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# MAXIMAL MEASURE AND ENTROPIC CONTINUITY OF LYAPUNOV EXPONENTS FOR $C^r$ SURFACE DIFFEOMORPHISMS WITH LARGE ENTROPY

DAVID BURGNET

ABSTRACT. We prove a finite smooth version of the entropic continuity of Lyapunov exponents of Buzzi-Crovisier-Sarig for  $C^\infty$  surface diffeomorphisms [9]. As a consequence we show that any  $C^r$ ,  $r > 1$ , smooth surface diffeomorphism  $f$  with  $h_{top}(f) > \frac{1}{r} \limsup_n \frac{1}{n} \log^+ \|df^n\|$  admits a measure of maximal entropy.

## INTRODUCTION

The entropy of a dynamical system quantifies the dynamical complexity by counting distinct orbits. There are topological and measure theoretical versions which are related by a variational principle : the topological entropy of a continuous map on a compact space is equal to the supremum of the entropy of the invariant (probability) measures. An invariant measure is said of maximal entropy when its entropy is equal to the topological entropy, i.e. this measure realizes the supremum in the variational principle. In general a topological system does not admit measures of maximal entropy. But such measures exist for systems satisfying some expansiveness properties. In particular Newhouse [12] has proved their existence for  $C^\infty$  systems by using Yomdin's theory. In the present paper we show the existence of a measure of maximal entropy for  $C^r$  smooth surface diffeomorphisms with  $1 < r < +\infty$  with large entropy.

Other important dynamical quantities for smooth systems are given by the Lyapunov exponents which estimate the exponential growth of the derivative. For  $C^\infty$  surface diffeomorphisms, J. Buzzi, S. Crovisier and O. Sarig proved recently a property of continuity in the entropy of the Lyapunov exponents with many statistical applications [9]. More precisely, for a  $C^\infty$  surface diffeomorphism  $f$ , if  $\nu_k$  is a sequence of ergodic measures with  $\lim_k h(\nu_k) = h_{top}(f)$ , then the Lyapunov exponents of  $\nu_k$  are going to the (average) Lyapunov exponents of  $\mu$ . We prove a  $C^r$  version of their result for  $1 < r < +\infty$ .

## 1. STATEMENTS

We define now some notations to state our main result. For a diffeomorphism  $f$  on a compact Riemannian surface  $(M, \|\cdot\|)$  we let  $F : \mathbb{P}TM \circlearrowright$  be the induced map on the projective tangent bundle  $\mathbb{P}TM = T^1M/\pm 1$  and  $\phi : \mathbb{P}TM \rightarrow \mathbb{R}$  be the continuous observable on  $\mathbb{P}TM$  given by  $(x, v) \mapsto \log \|d_x f(v)\|$ . For  $k \in \mathbb{N}^*$  we define more generally  $\phi_k : (x, v) \mapsto \log \|d_x f^k(v)\|$ . Then we let  $\lambda^+(x) = \limsup_{n \rightarrow +\infty} \frac{1}{n} \log \|d_x f^n\|$ , resp.  $\lambda^-(x) = \liminf_{n \rightarrow -\infty} \frac{1}{n} \log \|d_x f^n\|$ , for any  $x \in M$  and  $\lambda^+(\mu) = \int \lambda^+(x) d\mu(x)$  for any  $f$ -invariant measure  $\mu$ .

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Also we put  $\lambda^+(f) := \lim_n \frac{1}{n} \log \|df^n\|$ . For a  $f$ -invariant measure  $\mu$  with  $\lambda^+(x) > 0 \geq \lambda^-(x)$  for  $\mu$  a.e.  $x$ , there are by Oseledets\* theorem one-dimensional invariant vector spaces  $\mathcal{E}_+(x)$  and  $\mathcal{E}_-(x)$ , resp. called the unstable and stable Oseledets bundle, such that

$$\forall \text{ a.e. } x \forall v \in \mathcal{E}_\pm(x) \setminus \{0\}, \quad \lim_{n \rightarrow \pm\infty} \frac{1}{n} \log \|d_x f^n(v)\| = \lambda^\pm(x).$$

Then we let  $\hat{\mu}^+$  be the  $F$ -invariant measure given by the lift of  $\mu$  on  $\mathbb{P}TM$  supported on the one-dimensional Oseledets unstable bundle. When writing  $\hat{\mu}^+$  we assume implicitly that the push-forward measure  $\mu$  on  $M$  satisfies  $\lambda^+(x) > 0 \geq \lambda^-(x)$  for  $\mu$  a.e.  $x$ .

**Theorem** (Buzzi-Crovisier-Sarig, Theorem C in [9]). *Let  $f$  be a  $\mathcal{C}^r$ , with  $r > 1$ , surface diffeomorphism. Assume there is a sequence  $(\hat{\nu}_k^+)_k$  of ergodic  $F$ -invariant measures converging to  $\hat{\mu}$ .*

*Then there are  $F$ -invariant measures  $\hat{\mu}_0$  and  $\hat{\mu}_1^+$  with  $\hat{\mu} = (1 - \beta)\hat{\mu}_0 + \beta\hat{\mu}_1^+$ ,  $\beta > 0$ , such that:*

- $\lambda^+(x) > 0 \geq \lambda^-(x)$  for  $\mu_1$ -a.e.  $x$ ,
- $\int \phi d\hat{\mu}_0 = 0$ ,
- $\limsup_{k \rightarrow +\infty} h(\nu_k) \leq \beta h(\mu_1) + \frac{\lambda^+(f) + \lambda^+(f^{-1})}{r-1}$ .

Observe that  $\lambda^+(\nu_k) = \int \phi d\hat{\nu}_k^+ \xrightarrow{k} \int \phi d\hat{\mu} = \beta\lambda^+(\mu_1)$ , therefore  $\beta = \lim_k \frac{\lambda^+(\nu_k)}{\lambda^+(\mu_1)}$ . In particular when  $f$  is  $\mathcal{C}^\infty$  and  $h(\nu_k)$  goes to the topological entropy, then  $\beta$  is equal to 1 and therefore  $\lambda^+(\nu_k)$  goes to  $\lambda^+(\mu)$ . We state an improved version of Buzzi-Crovisier-Sarig Theorem, which allows to prove the same entropy continuity of Lyapunov exponents for  $\mathcal{C}^r$  surface diffeomorphisms with large enough entropy.

**Main Theorem.** *Let  $f$  be a  $\mathcal{C}^r$ , with  $r > 1$ , surface diffeomorphism. Assume there is a sequence  $(\hat{\nu}_k^+)_k$  of ergodic  $F$ -invariant measures converging to  $\hat{\mu}$  with  $\int \phi d\hat{\mu} > \alpha > \frac{\lambda^+(f)}{r}$ .*

*Then there are  $F$ -invariant measures  $\hat{\mu}_0$  and  $\hat{\mu}_1^+$  with  $\hat{\mu} = (1 - \beta)\hat{\mu}_0 + \beta\hat{\mu}_1^+$ ,  $\beta > 0$ , such that*

- $\lambda^+(x) \geq \alpha > 0 \geq \lambda^-(x)$  for  $\mu_1$ -a.e.  $x$ ,
- $\int \phi d\hat{\mu}_0 = \alpha$ ,
- $\limsup_{k \rightarrow +\infty} h(\nu_k) \leq \beta h(\mu_1) + (1 - \beta)\alpha$ .

The Main Theorem implies Buzzi-Crovisier-Sarig statement. Indeed, either  $\lim_k \lambda^+(\nu_k) = \int \phi d\hat{\mu} \leq \frac{\lambda^+(f)}{r}$  and we get by Ruelle inequality,  $\limsup_k h(\nu_k) \leq \frac{\lambda^+(f)}{r}$  or we are in the settings of the Main Theorem for some  $\alpha \in \left] \frac{\lambda^+(f)}{r}, \min\left(\int \phi d\hat{\mu}, \frac{\lambda^+(f)}{r-1}\right) \right[$ . By applying the Main Theorem, there is then a decomposition  $\hat{\mu} = (1 - \beta_\alpha)\hat{\mu}_{0,\alpha} + \beta_\alpha\hat{\mu}_{1,\alpha}^+$  satisfying  $\limsup_{k \rightarrow +\infty} h(\nu_k) \leq \beta_\alpha h(\mu_{1,\alpha}) + (1 - \beta_\alpha)\alpha$ . But it follows from the proofs that  $\beta_\alpha\mu_{1,\alpha}$  is a component of  $\beta\mu_1$  with  $\beta$  and  $\mu_1$  being as in Buzzi-Crovisier-Sarig's statement (see Remark 2). In particular  $\beta_\alpha h(\mu_{1,\alpha}) \leq \beta h(\mu_1)$ , therefore  $\limsup_{k \rightarrow +\infty} h(\nu_k) \leq \beta h(\mu_1) + \frac{\lambda^+(f) + \lambda^+(f^{-1})}{r-1}$ .

