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# Minors in graphs of large $\theta_r$ -girth\*

Dimitris Chatzidimitriou<sup>†</sup>    Jean-Florent Raymond<sup>‡§¶</sup>    Ignasi Sau<sup>‡</sup>  
Dimitrios M. Thilikos<sup>†‡</sup>

## Abstract

For every  $r \in \mathbb{N}$ , let  $\theta_r$  denote the graph with two vertices and  $r$  parallel edges. The  $\theta_r$ -girth of a graph  $G$  is the minimum number of edges of a subgraph of  $G$  that can be contracted to  $\theta_r$ . This notion generalizes the usual concept of girth which corresponds to the case  $r = 2$ . In [Minors in graphs of large girth, *Random Structures & Algorithms*, 22(2):213–225, 2003], Kühn and Osthus showed that graphs of sufficiently large minimum degree contain clique-minors whose order is an exponential function of their girth. We extend this result for the case of  $\theta_r$ -girth and we show that the minimum degree can be replaced by some connectivity measurement. As an application of our results, we prove that, for every fixed  $r$ , graphs excluding as a minor the disjoint union of  $k$   $\theta_r$ 's have treewidth  $O(k \cdot \log k)$ .

**Keywords:** girth, clique minors, tree-partitions, unavoidable minors, exclusion theorems.

2000 MSC: 05C83.

## 1 Introduction

A classic result in graph theory asserts that if a graph has minimum degree  $ck\sqrt{\log k}$ , then it can be transformed to a complete graph of at least  $k$  vertices by applying edge contractions (i.e., it contains a  $k$ -clique minor). This result has been proved by Kostochka in [Kos84] and Thomason in [Tho83] and a precise estimation of the universal

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<sup>†</sup>Department of Mathematics, National and Kapodistrian University of Athens, Athens, Greece.

<sup>‡</sup>AlGCo project team, CNRS, LIRMM, France.

<sup>§</sup>University of Montpellier, Montpellier, France.

<sup>¶</sup>Faculty of Mathematics, Informatics and Mechanics, University of Warsaw, Warsaw, Poland.

constant  $c$  has been given by Thomason in [Tho01]. For recent results related to conditions that force a clique minor see [Mar04, JW13, DHJ<sup>+</sup>13, FKO09, KO04].

The *girth* of a graph  $G$  is the minimum length of a cycle in  $G$ . Interestingly, it follows that graphs of large minimum degree contain clique-minors whose order is an *exponential* function of their girth. In particular, it follows by the main result of Kühn and Osthus in [KO03] that there is a universal constant  $c$  such that, if a graph has minimum degree  $d \geq 3$  and girth  $z$ , then it contains as a minor a clique of size  $k$ , where

$$k \geq \frac{d^{cz}}{\sqrt{z \cdot \log d}}.$$

In this paper we provide conditions, alternative to the above one, that can force the existence of a clique-minor whose size is exponential.

***H*-girth.** We say that a graph  $H$  is a *minor* of a graph  $G$ , if  $H$  can be obtained by some subgraph of  $G$  after contracting edges. An *H-model* of  $G$  is a subgraph of  $G$  that contains  $H$  as a minor. Given two graphs  $G$  and  $H$ , we define the *H-girth* of  $G$  as the minimum number of edges of an  $H$ -model of  $G$ . If  $G$  does not contain  $H$  as a minor, we will say that its  $H$ -girth is equal to infinity. For every  $r \in \mathbb{N}$ , let  $\theta_r$  denote the graph with two vertices and  $r$  parallel edges, e.g. in Figure 1 the graph  $\theta_5$  with 5 parallel edges. Clearly, the girth of a graph is its  $\theta_2$ -girth and, for every  $r_1 \leq r_2$ , the  $\theta_{r_1}$ -girth of

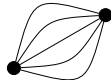


Figure 1: The graph  $\theta_5$ .

a graph is at most its  $\theta_{r_2}$ -girth.

Our first result is the following extension of the result of Kühn and Osthus in [KO03] for the case of  $\theta_r$ -girth.

**Theorem 1.** *There is a universal constant  $c$  such that, for every  $r \geq 2$ ,  $d \geq 3r$ , and  $z \geq r$ , if a graph has minimum degree  $d$  and  $\theta_r$ -girth at least  $z$ , then it contains as a minor a clique of size  $k$ , where*

$$k \geq \frac{\left(\frac{d}{r}\right)^{c \frac{z}{r}}}{\sqrt{\frac{z}{r} \cdot \log d}}.$$

In the formula above, a lower bound to the minimum degree as a function of  $r$  is necessary. Our second finding is that this degree condition can be replaced by some “loose connectivity” requirement.

**Loose connectivity.** For two integers  $\alpha, \beta \in \mathbb{N}$ , a graph  $G$  is called  $(\alpha, \beta)$ -loosely connected if for every  $A, B \subseteq V(G)$  such that  $V(G) = A \cup B$  and  $G$  has no edge between

$A \setminus B$  and  $B \setminus A$ , we have that  $|A \cap B| < \beta \Rightarrow \min(|A \setminus B|, |B \setminus A|) \leq \alpha$ . Intuitively, this means that a *small* separator (i.e., on less than  $\beta$  vertices) cannot “split” the graph into two *large* parts (that is, with more than  $\alpha$  vertices each).

Our second result indicates that the requirement on the minimum degree in Theorem 1 can be replaced by the loose connectivity condition as follows.

**Theorem 2.** *There is a universal constant  $c$  such that, for every  $r \geq 2$ ,  $z > r$ , and  $\alpha \geq 1$ , it holds that if a graph has more than  $(\alpha + 1) \cdot (2r - 1)$  vertices, is  $(\alpha, 2r - 1)$ -loosely connected, and has  $\theta_r$ -girth at least  $z$ , then it contains as a minor a clique of size  $k$  where*

$$k \geq \frac{2^c \frac{z}{r\alpha}}{\sqrt{r}}.$$

Both Theorems 1 and 2 are derived from two more general results, namely Theorem 4 and Theorem 3, respectively. Theorem 4 asserts that graphs with large  $\theta_r$ -girth sufficiently large minimum degree contain as a minor a graph whose minimum degree is exponential in the girth. Theorem 3 replaces the minimum degree condition with the absence of sufficiently large “edge-protrusions”, that are roughly tree-like structured subgraphs with small boundary to the rest of the graph (see Section 2 for the detailed definitions).

**Treewidth.** A *tree-decomposition* of a graph  $G$  is a pair  $(T, \mathcal{X})$  where  $T$  is a tree and  $\mathcal{X}$  is a family of subsets of  $V(T)$ , called *bags*, indexed by the vertices of  $T$  and such that:

- (i) for each edge  $e = (x, y) \in E(G)$  there is a vertex  $t \in V(T)$  such that  $\{x, y\} \subseteq X_t$ ;
- (ii) for each vertex  $u \in V(G)$  the subgraph of  $T$  induced by  $\{t \in V(T), u \in X_t\}$  is connected; and
- (iii)  $\bigcup_{t \in V(T)} X_t = V(G)$ .

The *width* of a tree-decomposition  $(T, \mathcal{X})$  is the maximum size of its bags minus one. The *treewidth* of a graph  $G$ , denoted  $\text{tw}(G)$ , is defined as the minimum width over all tree-decompositions of  $G$ .

Treewidth has been introduced in the Graph Minors Series of Robertson and Seymour [RS86] and is an important parameter in both combinatorics and algorithms. In [RS86], Robertson and Seymour proved that for every planar graph  $H$ , there exists a constant  $c_H$  such that every graph excluding  $H$  as a minor has treewidth at most  $c_H$ . This result has several applications in algorithms and a lot of research has been devoted to optimizing the constant  $c_H$  in general or for specific instantiations of  $H$  (see [RST94, DJGT99]). In this direction, Chekury and Chuzhoy proved in [CC14, Chu15] that  $c_H$  is bounded by a polynomial on the size of  $H$ . Specific results for particular  $H$ 's where  $c_H$  is a low polynomial function have been derived in [Bod93, BvLTT97, BBR07, RT13].

Given a graph  $J$ , we denote by  $k \cdot J$  the disjoint union of  $k$  copies of  $J$ . A consequence of the general results of Chekury and Chuzhoy in [CC13] is that  $c_{k \cdot J} = k \cdot (\log k)^{O(1)}$  for every planar graph  $J$ . Prior to this, a quadratic (on  $k$ ) upper bound was derived for the case where  $J = \theta_r$  [FLM<sup>+</sup>13, BBR07]. As an application of our results, we prove that for every fixed  $r$ ,  $c_{k \cdot \theta_r} = O(k \cdot \log k)$  (Theorem 5). We also argue that this bound is *tight* in the sense that it cannot be improved to  $o(k \cdot \log k)$ . Our proof is based on Theorem 3 and the results of Geelen, Gerards, Robertson, and Whittle on the excluded minors for the matroids of branch-width  $k$  [GGRW03].

