GIBBS-MARKOV STRUCTURES AND LIMIT LAWS FOR PARTIALLY HYPERBOLIC ATTRACTORS WITH MOSTLY EXPANDING CENTRAL DIRECTION

by

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Abstract. — We consider a partially hyperbolic set $K$ on a Riemannian manifold $M$ whose tangent space splits as $T_K M = E^{cu} \oplus E^s$, for which the centre-unstable direction $E^{cu}$ expands non-uniformly on some local unstable disk. We show that under these assumptions $f$ induces a Gibbs-Markov hyperbolic structure. Moreover, the decay of the return time function can be controlled in terms of the time typical points need to achieve some uniform expanding behavior in the centre-unstable direction. As an application of the main result we obtain certain rates for decay of correlations, large deviations, an almost sure invariance principle and the validity of the Central Limit Theorem.

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1. Introduction

Remarkable advances in the study of dynamical systems, specially the statistical properties of systems with chaotic behavior, have been achieved through the idea of *inducing*. Roughly speaking, this consists of replacing the initial dynamical system by another one whose dynamical features are easier to understand and from which one can recover much information on the initial system. This idea goes back to the 70’s where Markov partitions have been used to study the statistical properties of uniformly hyperbolic dynamical systems via conjugations to shifts. Since then, a main goal in dynamical systems theory is to enlarge that strategy to wider classes of dynamical systems.

A main achievement in this direction has been attained by Young in [19], where she developed an abstract framework that proved to be very useful in a systematic treatment of several classes of dynamical systems, including Axiom A attractors, piecewise hyperbolic maps, billiards with convex scatterers, logistic maps and Hénon-type attractors. The latter case had actually been considered by Benedicks and Young in [6]. A preponderant role in this context is played by *Gibbs-Markov structures*, which may be understood as a generalization of the classical Markov partitions, and are naturally associated to an inducing scheme.

Dynamical systems that do not fit the class of uniformly hyperbolic ones but combine non-uniform expanding/contracting central directions with other directions of uniformly hyperbolic behavior give rise to a wider class of partially hyperbolic dynamical systems. The case of partially hyperbolic diffeomorphisms for which the tangent bundle over some attracting set splits as $E^{cs} \oplus E^{cu}$, the sum of one invariant sub-bundle with non-uniformly contracting behavior and another one with uniformly expanding behavior, has been treated in [9], where some Gibbs-Markov structures were obtained to deduce decay of correlations and the validity of the Central Limit Theorem for the SRB measures which had been obtained in [7]; see also [8, 17]. Limit theorems for partially hyperbolic systems of this type were also obtained in [10].

Our main goal in this work is to prove the existence of Gibbs-Markov structures in the dual case of partially hyperbolic diffeomorphisms with an attracting set over which the tangent bundle splits as $E^{s} \oplus E^{cu}$, the sum of a sub-bundle $E^{s}$ with uniformly contracting behavior and another one $E^{cu}$ with non-uniform expanding behavior. This kind of attracting sets has been previously considered in [2], where the existence of *SRB measures* was established. The method used in [2] is based on the simple idea of iterating Lebesgue measure on some centre-unstable disk and deduce the absolute continuity of weak* accumulation points. For that reason it gives not much information on the properties of such SRB measures. As a byproduct of the machinery that we develop here, we are also able to deduce the existence of the SRB measure. Our method uses deeper knowledge on the geometrical structure of the attractor, thus enabling us to prove the existence of a Gibbs-Markov structure inside it, leading to an inducing scheme. As an immediate consequence of our main result, combined with others from [5, 14, 16], we easily deduce some statistical properties of these dynamical systems, namely decay of correlations, central limit theorem, large deviations and a multidimensional almost sure invariant principle. Let us point out that the case $E^{s} \oplus E^{cu}$ that we consider here is, for our purposes, considerably more difficult to deal with than the dual case $E^{cs} \oplus E^{u}$, since the richest part of the dynamics in the
neighborhood of an attracting set occurs in the unstable direction, where in our case the expansion is attained just asymptotically.

A Gibbs-Markov structure is characterized by the existence of a suitable region of the phase space partitioned into subsets (possibly infinitely many), and associated to each of these subsets a given return time. Comparing to classical constructions using Markov partitions, the big difference lies on the possibility of infinitely many return times, as long as the measure of points with larger returns decays to zero. The flexibility conferred by the chance of arbitrarily large return times is a fundamental step to applications in non-uniformly hyperbolic settings, where some times large waiting times are needed to reach good expansion rates in the centre-unstable direction for typical points. In certain cases we are able to determine the speed at which the return times decay, given in terms of the time that generic points need to achieve those good expansion properties.

The final part of the argument for proving our main theorem follows the strategy used in [3] for non-uniformly expanding endomorphisms (non-invertible smooth dynamical systems). The argument gives no optimal conclusions out of the polynomial case. The lack of efficiency for exponential or subexponential decays relies on [3, Proposition 6.1] which still has no suitable generalizations. A main achievement in this direction has been obtained in [11] by mean of a different geometrical construction, leading to exponential and subexponential decays of return times. The construction performed in [3] can be thought of as being local, in the sense that the partition is obtained by considering convenient returns of points in a small disk to itself. The construction in [11] instead uses a finite global partition of the whole ambient manifold as a starting point. However, this strategy has no natural generalization to the diffeomorphism case due to the non-compactness of unstable manifolds.

Overview. — This paper is organized as follows. In the remaining of this introduction we consider three subsections. In the first one we define the Gibbs-Markov structures. In the second one we introduce partial hyperbolicity and state our main result on the existence of Gibbs-Markov structures for certain partially hyperbolic attractors. In the final subsection we define some limit laws and state some statistical consequences of our main result. In Section 2 we recall some results on hyperbolic times and bounded distortion from [2]. The construction of the Gibbs-Markov structure for partially hyperbolic attractors is performed in Section 3. We begin with some results on the recurrence of disks, and then we perform an algorithmic construction that gives rise to the product structure. Finally, in Subsection 3.5 we prove some results on the regularity of the stable and unstable foliations. This comprises the generalization of classical results for uniformly hyperbolic attractors to our setting, namely the Hölder continuity of the central-unstable direction and the absolute continuity of the stable foliation. Finally, the estimates on the decay of return times is obtained in Section 4.

1.1. Gibbs-Markov structures. — Let \( f : M \to M \) be a diffeomorphism of a Riemannian manifold \( M \). We say that \( f \) is \( C^{1+} \) if \( f \) is \( C^1 \) and \( Df \) is Hölder continuous. Let \( \text{Leb} \) denote the Lebesgue measure on the Borel sets of \( M \) associated to the Riemannian structure. Given a submanifold \( \gamma \subset M \) we use \( \text{Leb}_\gamma \) to denote the Lebesgue measure on \( \gamma \) induced by the restriction of the Riemannian structure to \( \gamma \).
An embedded disk \( \gamma \subset M \) is called an \textit{unstable manifold} if \( \text{dist}(f^{-n}(x), f^{-n}(y)) \to 0 \) as \( n \to \infty \) for every \( x, y \in \gamma \). Similarly, \( \gamma \) is called a \textit{stable manifold} if \( \text{dist}(f^n(x), f^n(y)) \to 0 \) as \( n \to \infty \) for every \( x, y \in \gamma \).

Let \( \text{Emb}^1(D^u, M) \) be the space of \( C^1 \) embeddings from \( D^u \) into \( M \). We say that \( \Gamma^u = \{\gamma^u\} \) is a \textit{continuous family of \( C^1 \) unstable manifolds} if there is a compact set \( K^s \), a unit disk \( D^u \) of some \( \mathbb{R}^n \), and a map \( \Phi^u : K^s \times D^u \to M \) such that

- \( \gamma^u = \Phi^u(\{x\} \times D^u) \) is an unstable manifold;
- \( \Phi^u \) maps \( K^s \times D^u \) homeomorphically onto its image;
- \( x \mapsto \Phi^u|\{(x) \times D^u\} \) is a continuous map from \( K^s \) to \( \text{Emb}^1(D^u, M) \).

Continuous families of \( C^1 \) stable manifolds are defined similarly. We say that \( \Lambda \subset M \) has a \textit{product structure} if there exist a continuous family of unstable manifolds \( \Gamma^u = \{\gamma^u\} \) and a continuous family of stable manifolds \( \Gamma^s = \{\gamma^s\} \) such that

- \( \Lambda = (\cup \gamma^u) \cap (\cup \gamma^s) \);
- \( \dim \gamma^u + \dim \gamma^s = \dim M \);
- each \( \gamma^s \) meets each \( \gamma^u \) in exactly one point;
- stable and unstable manifolds meet transversally at angles bounded away from 0.

Let \( \Lambda \subset M \) have a product structure whose associated defining families are \( \Gamma^s \) and \( \Gamma^u \). A subset \( \Lambda_0 \subset \Lambda \) is called an \textit{s-subset} if \( \Lambda_0 \) also has a hyperbolic product structure, and its defining families, \( \Gamma^s_0 \) and \( \Gamma^u_0 \), can be chosen with \( \Gamma^s_0 \subset \Gamma^s \) and \( \Gamma^u_0 = \Gamma^u \); \textit{u-subsets} are defined similarly. Given \( x \in \Lambda \), let \( \gamma^s(x) \) denote the element of \( \Gamma^s \) containing \( x \), for \( s = \text{a, u} \). For each \( n \geq 1 \) we let \( f^n(x) \) denote the restriction of the map \( f^n \) to \( \gamma^u \)-disks and \( \det D(f^n(x)) \) denote the Jacobian of \( D(f^n) \).

We require that the product structure satisfies several properties that we explicit below in (P₁)-(P₅). From here on we assume that \( C > 0 \) and \( 0 < \beta < 1 \) are constants depending only on \( f \) and \( \Lambda \).

