DETECTING SURFACE BUNDLES IN FINITE COVERS
OF HYPERBOLIC CLOSED 3-MANIFOLDS

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Abstract. The main theorem of this article provides sufficient conditions for a degree $d$ finite cover $M'$ of a hyperbolic 3-manifold $M$ to be a surface bundle. Let $F$ be an embedded, closed and orientable surface of genus $g$, close to a minimal surface in the cover $M'$, splitting $M'$ into a disjoint union of $q$ handlebodies and compression bodies. We show that there exists a fiber in the complement of $F$ provided that $d$, $q$ and $g$ satisfy some inequality involving an explicit constant $k$ depending only on the volume and the injectivity radius of $M$. In particular, this theorem applies to a Heegaard splitting of a finite covering $M'$, giving an explicit lower bound for the genus of a strongly irreducible Heegaard splitting of $M'$. Applying the main theorem to the setting of a circular decomposition associated to a non-trivial homology class of $M$ gives sufficient conditions for this homology class to correspond to a fibration over the circle. Similar methods also lead to a sufficient condition for an incompressible embedded surface in $M$ to be a fiber.

Introduction

Thurston conjectured that every complete hyperbolic, connected and orientable 3-manifold of finite volume virtually fibers over the circle, i.e. such a manifold has a finite covering that is a surface bundle over the circle.

This conjecture received a great deal of attention during the past few years, very recently culminating with the announcement of its proof by Ian Agol (thanks to works of Daniel Wise, Jeremy Kahn and Vladimir Markovic, Frédéric Haglund, Nicolas Bergeron, and many other people). The proof is based on Daniel Wise’s program.

The aim of this article is to provide explicit criteria for a given finite cover of a closed hyperbolic 3-manifold to be a surface bundle. More explicitly, given a cover $M' \to M$ of $M$ with finite degree $d$, a natural question is to wonder whether $M'$ contains an embedded surface that is a fiber, and to give an upper bound for its genus. The idea is to start with surfaces that already exist in $M'$, such as Heegaard surfaces.

This method was inspired by Lackenby’s program to find surface bundles in towers of finite coverings of a given closed hyperbolic 3-manifold.

Let us be more precise. For a surface $F$, denote by $\chi_-(F) = \max\{0, -\chi(F)\}$ the negative part of the Euler characteristic of $F$. If $C$ is a handlebody or a compression body, set $\chi_-(C) := \chi_-(\partial_+ C)$. If $S$ is a union of connected components of $\partial_- C$, the definition implies that $\chi_-(S) \leq \chi_-(C)$.

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Definition 0.1. An embedded surface $S$ in a Riemannian 3-manifold $M$ is called pseudo-minimal if it is orientable, closed, and $S$ is a minimal surface or the boundary of a regular neighborhood of a minimal non-orientable surface, possibly with a little tube attached vertically in the $I$-bundle structure.

The main result of this article is the following theorem.

**Theorem A.** Let $M$ be a hyperbolic, connected, oriented and closed 3-manifold. Denote by $\text{Inj}(M)$ the injectivity radius of $M$ and set $\epsilon = \frac{1}{2} \text{Inj}(M)$.

There exists an explicit constant $k = k(\epsilon, \text{Vol}(M)) > 0$, depending only on $\epsilon$ and the volume $\text{Vol}(M)$ satisfying the following properties.

Let $M' \to M$ be a cover of finite degree $d$ which contains a closed, orientable, embedded and pseudo-minimal surface $F$, splitting $M'$ into a disjoint union of $q$ handlebodies and compression bodies $C_1, \ldots, C_q$. Suppose that:

1. the union $F^-$ of the components of $F$ corresponding to the negative boundary components of $C_j$ is a union of incompressible surfaces, and
2. the inequality $k c \ln c < \ln \ln d$ holds, where $c = \max_{j=1, \ldots, q} \{ \chi_-(C_j) \}$.

Then one of the components of $F^-$ is the fiber of a surface-bundle structure for $M'$ (corresponding to a bundle over the circle or a twisted $I$-bundle).

The proof of this theorem leads to the following corollary.

**Corollary 0.2.** Under the assumptions of Theorem A, the volume of a handlebody $C_j$ (i.e. such that $\partial_- C_j = \emptyset$), among the $q$ compression bodies, must satisfy $\text{Vol}(C_j) < \text{Vol}(M)d/q$.

The topological assumption (1) of Theorem A may not be necessary. We conjecture that:

**Conjecture (\ast).** Theorem A is still true even if assumption (1) is not a priori satisfied.

If $N$ is a connected, compact and orientable 3-manifold, the Heegaard Euler characteristic $\chi_h^-(N)$ of $N$ is the minimum over all Heegaard surfaces $F$ of the negative part $\chi_-(F) = \min\{-\chi(F), 0\}$ of the Euler characteristic of $F$. Likewise, the strong Heegaard Euler characteristic $\chi_{sh}^-(N)$ is the minimum of $\chi_-(F)$ over all the strongly irreducible Heegaard surfaces $F$ of $N$. By convention, if the manifold $N$ does not contain any strongly irreducible Heegaard surface, $\chi_{sh}^-(N) = +\infty$. For further definitions and details about the theory of Heegaard splittings, see section 1.

As a Heegaard surface divides a 3-manifold into two compression bodies, after some work, this general theorem applies in the setting of Heegaard splittings. A consequence is the following result, which gives a stronger and explicit version of a theorem of J. Maher [Mah], stating that an infinite tower of finite coverings of $M$ with a uniform bound on the Heegaard genus does contain surface bundles. This theorem of Maher and its proof were the starting point of this work.

**Theorem 0.3.** Let $M$ be a hyperbolic, connected, oriented and closed 3-manifold. Denote by $\text{Inj}(M)$ the injectivity radius of $M$ and set $\epsilon = \frac{1}{2} \text{Inj}(M)$.

1. There exists an explicit constant $\bar{k} = \bar{k}(\epsilon, \text{Vol}(M))$ such that for every covering $M' \to M$ with finite degree $d$ such that $\bar{k} \chi_h^-(M') \ln \chi_h^-(M') \leq \ln \ln d$, $M'$ is a surface bundle with fiber of genus at most $g(M')$. License or copyright restrictions may apply to redistribution; see https://www.ams.org/journal-terms-of-use
Moreover, for every covering $M' \to M$ with finite degree $d$, one always has
\[ \bar{k} \chi^sh(M') \ln \chi^sh(M') > \ln \ln d. \]

Lackenby [L] in his program introduced the notion of a Heegaard gradient.

**Definition 0.4** ([L, pp. 319 and 320]). Let $M$ be a compact, connected and orientable 3-manifold. One defines the **infimal Heegaard gradient** of the collection of finite coverings $(M_i \to M)_{i \in \mathbb{N}}$ with degree $d_i$ as
\[
\nabla^h((M_i \to M)_{i \in \mathbb{N}}) = \inf_{i \in I} \left\{ \frac{\chi^h(M_i)}{d_i} \right\}.
\]

Likewise, the **infimal strong Heegaard gradient** of the collection $(M_i \to M)_{i \in \mathbb{N}}$ is
\[
\nabla^sh((M_i \to M)_{i \in \mathbb{N}}) = \inf_{i \in I} \left\{ \frac{\chi^sh(M_i)}{d_i} \right\},
\]
where $\chi^sh(M_i)$ is the strong Heegaard Euler characteristic of the finite covering $(M_i \to M)_{i \in \mathbb{N}}$.

If the family of finite covers is not specified, by convention it is the family of all finite covers of $M$. The corresponding gradients are called the Heegaard gradient of $M$, denoted by $\nabla^h(M)$, and the strong Heegaard gradient of $M$, denoted by $\nabla^sh(M)$.

Results of Lackenby show that those two quantities provide information about the existence of incompressible surfaces in finite covers of a manifold $M$ with sufficiently large degrees. They led Lackenby to formulate the following conjectures.

**Conjecture 0.1** (Heegaard gradient conjecture, [L, p. 320]). The Heegaard gradient of a compact, connected and orientable hyperbolic 3-manifold is zero if and only if the manifold $M$ virtually fibers over the circle $S^1$.

This conjecture would follow immediately from the announcement of Thurston’s virtual fibration conjecture.

A second conjecture deals with the strong Heegaard genus, and remains open.

**Conjecture 0.2** (Strong Heegaard gradient conjecture, [L, p. 320]). The strong Heegaard gradient of a closed, connected and orientable hyperbolic 3-manifold is always strictly positive.

Theorem 0.3 leads to a “sub-logarithmic” version of Conjecture 0.1 (for given collections of finite coverings) and Conjecture 0.2. As there exist infinite towers of non-fibered finite coverings of a hyperbolic 3-manifold $M$ (see [BW]), it makes sense to ask for a condition to ensure that a given collection $(M_i \to M)_{i \in \mathbb{N}}$ of finite covers of $M$ contains surface bundles.

**Definition 0.5.** Let $\eta \in (0, 1)$.

The **$\eta$-sub-logarithmic Heegaard gradient** associated to a sequence of finite covers $(M_i \to M)_{i \in \mathbb{N}}$ with finite degrees $d_i$ is defined by
\[
\nabla^h_{log, \eta}((M_i \to M)_{i \in \mathbb{N}}) = \inf_{i \in I} \left\{ \frac{\chi^h(M_i)}{(\ln \ln d_i)^\eta} \right\}.
\]

One can also define the **strong $\eta$-sub-logarithmic Heegaard gradient** of $M$ by
\[
\nabla^{sh}_{log, \eta}(M) = \inf \left\{ \frac{\chi^sh(M_i)}{(\ln \ln d_i)^\eta} \right\},
\]
where the infimum is over the (countable) collection of all finite covers \((M_i \to M)_{i \in \mathbb{N}}\) of \(M\).

**Corollary 0.6.**

1. If the \(\eta\)-sub-logarithmic Heegaard gradient \(\nabla^{h}_{\log,\eta}((M_i \to M)_{i \in \mathbb{N}})\) is zero, then for infinitely many \(i \in \mathbb{N}\) the finite covering \(M_i\) is a surface bundle.

2. The strong \(\eta\)-sub-logarithmic Heegaard gradient of \(M\) is always positive: \(\nabla^{h}_{\log,\eta}(M) > 0\).

Theorem A also applies in the setting of circular decompositions associated to a non-trivial cohomology class in order to give a sufficient condition for this class to be fibered.

**Definition 0.7.** Let \(M\) be a hyperbolic, connected, oriented and closed 3-manifold. If \(\alpha \in H^1(M) = H^1(M, \mathbb{Z})\) is a non-trivial cohomology class, let us denote by \(\|\alpha\|\) the Thurston norm of \(\alpha\). By definition,

\[
\|\alpha\| = \min\{\chi_-(R), [R] = \mathcal{P}(\alpha)\},
\]

where \(R\) is an embedded surface and \(\mathcal{P}(\alpha)\) the Poincaré-dual class of \(\alpha\). We will call such a surface \(R\) realizing the Thurston norm of \(\alpha\) an \(\|\alpha\|\)-minimizing surface.

If \(R\) is a non-separating and \(\|\alpha\|\)-minimizing surface for a given non-trivial cohomology class \(\alpha \in H^1(M)\), take \(\mathcal{N}(R) \cong R \times (-1, 1)\) to be a regular neighborhood of \(R\) in \(M\), and denote it by \(M_R = M \setminus \mathcal{N}(R)\). Set

\[
h(M, \alpha, R) = \min\{\chi(R) - \chi(S)\},
\]

where \(S\) is a Heegaard surface for \((M_R, R \times \{1\}, R \times \{-1\})\). Said differently, \(\frac{1}{2}h(M, \alpha, R)\) is the minimal number of 1-handles we need to attach to a regular neighborhood of \(R \times \{1\}\) in \(M_R\) to get the first compression body of a Heegaard splitting of \((M_R, R \times \{1\}, R \times \{-1\})\). Set

\[
h(M, \alpha) = h(\alpha) = \min\{h(M, \alpha, R), [R] = \mathcal{P}(\alpha), \chi_{-}(R) = \|\alpha\|\}.
\]

For each non-trivial cohomology class \(\alpha \in H^1(M)\), let \(\chi_{-}(\alpha) = \|\alpha\| + h(\alpha)\) be the **circular characteristic** of \(\alpha\). It is the negative part of the Euler characteristic of a minimal genus Heegaard surface for \(M_R\), where \(R\) is an \(\|\alpha\|\)-minimizing surface such that the number \(h(M, \alpha, R)\) is minimal among all \(\|\alpha\|\)-minimizing surfaces.

In this setting, Theorem A leads to the following corollary, which is analogous to Theorem 0.3 for circular decompositions associated to a non-trivial cohomology class.

**Corollary 0.8.** Let \(M\) be a hyperbolic, connected, oriented and closed 3-manifold. Set \(\epsilon = \text{Inj}(M)/2\). There exists an explicit constant \(\ell' = \ell'(\epsilon, \text{Vol}(M))\), depending only on \(\epsilon\) and the volume of \(M\), satisfying the following property. Let \(M' \to M\) be a covering of \(M\) of finite degree \(d\), and \(\alpha' \in H^1(M')\) a non-trivial cohomology class.

If \(\ell' \chi_{-}(\alpha') \ln \chi_{-}(\alpha') \leq \ln \ln d\), then every \(\|\alpha'\|\)-minimizing surface \(R'\) in \(M'\) is a fiber.

Thus we have a criterion to ensure that a non-trivial homology class can be represented by a fiber. If \(R\) is an incompressible embedded surface in \(M\), its homology class is trivial if and only if \(R\) is separating. We have also established a sufficient condition for an incompressible surface \(R\) to be a virtual fiber.
Definition 0.9. Let $M$ be a hyperbolic, connected, oriented and closed 3-manifold. Suppose that $R$ is an incompressible, orientable and connected embedded surface in $M$. If $R$ is non-separating, the homology class $[R] \in H_2(M)$ is non-trivial. Let the **Heegaard characteristic of the surface** $R$ be the minimum of $|\chi(S)|$, where $S$ is a Heegaard surface for $(M_R := M \setminus \mathcal{N}(R), R \times \{1\}, R \times \{-1\})$.

If the surface $R$ is separating, the manifold $M_R := M \setminus \mathcal{N}(R)$ is the disjoint union of two connected components $M_l$ and $M_r$. Let the **Heegaard characteristic of the surface** $R$ be the maximum of $\{\chi^h(M_l), \chi^h(M_r)\}$.

In both cases, let us denote by $\chi^h(R)$ the Heegaard characteristic of the incompressible surface $R$.

In the following corollary, the surface $R$ can either be separating or non-separating.

**Corollary 0.10.** Let $M$ be a hyperbolic, connected, oriented and closed 3-manifold, and set $\epsilon = \mathrm{Inj}(M)/2$. There exists an explicit constant $\ell'' = \ell''(\epsilon, \mathrm{Vol}(M))$, depending only on $\epsilon$ and $\mathrm{Vol}(M)$ and satisfying the following property. Let $R$ be an incompressible, connected, orientable and closed embedded surface in $M$. Let $M' \to M$ be a covering of $M$ of finite degree $d$. Also let $R'$ be a connected component of the preimage of $R$ in $M'$.

If $\ell'' \ln \chi^h(R') \leq \ln d$, then the incompressible surface $R$ is a fiber. Moreover, if $R'$ is non-separating, $R'$ is the fiber of a bundle over the circle, and the same holds for $R$ if it is non-separating. Otherwise, it is the fiber of a twisted 1-bundle.

**Remark 0.11.** The explicit expression of constants $k, \bar{k}, \ell'$ and $\ell''$ involved in Theorem A and corollaries of this work allows us to study their behavior. If the volume $\mathrm{Vol}(M)$ is fixed and $\epsilon$ tends to zero, or if $\epsilon$ is fixed and $\mathrm{Vol}(M)$ tends to infinity, all those constants tend to infinity. Thus, the sufficient conditions become more and more difficult to satisfy when the injectivity radius decreases, or if the volume grows.

**Outline of the paper.** After some definitions and generalities about Heegaard splittings in the first section, we prove Theorem A in the second section. The third section is dedicated to the application of Theorem A to Heegaard splittings and the proofs of Theorem 0.3 and Corollary 0.6. The last section deals with applications to circular decompositions and the proofs of Corollaries 0.8 and 0.10.

1. **Background on Heegaard splittings**

In this section, we briefly summarize the theory of Heegaard splittings. We also refer to [Section 3](#) for a survey on the subject.

A **handlebody** is the regular neighborhood of a connected graph. Its boundary is a connected, orientable and closed surface. The genus $g$ of this surface is called the **genus** of the handlebody. The original graph is called a **spine** for the handlebody. If an orientable 3-manifold $M$ is closed, a **Heegaard splitting** of $M$ is a decomposition of $M$ as the union of two handlebodies with the same genus, glued together by a diffeomorphism of their boundaries. A **compression body** is a connected and orientable 3-manifold $H$ with boundary, obtained from a regular neighborhood $S \times [0, 1]$ of a closed surface $S$, not necessarily connected. One glues some 1-handles to the surface $S \times \{1\}$ to get the compression body $H$. The surface $S \times \{0\}$, denoted by $\partial_- H$, is called the **negative boundary** of the compression...
body \( H \). The boundary of \( H \) minus the negative boundary \( \partial_- H \) is a connected surface \( \partial_+ H \), called the positive boundary of \( H \). The genus of the closed surface \( \partial_+ H \) is called the genus of the compression body \( H \) and denoted by \( g(H) \). By convention, a handlebody as defined above is a compression body \( H \) for which \( \partial_- H = \emptyset \). A spine for a compression body \( H \) is the union \( \Gamma \) of the negative boundary \( \partial_- H \) together with a graph whose vertices lie on \( \partial_- H \), such that \( H \) deformation retracts on \( \Gamma \).

**Definition 1.1** (Heegaard splittings). Let \((M, N_0, N_1)\) be a cobordism of \( M \), with possibly \( N_0 = \emptyset \) or \( N_1 = \emptyset \). In particular, if \( M \) is closed, \( N_0 = N_1 = \emptyset \). A Heegaard splitting of \( M \) associated to the cobordism \((M, N_0, N_1)\) is a decomposition of \( M \) into two compression bodies \( H_0 \) and \( H_1 \) such that:

1. \( \partial_- H_0 = N_0, \partial_- H_1 = N_1 \),
2. \( \partial_+ H_0 \cong \partial_+ H_1 \cong S \), where \( S \) is a closed surface, and
3. \( M = H_0 \cup_S H_1 \) is obtained from \( H_0 \) and \( H_1 \) by gluing their positive boundaries by a homeomorphism of \( S \).

The surface \( S \) is called a Heegaard surface for \( M \), and its genus is called the genus of the Heegaard splitting \( M = H_0 \cup_S H_1 \).

Every compact and orientable 3-manifold \( M \) admits a Heegaard splitting. The Heegaard genus of the manifold \( M \), denoted by \( g(M) \), is the minimal genus of all Heegaard splittings of \( M \). The Heegaard Euler characteristic of \( M \) is \( \chi^h(M) = 2g(M) - 2 \), the negative part of the Euler characteristic of a minimal genus Heegaard surface for \( M \).

A meridian disc for a Heegaard splitting of \( M \) is a properly embedded disc in one of the compression bodies which bounds an essential curve in the Heegaard surface. A Heegaard splitting (or a Heegaard surface) is said to be strongly irreducible if there does not exist any pair of disjoint meridian discs, one in each compression body. In other words, in a strongly irreducible Heegaard splitting, the boundaries of any two meridian discs, each in one side of the Heegaard surface, necessarily intersect. For any orientable 3-manifold \( M \), one defines the strong Heegaard Euler characteristic \( \chi^{sh}(M) \) of \( M \) as the minimum over all strongly irreducible Heegaard surfaces \( F \) of the negative part \( \chi_-(F) \) of the Euler characteristic of \( F \). If the manifold \( M \) does not have any strongly irreducible Heegaard splitting, then \( \chi^{sh}(M) = +\infty \).

Note that in the case of hyperbolic 3-manifolds, the Heegaard Euler characteristics and the strong Heegaard Euler characteristics are always at least 2.

A Heegaard splitting can be seen as a handle decomposition for a closed 3-manifold \( M \). Starting from a collection of 0-handles, one attaches some 1-handles to them, then a collection of 2-handles, and finishes with 3-handles. The first handlebody corresponds to the 0- and 1-handles, to which the 2- and 3-handles that compose the second handlebody are attached. More generally, a generalized Heegaard splitting for a 3-manifold \( M \) corresponds to a handle decomposition: starting from 0-handles and possibly collars of some boundary components of \( M \), one attaches some 1-handles, then a collection of 2-handles, then another collection of 1-handles, and so on, alternating 1- and 2-handles, to finish after the last collection of 2-handles with a collection of 3-handles. If one stops during the process, the object obtained after attaching the \( j \)-th batch of 1- or 2-handles is a 3-manifold embedded in \( M \). Let \( F_j \) be its boundary after discarding any 2-sphere component.
that bounds a 0- or a 3-handle. After a small isotopy to make all the surfaces $F_j$ disjoint, one gets a collection of $2n - 1$ disjoint surfaces $F_j$ in $M$. The surfaces $F_{2j}$, called the even surfaces, separate the manifold $M$ into $n$ 3-manifolds, for which the surfaces $F_{2j-1}$, called the odd surfaces, form Heegaard surfaces.

To each 1- and 2-handle of a generalized Heegaard splitting, one can associate a meridian disc. If the splitting of the region between two even surfaces is not strongly irreducible, two disjoint meridian discs can be used to change the order in which the handles are attached. A 2-handle corresponding to one of the meridian discs can be attached before a 1-handle corresponding to the other meridian disc. We will call this operation a surgery of generalized Heegaard splitting.