**Organisation of the paper.** The main notions used in this paper are defined in Section 2. Then, we show in Section 3 that the proofs of Theorem 1 and Theorem 2 can be derived from Theorem 4 and Theorem 3, which are proved in Section 4. Finally, in Section 5, we prove our tight bound on the minor-exclusion of  $k \cdot \theta_r$ .

## 2 Definitions

Given a function  $\phi : A \rightarrow B$  and a set  $C \subseteq A$ , we define  $\phi(C) = \{\phi(x) \mid x \in C\}$ . Let  $\mathbf{t} = (x_1, \dots, x_l) \in \mathbb{N}^l$  and  $\chi, \psi : \mathbb{N} \rightarrow \mathbb{N}$ . We say that  $\chi(n) = O_{\mathbf{t}}(\psi(n))$  if there exists a computable function  $\phi : \mathbb{N}^l \rightarrow \mathbb{N}$  such that  $\chi(n) = O(\phi(\mathbf{t}) \cdot \psi(n))$ .

**Graphs.** All graphs in this paper are undirected, loopless, and may have multiple edges. For this reason, a graph is represented by a pair  $G = (V, E)$  where  $V$  is its vertex set, denoted by  $V(G)$  and  $E$  is its edge multi-set, denoted by  $E(G)$ . We set  $n(G) = |V(G)|$  and  $m(G) = |E(G)|$ . In this paper, when giving the running time of an algorithm involving some graph  $G$ , we agree that  $n = n(G)$  and  $m = m(G)$ . Given a vertex  $v$  of a graph  $G$ , the set of vertices of  $G$  that are adjacent to  $v$  is denoted by  $N_G(v)$  and the *degree* of  $v$  in  $G$  is  $|N_G(v)|$ . For every subset  $S \subseteq V(G)$ , we set  $N_G(S) = \bigcup_{v \in S} N_G(v) \setminus S$  (all vertices of  $V(G) \setminus S$  that have a neighbor in  $S$ ). The minimum degree over all vertices of a graph  $G$  is denoted by  $\delta(G)$ . For a given graph  $G$  and two vertices  $u, v \in V(G)$ ,  $\mathbf{dist}_G(u, v)$  denotes *the distance between  $u$  and  $v$* , which is the number of edges on a shortest path between  $u$  and  $v$ , and  $\mathbf{diam}(G)$  denotes  $\max\{\mathbf{dist}_G(u, v) \mid u, v \in V(G)\}$ . For a set  $S \subseteq V(G)$  and a vertex  $w \in V$ ,  $\mathbf{dist}_G(S, w)$  denotes  $\min\{\mathbf{dist}_G(v, w) \mid v \in S\}$ . Also, for a given vertex  $u \in V(G)$ ,  $\mathbf{ecc}_G(u)$  denotes *the eccentricity* of vertex  $u$ , that is,  $\max\{\mathbf{dist}_G(u, v) \mid v \in V(G)\}$ .

**Rooted trees.** A *rooted tree* is a pair  $(T, s)$  such that  $s$ , which we call the *root*, belongs to  $V(T)$ . Given a vertex  $x \in V(T)$ , the *descendants* of  $x$  in  $(T, s)$ , denoted by  $\mathbf{des}_{(T,s)}(x)$ , is the set containing each vertex  $w$  such that the unique path from  $w$  to  $s$  in  $T$  contains  $x$ . Given a rooted tree  $(T, s)$  and a vertex  $x \in V(G)$ , the *height* of  $x$  in  $(T, s)$  is the maximum distance between  $x$  and a vertex in  $\mathbf{des}_{(T,s)}(x)$ . The *height* of  $(T, s)$  is the height of  $s$  in  $(T, s)$ . The *children* of a vertex  $x \in V(T)$  are the vertices in  $\mathbf{des}_{(T,s)}(x)$ .

that are adjacent to  $x$ . A *leaf* of  $(T, s)$  is a vertex of  $T$  without children. The *parent* of a vertex  $x \in V(T) \setminus \{s\}$ , denoted by  $\mathbf{p}(x)$ , is the unique vertex of  $T$  that has  $x$  as a child.

**Critical vertices and unimportant paths.** Let  $(T, s)$  be a rooted tree and let  $N$  be a subset of its leaves. We say that a vertex  $u$  of  $T$  is  *$N$ -critical* if either it belongs in  $N \cup \{s\}$  or there are at least two vertices in  $N$  that are descendants of two distinct children of  $u$ . An  *$N$ -unimportant* path of  $T$  is a path with at least 2 vertices, with exactly two  $N$ -critical vertices which are its endpoints. Notice that an  $N$ -unimportant path of  $T$  cannot have an internal vertex that belongs in some other  $N$ -unimportant path. Also, among the two endpoints of an  $N$ -unimportant path there is always one which is a descendant of the other.

**Partitions and protrusions.** A *rooted tree-partition* of a graph  $G$  is a triple  $\mathcal{D} = (\mathcal{X}, T, s)$  where  $(T, s)$  is a rooted tree and  $\mathcal{X} = \{X_t\}_{t \in V(T)}$  is a partition of  $V(G)$  where either  $n(T) = 1$  or for every  $\{x, y\} \in E(G)$ , there exists an edge  $\{t, t'\} \in E(T)$  such that  $\{x, y\} \subseteq X_t \cup X_{t'}$  (see also [See85, Hal91, DO96]). Given an edge  $f = \{t, t'\} \in E(T)$ , we define  $E_f$  as the set of edges with one endpoint in  $X_t$  and the other in  $X_{t'}$ . Notice that all edges in  $E_f$  are non-loop edges. The *width* of  $\mathcal{D}$  is defined as  $\max\{|X_t|_{t \in V(T)} \cup \{|E_f|_{f \in E(T)}\}$ . The elements of  $\mathcal{X}$  are called *bags*.

In order to decompose graphs along edge cuts, we introduce the following edge-counterpart of the notion of (*vertex-*)*protrusion* used in [BFL+09a, BFL+09b] (among others). A subset  $Y \subseteq V(G)$  is a  *$t$ -edge-protrusion* of  $G$  with *extension*  $w$  (for some positive integer  $w$ ) if the graph  $G[Y \cup N_G(Y)]$  has a rooted tree-partition  $\mathcal{D} = (\mathcal{X}, T, s)$  of width at most  $t$  and such that  $N_G(Y) = X_s$  and  $n(T) \geq w$ . The protrusion  $Y$  is said to be *connected* whenever  $Y \cup N_G(Y)$  induces a connected subgraph in  $G$ .

**Distance-decompositions.** A *distance-decomposition* of a connected graph  $G$  is a rooted tree-partition  $\mathcal{D} = (\mathcal{X}, T, s)$  of  $G$ , where the following additional requirements are met (see also [YBdFT97]):

- (i)  $X_s$  contains only one vertex, we shall call it  $u$ , referred to as the *origin* of  $\mathcal{D}$ ;
- (ii) for every  $t \in V(T)$  and every  $x \in X_t$ ,  $\mathbf{dist}_G(x, u) = \mathbf{dist}_T(t, s)$ ;
- (iii) for every  $t \in V(T)$ , the graph  $G_t = G \left[ \bigcup_{t' \in \mathbf{des}_{(T,s)}(t)} X_{t'} \right]$  is connected; and
- (iv) if  $C$  is the set of children of a vertex  $t \in V(T)$ , then the graphs  $\{G_{t'}\}_{t' \in C}$  are the connected components of  $G_t \setminus X_t$ .

An example of distance-decomposition is given in [Figure 2](#). For every vertex  $u$  of a graph on  $m$  edges, a distance-decomposition  $(\mathcal{X}, T, s)$  of origin  $u$  can obviously be constructed in  $O(m)$  steps by breadth-first search.

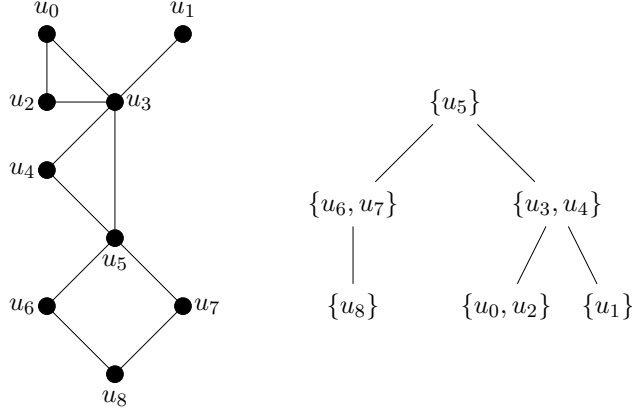


Figure 2: A graph (left) and a distance-decomposition of origin  $u_5$  of it (right).