(P₁) \textbf{Markov:} there are pairwise disjoint \( s \)-subsets \( \Lambda_1, \Lambda_2, \ldots \subset \Lambda \) such that

(a) \( \text{Leb}_\gamma((\Lambda \setminus \cup \Lambda_i) \cap \gamma) = 0 \) on each \( \gamma \in \Gamma^u \);

(b) for each \( i \in \mathbb{N} \) there is \( R_i \in \mathbb{N} \) such that \( f^{R_i}(\Lambda_i) \) is \( u \)-subset, and for all \( x \in \Lambda_i \)

\( f^{R_i}(\gamma^s(x)) \subset \gamma^s(f^{R_i}(x)) \) \quad \text{and} \quad f^{R_i}(\gamma^u(x)) \supset \gamma^u(f^{R_i}(x)).

(P₂) \textbf{Contraction on} \( \Gamma^s \): for all \( y \in \gamma^s(x) \) and \( n \geq 1 \)

\( \text{dist}(f^n(y), f^n(x)) \leq C\beta^n. \)

(P₃) \textbf{Backward contraction on} \( \Gamma^u \): for all \( x, y \in \Lambda_i \) with \( y \in \gamma^u(x) \), and \( 0 \leq n < R_i \)

\( \text{dist}(f^n(y), f^n(x)) \leq C\beta^{R_i-n} \text{dist}(f^{R_i}(x), f^{R_i}(y)). \)

(P₄) \textbf{Bounded distortion:} for all \( x, y \in \Lambda_i \) with \( y \in \gamma^u(x) \)

\( \log \frac{\det D(f^{R_i})u(x)}{\det D(f^{R_i})u(y)} \leq C \text{dist}(f^{R_i}(x), f^{R_i}(y))\gamma. \)

(P₅) \textbf{Regularity of the foliations:}

(a) for all \( y \in \gamma^s(x) \) and \( n \geq 0 \)

\( \log \prod_{i=n}^{\infty} \frac{\det Df^u(f^i(x))}{\det Df^u(f^i(y))} \leq C\beta^n; \)
(b) given $\gamma, \gamma' \in \Gamma^u$, define $\phi: \gamma \cap \Lambda \to \gamma' \cap \Lambda$ as $\phi(x) = \gamma^s(x) \cap \gamma$. Then $\phi$ is absolutely continuous and
\[
\frac{d(\phi^{-1}_{\gamma} \text{Leb}_\gamma)}{d\text{Leb}_{\gamma'}}(x) = \prod_{i=0}^{\infty} \frac{\det Df^i(x)}{\det Df^i(\phi(x))}. 
\]
See Section 3.5 for a precise definition of absolute continuity. A product structure for which the five properties above hold will be called a Gibbs-Markov structure.

1.2. Partially hyperbolic attractors. — Let $K \subset M$ be a compact invariant set for a $C^1$ diffeomorphism $f: M \to M$, meaning that $f(K) = K$. We say that $K$ has a dominated splitting if there exists a continuous $Df$-invariant splitting $T_K M = E^{cs} \oplus E^{cu}$ and $0 < \lambda < 1$ such that for some choice of a Riemannian metric on $M$
\[
\|Df|E^{cs}_x\| \cdot \|Df^{-1}|E^{cu}_{f(x)}\| \leq \lambda, \quad \text{for all } x \in K. \tag{1}
\]
We call $E^{cs}$ the centre-stable bundle and $E^{cu}$ the centre-unstable bundle. We say that $K$ is partially hyperbolic if it has a dominated splitting $T_K M = E^{cs} \oplus E^{cu}$ for which $E^{cs}$ is uniformly contracting: there is $0 < \lambda < 1$ such that for some choice of a Riemannian metric on $M$
\[
\|Df|E^{cs}_x\| \leq \lambda, \quad \text{for all } x \in K. \tag{2}
\]
Fix now some small number $c > 0$. We say that $f$ is non-uniformly expanding in the central-unstable direction at a point $x \in K$ if
\[
\limsup_{n \to +\infty} \frac{1}{n} \sum_{j=1}^{n} \log \|Df^{-1}|E^{cu}_{f^j(x)}\| < -c. \tag{NUE}
\]
We define the expansion time function
\[
\mathcal{E}(x) = \min \left\{ N \geq 1: \frac{1}{n} \sum_{i=0}^{n-1} \log \|Df^{-1}|E^{cu}_{f^i(x)}\| < -c, \quad \forall n \geq N \right\}. \tag{3}
\]
Note that $\mathcal{E}(x)$ is finite for the points $x \in K$ satisfying NUE.

In this work we shall be considering partially hyperbolic sets of the same type of those considered in [2], for which the centre-stable direction is uniformly contracting and the central-unstable direction is non-uniformly expanding. To highlight the uniform contraction in the centre-stable direction we shall write $E^{s}$ instead of $E^{cs}$.

**Theorem A.** — Let $f: M \to M$ be a $C^{1+}$ diffeomorphism and let $K \subset M$ be a transitive partially hyperbolic set such that $T_K M = E^{s} \oplus E^{cu}$. Assume that for some local unstable disk $D \subset K$ and $\tau > 0$ one has $\text{Leb}_D \{\mathcal{E} > n\} = O(n^{-\tau})$. Then there exists $\Lambda \subset K$ with a Gibbs-Markov structure. Moreover, $\text{Leb}_\gamma \{R > n\} = O(n^{-\tau})$ for any $\gamma \in \Gamma^u$.

**Remark 1.1.** — The existence of a disk $D$ for which NUE is satisfied Lebesgue almost everywhere can actually hold under very mild conditions. Indeed, as shown in [4, Theorem A], if $K$ attracts a positive Lebesgue measure set of points for which NUE holds, then $K$ contains some local unstable disk $D$ for which NUE holds for $\text{Leb}_D$ almost every point.
Remark 1.2. — In the present situation, under the assumptions of Theorem A we are able to say more about the set $\Lambda$ with the product structure. Actually, our construction gives that the set $\Lambda$ itself coincides with the union of the leaves in $\Gamma^u$. This is not always the case, e.g. for Hénon attractors $\Lambda$ is a Cantor set; see [6].

An open class of diffeomorphisms for which $K = M$ is partially hyperbolic and satisfies the assumptions of Theorem A can be found in [2, Appendix A]. The calculations in [2] give that for such diffeomorphisms one has $\text{Leb}_D\{E > n\}$ decaying exponentially fast, which then implies that $\text{Leb}_\gamma\{R > n\}$ has super-polynomial decay, meaning that it decays faster than any polynomial. The transitivity of the diffeomorphisms in that class has been proved in [18].

1.3. Limit laws. — An $f$-invariant Borel probability $\mu$ in $M$ is called an SRB measure if, for a positive Lebesgue measure set of points $x \in M$,

$$\lim_{n \to +\infty} \frac{1}{n} \sum_{j=0}^{n-1} \varphi(f^j(x)) = \int \varphi \, d\mu, \quad \text{for any continuous } \varphi : M \to \mathbb{R}. \quad (4)$$

Defining the correlation function of observables $\varphi, \psi : M \to \mathbb{R}$ as

$$C_n(\varphi, \psi) = \left| \int (\varphi \circ f^n)\psi \, d\mu - \int \varphi \, d\mu \int \psi \, d\mu \right|,$$

it is sometimes possible to obtain specific rates for which $C_n(\varphi, \psi)$ decays to 0 as $n$ tends to infinity, at least for certain classes of observables with some regularity. Note that taking the observables as characteristic functions of Borel sets we are led to the classical definition of mixing. The next two results follow from Theorem A together with [5, Theorem B]; see also [5, Remark 2.4].

**Corollary B (Decay of Correlations).** — Let $f : M \to M$ be a $C^{1+}$ diffeomorphism and let $K \subset M$ be a transitive partially hyperbolic set such that $T_K M = E^s \oplus E^{cu}$. Assume that there is a local unstable disk $D \subset K$ and $\tau > 1$ such that $\text{Leb}_D\{E > n\} = O(n^{-\tau})$. Then some power of $f$ has an SRB measure $\mu$ and $C_n(\varphi, \psi) = O(n^{-\tau+1})$ for Hölder continuous $\varphi, \psi : M \to \mathbb{R}$.

The existence of the SRB measure for $f$ has been proved in [2, Theorem A]. In general, we can only assure that the correlation decay holds for some power of $f$. However, if the return times associated to the elements of the product structure given by Theorem A are relatively prime, i.e. $\gcd\{R_i\} = 1$, then the same conclusion holds with respect to $f$. For simplicity, from here on we assume that $\gcd\{R_i\} = 1$. Otherwise, the same conclusions hold for some power of $f$.

In the next result we obtain conditions for the validity of the Central Limit Theorem (CLT), which states that the deviation of the average values of an observable along an orbit from the asymptotic average is given by a Normal Distribution: given any Hölder continuous $\varphi : M \to \mathbb{R}$ which is not a coboundary ($\varphi \neq \psi \circ f - \psi$ for any $\psi$) there exists
\( \sigma > 0 \) such that
\[
\frac{1}{\sqrt{n}} \sum_{j=0}^{n-1} \left( \varphi \circ f^j - \int \varphi d\mu \right) \xrightarrow{\text{distr}} N(0, \sigma), \quad \text{as } n \to \infty.
\]

**Corollary C (Central Limit Theorem).** — Let \( f : M \to M \) be a \( C^{1+} \) diffeomorphism and let \( K \subset M \) be a transitive partially hyperbolic set with \( T_K M = E^s \oplus E^{cu} \). Assume that there is a local unstable disk \( D \subset K \) and \( \tau > 2 \) such that \( \text{Leb}_D \{ \mathcal{E} > n \} = O(n^{-\tau}) \). Then CLT holds for any Hölder continuous \( \varphi : M \to \mathbb{R} \) which is not a coboundary.