Let $F$ be a closed and orientable surface. If $F$ is connected, one defines the complexity of $F$ as $c(F) = 0$ if $F$ is the 2-sphere $S^2$, and $c(F) = 2g(F) - 1 = 1 - \chi(F)$ otherwise. If $F$ is not connected, the complexity of $F$ is the sum over all components of $F$ of the complexity of the component.

If $\mathcal{H} = \{F_1, F_2, \ldots, F_{2n-1}\}$ is a generalized Heegaard splitting of $M$, the width of this decomposition is the set $w(\mathcal{H}) = \{c(F_1), \ldots, c(F_{2n-1})\}$ of the complexities of the odd surfaces, with repetitions and arranged in monotonically non-increasing order. Widths are compared using the lexicographic order.

Starting from a generalized Heegaard splitting $\mathcal{H} = \{F_1, F_2, \ldots, F_{2n-1}\}$ in which at least one of the surfaces $F_{2j-1}$ is not strongly irreducible, one can do a surgery of generalized Heegaard splittings to change the order in which the 1- and 2-handles are attached, to get a new generalized Heegaard splitting $\mathcal{H}'$ with $w(\mathcal{H}') < w(\mathcal{H})$.

If $\mathcal{H}$ is a generalized Heegaard splitting for $M$, let $\mathcal{S}_\mathcal{H}$ be the set of all generalized Heegaard splittings obtained from $\mathcal{H}$ by surgery. An element $\mathcal{H}' \in \mathcal{S}_\mathcal{H}$ of minimal width is called an $\mathcal{H}$-thin generalized Heegaard splitting.

**Proposition 1.2.** Let $M$ be a connected, oriented and compact 3-manifold, and $\mathcal{H}$ be a generalized Heegaard splitting for $M$.

Every $\mathcal{H}$-thin generalized Heegaard splitting $\mathcal{H}' = (F_1, \ldots, F_{2n-1})$ satisfies the following properties.
(1) The odd surfaces $F_{2i-1}$ correspond to strongly irreducible Heegaard surfaces.
(2) The even surfaces $F_{2i}$ are incompressible surfaces in $M$.
(3) Furthermore, if the manifold $M$ is irreducible, then no component of any even surface is a 2-sphere.

The proof of this proposition is a consequence of the definition of a surgery of generalized Heegaard splittings. See for example [CG] and [ST].

A generalized splitting of minimal width among all generalized Heegaard splittings of $M$ is called a thin position (see [ST]).

2. Finding a fibration

2.1. Main theorem. The aim of this section is to prove Theorem A.

If $S$ is a surface, let us denote by $\chi_-(S) = \max\{0, -\chi(S)\}$ the negative part of the Euler characteristic of $S$.

If $C$ is a compression body, set $\chi_-(C) := \chi_-(\partial_+ C)$. If $S$ is a union of connected components of $\partial_- C$, the definition implies that $\chi_-(S) \leq \chi_-(C)$.

Definition 2.1. An embedded surface $S$ in a Riemannian 3-manifold $M$ is called pseudo-minimal if it is orientable, closed, and $S$ is a minimal surface or the boundary of a regular neighborhood of a minimal non-orientable surface, possibly with a little tube attached vertically in the $I$-bundle structure.

Proof of Theorem A. Suppose that there exists a finite cover $M' \to M$ of degree $d$ satisfying the hypotheses of Theorem A. The proof relies on three key propositions, the proof of which we postpone to the next three subsections. Let us denote $g = \frac{q}{2} + 1$. It is an upper bound for the genus of the compression bodies of $M'$.

Lemma 2.2. There exists a compression body $C$ among the $q$ compression bodies $C_1, \ldots, C_q$ of $M'$ such that

$$\text{Vol}(C) \geq \text{Vol}(M) \frac{d}{q}.$$
Proof of Lemma 2.2. The proof is straightforward, as there are \( q \) compression bodies \( C_1, \ldots, C_q \), and \( \text{Vol}(M') = d \text{Vol}(M) \).

Let \( C \) be a compression body as in Lemma 2.2.

**Lemma 2.3.** Let \( k_0 = \max \left\{ \frac{\ln(4(2a'+1))}{2 \ln 2}, 1 + \frac{\ln(1+\ln(12V_3/\text{Vol}(M)))}{2 \ln 2} \right\} \), where \( V_3 \) is the maximal volume of an ideal hyperbolic tetrahedron in \( \mathbb{H}^3 \), and

\[
a' = 6(21/4 + 3/4\pi + 3/4\epsilon + 2/\sinh^2(\epsilon/4)).
\]

If \( k_0 \chi_-(C) \ln \chi_-(C) \leq \ln \ln d/q \) and \( \text{Vol}(M) \geq \pi/2 \), then there is a way of replacing the boundary surfaces of \( C \) by simplicial surfaces to obtain a new compression body \( C'' \) with

\[
\text{Vol}(C'') \geq \frac{1}{4} \text{Vol}(C) \geq \frac{\text{Vol}(M)d}{4q}.
\]

This lemma is proven in subsection 2.2.1. To simplify notation, this new compression body \( C'' \) will still be denoted by \( C \).

**Definition 2.4.** Let \( x \) be a point in \( C \) and \( S \) an immersed surface in \( C \). We say that \( S \) **separates** \( x \) from \( \partial_+ C \) if every oriented path from \( x \) to \( \partial_+ C \) has its algebraic intersection number with \( \partial_+ C \) equal to +1.

If two surfaces \( S \) and \( T \) immersed in \( C \) are such that \( S \) separates every point of \( T \) from \( \partial_+ C \), we say that \( T \) **separates** \( S \) **from** \( \partial_+ C \). In this case, the surfaces \( S \) and \( T \) are said to be **nested**.

We will denote the ceil function of the real number \( x \) by \( \lceil x \rceil \), i.e. the smallest integer not less than \( x \). Similarly, \( \lfloor x \rfloor \) is the floor function of \( x \), and represents the largest integer no greater than \( x \). By convention, we set \( \lceil x \rceil \) and \( \lfloor x \rfloor \) equal to zero if \( x \) is non-positive.

The following proposition is a step towards the construction of a certain amount of parallel surfaces in the compression body \( C \). It is an adaptation of Lemma 4.5, p. 2251 of [Mah]. We postpone its proof to section 2.2.

**Proposition B** (of nested surfaces). Let \( \delta \) be the diameter of the compression body \( C \) of \( M' \), \( \epsilon = \text{Inj}(M)/2, K = 4 \left( 3 + \frac{1}{\sinh \frac{\delta}{2}} \right) g(C) - 10 \) and \( K' = 2a' \chi_-(C) \).

Moreover, suppose that \( k_0 \chi_-(C) \ln \chi_-(C) \leq \ln \ln \frac{d}{q} \).

Under those assumptions, there exist at least \( n = \lceil \frac{\delta}{36\epsilon K} - \frac{2}{9} - \frac{K'}{3K} \rceil \) orientable, disjoint and nested surfaces, immersed in \( C \). All of those surfaces are homotopic to components of surfaces obtained by compressing \( \partial_+ C \). Moreover, the \( \epsilon \)-diameter of those surfaces in \( M' \) is bounded from above by \( K \) and they are separated from each other by a distance greater than or equal to \( 10\epsilon K \).

With this proposition, we obtain at least \( n = \lceil \frac{\delta}{36\epsilon K} - \frac{2}{9} - \frac{K'}{3K} \rceil \) nested immersed surfaces in the handlebody \( C \). Those surfaces are all disjoint and homotopic to components of surfaces obtained from \( \partial_+ C \) by surgery. This implies that the genus of those surfaces is between 0 and \( g(C) \), the genus of \( C \) (which is, by assumption, less than or equal to \( g \)). We can thus find at least \( \lceil \frac{\delta}{g(C) + 1} \rceil \) such nested immersed surfaces of the same genus. The next step is then to replace those nested immersed surfaces by parallel embedded surfaces.
Proposition C (of parallel surfaces). Let \( \delta \) be the diameter of the compression body \( C \) in \( M' \), \( \epsilon = \text{Inj}(M)/2 \), \( K = 4 \left( 3 + \frac{1}{\sinh \left( \frac{\delta}{8} \right)} \right) g(C) - 10 \) and \( K' = 2a'\chi_-(C) \).

Suppose that \( k_0 \chi_-(C) \ln \chi_-(C) \leq \ln \ln \frac{d}{q} \).

Under those assumptions, there exists at least \( m = (\left\lfloor \frac{1}{g(C)} + 1 \right\rfloor \left[ \frac{3 \delta}{36 \epsilon K} - \frac{2}{9} \right] - 4) \) orientable, parallel and connected surfaces embedded in \( C \), separated from each other by a distance greater than or equal to \( \epsilon K \), and each of those surfaces can be covered by at most \( K \) embedded balls in \( M' \) of radius \( 2\epsilon \). In particular, their diameter in the manifold \( M' \) is uniformly bounded from above by \( 4\epsilon K \).

For the proof of this proposition, see section 2.3.

Let
\[
a = 2 \left( 3 + \frac{1}{\sinh^2 \left( \frac{\delta}{8} \right)} \right),
\]
\[
b = 2 \left( 1 + \frac{2}{\sinh^2 \left( \frac{\delta}{8} \right)} \right) \quad \text{and}
\]
\[
a' = 6 \left( \frac{21}{4} + \frac{3}{4\pi} + \frac{3}{4\epsilon} + \frac{2}{\sinh^2 \left( \frac{\delta}{8} \right)} \right). \]

Lemma 2.5. Under assumptions of Theorem A, according to Proposition C, there exist \( m \) parallel surfaces embedded in the compression body \( C \) of \( M' \), with
\[
m \geq 2 \left( \ln \left( \frac{d}{q} \right) + \ln \left( \frac{\text{Vol}(M)}{2\pi} \right) \right) \frac{72\epsilon}{a\chi_-(C) + b} - \frac{2}{9} \left( 1 + \frac{3a'}{a} \right) - 5.
\]

Proof of Lemma 2.5. The number \( m \) of embedded parallel surfaces in \( C \) obtained by Proposition C is equal to
\[
m = \left\lfloor \frac{1}{g(C) + 1} \left[ \frac{\delta}{36 \epsilon K} - \frac{2}{9} + \frac{K'}{3K} \right] - 4 \right\rfloor,
\]
where
\[
K = 4 \left( 3 + \frac{1}{\sinh \left( \frac{\delta}{8} \right)} \right) g(C) - 10 = a\chi_-(C) + b,
\]
and
\[
K' = 2a'\chi_-(C).
\]

The diameter \( \delta \) of the compression body \( C \) and the ratio \( d/q \) are related. On the one hand,
\[
\text{Vol}(C) \leq \text{Vol} \left( \mathbb{B}_{\mathbb{H}^3} (\delta) \right) = \pi (\sinh(2\delta) - 2\delta) \leq \frac{\pi}{2} e^{2\delta}.
\]

Remark 2.6. The second logarithm of the expression \( \ln \ln \frac{d}{q} \) comes from this estimation linking the diameter with the volume of a hyperbolic 3-manifold.

On the other hand, Lemmas 2.2 and 2.3 give the lower bound
\[
\text{Vol}(C) \geq \text{Vol}(M) \frac{d}{4q},
\]
which leads to the inequality
\begin{equation}
\delta \geq \frac{1}{2} \ln \left( \frac{d}{q} \right) + \frac{1}{2} \ln \left( \frac{\text{Vol}(M)}{2\pi} \right).
\end{equation}

In particular, if \( \frac{d}{q} \) tends to infinity, \( \delta \) also tends to infinity.

The expression of \( m \) involves the ratio \( \frac{K'}{3K} \). Now,
\[
\frac{K'}{3K} = \frac{2a'\chi_-(C)}{3a\chi_-(C) + 3b} \\
\leq \frac{2a'}{3a}.
\]

Replacing the ratio \( \frac{K'}{3K} \) by \( \frac{2a'}{3a} \) and taking inequality (1) into account, one obtains
\[
m \geq \left\lfloor \frac{2}{\chi_-(C) + 4} \left( \ln \left( \frac{d}{q} \right) + \ln \left( \frac{\text{Vol}(M)}{2\pi} \right) - \frac{2}{9} \left( \frac{2a'}{3a} \right) \right) - 4 \right\rfloor.
\]

which ends the proof of Lemma 2.5. \( \square \)

Those \( m \) parallel surfaces obtained by Proposition C are candidates for a fiber. But we still have to select some of them to get a virtual fibration of the base manifold \( M \).

Let \( \mathcal{D} \) be a Dirichlet fundamental polyhedron for \( M \) in its universal cover \( \widehat{M} \simeq \mathbb{H}^3 \). Translates of \( \mathcal{D} \) by the covering transformations give a tiling of the universal cover \( \widehat{M} \). This tiling descends to a tiling of the finite cover \( M' \) by \( d \) copies of \( \mathcal{D} \). Each of the \( m \) parallel, connected and embedded surfaces in \( M' \) obtained by Proposition C intersects a finite and connected set of copies of \( \mathcal{D} \).

We call such a set a pattern of fundamental domains. We can suppose that each of the embedded surfaces is transverse to the 2-skeleton of the tiling. More precisely, we can suppose that each surface does not meet the vertices of the fundamental polyhedra, that it intersects the edges in isolated points and it is transverse to the 2-dimensional faces of the polyhedra. Thus a pattern of fundamental domains is a connected set that is the union of copies of \( \mathcal{D} \) glued along some of their 2-dimensional faces.

**Lemma 2.7.** Let \( \mathcal{D} \) be a Dirichlet fundamental polyhedron for \( M \) in \( \mathbb{H}^3 \). Let \( \alpha \) be the number of faces of \( \mathcal{D} \) of dimension two.

For each \( \ell \in \mathbb{N} \), the number of possibilities to glue together at most \( \ell \) copies of \( \mathcal{D} \) to form a pattern of \( \ell \) fundamental domains is less than or equal to \( (\alpha \sqrt{2} \ell)^{\alpha \ell} \).

**Proof of Lemma 2.7.** For every \( \ell \in \mathbb{N} \), let us denote by \( B(\ell) \) the number of possibilities to glue together \( \ell \) copies of \( \mathcal{D} \) to form a pattern of \( \ell \) fundamental domains. We have to find an upper bound for the number of possibilities to identify pairwise some 2-dimensional faces of at most \( \ell \) Dirichlet polyhedra.

First, let us notice that there are at most \( \alpha \ell \) such 2-dimensional faces. Thus, there are at most \( (\alpha \ell)! \leq (\alpha \ell)^{\alpha \ell} \) ways to match those faces pairwise.
If \((F_1, F_2)\) is a pair of such faces, we can choose to glue them together by an orientation-reversing isometry \(h : F_1 \to F_2\) (if such an isometry between those two faces exists). This isometry corresponds to a “pairing transformation” (see for example [Mar, Proposition 3.5.1, p. 117]). It is a reflection in \(H^3\) and its hyperplane contains one of the faces of \(D\). Thus, if such an isometry exists, it is unique. We can also decide not to glue those two faces together: by convention, we will say that we glue them by the empty gluing. Therefore, there are at most 2 ways to glue \(F_1\) and \(F_2\) together, including the empty gluing.

Thus there are at most \((\alpha \ell)!2^{\alpha \ell} \leq (\alpha \sqrt{2} \ell)^{\alpha \ell}\) ways to glue together at most \(\ell\) copies of fundamental domains to form a pattern of fundamental domains, which ends the proof of Lemma 2.7.

The following lemma is a way to bound the number \(\alpha\) of 2-faces of a fundamental polyhedron \(D\) and its diameter in \(H^3\) in terms of the volume of the manifold \(M\) and a lower bound for its injectivity radius.

**Lemma 2.8.** Let \(D\) be a Dirichlet fundamental polyhedron for the manifold \(M\), embedded in the universal cover \(\tilde{M} \simeq H^3\). Let \(D\) be an upper bound for the diameter of \(D\) in \(H^3\) and \(\alpha\) be the number of its 2-faces. We have the following estimates:

\[
(2) \quad \text{diam}(D) \leq \frac{8\epsilon \text{Vol}(M)}{\pi(\sinh(2\epsilon) - 2\epsilon)} = D
\]

and

\[
(3) \quad \alpha \leq \frac{\pi(\sinh(4D) - 4D)}{\text{Vol}(M)} - 1.
\]

If \(S\) is an embedded surface in the finite cover \(M'\) of \(M\), which can be covered by at most \(K\) embedded balls in \(M'\) of radius \(\epsilon' \leq \text{Inj}(M)\), then \(S\) intersects at most \(L\) images of \(D\) in \(M'\), with

\[
(4) \quad L = \left\lfloor \frac{\pi(\sinh(2D + 2\epsilon') - 2D - 2\epsilon')}{\text{Vol}(M)} \right\rfloor K.
\]

**Proof of Lemma 2.8.** To prove inequality (2), first notice that \(\text{diam}(D) \leq 2 \text{diam}(M)\). To prove it, recall that there exists \(w \in H^3\) such that \(D = \{ x \in H^3, d(\gamma(w), x) \geq d(w, x) \forall \gamma \in \pi_1(M) \}\). If \(x\) and \(y\) in \(D\) satisfy \(d(x, y) = \text{diam}(D)\), then

\[
\text{diam}(D) = d(x, y) \leq d(x, w) + d(y, w) \leq 2 \text{diam}(M).
\]

Take \(x\) and \(y\) in \(M\) such that \(d(x, y) = \text{diam}(M)\), and let \(\gamma\) be a minimizing geodesic from \(x\) to \(y\). By definition, \(\text{length}(\gamma) = \text{diam}(M)\). Let \(B\) be a collection of points in \(\gamma\) which is maximal among collections of points of \(\gamma\) such that two balls of radius \(\epsilon\) and whose centers are two distinct points of \(B\) have disjoint interiors. Then, by maximality of \(B\), the union of balls with centers in \(B\) and radius \(2\epsilon\) cover the geodesic \(\gamma\).
Thus, $|\mathcal{B}| \geq \frac{\text{length}(\gamma)}{4\epsilon}$. As balls of centers in $\mathcal{B}$ and radius $\epsilon$ have disjoint interiors, considering volumes, we deduce

$$
\text{Vol}(M) \geq \sum_{u \in \mathcal{B}} \text{Vol}(B(u, \epsilon)) \\
\geq \frac{\text{length}(\gamma)}{4\epsilon} \text{Vol}(B_{\mathbb{H}^3}(\epsilon)) \\
\geq \frac{\text{diam}(M)}{4\epsilon} \pi (\sinh(2\epsilon) - 2\epsilon),
$$

proving inequality (2).

Let us show inequality (3). To each 2-face of $D$, one can associate a unique translate $g_F(D)$ of $D$ adjacent to $D$ along $F$. As the diameter of $g_F(D)$ is also $\text{diam}(D) \leq D$, every point $x \in g_F(D)$ lies at distance at most $\text{dist}(x, F) + \text{diam}(D) \leq 2D$ from $w \in D$. Thus, the ball of center $w$ and radius $2D$ contains the fundamental polyhedron $D$ together with the union of all its translates $g_F(D)$, where $F$ is a 2-face of $D$. As those polyhedra have disjoint interiors, for volumes, we obtain

$$(\alpha + 1) \text{Vol}(D) \leq \text{Vol}(B_{\mathbb{H}^3}(w, 2D)),$$

and thus

$$
\alpha \leq \frac{\pi (\sinh(4D) - 4D) - 1}{\text{Vol}(M)}.
$$

The proof of inequality (4) is similar. Denote by $\mathcal{B}$ the set of the centers of a collection of $K$ embedded balls in $M'$ of radius $\epsilon'$ covering the surface $S$. Let $\mathcal{N} = \bigcup_{x \in \mathcal{B}} B(x, D + \epsilon')$. Those balls are not necessarily isometric to hyperbolic embedded balls in $\mathbb{H}^3$ as $D + \epsilon' > \text{Inj}(M)$. However, let us show that $\mathcal{N}$ contains every fundamental polyhedron of $M'$ intersecting $S$.

To prove it, let $x$ be a point in a fundamental polyhedron of $M'$ intersecting $S$. Take $y \in S$ such that $d(x, y) = \text{dist}(x, S) \leq D$. As $y$ is a point of $S$, there exists $x \in \mathcal{B}$ such that the ball $B(x, \epsilon')$ contains $y$. Therefore $d(z, x) \leq d(z, y) + d(y, x) \leq D + \epsilon'$, showing that $z \in B(x, \epsilon' + D) \subset \mathcal{N}$.

Comparing volumes, we get

$$
L \text{Vol}(D) \leq \text{Vol}(\mathcal{N}), \\
L \text{Vol}(M) \leq |\mathcal{B}| \text{Vol}(B_{\mathbb{H}^3}(\epsilon' + D)), \\
L \leq \frac{\pi (\sinh(2\epsilon' + 2D) - 2\epsilon' - 2D) K}{\text{Vol}(M)},
$$

proving inequality (4), as $L$ is a natural integer. □

The following key proposition is a quantitative version of Lemma 4.12, p. 2258 of [Mah]. We postpone its proof to section 2.4.

**Proposition D (Pattern Proposition).** Assume that in the cover $M'$ we have $m$ connected, orientable, embedded, disjoint and parallel surfaces, at distance at least $r > 0$ from each other. Moreover, suppose that each of those surfaces can be covered by at most $K$ embedded balls in $M'$ of radius $\epsilon' \leq \text{Inj}(M)$.

Let $D$ be a Dirichlet fundamental domain for the manifold $M$ in its universal cover $\tilde{M} \simeq \mathbb{H}^3$. Let us denote by $D$ an upper bound for the diameter of $D$ and $\alpha$ an upper bound for the number of its 2-dimensional faces.
For all \( \ell \in \mathbb{N} \), let \( B(\ell) \) be an upper bound for the number of possibilities of patterns obtained by gluing together at most \( \ell \) fundamental domains that intersect a connected, orientable and embedded surface. Let \( L = \left[ \frac{\pi(\sinh(2D+2\epsilon') - 2D - 2\epsilon')}{\text{Vol}(M)} \right] \).

