

## Contents

<b>1</b>	<b>Problem Statement</b>	<b>1</b>
<b>2</b>	<b>Toy Version</b>	<b>3</b>
2.1	Promote elliptic containment to equality . . . . .	3
2.2	Toy version of main result . . . . .	4
2.2.1	Definitions . . . . .	4
2.2.2	Result . . . . .	5
2.3	Definitions . . . . .	6
2.3.1	Miscellaneous . . . . .	7
<b>3</b>	<b>Outlines</b>	<b>9</b>
3.1	Misc lemmas . . . . .	9
3.2	Main Equivariant Map Construction . . . . .	10
3.3	Combining into main argument . . . . .	10
<b>4</b>	<b>Core has quadrant convex hyperplanes</b>	<b>11</b>

## 1 Problem Statement

1.1 THEOREM. If  $G$  has algebraic cohomological dimension 2 9 then there are at most two non-trivial finite type 5 pairwise transverse 6  $G$ -trees up to deformation 4.

*Proof.* Suppose for sake of a contradiction there were three non-trivial  $G$ -trees  $T_1, T_2$ , and  $T_3$  of finite type 5 that were pairwise transverse 6 and no two are in the same deformation space. By 1.5 without loss of generality, we may assume that these are minimal  $G$ -trees. Applying the tranverse construction lemma 3 we obtain  $X_{12}$ . Let  $\widetilde{X}_{12}$  denote it's universal cover. Applying the affine equivariant map construction 2.9 to the actions on  $\widetilde{X}_{12}$  and  $T_3$  gives a map and a fibration that we denote by  $f_{123}$  and  $\mathcal{F}_{123}$  respectively. Due to 2.7 we have geomeriic actions. Additional technical assumptions are handled here 1.3. Then using 2.8 and the proof theoreof 1.1 we obtain  $\widetilde{X}_{12}^+$ , an extension  $f_{123}^+$ , and a fibration  $\mathcal{F}_{123}$ .

Next let  $f_{121}$  and  $f_{122}$  denote the projection maps from  $\widetilde{X}_{12}$  to  $T_1$  and  $T_2$  respectively. (aka Bass-Serre maps) After coning off as described in 2.6 we get extensions  $f_{121}^\wedge$  and  $f_{122}^\wedge$  and similarly  $\mathcal{F}_{121}^\wedge$  and  $\mathcal{F}_{122}^\wedge$ . Lastly we form the product map  $f := f_{121}^\wedge \times f_{122}^\wedge \times f_{123}^+$ .

Consider  $J := \text{Im}(f)$ . By lemma 4.2 we get that  $J$  has property CCP 22, since it is the image of a cocompact set under a continuous  $G$ -map it is cocompact and is in fact cocompact by factor 7 since the action is diagonal. Let  $S_{12}$  denote the cellular neighborhood of  $J$ , because this set is defined in an invariant way as the smallest such complex with a property it is  $G$  invariant and because our trees are locally finite and a cellular neighborhood is contained in a bounded neighborhood we have that  $S_{12}$  is cocompact and therefore cocompact

by factor 7. Taking a cellular neighborhood respects slices by 1.2 so  $S_{12}$  has property CCP 22.

Next we repeatedly apply lemma 3.8 and use the fact that filling preserves CCP 22 by construction to get that  $C := S_{12}xyz$  is cocompact and has CCP 22. By switching 4.4  $C$  has connected 1-dimensional fibers.

By lemma 1.4 we have that  $C$  is simply connected and  $C/G$  comes with three splittings as a graph of spaces.

We will now iterate the splitting process and then apply Bieri. To begin, by assumption each splitting is non-trivial. Now, consider the vertex groups of a given splitting. By lemma 1.6 those vertex groups act non-trivially on the two trees coming from splittings of the VH-complexes by Wise. These last splittings are themselves splittings over trivial groups - but are they trivial splittings? Here we need to assume that one such iterated sequence of splittings ends in a graph with positive rank.

Then by the Bieri dimension argument,  $G$  has dimension 3 a contradiction.  $\square$

1.1 LEMMA (Shortcircuit Guirardel Proof). *Proof.* (fix) (sketch) Stopping after a certain point in Guirardel is beneficial. Uses statements already in Guirardel  $\square$

1.2 LEMMA (Cell Respects Slices). *Proof.* (fix) (sketch) By direct set theory  $\square$

1.3 LEMMA (Technical assumptions for Guirardel). (fix) we use a result of leveitt and paulin for geomeic (see elsewhere) and prove the rest here, e.g. "measured foliations" follows from standard constructions

1.4 LEMMA (Expanded Core is simply connected). Our  $C$  inherits a VHD structure from the product of three trees that it sits in. Because the action is diagonal we also get that the quotient  $C/G$  is VHD. Our tree actions do not invert edges so we get that the hyperplanes of  $C/G$  are two-sided. Recall, a given hyperplane only touches a single parallelism class of edges.

Next, we need the push maps from the hyperplanes to be injective on fundamental groups. The push map from a hyperplane to a vertex space (we necessarily send hyperplanes - itself a connected set - to a component i.e. a vertex space) followed by inclusion is the same (up to homotopy) as globally including the hyperplane into  $C/G$ . We will show that the composition is injective so that the induced map from the vertex to the edge is injective as needed. (fix) needs details, see diagram tracking how we consider this set

COROLLARY. If a VH-complex has horizontal and vertical splittings of finite type then up to deformation, these are the only such  $G$ -trees.

