmentation or growth lemmas, see for example [13]).

B.1. Entropy expansiveness. In Bowen’s proof, the local product structure is the main tool in order to prove flow expansiveness. In the case of the billiard flow, there is no such structure. Indeed, stable and unstable manifolds exist only for Lebesgue-almost every point and there is no deterministic control of their length (hence no uniform scale for a local structure). One might argue that a billiard flow admits invariant “cone” fields [5, Section 2] and construct stable and unstable curves, but then the control on the length of those curves when applying the flow is in term of expansion, not in term of contraction.

It then seems that h-expansiveness of each time φ^t of the flow is too much to ask for. Still, one might hope that each φ^t is *asymptotically h-expansive*, that is $h^*(\varphi^t) := \lim_{\varepsilon \rightarrow 0} h^*(\varphi^t, \varepsilon) = 0$, where $h^*(\varphi^t, \varepsilon) = \sup_{x \in X} h(\varphi^t, \overline{B}(x, \varepsilon))$. This definition was first introduced by Misiurewicz in [26] where he proved that the metric entropy of an asymptotic h-expansive transformation is upper semi-continuous.

The quantity $h^*(\varphi^t)$ is usually referred to as the *topological tail entropy* of φ^t [19]. In the context of smooth dynamics, Buzzi [10] has shown that if $f \in \mathcal{C}^r(M)$, then $h^*(f) \leq \frac{\dim(M)R(f)}{r}$ for some constant $R(f)$. In particular, the metric entropy of a \mathcal{C}^∞ transformation is upper semi-continuous. Clearly, this result does not apply to billiard flows.

Proving that the topological tail entropy of the billiard flow is zero is enough to prove the upper semi-continuity of the metric entropy, hence the existence of some measure of maximal entropy.

B.2. Relations with the Collision Map. In [8, Theorem 6], Bowen and Walters prove that the special flow constructed over a continuous transformation and under a continuous return time function, is flow expansive if and only if the base map is expansive. Since flow expansiveness is an invariant for flow under reparametrization, without loss of generality, the return time function can be chosen constant.

In [3], Baladi and Demers show that the collision map is expansive. However, since the return time is only piecewise continuous, it is not easy to relate the expansivity of the collision map to flow expansiveness of the billiard flow. As shown in Figure 2, two trajectories can be easily separated by the collision map, but they remain *close* in the phase space of the flow. We see that for a δ too large in (A.2) (and a natural choice of h), the two trajectories cannot be distinguished. What could be a good choice for δ ? The main problem being to find a δ independent of trajectories (it is *easier* to find a δ for specific trajectories, such as those ones in Figure 2, but the inf of those δ over all trajectories might be 0). If such δ existed, we expect it is controlled in some way by τ_{min} .

For similar reasons, it appears that it is not a simple consequence of the collision map expansiveness for the flow to satisfy condition (A.3) (which is a weaker than *flow expansiveness*). For example, the two orbits shown in Figure 2 (b) are close in the phase space of the flow, but far apart in the phase space of the collision map (since the collisions they make are distinct).

REFERENCES

- [1] V. Baladi. *Dynamical zeta functions and dynamical determinants for hyperbolic maps*, volume 68 of *Ergebnisse der Mathematik und ihrer Grenzgebiete. 3. Folge. A Series of Modern Surveys in Mathematics [Results in Mathematics and Related Areas. 3rd Series. A Series of Modern Surveys in Mathematics]*. Springer, Cham, 2018. A functional approach.
- [2] V. Baladi, J. Carrand, and M. F. Demers. Measure of maximal entropy for finite horizon Sinai billiard flow. *in preparation*.
- [3] V. Baladi and M. F. Demers. On the measure of maximal entropy for finite horizon Sinai billiard maps. *J. Amer. Math. Soc.*, 33(2):381–449, 2020.
- [4] V. Baladi and M. Demers. Thermodynamic formalism for dispersing billiards. *arXiv preprint arXiv:2009.10936*, 2020, to appear J. Mod. Dyn.
- [5] V. Baladi, M. F. Demers, and C. Liverani. Exponential decay of correlations for finite horizon Sinai billiard flows. *Invent. Math.*, 211(1):39–177, 2018.