If \( r/(2D + 1) \geq 1 \) and \( \frac{m}{\alpha^2L^2B(L)} \geq 4 \), or if \( r/(2D + 1) \leq 1 \) and

\[
\left( \frac{r}{2D + 1} m - 1 \right) \frac{1}{\alpha^2L^2B(L)} \geq 4,
\]

then the manifold \( M \) virtually fibers over the circle \( \mathbb{S}^1 \), and the \( m \) parallel surfaces in \( M' \) are fibers of a bundle over the circle or of a twisted \( I \)-bundle.

**Remark 2.9.** The first logarithm in the expression \( \ln \ln \frac{d}{q} \) and the function of the complexity \( c \ln(c) \) in the assumption \( kc \ln(c) < \ln \ln \frac{d}{q} \) arise from the use of Lemma 2.7 (providing an estimate of the number \( B(\ell) \)) in the proof of this proposition.

We can now finish the proof of Theorem A assuming Propositions B, C and D, which will be proved in the next sections.

The aim is to apply Proposition D to the \( m \) parallel surfaces obtained in Proposition C with

\[
K = a\chi_- (C) + b \quad \text{and} \quad r = \epsilon K = \epsilon (a\chi_- (C) + b).
\]

Set

\[
D := \frac{8\epsilon \text{Vol}(M)}{\pi(\sinh(2\epsilon) - 2\epsilon)}, \quad \alpha := \frac{\pi(\sinh(4D) - 4D)}{\text{Vol}(M)} - 1, \quad \text{and} \quad \sigma := \frac{\pi(\sinh(2D + 4\epsilon) - 2D - 4\epsilon)}{\text{Vol}(M)}.
\]

From Lemma 2.8, \( D \) is an upper bound for the diameter of the fundamental polyhedron \( D \), and the number of \( 2 \)-faces of \( D \) is at most \( \alpha \).

In addition, from Lemma 2.8 again, \( L = \left[ \frac{\pi(\sinh(2D+4\epsilon) - 2D - 4\epsilon)}{\text{Vol}(M)} \right] \). In particular,

\[
L \leq \frac{\pi(\sinh(2D + 4\epsilon) - 2D - 4\epsilon)}{\text{Vol}(M)} (a\chi_- (C) + b) = \sigma (a\chi_- (C) + b).
\]

**Claim 1.** There exist \( c_1 \geq 2 \) and \( k_1 > 0 \), depending only on \( \epsilon \) and \( \text{Vol}(M) \), such that if \( \chi_- (C) \leq c_1 \) and \( k_1 \chi_- (C) \ln \chi_- (C) \leq \ln \ln d/q \), then assumptions of Proposition D are satisfied. In particular, \( M \) virtually fibers over the circle, and the \( m \) embedded surfaces in \( M' \) are fibers.

Furthermore, one can take \( c_1 := \frac{1}{a} \left( \frac{16 \text{Vol}(M)}{\pi(\sinh(2\epsilon) - 2\epsilon)} + \frac{1}{\epsilon} - b \right) \) and

\[
k_1 := \frac{1}{2 \ln 2} \ln \left( 72(2D + 1)(c_1 + 4) \left( 3 + 2(\alpha \sigma)^2 (ac_1 + b)^2 (\sqrt{2} \alpha \sigma (ac_1 + b))^{\alpha \sigma (ac_1 + b)} \right) + 16 \epsilon (1 + \frac{3a'}{a}) (ac_1 + b) - \ln \left( \frac{\text{Vol}(M)}{2\pi} \right) \right).
\]
Proof of Claim 1. Recall that \( r = \epsilon(a\chi_-(C) + b) \) and \( 2D + 1 = \frac{16\text{Vol}(M)}{\pi(\sinh(2\sigma) - 2\epsilon)} + 1 \). Thus, if \( \chi_-(C) \leq c_1 = \frac{1}{a}\left(\frac{16\text{Vol}(M)}{\pi(\sinh(2\sigma) - 2\epsilon)} + \frac{1}{\epsilon} - b\right) \), then \( r \leq 2D + 1 \). Assumptions of the second case of Proposition D are then satisfied if \( \left(\frac{r}{2D+1}m - 1\right) \frac{1}{\alpha^2L^2B(L)} \geq 4 \).

Taking Lemma 2.5 and the expression of \( r \) into account, one obtains the sufficient condition

\[
\left(\frac{2\epsilon(a\chi_-(C) + b)}{(2D + 1)(\chi_-(C) + 4)} \left(\ln\left(\frac{d}{\epsilon}\right) + \ln\left(\frac{\text{Vol}(M)}{2\pi}\right) - \frac{2}{9}(1 + \frac{3a'}{a})\right) - 6\right) \frac{1}{\alpha^2L^2B(L)} \geq 4.
\]

Replace \( L \) by its upper bound \( \sigma(a\chi_-(C) + b) \). From Lemma 2.7, one can choose for \( B(L) \) the function \( B(L) = (\sqrt{2\alpha L})^{aL} \leq (\sqrt{2\alpha \sigma(a\chi_-(C) + b)})^{\alpha \sigma(a\chi_-(C) + b)} \).

Thus one obtains the sufficient condition

\[
\left(\frac{2\epsilon(a\chi_-(C) + b)}{(2D + 1)(\chi_-(C) + 4)} \left(\ln\left(\frac{d}{\epsilon}\right) + \ln\left(\frac{\text{Vol}(M)}{2\pi}\right) - \frac{2}{9}(1 + \frac{3a'}{a})\right) - 6\right) \frac{1}{\alpha^2L^2B(L)} \geq 4(a\sigma)^2(a\chi_-(C) + b)^2(\sqrt{2\alpha \sigma(a\chi_-(C) + b)})^{\alpha \sigma(a\chi_-(C) + b)}.
\]

Under the assumptions of Claim 1, \( 2 \leq \chi_-(C) \leq c_1 \). One can then easily check that if \( k_1 \chi_-(C) \ln \chi_-(C) \leq \ln \ln d/q, \) the sufficient condition above is satisfied. \( \square \)

Claim 2. Suppose that \( \text{Vol}(M) \geq 2\pi \). There exist \( c_2 \geq c_1 \) and \( k_2 > 0 \), depending only on \( \epsilon \) and \( \text{Vol}(M) \), such that if \( \chi_-(C) \geq c_2 \) and \( k_2 \chi_-(C) \ln \chi_-(C) \leq \ln \ln d/q, \) then the assumptions of Proposition D are satisfied. In particular, \( M \) virtually fibers over the circle and the \( m \) embedded surfaces in \( M' \) are fibers.

Furthermore, one can take \( k_2 := 4a\sigma a \) and

\[
c_2 = \max\{c_1, \frac{1}{a}\left(\frac{1}{a}\left(\ln 5 - \ln(4a^2\sigma^2(2a + b)^2)\right) - b\right), \frac{1}{a}\left(\ln(1 + \frac{3a'}{a}) - \ln(108a^2\sigma^2(2a + b)^2)\right) - b, 4, 2\sqrt{2a\sigma a}, \frac{b}{a} + \frac{4}{a\sigma a}, \frac{1}{a\sigma a}\ln\left(\frac{\text{Vol}(M)}{2\pi}\right) - \frac{2}{3}\left(1 + \frac{3a'}{a}\right)\ln\left(\frac{\text{Vol}(M)}{2\pi\sigma a(2a + b)}\right) \leq 5\right) - b\}.
\]

Proof of Claim 2. As \( \chi_-(C) \geq c_2 \geq c_1 \), from the proof of the first claim, \( r \geq 2D + 1 \). Assumptions of the first case of Proposition D are then satisfied if \( \frac{\text{Vol}(M)}{\alpha^2L^2B(L)} \geq 4 \). Now, taking Lemma 2.5 into account, together with the inequalities \( L \leq \sigma(a\chi_-(C) + b) \) and \( B(L) \leq (\sqrt{2\alpha \sigma(a\chi_-(C) + b)})^{\alpha \sigma(a\chi_-(C) + b)}, \) one obtains the
following sufficient condition:

\[
\frac{2}{\chi_-(C)} + 4 \left( \ln \left( \frac{d}{q} \right) + \ln \left( \frac{\Vol(M)}{2\pi} \right) - \frac{2}{9} \left( 1 + \frac{3a'}{a} \right) \right) - 5 \geq 4a^2 \sigma(\chi_-(C) + b)^2 (\sqrt{2a} \sigma(\chi_-(C) + b))^{\alpha(\chi_-(C) + b)},
\]

which can also be written as

\[
\ln \left( \frac{d}{q} \right) \geq 72\epsilon(a\chi_-(C) + b)\left( \chi_-(C) + 4 \left( \frac{\Vol(M)}{2\pi} \right) - \frac{2}{9} \left( 1 + \frac{3a'}{a} \right) \right) - \ln \left( \frac{\Vol(M)}{2\pi} \right),
\]

or also

\[
\ln \left( \frac{d}{q} \right) \geq \ln \left( 72\epsilon(a\chi_-(C) + b)\left( \chi_-(C) + 4 \left( \frac{\Vol(M)}{2\pi} \right) - \frac{2}{9} \left( 1 + \frac{3a'}{a} \right) \right) - \ln \left( \frac{\Vol(M)}{2\pi} \right) \right) - 5 \chi_-(C) \ln \chi_-(C)
\]

(see \cite{R2} Chapter 1) for explicit details and calculations).

Thus, if \( k_2 := 4a\sigma a \), if \( \chi_-(C) \geq c_2 \), assuming that \( k_2 \chi_-(C) \ln \chi_-(C) \leq \ln \ln d/q \) implies that the sufficient condition above is satisfied, hence conclusions of the Pattern Proposition D. \( \square \)

Claim 3. If \( c_1 \leq \chi_-(C) \leq c_2 \), the conclusions of Proposition D still hold if \( k_3 \chi_-(C) \ln \chi_-(C) \leq \ln \ln d/q \), with

\[
k_3 = \frac{1}{c_1 \ln c_1} \ln \left( 36\epsilon(ac_2 + b)(c_2 + 4) \left( 4\alpha^2 \sigma^2(ac_2 + b)^2(\sqrt{2a} \sigma(ac_2 + b))^{\alpha(\chi_-(C) + b) + 5} \right) + 16\epsilon(ac_2 + b)(1 + \frac{3a'}{a}) - \ln \left( \frac{\Vol(M)}{2\pi} \right) \right).
\]

Proof of Claim 3. As \( \chi_-(C) \geq c_1 \), it is the case where \( r \geq 2D + 1 \), and we proceed as above using as we did in the proof of Claim 1 that one has the bounds \( c_1 \leq \chi_-(C) \leq c_2 \). \( \square \)

Set \( k := \max\{k_0, k_1, k_2, k_3\} \). It follows from the last three claims that if \( k \chi_-(C) \ln \chi_-(C) \leq \ln \ln d/q \), then the conclusions of Proposition D hold. In particular, \( M \) virtually fibers over the circle and the \( m \) embedded surfaces in \( M' \) are fibers. Furthermore, the constant \( k = k(\epsilon, \Vol(M)) \) depends only on \( \epsilon = \text{Inj}(M)/2 \) and the volume \( \Vol(M) \), and its expression is explicit. This ends the proof of Theorem A. \( \square \)
Proof of Corollary 0.2. If $C_j$ is a handlebody and $\text{Vol}(C_j) \geq \text{Vol}(M)d/q$, the proof of Theorem A shows that one can construct in $C_j$ surfaces that are fibers. In particular, the handlebody $C_j$ contains incompressible surfaces, which is a contradiction. □

2.2. Proof of Proposition B: Finding nested surfaces. Let $C$ be the compression body of $M'$ obtained in Lemma 2.2. The boundary of $C$ is a union of pseudo-minimal surfaces, the genus of each boundary component is at most $g$, and $\text{Vol}(C) \geq \text{Vol}(M)d/q$.

2.2.1. Some modifications of the compression body. Instead of the manifold with boundary $C$, we need to work in a complete Riemannian manifold of sectional curvature at most $-1$. This is the aim of the following lemma.

Lemma 2.10. Up to modifying the compression body $C$ without significant changes of volume, one can add collars to boundary components of $C$ to obtain a (non-compact) Riemannian 3-manifold homeomorphic to the interior of $C$. Let $\rho > 0$ be as small as desired. This manifold is equipped with a complete metric of sectional curvature at most $-1 + \rho$, which coincides on $C$ with the induced metric given by the embedding of $C$ in $M'$.

Proof of Lemma 2.10. We start with the compression body $C$ embedded in $M'$ and its non-complete induced hyperbolic metric. If necessary, we need to slightly modify the compression body $C$ in order for each boundary component of $C$ to have its intrinsic sectional curvature at most $-1$.

That is not a problem for boundary components which are minimal surfaces, as their sectional curvature is always at most $-1$ as in the ambient hyperbolic manifold.

If a boundary component of $C$ is the boundary of a small neighborhood of a non-orientable minimal surface, we can choose this neighborhood small enough in order for the sectional curvature of this pseudo-minimal surface to be bounded from above by $-1 + \rho$, with $\rho > 0$ as small as desired. This is a consequence of the continuity of the intrinsic sectional curvature in a neighborhood of the minimal surface (because of the continuity of the Gauss curvature).

If $\partial_+ C$ is the boundary of a regular neighborhood $N(S)$ of a non-orientable minimal surface $S$ with a small tube attached vertically in the $I$-bundle structure, we have to consider two cases. If this tube $\mathbb{D}^2 \times I$ belongs to the compression body $C$, we can remove it. More precisely, we compress $C$ along the disc $\mathbb{D}^2 \times \{1/2\}$ to get a new compression body of lower genus. We lose the tube $\mathbb{D}^2 \times I$ during this process, but as we can make this tube as small as we like, this compression does not significantly change the volume of the compression body. As the positive boundary of this new compression body $C'$ is then the boundary of a small regular neighborhood of the minimal non-orientable surface $S$, the previous argument shows that we can suppose that the intrinsic curvature of $\partial_+ C'$ is at most $-1 + \rho$.

Otherwise, in the second case the tube $\mathbb{D}^2 \times I$ lies outside $C$, meaning that $C$ is contained in $N(S)$. We can then collapse the small tube to an arbitrarily small geodesic arc $\gamma$ in the regular neighborhood of the minimal non-orientable surface $S$. The positive boundary $\partial_+ C$ becomes the union of the boundary of $N(S)$ and the arc $\gamma$. As before, we can suppose that the sectional curvature of the surface $\partial N(S)$ is at most $-1 + \rho$. 

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For each boundary component \( F \) of \( C \), we glue a copy of \( F \times [0, +\infty) \) equipped with a warped product metric. A computation of the sectional curvature of a warped product (see for example Bishop and O’Neil [BO, p. 26]) shows that as we start from a surface \( F \) with sectional curvature at most \(-1 + \rho\), there exists a warped product metric on \( S \times [0, +\infty) \) such that this Riemannian manifold is complete of sectional curvature at most \(-1 + \rho\). If we are in the last case where \( F \) is the boundary of a regular neighborhood \( N(S) \) of a minimal non-orientable surface \( S \) with a small tube attached, and this tube is lying outside \( C \), then we forget the arc \( \gamma \) for this construction and we just glue a copy of \( \partial N(S) \times [0, +\infty) \) with a Riemannian metric of curvature at most \(-1 + \rho\). We slightly perturb this metric to make it smooth, and we thus obtain a complete Riemannian metric for the interior of \( C \) (union \( \gamma \) if we are in this last case) with sectional curvature at most \(-1 + \rho\), which extends the induced metric given by the embedding of \( C \) in \( M' \). \( \square \)

The boundary surfaces of \( C \) are pseudo-minimal surfaces. This fact is crucial as one can homotop a minimal surface of genus \( g \) to a simplicial surface not too far away in \( C \). This can be done by the following lemmas.

**Definition 2.11.** Let \( \epsilon > 0 \). The (intrinsic) \( \epsilon \)-diameter of a Riemannian surface \( S \) is the minimal number of balls of radius \( \epsilon \) for the metric of \( S \) needed to cover the surface \( S \).

**Lemma 2.12.** Suppose \( S \) is a pseudo-minimal surface in a closed Riemannian 3-manifold \( N \) of sectional curvature at most \(-1\). Let \( \epsilon \leq \text{Inj}(N) \) and

\[
a' = 6 \left( \frac{21}{4} + \frac{3}{4\pi} + \frac{3}{4\epsilon} + \frac{2}{\sinh^2(\frac{\epsilon}{4})} \right).
\]

Then the surface \( S \) has \( \epsilon \)-diameter at most \( a' |\chi(S)| \), and it admits a one-vertex triangulation in which each edge has length at most \( 2a' |\chi(S)| \).

**Proof of Lemma 2.12** This lemma is a direct consequence of [Mah] Lemma 4.2, p. 2249 and [L] Proposition 6.1 in the case where the surface \( S \) is minimal and orientable, and we can take \( a'/6 \) instead of \( a' \). If \( S \) is minimal, but not orientable, its homology class \([S]\) is non-zero in \( H_2(N, \mathbb{Z}/2\mathbb{Z}) \). By Poincaré’s duality, it corresponds to a non-trivial element \( \alpha \in H^1(N, \mathbb{Z}/2\mathbb{Z}) \). As the homology class of the double cover of \( S \) can be represented by the boundary of a small regular neighborhood of the non-orientable surface \( S \), we have \( 2[S] = 0 \) in \( H_2(N, \mathbb{Z}) \). If we take the double cover \( N' \) of \( N \) corresponding to the kernel of \( \alpha \), the surface \( S \) lifts to a minimal orientable surface \( S' \). We can apply the stronger version of Lemma 2.12 and bound the \( \epsilon \)-diameter of \( S' \) by \( a'/6 |\chi(S')| = a'/6 \times 2 |\chi(S)| = a'/3 |\chi(S)| \), and the length of a one-vertex triangulation for \( S' \) by \( 2a'/3 |\chi(S)| \). As those numbers also bound from above the \( \epsilon \)-diameter and the length of a one-vertex triangulation of \( S \), this proves the lemma for a minimal non-orientable surface, with \( a'/3 \) instead of \( a' \).

If the surface \( S \) is just pseudo-minimal, it is the boundary of an arbitrarily small regular neighborhood of a minimal surface \( S' \). As the diameter and the length of the edges of a one-vertex triangulation are at most \( a'/3 |\chi(S')| \) and \( 2a'/3 |\chi(S')| \), with \( |\chi(S)| \leq 2 |\chi(S')| \), this ends the proof of Lemma 2.12. \( \square \)

As from Lemma 2.10 the boundary components of \( C \) are pseudo-minimal surfaces, and Lemma 2.12 applies to bound from above the \( \epsilon \)-diameter and the length...
of the edges of a one-vertex triangulation of those surfaces. Furthermore, if some geodesic arcs need to be added, they can be made as small as necessary.

Recall some definitions and results of [Mah, Sections 2 and 3].

**Definition 2.13.** A coned \( n \)-simplex in a compact Riemannian manifold \( N \) of sectional curvature at most \(-1\) is defined inductively as follows. A coned 1-simplex \( \Delta^1 = (v_0, v_1) \) is a constant speed geodesic from \( v_0 \) to \( v_1 \). The speed is allowed to be zero, and in this case the 1-simplex degenerates to the point \( v_0 \). A coned \( n \)-simplex is a map \( \phi : \Delta^n \to N \) such that \( \phi|_{\Delta^{n-1}} \) is a coned \((n - 1)\)-simplex, and for all \( x \in \Delta^{n-1} \), \( \phi|_{\{tx+(1-t)v_n \mid t \in [0,1] \}} \) is a constant speed geodesic. The map \( \phi \) depends on the order of the vertices \((v_0, \ldots, v_n)\), and its image may not be embedded in \( N \), just immersed.

A simplicial surface is a continuous map \( \phi : S \to N \) where \( S \) is a triangulated surface, such that the restriction of the map \( \phi \) to each triangle \( \Delta \) of \( S \) is a coned 2-simplex.

**Lemma 2.14.** Let \( N \) be a complete Riemannian manifold with sectional curvature at most \(-1\). Suppose that \( T \) is a connected and orientable pseudo-minimal surface in \( N \) with diameter bounded from above by \( N \) and admitting a one-vertex triangulation in which the length of the edges is at most \( N' \). Then \( T \) can be homotoped to a simplicial surface \( T' \) with diameter at most \( 2N' \) and such that any point \( x \in T \) and \( x' \in T' \) are at distance at most \( N + N' \) from each other. Furthermore, every point of \( T' \) is at distance at most \( N' \) from the vertex of the one-vertex triangulation of \( T \).

**Proof of Lemma 2.14** Let \( v \) be the vertex of the one-vertex triangulation of \( T \). First, we homotop each edge \( e \) of the triangulation of \( T \) to its closed length-minimizing geodesic representative \( e' \) in \( \pi_1(N, v) \). If the homotopy class of \( e \) is zero (meaning that the surface \( T \) is compressible in \( N \)), we homotop \( e \) to the degenerate constant speed geodesic \( \{v\} \).

Let \( T \) be a triangle in \( T \). If all edges of \( T \) are null-homotopic, \( T' \) is the degenerate 2-simplex corresponding to \( \{v\} \). If at least one edge of \( T \) corresponds to a null-homotopic curve, then we build a simplicial triangle \( T' \) containing the closed geodesic at \( v \) corresponding to this edge, coned from \( v \). More precisely, the 1-skeleton of \( T' \) is the union of closed geodesics corresponding to its non-homotopically trivial edges. To build the 2-skeleton, we choose one of those non-trivial edges and we cone \( v \) to this edge with constant speed geodesics. In this case, each point in \( T' \) is at distance at most \( N'/2 \) from the vertex \( v \) (as it is on a closed geodesic of length at most \( N' \)).