1.5 LEMMA (Minimality is enough). If the theorem is true for minimal trees then it is true for trees in general

1.6 LEMMA (Iterated Splitting). Suppose  $x$  were a vertex of  $T_V$ , Let  $K$  be it's stabilizer. Now  $K$  is a subgroup of  $G$  and so also acts on  $T_H$ . If  $K$  had a global

fixed point in  $T_H$  then by local finiteness of  $T_V$  every vertex group of  $T_V$  would as well. Then if you are elliptic for  $T_V$  you are elliptic for  $T_H$  which by a previous lemma in our setting gives that  $T_H$  and  $T_V$  are in the same deformation space; a contradiction.

## 2 Toy Version

### 2.1 Promote elliptic containment to equality

1 DEFINITION (Simplicial Map). A map between simplicial complexes is simplicial if the image of a set of vertices that spans a simplex also spans a simplex.

2 DEFINITION (Morphism). We say a simplicial map between trees is a morphism if edges go to edges.

3 DEFINITION (Collapse Map). Given a  $G$ -tree, collapsing components of an invariant forest to points gives a  $G$ -map.

1 PROPOSITION (Subgraph Collapse). Replacing a connected subgraph in a graph of groups decomposition with a vertex group with the same group as the collapsed graph corresponds to collapsing an invariant forest to points.

2 PROPOSITION (Folds “factor” as an elementary collapse and a collapse map). If  $X \rightarrow Y$  is a fold, then there exists a tree  $Z$  along with collapse maps to  $X$  and  $Y$ . Moreover, the map to  $X$  is a collapse map corresponding to an elementary collapse.

2.1 LEMMA (Hyperbolic elements are preserved). Suppose  $X \rightarrow Y$  is a collapse map between locally finite  $G$ -trees. Suppose  $Y$  is not a single point. Then, if an element is hyperbolic for  $X$  it is also hyperbolic for  $Y$ .

*Proof.* Suppose for sake of a contradiction that  $g \in G$  were hyperbolic for  $X$  and elliptic for  $Y$ . Let  $y \in Y$  be some vertex fixed by the elliptic element  $g$  and  $G_y$  its stabilizer. Since  $Y$  is not a single point, there is another vertex  $y \neq z \in Y$ . Because  $Y$  is locally finite,  $G_y$  and  $G_z$  are commensurable. For  $G$ -maps, preimages are invariant. By the construction of a collapse map, the preimage of vertices are connected and non-empty. Putting these together we have that the preimages of vertices are invariant trees. This means that the minimal subtrees of  $G_y$  and  $G_z$  acting on  $X$  are contained in the disjoint preimages of  $y$  and  $z$  respectively. However, since they are commensurable and  $G_y$  contains the hyperbolic element  $g$ , these minimal trees are non-empty and equal. This is a contradiction.  $\square$

2.1 THEOREM (Elliptic elements determine elliptic subgroups). Let  $X$  and  $Y$  be cocompact  $G$ -trees with finitely generated vertex groups. Then the following are equivalent:

1.  $X$  and  $Y$  define the same partition of  $G$  into elliptic and hyperbolic elements.

2.  $X$  and  $Y$  have the same elliptic subgroups.

*Proof.* By Proposition 2.6, Theorem 4.2, and Corollary 4.3 of [F, deformation and rigidity].  $\square$

2.2 THEOREM (Factoring as folds, from Bestvina paper, p455). Let  $G$  be a finitely generated group. Suppose that  $\alpha : T' \rightarrow T$  is a simplicial equivariant map from a  $G$ -tree  $T'$  to a minimal  $G$ -tree  $T$  such that no edge in  $T'$  is mapped to a point by  $\alpha$ . If all edge stabilizers of  $T$  are finitely generated and if  $T'/G$  is finite, then  $\alpha$  can be represented as a finite composition of folds.

2.2 LEMMA (Minimal trees invariant under commensurability). Suppose  $G$  acts on a tree  $X$  and  $H$  and  $K$  are commensurable subgroups. If  $H$  contains a hyperbolic element, then so does  $K$  and the minimal subtrees for  $H$  and for  $K$  are equal.

2.3 LEMMA (Local finiteness preserves hyperbolicity). Suppose  $f : X \rightarrow Y$  is a  $G$ -map of  $G$ -trees which is onto, where  $Y$  is locally finite and not a single point. Then no element of  $G$  is hyperbolic for  $X$  and elliptic for  $Y$ .

2.1 Remark. Note, if the above  $Y$  is minimal then we get surjectivity for free.

2.3 THEOREM (Elliptic containment implies equality). If  $X$  and  $Y$  are locally finite cocompact  $G$ -trees with finitely generated vertex and edge stabilizers then  $\mathcal{E}(X) \subseteq \mathcal{E}(Y) \implies \mathcal{E}(X) = \mathcal{E}(Y)$ .

*Proof.* (fix) this is now fixed due to 2.4 and 2.3.  $\square$

## 2.2 Toy version of main result

### 2.2.1 Definitions

2.4 LEMMA (Core non-empty).

4 DEFINITION (Deformation). Definition of deformation moves and the corresponding equivalence classes.

5 DEFINITION (Finite Type). We say a tree action is of *finite type* if the action is non-trivial, the tree is locally finite, and the vertex stabilizers are FP, with finite quotient graph.

2.2 Remark. We will assume a group of dimension 2 and in that case Bieri gives that actions of finite type have vertex and edge stabilizers that are finitely generated free groups.