Given a Hölder continuous observable \( \varphi : M \to \mathbb{R} \) and \( \epsilon > 0 \), we define the deviation of the time average with respect to the mean of \( \varphi \) as
\[
\mathcal{D}_n(\varphi, \epsilon) = \mu \left( \left\{ x \in M : \left| \frac{1}{n} \sum_{j=0}^{n-1} \varphi(f^j(x)) - \int \varphi d\mu \right| > \epsilon \right\} \right).
\]

The next result is a consequence of Theorem A together with \[15, \text{Theorem 4.2}\] and \[14, \text{Theorem 1.2}\].

**Corollary D (Large Deviations).** — Let \( f : M \to M \) be a \( C^{1+} \) diffeomorphism and let \( K \subset M \) be a transitive partially hyperbolic set with \( T_K M = E^s \oplus E^{cu} \). Assume that there is a local unstable disk \( D \subset K \) and \( \tau > 2 \) such that \( \text{Leb}_D \{ \mathcal{E} > n \} = O(n^{-\tau}) \). Then, for any Hölder continuous \( \varphi : M \to \mathbb{R} \) and any \( \epsilon > 0 \), we have \( \mathcal{D}_n(\varphi, \epsilon) = O(n^{-\tau+1}) \).

Given a Hölder continuous function \( \varphi : M \to \mathbb{R}^d \), we denote \( \varphi_n = \sum_{j=0}^{n-1} (\varphi \circ f^j - \int \varphi d\mu) \), for each \( n \geq 1 \). We say that the sequence \( \{ \varphi_n \} \) satisfies a \( d \)-dimensional almost sure invariance principle (ASIP) if there exists \( \lambda > 0 \) and a probability space supporting a sequence of random variables \( \{ \varphi^*_n \} \) and a \( d \)-dimensional Brownian motion \( W(t) \) such that
1. \( \{ \varphi_n \} \) and \( \{ \varphi^*_n \} \) are equally distributed;
2. \( \varphi^*_n = W(n) + O(n^{1/2-\lambda}) \), as \( n \to \infty \), almost everywhere.

The next result is a consequence of Theorem A together with \[16, \text{Theorem 4.2}\].

**Corollary E (Almost Sure Invariance Principle).** — Let \( f : M \to M \) be a \( C^{1+} \) diffeomorphism and let \( K \subset M \) be a transitive partially hyperbolic set with \( T_K M = E^s \oplus E^{cu} \). Assume that there is a local unstable disk \( D \subset K \) and \( \tau > 3 \) such that \( \text{Leb}_D \{ \mathcal{E} > n \} = O(n^{-\tau}) \). Then \( \{ \varphi_n \} \) satisfies an ASIP for any Hölder continuous \( \varphi : M \to \mathbb{R}^d \).

2. Preliminaries

With the only exception of Lemma 2.7, the material contained in this section comes from \[2\]. Our aim is to recall some results on the Hölder continuity of the tangent direction of centre-unstable submanifolds, to introduce hyperbolic times and recall their main features.

We fix continuous extensions of the two subbundles \( E^s \) and \( E^{cu} \) to some neighborhood \( U \) of \( K \) that we denote by \( \tilde{E}^s \) and \( \tilde{E}^{cu} \). We do not require these extensions to be invariant...
under $Df$. Given $0 < a < 1$, we define the centre-unstable cone field $C^cu_a = (C^cu_a(x))_{x \in U}$ of width $a$ by

$$C^cu_a(x) = \{ v_1 + v_2 \in \tilde{E}^s_x \oplus \tilde{E}^{cu}_x \text{ such that } \|v_1\| \leq a\|v_2\| \}. \quad (5)$$

We define the centre-stable cone field $C^s_a = (C^s_a(x))_{x \in U}$ of width $a$ in a similar way, simply reversing the roles of the subbundles in $(5)$. We fix $a > 0$ and $U$ small enough so that, up to slightly increasing $\lambda < 1$, the domination condition $(1)$ remains valid for any pair of vectors in the two cone fields:

$$\|Df(x)v^s\| \cdot \|Df^{-1}(f(x))v^{cu}\| \leq \lambda\|v^s\|\|v^{cu}\|$$

for every $v^s \in C^s_a(x)$, $v^{cu} \in C^cu_a(f(x))$, and any point $x \in U \cap f^{-1}(U)$. Note that the centre-unstable cone field is positively invariant:

$$Df(x)C^cu_a(x) \subset C^cu_a(f(x)),$$

whenever $x, f(x) \in U$. Actually, the domination property together with the invariance of $E^{cu} = \tilde{E}^{cu}|K$ imply that

$$Df(x)C^cu_a(x) \subset C^cu_\lambda(f(x)) \subset C^cu_a(f(x)),$$

for every $x \in K$, and this extends to any $x \in U \cap f^{-1}(U)$ just by continuity.

We say that an embedded $C^1$ submanifold $N \subset U$ is tangent to the centre-unstable cone field, if the tangent subspace to $N$ at each point $x \in N$ is contained in the corresponding cone $C^cu_a(x)$. Then $f(N)$ is also tangent to the centre-unstable cone field, if it is contained in $U$, by the domination property. The tangent bundle of $N$ is said to be Hölder continuous if $x \mapsto T_xN$ defines a Hölder continuous section from $N$ to the corresponding Grassman bundle of $M$. Given a $C^1$ submanifold $N \subset U$, we define

$$\kappa(N) = \inf \{ C > 0 : \text{the tangent bundle of } N \text{ is } (C, \zeta)\text{-Hölder} \}. \quad (6)$$

The next result contains all the information we need on the Hölder control of the tangent direction and its proof can be found in [2, Corollary 2.4].

**Proposition 2.1.** — There exists $C_1 > 0$ such that, given any $C^1$ submanifold $N \subset U$ tangent to the centre-unstable cone field, then

1. there exists $n_0 \geq 1$ such that $\kappa(f^n(N)) \leq C_1$ for every $n \geq n_0$ such that $f^k(N) \subset U$ for all $0 \leq k \leq n$;
2. if $\kappa(N) \leq C_1$, then $\kappa(f^n(N)) \leq C_1$ for every $n \geq 1$ such that $f^k(N) \subset U$ for all $0 \leq k \leq n$;
3. if $N$ and $n$ are as in the previous item, then the functions

$$J_k : f^k(N) \ni x \mapsto \log |\det (Df | T_xf^k(N))|, \quad 0 \leq k \leq n,$$

are $(L_1, \zeta)$-Hölder continuous with $L_1 > 0$ depending only on $C_1$ and $f$.

The notion we introduce next allows us to derive uniform expansion and bounded distortion estimates from the non-uniform expansion assumption in the centre-unstable direction.

**Definition 2.2.** — Given $0 < \sigma < 1$, we say that $n$ is a $\sigma$-hyperbolic time for $x \in K$ if

$$\prod_{j=n-k+1}^n \|Df^{-1}|E^{cu}_{f^j(x)}\| \leq \sigma^k, \quad \text{for all } 1 \leq k \leq n.$$
In particular, if $n$ is a $\sigma$-hyperbolic time for $x$, then $Df^{-k} \mid E^{cu}_{f^n(x)}$ is a contraction for every $1 \leq k \leq n$:

$$\|Df^{-k} \mid E^{cu}_{f^n(x)}\| \leq \prod_{j=n-k+1}^n \|Df^{-1} \mid E^{cu}_{f^j(x)}\| \leq \sigma^k. \quad (7)$$

If $a > 0$ is sufficiently small and we choose $\delta_1 > 0$ also small so that the $\delta_1$-neighborhood of $K$ is contained in $U$, then, by continuity,

$$\|Df^{-1}(f(y))v\| \leq \frac{1}{\sqrt{\sigma}} \|Df^{-1}|E^{cu}_{f^n(x)}\| \|v\|, \quad (8)$$

whenever $x \in K$, $\operatorname{dist}(x, y) \leq \delta_1$, and $v \in C^{cu}_a(y)$.

Given any disk $\Delta \subset M$, we use $\operatorname{dist}_\Delta(x, y)$ to denote the distance between $x, y \in \Delta$, measured along $\Delta$. The distance from a point $x \in \Delta$ to the boundary of $\Delta$ is $\operatorname{dist}_\Delta(x, \partial \Delta) = \inf_{y \in \partial \Delta} \operatorname{dist}_\Delta(x, y)$. The next result has essentially been proved in [2, Lemma 2.7]; see [4, Lemma 4.2] for a detailed proof.

**Lemma 2.3.** — Let $\Delta \subset U$ be a $C^1$ disk of radius $\delta$, with $0 < \delta < \delta_1$, tangent to the centre-unstable cone field. There is $n_0 \geq 1$ such that for $x \in \Delta \cap K$ with $\operatorname{dist}_\Delta(x, \partial \Delta) \geq \delta/2$ and $n \geq n_0$ a $\sigma$-hyperbolic time for $x$ there is a neighborhood $V_n$ of $x$ in $\Delta$ such that:

1. $f^n$ maps $V_n$ diffeomorphically onto a centre-unstable disk of radius $\delta_1$ around $f^n(x)$;
2. for every $1 \leq k \leq n$ and $y, z \in V_n$,
   $$\operatorname{dist}_{f^{-k}(V_n)}(f^{n-k}(y), f^{n-k}(z)) \leq \sigma^{k/2} \operatorname{dist}_{f^n(V_n)}(f^n(y), f^n(z)).$$

We call the sets $V_n$ hyperbolic pre-balls and their images $f^n(V_n)$ hyperbolic balls. Notice that the latter are indeed centre-unstable balls of radius $\delta_1$. The next result follows from Proposition 2.1 and Lemma 2.3 above exactly as in the proof of [2, Proposition 2.8].

**Corollary 2.4.** — There exists $C_2 > 1$ such that given a disk $\Delta$ as in Lemma 2.3 with $\kappa(\Delta) \leq C_1$, and given any hyperbolic pre-ball $V_n \subset \Delta$ with $n \geq n_0$, then for all $y, z \in V_n$

$$\log \left| \frac{\det Df^n \mid T_y\Delta}{\det Df^n \mid T_z\Delta} \right| \leq C_2 \operatorname{dist}_{f^n(D)}(f^n(y), f^n(y))^{C}.$$

The next result states the existence of $\sigma$-hyperbolic times for points satisfying NUE and its proof can be found in [2, Lemma 3.1, Corollary 3.2].