If all the edges of \( T \) are non-zero in \( \pi_1(N, v) \), they correspond to three non-trivial closed geodesics \( c_1, c_2 \) and \( c_3 \), starting and ending at the point \( v \). In the universal cover \( \tilde{N} \) of \( N \), we can choose lifts \( a_1, a_2 \) and \( a_3 \) of \( c_1, c_2 \) and \( c_3 \) that bound a totally geodesic triangle \( \tilde{T} \). By definition, the covering projection maps \( a_i \) to \( c_i \) for \( i = 1, 2, 3 \). The simplicial triangle \( T' \) corresponding to \( T \) is the image under the covering projection of the totally geodesic triangle \( \tilde{T} \) in \( \tilde{N} \). As the covering projection is an isometry from the interior of \( T \) to the interior of \( T' \), and as each point in the interior of \( T \) lies at distance at most \( N' \) (which is an upper bound for the maximum of the lengths of the sides \( a_1, a_2 \) and \( a_3 \)), each point \( x' \) in the interior of \( T' \) lies at distance at most \( N' \) from the vertex \( v \).
Therefore, starting from the triangulated surface $T$, we can build a simplicial surface $T'$ such that $v$ is the only vertex of the simplicial structure of $T'$ and each point $x'$ in $T'$ is at distance at most $N'$ from $v$. In particular, the diameter of $T'$ is at most $2N'$. As the diameter of $T$ is at most $N$ and $v$ is also a point of $T$, for any points $x' \in T'$ and $x \in T$, we have

$$d(x, x') \leq d(x, v) + d(x', v) \leq \text{diam}(T) + N' \leq N + N'$,

which proves Lemma 2.14. □

Given a spine $\Gamma$ for the compression body $C$ which is a union of simplicial surfaces corresponding to $\partial_- C$ joined by geodesic arcs, there exists a simplicial surface homotopic to this spine by a homotopy that does not sweep out too much volume. More precisely, this follows from the next lemma, proven in [Mah, Lemma 4.3, p. 2250].

**Lemma 2.15** ([Mah, Lemma 4.3]). Let $\sigma_1, \ldots, \sigma_n$ be a collection of simplicial surfaces, with basepoints $v_i$ in $M$ and a complete Riemannian 3-manifold of sectional curvature at most $-1$. Join the basepoint $v_1$ to each of the other basepoints by at least one geodesic arc to obtain a geodesic 2-complex $\Gamma$ homotopic to a surface of genus $g$. Then, there exists a homotopy of $\Gamma$ to a simplicial surface $\Sigma_0$ of genus $g$, and this homotopy sweeps out a volume of at most $3(2g + 2)V_3$, where $V_3$ is the maximal volume of an ideal hyperbolic tetrahedron. □

Recall that $\epsilon \leq \text{Inj}(M)/2$ and $a' = 6 \left( \frac{1}{4} + \frac{3}{4\pi} + \frac{3}{4\epsilon} + \frac{\sinh(\epsilon/4)}{\epsilon} \right)$. The constant $2\epsilon$ is a uniform lower bound for the injectivity radius of any finite cover of $M$. In particular, $\text{Inj}(M') \geq 2\epsilon$.

**Lemma 2.3**. Let $k_0 = \max \left\{ \frac{\ln(4(2a' + 1))}{2\ln^2}, 1 + \frac{\ln(1 + \ln(12V_3/\text{Vol}(M)))}{2\ln^2} \right\}$.

If $k_0 \chi_-(C) \ln \chi_-(C) \leq \ln \ln d/q$ and $\text{Vol}(M) \geq \pi/2$, then by applying Lemmas 2.14 and 2.15 to replace the boundary surfaces of $C$ to simplicial surfaces, one obtains a new compression body $C''$ corresponding to the region between the simplicial surfaces that is swept out in a degree one manner. The volume of $C''$ satisfies

$$\text{Vol}(C'') \geq \frac{1}{4} \text{Vol}(C) \geq \frac{\text{Vol}(M)d}{4q}.$$

**Proof of Lemma 2.3**. Let $\partial_- C = T_1 \cup \ldots \cup T_n$ be the components of $\partial_- C$, with $g(T_1) + \ldots + g(T_n) \leq g(\partial_+ C)$. As in Lemma 2.14 replace $\partial_+ C =: S_0$ and $\partial_- C = S_1 \cup \ldots \cup S_n$ by simplicial surfaces $S'_0$ and $T'_1 \cup \ldots \cup T'_n$, close to the previous surfaces. If $v_j \in T_j$ is the vertex of the one-vertex triangulation of $T_j$, then Lemmas 2.12 and 2.14 show that every point of $T'_j$ lies at distance at most $N'' = 2ea' |\chi(T_j)|$ from $v_j$. Thus, each new surface $T'_j$ is contained in the ball of center $v_j$ and radius $2ea' \chi_-(C)$. Let $C'$ be the new compression body obtained by taking the region between the simplicial surfaces $T'_j$ swept out in a degree one manner. The
The modification of volume is at most
\[
\text{Vol}(C') \geq \text{Vol}(C) - \sum_{j=0}^{n} \text{Vol}(B_j, 2ea'\chi_-(C)) \\
\geq \text{Vol}(C) - (g(C) + 1)\text{Vol}(B_{gg}(2ea'\chi_-(C))) \\
\geq \text{Vol}(C) \left(1 - \frac{\pi(\chi_-(C) + 4)(\sinh(4ea'\chi_-(C)) - 4ea'\chi_-(C))}{2\text{Vol}(M)d/q}\right).
\]

Let us show that \(\text{Vol}(C') \geq \text{Vol}(C)/2\), which is the same as proving that
\[
\frac{\pi(\chi_-(C) + 4)(\sinh(4ea'\chi_-(C)) - 4ea'\chi_-(C))}{2\text{Vol}(M)d/q} \leq \frac{1}{2}.
\]
It suffices to prove that
\[
\ln \left(\frac{\pi(\chi_-(C) + 4)(\sinh(4ea'\chi_-(C)) - 4ea'\chi_-(C))}{2\text{Vol}(M)d/q}\right) \leq 0.
\]

As by assumption, \(\text{Vol}(M) \geq \pi/2\).

As for every \(x \geq 2\), \(\ln(x + 4) \leq 2x\), it suffices to prove that
\[
(2 + 4ea')\chi_-(C) \leq \ln(d/q),
\]
which is the same as
\[
\ln(2 + 4ea') + \ln \chi_-(C) \leq \ln \ln(d/q).
\]
Now by assumption, \(\frac{\ln \ln d/q}{\chi_-(C) \ln \chi_-(C)} \geq k_0 \geq \frac{\ln(4(2ea' + 1))}{2\ln 2}\). Thus,
\[
\ln \ln d/q \geq \frac{\ln(4(2ea' + 1))}{2\ln 2}\chi_-(C) \ln \chi_-(C) \\
\geq \frac{\ln 2 + \ln(2 + 4ea')}{2\ln 2}\chi_-(C) \ln \chi_-(C) \\
\geq \frac{\chi_-(C) \ln \chi_-(C)}{2} + \frac{\ln(2 + 4ea')\chi_-(C) \ln \chi_-(C)}{2\ln 2} \\
\geq \ln \chi_-(C) + \ln(2 + 4ea');
\]
as \(\chi_-(C) \geq 2\), showing that \(\text{Vol}(C') \geq \text{Vol}(C)/2\).

From Lemma 2.15 the volume swept out by the homotopy between \(\Gamma\) and \(\Sigma_0\) is at most \(3(\chi_-(C) + 4)V_3\). As the volume of \(C\) is at least \(\text{Vol}(M)d/q\) by Lemma 2.2, the volume of what remains after cutting the metric completion of \(C'\) along \(\Sigma_0\) and throwing off components containing the infinite products to obtain a new compression body \(C''\) is at least
\[
\text{Vol}(C') - 3(\chi_-(C) + 4)V_3 \geq \text{Vol}(C)/2 \left(1 - 3V_3(\chi_-(C) + 4)\frac{2q}{\text{Vol}(M)d}\right).
\]
Therefore, it suffices to prove that $3V_3(\chi_-(C)+4)\frac{2q}{\text{Vol}(M)d} \leq \frac{1}{2}$, or \(\ln(\frac{12V_3(\chi_-(C)+4)}{\text{Vol}(M)d/q}) \leq 0\), or also
\[
\ln \left( \ln \frac{12V_3}{\text{Vol}(M)} + \ln(\chi_-(C) + 4) \right) \leq \ln \ln(d/q).
\]
As $\chi_-(C) \geq 2$, $\ln(\chi_-(C) + 4) \geq \ln 6 > 1$. Thus,
\[
\ln \left( \ln \frac{12V_3}{\text{Vol}(M)} + \ln(\chi_-(C) + 4) \right) = \ln \left( \ln(\chi_-(C) + 4)(1 + \frac{\ln \frac{12V_3}{\text{Vol}(M)}}{\ln(\chi_-(C) + 4)}) \right) \]
\[
= \ln \ln(\chi_-(C) + 4) + \ln \left( 1 + \frac{\ln \frac{12V_3}{\text{Vol}(M)}}{\ln(\chi_-(C) + 4)} \right) \]
\[
\leq \ln \ln(\chi_-(C) + 4) + \ln \left( 1 + \frac{12V_3}{\text{Vol}(M)} \right).
\]
As soon as $c \geq 2$, $\frac{\ln\ln(c+4)}{c\ln c} \leq 1$. Then,
\[
\frac{\ln \left( \ln \frac{12V_3}{\text{Vol}(M)} + \ln(\chi_-(C) + 4) \right)}{\chi_-(C) \ln \chi_-(C)} \leq \frac{\ln \ln(\chi_-(C) + 4) + \ln \left( 1 + \frac{12V_3}{\text{Vol}(M)} \right)}{\chi_-(C) \ln \chi_-(C)} \]
\[
\leq 1 + \frac{\ln \left( 1 + \frac{12V_3}{\text{Vol}(M)} \right)}{2 \ln 2}.
\]
Now, as $\frac{\ln\ln d/q}{\chi_-(C) \ln \chi_-(C)} \geq k_0 \geq 1 + \frac{\ln(1+\ln(12V_3/\text{Vol}(M)))}{2 \ln 2}$,
\[
\frac{\ln d/q}{\chi_-(C) \ln \chi_-(C)} \geq \frac{\ln \left( \ln \frac{12V_3}{\text{Vol}(M)} + \ln(\chi_-(C) + 4) \right)}{\chi_-(C) \ln \chi_-(C)},
\]
and so $\text{Vol}(C'') \geq \text{Vol}(C)/4 \geq \text{Vol}(M) \frac{d}{4q}$, which ends the proof of Lemma 2.3. \(\square\)

In the sequel, to simplify notation, we will still denote by $C$ the new compression body $C''$ and we will work in the closure of the region of $C$ bounded by the two connected simplicial surfaces $\Sigma_0$ (corresponding to the $\partial_- C$ union some arcs, and forming a spine for $C$) and $\Sigma_1$ corresponding to $\partial_+ C$.

2.2.2. Sweepouts.

**Definition 2.16.** Let $C$ be a compression body. Set $S = \partial_+ C$. A sweepout of the compression body $C$ is a 1-parameter family of surfaces $\{S_t\}_{t \in [0,1]}$ such that $S_0$ is a spine of $C$, $S_1 = S = \partial_+ C$, for all $t \in (0, 1]$ the surface $S_t$ is homeomorphic to $S$, and the application $\Phi : S \times I \to C$ is of homological degree one.

There exists a sweepout $\{S_t\}_{t \in [0,1]}$ of the compression body $C$ such that $S_0 = \Sigma_0$ and $S_1 = \Sigma_1$. The sweepout surfaces $S_t$ for $t > 0$ are of interest in order to construct a long product in the compression body $C$. But, if we can control the diameter of a minimal surface in terms of its genus and the injectivity radius of the ambient manifold, we cannot uniformly control the diameter of all the sweepout surfaces $S_t$: there may appear some long and thin Margulis tubes, containing a closed geodesic of the surface with length less than the injectivity radius of $M'$. 

To face this problem, we work with the notion of $\epsilon$-diameter, for which non-connected surfaces with small diameter components are considered as “small”. Recall the definition.

**Definition 2.17.** Let $\epsilon > 0$. The (intrinsic) $\epsilon$-diameter of a non-necessarily connected surface $F$ is the minimal number of balls of radius $\epsilon$ for the metric of $F$ required to cover the surface $F$.

If $F$ is immersed in a Riemannian 3-manifold $N$, the $\epsilon$-diameter of $F$ in $N$ is the minimal number of 3-balls in $N$ of radius $\epsilon$ for the metric of $N$ required to cover $F$.

**Remark 2.18.** If $F$ is immersed in a Riemannian 3-manifold $N$, the $\epsilon$-diameter of $F$ in $N$ is always at most the intrinsic $\epsilon$-diameter of $F$ with respect to the induced metric.

At this point, we recall the technique of Maher to construct from the original sweepout $\{S_t\}_{t \in I}$ of $C$ what he calls a “generalized sweepout” $\{\tilde{S}_t\}_{t \in I}$ in which the $\epsilon$-diameter of good sweepout surfaces is uniformly bounded from above (see [Mah, Sections 2 and 3]).

The first step is to straighten the sweepout $\{S_t\}_{t \in I}$ to a simplicial sweepout, using results of Bachman, Cooper and White [BCW]. We recall terminology and results stated in [Mah, Sections 2 and 3].

**Definition 2.19.** A simplicial sweepout is a sweepout $\Phi : S \times I \to N$ such that each surface $S_t$ is mapped to a simplicial surface with at most $4g(S)$ triangles, and at most one vertex of angle sum less than $2\pi$.

The following lemma ensures that we can homotop the sweepout $\{S_t\}_{t \in [0,1]}$ between $\Sigma_0$ and $\Sigma_1$ to a simplicial sweepout. It is an improvement of [BCW, Theorem 2.3], and is proven by Maher [Mah, Lemma 2.5, p. 2236].

**Lemma 2.20 (Mah, Lemma 2.5).** Let $N$ be a closed orientable Riemannian manifold of sectional curvature at most $-1$. If $\Sigma_0$ and $\Sigma_1$ are simplicial surfaces with one-vertex triangulations, which are homotopic by a homotopy $\Phi : S \times I \to N$, then there exists a simplicial sweepout $\Phi' : S \times I \to N$ homotopic to $\Phi$ relative to $S \times \partial I$. \hfill $\square$

Therefore, we can suppose that the sweepout in the compression body $C$ is simplicial between the simplicial surfaces $\Sigma_0 = S_0$ and $\Sigma_1 = S_1$.

After getting this simplicial sweepout in the compression body $C$, the next step will be to get rid of the long and thin tubes in the sweepout surfaces to get a “generalized sweepout” in which the $\epsilon$-diameter of all sweepout surfaces is uniformly bounded from above.

**Definition 2.21 (Mah, Definition 3.2, p. 2237).** Let $N$ be a compact, connected and oriented 3-manifold. A generalized sweepout of $N$ is given by a triple $(\Sigma, f, h)$, where $\Sigma$ is an orientable and compact 3-manifold, and the map $h : \Sigma \to \mathbb{R}$ is a Morse function, constant on each boundary component of $\Sigma$ and such that for all but finitely many $t \in \mathbb{R}$, the set $f^{-1}(\{t\})$ is an immersed surface. Moreover, it is required that $f : (\Sigma, \partial \Sigma) \to (N, \partial N)$ is of homological degree one.

Of course, an ordinary sweepout $\Phi : S \times I \to N$ is an example of a generalized sweepout: the Morse function $h : S \times I \to \mathbb{R}$ is given by the projection to the factor.
surgeries take place. The new maps (ς sweepout can be seen as a one-parameter family of immersed surfaces $S_t$ with singular times $t$ where the genus or the number of components of those surfaces change.

Starting from the simplicial sweepout $\{S_t\}_{t \in I}$ of $C$, we wish to obtain a generalized sweepout in which each sweepout surface has bounded $\epsilon$-diameter. To this aim, we follow Maher and introduce the notion of surgery of a generalized sweepout.

**Definition 2.22.** One can obtain from a generalized sweepout given by $(\Sigma, f, h)$ a new generalized sweepout $(\Sigma', f', h')$ by an operation called a surgery of generalized sweepouts, as described below. (In fact, it is a special case of a more general construction called a modification of generalized sweepout, described by Maher and Rubinstein in [MR].)

Let $(\Sigma, f, h)$ be a generalized sweepout of a 3-manifold $N$. Take a submanifold in $\Sigma$ of the form $A \times [a, b]$, where $0 < a < b < 1$ and $A$ is an annulus in the surfaces $S_t$ for $t \in [a, b]$. We do $(0, 1)$ surgery to this solid torus $A \times [a, b]$ in the following way: choose two times $c$ and $d$ such that $a < c < d < b$. Take a core geodesic $\gamma$ for the annulus $A$ in the surface $S_a$. Shrink this geodesic: it gets shorter and shorter, until it collapses to a point in a modification $S_t'$ of the surface $S_c$. For all $t \in (c, d)$, replace the surface $S_t$ by the surface $S_t'$ obtained from $S_t$ by surgering along $\gamma$, i.e. we cut $S_t$ along $\gamma$ and cap off the resulting surface with two discs. Do this in a smooth way, such that the two discs of $S_t'$ get closer and shrink to a single point at time $d$. The new surface $S_t''$ is then singular, with a singular point corresponding to the former two discs. This point again becomes the geodesic $\gamma$ that gets larger when $t \in (d, b]$ increases. Do this in such a way that you do not modify $S_a$ or $S_b$ or $\partial A \times [a, b]$. In this way, we get a new generalized sweepout $(\Sigma', f', h')$, where $\Sigma'$ is obtained by replacing $A \times [a, b] \subset \Sigma$ by the new manifold where $S_t$ is replaced by $S_t'$ for all $t \in [a, b]$. Let us denote by $T$ the small tube in $N$ bounded by $A$, where the surgeries take place. The new maps $(f', h')$ coincide with $(f, h)$ outside $T \times [a, b]$ and in $\partial(T \times [a, b])$. As the modification of the sweepout takes place in a proper compact subset of $N$, there exists a point $x$ in the interior of $N \setminus (T \times [a, b])$. As the map $f$ is not modified in a neighborhood of $f^{-1}\{x\}$, the homological degree of $f'$ is the same as the homological degree of $f$, so it is still equal to one. Thus the triple $(\Sigma', f', h')$ is still a generalized sweepout. (See Figure 1.)

Set $\mathcal{N}_+ = \mathcal{N}(\partial_+ C) = \{x \in C, d(x, \Sigma_1) \leq \epsilon/2\}$.

Let $K = 4 \left(3 + 1/ \sinh^2(\epsilon/8)\right) g(C) - 10$ and $K' := 2a' |\chi(\partial_+ C)|$.

**Proposition 2.23.** Let $\mu > 0$. There exists a constant $\eta > 0$ as small as wanted, depending only on the simplicial sweepout $\{S_t\}_{t \in I}$ and $\mu$, and a finite sequence of surgeries of the simplicial sweepout giving a generalized sweepout $\{\tilde{S}_t\}_{t \in I}$ of $C$ and satisfying the following properties.

For every regular time $t \in [\eta, 1 - \eta]$, the intrinsic $\epsilon$-diameter of every component of $\tilde{S}_t$ disjoint from $\mathcal{N}_+$ is less than or equal to $K$. In every case, the diameter of any connected component of $\tilde{S}_t$ in the compression body $C$ is at most $\epsilon(1 + 2K' + 2K)$. For $t \geq 1 - \eta$, each point on the surface $\tilde{S}_t$ lies at distance at most $\epsilon K'$ from $\Sigma_1$. For $t \leq \eta$, any point on one of the original surfaces $S_t$ is at distance at most $\mu/2$
from \( \Sigma_0 \). Furthermore, for each regular time \( t \), the surface \( \tilde{S}_t \) is homotopic to an embedded surface obtained from \( \partial X \) by surgeries.

**Proof of Proposition 2.23.** In order to prove this proposition, the general idea is to cut the simplicial surfaces \( S_t \) along curves that are too short, namely of length less than or equal to \( \epsilon \), and to replace them by ruled discs, to get rid of long and thin tubes. This is described by Maher in the third section of [Mah, pp. 2238–2245]. Here we recall the proof, and we bring some precisions when they appear to be necessary.

Let \( t \) be a regular time. The simplicial surface \( S_t \) is composed of ruled triangles with at most one vertex of angle sum less than \( 2 \pi \), denoted by \( \nu_t \). Let \( \overline{S}_t \) be the completion of the universal cover \( \tilde{S}_t \) of \( S_t \{ \nu_t \} \). As it is a metric 2-complex composed of triangles of curvature at most \(-1\) and with vertices whose cone angles are all greater than or equal to \( 2 \pi \), \( \overline{S}_t \) is a complete CAT\((-1)\) geodesic metric space. Those spaces satisfy some useful properties; see [BH] and [Mah] p. 2239.