**Corollary.** *Let  $f$  be a  $\mathcal{C}^r$ , with  $r > 1$ , surface diffeomorphism satisfying  $h_{\text{top}}(f) > \frac{\lambda^+(f)}{r}$ .*

*Then  $f$  admits a measure of maximal entropy. More precisely, if  $(\nu_k)_k$  is a sequence of ergodic measures converging to  $\mu$  with  $\lim_k h(\nu_k) = h_{\text{top}}(f)$ , then*

- $h(\mu) = h_{\text{top}}(f)$ ,

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\*We refer to [13] for background on Lyapunov exponents and Pesin theory.

- $\lim_k \lambda^+(\nu_k) = \lambda^+(\mu)$ .

It was proved in [8] that any  $C^r$  surface diffeomorphism satisfying  $h_{top}(f) > \frac{\lambda^+(f)}{r}$  admits at most finitely many ergodic measures of maximal entropy. In the other hand, J. Buzzi has built examples of  $C^r$  surface diffeomorphisms for any  $+\infty > r > 1$  with  $\frac{h_{top}(f)}{\lambda^+(f)}$  arbitrarily close to  $1/r$  without measure of maximal entropy [6]. Such results were already known for interval maps [3, 5, 7].

*Proof of the Corollary.* By using the notations of the Main Theorem with  $h_{top}(f) > \alpha > \frac{\lambda^+(f)}{r}$ , we have

$$\begin{aligned} h_{top}(f) &= \lim_{k \rightarrow +\infty} h(\nu_k), \\ &\leq \beta h(\mu_1) + (1 - \beta)\alpha, \\ &\leq \beta h_{top}(f) + (1 - \beta)\alpha, \\ (1 - \beta)h_{top}(f) &\leq (1 - \beta)\alpha. \end{aligned}$$

But  $h_{top}(f) > \alpha$ , therefore  $\beta = 1$ , i.e.  $\mu_1 = \mu$  and  $\lim_k \lambda^+(\nu_k) = \lambda^+(\mu)$ . Moreover  $h_{top}(f) = \lim_{k \rightarrow +\infty} h(\nu_k) \leq \beta h(\mu_1) + (1 - \beta)\alpha = h(\mu)$ . Consequently  $\mu$  is a measure of maximal entropy.  $\square$

## 2. MAIN STEPS OF THE PROOF

We follow the strategy of the proof of [9]. We point out below the main differences:

- *hyperbolic and neutral empirical component.* For  $\lambda^+(\nu_k) > \alpha > 0$  we split the orbit of a  $\nu_k$ -typical point  $x$  into the *hyperbolic* part and its complement the *neutral* part. The hyperbolic part is given by the integers  $k$  lying between to  $M$ -close consecutive  $\alpha$ -hyperbolic times for the sequence  $(\phi(F^k \hat{x}))_k$  with  $\hat{x} = (x, \mathcal{E}_+(x))$ . We then consider the associated  $M$ -empirical measures and their limit in  $k$ , then in  $M$ . In this way we get an invariant component of  $\hat{\mu}$  (called the hyperbolic component). This decomposition follows exactly the approach in [9]. But here  $\alpha > 0$  is fixed, whereas  $\alpha$  is taken close to zero in [9].
- *Entropy computations.* To compute the asymptotic entropy of the  $\nu_k$ 's in terms of the entropy of its neutral and hyperbolic empirical component, we use the static entropy w.r.t. partitions and its conditional version. Instead the authors in [9] used Katok's like formulas and combinatorial arguments.
- *$C^r$  Reparametrizations.* Finally to estimate the entropy of the neutral component and the local entropy of the hyperbolic component we use here reparametrization methods from [4] and [2] respectively rather than Yomdin's reparametrizations of the projective action  $F$  as done in [9]. This is the principal difference with [9].

**2.1. Hyperbolic times and associated empirical measures.** In this section we mostly follow the presentation of the neutral decomposition of Section 6 in [9]. We work with the map  $F$  induced on the projective tangent bundle and with the continuous observable  $\phi$ , but the same construction may be applied to any continuous observable of a topological system.

We let  $H$  be the  $\alpha$ -hyperbolic set and  $E(\hat{x}) \subset \mathbb{Z}$  for  $\hat{x} \in \mathbb{P}TM$  be the associated set of  $\alpha$ -hyperbolic times at  $\hat{x}$ :

$$H = \left\{ \hat{x} \in \mathbb{P}TM, \forall l > 0 \phi_l(F^{-l} \hat{x}) \geq \alpha l \right\},$$

$$E(\hat{x}) = \{n \in \mathbb{Z}, F^n \hat{x} \in H\}.$$

When  $a < b$  are two consecutive times in  $E(\hat{x})$ , then  $[a, b[$  is a *neutral block* as defined in [9], i.e.  $\phi_k(F^a \hat{x}) < k\alpha$  for all  $1 \leq k < \dots < b - a$ . From  $\phi_{b-a-1}(F^a \hat{x}) < (b - a - 1)\alpha$  and  $\phi_{b-a}(F^a \hat{x}) \geq (b - a)\alpha$  we get:

$$(2.1) \quad |\phi_{b-a}(F^a \hat{x}) - (b - a)\alpha| \leq \|\phi\|_\infty.$$

For all  $M$  we let

$$E^M(\hat{x}) = \bigcup_{a < b \in E(\hat{x}), |a-b| \leq M} [a, b[.$$

The complement of  $E^M(\hat{x})$  is made of neutral blocks of length larger than  $M$ . We consider the associated empirical measures :

$$\forall n, \hat{\mu}_{\hat{x}, n}^M = \frac{1}{n} \sum_{k \in E^M(\hat{x}) \cap [0, n[} \delta_{F^k \hat{x}}.$$

Let  $\nu$  be an ergodic measure with  $\lambda^+(\nu) > \alpha > 0$ . By applying the Ergodic Maximal Inequality (see e.g. Theorem 1.1 in [1]) to the measure preserving system  $(F^{-1}, \hat{\nu}^+)$  with the observable  $\psi = \alpha - \phi \circ F^{-1}$ , we get with  $A = \{\hat{x}, \exists k \geq 1 \sum_{l=0}^{k-1} \psi(F^{-l} \hat{x}) > 0\}$ :

$$\int_A \psi d\hat{\nu}^+ \geq 0.$$

But  $A = \mathbb{P}TM \setminus H$ , therefore  $\int_H (\alpha - \phi \circ F^{-1}) d\hat{\nu}^+ \leq \int (\alpha - \phi \circ F^{-1}) d\hat{\nu}^+ = \alpha - \lambda^+(\nu)$ . In particular we have  $\hat{\nu}^+(H) > \frac{\lambda^+(\nu) - \alpha}{\|\phi\|_\infty} > 0$ . Let  $\chi^M$  be the indicator function of  $\{\hat{x}, 0 \in E^M(\hat{x})\}$ . By Birkhoff ergodic theorem, there is a set  $\mathbf{G}$  of full  $\nu$ -measure such that the empirical measures  $(\hat{\mu}_{\hat{x}, n}^M)_n$  with  $\hat{x} = (x, \mathcal{E}_+(x))$  are converging for any  $x \in \mathbf{G}$  and any  $M \in \mathbb{N}^*$  to  $\hat{\xi}^M := \chi^M \hat{\nu}^+$  in the weak-\* topology. We also let  $\hat{\eta}^M = \hat{\nu}^+ - \hat{\xi}^M$ . Moreover we put  $\beta_M = \int \chi^M d\hat{\nu}^+$ , then  $\hat{\xi}^M = \beta_M \cdot \hat{\xi}^M$  and  $\hat{\eta}^M = (1 - \beta_M) \cdot \hat{\eta}^M$  with  $\hat{\xi}^M, \hat{\eta}^M$  being thus probability measures. Finally in the next sections we will write  $\xi^M, \eta^M, \mu_{x, n}^M, \dots$  for the push-forward measures on  $M$  of  $\hat{\xi}^M, \hat{\eta}^M, \hat{\mu}_{\hat{x}, n}^M, \dots$

**Lemma 1.** *The empirical measures  $\hat{\xi}^M$  and  $\hat{\eta}^M$  satisfy the following properties:*

- (1)  $\hat{\xi}^M \geq \hat{\xi}^N$  for  $M \geq N$ .
- (2)  $\beta_M > 0$  for  $M$  large enough,
- (3)  $|\int \phi d\hat{\eta}^M - \alpha| \leq \frac{\|\phi\|_\infty}{M}$ ,
- (4) for  $\hat{\xi}^M(K_M) = 1$  with  $K_M := \{\hat{x}, \exists 0 \leq m \leq M \text{ with } \phi_m(\hat{x}) \geq m\alpha\}$ .