For every  $t \in V(T) \setminus \{s\}$ , we define  $E^{(t)}$  as the set of edges of  $G$  that go from the bag of  $t$  to the one of its parent. More formally,  $E^{(t)}$  is the set of edges that have the one endpoint in  $X_t$  and the other in  $X_{\mathbf{p}(t)}$ .

Let  $P$  be a path in  $G$  that has some distance-decomposition  $\mathcal{D} = (\mathcal{X}, T, s)$ . We say that  $P$  is a *straight path* if the heights, in  $(T, s)$ , of the indices of the bags in  $\mathcal{D}$  that contain vertices of  $P$  are pairwise distinct. Obviously, in that case, the sequence of the heights of the bags that contain each subsequent vertex of the path is strictly monotone.

**Grouped partitions.** Let  $G$  be a connected graph and let  $d \in \mathbb{N}$ . A *d-grouped partition* of  $G$  is a partition  $\mathcal{R} = \{R_1, \dots, R_l\}$  of  $V(G)$  (for some positive integer  $l$ ) such that for each  $i \in \{1, \dots, l\}$ , the graph  $G[R_i]$  is connected and there is a vertex  $s_i \in R_i$  with the following properties:

- (i)  $\mathbf{ecc}_{G[R_i]}(s_i) \leq 2d$  and
- (ii) for each edge  $e = \{x, y\} \in E(G)$  where  $x \in R_i$  and  $y \in R_j$  for some distinct integers  $i, j \in \{1, \dots, l\}$ , it holds that  $\mathbf{dist}_G(x, s_i) \geq d$  and  $\mathbf{dist}_G(y, s_j) \geq d$ .

A set  $S = \{s_1, \dots, s_l\}$  as above is a *set of centers* of  $\mathcal{R}$  where  $s_i$  is the *center* of  $R_i$  for  $i \in \{1, \dots, l\}$ .

Given a graph  $G$ , we define a *d-scattered set*  $W$  of  $G$  as follows:

- $W \subseteq V(G)$  and
- $\forall u, v \in W, \mathbf{dist}_G(u, v) > d$ .

If  $W$  is inclusionwise maximal, it will be called a *maximal d-scattered set* of  $G$ .

**Frontiers and ports.** Let  $G$  be a graph, let  $\mathcal{R} = \{R_1, \dots, R_l\}$  be a  $d$ -grouped partition of  $G$ , and let  $S = \{s_1, \dots, s_l\}$  be a set of centers of  $\mathcal{R}$ . For every  $i \in \{1, \dots, l\}$ , we denote by  $\mathcal{D}_i = (\mathcal{X}_i, T_i, r_i)$  the distance-decomposition of origin  $s_i$  of the graph  $G[R_i]$  and where  $\mathcal{X}_i = \{X_t^i\}_{t \in V(T_i)}$ . For every  $i \in \{1, \dots, l\}$  and every  $h \in \{0, \dots, \text{ecc}_{T_i}(r_i)\}$ , we denote by  $I_i^h$  the vertices of  $(T_i, r_i)$  that are at distance  $h$  from  $r_i$ , and we set  $I_i^{<h} = \bigcup_{h'=0}^{h-1} I_{h'}^i$  and  $I_i^{\geq h} = \bigcup_{h'=h}^{\text{ecc}_{T_i}(r_i)} I_{h'}^i$ . We also set

$$V_i^h = \bigcup_{t \in I_i^h} X_t^i, \quad V_i^{<h} = \bigcup_{t \in I_i^{<h}} X_t^i, \quad \text{and} \quad V_i^{\geq h} = \bigcup_{t \in I_i^{\geq h}} X_t^i.$$

The *vertex-frontier*  $F_i$  of  $R_i$  is the subset of vertices of  $V_i^{d-1}$  that are connected in  $G$  to a vertex  $x \in V(G) \setminus R_i$  via a path, the internal vertices of which belong to  $V_i^{\geq d}$ . The *node-frontier* of  $T_i$  is

$$N_i = \{t \in V(T_i), F_i \cap X_t \neq \emptyset\}. \quad (1)$$

A vertex  $t \in I_i^{\geq d-1}$  is called a *port* of  $T_i$  if  $X_t^i$  contains some vertex that is adjacent in  $G$  to a vertex of  $V(G) \setminus R_i$ .

### 3 Finding small $\theta_r$ -models

#### 3.1 Two intermediate results

The main results of this section are the following.

**Theorem 3.** *There exists an algorithm that, with input three positive integers  $r, w, z$  and an  $n$ -vertex graph  $G$ , outputs one of the following:*

- a  $\theta_r$ -model of  $G$  of at most  $z$  edges,
- a connected  $(2r - 2)$ -edge-protrusion  $Y$  of  $G$  with extension more than  $w$ , or
- an  $H$ -model of  $G$  for some graph  $H$  where  $\delta(H) \geq \frac{1}{r-1} 2^{\frac{z-5r}{4r(2w+1)}}$ ,

in  $O_r(m)$  steps.

**Theorem 4.** *There exists an algorithm that, with input three integers  $r, \delta, z$ , where  $r \geq 2$ ,  $\delta \geq 3r$ , and  $z \geq r$  and an  $n$ -vertex graph  $G$ , outputs one of the following:*

- a  $\theta_r$ -model of  $G$  of at most  $z$  edges,
- a vertex  $v$  of  $G$  of degree less than  $\delta$ , or
- an  $H$ -model of  $G$  for some graph  $H$  where  $\delta(H) \geq \frac{\delta-2r+3}{r-1} \cdot \lfloor \frac{\delta}{r-1} - 1 \rfloor^{\frac{z-r}{4r}}$ ,

in  $O_r(m)$  steps.



The results of Chandran and Subramanian in [CS05] imply that if  $G$  has girth at least  $z$  and minimum degree at least  $\delta$ , then  $\mathbf{tw}(G) \geq \delta^{c \cdot z}$ , for some constant  $c$ . As in the third condition of Theorem 4 it holds that  $\mathbf{tw}(G) \geq \mathbf{tw}(H) \geq \delta(H)$ , Theorem 4 can also be seen as a qualitative extension of [CS05].

The above two results will be used to prove Theorem 1 and Theorem 2. We will also need the following result of Kostochka [Kos84].

**Proposition 1** ([Kos84], see also [Tho83, Tho01]). *There exists a universal constant  $c_K \in \mathbb{R}$  such that for every  $p \in \mathbb{N}$ , every graph of average degree at least  $d$  contains a clique of order  $k$  as a minor, for some integer  $k$  satisfying*

$$k \geq c_K \cdot \frac{d}{\sqrt{\log d}}.$$

*Proof of Theorem 1.* Observe that since  $G$  has no  $\theta_r$ -model with at most  $z$  edges and  $G$  has minimum degree  $\delta \geq 3r$ , a call to the algorithm of Theorem 4 on  $(r, \delta, z, G)$  should return an  $H$ -model of  $G$ , for some graph  $H$  where  $\delta(H) \geq \frac{\delta - 2r + 3}{r - 1} \cdot \lfloor \frac{\delta}{r - 1} - 1 \rfloor^{\frac{z - r}{4r}} =: d$ . It is not hard to check that there is a constant  $c' \in \mathbb{R}$  such that

$$c_K \cdot \frac{d}{\sqrt{\log d}} \geq \frac{\left(\frac{\delta}{r}\right)^{c' \cdot \frac{z}{r}}}{\sqrt{\frac{z}{r} \cdot \log \delta}}.$$

Hence by Proposition 1,  $G$  has a clique of the desired order as a minor.  $\square$

*Proof of Theorem 2.* As in the proof of Theorem 1, the properties that  $G$  enjoys will force a minor of large minimum degree. Let us call the algorithm of Theorem 3 on  $(r, 3\alpha, z, G)$ . We assumed that  $G$  has no  $\theta_r$ -model on  $z$  edges or less, hence the output of the algorithm cannot be such a model. Let us now assume that the algorithm outputs a  $(2r - 2)$ -edge-protrusion  $Y$  of extension more than  $3\alpha$ , and let  $(\mathcal{X}, T, s)$  be a rooted tree-partition of  $Y$  of width at most  $2r - 2$  such that  $N_G(Y) = X_s$  and  $n(T) > 3\alpha$ . It is known that every tree of order  $n$  has a vertex, the removal of which partitions the tree into components of size at most  $n/2$  each. Hence, there is a vertex  $v \in V(T)$  and a partition  $(Z, Z')$  of  $V(T) \setminus \{v\}$  such that:

- both  $Z \cup \{v\}$  and  $Z' \cup \{v\}$  induce connected subtrees of  $T$ ;
- $\frac{1}{3}n(T) \leq |Z|, |Z'| \leq \frac{2}{3}n(T)$ ; and
- $X_s \subseteq Z$  or  $v = s$ .