Let \( \alpha \) be a homotopy class in \( S_t \{ \nu_t \} \). To \( \alpha \), we can associate a covering transformation of the universal cover of \( S_t \{ \nu_t \} \), which can be extended to an isometry of \( \overline{S}_t \). As the completion of a fundamental domain for \( S_t \{ \nu_t \} \) is compact, this isometry cannot be parabolic. Thus it is hyperbolic or elliptic. Let \( \overline{\gamma}_t \) be the set of points in \( \overline{S}_t \) which are moved the least distance by the isometry. This is a geodesic if the isometry is hyperbolic, or isolated points if the isometry is elliptic. We denote by \( \gamma_t \) the projection of \( \overline{\gamma}_t \) under the covering map, in the sense that if \( \overline{\gamma}_t \) is a geodesic and does not meet \( \overline{S}_t \setminus \tilde{S}_t \), \( \gamma_t \) is a closed piecewise geodesic homotopic to \( \alpha \) in \( S_t \{ \nu_t \} \). If \( \overline{\gamma}_t \) is a geodesic meeting \( \overline{S}_t \setminus \tilde{S}_t \), then we perturb it slightly and in an equivariant way such that it avoids \( \overline{S}_t \setminus \tilde{S}_t \) and its projection \( \gamma_t \) in \( S_t \{ \nu_t \} \) is an embedded closed curve in the homotopy class of \( \alpha \). Finally, if \( \overline{\gamma}_t \) is a set of points, it corresponds to the constant loop \( \gamma_t \) of length zero and is equal to the
point \(v_t\). By extension, in any case we will call \(\gamma_t\) the geodesic representative of \(\alpha\). Notice that \(\gamma_t\) is an embedded curve or a point in \(C\).

As the negatively curved triangles that compose the surfaces \(S_t\) vary continuously with time \(t\), we can expect the geodesic representatives \(\gamma_t\) to also vary continuously. This is proven by Maher [Mah, Lemma 3.4, p. 2240].

**Lemma 2.24** ([Mah, Lemma 3.4]). Let \(\gamma\) be a simple closed curve in \(S \setminus \{v\}\) where \(v\) is a point of \(S\) mapping to the point \(v_t\) for each time \(t\). Then the geodesic representatives \(\gamma_t\) of \(\gamma\) vary continuously with \(t\).

**Definition 2.25.** A geodesic representative \(\gamma_t\) is said to be short if its length is less than or equal to \(\epsilon\).

For all \(t\), let \(\Gamma_t\) be the set of short geodesic representatives of \(S_t\). This is a finite set and is not empty, as the geodesic representative of the homotopy class of the loop around \(v_t\) has length zero.

Let \(\gamma_t\) be a short geodesic representative. Pick up a connected component \(\tilde{\gamma}_t\) of \(\gamma_t\), the preimage of \(\gamma_t\) in \(\tilde{S}_t\). Choose an orientation for \(\tilde{\gamma}_t\) so that the distance function from \(\tilde{\gamma}_t\) has a well defined sign. In the special case where the length of \(\gamma_t\) is zero, the distance from \(\tilde{\gamma}_t\) will always be non-negative. If \([p, q]\) is an interval of \(\mathbb{R}\), let \(\tilde{N}_{[p, q]}(\tilde{\gamma}_t)\) be the set of points \(x \in \tilde{S}_t\) such that \(p \leq d(x, \tilde{\gamma}_t) \leq q\). Let \(N_{[p, q]}(\gamma_t)\) be the image in \(S_t\) of \(\tilde{N}_{[p, q]}(\tilde{\gamma}_t)\) under the covering projection. If the interval is the single point \(\{r\}\), we will denote this neighborhood by \(N_{[r]}(\gamma_t)\).

**Definition 2.26.** Let \(A(\gamma_t)\) be the maximal neighborhood \(N_{[p, q]}(\gamma_t)\) such that for every length \(r \in [p, q]\), \(N_{[r]}(\gamma_t)\) is an embedded simple curve of length at most \(\epsilon\). The set \(A(\gamma_t)\) is called the annular neighborhood of \(\gamma_t\).

Define \(E(\gamma_t) = N_{[p+\epsilon/2, q-\epsilon/2]}(\gamma_t)\) to be the surgery neighborhood corresponding to \(\gamma_t\), with the convention that \(E(\gamma_t)\) is the empty set if \(q - p < \epsilon\). This neighborhood is the subset of \(A(\gamma_t)\) corresponding to the union of all curves \(N_{[r]}(\gamma_t)\) lying at distance at least \(\epsilon/2\) from the boundary of \(A(\gamma_t)\).

As the annular neighborhood \(A(\gamma_t)\) contains \(\gamma_t = N_{[0]}(\gamma_t)\), it is not empty. The annular neighborhood and the surgery neighborhood vary continuously with \(t\), but the surgery neighborhood \(E(\gamma_t)\) can be empty and does not necessarily contain the geodesic representative \(\gamma_t\).

The following lemma is proven by Maher in [Mah, Lemma 3.7, p. 2242].

**Lemma 2.27** ([Mah, Lemma 3.7]). If \(\alpha_t\) and \(\beta_t\) are short geodesic representatives of distinct homotopy classes in \(S_t \setminus v_t\), then their surgery neighborhoods \(E(\alpha_t)\) and \(E(\beta_t)\) are disjoint.
simple curves $N_{[r_a]}(\gamma_a)$ and $N_{[r_b]}(\gamma_b)$ for lengths $r_a$ and $r_b$, and the union of the surgery neighborhoods $E(\gamma_{[a,b]}) = \{ E(\gamma_t) : t \in [a, b] \}$, is a solid torus in $\Sigma$, on which we wish to do a surgery of generalized sweepouts. When it is possible, we follow Maher’s construction.

There is a difficulty here, as the surgery of generalized sweepouts described above is possible only if the geodesic $\gamma_t$ bounds an immersed disc in the compression body $C$. Therefore, we need to make a distinction between two cases of surgery neighborhoods.

**Definition 2.28.** A persistent surgery neighborhood of $S_t$ is a surgery neighborhood $E(\gamma_t)$ for which the corresponding geodesic $\gamma_t$ is not homotopically trivial in $C$.

**Lemma 2.29.** Let $t \in (0, 1)$ and $E(\gamma_t)$ be a persistent surgery neighborhood for $S_t$. If the corresponding surgery curve $\gamma_t$ is homotopically trivial in $C$, then $E(\gamma_t)$ is entirely contained in $N_+$. In particular, for every point $x$ and $y$ in the union of the persistent surgery neighborhoods of $S_t$, the distance in $C$ between $x$ and $y$ is at most $\epsilon + \text{diam}(\Sigma_1) \leq \epsilon(1 + 2K')$.

**Proof of Lemma 2.29.** For each $r \in [p, q]$, as the curve $N_{[r]}(\gamma_t)$ is of length at most $\epsilon < \text{Inj}(M')$, it is null-homotopic in $M'$ and is contained in a hyperbolic 3-ball $B$, isometrically embedded in $M'$ and of diameter $\epsilon/2$.

The curve $\gamma_t$ is not homotopically trivial in $C$ and $N_{[r]}(\gamma_t)$ is homotopic to $\gamma_t$, so $B \cap \partial C \neq \emptyset$. By assumption (1) of Theorem A, the negative boundary $\partial^- C$ is a union of incompressible surfaces. Necessarily, $B \cap \partial^+ C \neq \emptyset$, which, with the simplicial surfaces, implies $B \cap \Sigma_1 \neq \emptyset$. Thus, as the curve $N_{[r]}(\gamma_t)$ is contained in $B$ and $B$ intersects $\Sigma_1$, each point of $N_{[r]}(\gamma_t)$ is at distance at most $\epsilon/2$ from $\Sigma_1$. It follows that the surgery neighborhood $E(\gamma_t)$ is entirely contained in $N_+$.

Then noticing that the diameter of $N_+$ in the manifold $C$ is at most $\epsilon + \text{diam}(\Sigma_1) \leq \epsilon(1 + 2K')$ suffices to prove Lemma 2.29. □

**Remark 2.30.** Let $E(\gamma_{t_0})$ be a surgery neighborhood for a given time $t_0 \in (0, 1)$ and $[a, b]$ a maximal time interval on which $E(\gamma_t)$ is not empty. If one of the surgery neighborhoods $E(\gamma_{t_i})$ is persistent, then all surgery neighborhoods $E(\gamma_t)$ are persistent for every time $t$ in $[a, b]$.

Indeed, for $t \in [a, b]$, the curves $\gamma_t$ are homotopic, so if one of them is homotopically non-trivial in $C$, it is the case for each of them. □

We can now carry on with the proof of Proposition 2.22. Suppose that $E(\gamma_t)$ is a non-persistent surgery neighborhood. We describe the operation of surgery on $E(\gamma_t)$, following Maher [Mah] pp. 2242 and 2243.

Choose a continuous family of basepoints on the boundary of $E(\gamma_t)$ such that the two basepoints agree at times $a$ and $b$. We modify the sweepout by expanding times $a$ and $b$ to short intervals $I_a$ and $I_b$ on which the map is constant for the moment.

On the interval $I_a$, the curve $N_{[r_a]}(\gamma_a)$ is an embedded simple curve homotopic to the geodesic $\gamma_a$. As by assumption $\gamma_t$ is null-homotopic in $C$, the curve $N_{[r_a]}(\gamma_a)$ bounds an immersed disc in $C$.

In the interval $I_a$, we replace in a continuous way the curve $N_{[r_a]}(\gamma_a) = E(\gamma_a)$ by a pair of ruled discs in $C$ coned from the basepoint $x_a$. More precisely, as the
metric of \( C \) is complete, the ruled disc is the union of all minimizing geodesics between each point of \( N_{[a,b]}(\gamma_a) \) and the basepoint \( x_a \). Its curvature is then at most \(-1\). In the interval \((a,b)\), we remove the surgery neighborhood \( E(\gamma_t) \) and replace it by a pair of such ruled discs in \( C \) coned from the basepoints of the boundary of the surgery neighborhood. Finally, in the interval \( I_0 \) we paste the discs together to come back to the original surface. This is a surgery of a generalized sweepout as defined above.

The following lemma directly follows from Lemmas 3.8 to 3.10 of Maher and is proven in [Mah, pp. 2243–2246].

**Lemma 2.31.** Suppose that all surgery neighborhoods \( E(\gamma_t) \) of \( S_t \) can be replaced by pairs of ruled discs as described above and let \( \hat{S}_t \) be the resulting surface. Then the \( \epsilon \)-diameter of \( \hat{S}_t \) is at most \( K = 4 \left( 3 + 1/\sinh^2 (\epsilon/8) \right) g(C) - 10. \)

The construction is now the following. Let \( t \in [\eta, 1-\eta] \). From Remark 2.30 the fact that a given surgery neighborhood \( E(\gamma_t) \) of \( S_t \) is persistent or not depends only on the maximal time interval \([a, b]\) on which it exists. If it is not persistent, then apply the surgery procedure described above. If it is persistent, leave it unchanged. Let \( \hat{S}_t \) be the new generalized sweepout surface obtained.

If none of the surgery neighborhoods \( E(\gamma_t) \) of \( S_t \) are persistent, they have been removed by the surgery procedure. From Lemma 2.31 the intrinsic \( \epsilon \)-diameter of \( \hat{S}_t \) is at most \( K \).

Otherwise, Lemma 2.29 ensures that the diameter of the union of all persistent surgery neighborhoods in \( C \) is at most \( \epsilon(1 + 2K') \), as they are contained in \( N_\epsilon \). As the intrinsic \( \epsilon \)-diameter of each component of \( \hat{S}_t \) cut along persistent surgery neighborhoods is at most \( K \) from Lemma 2.31 the diameter in the compression body \( C \) of each connected component of \( \hat{S}_t \) is at most \( \epsilon(1 + 2K' + 2K) \).

Furthermore, if a component of \( \hat{S}_t \) does not intersect \( N_\epsilon \), it does not contain any persistent surgery neighborhood, and its intrinsic \( \epsilon \)-diameter is at most \( K \) from Lemma 2.31.

Another difficulty is that Maher’s construction does not take the boundaries of the time interval \( I \) into account. However, it may happen that \( a = 0 \) or \( b = 1 \), and in this case we might be obliged to modify the start and finish of simplicial sweepout surfaces \( S_0 = \Sigma_0 \) and \( S_1 = \Sigma_1 \), which we want to avoid. Therefore, if this case occurs, we need to refine the construction to modify the simplicial sweepout in a small regular neighborhood of \( S_0 \cup S_1 \) in such a way that we do not modify the surfaces \( S_0 \) and \( S_1 \). As we will lose control on the diameter of the sweepout surfaces in this regular neighborhood, we have to choose it small enough in order that the sweepout surfaces we will pick up later to be some of the nested surfaces are not in this neighborhood. Thus we can control their diameter well. The constant \( \mu \) has been introduced in assumptions of Proposition 2.29 in order to take care of that, and its value will be defined later.

To finish modifying the original simplicial sweepout to get the desired generalized sweepout, there remains to consider the case when \( a = 0 \) or \( b = 1 \). If \( E(\gamma_0) \) is a non-persistent surgery neighborhood and just a single closed curve, we can apply the previous construction, replacing the time 0 by an interval \( I_0 \) and doing surgery on this interval, without modifying the starting boundary surface \( S_0 = \Sigma_0 \). It works similarly if \( E(\gamma_1) \) is a single closed curve. The problem is when \( E(\gamma_0) \) or \( E(\gamma_1) \) have non-empty interior and are non-persistent surgery neighborhoods. As the two cases
are similar, let us suppose for instance that the interior of $\mathcal{E}(\gamma_0)$ is not empty. As everything is continuous, there exists a maximal time $b \in (0, 1]$ such that $\mathcal{E}(\gamma_t)$ is a non-empty and non-persistent surgery neighborhood for all $t \in [0, b]$.

As the sweepout surfaces $(S_t)_{t \in I}$ vary continuously with $t$, there exists a constant $\eta > 0$ as small as we like, depending only on the original simplicial sweepout $(S_t)_{t \in I}$ and the choice of the point $x_0$ and the geodesic arc $c$, such that for every $t \in [0, \eta]$, each point of $S_t$ lies at distance at most $\mu/2$ from $\Sigma_0 = S_0$, and that for every $t \in [1 - \eta, 1]$, each point in $S_t$ is at distance at most $\epsilon K'/2$ from $\Sigma_1 = S_1$. If $b \leq \eta$, we do not modify the sweepout. Otherwise, if $\eta < b < 1$, we apply the surgery construction for all $t \in [\eta, b]$; we replace the surgery neighborhoods $\mathcal{E}(\gamma_t)$ by a pair of ruled discs coned from basepoints in the boundary of $\mathcal{E}(\gamma_t)$ in a continuous way. On the interval $[0, \eta]$, we replace the surgery neighborhoods by a pair of discs for $t$ near $\eta$ that get pasted to the initial surgery neighborhood $\mathcal{E}(\gamma_0)$ as the time is decreasing to 0, not too far from the original surface $S_t$ and in a continuous way. We can do this in such a way that it is still a modification of a generalized sweepout. If $b = 1$, do the same for all $t \in [1 - \eta, 1]$. As the diameter of the ruled discs is less than $\epsilon$ and $K'/2 \geq 1$, one can suppose that every point in $\hat{S}_t$ is at distance at most $\epsilon K'$ from $\Sigma_1$ for all $t \in [1 - \eta, 1]$.

This ends the proof of Proposition 2.23.

2.2.3. Sweepout surfaces and nested surfaces. To go on with the proof of Proposition B, we now need a lemma to precisely determine the constant $\mu$ which corresponds to the size of the collar neighborhood of $S_0$ that one has to take into consideration. Set $K' := 2a' \chi_\mu(C)$. From Lemma 2.12, the number $2\epsilon K'$ is an upper bound for the diameter of the simplicial surface $\Sigma_1$, identified with $\partial_+ C$. Let $\delta$ be the diameter of the compression body $C$.

**Lemma 2.32.** There exists a point $x_0$ in the interior of $C$ and lying at distance at least $(\frac{\delta}{2} - 2\epsilon K')$ from $\partial_+ C$.

**Proof of Lemma 2.32** Suppose that the lemma is false: for every point $z$ in the interior of $C$, $\text{dist}(z, \partial_+ C) < \frac{\delta}{2} - 2\epsilon K'$. For every point $z$ of $C$, the following inequality remains true: $\text{dist}(z, \partial_+ C) \leq \frac{\delta}{2} - 2\epsilon K'$. Take two points $x$ and $y$ in $C$ such that $d(x, y) = \text{diam}(C) = \delta$. Then

$$d(x, y) = \delta \leq \text{dist}(x, \partial_+ C) + \text{diam}(\partial_+ C) + \text{dist}(y, \partial_+ C)$$

$$\leq \left(\frac{\delta}{2} - 2\epsilon K'\right) + 2\epsilon K' + \left(\frac{\delta}{2} - 2\epsilon K'\right)$$

$$\leq \delta - 2\epsilon K' < \delta,$$

which is a contradiction, proving Lemma 2.32.

Let $c$ be a length-minimizing geodesic arc between $x_0$ and $\partial_+ C$. Let $\mu$ be the distance between the geodesic $c$ and $\Sigma_0$. As $c$ is embedded in the interior of $C$ (except for one extremity which belongs to $\partial_+ C = \Sigma_1$), the constant $\mu$ is strictly positive.

Now, for completeness of the proof of Proposition B, we state and prove a few lemmas which are implicit in [Mah, proof of Lemma 4.5, p. 2251].

We recall from Definition 2.4 that if $x$ is a point in $C$ and $S$ an immersed surface of $C$, we say that $S$ separates $x$ from $\partial_+ C$ if every oriented path from $x$ to $\partial_+ C$ has its algebraic intersection number equal to +1.
If two surfaces $S$ and $T$ immersed in $C$ are such that $S$ separates every point of $T$ from $\partial_+ C$, we say that $S$ separates $T$ from $\partial_+ C$. In this case, the surfaces $S$ and $T$ are said to be nested.

**Lemma 2.33.** A point $x$ lying in the interior of $C$ is separated from $\partial_+ C$ by $\hat{S}_t$ if and only if there exists a path $\gamma$ from $x$ to $\partial_+ C$ intersecting the surface $\hat{S}_t$ with algebraic intersection number $+1$.

**Proof of Lemma 2.33.** It suffices to show that if there exists a path $\gamma$ from $x$ to $\partial_+ C$ with an algebraic intersection number with $\hat{S}_t$ equal to $+1$, then every path $\gamma'$ from $x$ to $\partial_+ C$ intersects $\hat{S}_t$ with algebraic intersection number $+1$.

Let $\gamma'$ be another path from $x$ to $\partial_+ C$ in $C$. As the immersed surface $\hat{S}_t$ is homologous to $\partial_+ C$, the homology class of $[\hat{S}_t]$ is equal to zero in $H_2(C, \partial_+ C)$. The composition $\alpha = \gamma^{-1} \cdot \gamma'$ is a 1-cycle in $H_1(C, \partial_+ C)$.

As $\partial C = \partial_- C \cup \partial_+ C$, $[\alpha] \cdot [\hat{S}_t] = [\alpha] \cdot 0 = 0$, and thus $\gamma' \cdot \hat{S}_t = \gamma \cdot \hat{S}_t = +1$, proving Lemma 2.33. $\square$

For all $t \in [0, 1]$, let $D_t$ be the closure of the set of points $x \in C$ separated from $\partial_+ C$ by $\hat{S}_t$. As the immersed surfaces $(\hat{S}_t)_{t \in [0, 1]}$ are generalized sweepout surfaces of the compression body $C$, $D_0$ is the starting sweepout surface $\hat{S}_0$, and $D_1$ is equal to the whole compression body $C$. Let $E_t$ be the component of $D_t$ containing $x_0$. As before, $E_0$ is a complex of dimension at most 2, and $E_1 = C$.

**Lemma 2.34.** The boundary of the set $D_t$ is a subset of the surface $\hat{S}_t$.

**Proof of Lemma 2.34.** Let us assume that there exists a point $x$ in the boundary of $D_t$ which does not belong to the surface $\hat{S}_t$, and seek a contradiction. The distance $d = \text{dist}(x, \hat{S}_t)$ is then strictly positive. As the point $x$ belongs to the boundary of $D_t$, there exists a point $y$ in the complement of $D_t$ in $C$ such that $d(x, y) \leq \frac{d}{2}$. As $y$ is in the complement of $D_t$, there is a path $c$ from $y$ to the boundary $\partial_+ C$ with algebraic intersection number with $\hat{S}_t$ different from $+1$. Let $c'$ be a minimizing geodesic from $x$ to $y$; as the length of $c'$, which is equal to the distance between $x$ and $y$, is strictly less than the distance of $x$ to $\hat{S}_t$, the geodesic $c'$ does not intersect the surface $\hat{S}_t$. If $c'' = c' \cup c$, $c''$ is a path from $x$ to $\partial_+ C$ with algebraic intersection number with $\hat{S}_t$ not equal to $+1$. Therefore, the point $x$ is not separated from $\partial_+ C$ by $\hat{S}_t$. (See Figure 2.)

But as the point $x$ also belongs to $D_t$, there exists a point $z$ in $C$ separated from $\partial_+ C$ by $\hat{S}_t$ and such that the distance between $z$ and $x$ is less than $\frac{d}{2}$. Take a minimizing geodesic $a$ from $z$ to $x$. Let us denote it by $b = a \cup c''$. The path $b$ is linking $z$ to $\partial_+ C$, which implies that the algebraic intersection number of $b$ with $\hat{S}_t$ is equal to $+1$. On the other hand, the distance between $z$ and $x$ is at most $\frac{d}{2} < \text{dist}(x, \hat{S}_t)$, which implies that the minimizing geodesic $a$ does not intersect the surface $\hat{S}_t$. But then, the algebraic intersection number of the path $b = a \cup c''$ with the surface $\hat{S}_t$ is not equal to $+1$, which contradicts the fact that $z$ is separated from $\partial_+ C$ by $\hat{S}_t$. Thus, the point $x$ necessarily belongs to the surface $\hat{S}_t$, which ends the proof of Lemma 2.34. $\square$

**Lemma 2.35.** For every time $t$, the boundary of $E_t$ is connected.
Proof of Lemma 2.35. Indeed, if the boundary of $E_t$ were not connected, it would have at least two components $S$ and $T$ of $\hat{S}_t$. But then, $S$ and $T$ would be two disjoint and separating surfaces in the compression body $C$. If they are not nested, the set of the points separated from $\partial_+ C$ by $S$ is disjoint to the set of points separated from $\partial_+ C$ by $T$, which contradicts the fact that $E_t$ is connected. Therefore, the surfaces $S$ and $T$ are nested. But the surface $\hat{S}_t$ is homotopic to a surface obtained from $\partial_+ C$ by surgeries, and as surgeries preserve the algebraic intersection number in homology, two components of the same surface $\hat{S}_t$ cannot be nested, which ends the proof of Lemma 2.35.