*Proof.* The first item follows obviously from the definitions. The second item follows from  $\hat{\nu}^+(H) = \lim_n \frac{1}{n} \# E(\hat{x}) \cap [1, n] > 0$  for  $\hat{\nu}^+$  a.e.  $\hat{x}$  and the inequality  $\limsup_n \frac{1}{n} \sup_{\hat{x}} \# (E(\hat{x}) \setminus E^M(\hat{x})) \cap [1, n] < 1/M$ . To prove the third item, it is enough to sum Inequality (2.1) over all neutral blocks  $[a, b[$  in the complement set of  $E^M(\hat{x})$ . The last item follows immediately from the definition of the empirical measure  $\hat{\xi}^M$  and the compactness of  $K_M$ .  $\square$

For  $\hat{x} \in \mathbb{P}TM$  we let  $m_n(\hat{x}) = \max E(\hat{x}) \cap [0, n[$ .

**Lemma 2.**

$$\frac{m_n(\hat{x})}{n} \xrightarrow{n} 1 \text{ for } \hat{\nu}^+ \text{ a.e. } \hat{x}.$$

*Proof.* For  $\hat{\nu}^+$  a.e.  $\hat{x}$ , we have  $\epsilon_n(\hat{x}) := \frac{1}{n}\phi_n(\hat{x}) - \lambda^+(\nu) \xrightarrow{n} 0$  and  $m_n(\hat{x}) \xrightarrow{n} +\infty$ . Then by definition of  $m_n(\hat{x})$ , the interval of integers  $[m_n(\hat{x}), n]$  lies in a neutral block starting at  $m_n(\hat{x})$ , therefore  $\phi_{n-m_n(\hat{x})}(F^{m_n(\hat{x})}\hat{x}) \leq \alpha(n - m_n(\hat{x}))$ . Consequently

$$\begin{aligned} \phi_n(\hat{x}) - \phi_{m_n(\hat{x})}(\hat{x}) &= \phi_{n-m_n(\hat{x})}(F^{m_n(\hat{x})}\hat{x}), \\ (n - m_n(\hat{x}))\lambda^+(\nu) + n\epsilon_n(\hat{x}) - m_n(\hat{x})\epsilon_{m_n(\hat{x})}(\hat{x}) &\leq \alpha(n - m_n(\hat{x})), \\ \frac{1}{n}(\lambda^+(\nu) - \alpha)(n - m_n(\hat{x})) &\leq |\epsilon_n(\hat{x})| + |\epsilon_{m_n(\hat{x})}(\hat{x})| \xrightarrow{n} 0. \end{aligned}$$

□

**2.2. Entropy of conditional measures.** A measurable partition  $\varsigma$  is *subordinated* to the Pesin unstable local lamination  $W^u$  of  $\nu$  if the atom of  $\varsigma$  containing  $x$  is a neighborhood of  $x$  inside the curve  $W^u(x)$  and  $f^{-1}\varsigma \succ \varsigma$ . By Rokhlin's disintegration theorem, there is for  $\nu$ -a.e.  $x$  a probability measure  $\nu_x$  on  $\varsigma(x)$ , called the conditional measures on unstable manifolds, satisfying  $\nu = \int \nu_x d\nu(x)$ . Ledrappier-Young [11] proved the existence of such subordinated measurable partitions and that for  $\nu$ -a.e.  $x$ , we have with  $B_n(x, \rho)$  being the Bowen ball  $B_n(x, \rho) = \bigcap_{0 \leq k < n} f^{-k}B(f^k x, \rho)$ :

$$(2.2) \quad \lim_{\rho \rightarrow 0} \liminf_n -\frac{1}{n} \log \nu_x(B_n(x, \rho)) = h(\nu).$$

Fix an error term  $\delta$  depending<sup>†</sup> on  $\nu$ . There is  $\rho > 0$  and a measurable set  $\mathbf{F} \subset \mathbf{G}$  with  $\nu(\mathbf{F}) > 0$  such that the empirical measures  $\left(\hat{\mu}_{\hat{x}, n}^M\right)_n$  are converging uniformly in  $x \in \mathbf{F}$  to  $\hat{\xi}^M$ , i.e. for all continuous function  $\psi : \mathbb{P}TM \rightarrow \mathbb{R}$

$$(2.3) \quad \frac{1}{n} \sum_{k \in E^M(\hat{x}) \cap [1, n[} \psi(F^k \hat{x}) \xrightarrow{n} \int \psi d\xi^M \text{ uniformly in } x \in \mathbf{F}$$

and such that

$$\forall x \in \mathbf{F}, \liminf_n -\frac{1}{n} \log \nu_x(B_n(x, \rho)) \geq h(\nu) - \delta.$$

We fix  $x_* \in \mathbf{F}$  with  $\nu_{x_*}(\mathbf{F}) > 0$  and we let  $\zeta$  be the probability measure induced by  $\nu_{x_*}$  on  $\mathbf{F}$ . We let  $D$  be the  $C^r$  curve given by the Pesin local unstable manifold  $W^u(x_*)$  at  $x_*$ . For a finite measurable partition  $P$  and a Borel probability measure  $\mu$  we let  $H_\mu(P)$  be the static entropy,  $H(\mu) = -\sum_{A \in P} \mu(A) \log \mu(A)$ . For a partition  $P$  of  $M$ , we let  $P^n = \bigvee_{k=0}^{n-1} f^{-k}P$  be the  $n$ -iterated partition,  $n \in \mathbb{N}$ . We also let  $P_x$  be the atom of  $P$  containing the point  $x \in M$ .

**Lemma 3.** *For any (finite measurable) partition  $P$  with diameter less than  $\rho$ , we have*

$$\liminf_n \frac{1}{n} H_\zeta(P^n) \geq h(\nu) - \delta.$$

<sup>†</sup>In the proof of the Main Theorem we will take  $\delta = \delta(\nu_k) \xrightarrow{k} 0$  for the converging sequence of ergodic measures  $(\nu_k)_k$ .

*Proof.*

$$\begin{aligned}
\liminf_n \frac{1}{n} H_\zeta(P^n) &= \liminf_n \int -\frac{1}{n} \log \zeta(P_x^n) d\zeta(x), \text{ by definition of } H_\zeta, \\
&\geq \int \liminf_n -\frac{1}{n} \log \zeta(P_x^n) d\zeta(x), \text{ by Fatou's Lemma,} \\
&\geq \int \liminf_n -\frac{1}{n} \log \nu_x(P_x^n) d\zeta(x), \text{ by definition of } \zeta, \\
&\geq \int \liminf_n -\frac{1}{n} \log \nu_x(B_n(x, \rho)) d\zeta(x), \text{ as } \text{diam}(P) < \rho, \\
&\geq h(\nu) - \delta, \text{ by the choice of } \mathbf{F}.
\end{aligned}$$

□

**2.3. Entropy splitting of the neutral and the hyperbolic component.** In this section we split the entropy contribution of the neutral and hyperbolic components. We consider a partition  $P$  with  $\nu(\partial P) = 0$  and with diameter less than  $\rho$ . Fix  $M$ . For each  $n \in \mathbb{N}$  and  $x \in \mathbf{F}$  we let  $E_n^M(x) = E^M(\hat{x}) \cap [0, n[$ . We also let  $\mathbf{E}_n^M$  be the partition of  $\mathbf{F}$  with atoms  $A_E := \{x \in D, E_n^M(x) = E\}$  for  $E \subset [0, n[$ . Given a partition  $Q$  of  $M$ , we also let  $Q^{\mathbf{E}_n^M}$  be the partition of  $\mathbf{F}$  finer than  $\mathbf{E}_n^M$  with atoms  $\{x \in \mathbf{F}, E_n^M(x) = E \text{ and } \forall k \in E, f^k x \in Q_k\}$  for  $E \subset [0, n[$  and  $(Q_k)_{k \in E} \in Q^E$ . For a measure  $\eta$  and a subset  $A$  of  $M$  with  $\eta(A) > 0$  we denote by  $\eta_A = \frac{\eta(A \cap \cdot)}{\eta(A)}$  the induced probability measure on  $A$ . Moreover, for sets  $A, B$  we let  $A \Delta B$  denote the symmetric difference of  $A$  and  $B$ , i.e.  $A \Delta B = (A \setminus B) \cup (B \setminus A)$ .