Let  $A = Z' \cup \{X_v\}$  and  $B = V(G) \setminus Z'$ . Notice that  $V(G) = A \cup B$  and that no edge of  $G$  lies between  $A$  and  $B$ . As  $A \cap B = X_v$ , we have  $|A \cap B| < 2r - 1$ . Last,  $Z' \subseteq A \setminus B$  and  $Z \subseteq B \setminus A$  give that  $|A \setminus B|, |B \setminus A| \geq \alpha$ . The existence of  $A$  and  $B$  contradicts the fact that  $G$  is  $(\alpha, 2r - 1)$ -loosely connected. Thus  $G$  has no  $(2r - 2)$ -edge-protrusion  $Y$  of extension more than  $3\alpha$ .

A consequence of this observation is that the only possible output of the algorithm mentioned above is an  $H$ -model of  $G$  for some graph  $H$ , where

$$\delta(H) \geq \frac{1}{r-1} \cdot 2^{\frac{z-5r}{4r(6\alpha+1)}} =: d.$$

As in the proof of [Theorem 1](#), it suffices to remark that there is a constant  $c'' \in \mathbb{R}$  such that

$$c_K \cdot \frac{d}{\sqrt{\log d}} \geq \frac{2^{c'' \cdot \frac{z}{r\alpha}}}{\sqrt{r}}$$

in order to conclude the proof. □

## 4 The proofs of [Theorem 3](#) and [Theorem 4](#)

### 4.1 Preliminary results

Before proving [Theorem 3](#) and [Theorem 4](#) (in [Subsection 4.2](#) and [Subsection 4.3](#), respectively) we need some preliminary results.

**Lemma 1.** *Let  $(T, s)$  be a rooted tree and let  $N$  be a set of leaves of  $(T, s)$ , each of which is at distance smaller than  $d$  from  $s$ . If for some integer  $k$ , every  $N$ -unimportant path of  $T$  has length at most  $k$ , then  $|N| \geq 2^{(d-1)/k}$ .*

*Proof.* For any  $N$ -unimportant path  $P$  in  $(T, s)$  with  $u, v$  as its endpoints, we denote by  $T_u(P)$  the connected component of  $T - E(P)$  containing  $u$ ,  $T_v(P)$  the connected component of  $T - E(P)$  containing  $v$ , and  $T_\emptyset(P)$  the rest of the connected components of  $T - E(P)$ . Since  $P$  is  $N$ -unimportant, it follows immediately that  $T'_\emptyset(P)$  does not contain any  $N$ -critical vertex.

Now consider the following procedure:

1. Select an  $N$ -unimportant path in  $T$ , namely  $P$ , and let  $u, v$  be its endpoints;
2. Remove all edges of  $P$  from  $T$ ;
3. Remove all vertices and edges of  $T_\emptyset(P)$  from  $T$  (notice that in this step no  $N$ -critical vertices are removed);
4. Add the edge  $\{u, v\}$  to  $T$ ;
5. Repeat the procedure until there is no  $N$ -unimportant path that is not an edge in  $T$  and let  $T'$  be the resulting graph;

An immediate but crucial observation is that  $(T', s)$  is a rooted tree that contains exactly the  $N$ -critical vertices of  $T$  and also its leaves are exactly the vertices in  $N$ . It follows that every vertex of  $T'$  other than the root and leaves has degree at least 3. Consequently, if  $d'$  is the height of  $T'$ , then the leaves of  $T'$  are at least  $2^{d'}$ , or  $|N| \geq 2^{d'}$ . But since  $T'$

is a minor of  $T$  and each edge of  $T'$  corresponds to a path of length at most  $k$  in  $T$ , we also have that  $d - 1 \leq k \cdot d'$ , so  $d' \geq (d - 1)/k$ . Combining these two observations, we get  $|N| \geq 2^{(d-1)/k}$ .  $\square$

**Lemma 2.** *Let  $G$  be a  $n$ -vertex graph, let  $r$  be a positive integer, let  $\mathcal{D} = (\mathcal{X}, T, s)$  be a distance-decomposition of  $G$ , and let  $d > 1$  be the height of  $(T, s)$ . Then either  $G$  contains a  $\theta_r$ -model with at most  $2 \cdot r \cdot d$  edges or for every vertex  $i \in V(T) \setminus s$ , it holds that  $|E^{(i)}| \leq r - 1$ . Moreover there exists an algorithm that, in the first case, can find such a model in  $O_r(m)$  steps.*

*Proof.* We consider the non-trivial case where  $r \geq 2$ . Suppose that there exists a node  $t$  of  $(T, s)$  such that  $|E^{(t)}| \geq r$ . Clearly, such a  $t$  can be found in  $O(m)$  steps. We will prove that  $G$  contains a  $\theta_r$ -model. Let  $k$  be the height of  $t$  in  $T$ .

We need first the following claim.

**Claim 1.** *Given a non-empty subset  $U$  of  $X_t$  with less than  $r$  vertices, we can find in  $G_t$  a path of length at most  $2 \cdot k$  from a vertex of  $U$  to a vertex of  $X_t \setminus U$ , in  $O(m)$  steps.*

*Proof of Claim 1.* Starting with the graph  $G_t$ , we add a vertex  $u_{\text{in}}$  adjacent to every vertex in  $U$  and a vertex  $u_{\text{out}}$  adjacent to every vertex in  $X_t \setminus U$ , thus constructing  $G'_t$ . Then we will use the algorithm in [Tho99] to find a shortest path  $P$  between  $u_{\text{in}}$  and  $u_{\text{out}}$  in  $G'_t$  in  $O(m)$  steps. Let  $u$  and  $v$  be the neighbors in  $P$  of  $u_{\text{in}}$  and  $u_{\text{out}}$ , respectively, and let  $w$  be a vertex of  $P$  of the lowest possible height  $h$  ( $0 \leq h \leq k$ ). Then it holds that  $\mathbf{dist}_{G_t}(v, u) = \mathbf{dist}_{G_t}(U, v)$ . We examine the non-trivial case where  $P$  has more than three edges. Clearly,  $w \notin X_t$  as, otherwise, either the path from  $u$  to  $w$ , or the path from  $v$  to  $w$  would be a path connecting  $U$  and  $X_t \setminus U$ , but it would also be shorter than  $P$ , a contradiction to the construction of  $P$ .

Our next step is to prove that if  $P$  has more than three edges, then both the subpaths of  $P$  from  $u$  to  $w$  and from  $v$  to  $w$  are straight. Suppose now, without loss of generality, that the subpath from  $u$  to  $w$  is not straight and let  $z$  be the first vertex of it (starting from  $u$ ) which is contained in a bag of height greater than or equal to the height of the bag of its predecessor in  $P$ . By definition of a distance-decomposition (in particular items (ii) and (iii)), there is at least one vertex  $x \in X_t$  which is connected by a straight path  $P'$  to  $z$  in  $G$ . Then there are two possibilities:

- either  $x \in U$ , and then the union of the path  $P'$  and the portion of  $P$  between  $z$  and  $v$  is a path that is shorter than  $P \setminus \{u_{\text{in}}, u_{\text{out}}\}$ ;
- or  $x \in X_t \setminus U$ , and in this case the union of the path  $P'$  and the portion of  $P$  between  $u$  and  $z$  is a path that is shorter than  $P \setminus \{u_{\text{in}}, u_{\text{out}}\}$ .

As, in both cases, the occurring paths contradict the construction of  $P$ , we conclude that both the subpath of  $P$  from  $u$  to  $w$  and the one from  $v$  to  $w$  are straight. This implies that  $P \setminus \{u_{\text{in}}, u_{\text{out}}\}$  has length at most  $2 \cdot (k - h) \leq 2 \cdot k$  and the claim follows.

$\diamond$

Our next step is to construct a vertex set  $U$  and a set of paths  $\mathcal{P}$  as follows. We set  $\mathcal{P} = \emptyset$ ,  $U = \emptyset$ , and we start by adding in  $U$  an arbitrarily chosen vertex  $u \in X_t$ . Using the procedure of [Claim 1](#), we repeatedly find a path from a vertex of  $U$  to a vertex of  $X_t \setminus U$ , add this second vertex to  $U$  and the path to  $\mathcal{P}$ , until there are at least  $r$  edges in  $E^{(t)}$  that have endpoints in  $U$ .