To prove Proposition B, we will pick up the desired nested surfaces among the family of connected surfaces $(\partial E_t)_{t \in [0,1]}$.

End of the proof of Proposition B. Let $c$ be the length-minimizing geodesic arc from the point $x_0$ obtained in Lemma 2.32 to $\partial_+ C$. As before, denote by $\mu$ the distance between the geodesic $c$ and $\Sigma_0$. Let $L$ be the length of $c$. One has $L \geq \frac{\delta}{2} - 2\epsilon K'$. Take $\ell \mapsto c(\ell)$ as an arc-length parameterization of $c$, such that $c(0) = x_0$ and $c(L) = y_0 \in \partial_+ C$.

First, let us show that $E_t = \emptyset$ for $t \in [0,\eta]$, where $\eta$ is the constant given by Proposition 2.23. As every original sweepout surface $S_t$ is contained in a $\mu/2$-neighborhood of $S_0 = \hat{S}_0$ for all $t \leq \eta$, and the distance between $c$ and $S_0$ is at least $\mu$, the geodesic $c$ does not meet the sweepout surfaces $S_t$ for every $t \leq \eta$. As the new sweepout surfaces $\hat{S}_t$ are obtained from the surfaces $S_t$ by surgery, the intersection number between $c$ and $\hat{S}_t$ is the same as the intersection number between $c$ and $S_t$, so it is zero for $t \leq \eta$. Therefore, the geodesic $c$ is an arc joining $x_0$ to $\partial_+ C$ with an intersection number with $\hat{S}_t$ equal to zero for $t \leq \eta$. By definition, the surfaces $\hat{S}_t$ do not separate $x_0$ from $\partial_+ C$ for $t \leq \eta$, showing that there is no component of $D_t$ containing $x_0$. Thus, $E_t = \emptyset$ for every $t \in [0,\eta]$.

Let us assume that $\frac{\delta}{2} - 6\epsilon K' \geq 5\epsilon K$. As the sets $E_t$ vary continuously with time $t$, the function $L$ which maps time $t$ to the length of $c \cap E_t$ is a continuous map.
From the fact that $\mathcal{L}(\eta) = 0$ and $\mathcal{L}(1) = L$ the length of $c$, we deduce that there is a time $t_1 \in (\eta, 1)$ such that $\mathcal{L}(t_1) = L - 2\epsilon(1 + K + K')$. Let $S_1$ be the boundary of $E_{t_1}$. From Lemma 2.35 the immersed surface $S_1$ is a connected component of $\tilde{S}_{t_1}$. As $c$ is a minimizing arc-length parametrized geodesic, for every $a$ and $b \in [0, L]$, we have $d(c(a) , c(b)) = |b - a|$. Thus, the intersection point $c(\mathcal{L}(t_1))$ between $S_1$ and $c$ is lying at distance $2\epsilon(1 + K + K')$ from $\partial_+ C$. Since by construction every point in the surface $\tilde{S}_{t}$ for $t \geq 1 - \eta$ is at distance at most $\epsilon K'$ from $\partial_+ C$, necessarily $t_1 < 1 - \eta$. As the sets $E_t$ are empty for $t \leq \eta$, in fact $\eta < t_1 < 1 - \eta$. By definition of $E_{t_1}$, the surface $S_1$ separates $x_0$ from $\partial_+ C$. By Proposition 2.23 $S_1$ is connected. Let us show that its $\epsilon$-diameter is at most $K$. By Proposition 2.23 the diameter in $C$ of a component of $\tilde{S}_{t}$ is at most $\epsilon(1 + 2K + 2K')$. Furthermore, if $S_1$ contains a persistent surgery neighborhood, it means that $S_1$ intersects $N_+$. This implies that every point of $S_1$ is at distance at most $\epsilon(1 + 2K + 2K') + \epsilon/2$ of $\partial_+ C$, contradicting the fact that the intersection point between $S_1$ and $c$ is at distance $2\epsilon(1 + K + K') > \epsilon(1 + 2K + 2K') + \epsilon/2$ of $\partial_+ C$. Thus, $S_1$ does not contain any persistent surgery neighborhood. Proposition 2.23 ensures that its intrinsic $\epsilon$-diameter is at most $K$ and its diameter in $C$ is at most $2\epsilon K$. Therefore, the surface $S_1$ cannot meet $\{c(\ell), 0 \leq \ell < L - 2\epsilon(1 + K + K') - 2\epsilon K\} \cup \{c(\ell), L - 2\epsilon(1 + K + K') < \ell \leq L\}$. Let $\ell_1$ be the smallest value of $\ell$ such that $c(\ell) \in S_1$. We have $L - 2\epsilon(1 + 2K + K') \leq \ell_1 \leq L - 2\epsilon(1 + K')$. As $K' > 1$, this implies that $L - 2\epsilon(1 + 2K + K') \geq L - 4\epsilon(1 + K) \geq \frac{\delta}{2} - 4\epsilon K - 6\epsilon K' \geq \epsilon K > 0$.

Let $c_1 = \{c(\ell), 0 \leq \ell \leq \ell_1 - 14\epsilon K\}$. Replacing $c$ by $c_1$, we can iterate the previous process. If $K$ is small enough compared to $\delta$, there exists a time $t_2$ such that the length of $c_1 \cap E_{t_2}$ is equal to: $\text{length}(c_1) - 2\epsilon K = \ell_1 - 16\epsilon K \geq L - 20\epsilon K - 2\epsilon(1 + K') \geq L - 20\epsilon K - 4\epsilon K'$. For the same reasons as before, the boundary of $E_{t_2}$ is a surface $S_2$ which is a connected component of $\tilde{S}_{t_2}$ separating $x_0$ from $\partial_+ C$, and it intersects $c_1$ only on the set $\{c(\ell), (\ell_1 - 14\epsilon K) - 4\epsilon K \leq \ell \leq \ell_1 - 14\epsilon K\}$. Furthermore, the surface $S_2$ is too far from the boundary $\partial_+ C$ to contain a persistent surgery neighborhood, and its intrinsic $\epsilon$-diameter is at most $K$ by Proposition 2.23.

Let us prove that the distance between the surfaces $S_1$ and $S_2$ is less than or equal to $10\epsilon K$. Let $\ell_2$ be the smallest real number such that $c(\ell) \in S_2$. From the former discussion, $\ell_2 \leq \ell_1 - 14\epsilon K$. As $c(\ell_1) \in S_1$ and $c(\ell_2) \in S_2$, we have

$$\text{dist}(S_1, S_2) \geq \text{dist}(c(\ell_1), c(\ell_2)) - \text{diam}(S_1) - \text{diam}(S_2) \geq (\ell_1 - \ell_2) - 4\epsilon K \geq 14\epsilon K - 4\epsilon K = 10\epsilon K.$$ 

We can iterate the process with $c_2 = \{c(\ell), 0 \leq \ell \leq \ell_2 - 14\epsilon K\}$, on the condition that $\ell_2 - 14\epsilon K > 4\epsilon K$, so for example if $L - 2 \times 18\epsilon K - 4\epsilon K' > 4\epsilon K$.

The iteration process stops when $L - 18\epsilon K(n - 1) - 4\epsilon K' > 4\epsilon K$ but $L - 18\epsilon K(n - 4\epsilon K' \leq 4\epsilon K$, so for $n = \lceil \frac{L - 4\epsilon(K + K')}{18\epsilon K} \rceil$. As $L \geq \frac{\delta}{2} - \epsilon K'$, $n \geq \lceil \frac{\delta}{36\epsilon K} - \frac{\epsilon}{3} - \frac{K'}{3\epsilon K} \rceil$, which proves Proposition B.

2.3. Proof of Proposition C: From nested to parallel surfaces. With Proposition B, we know that we can find $n = \lceil \frac{\delta}{36\epsilon K} - \frac{\epsilon}{3} - \frac{K'}{3\epsilon K} \rceil$ immersed surfaces in the compression body $C$ of the cover $M'$. All those surfaces are nested, their $\epsilon$-diameter is at most $K$ and they are at distance at least $10\epsilon K$ from each other, where $K = 4 \left(3 + 1/\sinh^2(\epsilon/8)\right) g(C) - 10$. Furthermore, all those surfaces are homotopic to embedded surfaces obtained from $\partial_+ C$ by surgery.
Thus the genus of those immersed surfaces is between 0 and \( g(C') = g(\partial_+ C) \). So there are at least \( n' = \lfloor n/(g(C) + 1) \rfloor \) surfaces \( S_1, \ldots, S_{n'} \) with the same genus, and this genus is at most \( g(C) \). We take the indices \( j \) such that \( S_{j+1} \) separates \( S_j \) from \( \partial_+ C \).

We then follow the proof of Maher [Mah pp. 2252–2257]. Let \( S = S_j \) be one of the previous immersed and nested surfaces with the same genus. A collection \( \Delta_S \) of compression discs of \( \partial_+ C \) to get \( S \) is a finite set of properly embedded discs in \( C \), such that the sweepout gives a homotopy from \( S \) to a subset of \( \partial_+ C \cup \Delta_S \).

The first step is to show that for two connected and nested sweepout surfaces, one can choose collections of compression discs such that one of them is a subset of the other one. This is done in [Mah, Lemma 4.6, p. 2252]. In particular, if the two surfaces have the same genus, they are homotopic.

**Lemma 2.36 ([Mah] Lemma 4.6).** Let \( S_1 \) and \( S_2 \) be two of the immersed surfaces obtained in Proposition B. Suppose for example that \( S_2 \) separates \( S_1 \) from \( \partial_+ C \). Then we can choose a collection of compression discs of \( \partial_+ C \), say \( \Delta_{S_1} \), to get \( S_1 \) and \( \Delta_{S_2} \) to get \( S_2 \), such that \( \Delta_{S_2} \) is a subset of \( \Delta_{S_1} \). In particular, if the two surfaces \( S_1 \) and \( S_2 \) have the same genus, \( \Delta_{S_1} = \Delta_{S_2} \). \( \square \)

This lemma shows that all the nested surfaces \( S_1, \ldots, S_{n'} \) are homotopic, as they have the same genus.

The following lemma is crucial: we wish to replace the nested immersed surfaces by embedded surfaces of the same genus in an arbitrarily small neighborhood of the original immersed surfaces. This lemma is proven in [Mah] Lemma 4.7, p. 2253.

**Lemma 2.37 ([Mah] Lemma 4.7).** Let \( S \) be one of the surfaces obtained in Proposition B. Let \( T \) be a least genus, connected and embedded surface, separating \( S \) from \( \partial_+ C \). Then \( T \) is incompressible in \( C \setminus S \) and the genus of \( T \) is greater than or equal to the genus of \( S \).

**Proof of Lemma 2.37.** Here we recall Maher’s proof.

If the surface \( T \) were compressible in \( C \setminus S \), it could be compressed along embedded discs in \( C \setminus S \) to obtain a new surface \( T' \) embedded in \( C \setminus S \). But one component of \( T' \) would be an embedded surface in \( C \) separating \( S \) from \( \partial_+ C \), with genus strictly less than the genus of \( T \), which is a contradiction. So the surface \( T \) is incompressible in \( C \setminus S \).

The surface \( S \) is homotopic to \( \partial_+ C \) compressed along a collection \( \Delta_S \) of embedded discs. Thus, if \( C' \) is the component of \( C \setminus \Delta_S \) containing the surface \( S \), \( C' \) is a compression body and we can find for it a spine \( \Gamma \) that is homotopic to the immersed surface \( S \). The map on the first homology \( H_1(\Gamma) \to H_1(C) \) induced by the inclusion of \( \Gamma \) in \( C \) is injective.

The surface \( T \) is an embedded surface in the compression body \( C \), so it is separating and there exists a set \( D_T \) of embedded compression discs for \( T \) such that \( T \) compressed along \( D_T \) is parallel to some components of \( \partial_+ C \) (cf. [B, Lemma 2.3]). As \( T \) is incompressible in \( C \setminus S \), the compression discs of \( D_T \) for the surface \( T \) are only in one side of \( T \). So the surface \( T \) bounds a compression body \( C'' \) in \( C \). As the composition of the maps induced by the inclusions \( H_1(\Gamma) \to H_1(C'') \to H_1(C) \) is injective, the map \( H_1(\Gamma) \to H_1(C'') \) is injective. Thus the rank of \( H_1(C'') \) is greater than or equal to the rank of \( H_1(\Gamma) \), and necessarily the genus of \( T \) is greater than or equal to the genus of \( S \). \( \square \)
A consequence of Lemma 2.36 is that all the nested and immersed surfaces $S_1, \ldots, S_{n'}$ are homotopic. We want a little more: we need to find for all $j$ between 1 and $(n' - 1)$ a homotopy between $S_j$ and $S_{n'}$ that is disjoint from $S_k$ for all $k < j$. We follow the arguments of the proof of Lemma 4.8, p. 2254, but we compute precise upper bounds.

**Lemma 2.38.** From the surfaces $S_1, \ldots, S_{n'}$, one can construct a collection of immersed surfaces $S'_1, \ldots, S'_{n'-1}, S''_{n'}$ which are disjoint, nested and homotopic, and the homotopy from $S''_{n'}$ to $S'_j$ is disjoint from $S_k$ for $1 \leq k < j$. Furthermore, the diameter of the surfaces $S'_j$ is at most $8\epsilon K$, they are at distance at least $2\epsilon K$ from each other, and the $\epsilon$-diameter of $S'_2, \ldots, S'_{n'-1}$ is at most $K$.

**Proof of Lemma 2.38.** Each surface $S_j$ admits a one-vertex triangulation with edge-length bounded by $4\epsilon K$, and its diameter is at most $2\epsilon K$. Therefore, by Lemma 2.14 the surfaces $S_1$ and $S_{n'}$ are homotopic to simplicial surfaces $S'_1$ and $S''_{n'}$ with diameter at most $4\epsilon K$ and such that for every point $x \in S_j$ and $x' \in S'_j$ (where $j = 1$ and $n'$), the distance between $x$ and $x'$ is at most $6\epsilon K$. In fact, by construction of $S'_j$, each point of $S'_j$ is at distance at most $4\epsilon K$ from the original surface $S_j$.

The homotopy between the two simplicial surfaces $S'_1$ and $S''_{n'}$ can be modified into a simplicial sweepout as in section 2.2. By Proposition 2.23, there exists a finite sequence of surgeries of generalized sweepouts, starting from this simplicial sweepout and ending with a generalized sweepout in which all the sweepout surfaces $S'_t$ for $t \in [\eta, 1 - \eta]$ have $\epsilon$-diameter bounded above by $K$. We can use the same constant $K$ as before since the genus of the surfaces $S_j$ is at most $g(C)$. Moreover, the surfaces $S''_{n'}$ are homotopic to the surface $S_{n'}$ after some compressions if necessary. For $j$ between 2 and $(n' - 1)$, let $S'_j$ be the first sweepout surface $S'_t$ intersecting $S_j$. As $S'_j$ is a generalized sweepout surface, its $\epsilon$-diameter is at most $K$.

We know from the construction of a generalized sweepout that the genus of the surface $S'_j$ is at most the genus of the surface $S_j$. In fact, we show that those two genera are equal.

**Claim.** For all $1 \leq j \leq n' - 1$, the genus of the surface $S'_j$ is the same as the genus of the original sweepout surface $S_j$.

Assuming the Claim, since the modified sweepout surfaces $S'_j$ have the same genus as the original sweepout surfaces $S_j$, there is in fact no compression to obtain the surfaces $S'_j$ and they were already sweepout surfaces of the original simplicial sweepout between $S'_1$ and $S''_{n'}$. So the surfaces $S'_j$ are homotopic to the surface $S''_{n'}$, and by definition of a sweepout, this homotopy is disjoint from the surfaces $S'_k$ for every $k < j$.

**Proof of the Claim.** Suppose that there exists some $j$ such that the genus of $S'_j$ is strictly less than the genus of $S_j$. By a result of Gabai, we can then replace our simplicial surface $S'_j$ by an embedded surface $T'_j$ in an arbitrarily small neighborhood of the immersed surface $S'_j$. More precisely, take a small regular neighborhood $N(S'_j)$ of the immersed surface $S'_j$. This neighborhood contains embedded surfaces in the same homology class as $S'_j$ in $H_2(N(S'_j), \partial N(S'_j))$. Gabai showed that the singular norm on homology is the same as the embedded Thurston norm [GL], hence there exists an embedded surface $T'_j$ in $N(S'_j)$ with the same homology class as $S'_j$ and of genus less than or equal to the genus of $S'_j$. If we choose sufficiently small neighborhoods $N(S'_j)$, we can ensure that the diameter of the embedded surface $T'_j$
As the surfaces $S_j$ were at distance at least $10\epsilon K$ from each other and every point of $S_j'$ is at distance at most $4\epsilon K$ from the original surface $S_j$ for all $j = 1, \ldots, n'$, the new surfaces $S_j'$ are at distance at most $2\epsilon K$ from each other (which also shows that the surfaces $S_j'$ are all disjoint). Furthermore, their diameter is bounded from above by $8\epsilon K$ and the $\epsilon$-diameter of $S_2', \ldots, S_{n'-1}'$ is at most $K$.

There remains to show that the surfaces $S_1', \ldots, S_{n}'$ are nested. In the spirit of the proof of Proposition B, let us denote by $D_n'$ the closure of the subset of the points of $C$ separated from $\partial_+ C$ by $S_n'$. For all $j < n'$, the surface $S_j'$ intersects the surface $S_j$, which lies in $D_n'$. As $S_j'$ is at distance at least $2\epsilon K$ from $S_n'$, $S_j'$ is contained in the interior of $D_n'$. So it is separated from $\partial_+ C$ by $S_n'$. Therefore, we denote by $D_j$ the closure of the points of $C$ separated from $\partial_+ C$ by $S_j'$, $D_j \subset D_n'$. Let $1 \leq k < j < n'$. If we take a point $x$ in $D_k$, as $D_k \subset D_n'$, every path $\gamma$ from $x$ to $\partial_+ C$ has its algebraic intersection number with $\partial_+ C$ equal to $+1$. As the surface $S_j'$ is homotopic to $S_k'$ by a homotopy that is disjoint from $S_k'$, this homotopy does not change the intersection number, so the intersection number of $\gamma$ with $S_j'$ is still equal to $+1$, and $x$ is in $D_j$. Thus $D_k \subset D_j$ for $1 \leq k < j \leq n'$, showing that the surfaces $S_1', \ldots, S_{n}'$ are nested. This ends the proof of Lemma 2.39.

In the sequel, we replace the family $S_1, \ldots, S_n$ by the new family $S_1', \ldots, S_{n}'$, of surfaces obtained by Lemma 2.39, and, for simplicity, we will still denote this family by $S_1, \ldots, S_n$.

We then wish to replace our immersed surfaces by embedded surfaces in an arbitrarily small neighborhood of the immersed surfaces. It is the aim of the following lemma.

**Lemma 2.39.** For every $j$ from 1 to $n'$, there exists an embedded surface $T_j$ in a small regular neighborhood of $S_j$, with the same genus as $S_j$, and which can be covered by at most $\text{diam}_K(S_j) \leq K$ embedded balls in $M'$ of radius $2\epsilon$. Furthermore, two surfaces $T_j$ and $T_k$ for $j \neq k$ are at distance at least $\epsilon K$ from each other.

**Proof of Lemma 2.39.** Take a small regular neighborhood $N(S_j)$ of one of the immersed and nested surfaces $S_j$. As in the proof of the claim, by Gabai [G1], this neighborhood contains an embedded surface $T_j$ in the same homology class as $S_j$ in $H_2(N(S_j), \partial N(S_j))$ and of genus less than or equal to the genus of $S_j$. If we choose sufficiently small neighborhoods $N(S_j)$, we can ensure that the diameter of the embedded surfaces $T_j$ in the ambient manifold $M'$ is less than $9\epsilon K$, and two embedded surfaces $T_j$ and $T_k$ are at distance at least $\epsilon K$. Furthermore, if we take a set $B$ of $\text{diam}_K(S_j)$ embedded balls of radius $\epsilon$ and centers on the surface $S_j$, one can choose $N(S_j)$ small enough such that it is contained in the union of corresponding balls with the same center and radius $2\epsilon$. Thus, the surface $T_j$ can be covered by at most $\text{diam}_K(S_j)$ embedded balls of $M'$ with radius $2\epsilon$.

The genus of $T_j$ is at most the genus of $S_j$, but we wish to show that in fact the genus of $T_j$ is the same as the genus of $S_j$. 


With Lemma 2.37, we know that the genus of the embedded surface $T_j$ for $j = 2, \ldots, n'$ is greater than or equal to the genus of the immersed surface $S_1$ that it separates from $\partial_+ C$. But as the genus of $T_j$ is at most the genus of $S_1$, which is equal to the genus of $S_1$, in fact the genus of $T_j$ is equal to the genus of $S_j$: the surfaces $T_2, \ldots, T_{n'}$ have the same genus as the immersed surfaces $S_2, \ldots, S_{n'}$. This proves Lemma 2.39.

The final step in the proof of Proposition C is to show that some of the embedded surfaces are actually parallel.

**Lemma 2.40.** The embedded surfaces $T_4, \ldots, T_{n'-1}$ are parallel.

**Proof of Lemma 2.40** This lemma relies on homological arguments; see [Mah] Lemmas 4.9 to 4.11. For completeness, here we give a shorter proof, based on classical 3-manifold topological results.