**Lemma 4.** *For any partition  $Q$  with  $\xi^M(\partial Q) = 0$  we have*

$$(2.4) \quad h(\nu) \leq \beta_M \frac{1}{m} H_{\underline{\xi}^M}(Q^m) + \limsup_n \frac{1}{n} H_\zeta(P^n | Q^{\mathbf{E}_n^M}) + \frac{2}{M} + \frac{12 \log \#Q}{M} + \delta.$$

*Proof.* As the complement of  $E_n^M(x)$  is the disjoint union of neutral blocks with length larger than  $M$ , there are at most  $A_n^M = \sum_{k=0}^{\lfloor 2n/M \rfloor + 1} \binom{n}{k}$  possible values for  $E_n^M(x)$  so that

$$\begin{aligned}
\frac{1}{n} H_\zeta(P^n) &= \frac{1}{n} H_\zeta(P^n | \mathbf{E}_n^M) + H_\zeta(\mathbf{E}_n^M), \\
&\leq \frac{1}{n} H_\zeta(P^n | \mathbf{E}_n^M) + \log A_n^M, \\
\liminf_n \frac{1}{n} H_\zeta(P^n) &\leq \limsup_n \frac{1}{n} H_\zeta(P^n | \mathbf{E}_n^M) + \frac{2}{M}.
\end{aligned}$$

Then

$$\frac{1}{n} H_\zeta(P^n | \mathbf{E}_n^M) \leq \frac{1}{n} H_\zeta(Q^{\mathbf{E}_n^M} | \mathbf{E}_n^M) + \frac{1}{n} H_\zeta(P^n | Q^{\mathbf{E}_n^M}).$$

For  $E \subset [0, n[$  we let  $\zeta_{E,n} = \frac{n}{\#E} \int \mu_{x,n}^M d\zeta_{A_E}$ . Observe that  $\zeta_{E,n}$  and  $\#E/n$  are converging to  $\underline{\xi}^M$  and  $\beta_M$  respectively uniformly in  $E$  when  $n$  goes to infinity (as  $\zeta(\mathbf{F}) = 1$ ). By Lemma 6

in [2] we have for all  $n > m \in \mathbb{N}^*$ :

$$\begin{aligned} H_\zeta \left( Q^{\mathbb{E}_n^M} | \mathbb{E}_n^M \right) &= \sum_E \zeta(A_E) H_{\zeta_{A_E}}(Q^E), \\ &\leq \sum_E \zeta(A_E) \#E \left( \frac{1}{m} H_{\zeta_{E,n}}(Q^m) + 6m \log \#Q \frac{\#(E+1)\Delta E}{\#E} \right). \end{aligned}$$

Then as  $\xi^M(\partial Q) = 0$  we get by taking the limit in  $n$ :

$$\begin{aligned} \limsup_n \frac{1}{n} H_\zeta \left( Q^{\mathbb{E}_n^M} | \mathbb{E}_n^M \right) &\leq \beta_M \frac{1}{m} H_{\xi^M}(Q^m) + \frac{12 \log \#Q}{M}, \\ h(\nu) - \delta &\leq \liminf_n \frac{1}{n} H_\zeta(P^n) \leq \beta_M \frac{1}{m} H_{\xi^M}(Q^m) + \limsup_n \frac{1}{n} H_\zeta(P^n | Q^{\mathbb{E}_n^M}) + \frac{2}{M} + \frac{12 \log \#Q}{M}. \end{aligned}$$

□

**2.4. Bounding the entropy of the neutral component.** In this section we assume the ergodic measure  $\nu$  satisfies  $\lambda^+(\nu) > \alpha > \frac{\lambda^+(f)}{r}$ . We bound the term  $\limsup_n \frac{1}{n} H_\zeta(P^n | Q^{\mathbb{E}_n^M})$  in the right member of Lemma 4, which corresponds to the local entropy contribution plus the entropy in the neutral part. In the next statement, for any  $\epsilon > 0$  we let  $\|df^p\|_\epsilon : x \mapsto \|d_x f^p\|_\epsilon := \sup_{y \in B(x, \epsilon)} \|d_y f^p\|$ .

**Lemma 5.** *For all  $p, M \in \mathbb{N}^*$ , there are  $\epsilon_p > 0$  and  $\gamma_{p,M} > 0$  with  $\limsup_p \limsup_M \gamma_{p,M} = 0$  such that for any partition  $Q$  with diameter less than  $\epsilon < \epsilon_p$ , we have:*

$$\limsup_n \frac{1}{n} H_\zeta(P^n | Q^{\mathbb{E}_n^M}) \leq (1 - \beta_M) \alpha + \left( \log 2 + \frac{1}{r-1} \right) \left( \int \frac{\log^+ \|df^p\|_\epsilon}{p} d\xi^M - \int \phi d\hat{\xi}^M \right) + \gamma_{p,M}.$$

We will prove Lemma 5 assuming a *semi-local Reparametrization Lemma* (Proposition 1). Let  $r > 1$ . Following [ ] curve  $\sigma : [-\epsilon, \epsilon] \rightarrow M$  is said (resp. strongly)  $(\epsilon, r)$ -bounded when the image of  $\sigma$  is contained in the ball centered at  $\sigma(0)$  with radius equal to the radius of injectivity of the Riemannian surface and  $\tilde{\sigma} := \exp_{\sigma(0)}^{-1} \circ \sigma$  satisfies  $\max_{k=1, \dots, r} \|d^k \tilde{\sigma}\| \leq \|d\tilde{\sigma}\|$  (resp.  $\leq 1$ ). The curve  $\sigma$  is said strongly  $(\epsilon, r, n)$ -bounded for  $n \in \mathbb{N}^*$  if  $f^k \circ \sigma$  is  $(\epsilon, r)$ -bounded for all  $k = 0, \dots, n-1$ . When  $\sigma$  is strongly  $(\epsilon, r, n)$ -bounded, then the distorsion is uniformly bounded along  $\sigma$ , i.e. for all  $\hat{x} = (x, v_x)$ ,  $\hat{y} = (y, v_y)$  in  $\mathbb{P}TM$  tangent to  $\sigma$  and for all  $k = 0, \dots, n-1$  we have  $|\phi_{n-k}(F^k \hat{x}) - \phi_{n-k}(F^k \hat{y})| \leq \log 2$  for  $\epsilon < 1/100$  (see [2, 4] for details).

**Lemma 6.** *For any  $0 < \alpha' < \alpha$ , there exists  $C > 0$  such that for any strongly  $(\epsilon, r, n)$ -bounded subcurve  $\sigma$  of  $D$  intersecting  $F$ , the length of  $f^k \circ \sigma$  is less than  $Ce^{-\alpha'(n-k)}$ .*

*Proof.* Let  $x \in F \cap \text{Im}(\sigma)$  and  $\hat{x} = (x, \mathcal{E}_+(x))$ . For  $0 \leq k \leq m_n(x)$ , we have  $\phi_{m_n(\hat{x})-k}(F^k \hat{x}) \geq \alpha(m_n(\hat{x})-k)$  as  $m_n(\hat{x})$  belongs to  $E(\hat{x})$ . Therefore the length of  $f^k \circ \sigma$  is less than  $8\epsilon e^{\alpha(k-m_n(x))}$  by the aforementioned bounded distorsion property. Finally, observe that  $\frac{m_n(\hat{x})}{n}$  is converging uniformly to 1 on  $F$  by Lemma 2 and the definition of  $F$ . □

**Proposition 1.** *For all  $p \in \mathbb{N}^*$  there are  $\epsilon_p > 0$  and  $\gamma_{p,M} > 0$  with  $\limsup_p \limsup_M \gamma_{p,M} = 0$  such that for any partition  $Q$  with diameter less than  $\epsilon < \epsilon_p$ , the following property holds for  $n$  large enough.*



The intersection of any atom  $F_n$  of the partition  $Q^{\mathbb{E}^M}$  with  $D \cap \mathbf{F}$  may be covered by a family  $\Psi_{F_n}$  of strongly  $(\epsilon, r, n)$ -bounded curves satisfying

$$\frac{1}{n} \log \#\Psi_{F_n} \leq \left(1 - \frac{\#E_n}{n}\right) \alpha + \left(\log 2 + \frac{1}{r-1}\right) \left(\int \frac{\log^+ \|d_x f^p\|_\epsilon}{p} d\zeta_{F_n}^M(x) - \int \phi d\hat{\zeta}_{F_n}^M\right) + \gamma_{p,M}.$$

where  $E_n = E_n^M(x)$  for  $x \in F_n$ ,  $\hat{\zeta}_{F_n}^M = \frac{1}{n} \int \hat{\mu}_{\hat{x},n} d\zeta_{F_n}^M(x)$  and  $\zeta_{F_n}^M$  its push-forward on  $M$ .

The proof of Proposition 1 is given in the last section. Proposition 1 is very similar to the Reparametrization Lemma in [4]. Here we reparametrize  $D \cap \mathbf{F} \cap F_n$  for  $F_n$  an atom of  $Q^{\mathbb{E}^n}$  instead of  $Q^n$  in [4]. The arguments are the same as in [4] for the hyperbolic part, whereas in the neutral part we use the bounded geometry property at hyperbolic times established in [2].