**Proposition 2.5.** — There are $\theta > 0$ and $\sigma > 0$ such that for every $x \in K$ with $\mathcal{E}(x) \leq n$ there exist $\sigma$-hyperbolic times $1 \leq n_1 < \cdots < n_l \leq n$ for $x$ with $l \geq \theta n$.

Given $n \geq 1$, we define

$$H_n = \{ x \in K : \text{ $n$ is a $\sigma$-hyperbolic time for $x$} \}.$$ 

The next result follows from the proposition above as in [2, Proposition 3.5] or [3, Corollary 2.3]. It plays important role in the metric estimates of Section 4.
Corollary 2.6. — Let $D$ be a local unstable disk for which NUE holds Leb$_D$ almost everywhere. Given $n \ge 1$ and $A \subset D \setminus \{E > n\}$ with Leb$_D(A) > 0$ we have

$$\frac{1}{n} \sum_{j=1}^{n} \frac{\text{Leb}_D(A \cap H_j)}{\text{Leb}_D(A)} \ge \theta.$$  

We finish this section with a technical lemma which will be useful in the proof of Proposition 4.3.

Lemma 2.7. — Given $0 < \varepsilon < \delta_1$, there exists $N_{\varepsilon} > 0$ such that for every $n \ge n_0$ and every $x \in D \cap H_n$, the ball of radius $\varepsilon$ centered at $f^n(z)$ inside the hyperbolic ball $f^n(V_n(x))$ contains a hyperbolic pre-ball $V_k(z)$ with $k \le N_{\varepsilon}$.

Proof. — Given $n \ge n_0$ and $x \in D \cap H_n$, let $B^n_x = f^n(V_n(x))$ be the hyperbolic ball associated to $x$ with hyperbolic time $n$. Recall that $B^n_x$ is a centre-unstable ball of radius $\delta_1$ around $f^n(x)$. We define the cylinder

$$C^n_x = \bigcup_{y \in B^n_x} W^s_{\delta_1}(y).$$  

Since NUE holds for Leb$_D$ almost every point and it remains valid by forward iteration, it follows that Leb$_{B^n_x}$ almost every point in $B^n_x$ also satisfies NUE. Given $z \in C^n_x$, we define

$$\tilde{E}(z) = \min \left\{ N \ge 1 : \frac{1}{n} \sum_{i=0}^{n-1} \log \|Df^{-1}|\tilde{E}^n_{f(w)}\| < -\frac{3c}{4}, \quad \forall n \ge N \right\}.$$  

The fact that NUE holds for Leb$_{B^n_x}$ almost every point in $B^n_x$ together with (15) imply that $\tilde{E}(z)$ is well defined for Leb almost every point $z \in C^n_x$. Hence $\tilde{E}(z)$ is well defined for Leb almost every point $z$ belonging to the set

$$C = \bigcup_{x \in D \cap H_n} C^n_x.$$  

Using Lemma 2.3 we may choose $n_{\varepsilon}$ large enough so that any hyperbolic pre-ball of $\sigma$-hyperbolic time $n \ge n_{\varepsilon}$ will have diameter not exceeding $\varepsilon/2$. Let now $B^n_x(\varepsilon/2)$ denote the ball of radius $\varepsilon/2$ around $f^n(x)$ inside $B^n_x$, and take

$$v_{\varepsilon} = \min_{x \in D \cap H_n} \left\{ \text{Leb} \left( \bigcup_{y \in B^n_x(\varepsilon/2)} W^s_{\delta_1}(y) \right) \right\}.$$  

Since the sizes and tangent directions of hyperbolic balls and stable disks are uniformly controlled, this minimum $v_{\varepsilon}$ must be strictly positive. Hence, as

$$\text{Leb} \left\{ z \in C : \tilde{E}(z) > n \right\} \rightarrow 0, \quad \text{when } n \rightarrow \infty,$$

it is possible to choose $N_{\varepsilon} \in \mathbb{N}$ large enough so that

$$\text{Leb} \left\{ z \in C : \tilde{E}(z) > N_{\varepsilon} \right\} \le v_{\varepsilon}. \quad (9)$$  

We take $N_{\varepsilon}$ also satisfying $\theta N_{\varepsilon} > n_{\varepsilon}$. By the choice of $v_{\varepsilon}$, given $n \ge n_0$ and $x \in D \cap H_n$ there must be some $z \in W^s_{\delta_1}(y)$ with $y \in B^n_x(\varepsilon/2)$ such that $\tilde{E}(z) \le N_{\varepsilon}$. Using (15) we easily deduce that $\mathcal{E}(z) \le N_{\varepsilon}$; recall (3). Hence, by Proposition 2.5 there exists some
σ-hyperbolic time $h$ for $y$ with $θN_ε < h ≤ N_ε$. Since we have taken $θN_ε > n_ε$, then by the choice of $n_ε$ we are done.

3. Gibbs-Markov structure

In this section we describe the geometric construction of the product structure. This will be made in three steps. In the first one we prove the existence of a centre-unstable disk (a reference disk) for which forward iterates come back to a neighborhood of itself, and whose projection along stable leaves cover the disk completely. In the next step we use these returns to define a partition on the reference disk. This part of the construction follows the ideas of [3, Section 3]. Finally we use the partition on the reference leaf and the returns to define the product structure.

3.1. Returning disks. — Let $D$ be a local unstable disk as in Theorem A. Diminishing $δ_1 > 0$, if necessary, we may assume that $D$ has radius $δ_1$. Take $0 < δ_s < δ_1/2$ such that points in $K$ have local stable manifolds of radius $δ_s$. In particular, these local stable manifolds are contained in $U$; recall (8).

**Lemma 3.1.** — There are $N_0 ≥ 1$ and $q ∈ K$ such that:

1. $W_{δ_s/2}(q)$ intersects $D$ in a point $p$ with $dist_D(p, ∂D) > δ_1/2$;
2. for each centre-unstable disk $δ_1$ of radius $δ_1$ centered at a point in $K$ there are $0 ≤ j ≤ N_0$ and a disk $γ^u_1$ of radius $δ_1/2$ centered at a point $z ∈ W_{δ_s/4}(f^{-j}(q))$.

**Proof.** — We start by observing that there is a constant $α > 0$ (depending only on the minimum angle between the two spaces of the dominated splitting over $K$) with the following property: given $x ∈ K$, $ρ > 0$ and $y ∈ K$ with $dist(x, y) < ρ$ having a local unstable disk of radius $δ_1$ centered at $y$, then $W_{δ_1}^s(x)$ intersects $W_{δ_1}^u(y)$ in a point $z$ with

$$dist_{W_{δ_1}^s}(z, x) < αρ \quad \text{and} \quad dist_{W_{δ_1}^u}(z, y) < δ_1/2.$$

In particular, such a point $z$ has a neighborhood of radius $δ_1/2$ inside $W_{δ_1}^u(y)$.

Since we are assuming $f|K$ transitive, we may fix $q ∈ K$, a small number $0 < ρ < δ_s/(4α)$ and $N_0 ∈ N$ such that both i) $W_{δ_s/2}(q)$ intersects $D$ in a point $p$ with $dist_D(p, ∂D) > δ_1/2$, and ii) $\{f^{-N_0}(q), \ldots, f^{-1}(q), q\}$ is $ρ$-dense in $K$. By $ρ$-dense we mean that any other point in $K$ has one of those pre-images at a distance less than $ρ$.

Hence, given any centre-unstable disk $γ^u_1$ of radius $δ_1$ centered at a point $y ∈ K$, there is $0 ≤ j ≤ N_0$ such that $dist(f^{-j}(q), y) < ρ$. Then, by the choice of $α$ and $ρ$, we have that $W_{δ_s}(f^{-j}(q))$ intersects $γ^u_1$ in a point $z$ with $dist_{W_{δ_1}(f^{-j}(q))}(z, f^{-j}(q)) < αρ < δ_s/4$ and $dist_{γ^u_1}(z, y) < δ_1/2$.

**Lemma 3.2.** — There is $δ_2 > 0$ such that if $γ^u$ is a centre-unstable disk of radius $δ_1/2$ centered at a point $z ∈ W_{δ_2}(w)$ with $w ∈ K$, then $f(γ^u)$ contains a centre-unstable disk of radius $δ_2$ centered at $f^j(z)$, for each $1 ≤ j ≤ N_0$.

**Proof.** — Let us first prove the result for $j = 1$. Let $f(y)$ be a point in $∂f(γ^u)$ minimizing the distance from $f(z)$ to $∂f(γ^u)$, and let $η_1$ be a curve of minimal length in $f(γ^u)$
connecting \( f(z) \) to \( f(y) \). Define \( \eta_0 = f^{-1}(\eta_1) \). Denote by \( \dot{\eta}_1(x) \) the tangent vector to the curve \( \eta_1 \) at the point \( x \). Then,

\[
\|Df^{-1}(w)\dot{\eta}_1(x)\| \leq C \|\dot{\eta}_1(x)\|
\]

where

\[
C = \max_{x \in \mathcal{M}} \left\{ \|Df^{-1}(x)\| \right\} \geq 1.
\]

Hence,

\[
\text{length}(\eta_0) \leq C \text{length}(\eta_1).
\]

Noting that \( \eta_0 \) is a curve connecting \( z \) to \( y \in \partial \gamma^u \), this implies that

\[
\text{length}(\eta_0) \geq \delta_1/2.
\]

Hence

\[
\text{length}(\eta_1) \geq C^{-1} \text{length}(\eta_0) \geq C^{-1} \delta_1/2.
\]

Thus \( f(\gamma^u) \) contains the disk \( \gamma_1^u \) of radius \( C^{-1} \delta_1/2 \) around \( f(z) \). Moreover,

\[
\text{dist}(f(z), f(w)) \leq \lambda \delta_s < \delta_s,
\]

and so, by the choice of \( \delta_s \), we have that \( \gamma_1^u \) is also a centre-unstable disk. Making now \( \gamma_1^u \) play the role of \( \gamma^u \) and \( f^2(z) \) play the role of \( f(z) \) we prove that:

(a) \( f(\gamma_1^u) \) contains a centre-unstable disk of radius \( C^{-2} \delta_1/2^2 \) centered at \( f^2(z) \);

(b) \( \text{dist}(f^2(z), f^2(w)) \leq \lambda^2 \delta_s < \delta_s \).