The construction of  $U$  requires at most  $r$  repetitions of the procedure of [Claim 1](#), and therefore  $O(r \cdot m)$  steps in total. Clearly  $|U| \leq r$ , hence  $|\mathcal{P}| \leq r - 1$ . Besides, every path of  $\mathcal{P}$  has length at most  $2k$  according to [Claim 1](#). Notice now that  $\mathbf{UP}$  is a connected subgraph of  $G_t$  with at most  $2k \cdot (r - 1)$  edges and such that  $U = V(\mathbf{UP}) \cap X_t$ .

As there are at least  $r$  edges in  $E^{(t)}$  with endpoints in  $U$  we may consider a subset  $F$  of them where  $|F| = r$ . Since  $\mathcal{D}$  is a distance-decomposition (by item (ii) of the definition), each edge  $e \in F$  is connected to the origin by a path of length  $d - k - 1$  whose edges do not belong to  $G_t$ . Let  $\mathcal{P}'$  be the collection of these paths. Clearly, the paths in  $\mathcal{P}'$  contain, in total, at most  $r \cdot (d - k - 1)$  edges.

If we now contract in  $G$  all edges in  $\mathcal{P}$  and all edges in  $\mathcal{P}'$ , except those in  $F$ , and then remove all edges not in  $F$ , we obtain a graph isomorphic to  $\theta_r$ . Therefore we found in  $G$  a  $\theta_r$ -model with at most

$$\begin{aligned} r \cdot (d - k - 1) + 2 \cdot k \cdot (r - 1) + r &\leq r \cdot (d - k - 1) + 2 \cdot k \cdot r + r \\ &= r \cdot (d + k) \\ &\leq 2 \cdot r \cdot d && \text{(since } d \geq k \text{)} \end{aligned}$$

edges in  $O(r \cdot m)$  steps. □

The following result is a direct consequence of [Lemma 2](#) and item (ii) of the definition of a distance-decomposition.

**Corollary 1.** *Let  $G$  be an  $n$ -vertex graph, let  $r$  be a positive integer, let  $\mathcal{D} = (\mathcal{X}, T, s)$  be a distance-decomposition of  $G$ , and let  $d > 1$  be the height of  $(T, s)$ . If some bag of  $\mathcal{D}$  contains at least  $r$  vertices, then  $G$  contains a  $\theta_r$ -model with at most  $2 \cdot r \cdot d$  edges, which can be found in  $O_r(m)$  steps.*

The remaining lemmata will be related to [grouped partitions](#).

**Lemma 3.** *For every positive integer  $d$  and every connected graph  $G$  there is a  $d$ -grouped partition of  $G$  that can be constructed in  $O(m)$  steps.*

*Proof.* If  $\text{diam}(G) \leq 2d$ , then obviously  $\{V(G)\}$  is a  $d$ -grouped partition of  $G$ . Otherwise, let  $R = \{s_1, \dots, s_l\}$  be a maximal  $2d$ -scattered set in  $G$ . As mentioned earlier, this set can be constructed in  $O(m)$  steps. The sets  $\{R_i\}_{i \in \{1, \dots, l\}}$  are constructed by the following procedure:

1. Set  $k = 0$  and  $R_i^0 = \{s_i\}$  for every  $i \in \{1, \dots, l\}$ ;

2. For every  $i \in \{1, \dots, l\}$ , every  $v \in R_i^k$  and every  $u \in N_G(v)$ , if  $u$  has not been considered so far, add  $u$  to  $R_i^{k+1}$ ;
3. If  $k < 2d$ , increment  $k$  by 1 and go to step 2;
4. Let  $R_i = \bigcup_{k=0}^{2d} R_i^k$  for every  $i \in \{1, \dots, l\}$ .

Let  $\mathcal{R} = \{R_i\}_{i \in \{1, \dots, l\}}$ . By construction, each set  $R_i$  induces a connected graph in  $G$ . It remains to prove that  $\mathcal{R}$  is a partition of  $V(G)$  and that it has the desired properties.

Notice that in the above construction if a vertex is assigned to the set  $R_i$ , then it is not assigned to  $R_j$ , for every distinct integers  $i, j \in \{1, \dots, l\}$ . Let  $v \in V(G)$  be a vertex that does not belong to  $R_i$  for any  $i \in \{1, \dots, l\}$  after the procedure is completed. Then for every  $i \in \{1, \dots, l\}$  we have  $\mathbf{dist}_G(v, s_i) > 2d$  and  $v \notin R$ , which contradicts the maximality of  $R$ . Therefore  $\mathcal{R}$  is a partition of  $V(G)$ .

Since for each vertex  $v$  of  $R_i$  it holds that  $\mathbf{dist}_G(v, s_i) \leq 2d$ ,  $\mathcal{R}$  obviously satisfies property (i) of the definition.

For property (ii) of the definition, let  $e = \{x, y\}$  be an edge of  $G$  such that  $x \in R_i$ ,  $y \in R_j$ , for some distinct integers  $i, j \in \{1, \dots, l\}$ . Towards a contradiction, we assume without loss of generality that  $\mathbf{dist}_G(x, s_i) < d$ . This means that during the construction of  $R_i$ , the vertex  $x$  was added to the set  $R_i^k$  for some  $k \leq d - 1$ . Also, since the vertex  $y$  is adjacent to  $x$  but was added to  $R_j^l$  for some  $l \leq 2d$  instead of  $R_i^{k+1}$ , it follows that  $l \leq k + 1$ , which means that  $\mathbf{dist}_G(y, s_j) \leq k + 1$ . Hence  $\mathbf{dist}_G(s_i, s_j) \leq \mathbf{dist}_G(s_i, x) + \mathbf{dist}_G(x, y) + \mathbf{dist}_G(y, s_j) \leq k + 1 + k + 1 \leq 2d$  again is not possible since  $R$  is a  $2d$ -scattered set.

Finally, in the procedure above, each edge of the graph is encountered at most once, hence the whole algorithm will take at most  $O(m)$  time. This concludes the proof of the lemma.  $\square$

**Lemma 4.** *Let  $G$  be a graph, let  $\mathcal{R} = \{R_1, \dots, R_l\}$  be a  $d$ -grouped partition of  $G$ , and let  $s_i$  be a center of  $R_i$ , for every  $i \in \{1, \dots, l\}$ . If for some distinct  $i, j \in \{1, \dots, l\}$ ,  $G$  has at least  $r$  edges from vertices of  $R_i$  to vertices of  $R_j$  then  $G[R_i \cup R_j]$  contains a  $\theta_r$ -model with at most  $4 \cdot r \cdot d + r$  edges, which can be found in  $O_r(m)$  steps.*

*Proof.* Suppose that for some  $i \in \{1, \dots, l\}$ ,  $G$  has a set  $F$  of at least  $r$  edges from vertices of  $R_i$  to vertex of  $R_j$ . Let  $R'_i \subseteq R_i$  and  $R'_j \subseteq R_j$  be the sets of the endpoints of those edges. Since  $\mathcal{R}$  is a  $d$ -grouped partition of  $G$ , it holds that, for each  $x \in R'_i$  and  $y \in R'_j$ ,  $\mathbf{dist}_G(x, s_i) \leq 2d$  and  $\mathbf{dist}_G(y, s_j) \leq 2d$ . That directly implies that for every  $h \in \{i, j\}$ , there is a collection  $\mathcal{P}_h$  of  $r$  paths, each of length at most  $2d$  and not necessarily disjoint, in  $G[R_h]$  connecting  $s_h$  with each vertex of  $R'_h$ , which we can find in  $O_r(m)$  steps. It is now easy to observe that the graph  $Q$ , obtained from  $\bigcup \mathcal{P}_i \cup \bigcup \mathcal{P}_j$  by adding all edges of  $F$ , is the union of  $r$  paths between  $s_i$  and  $s_j$ , each containing at most  $4 \cdot d + 1$  edges. Therefore,  $Q$  is a model of  $\theta_r$  of at most  $4 \cdot r \cdot d + r$  edges, as required. As mentioned earlier the construction of  $\mathcal{P}_i$  and  $\mathcal{P}_j$  takes  $O_r(m)$  steps.  $\square$