*Proof of Lemma 5.* First observe that

$$H_\zeta(P^n | Q^{\mathbb{E}^n}) \leq \sum_{F_n \in Q^{\mathbb{E}^n}} \zeta(F_n) \log \#\{A^n \in P^n, A^n \cap D \cap \mathbf{F} \cap F_n \neq \emptyset\}.$$

As  $\nu(\partial P) = 0$ , for all  $\gamma > 0$ , there is  $\chi > 0$  and a continuous function  $\psi : X \rightarrow \mathbb{R}^+$  equal to 1 on the  $\chi$ -neighborhood  $\partial P^\chi$  of  $\partial P$  satisfying  $\int \psi d\nu < \gamma$ . Then we have uniformly in  $x \in \mathbf{F}$ :

$$(2.5) \quad \limsup_n \frac{1}{n} \#\{0 \leq k < n, f^k x \in \partial P^\chi\} \leq \lim_n \frac{1}{n} \sum_{k=0}^{n-1} \psi(f^k x) < \gamma.$$

Assume that for arbitrarily large  $n$  there is  $F_n \in Q^{\mathbb{E}^n}$  and  $\sigma \in \Psi_{F_n}$  with  $\#\{A^n \in P^n, A^n \cap \text{Im}(\sigma) \neq \emptyset\} > \#P^{\gamma n}$ . Then we have  $\#\{0 \leq k < n, \partial P \cap \text{Im}(f^k \circ \sigma) \neq \emptyset\} > \gamma n$ . By Lemma 6, the length of  $f^k \circ \sigma$  is less than  $\chi$  for all  $0 \leq k \leq n - C$  for some constant  $C$  independent of  $n$ . In particular we get  $\#\{0 \leq k < n, f^k x \in \partial P^\chi\} > \gamma n - C$  for any  $x \in \text{Im}(\sigma)$ , which contradicts (2.5). Therefore we have

$$\limsup_n \sup_{F_n, \sigma \in \Psi_{F_n}} \frac{1}{n} \log \#\{A^n \in P^n, A^n \cap \text{Im}(\sigma) \neq \emptyset\} = 0.$$

Together with Proposition 1 this concludes the proof of Lemma 5.  $\square$

**2.5. Proof of the Main Theorem.** Let  $(\hat{\nu}_k^+)_k$  be a sequence of ergodic measures converging to  $\hat{\mu}$  with  $\int \phi d\hat{\mu} = \lim_k \lambda^+(\nu_k) > \alpha > \frac{\lambda^+(f)}{r}$ . Without loss of generality we can assume  $\liminf_k h(\nu_k) > 0$ . For  $\mu$  a.e.  $x$ , we have  $\lambda^-(x) \leq 0$ . If not, some ergodic component  $\tilde{\mu}$  of  $\mu$  would have two positive Lyapunov exponents and therefore should be the periodic measure at a source. But then  $\nu_k$  would be equal to  $\tilde{\mu}$  for large  $k$  contradicting  $h(\nu_k) > 0$ .

There is a subsequence in  $k$  such that  $\hat{\xi}_k^M \rightarrow \hat{\xi}_\infty^M$  for all  $M$ . Let us also denote by  $\beta_M^\infty$  the limit of  $\beta_M^k$ . Then consider a subsequence in  $M$  such that  $\hat{\xi}_\infty^M$  is converging to  $\beta\hat{\mu}_1 (= \beta_\alpha \hat{\mu}_{1,\alpha})$  with  $\beta = \lim_M \beta_M^\infty$ . We also let  $(1 - \beta)\hat{\mu}_0 = \hat{\mu} - \beta\hat{\mu}_1$ . In this way,  $\hat{\mu}_0$  and  $\hat{\mu}_1$  are both probability measures.

**Lemma 7.** *The measures  $\hat{\mu}_0$  and  $\hat{\mu}_1$  satisfy the following properties:*

- $\hat{\mu}_1$  is  $F$ -invariant,
- $\lambda^+(x) \geq \alpha$  for  $\mu_1$ -a.e.  $x$  and  $\hat{\mu}_1 = \hat{\mu}_1^+$ ,
- $\int \phi d\hat{\mu}_0 = \alpha$ .

*Proof.* For any continuous function  $\psi : \mathbb{P}TM \rightarrow \mathbb{R}$  and for any  $k$ , we have

$$\left| \int \psi d\hat{\xi}_k^M - \int \psi \circ F d\hat{\xi}_k^M \right| \leq \frac{2 \sup_{\hat{x}} |\psi(\hat{x})|}{M}.$$

Letting  $k$ , then  $M$  go to infinity, we get  $\int \psi d\hat{\mu}_1 = \int \psi \circ F d\hat{\mu}_1$ , i.e.  $\hat{\mu}_1$  is  $F$ -invariant. In particular  $\hat{\mu}_1$  is supported on the Oseledets bundles. But the set  $K_M$  being compact, we have  $\hat{\xi}_\infty^M(K_M) \geq \limsup_k \hat{\xi}_k^M(K_M) = \beta_M^\infty$  by Lemma 1 (4). Therefore we have  $\hat{\mu}_1(\bigcup_M K_M) = 1$  as  $\hat{\xi}_\infty^M$  goes increasingly in  $M$  to  $\hat{\mu}_1$  by Lemma 1 (1). The  $F$ -invariant set  $\bigcap_k F^{-k}(\bigcup_M K_M)$  has also full  $\hat{\mu}_1$ -measure and for all  $\hat{x} = (x, v)$  in this set we have  $\limsup_n \frac{1}{n} \log \|d_x f^n(v)\| \geq \alpha$ . Consequently the measure  $\hat{\mu}_1$  is supported on the unstable bundle and  $\lambda^+(x) \geq \alpha$  for  $\mu_1$ -a.e.  $x$ . To check finally  $\int \phi d\hat{\mu}_0 = \alpha$ , it is enough to let  $M$  go to infinity in the third item of Lemma 1.  $\square$

**Remark 2.** The measure  $\hat{\mu}_{1,\alpha}^+$  increases when  $\alpha$  decreases to zero. In Theorem C of [9], the measure  $\hat{\mu}_1^+$  is obtained as the limit of  $\hat{\mu}_{1,\alpha}^+$  when  $\alpha$  goes to zero.

We pursue now the proof of the Main Theorem. Fix a sequence  $(\delta_k)_k$  of positive numbers with  $\delta_k \xrightarrow{k} 0$ . Let  $p, M \in \mathbb{N}^*$ . We consider a partition  $Q$  satisfying  $\text{diam}(Q) < \epsilon < \epsilon_p$  with  $\epsilon_p$  as in Lemma 5. We may also assume  $\partial Q$  has zero-measure for  $\mu_1$  and all the measures  $\xi_k^M$ ,  $M \in \mathbb{N}^*$  and  $k \in \mathbb{N} \cup \{\infty\}$ . Combining Lemma 5 and Lemma 4 we get for  $\epsilon < \epsilon_p$  and for some constant<sup>‡</sup>  $\gamma_{p,Q,M}$  with  $\limsup_p \sup_Q \limsup_M \gamma_{p,Q,M} = 0$ :

$$h(\nu_k) \leq \beta_M^k \frac{1}{m} H_{\xi_k^M}(Q^m) + (1 - \beta_M^k) \alpha + \left( \log 2 + \frac{1}{r-1} \right) \left( \int \frac{\log^+ \|df^p\|_\epsilon}{p} d\xi_k^M - \int \phi d\hat{\xi}_k^M \right) + \gamma_{p,Q,M} + \delta_k.$$

By letting  $k$ , then  $M$  go to infinity, we obtain for all  $m$ :

$$\limsup_k h(\nu_k) \leq \beta \frac{1}{m} H_{\mu_1}(Q^m) + (1 - \beta) \alpha + \left( \log 2 + \frac{1}{r-1} \right) \left( \int \frac{\log^+ \|df^p\|_\epsilon}{p} d\mu_1 - \int \phi d\hat{\mu}_1^+ \right) + \limsup_M \gamma_{p,Q,M}.$$

By letting  $m$  go to infinity, then  $\epsilon < \epsilon_p$  go to 0, we get:

$$\limsup_k h(\nu_k) \leq \beta h(\mu_1) + (1 - \beta) \alpha + \left( \log 2 + \frac{1}{r-1} \right) \left( \int \frac{\log^+ \|df^p\|}{p} d\mu_1 - \int \phi d\hat{\mu}_1^+ \right) + \sup_Q \limsup_M \gamma_{p,Q,M}.$$

But  $\int \phi d\hat{\mu}_1^+ = \lambda^+(\mu_1) = \lim_p \int \frac{\log^+ \|df^p\|}{p} d\mu_1$ . Therefore by letting  $p$  go to infinity we finally obtain :

$$\limsup_k h(\nu_k) \leq \beta h(\mu_1) + (1 - \beta) \alpha.$$

### 3. DYNAMICAL REPARAMETRIZATIONS WITH BOUNDED DISTORSION

In this section we establish a  $C^r$ ,  $+\infty > r > 1$ , version of the bounded geometry property at hyperbolic times established in [2]. Then we prove the semi-local *Reparametrization Lemma* stated in Proposition 1. We first recall some terminology from [2].