2.3 Remark. Bieri gives us that if we have an action of finite type then the group is FP.

6 DEFINITION (Transverse). We say that two tree actions  $X$  and  $Y$  are *transverse* if they are not in the same deformation space and there exist two stabilizers, one for each tree, such that their intersection is FP.

2.4 Remark. The definition of transverse does not depend on the vertices chosen and remains unchanged up to deformation spaces

### 2.2.2 Result

3 PROPOSITION (Transverse Construction). Let  $G$  a group of cohomological dimension 2. If  $X$  and  $Y$  are non-trivial  $G$ -trees of finite type that are in different deformation spaces then the following are equivalent:

1.  $X, Y$  transverse
2.  $x \in V(X), y \in V(Y) \implies G_x \cap G_y = \{1\}$
3. There exists a cocompact VH-complex  $K$  with  $\pi_1(K) = G$  whose horizontal and vertical splittings are  $X$  and  $Y$ .

*Proof.* 1.  $1 \Rightarrow 2$ : Fix  $x_0 \in V(X)$  Let  $y \in V(Y)$ . Then  $G_{x_0} \cap G_y = (G_{x_0})_y$ . By (1)  $X$  is transverse to  $Y$  hence  $G_{x_0} \cap G_y$  is FP. Since the choice of  $y \in V(Y)$  was arbitrary, the vertex groups of the  $G_{x_0}$  action on  $Y$  are FP. Note,  $Y$  locally finite implies it's edge groups are finite index subgroups of it's vertex groups. Hence the edge groups are also FP. We claim that the action of  $G_{x_0}$  on  $Y$  is non-trivial. Given this we apply Bieri to get:

$$\begin{aligned}
 2 &= dG \\
 &= dG_{x_0} + 1 \\
 &= d(G_{x_0})_y + 1 + 1 \\
 &= d(G_{x_0} \cap G_y) + 2
 \end{aligned}$$

Hence,  $d(G_{x_0} \cap G_y) = 0$  so  $G_{x_0} \cap G_y$  is trivial.

CLAIM. The action of  $G_{x_0}$  on  $Y$  is non-trivial.

*Proof.* Suppose the action were trivial. That is, there exists some  $y \in V(Y)$  such that  $(G_{x_0})_y = G_{x_0}$ . Hence,  $G_{x_0}$  is elliptic for the action of  $G$  on  $Y$ . By the local finiteness of  $Y$ , for all  $x \in V(X)$   $G_x$  acts elliptically on  $Y$ . Hence,  $\mathcal{E}(X) \subset \mathcal{E}(Y)$ . Again by local finiteness we can promote this using 2.3 to  $\mathcal{E}(X) = \mathcal{E}(Y)$  which by theorem 3.1 gives  $X \sim Y$  which contradicts the fact that  $X$  and  $Y$  were assumed to be in different deformation spaces.  $\square$

2.  $2 \Rightarrow 1$ : Trivial groups are FP.
3.  $2 \Rightarrow 3$ : Take  $X \times Y$  and give it the VH-structure where  $X$  and  $Y$  correspond to horizontal and vertical edges respectively. By 2.5 the core is non-empty. Condition (2) says that  $G$  acts freely on  $X \times Y$ . By 3.2 the core is connected. By the remark after Proposition 4.17 in Guirardel the core is simply connected. The action is also free on subsets of  $X \times Y$ . Since the action is cellular and free it's a covering space action. (We avoid situations like irrational rotations on a circle that are free but not covering space actions)

It remains to show that  $C/G$  is VH. Is it enough to say that the action respects the tree factors. (The edge partition on the cover descends to a well-defined edge partition on the quotient and attaching maps constructed in the standard way for the quotient alternate between vertical and horizontal edges)

4.  $3 \Rightarrow 2$ : Suppose  $1 \neq g \in G$  is an element of  $G_x \cap G_y$  where  $x \in V(X)$  and  $y \in V(Y)$ . Since  $K$  is a VH-complex it has a decomposition as a graph of groups where the vertex spaces are connected subgraphs whose edges are all vertical. Each  $x \in V(X)$  is in correspondence with the inclusion of a vertex space (composed entirely of vertical edges) into  $K$ . The inclusion of vertex spaces is always injective on fundamental groups. Lastly, after picking basepoints the image of the induced map is the stabilizer of  $x$ .

By Wise, we have that the universal cover of  $K$  is contained in  $X \times Y$ . Because the action respects the product structure, and because vertex spaces (in our case, graphs) are covered by embedded copies of their own universal covers we have that the non-trivial element  $g$  when represented by a loop in a vertex space lifts to a path with distinct endpoints in a tree consisting entirely of vertical edges in  $X \times Y$ . In fact,  $G_x$  acts on  $\{x\} \times Y$  and freely on  $\tilde{K} \cap (\{x\} \times Y)$  because the action on  $\tilde{K}$  is a covering space action. This means that  $g$  acts hyperbolically on  $Y$  and we get an axis in  $Y$ . This remains an axis in  $X \times Y$ .

Thus from looking at the vertical splitting we obtained an axis consisting entirely of vertical edges. Similarly, after looking at the horizontal splitting we obtain an axis consisting entirely of horizontal edges.

Finally, since  $X \times Y$  is CAT(0) these axes would have to be parallel. This is a contradiction.

□

## 2.3 Definitions

2.5 LEMMA (Cone extension). Call the original complex  $X$ , pick out a subcomplex  $Y$  with non-overlapping orbits, take products with  $[0, 1]$ , send the 1 factor copy of  $Y$  to somewhere in the  $\text{Im}(f)$  and extend using the product fibers and geodesics in the target tree.