Let $V$ be the 3-complex in $C$ bounded by the immersed surfaces $S_1$ and $S_{n'}$. There is a sweepout $\phi$ between $S_1$ and $S_{n'}$ such that for each $1 \leq j \leq n'$, the surface $S_j$ is a sweepout surface. In other words, the application $\phi : S \times I \to V$ induces in homology an isomorphism $\phi_* : H_3(S \times I, \partial(S \times I)) \to H_3(V, \partial V)$, and for each $j$, there exists a time $t_j \in I$ such that $S_j = \phi(S \times \{t_j\})$. Moreover, we have $0 = t_1 < t_2 < \ldots < t_{n'} = 1$.

By a classical construction (see [Si] point 3, p. 96 for example), we can homotop the sweepout $\phi$ to a map $\phi'$ which is still degree one, and such that for every $2 \leq j \leq n'$, $\phi'^{-1}(T_j)$ is an embedded incompressible surface (not necessarily connected) in $S \times I$.

Take $3 < j < k \leq n' - 1$. As the homology class of the surfaces $T_j$ and $T_k$ is the same as the homology class of $S_3$, the homology class of the preimages $\phi'^{-1}(T_j)$ and $\phi'^{-1}(T_k)$ in $H_2(S \times [t_3, 1], \partial(S \times [t_3, 1]))$ is the same as the homology class of the fiber $S \times \{t\}$. As those preimages are incompressible embedded surfaces, $\phi'^{-1}(T_j)$ and $\phi'^{-1}(T_k)$ are each composed of an odd number of connected surfaces isotopic to the fiber $S \times \{t\}$ with total algebraic intersection number, with any path from $S \times \{t_3\}$ to $S \times \{1\}$ equal to +1. Up to isotopy, we can suppose that there exist times $t_3 < t'_j < \ldots < t_{2n'+1}$ and $t_3 < t'_k < \ldots < t_{2n'+1}$ such that $\phi'^{-1}(T_j) = \bigcup_{\ell=1}^{2n'+1} c_{\ell}(S \times \{t'_j\})$ and $\phi'^{-1}(T_k) = \bigcup_{\ell=1}^{2n'+1} c_{\ell}(S \times \{t'_k\})$, with $c_{\ell}$ and $c'_{\ell}$ equal to +1 or −1, depending on the orientation of the component of $\phi'^{-1}(T_j)$ or $\phi'^{-1}(T_k)$ corresponding to the fiber $S \times \{t'_j\}$ or $S \times \{t'_k\}$. As $\sum_{\ell=1}^{n'+1} c_{\ell} = +1$ and $\sum_{\ell=1}^{n'+1} c'_{\ell} = +1$, there exists $\ell$ and $\ell'$ such that $c_{\ell} = +1 = c'_{\ell'}$. Suppose for example that $t'_j < t'_k$. Then $\phi' : S \times [t'_j, t'_k] \to V$ is a homotopy between the embedded surfaces $T_j$ and $T_k$ contained in the region in $V$ bounded by $S_3$ and $S_{n'}$. As the embedded surface $T_2$ is not in this region, if we denote by $Y$ the submanifold of $C$ bounded by $T_2$ and $\partial_+ C$, the two embedded surfaces $T_j$ and $T_k$ are homotopic in the interior of $Y$.

By Lemma 2.37, the surfaces $T_j$ and $T_k$ are incompressible in $C \setminus S_1$. As they are contained in the interior of $Y$ and $Y$ is included in the component of $C \setminus S_1$ containing $T_j$ and $T_k$, the surfaces $T_j$ and $T_k$ are incompressible in $Y$. Thus, by a result of Waldhausen [W], Corollary 5.5, p. 76, they are in fact isotopic in $Y$. Therefore, $T_j$ and $T_k$ are parallel in $C$, for $3 < j < k \leq n' - 1$. Thus we have $m = n' - 4$ embedded surfaces $T_4, \ldots, T_{n'-1}$ parallel in the compression body $C$, which ends the proof of Lemma 2.40. As the $c$-diameter of $S_2, \ldots, S_{n'}$ is at most
$K$ and the surfaces $T_4, \ldots, T_{n'} - 1$ can be covered by at most $K$ embedded balls in $M'$ of radius $2\epsilon$, this also ends the proof of Proposition C.

2.4. Proof of Proposition D: From patterns of fundamental domains to virtual fibration. This part is dedicated to the proof of Proposition D, which is based on [Mah, Lemma 4.12, p. 2258]. This proof is more involved than the one of Lemma 4.12 in [Mah], which is too quick for our purpose since we need explicit bounds and precise constants.

Assume that there are $m$ connected, orientable, embedded and disjoint parallel surfaces in $M'$. Furthermore, suppose that each of those surfaces can be covered by at most $K$ embedded balls in $M'$ of radius $2\epsilon$ and that any two surfaces are at distance at least $r > 0$ from each other. In particular, there exists an embedded product $T \times [0, m - 1]$ in the manifold $M'$ in which the surface $T_j$ coincides with the fiber $T \times \{j\}$ for all $j$ from 0 to $m - 1$.

Let $D$ be a Dirichlet fundamental domain for the manifold $M$ in its universal cover $\hat{M} \simeq \mathbb{H}^3$. The translates of $D$ by the covering maps form a tiling of the universal cover $\hat{M}$. This tiling descends to a tiling of the cover $M'$ by $d$ copies of $D$. Each of the $m$ embedded and parallel surfaces $T_1, \ldots, T_m$ in $M'$ intersects some copies of $D$.

**Definition 2.41.** The union in $M'$ of copies intersected by one of the surfaces $S_j$ is called a pattern (of fundamental domains) for $S_j$ and denoted by $P_j$.

As the surface is connected, a pattern is a connected 3-complex. We can suppose that each of the embedded surfaces intersects the 2-skeleton of the tiling transversally. More precisely, we can suppose that each surface does not meet the vertices of the fundamental polyhedra, that it intersects the edges in isolated points and it is transverse to the 2-dimensional faces of the polyhedra. Therefore, a pattern is a connected union of some copies of $D$ glued along their 2-dimensional faces. Let $D$ be an upper bound for the diameter of $D$, and $\alpha$ an upper bound for the number of its 2-dimensional faces.

For all $\ell \in \mathbb{N}$, we recall that $B(\ell)$ is an upper bound for the number of possibilities of patterns obtained by gluing together at most $\ell$ fundamental domains. Let $L = \left\lfloor \frac{\pi \sinh(2D + 4\epsilon) - 2D - 4\epsilon}{\text{Vol}(M)} \right\rfloor$ as in Lemma 2.8. The integer $L$ is an upper bound for the number of fundamental domains a given surface can intersect. Thus, a pattern is the union of at most $L$ fundamental domains.

Suppose that $r/(2D + 1) \geq 1$ and $\frac{m}{\alpha^2 L^2 B(L)} \geq 4$ (which will be called condition (a)), or that $r/(2D + 1) < 1$ and $\left(\frac{r}{2D + 1} m - 1\right) \frac{1}{\alpha^2 L^2 B(L)} \geq 4$ (called condition (b)).

**Lemma 2.42.** If conditions (a) or (b) are satisfied, there are at least $4\alpha^2 L^2 B(L)$ surfaces for which the corresponding patterns of fundamental domains are disjoints.

**Proof of Lemma 2.42** If two surfaces $T_j$ and $T_k$ are at distance strictly more than $2D$, the patterns of fundamental domains associated to $T_j$ and $T_k$ are necessarily disjoint, as the diameter of a fundamental domain is at most $D$.

If $r/(2D + 1) \geq 1$ as in condition (a), any pair of surfaces $T_j$ and $T_k$ with $j \neq k$ are at distance strictly more than $2D$, and all the $m$ patterns associated to the parallel surfaces are disjoint.
Thus, all corresponding patterns of fundamental domains are disjoint.

As in condition (a), \( m \geq 4\alpha^2 L^2 B(L) \), or in condition (b), \( \frac{r}{2D+1} m - 1 \geq 4\alpha^2 L^2 B(L) \), there are at least \( 4\alpha^2 L^2 B(L) \) surfaces whose corresponding patterns are disjoint. \( \square \)

**Lemma 2.43.** There exist an “abstract” pattern of fundamental domains \( P \) and at least \( 4\alpha^2 L^2 \) patterns of fundamental domains \( P_j \), which are disjoint and homeomorphic to \( P \). More precisely, for at least \( 4\alpha^2 L^2 \) of the previous indices \( j \) for which the corresponding patterns of fundamental domains are disjoint, there exists a homeomorphism \( \varphi_j : P_j \to P \) which preserves polyhedral decomposition and gluing isometries between the faces of the fundamental domains belonging to the patterns.

**Proof of Lemma 2.43** The proof is straightforward. Indeed, as a pattern is the union of at most \( L \) fundamental domains, there are at most \( B(L) \) possible patterns. Among the \( 4\alpha^2 L^2 B(L) \) disjoint previous patterns, there are at least \( 4\alpha^2 L^2 \) of them corresponding to the same “abstract” pattern \( P \). \( \square \)

From now on, we only consider \( 4\alpha^2 L^2 \) indices \( j \) satisfying the conclusions of the last lemma.

**Lemma 2.44.** The number of boundary components of the pattern \( P \) is between 2 and \( \alpha L \).

**Proof of Lemma 2.44** Each fundamental polyhedron in the pattern \( P \) has \( \alpha \) 2-faces. As \( P \) is the union of at most \( L \) polyhedra, it has at most \( \alpha L \) 2-faces. It is an upper bound for the number of boundary components of \( P \).

To see that there are at least two boundary components in \( P \), it suffices to show that for example \( P_1 \) has at least two boundary components. But as the surface \( T_1 \) is contained in the interior of the pattern \( P_1 \), \( P_1 \cap (T \times [0,1]) \neq \emptyset \) and \( P_1 \cap (T \times [1,2]) \neq \emptyset \). The pattern \( P_1 \) is disjoint to \( T_0 \) and \( T_2 \), so the product regions \( T \times [0,1] \) and \( T \times [1,2] \) are not contained in \( P_1 \). By the connectivity of \( T \times [0,1] \) and \( T \times [1,2] \), the boundary of the pattern \( P_1 \) has at least two components, one as a subset of \( T \times (0,1) \) and the other one in \( T \times (1,2) \). This proves Lemma 2.44. \( \square \)

Set \( \partial P = E_1 \cup E_2 \cup \ldots \cup E_s \), where the immersed surfaces \( E_j \) are the boundary components of the pattern \( P \), with \( 2 \leq s \leq \alpha L \).

**Definition 2.45.** For every index \( j \) between 1 and \( 4\alpha^2 L^2 - 2 \), the pattern \( P_j \) intersects \( T \times (j-1, j) \) and \( T \times (j, j+1) \). At least one component of the boundary of \( P_j \) is in the boundary of the component of \( (T \times [j-1, j]) \setminus (T \times [j-1, j]) \cap P_j \) containing the fiber \( T \times \{j-1\} \), which we will call a “left” component of the boundary of the pattern \( P_j \). Similarly, at least one component of the boundary of \( P_j \) is in the boundary of the connected component of \( (T \times [j, j+1]) \setminus (T \times [j, j+1]) \cap P_j \) containing the fiber \( T \times \{j+1\} \). We will call this component a “right” component for the boundary of \( P_j \).

**Lemma 2.46.** For every index \( j \) between 1 and \( 4\alpha^2 L^2 - 2 \), choose a left and a right component for the pattern \( P_j \) (arbitrarily, if there exist at least two such components). Those two components correspond to components \( E_j^- \) and \( E_j^+ \) in the
boundary of the abstract pattern $P$. There are at least two indices $j$ and $k$ for which the pairs of left and right components corresponding to the patterns $P_j$ and $P_k$ coincide in $\partial P$.

**Proof of Lemma 2.46.** As there are at most $s(s - 1) \leq \alpha L(\alpha L - 1) < \alpha^2 L^2$ pairs of left and right boundary components of $P$, there are at least $(4\alpha^2 L^2 - 2)/(\alpha^2 L^2) \geq 2$ surfaces $T_j$ and $T_k$ with $1 \leq j < k \leq 4\alpha^2 L^2 - 2$, for which the pairs of left and right components corresponding to the patterns $P_j$ and $P_k$ coincide.

In the sequel, in order to simplify notation, let us denote by $T_1$ the surface $T_j$, $T_2$ the surface $T_k$ and $T_3$ the last surface $T_{4\alpha^2 L^2 - 1}$. The surfaces $T_0$ and $T_3$ bound a product $T \times [0, 3]$ in $M'$, such that $T_1 = T \times \{1\}$ and $T_2 = T \times \{2\}$. The two patterns $P_1$ and $P_2$ are contained in the interior of the product $T \times [0, 3]$. Denote by $\psi := \varphi_2^{-1} \circ \varphi_1$ the composed homeomorphism between patterns $P_1$ and $P_2$. Let $T_1'$ be the image of the surface $T_1$ in the interior of the pattern $P_2$ under the action of $\psi$: $T_1' = \varphi_1^{-1}(T_1) = \psi(T_1)$. It is an embedded surface in the product $T \times [0, 3]$. Clearly, the surfaces $T_1$ and $T_2$ are parallel, but they may not be embedded in their patterns in the same way. However, the surfaces $T_1$ and $T_1'$ are embedded in the patterns $P_1$ and $P_2$ in exactly the same way, but there is no evidence to say a priori that those two surfaces are parallel. It is in fact true, thanks to the following lemma.

**Lemma 2.47.** The surfaces $T_1$ and $T_1'$ are parallel in $M'$.

**Proof of Lemma 2.47.**

**Claim.** The homology class of $T_1'$ in the product $T \times [0, 3]$ is equal to the homology class of the fiber $[T] = [T_1] = [T_2]$.

**Proof of the Claim.** By choice of the surfaces $T_1$ and $T_2$, the left component $E_1^-$ of the boundary of the pattern $P_1$ and the left component $E_2^-$ of the boundary of the pattern $P_2$ have the same image in the pattern $P$: $\varphi_1(E_1^-) = \varphi_2(E_2^-)$, so $E_2^- = \varphi_1^{-1}(E_1^-)$. By definition, $E_2^-$ is a boundary component of the connected component of $(T \times [1, 2]) \setminus (T \times [1, 2]) \cap P_2$ containing the fiber $T_1$, and the component $E_1^-$ is a boundary component of the pattern $P_1$ in the boundary of the component of $(T \times [0, 1]) \setminus (T \times [0, 1]) \cap P_1$ containing the fiber $T_0$. As $P_1 \cap (T \times [0, 1])$ is
connected, there exists a path \( \gamma_2 \) properly embedded in \( P_1 \cap (T \times [0, 1]) \) and joining the component \( E_2^- \) to the surface \( T_1 \). The image by the homeomorphism \( \varphi_2^{-1} \circ \varphi_1 \) between the patterns \( P_1 \) and \( P_2 \) of the path \( \gamma_2 \) is a path \( \gamma_2 = \varphi_2^{-1} \circ \varphi_1(\gamma_2) \) in \( P_2 \) from the boundary component \( E_2^- \) to the surface \( T_1' \). The interior of the path \( \gamma_2 \) is contained in the interior of the component of \( P_2 \setminus T_1' \) containing \( E_2^- \). Let \( x_2 \) be the extremity of \( \gamma_2 \) belonging to the boundary component \( E_2^- \), and \( x_3 \) the other one, on the surface \( T_1' \).

Similarly, there exists a path \( \gamma_3 \) from \( x_3 \) to a point \( x_4 \) lying on the right component \( E_2^+ \) of the boundary of \( P_2 \), and such that its interior is contained in the interior of the component of \( P_2 \setminus T_1' \) containing \( E_2^+ \).

As \( E_2^- \) is in the boundary of the connected component of \( (T \times [1, 2]) \setminus P_2 \cap (T \times [1, 2]) \) containing the fiber \( T_1 \), there exists a path \( \gamma_1 \) with its interior contained in the interior of this component, and joining a point \( x_1 \) of the fiber \( T_1 \) to the point \( x_2 \) of \( E_2^- \). Similarly, by choice of \( E_2^+ \), there exists a path \( \gamma_4 \) with its interior contained in the interior of the component of \( (T \times [2, 3]) \setminus P_2 \cap (T \times [2, 3]) \) containing the fiber \( T_3 \) and linking the point \( x_4 \) of \( E_2^+ \) to a point \( x_5 \) of \( T_3 \). Eventually, as the product \( T \times [0, 1] \) is connected, there exists a path \( \gamma_0 \) with interior contained in \( T \times (0, 1) \) joining the point \( x_1 \) of \( T_1 \) to a point \( x_0 \) of \( T_0 \).

Let \( \gamma \) be the path obtained by concatenating the paths \( \gamma_0, \gamma_1, \gamma_2, \gamma_3 \) and \( \gamma_4 \). The path \( \gamma \) joins the point \( x_0 \) of \( T_0 \) to the point \( x_5 \) of \( T_3 \) and intersects the surface \( T_1' \) only once, at the point \( x_3 \). As the orientations of the patterns \( P_1 \) and \( P_2 \) coincide, the intersection number of \( \gamma \) with the surface \( T_1' \) is +1. So it is the same as the intersection number of \( \gamma \) with the fiber \( T \). By Poincaré duality, as the homology group \( H_2(T \times [0, 3], \mathbb{Z}) \), is of rank one, generated by the class of the fiber \([T]\), the class of the surface \( T_1' \) is equal to the class of the fiber in the homology of the product, showing the claim. \( \square \)

As the surface \( T_1' \) is embedded in the product \( T \times [0, 3] \), by a result of Waldhausen [W], it follows that the surface \( T_1' \) is parallel to the fiber \( T_1 \), possibly after performing a finite number of compressions on \( T_1' \). But as the surface \( T_1' \) is homeomorphic to \( T_1 \), it is of the same genus as the fiber \( T_1 \). So in fact there is no compression. Therefore, those two surfaces bound a product in \( M' \). \( \square \)

**Lemma 2.48.** The manifold \( M \) admits a cover \( N \) of finite degree at most \( d \) which fibers over the circle, and the embedded surface \( T_1 \) in \( M' \) is an (incompressible) virtual fiber.

**Proof of Lemma 2.48** One can cut the manifold \( M' \) open along those two disjoint surfaces \( T_1 \) and \( T_1' \). We keep only the component corresponding to the product region between the two parallel surfaces, and we identify the two surfaces via the homeomorphism \( \psi = (\varphi_2^{-1} \circ \varphi_1)|_{T_1} \) to obtain a manifold \( N \) fibering over the circle, with fiber \( \hat{T}_1 = (T_1 \sim T_1') \). The homeomorphism \( \varphi_2^{-1} \circ \varphi_1 \) identifies the “left” part of the pattern \( P_2 \) with the “left” part of the pattern \( P_1 \), so we get a pattern \( \hat{P}_1 \) corresponding to \( \hat{T}_1 \) in \( N \) homeomorphic to the pattern \( P \): the “left” part of this pattern corresponds to the left part of the pattern \( P_2 \) via the homeomorphism \( \varphi_2 \), and the “right” part of the pattern corresponds to the right part of \( P_1 \) via the homeomorphism \( \varphi_1 \). As those homeomorphisms preserve the gluings between the 2-dimensional faces of the fundamental domains, the gluings between the fundamental domains in the pattern \( \hat{P}_1 \) are the same as the gluings in the model pattern \( P \).
Therefore, we obtain a tiling of $N$ by finitely many copies of fundamental domains homeomorphic to $D$ and with matching gluings. Thus, $N$ is a finite cover of the original manifold $M$, and $N$ is fibered over the circle, with fiber $\hat{T}_1$.

The two covers $M'$ and $N$ admit a common regular finite cover $W$, which fibers over the circle as it is a finite cover of $N$. A component of the preimage of $\hat{T}_1$ by the covering projection $W \to N$ is a fiber $F$ for the fibration of $W$ over the circle. As the diagram is commutative, it is also a component of the preimage of the embedded surface $T_1$ in $M'$, as $T_1$ and $\hat{T}_1$ have the same image in $M$, which is an immersed surface. As $F$ is incompressible in $W$, the surface $T_1$ embedded in $M'$ that we started from is also incompressible. Thus the embedded surface $T_1$ is a virtual fiber in $M'$ and is incompressible.

Therefore, the $m$ initial parallel surfaces are virtual fibers for the manifold $M'$. In fact, they are fibers of a bundle over the circle or of a twisted $I$-bundle. Indeed, if $T$ is one of those surfaces, the complement $M'_T$ of an open neighborhood of $T$ in $M'$ admits a finite cover that is the product of a $T'$ by an interval $I$. In particular, the fundamental group of the compact manifold $M'_T$ contains a finite index surface subgroup. By [H, Theorem 10.6], it is an $I$-bundle, possibly twisted. This ends the proof of the Pattern Proposition D.
3. Heegaard genera and fibration

The proof of Theorem 0.3 is the starting point for the proof of the main Theorem A. The aim was to establish a virtual fibration criterion standing between Lackenby’s Conjecture 0.1 and Maher’s theorem. Maher himself suggested in [Mah] the possibility of obtaining explicit constants and upper bounds at each stage of the proof of Theorem 1.1 of [Mah], but without precise statements.

This section is dedicated to the proof of Theorem 0.3 and Corollary 0.6.

3.1. Proof of Theorem 0.3 (1) and Corollary 0.6 (1): Heegaard genus.

Proof of Theorem 0.3 (1). Suppose that \( M' \to M \) is a cover of \( M \) with finite degree \( d \). Let \( S \subset M' \) be a minimal genus Heegaard surface for \( M' \): \( g(S) = g(M') \). The aim is to construct from \( S \) a pseudo-minimal surface which satisfies the assumptions of Theorem A. We start with the following lemma.