Item (a) gives in particular that \( f^2(\gamma^u) \) contains a centre-unstable disk of radius \( C^{-2} \delta_1/2^2 \) centered at \( f^2(z) \). Arguing inductively we are able to prove that \( f^j(\gamma^u) \) contains a disk of radius \( C^{-j} \delta_1/2^j \geq C^{-N_0} \delta_1/2^{N_0} \) around \( f^j(z) \), for each \( 1 \leq j \leq N_0 \). Hence, we just have to take \( \delta_2 = C^{-N_0} \delta_1/2^{N_0} \).

3.2. Partition on a reference leaf. — The construction that we are going to explain below requires the use several constants. First we take \( \delta_1 > 0 \) as in (8), and \( 0 < \delta_2 < \delta_1 \) as in Lemma 3.2. Then we take \( \delta_0 > 0 \) and \( \varepsilon > 0 \) so that

\[
\delta_0 \ll \delta_2 \quad \text{and} \quad \varepsilon \ll \delta_0.
\]

Next we describe the construction of the \((m_D \mod 0)\) partition \( \mathcal{P} \) of the unstable disk of radius \( \delta_0 \) centered at \( p \) contained in \( D \). For that we consider the following neighborhoods of \( p \) in \( D \)

\[
\Delta_0^0 = B^u(p, \delta_0), \quad \Delta_0^1 = B^u(p, 2\delta_0), \quad \Delta_0^2 = B^u(p, \sqrt{\delta_0}) \quad \text{and} \quad \Delta_0^3 = B^u(p, 2\sqrt{\delta_0}),
\]

and the cylinders over these sets,

\[
C^i = \bigcup_{x \in \Delta_0^i} W^s_{\delta_0}(x), \quad \text{for } i = 0, 1, 2, 3.
\]

Letting \( \pi \) denote the projection from \( C^3 \) onto \( \Delta_0^3 \) along local stable leaves, we have

\[
\pi(C^i) = \Delta_0^i, \quad \text{for } i = 0, 1, 2, 3.
\]

We say that a centre-unstable disk \( \gamma^u \) \( u \)-crosses \( C^i \) if \( \pi(\gamma^u) = \Delta_0^i \).
Remark 3.3. — To simplify the exposition we shall pretend that each centre-unstable disk $\gamma^u$ u-crossing $C^i$ is still a disk centered at a point in $W^s_{\delta_0}(p)$ and having the same radius of $\Delta^i_0$. Actually, the radius of such a disk $\gamma^u$ is proportional to the radius of $\Delta^i_0$, with the proportionality depending only on the height of the cylinder and the angles of the two fibre bundles in the dominated splitting.

Let $\partial^u C^3_i$ denote the top and bottom components of $\partial C^3$, i.e. the set of points $z \in \partial C^3$ such that $z \in \partial W^s_{\delta_0}(x)$ for some $x \in \Delta^3_0$. By the domination property, we may take $\delta_0 > 0$ small so that no centre-unstable disk contained in $C^3$ and intersecting $W^s_{\delta_0}(p)$ can reach $\partial^u C^3$. For $0 < \sigma < 1$ given by Lemma 2.5, let

$$I_k = \{x \in \Delta^1_0 : \delta_0(1 + \sigma^{k/2}) < \text{dist}_D(x, p) < \delta_0(1 + \sigma^{(k-1)/2})\}, \quad k \geq 1,$$

be a partition (Leb$_D$ mod 0) into countably many rings of $\Delta^1_0 \setminus \Delta^0_0$.

We are now able to start with the construction of the partition $\mathcal{P}$ of $\Delta_0$. The construction requires that we introduce inductively several objects. In particular, we will consider sequences of sets $(\Delta_n)$, $(A_n)$, and $(B_n)$. For each $n \geq 0$, the set $\Delta_n$ is that part of $\Delta_0$ that has not yet been partitioned up to time $n$. The set $\Delta_n$ is the disjoint union of $A_n$ and $B_n$, where $A_n$ is essentially the part of $\Delta_n$ where new elements of partition may be appear in the next step of the construction, and $B_n$ is some protection that we put around the sets previously constructed in order to avoid overlaps. For technical reasons, a small neighborhood $A^n_\varepsilon$ of each $A_n$ will also be considered.

First step of induction. — We fix $R_0$ some large integer, and we ignore any dynamics occurring up to time $R_0$. Let $k \geq R_0 + 1$ be the first time that $\Delta_0 \cap H_k \neq \emptyset$. For $j < k$ we define formally the objects

$$A_j = A^j_f = \Delta_j = \Delta_0, \quad \text{and} \quad B_j = \emptyset.$$

Let $(\omega^3_{k,j})$ be all the center-unstable disks in $A^k_{k-1}$ contained in hyperbolic pre-balls $V_m$, with $k - N_0 \leq m \leq k$, which are mapped by $f^k$ onto a centre-unstable disk $u$-crossing $C^3$ and intersecting $W^s_{\delta_0}(p)$. Then we let

$$\omega^1_{k,j} = \omega^3_{k,j} \cap f^{-k}(C^i), \quad i = 0, 1, 2$$

and set $R(x) = k$ for $x \in \omega^0_{k,j}$. We take

$$\Delta_k = \Delta_{k-1} \setminus \{R = k\},$$

and define a function $t_k : \Delta_k \to \mathbb{N}$ by

$$t_k(x) = \begin{cases} s, & \text{if } x \in \omega^1_{k,j} \text{ and } \pi(f^k(x)) \in I_s \text{ for some } j; \\ 0, & \text{otherwise.} \end{cases}$$

Finally let

$$A_k = \{x \in \Delta_k : t_k(x) = 0\}, \quad B_k = \{x \in \Delta_k : t_k(x) > 0\}$$

and

$$A^*_k = \{x \in \Delta_k : \text{dist}_{f^{k+1}(D)}(f^{k+1}(x), f^{k+1}(A_k)) < \varepsilon\}.$$
Lemma 3.4

\[ \omega_{n,j}^i = \omega_{n,j}^3 \cap f^{-n}(C_1^i), \quad i = 0, 1, 2 \]  

set \( R(x) = n \) for \( x \in \omega_{n,j}^0 \), and let

\[ \Delta_n = \Delta_{n-1} \setminus \{ R = n \}. \]

The definition of the function \( t_n : \Delta_n \to \mathbb{N} \) is slightly different in the general case:

\[ t_n(x) = \begin{cases} 
  x, & \text{if } x \in \omega_{n,j}^1 \setminus \omega_{n,j}^0 \text{ and } f^n(x) \in I_s \text{ for some } j, \\
  0, & \text{if } x \in A_{n-1} \setminus \bigcup_j \omega_{n,j}^1, \\
  t_{n-1}(x) - 1, & \text{if } x \in B_{n-1} \setminus \bigcup_j \omega_{n,j}^1.
\end{cases} \]

Finally, we let

\[ A_n = \{ x \in \Delta_n : t_n(x) = 0 \}, \quad B_n = \{ x \in \Delta_n : t_n(x) > 0 \} \]

and

\[ A_n^\varepsilon = \{ x \in \Delta_n : \text{dist}_{f^{n+1}(D)}(f^{n+1}(x), f^{n+1}(A_n)) < \varepsilon \}. \]

At this point we have described the construction of the sets \( A_n, A_n^\varepsilon, B_n \) and \( \{ R = n \} \).

Since the components of \( \{ R = n \} \) are taken in \( A_n^\varepsilon \), it could happen that these new components intersect \( B_{n-1} \). The next lemma shows that this is not the case as long as \( \varepsilon > 0 \) is taken small enough. For notational simplicity we will drop the index \( j \) in the elements defined at (10).

**Lemma 3.4** — If \( \varepsilon > 0 \) is small, then \( \omega_{n,j}^1 \cap \{ t_{n-1} \geq 1 \} = \emptyset \) for all \( n \geq 1 \).

**Proof.** — Take \( k \geq 1 \) and let \( \omega_{n-k}^0 \) be a component of \( \{ R = n - k \} \). Let \( Q_k \) be the part of \( \omega_{n-k}^1 \) that is mapped by \( \pi \circ f^{n-k} \) onto \( I_k \), and assume that \( Q_k \) intersects some \( \omega_{n}^3 \). Recall that, by construction, \( Q_k \) is precisely that part of \( \omega_{n-k}^1 \) on which \( t_{n-1} = 1 \), and \( \omega_{n}^3 \) is contained in a hyperbolic pre-ball \( V_m \) with \( n - N_0 \leq m \leq n \).