7 DEFINITION (Cocompact by factor). Given a diagonal action of  $G$  on a product, we say that a  $G$ -invariant subset  $S$  is cocompact by factor (with respect to some index  $\alpha$  in the product) if  $S \subseteq S' \times X_\alpha$  where  $S'$  is a  $G$ -invariant subset of the product restricted to every index except  $\alpha$  and  $S'$  is cocompact.

4 PROPOSITION (Filling respects slices).

### 2.3.1 Miscellaneous

8 DEFINITION (VHD-complex). We say a cube complex is VHD if its edges can be partitioned into three sets each with a different color such that the

link of each vertex is a tripartite simplicial graph.

9 DEFINITION (Cohomological Dimension). We are using the minimal resolution size over the integers

2.5 Remark. The only case when geo is not alg is possibly when geo=3 and alg=2

2.6 LEMMA (Geometric Condition). (Theorem 0.6 in LP97) A minimal simplicial action of a finitely generated group is geometric if and only if all edge groups are finitely generated.

10 DEFINITION (Fiberwise Connected). Let  $S \subseteq X \times Y \times Z$ . If  $S \cap \{\text{pt}_1\} \times \{\text{pt}_2\} \times Z$  and all similar sets as well as permutations are connected then we say  $S$  is one dimensional fiberwise connected.

2.7 LEMMA (Guirardel Extension). (Lemma 8.9 in Guirardel) Consider a geometric action of a finitely generated group  $G$  on an  $\mathbb{R}$ -tree  $T$ , and let  $X$  be a 2-complex endowed with a free properly discontinuous cocompact action of  $G$ . Let  $\mathcal{F}$  be a  $G$ -invariant measured foliation on  $X$ . Consider a map  $f : X \rightarrow T$  which is constant on leaves of  $\mathcal{F}$ , and isometric in restriction to transverse edges of  $X$ . Then there exists a 2-complex  $X'$  containing  $X$ , endowed with a free properly discontinuous cocompact action of  $G$ , a measured foliation  $\mathcal{F}'$  extending  $\mathcal{F}$ , and which induces an isometry between  $X'/\mathcal{F}'$  and  $T$ . Moreover, the inclusion  $X \subseteq X'$  induces an epimorphism of fundamental groups.

2.8 LEMMA (Affine Equivariant Map). Suppose that  $G$  acts freely on a simplicial complex  $K$  and acts on a simplicial tree  $T$ . Then there exists an equivariant map  $f : K \rightarrow T$  where  $\mathcal{F}$  the connected components of the fibration from  $f$  is a measured foliation and  $f$  is an isometry on edges transverse to  $\mathcal{F}$ .

*Proof.* Part 1: Construct an equivariant map.

We start by defining  $f$  on  $K^{(0)}$  the 1-skeleton. By equivariance it is enough to define the map on a single vertex in each vertex orbit. These choices can be arbitrary. Next we check that the resulting map is well-defined. Indeed, if  $gv = hv$  then  $g^{-1}h = 1$  by freeness and so

$$f(v) = g^{-1}hf(v) = g^{-1}f(hv)$$

but then

$$f(gv) = gf(v) = f(hv).$$

Next we define the map on edges. If  $vw$  is an edge, map it to the geodesic  $[f(v), g(w)]$ .

Lastly, for 2-cells we use the standard fibration from mapping triangles to tripods.

Part 2: Fibration details. □

2.9 LEMMA (Guirardel Lemma 5.4, Corollary 5.5). Let  $T_1, T_2$  be two  $\mathbb{R}$ -trees and let  $F$  be a nonempty connected subset of  $T_1 \times T_2$  with convex fibers. Then the complement of  $\overline{F}$  is a union of quadrants. That is,  $\overline{F}$  is also nonempty, connected, and has convex fibers.

11 DEFINITION (Filling). Let  $\{X_k\}_{k \in K}$  be a family of spaces where one can take convex hulls. Given  $S \subseteq X := \prod X_k$  define  $S_k$  for  $k \in K$  via:

$$p \in S_k \iff \exists q, r \in S : \forall j \neq k : p_j = q_j = r_j \text{ and } p_k \in \text{cvxhull}_k(\{q_k, r_k\}).$$

12 DEFINITION (Type  $FP$ ). A group is of type  $FP$  if it is (1) type  $FP_n$  for all  $n$  and (2) finite geometric cohomological dimension.

13 DEFINITION (Finite Type). An action of *finite type* is one on a locally finite tree where vertex stabilizers are of type  $FP$ .

14 DEFINITION (Open Direction). An open direction is a connected component of an  $\mathbb{R}$ -tree minus a point.

15 DEFINITION (Closed Direction). A closed direction is a connected component of an  $\mathbb{R}$ -tree minus a point, union that point.

16 DEFINITION (Open Halfspace). An open halfspace is an open direction obtained from deleting the midpoint of an edge.

17 DEFINITION (Closed Halfspace). A closed halfspace is a closed direction obtained from deleting the midpoint of an edge.

18 DEFINITION (Halfspaces of a product). An open (resp. closed) halfspace of a product (at a certain index) is a subset where exactly one projection is an open (resp. closed) halfspace in its factor and the others are onto.

19 DEFINITION (Generalized quadrants). A generalized open (resp. closed) quadrant with respect to a product of  $k$  spaces is an intersection of  $k$  open (resp. closed) product halfspaces where each one is at a different index.