<sup>‡</sup> $\gamma_{p,Q,M} = \gamma_{p,M} + \frac{2}{M} + \frac{12 \log \#Q}{M\beta}$

**3.1. Control of  $C^r$  norms with Landau-Kolmogorov inequality.** We let  $\exp$  and  $R = R_{inj}$  be respectively the exponential map and the radius of injectivity of the Riemannian manifold  $(M, \|\cdot\|)$ . For  $x \in M$  we let

$$f^x = \exp_{fx}^{-1} \circ f \circ \exp_x : B(R) \subset T_x M \sim \mathbb{R}^2 \rightarrow T_{fx} M \sim \mathbb{R}^2.$$

There is  $\epsilon > 0$  depending only on  $f$  so small that for any  $x \in M$  the map  $f_\epsilon^x = f^x(\epsilon \cdot)$  satisfies  $\|f_\epsilon^x\|_r := \max_{k=1, \dots, r} \|d^k f_\epsilon^x\| = \|df_\epsilon^x\|$ . For any  $1 \geq b > 0$  we let  $\psi_b : [-\epsilon, \epsilon] \circlearrowleft$ , be the linear map  $x \mapsto bx$ . For any  $(\epsilon, r)$ -bounded curve  $\sigma : [-\epsilon, \epsilon] \rightarrow M$  with  $\sigma(0) = x$  we let  $\sigma_\epsilon = \epsilon^{-1} \exp_x^{-1} \circ \sigma$ .

**Lemma 8.** *Let  $\sigma$  be a strongly  $(\epsilon, r)$ -bounded curve with  $\sigma(0) = x$  and  $v_x$  the projective vector tangent to  $\sigma$  at  $x$ . There exists a constant  $C = C(r) > 1$  depending only on  $r$  and  $(M, \|\cdot\|)$  such that the map  $f \circ \sigma \circ \psi_a : [-\epsilon, \epsilon] \rightarrow M$  is  $(\epsilon, r)$ -bounded with*

$$a = a(x, f) = C^{-1} (\|d_x f\|_\epsilon / \|d_x f(v_x)\|)^{-1/r-1}.$$

*Proof.* We compute for some constants  $C_1 > \dots > C_4$  depending only on  $r$  and  $(M, \|\cdot\|)$  and with  $b = (\|d_x f\|_\epsilon / \|d_x f(v_x)\|)^{-1/r-1}$ :

$$\begin{aligned} d^r(\exp_{fx}^{-1} \circ f \circ \sigma \circ \psi_b) &= d^r(\exp_{fx}^{-1} \circ f \circ \sigma) b^r, \\ \|d^r(\exp_{fx}^{-1} \circ f \circ \sigma \circ \psi_b)\| &\leq \frac{C_4}{2} \|f_\epsilon^x\|_r \|\sigma_\epsilon\|_r b^r, \text{ by Fa di Bruno's formula,} \\ &\leq \frac{C_4}{2} \|f_\epsilon^x\|_r \epsilon^{-1} \|\exp_x^{-1} \circ \sigma\|_r b^r, \\ &\leq \frac{C_4}{2} \|df_\epsilon^x\|_\epsilon \epsilon^{-1} \|\exp_x^{-1} \circ \sigma\|_r b^r, \text{ by the choice of } \epsilon, \\ &\leq \frac{C_4}{2} \|df_\epsilon^x\|_\epsilon \epsilon^{-1} \|d(\exp_x^{-1} \circ \sigma)\| b^r, \text{ since } \sigma \text{ is } (\epsilon, r)\text{-bounded,} \\ &\leq \frac{C_3}{2} b^{r-1} \|d_x f\|_\epsilon \|d\sigma\| b, \\ &\leq C_3 \|d_x f(v_x)\| \frac{\|d\sigma\|}{2} b, \text{ by definition of } b, \\ &\leq C_3 \|d_x f(v_x)\| \|\sigma'(0)\| b, \\ &\leq C_2 \|d(\exp_{fx}^{-1} \circ f \circ \sigma \circ \psi_b)\|. \end{aligned}$$

Then by the Landau-Kolmogorov inequality (see [2]), we have :

$$\|\exp_{fx}^{-1} \circ f \circ \sigma \circ \psi_b\|_r \leq C_1 \|d(\exp_{fx}^{-1} \circ f \circ \sigma \circ \psi_b)\|.$$

By taking  $a = b/C_1$  we get the desired result.  $\square$

**3.2. Bounded geometry at hyperbolic times  $k$ .** Let  $\sigma : I \rightarrow M$ , where  $I$  is an open bounded interval of  $\mathbb{R}$ , be a  $C^r$  embedded smooth curve with  $\bar{D} \subset \text{Im}(\sigma)$ . For  $x \in \text{Im}(\sigma)$  and  $n \in \mathbb{N}$  we let  $I_n^x = I_n^x(\epsilon, \sigma, r)$  be the largest subinterval of  $I$  such that  $\sigma \circ \psi_n^x$  is strongly  $(\epsilon, n, r)$ -bounded, where  $\psi_n^x$  denotes the affine reparametrization  $\psi_n^x = \psi_{n,r}^x : [-\epsilon, \epsilon] \rightarrow I_n^x$  with  $\sigma \circ \psi_n^x(0) = x$ . For  $y \in \text{Im}(\sigma)$  we let  $D_k(y) (= D_{k,\sigma}^\epsilon(y)) := \text{Im}(f^k \circ \sigma \circ \psi_k^y)$  and  $B_k(y) := \text{Im}(\sigma \circ \psi_k^y)$ .

A  $(\epsilon, r)$ -bounded curve  $\sigma$  with  $\sigma(0) = x$  is said **ample** when  $\|d(\exp_x^{-1} \circ \sigma)\| > 1/2$ . Then the length of  $\sigma$  is larger  $\frac{\epsilon}{2}$ .

Recall that for  $x \in D$  we let  $\hat{x} = (x, v_x) \in \mathbb{P}TM$  with  $v_x$  being the line tangent to  $D$  at  $x$ .

**Lemma 9.** *Let  $\alpha > \frac{\lambda^+(f)}{r}$ . There exist  $\epsilon > 0$  and  $1 > \tau > 0$  depending only on  $\alpha$  and  $f$ , and  $N$  depending on  $f$ ,  $\alpha$  and  $D$  such that for any  $x \in D$  and any  $n \in E(\hat{x})$  larger than  $N$ , the length of  $D_k(x)$  is larger than  $\tau\epsilon$ .*

*Proof.* Assume  $n$  is a  $\alpha$ -hyperbolic time for  $x$  with  $\alpha > \frac{\lambda^+(f)}{r}$ . Let  $C$  be the universal constant in Lemma 8. We may choose  $p$  so large that  $b := \alpha - \frac{\log \|df^p\| + (r-1)\log C}{pr} > 0$ . Finally take  $\epsilon > 0$  with  $\|(f^p)_\epsilon^x\|_r = \|d(f^p)_\epsilon^x\|$  for all  $x \in M$ .

Let  $m$  be the largest integer  $m'$  less than or equal to  $n$  such that  $f^{m'} \circ \sigma \circ \psi_m^x$  is ample, i.e.  $\left\| d \left( \exp_{f^{m'}x}^{-1} \circ f^{m'} \circ \sigma \circ \psi_{m'}^x \right) \right\| > 1/2$ . If there is no such  $m'$ , we let  $m = 0$ . For  $L \in \mathbb{N}$  we let  $A_L := \min_{0 \leq l < L, x \in M} a(x, f^l)$ . Let  $K_0 = K_0(\alpha, f)$  and  $K_1 = K_1(\alpha, f, D)$  be integers fixed later on.

- If  $m > n - K_0p$  and  $m > 0$  then  $\sigma \circ \psi_m^x(A_{K_0p} \cdot)$  is strongly  $(\epsilon, n, r)$ -bounded by Lemma 8. Indeed observe that for  $j = m+1, \dots, n$  we have  $\|d(\exp_{f^jx}^{-1} \circ f^j \circ \sigma \circ \psi_m^x(A_{K_0p} \cdot))\| \leq 1/2$ , otherwise this would contradict the definition of  $m$ . Moreover the length of  $D_n(x)$  is larger than  $\tau\epsilon$  with

$$\tau = \frac{A_{K_0p}}{2} \min_{k < K_0p} \|df^{-k}\|^{-1}.$$

- Consider now the case  $k := n - m \geq N := K_0p$  and  $m > 0$ . Write  $n - m = qp + r$  with  $0 \leq r < p$ . By Lemma 8 we have then with  $C$  as in Lemma 8:

$$\begin{aligned} \frac{|\psi_n^x|}{|\psi_m^x|} &\geq \left( \frac{(C^{r-1} \|df^p\|)^{k/p}}{e^{\phi_k(F^m \hat{x})}} \right)^{-1/r-1}, \\ &\geq \left( \frac{(C^{r-1} \|df^p\|)^{1/p}}{e^\alpha} \right)^{-k/r-1}, \text{ as } n \text{ is a } \alpha\text{-hyperbolic time,} \\ &\geq e^{-k\alpha} \left( \frac{(C^{r-1} \|df^p\|)^{1/pr}}{e^\alpha} \right)^{-kr/r-1}, \\ (3.1) \quad &\geq e^{-k\alpha} e^{\frac{K_0pbr}{r-1}}, \text{ as } b = \alpha - \frac{\log \|df^p\| + (r-1)\log C}{pr} > 0. \end{aligned}$$