Let \( q_1 \) and \( q_2 \) be any two points in distinct components (inner and outer, respectively) of the boundary of \( Q_k \). If we assume that \( q_1, q_2 \in \omega_{n-k}^3 \), then \( q_1, q_2 \in V_m \), and so by Lemma 2.3 we have

\[ \text{dist}_{f^{n-k}(D)}(f^{n-k}(q_1), f^{n-k}(q_2)) \leq C_0 \sigma^{k/2} \text{dist}_{f^{n}(D)}(f^n(q_1), f^n(q_2)) \quad (11) \]

for some \( C_0 \) depending on \( N_0 \). We also have for some \( C_1 > 0 \) depending on the angle of the stable and centre-unstable spaces over \( K_\infty \)

\[ \text{dist}_{f^{n-k}(D)}(f^{n-k}(q_1), f^{n-k}(q_2)) \geq C_1 \delta_0 (1 + \sigma^{(k-1)/2}) - \delta_0 (1 + \sigma^{k/2}) = C_1 \delta_0 \sigma^{k/2} (\sigma^{-1/2} - 1), \]

which combined with (11) gives

\[ \text{dist}_{f^n(D)}(f^n(q_1), f^n(q_2)) \geq \frac{C_1}{C_0} \delta_0 (\sigma^{-1/2} - 1). \]
On the other hand, since \( \omega^3_n \subset A^\varepsilon_{n-1} \) by construction of \( \omega^3_n \), taking
\[
\varepsilon < \frac{C_1}{C_0} \delta_0 (\sigma^{-1/2} - 1)
\]
we have \( \omega^3_n \cap \{ t_{n-1} > 1 \} = \emptyset \). This implies \( \omega^1_n \cap \{ t_{n-1} \geq 1 \} = \emptyset \).

3.3. Product structure. — Consider the center-unstable disk \( \Delta_0 \subset D \) and the partition \( \mathcal{P} \) of \( \Delta_0 \) \( (\text{Leb}_D \text{ mod } 0) \) defined in Section 3.2. We shall use the elements of \( \mathcal{P} \) to define the \( s \)-subsets that give rise to the hyperbolic structure. Given an arbitrary element \( \omega \in \mathcal{P} \), we have by construction some \( R(\omega) \in \mathbb{N} \) such that \( f^{R(\omega)}(\omega) \) is a center-unstable disk \( u \)-crossing \( C^0 \). We define \( C_\omega \) as the cylinder made by the stable leaves passing through the points in \( \omega \), i.e.
\[
C_\omega = \bigcup_{x \in \omega} W^s_{\delta_0}(x).
\]
The sets \( C_\omega \), with \( \omega \in \mathcal{P} \), are by definition the pairwise disjoint \( s \)-subsets \( \Lambda_1, \Lambda_2, \ldots \) which define the Markovian structure.

Now we define inductively some sets of center-unstable manifolds \( u \)-crossing \( C^0 \) that will give rise to the family \( \Gamma^u \). The first one is
\[
\Gamma_0 = \{ \Delta_0 \}.
\]
Having defined \( \Gamma_j \), for some \( j \geq 0 \), we define
\[
\Gamma_{j+1} = \{ f^{R(\omega)}(C_\omega \cap \gamma) : \omega \in \mathcal{P} \text{ and } \gamma \in \Gamma_j \}.
\]
Observe that each element of \( \Gamma_j \) is equal to an iterate of a subset of \( \Delta_0 \). In particular, the elements of each \( \Gamma_j \) are unstable manifolds. Moreover, since by construction \( f^{R(\omega)}(\omega) \) intersects \( W^s_{\delta_0/4}(p) \), then according to the choice of \( \delta_0 \) and the invariance of the stable foliation, we have that each element of \( \Gamma_j \) must \( u \)-cross \( C^0 \).

Since the union of the leaves of the sets \( \Gamma_j \), with \( j \geq 0 \), is not necessarily compact, we still need to take accumulation points of that union. Let
\[
\Delta_\infty = \bigcup_{j \geq 0} \bigcup_{\gamma_j \in \Gamma_j} \gamma_j.
\]
Given \( x \in \Delta_\infty \), there are \( (j_k)_k \to \infty \), disks \( \gamma_{j_k} \in \Gamma_{j_k} \) and points \( x_k \in \gamma_{j_k} \) converging to \( x \) as \( k \to \infty \). Using the domination property and Ascoli-Arzela theorem we conclude that the disks \( \gamma_{j_k} \) converge to a disk \( \gamma_\infty \) containing \( x \). Since the disk \( \gamma_\infty \) is accumulated by disks \( u \)-crossing \( C^0 \) then it also must \( u \)-cross \( C^0 \). We define \( \Gamma_\infty \) as the set of all these accumulation disks. Finally, we take
\[
\Gamma^u = \bigcup_{j \geq 0} \Gamma_j \cup \Gamma_\infty.
\]
3.4. Backward contraction and bounded distortion. — The backward contraction property (P₄) follows from Lemma 3.5 below. Bounded distortion is typically a consequence of backward contraction together with some Hölder control of log | det Dfⁿ|. Property (P₄) follows naturally from Proposition 2.1 together with Lemma 3.5 exactly as in the proof of [2, Proposition 2.8].

Lemma 3.5. — There is $C > 0$ such that, given $ω ∈ P$ and $γ ∈ Γ^n$, we have for all $1 ≤ k ≤ R(ω)$ and all $x, y ∈ C_ω ∩ γ$

$$\text{dist}_{f^{R(ω)−k}(C_ω ∩ γ)}(f^{R(ω)−k}(x), f^{R(ω)−k}(y)) ≤ Cσ^{k/2} \text{dist}_{f^{R(ω)}(C_ω ∩ γ)}(f^{R(ω)}(x), f^{R(ω)}(y)).$$

Proof. — Recall that, by construction, for each $ω ∈ P$ there is a hyperbolic pre-ball $V_{n(ω)}(x)$ containing $ω$ associated to some point $x ∈ D$ with $σ$-hyperbolic time $n(ω)$ satisfying $R(ω) − N_0 ≤ n(ω) ≤ R(ω)$. Taking $δ_x, δ_0 < δ_1/2$, it follows from (8) that $n(ω)$ is a $\sqrt{σ}$-hyperbolic time for every point in $C_ω ∩ γ$. Then, recall (7), this implies that for all $1 ≤ k ≤ n(ω)$ and all $x, y ∈ C_ω ∩ γ$ we have

$$\text{dist}_{f^{n(ω)−k}(C_ω ∩ γ)}(f^{n(ω)−k}(x), f^{n(ω)−k}(y)) ≤ σ^{k/2} \text{dist}_{f^{n(ω)}(C_ω ∩ γ)}(f^{n(ω)}(x), f^{n(ω)}(y)).$$

Since the difference between $R(ω)$ and $n(ω)$ is at most $N_0$, the result follows with $C$ depending only on $N_0$ and the the derivative of $f$.

3.5. Regularity of the foliations. — Here we prove property (P₅). This is standard for uniformly hyperbolic attractors, and we shall adapt classical ideas to our setting. We begin with the statement of a useful result on vector bundles whose proof can be found in [12, Theorem 6.1].

Lemma 3.6. — Let $p: Y → X$ be a vector bundle over a metric space $X$ endowed with an admissible metric. Let $D ⊂ Y$ be the unit ball bundle, and $F: D → D$ a map covering a homeomorphism $f: X → X$. Suppose $0 ≤ κ < 1$ and that for each $x ∈ X$, the restriction $F_x: D_x → D_x$ has Lipschitz constant $\text{Lip}(F_x) ≤ κ$. Then

1. There is a unique section $σ_0: X → D$ whose image is invariant under $F$.
2. Let $\text{Lip}(f) = c < ∞$ and $0 < α ≤ 1$ be such that $κc^α < 1$. Then $σ_0$ satisfies a Hölder condition of exponent $α$.

For the sake of completeness, let us mention that a metric $d$ on $E$ is admissible if there is a complementary bundle $E'$ over $X$, and an isomorphism $h: E ⊕ E' → X × A$ to a product bundle, where $A$ is a Banach space, such that $d$ is induced from the product metric on $X × A$.

Theorem 3.7. — Let $f: M → M$ be a $C^1$ diffeomorphism and let $K ⊂ M$ be a compact invariant set with a dominated splitting $T_K M = E^{cs} ⊕ E^{cu}$. Then the fiber bundles $E^{cs}$ and $E^{cu}$ are Hölder continuous on $K$.

Proof. — We consider the centre-unstable bundle, the other one is similar. For each $x ∈ K$ let $L_x$ be the space of bounded linear maps $L(E^{cu}_x, E^{cu})$. For each $x ∈ K$, let $L_x(1)$ denote the unit ball around $0 ∈ L_x$, and define $Γ_x: L_x(1) → L_{f(x)}(1)$ as the graph transform induced by $Df(x)$:

$$Γ_x(μ_x) = (Df|E^{cs}_x) ∙ μ_x ∙ (Df^{-1}|E^{cu}_{f(x)}).$$
Consider $L(E^u, E^s)$ the vector bundle over $K$ whose fiber over $x \in K$ is $L_x$, and let $D$ be its unit ball bundle. Then $\Gamma : D \to D$ is a bundle map covering $f|K$ with
\[
\text{Lip}(\Gamma_x) \leq \|Df \mid E^s_x\| \cdot \|Df^{-1} \mid E^u_{f(x)}\| \leq \lambda < 1.
\]
Let $c$ be a Lipschitz constant for $|K$, and choose $0 < \alpha \leq 1$ small so that $\lambda c^\alpha < 1$. By Lemma 3.6 there exists a unique section $\sigma_0 : X \to D$ whose image is invariant under $F$ and it satisfies a Hölder condition of exponent $\alpha$. This unique section is necessarily the null section.

The next result gives precisely $(P_5)(a)$.

**Corollary 3.8.** — There are $C > 0$ and $0 < \beta < 1$ such that for all $y \in \gamma^n(x)$ and $n \geq 0$
\[
\log \prod_{i=n}^{\infty} \frac{\det Df^n(f^i(x))}{\det Df^n(f^i(y))} \leq C\beta^n.
\]

**Proof.** — As we are assuming that $Df$ is Hölder continuous, it follows from Theorem 3.7 that \(\log |\det Df^n|\) is Hölder continuous. The conclusion is then an immediate consequence of the uniform contraction on stable leaves.