20 DEFINITION (cellular-product-convex). We say that  $K \subset X$  is cellular-product-convex if its complement is the open cellular neighborhood of a union of generalized closed quadrants.

## 3 Outlines

### 3.1 Misc lemmas

3.1 LEMMA (Parallel edges). Suppose  $X$  is a VHD-complex. Then parallel edges have the same color and edges that share a vertex have different colors.

This is false, for a single cube see picture in phone taken on 2020-08-22 The only property we need is that every cube is colored VHD, so we can reference splittings dual to an edge and that the sides are VH complexes



3.1 THEOREM (F, “On uniqueness...”, Thm 3.2). Let  $G$  be a group and let  $X$  and  $Y$  be cocompact  $G$ -trees. Then  $X$  and  $Y$  are related by an elementary deformation if and only if they have the same elliptic subgroups.

3.2 LEMMA (Guirardel Core is connected). Let  $X$  and  $Y$  be two locally finite  $G$ -trees that lie in different deformation spaces. Then the core is connected.

*Proof.* By Guirardel Proposition 4.14, the core is disconnected if and only if the two trees have a common refinement. This corresponds to collapse maps. This means there is an edge in the refinement that has an edge above it in both trees. Let  $K$  be the stabilizer of this edge. It appears in all three trees. Since the trees are all locally finite, we have that all vertex groups of all trees involved are commensurable. But the property of fixing a point is invariant under commensurability. Therefore, all vertex groups of the first tree are elliptic in the second tree and vice versa. Hence, both actions have the same elliptic subgroups which means they are in the same deformation space which contradicts our initial assumptions.  $\square$

3.3 LEMMA (Guirardel Core is nonempty). Let  $X$  and  $Y$  be two non-trivial actions of a finitely generated group  $G$  with finitely generated vertex groups that lie in different deformation spaces. Then the core of  $X$  and  $Y$  is non-empty.

*Proof.* By Guirardel Proposition 3.1, if they were in the same deformation space then they would have homothetic length functions i.e. one length function is a multiple of the other. Since elliptic elements fix a point, they have length zero. This means that  $X$  and  $Y$  have the same elliptic elements. From theorem 4.2 and corollary 4.3 in [F] we get that they have the same elliptic subgroups. This implies they lie in the same deformation space which contradicts our original assumption.  $\square$

3.4 LEMMA (equivariant map from elliptic inclusion). If  $X$  and  $Y$  are  $G$ -trees such that  $\mathcal{E}(X) \subset \mathcal{E}(Y)$ , then there exists an equivariant map  $X \rightarrow Y$ .

*Proof.* Consider the vertex orbits in  $X$ . Pick a vertex from each orbit. Consider how the stabilizers of these vertices in  $X$  act on  $Y$ . Because of the elliptic subgroup containment, each  $G_{x_i}$  we picked out fixes a non-empty set of vertices in  $Y$ . Begin to define a map on the 0-skeleton by sending  $x_i$  to something in  $Y$  fixed by  $G_{x_i}$ . There are several choices, but a fixed set of choices plus the invariant condition defines a map on the 0-skeleton.

The containment says such a map is well-defined. Indeed, pick  $x \in X^{(0)}$ . Suppose  $x = gx_0 = hx_0$ , then  $(h^{-1}g)x_0 = x_0$  and so  $h^{-1}g \in G_{x_0}$ . Then  $f(x_0) = f((h^{-1}g)x_0)$  which gives  $hf(x_0) = f(gx_0)$  and so  $f(hx_0) = f(gx_0)$  as needed.

Once we have a map on the 0-skeleton we can extend it to the entire tree by drawing unique geodesics in the trees.  $\square$

### 3.2 Main Equivariant Map Construction

Let  $X$  be a compact VH-complex and set  $G = \pi_1 X$ . Form the cover  $\tilde{X} \rightarrow X$ . Note that  $G$  acts on  $\tilde{X}$  freely and PDC. Since  $X$  is a VH-complex we get two actions of  $G$  on trees  $T_1$  and  $T_2$  along with invariant maps  $f_1$  and  $f_2$  from the splitting. Suppose we had a third action of  $G$  on a tree  $T_3$  with property *nice*. Given the covering space action and the action on  $T_3$  we use the affine construction 2.9 to get an equivariant map  $f_3 : \tilde{X} \rightarrow T_3$ . Using Guirardel 8.9 2.8 we extend  $f_3$  to  $\tilde{f}_3$  a map with connected fibers. We also need the proof of lemma 2.8 to ensure certain properties hold. Then, in order to extend the  $f_1$  and  $f_2$  maps we use the coning off construction. The product of these extensions gives  $f$ .

### 3.3 Combining into main argument

Finally, having enough dimension will follow from some assumptions about our actions. With this splitting in hand we want to verify that it's made of successive graphs of groups of items of a certain dimension so we can apply Bieri.

21 DEFINITION (Not All Trees). There is an iterated splitting that doesn't end in trees. (Ideally, we will show that this assumption only rules out  $\mathbb{Z} \times \mathbb{Z}$ , less ideally a statement about parabolics, less ideally we just assume it)

COROLLARY. Due to 21 we get that we can apply the dimension argument using Bieri to complete our result.