**Lemma 5.** *Let  $G$  be a graph, let  $\mathcal{R} = \{R_1, \dots, R_l\}$  be a  $d$ -grouped partition of  $G$ , and let  $S = \{s_1, \dots, s_l\}$  be a set of centers of  $\mathcal{R}$ . For every  $i \in \{1, \dots, l\}$ , let  $\mathcal{D}_i = (\mathcal{X}_i, T_i, r_i)$  be the distance-decomposition of origin  $s_i$  of the graph  $G[R_h]$ . If for some  $i \in \{1, \dots, l\}$  and  $w \in \mathbb{N}$ , the tree  $T_i$  has an  $N_i$ -unimportant path of length at least  $2(w + 1)$ , then  $W$  has a connected  $(2r - 2)$ -edge-protrusion  $Y$  with extension more than  $w$ , which can be constructed in  $O_r(m)$  steps.*

*Proof.* Let  $P = t_0 \dots t_p$  be a  $N_i$ -unimportant path of length  $p \geq 2(w + 1)$  in  $T_i$ . We assume without loss of generality that  $t_p \in \mathbf{des}_{(T_i, r_i)}(t_0)$ . Due to the definition of distance-decompositions, the vertices in  $X_{t_0}^i$  or  $X_{t_p}^i$  form a vertex-separator of  $W$ . Let  $Z \subseteq E(W)$  be the set containing all edges between  $X_{t_0}^i$  and  $X_{t_1}^i$  and all edges between  $X_{t_{p-1}}^i$  and  $X_{t_p}^i$  in  $W$ . Clearly,  $Z$  is an edge-separator of  $W$  of at most  $2r - 2$  edges. Let  $T'_i$  be the subtree of  $T_i$  that we obtain if we remove the descendants of  $t_p$  and any vertex that is not a descendant of  $t_1$ . Let  $Y = \bigcup_{t \in V(T'_i) \setminus \{t_0, t_p\}} X_t^i$ . In other words,  $Y$  consists of the vertices in the bags of  $T'_i$  excluding  $X_{t_0}^i$  and  $X_{t_p}^i$ . Obviously,  $N_W(Y) = X_{t_0} \cup X_{t_p}$ .

We will now construct a rooted tree-partition  $\mathcal{F} = (\mathcal{X}_{\mathcal{F}}, T_{\mathcal{F}}, r_{\mathcal{F}})$  of  $W[Y \cup N_W(Y)]$  of width at most  $2r - 2$  and such that  $n(T_{\mathcal{F}}) > w$ . Let  $T_{\mathcal{F}}$  be the tree obtained from  $T'_i$  by identifying, for every  $j \in \{0, \dots, \lfloor (p-1)/2 \rfloor\}$ , the vertex  $t_j$  with the vertex  $t_{p-j}$ . If multiple edges are created during this identification, we replace them with simple ones. We also delete loops that may be created. Let us define the elements of  $\mathcal{X}_{\mathcal{F}} = \{X_t^{\mathcal{F}}\}_{t \in V(T_{\mathcal{F}})}$  as follows. If  $t \in V(T_{\mathcal{F}})$  is the result of the identification of  $t_j$  and  $t_{p-j}$  for some  $j \in \{0, \dots, \lfloor (p-1)/2 \rfloor\}$ , then we set  $X_t^{\mathcal{F}} = X_{t_j} \cup X_{t_{p-j}}$ . On the other hand, if  $t \in V(T_{\mathcal{F}})$  is a vertex of  $T'_i$  that has not been identified with some other vertex, then  $X_t^{\mathcal{F}} = X_t$ . The construction of  $\mathcal{F}$  is completed by setting  $r_{\mathcal{F}}$  to be the result of the identification of  $t_0$  and  $t_p$ , the endpoints of  $P$ .

It is easy to verify that  $\mathcal{F}$  is a rooted tree-partition of  $W[Y \cup N_W(Y)]$  of width at most  $2r - 2$ . Notice also that the identification of the antipodal vertices of the path  $P$  creates a path in  $T_{\mathcal{F}}$  of length  $\lfloor (p-1)/2 \rfloor$ . This implies that the extension of  $\mathcal{F}$  is at least  $\lfloor (p-1)/2 \rfloor \geq w + 1$ . Besides, all the operations performed to construct  $\mathcal{F}$  can be implemented in  $O_r(m)$  steps. This completes the proof.  $\square$

We conclude this section with two easy lemmata related to **ports and frontiers**.

**Lemma 6.** *Let  $G$  be a graph, let  $\mathcal{R} = \{R_1, \dots, R_l\}$  be a  $d$ -grouped partition of  $G$ , and let  $S = \{s_1, \dots, s_l\}$  be a set of centers of  $\mathcal{R}$ . For every  $i \in \{1, \dots, l\}$ , let  $\mathcal{D}_i = (\mathcal{X}_i, T_i, r_i)$  be the distance-decomposition of origin  $s_i$  of the graph  $G[R_h]$ . Then, for every  $i \in \{1, \dots, l\}$ , there are at least  $|N_i|$  ports in  $T_i$ .*

*Proof.* Let  $i \in \{1, \dots, l\}$ . We will show that every vertex in the node-frontier of  $T_i$  has a descendant which is a port. For every vertex  $t \in N_i \subseteq V(T_i)$ , there is, by definition, a path from  $t$  to a vertex of  $G \setminus R_i$ , the internal vertices of which belong to  $V_i^{\geq d}$ . Let  $v$  be the last vertex of this path (starting from  $t$ ) which belongs to  $R_i$  and let  $t' \in V(T)$  be the vertex such that  $v \in X_{t'}^i$ . Then  $t'$  is a port of  $T_i$ . Observe that  $t'$  cannot be the descendant of any other vertex of  $N_i$ . Therefore there are at least  $|N_i|$  ports in  $T_i$ .  $\square$

**Corollary 2.** *Let  $G$  be a graph, let  $\mathcal{R} = \{R_1, \dots, R_l\}$  be a  $d$ -grouped partition of  $G$ , and let  $S = \{s_1, \dots, s_l\}$  be a set of centers of  $\mathcal{R}$ . For every  $i \in \{1, \dots, l\}$ , let  $\mathcal{D}_i = (\mathcal{X}_i, T_i, r_i)$  be the distance-decomposition of origin  $s_i$  of the graph  $G[R_h]$ . If for some integer  $k$ , every  $N_i$ -unimportant path of  $T_i$  has length at most  $k$ , then  $T_h$  contains at least  $2^{(d-1)/k}$  ports.*

*Proof.* Let  $i \in \{1, \dots, l\}$ . From [Lemma 6](#), it is enough to prove that  $|N_i| \geq 2^{(d-1)/k}$ . Then the result follows by applying [Lemma 1](#) for  $(T_i, s_i)$ ,  $d - 1$ ,  $N_i$ , and  $k$ .  $\square$

## 4.2 Proof of [Theorem 3](#)

*Proof.* Let  $d = \frac{z-r}{4r}$ . According to [Lemma 3](#), we can construct in  $O(m)$  steps a  $d$ -grouped partition  $\mathcal{R} = \{R_1, \dots, R_l\}$  of  $V(G)$ , with a set of centers  $S = \{s_1, \dots, s_l\}$ , and also, for every  $i \in \{1, \dots, l\}$ , the distance-decompositions  $\mathcal{D}_i = (\mathcal{X}_i, T_i, r_i)$  of origin  $s_i$  of the graphs  $G[R_i]$ . For every  $i \in \{1, \dots, l\}$ , we use the notation  $\mathcal{X}_i = \{X_t^i\}_{t \in V(T_i)}$  and denote by  $N_i$  the node-frontiers of  $T_i$ .

By applying the algorithm of [Lemma 4](#), in  $O_r(m)$  steps, we either find a  $\theta_r$ -model in  $G$  with at most  $z = 4 \cdot r \cdot d + r$  edges or we know that for every two distinct  $i, j \in \{1, \dots, l\}$  there are at most  $r - 1$  edges of  $G$  with one endpoint in  $R_i$  and one in  $R_j$ .

Similarly, by applying the algorithm of [Lemma 2](#), in  $O_r(m)$  steps we either find a  $\theta_r$ -model in  $G$  with at most  $2 \cdot r \cdot d \leq z$  edges or we know that for every  $i \in \{1, \dots, k\}$  and every  $t \in V(T_i)$ , the bag  $X_t^i$  contains at most  $r - 1$  vertices.

Using the algorithm of [Lemma 5](#), in  $O_r(m)$  steps we either find a  $(2r - 2)$ -edge-protrusion of extension more than  $w$ , or we know that for every  $i \in \{1, \dots, l\}$ , all  $N_i$ -unimportant paths of  $T_i$  have length at most  $2w + 1$ .