Now we are going to prove $(P_5)(b)$. We start by introducing some useful notions. We say that $\phi : N \to P$, where $N$ and $P$ are submanifolds of $M$, is absolutely continuous if it is an injective map for which there exists $J : N \to \mathbb{R}$, called the Jacobian of $\phi$, such that
\[
\text{Leb}_P(\phi(A)) = \int_A J \text{Leb}_N.
\]

Property $(P_5)(b)$ can be restated in the following terms:

**Proposition 3.9.** — Given $\gamma, \gamma' \in \Gamma^n$, define $\phi : \gamma' \to \gamma$ by $\phi(x) = \gamma^n(x) \cap \gamma$. Then $\phi$ is absolutely continuous and the Jacobian of $\phi$ is given by
\[
J(x) = \prod_{i=0}^{\infty} \frac{\det Df^n(f^i(x))}{\det Df^n(f^i(\phi(x)))}.
\]

One can easily deduce from Corollary 3.8 that this infinite product converges uniformly.

The remaining of this section is devoted to the proof of Proposition 3.10. We start with a general result about the convergence of Jacobians whose proof is given in [13, Theorem 3.3].

**Lemma 3.10.** — Let $N$ and $P$ be manifolds, $P$ with finite volume, and for each $n \geq 1$, $\phi_n : N \to P$ an absolutely continuous map with Jacobian $J_n$. Assume that

1. $\phi_n$ converges uniformly to an injective continuous map $\phi : N \to P$;
2. $J_n$ converges uniformly to an integrable function $J : N \to \mathbb{R}$.

Then $\phi$ is absolutely continuous with Jacobian $J$.

For the sake of completeness, let us mention that there is a slight difference in our definition of absolute continuity of maps. Contrarily to [13], and for reasons that will become clear in very short time, we do not impose continuity of the maps $\phi_n$. However, the proof of [13, Theorem 3.3] uses only the continuity of the limit function $\phi$, and so it still works in our case.
Consider now $\gamma, \gamma' \in \Gamma^u$ and $\phi : \gamma' \to \gamma$ as in Proposition 3.9. The proof of the next lemma is given in [13, Lemma 3.4] for uniformly hyperbolic diffeomorphisms. Nevertheless, one can easily see that it is obtained as a consequence of [13, Lemma 3.8] whose proof uses only the existence of a dominated splitting.

**Lemma 3.11.** — For each $n \geq 1$, there is an absolutely continuous $\pi_n : f^n(\gamma) \to f^n(\gamma')$ with Jacobian $G_n$ satisfying

1. $\lim_{n \to \infty} \sup_{x \in \gamma} \{\text{dist}_{f^n(\gamma')} (\pi_n(f^n(x)), f^n(\phi(x)))\} = 0$;
2. $\lim_{n \to \infty} \sup_{x \in f^n(\gamma)} \{|1 - G_n(x)|\} = 0$.

We consider the sequence of consecutive return times for points in $\Lambda$,

$$s_1 = R \text{ and } s_{n+1} = s_n + R \circ f^{s_n}, \text{ for } n \geq 1.$$ Notice that these return time functions are defined Leb-$\gamma$ almost everywhere on each $\gamma \in \Gamma^u$ and are piecewise constant.

**Remark 3.12.** — Using the sequence of return times one can easily construct a sequence of $(\text{Leb}_\gamma \mod 0$ on each $\gamma \in \Gamma^u$) partitions $(P_n)_n$ by $s$-subsets of $\Lambda$ with $s_n$ constant on each element of $P_n$, for which (P1)-(P5) hold when we take $s_n$ in the role of $R$ and the elements of $P_n$ in the role of the $s$-subsets. Moreover, the constants $C > 0$ and $0 < \beta < 1$ can be chosen not depending on $n$.

We define, for each $n \geq 1$, the map $\phi_n : \gamma \to \gamma'$ defined as

$$\phi_n = f^{-s_n} \pi_n f^{s_n}.$$ (13)

It is straightforward to check that $\phi_n$ is absolutely continuous with Jacobian

$$J_n(x) = \frac{|\det(Df^{s_n})^u(x)|}{|\det(Df^{s_n})^u(\phi_n(x))|} \cdot G_n(f^{s_n}(x)).$$ (14)

Observe that these functions are defined just Leb-$\gamma$ almost everywhere. So, we may find a Borel set $F \subset \gamma$ with full Leb-$\gamma$ measure on which they are all defined. We extend $\phi_n$ to $\gamma$ simply by considering $\phi_n(x) = \phi(x)$ and $J_n(x) = J(x)$ for all $n \geq 1$ and $x \in \gamma \setminus F$. Since $F$ has zero Leb-$\gamma$ measure one still has that $J_n$ is the Jacobian of $\phi_n$.

Proposition 3.9 is and immediate consequence of Lemma 3.10 together with the next one.

**Lemma 3.13.** — The maps $\phi_n$ converge uniformly to $\phi$ and the Jacobians $J_n$ converge uniformly to $J$.

**Proof.** — It is enough to prove the convergence of each sequence restricted to $F$, i.e. restricted to the set of points where the expressions of $\phi_n$ and $J_n$ are given by (13) and (14) respectively.

Let us prove first that $\phi_n$ converges uniformly to $\phi$. Using the backward contraction on unstable leaves given by (P3), recall Remark 3.12, we may write for $x \in \gamma$

$$\text{dist}_{\gamma'}(\phi_n(x), \phi(x)) = \text{dist}_{\gamma'}(f^{-s_n} \pi_n f^{s_n}(x), f^{-s_n} f^{s_n} \phi(x)) \leq C \beta^{s_n} \text{dist}_{f^s(\gamma)}(\pi_n f^{s_n}(x), f^{s_n} \phi(x)).$$
Since $s_n \to \infty$ as $n \to \infty$ and $\text{dist}_{f^n(\gamma)}(\pi_{s_n}f^{s_n}(x), f^{s_n}\phi(x))$ is bounded by Lemma 3.11, we have the uniform convergence of $\phi_n$ to $\phi$.

By (14) we have

$$J_n(x) = \frac{\det(Df^{s_n}u)(x)}{\det(Df^{s_n}u)(\phi_n(x))} \cdot G_{s_n}(f^{s_n}(x)).$$

Using the chain rule and Corollary 3.8 it easily follows that the first term in the product above converges uniformly to $J(x)$. Moreover, the third term converges uniformly to one, by Lemma 3.11. It remains to see that the middle term also converges uniformly to one. Recalling Remark 3.12, by bounded distortion we have

$$\frac{|\det(Df^{s_n}u)(\phi(x))|}{|\det(Df^{s_n}u)(\phi_n(x))|} \leq \exp(C \text{dist}_{f^{s_n}(\gamma)}(f^{s_n}(\phi(x)), f^{s_n}(\phi_n(x)))) = \exp(C \text{dist}_{f^{s_n}(\gamma)}(f^{s_n}(\phi(x)), \pi_{s_n}(f^{s_n}(x))))\).$$

Similarly we obtain

$$\frac{|\det(Df^{s_n}u)(\phi(x))|}{|\det(Df^{s_n}u)(\phi_n(x))|} \geq \exp\left(-C \text{dist}_{f^{s_n}(\gamma)}(f^{s_n}(\phi(x)), \pi_{s_n}(f^{s_n}(x)))\right).$$

The conclusion then follows from Lemma 3.11.

\[ \square \]

4. Decay estimates

In this section we obtain the metric estimates on the decay of $\text{Leb}_D\{R > n\}$ of Theorem A. These estimates are an adaptation of similar ones from [3, Section 5] to our setting. We start by proving estimates arising directly from the construction preformed in Section 3.2. In the final part of the argument we use some results that have been put into an abstract setting in [1, Section 4.5.2] and get the desired conclusion.

**Lemma 4.1.** There exists $a_0 > 0$ such that

$$\text{Leb}_D(B_{n-1} \cap A_n) \geq a_0 \text{Leb}_D(B_{n-1}),$$

for all $n \geq 1$.

**Proof.** It is enough to see this for each component of $B_{n-1}$. Let $C$ be a component of $B_{n-1}$ and let $Q$ be its outer ring, corresponding to $t_{n-1} = 1$. Observe that by Lemma 3.4 we have $Q = C \cap A_n$. Moreover, there must be some $k < n$ and a component $\omega_R^k$ of $\{R = k\}$ such that $\pi \circ f^k$ maps $C$ diffeomorphically onto $\cup_{i=k}^\infty I_i$ and $Q$ onto $I_k$, both with uniform bounded distortion as in Corollary 2.4. Thus, it is sufficient to compare the Lebesgue measures of $\cup_{i=k}^\infty I_i$ and $I_k$.

We have

$$\frac{\text{Leb}_D(I_k)}{\text{Leb}_D(\cup_{i=k}^\infty I_i)} \approx \frac{[\delta_0(1 + \sigma^{(k-1)/2})]^u - [\delta_0(1 + \sigma^{k/2})]^u}{[\delta_0(1 + \sigma^{(k-1)/2})]^u - \delta_0^u} \approx 1 - \sigma^{1/2},$$

where $u$ is the dimension of $E^{cu}$. \[ \square \]

**Lemma 4.2.** There exist $b_0, c_0 > 0$ with $b_0, c_0 \to 0$ as $\delta_0 \to 0$, such that

1. $\text{Leb}_D(A_{n-1} \cap B_n) \leq b_0 \text{Leb}_D(A_{n-1})$,
2. $\text{Leb}_D(A_{n-1} \cap \{R = n\}) \leq c_0 \text{Leb}_D(A_{n-1})$, 
for all $n \geq 1$.