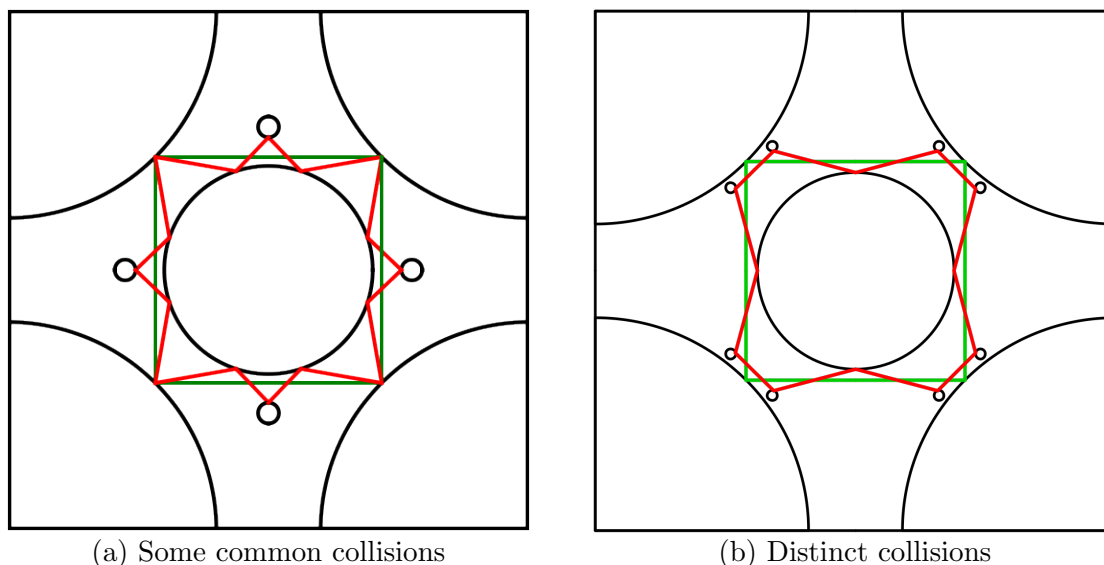


FIGURE 2. Two examples of two periodic trajectories.

- [6] R. Bowen. Entropy-expansive maps. *Transactions of the American Mathematical Society*, 164:323–331, 1972.
- [7] R. Bowen. Periodic orbits for hyperbolic flows. *American Journal of Mathematics*, 94(1):1–30, 1972.
- [8] R. Bowen and P. Walters. Expansive one-parameter flows. *Journal of differential Equations*, 12(1):180–193, 1972.
- [9] L. A. Bunimovič and J. G. Sinaï. The fundamental theorem of the theory of scattering billiards. *Mat. Sb. (N.S.)*, 90(132):415–431, 479, 1973.
- [10] J. Buzzi. Intrinsic ergodicity of smooth interval maps. *Israel J. Math.*, 100:125–161, 1997.
- [11] J. Buzzi. The degree of Bowen factors and injective codings of diffeomorphisms. *J. Mod. Dyn.*, 16:1–36, 2020.
- [12] J. Chen, F. Wang, and H.-K. Zhang. Markov partition and thermodynamic formalism for hyperbolic systems with singularities, 2017.
- [13] N. Chernov and R. Markarian. *Chaotic billiards*. Number 127. American Mathematical Soc., 2006.
- [14] N. I. Chernov. Sinai billiards under small external forces. *Ann. Henri Poincaré*, 2(2):197–236, 2001.
- [15] N. I. Chernov and C. Haskell. Nonuniformly hyperbolic K -systems are Bernoulli. *Ergodic Theory Dynam. Systems*, 16(1):19–44, 1996.
- [16] M. F. Demers and A. Korepanov. Rates of mixing for the measure of maximal entropy of dispersing billiard maps, 2022.
- [17] M. F. Demers, L. Rey-Bellet, and H.-K. Zhang. Fluctuation of the entropy production for the Lorentz gas under small external Forces. *Comm. Math. Phys.*, 363(2):699–740, 2018.
- [18] M. F. Demers and H.-K. Zhang. Spectral analysis of the transfer operator for the Lorentz gas. *J. Mod. Dyn.*, 5(4):665–709, 2011.
- [19] T. Downarowicz. *Entropy in dynamical systems*, volume 18 of *New Mathematical Monographs*. Cambridge University Press, Cambridge, 2011.
- [20] G. Gallavotti and D. S. Ornstein. Billiards and Bernoulli schemes. *Comm. Math. Phys.*, 38:83–101, 1974.
- [21] P. L. Garrido. Kolmogorov-Sinai entropy, Lyapunov exponents, and mean free time in billiard systems. *J. Statist. Phys.*, 88(3-4):807–824, 1997.
- [22] P. Gaspard and F. Baras. Chaotic scattering and diffusion in the Lorentz gas. *Phys. Rev. E (3)*, 51(6, part A):5332–5352, 1995.