It follows that for others universal constant  $B$ :

$$\begin{aligned} \|d(\exp_{f^n x}^{-1} \circ f^n \circ \sigma \circ \psi_n^x)\| &\geq B \|d_0(f^n \circ \sigma \circ \psi_n^x)\|, \\ &\geq B e^{k\alpha} \|d_0(f^m \circ \sigma \circ \psi_n^x)\|, \text{ as } n \text{ is a } \alpha\text{-hyperbolic time,} \\ &\geq B e^{k\alpha} \|d_0(f^m \circ \sigma \circ \psi_m^x)\| \times \frac{|\psi_n^x|}{|\psi_m^x|}, \text{ as } \psi_m^x \text{ and } \psi_n^x \text{ are affine,} \\ (3.2) \quad &\geq B e^{\frac{K_0pbr}{r-1}} \|d(f^m \circ \sigma \circ \psi_m^x)\|, \text{ by (3.1),} \\ \|d(\exp_{f^n x}^{-1} \circ f^n \circ \sigma \circ \psi_n^x)\| &\geq B e^{\frac{K_0pbr}{r-1}} \|d(\exp_{f^m x}^{-1} \circ f^m \circ \sigma \circ \psi_m^x)\|, \\ &\geq B e^{\frac{K_0pbr}{r-1}} / 2, \\ &\geq 1/2, \text{ by choosing } K_0 = K_0(\alpha, f) \text{ appropriately.} \end{aligned}$$

Therefore the  $(\epsilon, n, r)$ -bounded curve  $\exp_{f^n x}^{-1} \circ f^n \circ \sigma \circ \psi_n^x$  is ample, contradicting the definition of  $m$ . Consequently, only this case can not occur.

- Finally assume  $m = 0$  and  $n > K_1$ . We can follow the same lines as in the previous case till (3.2):

$$\begin{aligned} \|d(\exp_{f^n x}^{-1} \circ f^n \circ \sigma \circ \psi_n^x)\| &\geq B e^{\frac{K_0 p b r}{r-1}} \|d(\sigma \circ \psi_0^x)\|, \\ &\geq 1/2, \text{ by choosing } K_1 = K_1(\alpha, f, D) \text{ appropriately.} \end{aligned}$$

Again the  $(\epsilon, n, r)$ -bounded curve  $\exp_{f^n x}^{-1} \circ f^n \circ \sigma \circ \psi_n^x$  is ample, contradicting the definition of  $m$ .

This concludes the proof by taking  $N = pK_1(\alpha, f, D)$ .  $\square$

**3.3. Proof of Proposition 1.** Fix  $p \in \mathbb{N}^*$  and  $0 \leq q < p$ . Without loss of generality we can take  $M \gg p$ . Let  $Q$  be a partition with diameter less than some  $\epsilon < \epsilon_p$  with  $\epsilon_p$  being fixed later on in the proof of Lemma 11. We consider  $F_n \in Q^{\mathbb{E}_n^M}$  with  $n > N$  (as defined in Lemma 9). We let  $E_n$  be the set  $E_n^M(x)$  for any  $x \in F_n$ . Put  $E_n^{p,q} = E_n \cap (q + p\mathbb{N})$ . For a sequence of positive integers  $\mathcal{K} = (k_i)_{i \in E_n^{p,q}}$ , we let

$$\mathcal{H}(\mathcal{K}) := \left\{ y \in \mathbb{F}, \forall i \ k_i = \left\lceil \frac{\log^+ \|d_{f^i y} f^p\|}{\phi_p(F^i \hat{y})} \right\rceil + 1 \right\}.$$

We first estimate the number of sequences  $\mathcal{K}$  with  $\mathcal{H}(\mathcal{K}) \cap F_n \neq \emptyset$ , then reparametrize  $\mathcal{H}(\mathcal{K}) \cap F_n$  for each  $\mathcal{K}$ . Let  $\|df^\pm\| = \max(\|df\|, \|df^{-1}\|)$ .

**Lemma 10.** *There is a sequence  $(\epsilon_n)_n$  with  $\lim_n \epsilon_n = 0$  depending only on  $\mathbb{F}$  such that for any  $y \in F_n$  we have with  $\hat{\zeta}_{p,q,F_n}^M = \frac{1}{n} \int \sum_{k \in E_n^{p,q}} \delta_{F^k(x, v_x)} d\zeta_{F_n}(x)$  and  $\zeta_{p,q,F_n}^M$  its push-forward on  $M$ :*

$$(3.3) \quad \frac{1}{n} \log_2 \#\{\mathcal{K}, \mathcal{H}(\mathcal{K}) \cap F_n \neq \emptyset\} \leq \int \log^+ \|df^p\|_\epsilon d\zeta_{p,q,F_n}^M - \int \phi d\hat{\zeta}_{F_n}^M + \frac{4(p+1) \log \|df^\pm\|}{M} + \frac{1}{p} + \epsilon_n.$$

*Proof.* First observe  $E_n \Delta (\{0, \dots, p-1\} + E_n^{q,p}) \subset \{-p+1, \dots, p-1\} + E_n \Delta (E_n + 1)$ . As  $\#E_n \Delta (E_n + 1) \leq 2n/M$  we have also  $\#E_n \Delta (\{0, \dots, p-1\} + E_n^{q,p}) \leq 4pn/M$ . For all  $y \in F_n$  we have:

- $|\sum_{i \in E_n^{q,p}} \phi_p(F^i \hat{y}) - \sum_{i \in E_n} \phi(F^i \hat{y})| \leq n \frac{4p \log \|df^\pm\|}{M}$ , as observed above,
- $|\sum_{i \notin E_n} \phi(F^i \hat{y}) - \alpha(n - \#E_n)| \leq n \frac{\log \|df^\pm\|}{M}$ , by Lemma 1 (3),
- $\epsilon_n := 2 \sup_{y \in \mathbb{F}} |\sum_{0 \leq i \leq n} \phi(F^i \hat{y}) - n\lambda^+(\nu)| \xrightarrow{n} 0$  by (2.3).

By combining the two last inequalities we get for all  $y, z \in F_n$ :

$$\left| \sum_{i \in E_n} \phi(F^i \hat{y}) - \phi(F^i \hat{z}) \right| \leq n \left( \epsilon_n + 2 \frac{\log \|df^\pm\|}{M} \right),$$

then by integrating  $\hat{z}$  with respect to  $\hat{\zeta}_{F_n}^M$

$$\left| \sum_{i \in E_n} \phi(F^i \hat{y}) - n \int \phi d\hat{\zeta}_{F_n}^M \right| \leq n \left( \epsilon_n + 2 \frac{\log \|df^\pm\|}{M} \right).$$

Together the inequality of the first item we get

$$(3.4) \quad \left| \sum_{i \in E_n^{q,p}} \phi_p(F^i \hat{y}) - n \int \phi d\hat{\zeta}_{F_n}^M \right| \leq n \left( \varepsilon_n + \frac{4(p+1) \log \|df^\pm\|}{M} \right).$$

For any  $y, z \in F_n$  and any  $i \in E_n^{q,p}$ , the points  $f^i y$  and  $f^i z$  lie in the same atom of  $Q$ , thus they are  $\varepsilon$ -close, in particular  $\log^+ \|d_{f^i y} f^p\| \leq \log^+ \|d_{f^i z} f^p\|_\varepsilon$ . Therefore if  $y$  belongs moreover to  $\mathcal{H}(\mathcal{K})$  we get together with (3.4):

$$(3.5) \quad \frac{1}{n} \sum_i k_i \leq A_n := \int \log^+ \|df^p\|_\varepsilon d\zeta_{p,q,F_n}^M - \int \phi d\hat{\zeta}_{F_n}^M + \frac{4(p+1) \log \|df^\pm\|}{M} + \frac{1}{p} + \varepsilon_n.$$

Finally the cardinality of sequences of positive integers  $(k_1, \dots, k_N)$  with  $\sum_{i=1, \dots, N} k_i \leq S$  is less than  $\binom{N}{S} \leq 2^S$ .  $\square$

**Lemma 11.** *One can choose  $\varepsilon_p$  with the following property for any  $\varepsilon < \varepsilon_p$ . For any  $F_n$  as above there is a family  $\Psi_n = \Psi_n^q$  of affine reparametrizations  $\psi : [-\varepsilon, \varepsilon] \circlearrowleft$ , such that for some constant  $C$  depending only on  $r$  and  $f$  (not on  $p, M$  or  $n$ ):*

- $\text{Im}(\sigma) \cap \mathcal{H}(\mathcal{K}) \cap F_n \subset \bigcup_{\psi_n \in \Psi_n} \text{Im}(\sigma \circ \psi_n)$ ,
- $\forall \psi_n \in \Psi_n \forall q + p\mathbb{N} \ni k \leq n$ ,  $f^k \circ \sigma \circ \psi_n$  is strongly  $(\varepsilon, r)$ -bounded,
- 

$$(3.6) \quad \log \#\Psi_n \leq \frac{\sum_i k_i}{r-1} + \alpha(n - \#E_n) + C \left( \frac{n}{p} + n - m_n + p\#(E_n + 1)\Delta E_n \right).$$

*Proof.* First let us observe by arguing as in Lemma 8 that if  $\sigma$  is strongly  $(\varepsilon, r)$ -bounded, then there is a family  $\mathcal{F}$  of affine reparametrizations  $\phi$  of  $[-\varepsilon, \varepsilon]$  such that  $f \circ \sigma \circ \phi$  is strongly  $(\varepsilon, r)$ -bounded with  $\#\mathcal{F}$  depending only on  $f$  and  $r$ .