**Proof.** — It is enough to prove this for each neighborhood of a component $\omega^0_n$ of $\{R = n\}$. Observe that by construction we have $\omega^0_n \subset A^e_{n-1}$, which means that $\omega^0_n \subset A_{n-1}$, because we are taking $\varepsilon < \delta_0$. Using the uniform bounded distortion of Corollary 2.4 we obtain

$$
\frac{\text{Leb}_D(\omega^1_n \setminus \omega^0_n)}{\text{Leb}_D(\omega^2_n \setminus \omega^0_n)} \approx \frac{\text{Leb}_D(\Delta^1_0 \setminus \Delta^0_0)}{\text{Leb}_D(\Delta^2_0 \setminus \Delta^1_0)} \approx \frac{\delta^2_0}{\delta^4_0} \ll 1,
$$

which gives the first estimate. Moreover,

$$
\frac{\text{Leb}_D(\omega^0_n)}{\text{Leb}_D(\omega^2_n \setminus \omega^1_n)} \approx \frac{\text{Leb}_D(\Delta^0_0)}{\text{Leb}_D(\Delta^2_0 \setminus \Delta^1_0)} \approx \frac{\delta^4_0}{\delta^4_0} \ll 1,
$$

and this gives the second one. □

We take $\delta_n > 0$ sufficiently small so that

$$
\left| \log \|Df^{-1} \mid E^c_{x,n} \| - \log \|Df^{-1} \mid \tilde{E}^c_{y,n} \| \right| < \frac{c}{4},
$$

(15)

for each $x \in \Lambda$ and $y \in W^a_{s}(x)$.

**Proposition 4.3.** — There exist $c_1 > 0$ and a positive integer $N = N(\varepsilon)$ such that

$$
\text{Leb}_D \left( \bigcup_{i=0}^{N} \{ R = n + i \} \right) \geq c_1 \text{Leb}_D(A_{n-1} \cap H_n),
$$

for all $n \geq 1$.

**Proof.** — Let $K_0 = \max_{x \in \Lambda} \|Df^{-1}\|$ and take $r = 5\delta_0 K_0^{N_0}$, where $N_0$ is given by Lemma 3.1. Recall that by Lemma 2.3, for each $z \in f^n(A_{n-1} \cap H_n)$ there is $x \in H_n$ and a $\sigma$-hyperbolic pre-ball $V_n(x) \subset D$ which is sent diffeomorphically onto the centre-unstable ball of radius $\delta_1$ around $z$. Let $\{z_j\}$ be a maximal set in $f^n(A_{n-1} \cap H_n)$ with the property that the sets $B_r(z_j)$ are pairwise disjoint, where each $B_r(z_j)$ is the ball of radius $r$ centered at $z_j$ inside the hyperbolic ball around $z_j$. By maximality we have

$$
\bigcup_j B_{2r}(z_j) \supset f^n(A_{n-1} \cap H_n).
$$

(16)

For each $j$ let $x_j \in H_n$ be the point such that $f^n(x_j) = z_j$.

**Claim 1.** There is 0 $k \leq N_r + N_0$ such that $t_{n+k}$ is not identically zero in $f^{-n}(B_r(z_j))$.

Assume, by contradiction, that $t_{n+k}|f^{-n}(B_r(z_j)) = 0$ for all $0 \leq k \leq N_r + N_0$. This implies that $f^{-n}(B_r(z_j)) \subset A_{n+k}$ for all $0 \leq k \leq N_r + N_0$. Using Lemma 2.7 we may find a hyperbolic pre-ball $V_m \subset B_r(z_j)$ with $\sigma$-hyperbolic time $m \leq N_r$. Now, since $f^m(V_m)$ is a centre-unstable disk of radius $\delta_1$, it follows from Lemma 3.1 and Lemma 3.2 that there are $V \subset f^m(V_m)$ and $m' \leq N_0$ such that $u$-crossing $C^3$ and intersecting $W^s_{\delta_{s/4}}(p)$. Thus, taking $k = m + m'$ we have that $0 \leq k \leq N_r + N_0$ and $f^{-n}(V_m)$ contains an element of $\{R = n + k\}$ inside $f^{-n}(B_r(z_j))$. This contradicts the fact that $t_{n+k}|f^{-n}(B_r(z_j)) = 0$ for all $0 \leq k \leq N_r + N_0$.

**Claim 2.** $f^{-n}(B_{\delta_{s/4}}(z))$ contains a component of $\{R = n + k\}$ with $0 \leq k \leq N_r + N_0$.

Let $k$ be the smallest integer $0 \leq k \leq N_r + N_0$ for which $t_{n+k}$ is not identically zero in $f^{-n}(B_r(z_j))$. Since $f^{-n}(B_r(z_j)) \subset A^e_{n-1} \subset \{t_{n-1} \leq 1\}$, there must be some component $\omega^0_{n+k}$ of $\{R = n + k\}$ for which $f^{-n}(B_r(z_j)) \cap \omega^1_{n+k} = \emptyset$. Recall that, by definition, $f^{-n+k}$
sends $\omega^1_{n+k}$ diffeomorphically onto a centre-unstable disk (of radius $2\delta_0$) $u$-crossing $C^1$ and intersecting $W^u_{\delta_0/(4)}(p)$. Thus, the diameter of $f^n(\omega^1_{n+k})$ is at most $4\delta_0 K_0^N$. Since $B_\epsilon(z)$ intersects $f^n(\omega^1_{n+k})$ and $\epsilon < \delta_0 < \delta_0 K_0^N$, we have $f^{-n}(B_{\delta_1/4}(z)) \supset \omega^0_{n+k}$, as long as we take $\delta_0 > 0$ small so that $5\delta_0 K_0^N < \delta_1/4$. Hence, we have shown that $f^{-n}(B_{\delta_1/4}(z))$ contains some component of $\{R = n + k\}$ with $0 \leq k \leq N_\epsilon + N_0$, and so we have proved the claim.

Since $n$ is a hyperbolic time for $x_j$, we have by the distortion control given by Corollary 2.4 that there is some constant $C$ only depending on $C_2$ and $\delta_1$ for which

$$\frac{\text{Leb}_D(f^{-n}(B_{2r}(z_j)))}{\text{Leb}_D(f^{-n}(B_r(z_j)))} \leq C \frac{\text{Leb}_{f^n(D)}(B_{2r}(z_j))}{\text{Leb}_{f^n(D)}(B_r(z_j))}$$

(17)

and

$$\frac{\text{Leb}_D(f^{-n}(B_r(z_j)))}{\text{Leb}(\omega^0_{n+k})} \leq C \frac{\text{Leb}_{f^n(D)}(B_r(z_j))}{\text{Leb}_{f^n(D)}(f^n(\omega^0_{n+k}))}. \quad \text{(18)}$$

Recalling that from time $n$ up to $n+k$ we have at most $N_0$ iterates, from (17) and (17) we easily deduce that there is some positive constant, that we still denote by $C$, for which

$$\text{Leb}_D(f^{-n}(B_{2r}(z_j))) \leq C \text{Leb}_D(f^{-n}(B_r(z_j)))$$

and

$$\text{Leb}_D(f^{-n}(B_r(z_j))) \leq C \text{Leb}_D(\omega^0_{n+k_j}).$$

Finally, let us compare the Lebesgue measure of the sets $\bigcup_{i=0}^N \{R = n + i\}$ and $A_{n-1} \cap H_n$. By (16) we have

$$\text{Leb}_D\left(A_{n-1} \cap H_n\right) \leq \sum_j \text{Leb}_D(f^{-n}(B_{2r}(z_j))) \leq C \sum_j \text{Leb}_D(f^{-n}(B_r(z_j))).$$

On the other hand, by the disjointness of the balls $B_r(z_j)$ we have

$$\sum_j \text{Leb}_D(f^{-n}(B_r(z_j))) \leq C \sum_j \text{Leb}_D(\omega^0_{n+k}) \leq C \text{Leb}_D\left(\bigcup_{i=0}^N \{R = n + i\}\right).$$

We just have to take $c_1 = C^{-2}$. \hfill \Box

For completing the proof of Theorem A, it is enough to show that

$$\text{Leb}_D\{\mathcal{E} > n\} = O(n^{-\tau}) \quad \Rightarrow \quad \text{Leb}_D\{R > n\} = O(n^{-\tau}).$$

Recall that we have defined $H_n$ for $n \geq 1$ as the set of points for which $n$ is a $\sigma$-hyperbolic time. In Corollary 2.6 we obtained the following estimate:

\[(m_1) \quad \text{There is } \theta > 0 \text{ such that for all } n \geq 1 \text{ and } A \subset M \setminus \{\mathcal{E} > n\} \text{ with } \text{Leb}_D(A) > 0 \]

$$\frac{1}{n} \sum_{j=1}^n \frac{\text{Leb}_D(A \cap H_j)}{\text{Leb}_D(A)} \geq \theta.$$ 

In the construction of the Markov structure have taken a disk $\Delta$ of radius $\delta_0 > 0$ and defined inductively the subsets $A_n$, $B_n$, $\{R = n\}$ and $\Delta_n$ related in the following way:

$$\Delta_n = \Delta \setminus \{R \leq n\} = A_n \cup B_n.$$ 

Moreover, we have proved in Lemma 4.1, Lemma 4.2 and Proposition 4.3 that the following metric relations hold:
(m_2) There is \( a_0 > 0 \) (bounded away from 0 with \( \delta_0 \)) such that for all \( n \geq 1 \)
\[
\text{Leb}_D(B_{n-1} \cap A_n) \geq a_0 \text{Leb}_D(B_{n-1}).
\]

(m_3) There are \( b_0, c_0 > 0 \) with \( b_0, c_0 \to 0 \) as \( \delta_0 \to 0 \), such that for all \( n \geq 1 \)
\[
\frac{\text{Leb}_D(A_{n-1} \cap B_n)}{\text{Leb}_D(A_{n-1})} \leq b_0 \quad \text{and} \quad \frac{\text{Leb}_D(A_{n-1} \cap \{R = n\})}{\text{Leb}_D(A_{n-1})} \leq c_0.
\]

(m_4) There is \( r_0 > 0 \) and an integer \( N \geq 0 \) such that for all \( n \geq 1 \)
\[
\text{Leb}_D(\bigcup_{i=0}^N \{ R = n + i \}) \geq r_0 \text{Leb}_D(A_{n-1} \cap H_n).
\]

Estimates (m_1)-(m_4) are enough to use the results of [1, Section 4.5.2] and obtain the conclusion on the decay of \( \text{Leb}_\gamma\{ R > n \} \) in the conclusion of Theorem A.

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