Lemma 3.1. Let \( N \) be a connected, oriented and closed hyperbolic 3-manifold. Let \( S \) be a minimal genus Heegaard surface for \( N \) and \( H \) the Heegaard splitting of \( N \) with Heegaard surface \( S \). Let \( F \) be the union of the even and odd surfaces of an \( H \)-thin generalized Heegaard splitting for \( N \). Then \( F \) is a pseudo-minimal surface, which divides the manifold \( N \) in \( q \leq \chi_h(N) + 2 \) compression bodies \( C_1, \ldots, C_q \) with \( \chi_-(C_j) \leq \chi_h(N) \) for all \( j \) between 1 and \( q \).

Furthermore, if \( F^- \) is the union of the negative boundary components \( \partial_- C_j \), then it is a union of incompressible surfaces.

Proof of Lemma 3.1. The topological part (1) of the following theorem is a consequence of works of Casson and Gordon, Scharlemann and Thompson ([CG] and [ST]). The metric part (2) comes from results of Frohman, Freedman, Hass and Scott about incompressible surfaces ([FHS] and [FH]). The last part (3) is a result of Pitts and Rubinstein ([PR]; see also [So], [CDL] and [P]).

Theorem 3.2. Let \( N \) be a connected, oriented and closed hyperbolic 3-manifold, and \( H \) an \( H' \)-thin generalized Heegaard splitting for some Heegaard decomposition \( H' \). Then \( H \) satisfies the following properties:

(1) Each of the even surfaces is incompressible in \( N \) and the odd surfaces are strongly irreducible Heegaard surfaces for the components of the manifold \( N \) cut along the even surfaces.

(2) Each even surface can be isotoped to a minimal surface or the boundary of a small neighborhood of a non-orientable minimal surface.

(3) Each odd surface can be isotoped to a minimal surface, or to the boundary of a small regular neighborhood of a non-orientable minimal surface, with a small tube attached vertically in the \( I \)-bundle structure. \( \square \)

Thanks to Theorem 3.2, up to isotopy, one can assume that the surface \( F \) is pseudo-minimal, and it is immediate that \( F^- \) is a union of incompressible surfaces.

As described in section 1, surgeries of generalized Heegaard splittings are a modification in the order of attachment of the 1- and 2-handles of a corresponding handle decomposition of the manifold. Therefore, surgeries do not change the number of 1- and 2-handles. As it is equal in the starting Heegaard splitting to
2g(S) = χ^h(N) + 2, there are also (χ^h(N) + 2) 1- and 2-handles in a handle decomposition associated to the surface F. As this number is an upper bound for the number of compression bodies in the complement of F, the inequality q ≤ χ^h(N) + 2 holds.

Furthermore, as each component of F is obtained from S by surgery; the characteristic χ_-(C) of each compression body is at most |χ(S)| = χ^h(N).

End of the proof of Theorem 0.3 (1). Recall that S is a minimal genus Heegaard surface for the cover M' → M of finite degree d. Let F be the pseudo-minimal surface obtained in Lemma 3.1. The aim is to apply the main Theorem A to F. With notation of Theorem A and this choice of surface F, one has c = χ^h(M') and q = χ^h(M') + 2.

Set ε = Inj(M)/2 and let k = k(ε, Vol(M)) be the constant obtained in Theorem A. To satisfy assumptions of Theorem A, one needs to have

\[ k \chi^h(M') \ln \chi^h(M') \leq \ln \frac{d}{\chi^h(M') + 2}. \]

If the ratio \( \chi^h(M') \ln \chi^h(M')/\ln \ln d \) tends to zero, then the ratio \( \chi^h(M')/\sqrt{d} \) also tends to zero. Therefore, there exists an explicit constant \( \overline{k}_1 > 0 \) such that if \( \overline{k}_1 \chi^h(M') \ln \chi^h(M') \leq \ln \ln d \), then \( \chi^h(M') + 2 \leq \sqrt{d} \). Under this assumption, one has

\[ \ln \frac{d}{\chi^h(M') + 2} \geq \ln \ln \sqrt{d} = \ln \left( \frac{1}{2} \ln d \right) = \ln \ln d - \ln 2 \geq \frac{1}{2} \ln \ln d \]

if \( \ln \ln d \geq 2 \ln 2 \), which is the fact for example if \( \ln \ln d \geq \chi^h(M') \ln \chi^h(M') \) as \( \chi^h(M') \geq 2 \).

Therefore, if \( \chi^h(M') \ln \chi^h(M') \leq \ln \ln d, \overline{k}_1 \chi^h(M') \ln \chi^h(M') \leq \ln \ln d \) and \( 2k \chi^h(M') \ln \chi^h(M') \leq \ln \ln d \), then

\[ k \chi^h(M') \ln \chi^h(M') \leq \ln \frac{d}{\chi^h(M') + 2} \]

and the assumptions of Theorem A are satisfied. This proves Theorem 0.3 with \( \overline{k} = \max\{1, 2k, \overline{k}_1\} \).

Proof of Corollary 0.3 (1). It is obvious that if M virtually fibers over the circle, then the η-sub-logarithmic Heegaard gradient of M is zero for every \( \eta \in (0, 1) \), as M admits an infinite family of finite degree covers with bounded Heegaard genus.

If the η-sub-logarithmic Heegaard gradient of M is zero for some \( \eta \in (0, 1) \), this means that M admits an infinite family of covers \((M_i \to M)_{i \in \mathbb{N}}\) with finite degrees \(d_i\), and such that

\[ \lim_{i \to +\infty} \frac{\chi^h(M_i)}{(\ln \ln d_i)^\eta} = 0, \]

which can also be written as

\[ \lim_{i \to +\infty} \frac{\chi^h(M_i)^{1/\eta}}{\ln \ln d_i} = 0. \]
As $1/\eta > 1$, this implies that

$$\lim_{i \to +\infty} \frac{\chi^h(M_i) \ln \chi^h(M_i)}{\ln \ln d_i} = 0.$$  

Thus, for $i$ large enough, one has $k \chi^h(M_i) \ln \chi^h(M_i) \leq \ln \ln d_i$, and the assumptions of Theorem 0.3 are satisfied. In particular, the manifold $M$ virtually fibers over the circle, which proves Corollary 0.6 (1).

3.2. Proof of Theorem 0.3 (2) and Corollary 0.6 (2): Strong Heegaard genus.

Proof of Theorem 0.3 (2). Suppose by contradiction that in a finite cover $M' \to M$ of degree $d$, one has $k \chi^sh(M') \ln \chi^sh(M') \leq \ln \ln d$. Let $F$ be a strongly irreducible Heegaard surface for $M'$ such that $\chi^h_-(M') = \chi_-(F)$.

Thanks to Theorem 3.2, up to isotopy, one can assume that $F$ is pseudo-minimal. This surface separates $M'$ into two handlebodies, so the volume of one of those handlebodies $C$ must be at least $\text{Vol}(M)/d$. But as $k \chi_-(F) \ln \chi_-(F) \leq \ln \ln d$, the proof of Theorem 0.3 (1) shows that the surface $F$ satisfies the assumptions of Theorem A. This is in contradiction with Corollary 0.2. This proves Theorem 0.3 (2).

Proof of Corollary 0.6 (2). To prove Corollary 0.6 (2), just notice that as $k \chi^sh(M') \ln \chi^sh(M') > \ln \ln d$, for $\theta \in (0, 1)$, there is a constant $\tilde{k}_\theta > 0$ such that $\chi^sh(M')/(\ln \ln d)^\theta \geq \tilde{k}_\theta$, proving that the strong $\eta$-sub-logarithmic Heegaard gradient of $M$ is strictly positive.

4. Circular decomposition and fibered homology classes

The aim of this section is to consider the case of circular decompositions, and to prove Corollaries 0.8 and 0.10.

4.1. Circular decomposition and thin position. A circular decomposition is the equivalent of a Heegaard decomposition, but this decomposition is associated to a Morse function that no longer takes values in $I = [0, 1]$ but in the circle $S^1$.

Definition 4.1. A circular Morse function is a Morse function $f : M \to S^1$.

If $f : M \to S^1$ is a circular Morse function, the handle decomposition of $M$ given by the function $f$ is called the circular decomposition associated to $f$.

See F. Manjarrez-Gutiérrez [MG], Matsumoto [Mat] and Milnor [Mi] for further details about circular Morse functions. Let $f : M \to S^1$ be a circular Morse function. If we remove a small open neighborhood of a regular value $x \in S^1$, by restriction of $f$, we obtain a Morse function $g$ of $M_R = M \setminus \mathcal{N}(R)$, which is the manifold $M$ minus a small regular open neighborhood of the surface $R := f^{-1}\{x\}$, on the interval $I$. Thus, the theory of Heegaard splittings and generalized Heegaard splittings applies to the function $g$, as recalled in section 1.

Another viewpoint is to see a circular decomposition as a handle decomposition of the cobordism $(M \setminus \mathcal{N}(R), R \times \{1\}, R \times \{-1\})$. Starting with a Heegaard splitting of the Heegaard surface $S$ for $M_R = M \setminus \mathcal{N}(R)$, one can change the order in which 1- and 2-handles are attached to get a new generalized Heegaard splitting $(F_1 = R \times \{1\}, S_1, F_2, \ldots, S_n, F_{n+1} = R \times \{-1\})$ for $(M_R, R \times \{1\}, R \times \{-1\})$. Gluing back $R \times \{1\}$ to $R \times \{-1\}$, one obtains a circular decomposition for the manifold $M$.
Denote it by $\mathcal{H} = (F_1, S_1, F_2, \ldots, S_n, F_{n+1})$, with $F_1 = F_{n+1} = R$. The surfaces $F_j$ divide $M$ into $n$ 3-manifolds with boundary $W_1, \ldots, W_n$, and surfaces $S_j$ are Heegaard surfaces for those manifolds. For $1 \leq j \leq n$, $S_j$ divides the manifold $W_j$ into two compression bodies $A_j$ and $B_j$, such that $\partial_+ A_j = \partial_+ B_j = S_j$, $\partial_- A_j = F_j$ and $\partial_- B_j = F_{j+1}$.

Let $S$ be a closed surface. If $S$ is connected, recall that the complexity of $S$ is $c(S) = \max(0, 2g(S) - 1)$. If $S$ is the union of several connected components, the complexity of $S$ is the sum of the complexities of the components of $S$. There is a definition of the complexity of a circular decomposition analogous to the complexity of a generalized Heegaard splitting.

**Definition 4.2.** The **circular width** of a circular decomposition $\mathcal{H} = (F_1, S_1, F_2, \ldots, S_n, F_{n+1})$ is the set of the $n$ integers $(c(S_1), \ldots, c(S_n))$, with repetitions and arranged in monotonically non-increasing order. Widths are compared using the lexicographic order.

The integer $n \geq 1$ is called the **length** of the circular decomposition $\mathcal{H} = (F_1, S_1, F_2, \ldots, S_n, F_{n+1})$.

**Proposition 4.3.** Let $M$ be a hyperbolic, connected, oriented and closed 3-manifold. Let $R$ be an orientable, closed, non-separating, incompressible and embedded surface in $M$. Denote by $S$ a Heegaard surface for $M \setminus N(R)$. Starting from the circular decomposition $\mathcal{H} = (R, S, R)$ of $M$, there exists a finite number of surgeries to get a circular decomposition $\mathcal{H}' = (F_1, S_1, F_2, \ldots, S_n, F_{n+1})$ with $F_1 = F_{n+1} = R$, such that:

1. the circular width of $\mathcal{H}'$ is minimal among the widths of such circular decompositions obtained by a finite number of surgeries of $\mathcal{H}$,
2. each surface $F_j$ is incompressible, no component of $F_j$ is a sphere, and $g(F_j) \leq g(S)$,
3. each surface $S_j$ is a strongly irreducible Heegaard surface for the Heegaard decomposition $(A_j, B_j)$ of $W_j$ and $g(S_j) \leq g(S)$,
4. $n \leq \frac{1}{2}(\chi(R) - \chi(S))$.

**Definition 4.4.** Let $\mathcal{H}$ be a circular decomposition. A circular decomposition $\mathcal{H}' = (F_1, S_1, F_2, \ldots, S_n, F_{n+1})$ that is circular-length-minimizing among all circular decompositions obtained from $\mathcal{H}$ by a finite number of surgeries is said to be a thin position. We will call such a decomposition a **thin circular decomposition** associated to $\mathcal{H}$.

**Proof of Proposition 4.3.** The proof of this proposition is essentially the same as the proof of [MC Theorem 3.2], which is itself an adaptation of techniques of [ST] to the case of circular decompositions (see also [L]). See [R1], Proposition 1.1 and its proof. The proof is based on an operation called a surgery of circular decompositions, which is analogous to the surgery of generalized Heegaard splittings described in section II. Again, the crucial fact is that a surgery procedure strictly decreases the complexity of the circular decomposition.

**Corollary 4.5.** Let $M$ be a hyperbolic, connected, oriented and closed 3-manifold. Take $\mathcal{H} = (F_1, S_1, F_2, \ldots, S_n, F_{n+1})$ to be a thin circular decomposition of $M$. Then, up to isotopy, one can assume that all surfaces $F_j$ and $S_j$ are pseudo-minimal.
Proof of Corollary 4.5. From Proposition 4.3 (2) and (3), the surfaces $F_j$ are incompressible for each $j$ and the surfaces $S_j$ correspond to strongly irreducible Heegaard surfaces. The proof is then the same as for Theorem 3.2 (2) and (3) of section 3.

4.2. Circular characteristic and fibered homology classes. Recall Definition 0.7 from the introduction. Corollary 0.8 is analogous to Theorem 0.3 for circular decompositions associated to a non-trivial cohomology class.

Proof of Corollary 0.8. Let $M' 	o M$ be a cover of $M$ with finite degree $d$ and a non-trivial cohomology class $\alpha' \in H^1(M')$. The aim is to show that if the ratio $\chi_-(\alpha')/\ln d$ is small enough, then the assumptions of Theorem A are satisfied.

Let $R'$ be an embedded surface in $M'$ and $\|\alpha'\|$-minimizing. First, suppose that in addition $h(M', \alpha') = h(M', \alpha', R')$. Take $S'$ to be a minimal genus Heegaard surface for $M'_{R'}$. By construction, $\chi_-(\alpha') = |\chi(S')|$. From Proposition 4.3 starting from the circular decomposition $(R', S', R')$ of $M'$, we can construct a thin circular decomposition $H = (F_1, S_1, F_2, \ldots, S_n, F_{n+1})$. Set $F := \bigcup_{j} F_j \cup \bigcup_{j} S_j$. From Corollary 4.5, one can assume that $F$ is a pseudo-minimal surface.

Still from Proposition 4.3, the surface $F$ separates the manifold $M'$ into $q \leq \frac{1}{2}(\chi(R')-\chi(S')) \leq \chi_-(\alpha')/2$ compression bodies $C_1, \ldots, C_q$, with $\chi_-(C_j) \leq |\chi(S')| = \chi_-(\alpha')$ for every $j$.

As the surfaces $F_j$ are incompressible, assumption (1) of Theorem A is satisfied.

Let $k = k(\epsilon, \text{Vol}(M))$ be the constant given by Theorem A. To satisfy assumptions of Theorem A, there remains to show that $k \chi_-(\alpha') \ln \chi_-(\alpha') \leq \ln \frac{2d}{\chi_-(\alpha')}$. But as in section 3, one can find a constant $\ell' = \ell'(\epsilon, \text{Vol}(M))$ such that if $\ell' \chi_-(\alpha') \ln \chi_-(\alpha') \leq \ln \ln d$, then $k \chi_-(\alpha') \ln \chi_-(\alpha') \leq \ln \frac{2d}{\chi_-(\alpha')}$, and all the assumptions of Theorem A are satisfied.

Therefore, if $\ell' \chi_-(\alpha') \ln \chi_-(\alpha') \leq \ln \ln d$, then from Theorem A, the manifold $M'$ contains an embedded surface that is a virtual fiber.

Furthermore, all the constructions take place in fact in $M'_{R'} = M' \setminus \mathcal{N}(R')$. Thus, the virtual fiber built in Theorem A is in the complement of $R'$ in $M'$. This virtual fiber lifts to a connected fiber $\overline{T}$ in a fibered finite cover $\overline{M'} \to M'$ of $M'$. In this cover, the incompressible surface $R'$ lifts to a surface $\overline{R'}$ in the complement of the fiber. Cutting along $\overline{T}$, this shows that the connected components of $\overline{R'}$, which are all incompressible, are parallel in the product to the fiber $\overline{T}$ (see [W]). Thus, the homology class of $\overline{R'}$ is fibered. Still from Gabai [G2] Lemma 2.4, this implies that the homology class of $R'$ is fibered. As the surface $R'$ minimizes Thurston’s norm, it is also a fiber.

To complete the proof of Corollary 0.8, there remains to show that if $R''$ is an embedded surface in $M'$, $\|\alpha'\|$-minimizing, but that does not necessarily satisfy $h(M', \alpha') = h(M', \alpha', R')$, then $R'$ is still a fiber. But if one takes an embedded surface $R''$ such that $R''$ is $\|\alpha'\|$-minimizing, and satisfies $h(M', \alpha') = h(M', \alpha', R'')$, the proof above shows that $R''$ is a fiber. As $R'$ is norm-minimizing, it is an incompressible surface in the homology class of $R''$, hence also a fiber. This ends the proof of Corollary 0.8.

The following corollary is immediate from Corollary 0.8.

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Corollary 4.6. Let $M$ be a hyperbolic, connected, oriented and closed 3-manifold. Suppose that there exists an infinite family of covers $(M_i \to M)_{i \in \mathbb{N}}$ with finite degrees $d_i$, and for each $i \in \mathbb{N}$, a non-trivial cohomology class $\alpha_i \in H^1(M_i)$ such that

$$\inf_{i \in \mathbb{N}} \frac{\chi^c(\alpha_i) \ln \chi^c(\alpha_i)}{\ln \ln d_i} = 0.$$ 

Then, for infinitely many indices $i \in \mathbb{N}$, every embedded surface $R_i$ in $M_i$, $||\alpha_i||$-minimizing and such that $h(M_i, \alpha_i) = h(M_i, \alpha_i, R_i)$ is a fiber. In particular, the manifold $M$ virtually fibers over the circle $\mathbb{S}^1$.

4.3. Incompressible surfaces and fibrations. In section 4.2 we have established criteria in order to show that a non-trivial cohomology class of a hyperbolic 3-manifold $M$ lifts to fibered classes in finite covers. Now, if $R$ is a non-separating embedded surface in $M$, there is a dual cohomology class associated to $R$. In some cases, we have seen that $R$ could then be a fiber. But the question can be asked for any embedded, incompressible and connected surface $R$ in $M$, separating or not.

Recall Definition 0.9 from the introduction. Corollary 0.10 is different from the last section, as the surface $R$ is a priori not supposed to be non-separating.

Proof of Corollary 0.10. In the case where the surface $R'$ is not separating, it is a generalization of Corollary 0.8. Indeed, if $S'$ is a minimal genus Heegaard surface for $M_r'$, $\chi^h_-(R') = |\chi(S')|$ and $(R', S'$, $R')$ is a circular decomposition of $M'$. As the starting surface $R'$ is incompressible, we then apply Proposition 1.3 to build a thin circular decomposition. From the proof of Corollary 0.8 assumptions of Theorem A are satisfied if $\ell' \ln h(R') \ln \chi^h(R') \leq \ln \ln d$, and, in this case, the surface $R'$ is a virtual fiber. But as $R'$ belongs to the preimage of $R$, the surface $R$ is also a virtual fiber. Furthermore, if the surface $R$ is not separating, its homology class is non-zero, and the same argument applies to prove that this class is fibered. As the surface $R$ is incompressible, it is itself a fiber.

In the case where the surface $R'$ separates the manifold $M'$ into two connected components $M_l$ and $M_r$, let $S_l$ and $S_r$ be minimal genus Heegaard surfaces for $M_l$ and $M_r$, respectively. By definition, $\chi^h_-(R') = \max(|\chi(S_l)|, |\chi(S_r)|)$.

In each side of $R'$ we can then build a generalized Heegaard decomposition for $M_l$ and $M_r$ in thin position starting from surfaces $S_l$ and $S_r$. We then get a surface $F$ with one component which is the incompressible surface $R'$, separating the manifold $M'$ into $q \leq 2g(S_l) + 2g(S_r) \leq 2\chi^h_-(R') + 4$ compression bodies $C_1, \ldots, C_q$ with $\chi_-(C_j) \leq \chi^h_-(R')$ for all $j$.

As $F$ is the union of incompressible surfaces and strictly irreducible Heegaard surfaces, we may assume that $F$ is pseudo-minimal and $F^-$ is the union of incompressible surfaces.

Thus, to satisfy assumptions of Theorem A, it suffices to show that $k \chi^h_-(R') \ln \chi^h_-(R') \leq \frac{\ln d}{2\chi^h(R') + 4}$. But as before, one can find a constant $\ell'' \geq \ell'$ such that if $\ell'' \chi^h_-(R') \ln \chi^h_-(R') \leq \ln \ln d$, then $k \chi^h_-(R') \ln \chi^h_-(R') \leq \ln \ln \frac{d}{2\chi^h_-(R') + 4}$. From Theorem A, in this case, the manifold $M'$ contains an incompressible surface that is a virtual fiber. But as in the proof of Corollary 0.8, this incompressible surface is built in the complement of the incompressible surface $R'$. Thus, the surface $R'$ is also a virtual fiber. As $R'$ is a lift of $R$, the starting surface $R$ is a virtual fiber, hence the fiber of a twisted I-bundle, which ends the proof of Corollary 0.10. \hfill \square
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REFERENCES


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