We may now assume that none of the above algorithms provided a  $\theta_r$ -model with  $z$  edges, or a  $(2r - 2)$ -edge-protrusion.

From [Corollary 2](#), for every  $i \in \{1, \dots, l\}$  the tree  $T_i$  contains at least  $2^{\frac{d-1}{2w+1}} = 2^{\frac{z-5r}{4r \cdot (2w+1)}}$  ports, which by definition means that there are at least  $2^{\frac{z-5r}{4r \cdot (2w+1)}}$  edges in  $G$  with one endpoint in  $R_i$  and the other in  $V(G) \setminus R_i$ . By [Lemma 4](#), for every distinct integers  $i, j \in \{1, \dots, l\}$  there are at most  $r - 1$  edges with one endpoint in  $R_i$  and the other in  $R_j$ . As a consequence of the two previous implications, for every  $i \in \{1, \dots, l\}$  there is a set  $Z_i \subseteq \{1, \dots, l\} \setminus \{i\}$ , where  $|Z_i| \geq \frac{1}{r-1} 2^{\frac{z-5r}{4r \cdot (2w+1)}}$ , such that for every  $j \in Z_i$  there exists an edge with one endpoint in  $R_i$  and the other in  $R_j$ . Consequently, if we now contract all edges in  $G[R_i]$  for every  $i \in \{1, \dots, l\}$ , the resulting graph  $H$  is a minor of  $G$  of minimum degree at least  $\frac{1}{r-1} 2^{\frac{z-5r}{4r \cdot (2w+1)}}$ . Therefore, we output  $G$ , which is an  $H$ -model, as required in this case.  $\square$

## 4.3 Proof of [Theorem 4](#)

*Proof.* The proof is quite similar to the one of [Theorem 3](#). If  $G$  contains a vertex  $v$  of degree less than  $\delta$ , we can easily find it in  $O_r(m)$  steps.

Let  $d = \frac{z-r}{4r}$ . From [Lemma 3](#), in  $O(m)$  steps, we can construct a  $d$ -grouped partition  $\mathcal{R} = \{R_1, \dots, R_l\}$  of  $G$ , with a set of centers  $S = \{s_1, \dots, s_l\}$ , and also the distance-decomposition  $\mathcal{D}_i = (\mathcal{X}_i, T_i, r_i)$  of origin  $s_i$  of the graphs  $G[R_i]$ , for every  $i \in \{1, \dots, l\}$ . We use again the notation  $\mathcal{X}_i = \{X_t^i\}_{t \in V(T_i)}$ .

As in the proof of [Theorem 3](#), in  $O_r(m)$  steps, we can either find a  $\theta_r$ -model in  $G$  with at most  $z = 4 \cdot r \cdot d + r$  edges or we know that for every distinct integers  $i, j \in [l]$  there are at most  $r-1$  edges of  $G$  with one endpoint in  $R_i$  and one in  $R_j$  (cf. [Lemma 4](#)).

Using [Corollary 1](#), we can in  $O_r(m)$  steps either find a  $\theta_r$ -model in  $G$  with at most  $z$  edges or we know that every bag of  $\mathcal{D}_i$  has less than  $r$  vertices, for every  $i \in \{1, \dots, l\}$ . Let  $i \in \{1, \dots, l\}$  and let  $u \in R_i$  be a vertex at distance less than  $d$  from  $s_i$ . As  $u$  has degree at least  $3r$ , it must have neighbors in at least 3 different bags of  $\mathcal{D}_i$ , apart from the one containing it. This means that every vertex in  $T_i$  of distance less than  $d$  from  $r_i$  has degree at least  $\lfloor \frac{\delta}{r-1} \rfloor \geq 3$  and therefore  $T_i$  has at least  $\lfloor \frac{\delta}{r-1} - 1 \rfloor^d$  leaves. Notice also that if  $t$  is a leaf of  $T_i$ , then each vertex in  $X_t^i$  can have at most  $r-1$  neighbors in  $X_{\mathbf{p}(t)}^i$  and at most  $r-2$  neighbors in  $X_t^i$ . Therefore there are at least  $\delta - (r-1) - (r-2) = \delta - 2r + 3$  edges in  $G$  with one endpoint in  $X_t^i$  and the other in  $V(G) \setminus R_i$ . This means that for every  $i \in \{1, \dots, l\}$  there are at least  $(\delta - 2r + 3) \cdot \lfloor \frac{\delta}{r-1} - 1 \rfloor^d$  edges with one endpoint in  $R_i$  and the other  $V(G) \setminus R_i$ .

Similarly to the proof of [Theorem 3](#), we deduce that, for each  $i \in \{1, \dots, l\}$ , there is a set  $Z_i \subseteq \{1, \dots, l\} \setminus \{i\}$  where  $|Z_i| \geq \frac{\delta-2r+3}{r-1} \cdot \lfloor \frac{\delta}{r-1} - 1 \rfloor^d$  such that, for every  $j \in Z_i$ , there exists an edge with one endpoint in  $R_i$  and the other in  $R_j$ . This implies the existence of an  $H$ -model in  $G$  for some  $H$  with  $\delta(H) \geq \frac{\delta-2r+3}{r-1} \cdot \lfloor \frac{\delta}{r-1} - 1 \rfloor^{\frac{z-r}{4r}}$ . We then output  $G$ , which, in this case, is an  $H$ -model.  $\square$

## 5 Excluding $k$ copies of $\theta_r$ as a minor

This section is devoted to the proof of the following theorem.

**Theorem 5.** *For every graph  $G$ ,  $r \geq 2$ , and  $k \geq 1$ , if  $\text{tw}(G) \geq 2^{6r} \cdot k \cdot \log(k+1)$ , then  $G$  contains  $k \cdot \theta_r$  as a minor.*

For the proof, we need to introduce some definitions and related results.

### 5.1 Preliminaries

Let  $G$  be a graph and  $G_1, G_2$  two non-empty subgraphs of  $G$ . We say that  $(G_1, G_2)$  is a *separation* of  $G$  if:

- $V(G_1) \cup V(G_2) = V(G)$ ; and
- $(E(G_1), E(G_2))$  is a partition of  $E(G)$ .



Let  $G$  be a graph. Given a set  $E \subseteq E(G)$ , we define  $V_E$  as the set of all endpoints of the edges in  $E$ . Given a partition  $(E_1, E_2)$  of  $E(G)$  we define  $\delta(E_1, E_2) := |V_{E_1} \cap V_{E_2}|$ .

A *cut*  $C = (X, Y)$  of  $G$  is a partition of  $V(G)$  into two subsets  $X$  and  $Y$ . We define the *cut-set* of  $C$  as  $E_C := \{\{x, y\} \in E(G) \mid x \in X \text{ and } y \in Y\}$  and call  $|E_C|$  the *order* of the cut. Also, given a graph  $G$ , we denote by  $\sigma(G)$  the number of connected components of  $G$ .

**The branchwidth of a graph.** A *branch-decomposition* of a graph  $G$  is a pair  $(T, \tau)$  where  $T$  is a ternary tree and  $\tau$  a bijection from the edges of  $G$  to the leaves of  $T$ . Deleting any edge  $e$  of  $T$  bipartitions the leaves of  $T$ , and thus the edges of  $G$  into two subsets  $E_1^e$  and  $E_2^e$ . The *width* of a branch-decomposition  $(T, \tau)$  is equal to  $\max_{e \in E(T)} \{\delta(E_1^e, E_2^e)\}$ . The *branchwidth* of a graph  $G$ , denoted  $\mathbf{bw}(G)$ , is defined as the minimum width over all branch-decompositions of  $G$ .