3.5 LEMMA. The action of  $G$  on  $T_1 \times T_2$  is free.

*Proof.* ...look in section II.6 of BH... Need enough facts to avoid non-proper spaces, get a semisimple action, and axes.  $\square$

3.6 LEMMA (Cocompact beginning). We directly show that our  $S_{ij}$  are cocompact  $\times$  factor.

3.7 LEMMA (Cocompact factor after neighborhood).  $K \times T$  with  $K$  cocompact taking a neighborhood we get again  $K' \times T$  with  $K'$  cocompact

3.8 LEMMA (Filling preserves cocompactness). Since  $S_{23}$  is a cocompact  $G$ -invariant subcomplex that's contained in  $A \times B$  where  $A$  and  $B$  are subcomplexes of  $T_1$  and  $T_2 \times T_3$  respectively and  $B$  is itself cocompact and  $G$  acts freely on  $T_2 \times T_3$  we have that  $(S_{23})_x$  is cocompact as well.

*Proof.* For each vertex orbit of  $B$  choose a particular vertex. By cocompactness this list is finite; call them  $\{b_1, \dots, b_n\}$ . By freeness in the second factor, the stabilizer of  $S' := S_{23} \cap (T_1 \times \{b_1\})$  is trivial. This means that  $S'$  injects into  $S_{23}/G$  which is compact by assumption. Since we are dealing with cell complexes,  $S'$  is also compact. Repeating this argument a finite number of times we have that  $S_{23} \cap (T_1 \times \{b_k\})$  is compact for each  $1 \leq k \leq n$ . Compact items have a well defined diameter. Taking the maximum diameter (in the product

metric) and noting we're acting by isometries gives that there is a bound  $D$  on the diameters of  $S_{23} \cap (T_1 \times \{v\})$  as  $v$  ranges over vertices of  $B$ .

Let  $a \times b$  be a vertex of  $(S_{23})_x$ . By construction,  $a$  lies within the convex hull of the projection of  $S_{23} \cap (T_1 \times \{b\})$  (a slice of  $S_{23}$ ) to the  $T_1$  factor, hence slices of  $(S_{23})_x$  have diameter no greater than  $D$  in the product metric. This means each slice of  $(S_{23})_x$  has a finite number of vertices. It remains to show that there is a universal bound on the number of vertices as we range over all slices. Since  $S_{23}$  is  $G$ -invariant and we're acting by a product, (so the slice at  $gb$  is the slice at  $b$  acted on by  $g$ ) there are a finite number of isometry classes of slices since  $B$  is cocompact. Hence, there are a finite number of vertex orbits so  $(S_{23})_x$  is cocompact as needed.  $\square$

## 4 Core has quadrant convex hyperplanes

4.1 LEMMA (Coning Connected Fibers). Let  $p$  in  $X$  our 2-complex, let  $p'$  be the unique projection. Let  $\Gamma$  be a compact subgraph in our 2-complex  $X$ . Take  $T$  to be either  $T_1$  or  $T_2$ . For now suppose we have defined a map  $f : \Gamma \rightarrow T$ . We will define a map  $F : \Gamma \times I \rightarrow T$ . Choose an arbitrary  $t_0 \in f(\Gamma)$  and define:

$$F(x, s) = \begin{cases} f(x) & s = 0 \\ t_0 & s = 1 \\ \gamma_{f(x), t_0}(s|\gamma|)a & \text{else} \end{cases}$$

Let  $k_0 \in \Gamma \cap F^{-1}(F(x, s))$  be the nearest point to  $p'$ . Put  $\gamma_{p', k_0}$ . Then define  $g : \text{Im}(\gamma_{p', k_0}) \rightarrow I$  by  $g(t) = \frac{a(t)}{a(t)+b}$  where  $a(t) = d(f(t), F(x, s))$  and  $b = d(F(x, s), t_0)$ . Then we compute  $F(t, g(t)) = F(x, s)$  so  $\text{Graph}(g) \subseteq F^{-1}(x, s)$ . Now,  $g$  is continuous so  $\text{Graph}(g)$  is connected. Hence,  $(x, s)$  is connected to  $(k_0, 0)$  in  $F^{-1}(F(x, s))$  as needed.

4.2 LEMMA (Fibers homeomorphic to Coordinate planes). Put  $f = f_1 \times f_2 \times f_3 : X \rightarrow T_1 \times T_2 \times T_3$  and  $J = \text{Im}(f)$ . We claim that  $J \cap T_1 \times T_2 \times \{z\} = \text{Im}_f(f_3^{-1}(z))$ . Let  $p = (p_1, p_2, p_3) \in T_1 \times T_2 \times T_3$  then we have the following.

$$\begin{aligned} p \in \text{LHS} &\iff p \in \text{Im}(f) \wedge p_3 = z \\ &\iff \exists x \in X (f(x) = p \wedge f_3(x) = z) \\ &\iff \exists x \in X (f(x) = p \wedge x \in f_3^{-1}(z)) \\ &\iff p \in \text{Im}_f(f_3^{-1}(z)) \end{aligned}$$

4.3 LEMMA (Reduction to vertical subpath). Suppose  $S \subseteq T_1 \times T_2 \times T_3$  is a subcomplex with CCP. Let  $p, q, r \in S$  satisfy

1.  $r \notin S$
2.  $p, q \in S$
3.  $p_2 = q_2 = r_2$  and  $p_3 = q_3 = r_3$

4.  $r \in \text{cvx}_{T_1}(\{p, q\})$

then there is a path  $\sigma : [0, 1] \rightarrow S$  between  $p$  and  $q$  such that  $\sigma(t)$  is contained in  $S \cap (T_1 \times \{r_2\} \times \delta)$  where  $\delta$  is an open direction in  $T_3$  at  $r_3$  provided  $t \neq 0, 1$ .