We argue by induction on  $n$ . Let  $F_n \in Q^{E_n^M}$  and let  $E_n$  be the associated atom of  $E_n^M$ . Without loss of generality we can assume  $n$  belongs to  $E_n$  according to our first observation, i.e.  $m_n = n$ . The term  $C(n - m_n)$  in (3.6) follows from this reduction). Let  $n'$  be the largest integer in  $q + p\mathbb{N}$  less than or equal to  $n$ . We have the following alternative:

- (1)  $[n' - p, n'] \subset E_n$ , then we let  $m = n' - p$ ,
- (2) there is  $n' > m \in E_n$  with  $]m, n'[\cap E_n = \emptyset$ ,
- (3) there is  $q \in [n - 2p, n[\cap (E_n + 1)\Delta E_n$ , then we let  $m = q$  or  $q - 1$  depending whether  $q$  belongs to  $E_n$  or  $E_n + 1$ .

In the first case (1) we argue as in the Reparameterization Lemma in [4]. By induction hypothesis there is a family  $\Psi_m$  satisfying the conclusion of Lemma 11 for  $m$  with  $F_m$  being the atom of  $Q^{E_n^M}$  containing  $F_n$ . Let  $\psi_m \in \Psi_m$  with  $\text{Im}(\sigma \circ \psi_m) \cap \mathcal{H}(\mathcal{K}) \cap F_n \neq \emptyset$ . Let  $\varepsilon_p > 0$  so small that  $\|(f^p)_\varepsilon^x\|_r = \|d(f^p)_\varepsilon^x\|$  for all  $x \in M$  and for all  $\varepsilon < \varepsilon_p$ . By using Lemma 8 for  $f^p$  as in [4, Proposition 2], there is a family  $\Theta$  of affine reparametrizations of  $[-\varepsilon, \varepsilon]$  such that:

- $f^{n'} \circ \sigma \circ \psi_m \circ \theta$  is strongly  $(\varepsilon, r)$ -bounded,
- $\text{Im}(\sigma \circ \psi_m) \cap \mathcal{H}(\mathcal{K}) \cap F_n \subset \bigcup_{\theta \in \Theta} \text{Im}(\sigma \circ \psi_m \circ \theta)$ ,
- $\#\Theta \leq C e^{\frac{k_{n'}}{r-1}}$ .

This concludes the proof in case (1) by letting  $\Psi_n$  be the union of affine reparametrizations  $\psi_m \circ \theta$  over all  $\psi_m \in \Psi_m$  and  $\theta \in \Theta = \Theta(\psi_m)$ . The contribution of case (1) in (3.6) is given by  $\frac{\sum_i k_i}{r-1} + C\frac{n}{p}$ .

In the second case (2) we argue as in Lemma 13 in [2]. For any  $x \in F_n$ , the integers  $m$  and  $n$  are hyperbolic times. By Lemma 9, there is  $\tilde{\epsilon}$  and  $\tau$  depending only on  $f$  and  $\alpha$  such that for  $\epsilon' < \tilde{\epsilon}$  the sizes of  $D_m(x) = D_m^{\epsilon'}(x)$  and  $D_n(x) = D_n^{\epsilon'}(x)$  are bounded from below by some  $\epsilon = \tau\epsilon' < \epsilon'$ . But as already observed, the distorsion is bounded on these curves and  $[m, n']$  is contained in a neutral block, consequently:

$$|\phi_{n-m}(F^m \hat{x}) - \alpha(n-m)| \leq p \log \|df^\pm\|.$$

Therefore the length of  $f^{-(n-m)}D_n(x) \subset D_m(x)$  is larger than  $\|df^\pm\|^{-p}e^{-\alpha(n-m)}\epsilon/2$ .

We can choose  $\epsilon_p$  with  $\epsilon_p < \tau\tilde{\epsilon}/2$ . We assume the diameter of  $Q$  is less than  $\epsilon < \epsilon_p$ . Write  $F_n = \bigcap_{k \in E_n} f^{-k}Q_k$  for  $(Q_k)_k \in Q^{E_n}$ . For two points  $x, y \in F_n \cap f^{-n}Q_n$ , either  $D_n(x)$  and  $D_n(y)$  are disjoint or  $D_n(x) \cap Q_n = D_n(y) \cap Q_n$  by Lemma 11 in [2]. Let  $\Psi_m$  be the family of affine reparametrizations at step  $m$  with respect to the atom  $F_m$  of  $Q^{E_m}$  containing  $F_n$ . Let  $\psi_m \in \Psi_m$  with  $\text{Im}(\sigma \circ \psi_m) \cap \mathcal{H}(\mathcal{K}) \cap F_n \neq \emptyset$ . There is a minimal collection  $(x_i)_{i \in I(\psi_m)}$  of points in  $\text{Im}(\sigma \circ \psi_m) \cap \mathcal{H}(\mathcal{K})$  such that the pairwise disjoint curves  $(E_n(x_i))_i$  cover  $\text{Im}(\sigma \circ \psi_m) \cap \mathcal{H}(\mathcal{K}) \cap F_n$ . For any  $i$ , we have  $D_m(x_i) \cap \text{Im}(f^m \circ \sigma \circ \psi_m) \neq \emptyset$ . From the above lower bound on the length of  $D_m(x_i)$ , we get  $\sharp I(\psi_m) \leq 4\|df^\pm\|^{-1}e^{-\alpha(n-m)}$ . Moreover each strongly  $(\epsilon', r, n)$ -bounded curve  $\psi_n^{x_i} = E_n(x_i)$  may be obviously covered by a family  $\mathcal{F}_i$  of  $(\epsilon, r, n)$ -bounded curves with  $\sharp \mathcal{F}_i \leq \tau^{-1} + 1$ . We conclude by letting  $\Psi_n$  be the union of  $\mathcal{F}_i$  over  $i \in I(\psi_m)$  and  $\psi_m \in \Psi_m$ . Case (2) corresponds to the term  $\alpha(n - \sharp E_n) + Cp\sharp(E_n + 1)\Delta E_n$  in (3.6).

The last case follows easily from our starting observation and leads to another error term of the form  $Cp\sharp(E_n + 1)\Delta E_n$  in (3.6).  $\square$

By increasing the cardinality of  $\Psi_n$  with a factor depending only on  $p$  and  $f$  we may assume  $\sigma \circ \psi_n$  is  $(\epsilon, r, n)$ -bounded for any  $\psi_n \in \Psi_n$ . We recall that  $\frac{m_n(\hat{x})}{n}$  is converging uniformly to 1 on  $F$ . Together with (3.3), (3.6), (3.5), we get for some  $\gamma_{p,M}$  with  $\limsup_p \limsup_M \gamma_{p,M} = 0$ :

$$\frac{1}{n} \log \sharp \Psi_n^q \leq \left(1 - \frac{\sharp E_n}{n}\right) \alpha + \left(\log 2 + \frac{1}{r-1}\right) \left(\int \log^+ \|d_x f^p\|_{\epsilon_p} d\zeta_{p,q,F_n}^M(x) - \int \phi d\hat{\zeta}_{F_n}^M\right) + \gamma_{p,M}.$$

We finally let  $\Psi_{F_n}$  be the collection  $\Psi_n^{q'}$  with  $\sharp \Psi_n^{q'} = \min_{0 \leq q < p} \sharp \Psi_n^q$ . We conclude:

$$\begin{aligned} \frac{1}{n} \log \sharp \Psi_{F_n} &\leq \frac{1}{p} \sum_{0 \leq q < p} \frac{1}{n} \log \sharp \Psi_n^q, \\ &\leq \left(1 - \frac{\sharp E_n}{n}\right) \alpha + \left(\log 2 + \frac{1}{r-1}\right) \left(\frac{1}{p} \sum_{0 \leq q < p} \int \log^+ \|d_x f^p\|_{\epsilon} d\zeta_{p,q,F_n}^M(x) - \int \phi d\hat{\zeta}_{F_n}^M\right) + \gamma_{p,M}, \\ &\leq \left(1 - \frac{\sharp E_n}{n}\right) \alpha + \left(\log 2 + \frac{1}{r-1}\right) \left(\int \frac{\log^+ \|d_x f^p\|_{\epsilon}}{p} d\zeta_{F_n}^M(x) - \int \phi d\hat{\zeta}_{F_n}^M\right) + \gamma_{p,M}. \end{aligned}$$

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