- [23] A. Katok and B. Hasselblatt. *Introduction to the modern theory of dynamical systems*, volume 54. Cambridge university press, 1997.
- [24] A. Katok, J.-M. Strelcyn, F. Ledrappier, and F. Przytycki. *Invariant manifolds, entropy and billiards; smooth maps with singularities*, volume 1222 of *Lecture Notes in Mathematics*. Springer-Verlag, Berlin, 1986.
- [25] Y. Lima and C. Matheus. Symbolic dynamics for non-uniformly hyperbolic surface maps with discontinuities. *Ann. Sci. Éc. Norm. Supér. (4)*, 51(1):1–38, 2018.
- [26] M. Misiurewicz. Diffeomorphism without any measure with maximal entropy. *Bull. Acad. Polon. Sci. Sér. Sci. Math. Astronom. Phys.*, 21:903–910, 1973.
- [27] D. S. Ornstein. Imbedding Bernoulli shifts in flows. In *Contributions to Ergodic Theory and Probability (Proc. Conf., Ohio State Univ., Columbus, Ohio, 1970)*, pages 178–218. Springer, Berlin, 1970.
- [28] D. S. Ornstein and B. Weiss. Geodesic flows are Bernoullian. *Israel J. Math.*, 14:184–198, 1973.
- [29] M. Reed and B. Simon. *Methods of modern mathematical physics. I*. Academic Press, Inc. [Harcourt Brace Jovanovich, Publishers], New York, second edition, 1980. Functional analysis.
- [30] J. G. Sinaĭ. Dynamical systems with elastic reflections. Ergodic properties of dispersing billiards. *Uspehi Mat. Nauk*, 25(2 (152)):141–192, 1970.
- [31] Y. G. Sinaĭ and N. I. Chernov. Ergodic properties of some systems of two-dimensional disks and three-dimensional balls. *Uspekhi Mat. Nauk*, 42(3(255)):153–174, 256, 1987.
- [32] P. Walters. *An introduction to ergodic theory*, volume 79 of *Graduate Texts in Mathematics*. Springer-Verlag, New York-Berlin, 1982.
- [33] L.-S. Young. Statistical properties of dynamical systems with some hyperbolicity. *Ann. of Math. (2)*, 147(3):585–650, 1998.

LABORATOIRE DE PROBABILITÉS, STATISTIQUES ET MODÉLISATION (LPSM), CNRS, SORBONNE UNIVERSITÉ, UNIVERSITÉ DE PARIS, 4, PLACE JUSSIEU, 75005 PARIS, FRANCE

Email address: `jcarrand@lpsm.paris`