*Proof.* Property CCP implies that  $S \cap (T_1 \times \{r_2\} \times T_3)$  is connected. Let  $\sigma$  be a path in that set from  $p$  to  $q$ . Consider the pre-image of  $T_1 \times r_2 \times r_3$  by  $\sigma$ , call it  $K$ . Note that the complement of  $K$  is a countable disjoint union of open intervals in  $[0, 1]$  – we will choose one later. Each open interval is connected so considering projection and the fact that  $r_3$  is separating in  $T_3$  we have that under  $\sigma$  each open interval is mapped so the third coordinate lies in a single direction of  $T_3$  at  $r_3$ . After identifying,  $K$  maps into  $T_1$ . Color the points of  $K$  by which direction at  $r_1$  in  $T_1$  they map into. Here we use the fact that  $\sigma$  is a path that is disjoint from  $r$ . In fact, because  $S$  is a subcomplex it is closed and so there is an open neighborhood of  $r$  that is disjoint from  $S$  and therefore also  $\sigma$ . Intersecting this neighborhood with  $T_1 \times r_2 \times r_3$  gives an open neighborhood in  $T_1$  that is disjoint from  $\sigma$ .

The upside is that each monocolored subset of  $K$  is closed by looking at the image of  $\sigma$  in the slice and taking intersections with a closed halfspace pointing away from  $r_1$ . Take the smallest pairwise distance between the finite number of colored closed sets. Consider two points in  $K$  that achieve that distance. There cannot be any points of  $K$  between them because we chose the smallest distance. This picks out an interval with endpoints that map to different directions as needed.  $\square$

**22 DEFINITION** (Connected in coordinate planes). Let  $S$  be a subset of a product indexed by  $1 \leq k \leq N$ . Then  $S$  is connected in all coordinate planes if  $S \cap \pi_k^{-1}(p)$  is connected for all  $p \in X_k$  for all  $k$ .

**4.4 LEMMA** (Switching). Let  $S \subseteq \mathcal{T}$  be a subcomplex that is connected in all coordinate planes 22. Then  $S_x, S_y$ , and  $S_z$  are as well.

*Proof.* Without loss of generality, consider  $S_x$ , note that  $S_x$  will be connected in all  $xy$  and  $xz$  planes because  $S$  was. Consider the  $yz$ -planes in  $S_x$ , if there were no new points added then the planes are connected and we are done. Suppose that  $p \in (S_x \setminus S) \cap \pi_1^{-1}(p_1)$ , we need to connect  $p$  to a point in  $S$ . We will show that there is a path in  $S_x \cap \pi_2^{-1}(p_2)$  between  $p$  and some point in  $p' \in S$ .

Since  $r$  is in  $S_x \setminus S$  there exist distinct points  $p$  and  $q$  in  $S$  that agree in all coordinates except the first where we have that  $r_1 \in \text{cvxhull}_{T_1}(\{p_1, q_1\})$ . Now, because  $S$  is connected in all coordinate planes there is a path  $\sigma$  from  $p$  to  $q$  that lies in  $S \cap \pi_2^{-1}(r_2)$ . In fact, we can take  $\sigma$  to be a path that begins at  $p$  and ends at  $q$  with  $T_3$  coordinates lying in exactly one closed direction of  $T_3$  at  $r_3$ . We have factored out this situation into claim 4.3.

Take  $\sigma$  as in the claim 4.3. Consider  $D = r_1 \times r_2 \times \bar{\delta}$  a closed set. Let  $A$  be the set of points where  $\sigma$  crosses  $D$ . This is a closed set so we can consider the preimage under  $\sigma$  and look at the complement in  $[0, 1]$ . Color each interval by the direction in  $T_1$  at  $r_1$  that  $\pi_1 \sigma$  takes it to. Now, identifying  $D$  with a closed

direction at  $r_3$  in  $T_3$  we say that the colors at  $x \in D$  are the set of colors of intervals that the preimage of  $x$  under  $\pi_3\sigma$  hits.

Our goal is to find a geodesic from the root of  $D$  to a point in  $A$  that is multicolored. Note, because points in trees are separating, if the image of a continuous map contains two points it also contains the geodesic between those points. Suppose the claim were false. Then between every point of  $A$  and the root there is a point that is monocolored. A finite number of these points suffices to separate all of  $A$  from the root. Consider the first interval, it must cross one of these points. There must be another interval that eventually leaves that half space and enters a halfspace not entered yet. Because the geodesics have one color, and we always cross a monocolored point upon leaving, each segment has the same color. Including the last segment that goes back to the root. But this is impossible because we assumed the path begins and ends in different directions in  $T_1$  at  $r_1$ . □

4.5 LEMMA (Slice Switching). If  $R \subseteq T_1 \times T_2$  is a connected subcomplex then  $(R_x)_y = (R_y)_x$ .

*Proof.* We will first show that  $(R_x)_y$  has connected fibers. Note, it already has connected  $y$ -fibers, so it remains to show that it has connected  $x$ -fibers. Suppose that  $(R_x)_y \cap (T_1 \times \{y_0\})$  were a disconnected  $x$ -fiber. Then because  $(R_x)_y$  is a subcomplex we have that the fiber is separated by some edge. Let  $x_0$  be the midpoint of this edge. Let  $\ell$  and  $r$  denote the left and right closed halfspaces of  $T_1 \times \{y_0\}$  at the midpoint  $x_0$ . We will show that either  $\ell \cap (R_x)_y = \emptyset$  or  $r \cap (R_x)_y = \emptyset$ , applying this to all such  $x_0$  will show  $(R_x)_y$  has connected  $x$ -fibers.

Suppose this were false, and that  $\ell \cap (R_x)_y \neq \emptyset$  and  $r \cap (R_x)_y \neq \emptyset$ . We consider three cases: (1)  $\ell$  and  $r$  intersect  $R_x$  nontrivially (2)  $\ell$  and  $r$  don't intersect  $R_x$ , and (3) exactly one of  $\ell$  or  $r$  intersects  $R_x$  nontrivially.

1. Case 1: If both  $\ell$  and  $r$  intersect  $R_x$  then both contain points of  $R$  because we filled in the  $x$ -fiber, but then  $x_0 \times y_0 \in R_x$  a contradiction.
2. Case 2: Pick a point  $x^+$  in  $r \cap (R_x)_y \setminus R_x$ . Let  $q^+$  and  $q^-$  be points above and below  $x^+$  in  $R_x$ . These points are either in  $R$  already, or because we filled in the  $x$ -fiber there exist points above and below the line  $\ell \cup r$  but this is a contradiction since  $R$  is connected.
3. Case 3: Without loss of generality, suppose  $\ell \cap R_x = \emptyset$  and  $r \cap R_x \neq \emptyset$ . This implies there is some  $s \in R \cap r$ , we will get a contradiction by separating this point from another point in  $R$ .

Let  $u$  and  $d$  be directions of  $x_0 \times T_2$  at  $x_0 \times y_0$ . If both intersected  $R_x$  then  $x_0 \times y_0 \in R$  a contradiction so without loss of generality, suppose  $d \cap R_x \neq \emptyset$ . Now let  $x^-$  be a point in  $\ell$ , by assumption  $x^- \in (R_x)_y \setminus R_x$ . This gives a point  $q^-$  below  $\ell$  in  $R_x$  which is already in  $R$  or there exists a point  $t^- \in R$  to the left of  $q^-$ ; but this is a contradiction since  $\ell \cup d$  separates these points from  $s \in R$ .

Hence, either  $\ell \cap (R_x)_y = \emptyset$  or  $r \cap (R_x)_y = \emptyset$  as needed, so  $(R_x)_y$  has connected  $x$ -fibers. Similarly,  $(R_y)_x$  also has connected fibers. Hence by 2.10 their complements are unions of quadrants and so they contain  $QH(R)$ . It remains to show that they are contained within  $QH(R)$ .

CLAIM.  $(R_x)_y \subseteq QH(R)$

*Proof.* (sketch) The idea is to show that for every point  $p \in (R_x)_y$  that for every quadrant  $Q$  containing  $p$  (i.e. that would be attempting to remove it) we can find a point  $r \in R \cap Q$ . Picking an open quadrant containing  $p$  amounts to picking a point  $q = (q_1, q_2)$  with halfspaces at each coordinate that contain the corresponding  $p_i$ . The hard case is where  $p \in (R_x)_y \setminus R_x$  - so you pick a point in a vertical direction at  $p$  pointing towards  $p$ , because this point is only there due to filling there's another vertical direction that you're grabbing that contains some  $R_x$ . Then you pick a horizontal place and point towards  $p_1$ , this must contain at least one of the directions with  $R$  in it.  $\square$

*Proof.* We will show for every point  $p \in (R_x)_y$  and every open quadrant  $Q$  with  $p \in Q$  that there exists some  $r \in R \cap Q$ . Let  $q = (q_1, q_2)$  be the point where  $Q$  is based and label the halfspaces so that  $Q = q_1^+ \times q_2^+$ .

Case 1  $p \in R_x \setminus R$ : Let  $p \in R_x \setminus R$ : Let  $\ell = (\ell_1, p_2)$  and  $u = (u_1, p_2)$  be points in  $R$  that cause the vertical filling. Now,  $q_1^+$  contains all but one direction at  $p_1$  and so must contain either  $\ell_1$  or  $u_1$ . Since  $q_2^+$  must contain  $p_2$  we get that  $Q = q_1^+ \times q_2^+$  contains a point of  $R$ .

Case 2  $p \in (R_x)_y \setminus R_x$ : Let  $u = (p_1, u_2)$  and  $d = (p_1, d_2)$  be points that cause the vertical filling. Now,  $q_2^+$  contains all but one direction at  $p_2$  and so must contain either  $u_2$  or  $d_2$ . Without loss of generality, suppose it contains  $u_2$ . If  $u \in R$  then we are done. Suppose  $u \in R_x \setminus R$ . Then we can find  $u' = (p', u_2)$  and  $u'' = (p'', u_2)$  with  $p'$  and  $p''$  in different directions at  $p_1$ . Now,  $q_1^+$  contains all but one direction at  $p_1$  and so must contain either  $p'$  or  $p''$ . Suppose without loss of generality that it contains  $p'$ , then  $Q$  contains  $p' \times u_2 \in R$ .  $\square$

$\square$

4.6 LEMMA (Boxed Implication). Repeatedly applying 4.4 to both  $S$  and  $S_\alpha$  where  $\alpha$  is one of  $x, y$ , or  $z$  and noticing that  $\langle (12), (23) \rangle = S_3$  we get that  $((K_x)_y)_z$  is equal to any of the permutations of the indices. In particular,  $((K_x)_y)_z = ((K_y)_z)_x = ((K_z)_x)_y$  which shows that  $((K_x)_y)_z$  has connected one dimensional fibers.