**The branchwidth of a matroid.** We assume that the reader is familiar with the basic notions of matroid theory. We will use the standard notation from Oxley's book [Ox1992]. The branchwidth of a matroid is defined very similarly to that of a graph. Let  $\mathcal{M}$  be a matroid with finite ground set  $E(\mathcal{M})$  and rank function  $r$ . The *order* of a non-trivial partition  $(E_1, E_2)$  of  $E(\mathcal{M})$  is defined as  $\lambda(E_1, E_2) := r(E_1) + r(E_2) - r(E) + 1$ . A *branch-decomposition* of a matroid  $\mathcal{M}$  is a pair  $(T, \mu)$  where  $T$  is a ternary tree and  $\mu$  is a bijection from the elements of  $E(\mathcal{M})$  to the leaves of  $T$ . Deleting any edge  $e$  of  $T$  bipartitions the leaves of  $T$ , and thus the elements of  $E(\mathcal{M})$  into two subsets  $E_1^e$  and  $E_2^e$ . The *width* of a branch-decomposition  $(T, \mu)$  is equal to  $\max_{e \in E(T)} \{\lambda(E_1^e, E_2^e)\}$ . The *branchwidth* of a matroid  $\mathcal{M}$ , denoted  $\mathbf{bw}(\mathcal{M})$ , is again defined as the minimum width over all branch-decompositions of  $\mathcal{M}$ . The *cycle matroid of a graph*  $G$  denoted  $\mathcal{M}_G$ , has ground set  $E(\mathcal{M}_G) = E(G)$  and the cycles of  $G$  as the cycles of  $\mathcal{M}_G$ . Let  $G$  be a graph,  $\mathcal{M}_G$  its cycle matroid and  $(G_1, G_2)$  a separation of  $G$ . Then clearly  $(E(G_1), E(G_2))$  is a partition of  $E(\mathcal{M}_G)$ , but to avoid confusion we will henceforth denote it  $(E_1, E_2)$  and we will call it *the partition of  $\mathcal{M}_G$  that corresponds to the separation  $(G_1, G_2)$  of  $G$* . Observe that the order of this partition is:

$$\lambda(E_1, E_2) = \delta(E(G_1), E(G_2)) - \sigma(G_1) - \sigma(G_2) + \sigma(G) + 1. \quad (\star)$$

**Minor obstructions.** Let  $\mathcal{G}$  be a graph class. We denote by  $\mathbf{obs}(\mathcal{G})$  the set of all minor-minimal graphs  $H$  such that  $H \notin \mathcal{G}$  and we will call it *the minor obstruction set for  $\mathcal{G}$* . Clearly, if  $\mathcal{G}$  is closed under minors, the minor obstruction set for  $\mathcal{G}$  provides a complete characterization for  $\mathcal{G}$ : a graph  $G$  belongs in  $\mathcal{G}$  if and only if none of the graphs in  $\mathbf{obs}(\mathcal{G})$  is a minor of  $G$ .

Given a class of matroids  $\mathbf{M}$ , *the minor obstruction set for  $\mathbf{M}$* , denoted by  $\mathbf{obs}(\mathbf{M})$ , is defined very similarly to its graph-counterpart: it is simply the set of all minor-minimal matroids  $\mathcal{M}$  such that  $\mathcal{M} \notin \mathbf{M}$ .

We will need the following results.

**Proposition 2** ([RS91, Theorem 5.1]). *Let  $G$  be a graph of branchwidth at least 2. Then,  $\mathbf{bw}(G) \leq \mathbf{tw}(G) + 1 \leq \lfloor \frac{3}{2} \mathbf{bw}(G) \rfloor$ .*

**Proposition 3** ([BvLTT97]). *Let  $r \in \mathbb{N}_{\geq 1}$  and let  $G$  be a graph. If  $\mathbf{bw}(G) \geq 2r + 1$ , then  $G$  contains a  $\theta_r$ -model.*

**Proposition 4** ([HJ07, Theorem 4]). *Let  $G$  be a graph that has a cycle of length at least 2 and  $\mathcal{M}_G$  be its cycle matroid. Then,  $\mathbf{bw}(G) = \mathbf{bw}(\mathcal{M}_G)$ .*

**Proposition 5** ([GGRW03, Lemma 4.1]). *Let a matroid  $\mathcal{M}$  be a minor obstruction for the class of matroids of branchwidth at most  $k$  and let  $g : \mathbb{N} \rightarrow \mathbb{N}$  be a function such that  $g(n) = (6^{n-1} - 1)/5$ . Then, for every partition  $(X, Y)$  of  $\mathcal{M}$  with  $\lambda(X, Y) \leq k$ , it follows that either  $|X| \leq g(\lambda(X, Y))$  or  $|Y| \leq g(\lambda(X, Y))$ .*

The following observations are also crucial.

**Observation 1.** *Let  $\mathcal{G}$  be a graph class that is closed under minors and let  $\mathcal{M}_{\mathcal{G}} = \{\mathcal{M}_G, G \in \mathcal{G}\}$ .  $\mathcal{G}$  is minor closed if and only if  $\mathcal{M}_{\mathcal{G}}$  is minor closed. Moreover, for every  $H \in \mathbf{obs}(\mathcal{G})$  it holds that  $\mathcal{M}_H \in \mathbf{obs}(\mathcal{M}_{\mathcal{G}})$ .*

**Observation 2.** *There is a  $c \in \mathbb{R}_{\geq 2}$ , such that for any integer  $k \geq r \geq 2$ , if  $g(n) = (6^{n-1} - 1)/5$ , then  $\frac{1}{r-1} 2^{\frac{c^r \log k - 5r}{4r(2g(2r-2)+1)}} \geq k(r+1) - 1$ . Moreover, this holds for  $c = 2^6 \log_r \frac{2}{3}$ .*

## 5.2 Graphs with large minimum degree

In this subsection we show that every graph of large minimum degree contains  $\theta_r^k$  as minor. Our proof relies on the following result.

**Proposition 6** ([Sti96, Corollary 3]). *For every  $k, r \in \mathbb{N}_{\geq 1}$ , every graph  $G$  with  $\delta(G) \geq k(r+1) - 1$  has a partition  $(V_1, \dots, V_k)$  of its vertex set satisfying  $\delta(G[V_i]) \geq r$  for every  $i \in \{1, \dots, k\}$ .*

**Lemma 7.** *For every integer  $r \in \mathbb{N}_{\geq 1}$ , every graph of minimum degree at least  $r$  contains a  $\theta_r$ -model.*

*Proof.* Starting from any vertex  $u$ , we grow a maximal path  $P$  in  $G$  by iteratively adding to  $P$  a vertex that is adjacent to the previously added vertex but does not belong to  $P$ . Since  $\delta(G) \geq r$ , any such path will have length at least  $r + 1$ . At the end, all the neighbors of the last vertex  $v$  of  $P$  belong to  $P$  (otherwise  $P$  could be extended). Since  $v$  has degree at least  $r$ ,  $v$  has at least  $r$  neighbors in  $P$ . Therefore  $P$  is a  $\theta_r$ -model of  $G$ .  $\square$

**Corollary 3.** *For every  $k, r \in \mathbb{N}_{\geq 1}$ , every graph  $G$  with  $\delta(G) \geq k(r+1) - 1$  contains a  $\theta_r^k$ -model.*

*Proof.* According to **Proposition 6**,  $V(G)$  has a partition  $(V_1, \dots, V_k)$  such that  $\delta(G[V_i]) \geq r$  for every  $i \in \{1, \dots, k\}$ . Therefore, by **Lemma 7**, for every  $i \in \{1, \dots, k\}$  the graph  $G[V_i]$  has a  $\theta_r$ -model  $M_i$ . Clearly  $M_1 \cup \dots \cup M_k$  is a  $k \cdot \theta_r$ -model of  $G$ , as desired.  $\square$

Now we are ready to prove the main result of this section.

### 5.3 Proof of **Theorem 5**

We define  $f : \mathbb{N}_{\geq 2} \rightarrow \mathbb{R}$  such that  $f(x) = \frac{2}{3}2^{6x}$ . By **Proposition 2**, it is enough to prove that if  $\mathbf{bw}(G) \geq f(r) \cdot k \cdot \log(k+1)$ , then  $G$  contains  $k \cdot \theta_r$  as a minor. To prove this we use induction on  $k$ .

The case where  $k = 1$  follows from **Proposition 3** and the fact that  $f(r) \geq 2r + 1$ . We now examine the case where  $k > 1$ , assuming that the proposition holds for smaller values of  $k$ . As  $\mathbf{bw}(G) \geq f(r) \cdot k \cdot \log(k+1)$ ,  $G$  contains a minor obstruction for the class of graphs of branchwidth at most  $f(r) \cdot k \cdot \log(k+1) - 1$ .

**Claim 2.** *Any  $(2r - 2)$ -edge-protrusion of  $G$  has extension at most  $g(2r - 2)$ .*

*Proof of Claim 2.* Let  $C = (X, Y)$  be a cut of  $H$  of order at most  $2r - 2$  and let  $H_X$  be the subgraph of  $H$  with  $V(H_X) = X \cup N_H(X)$  and let  $E(H_X) = E(H[X]) \cup E_C$ . Clearly the set  $(H_X, H[Y])$  forms a separation of  $H$ . Let  $\mathcal{M}_H$  be the cycle matroid of  $H$  and  $(E_X, E_Y)$  be the partition of  $\mathcal{M}_H$  that corresponds to the aforementioned separation. By **Proposition 4**,  $\mathbf{bw}(\mathcal{M}_H) = \mathbf{bw}(H) \geq f(r) \cdot k \cdot \log(k+1)$ . Therefore, by **Observation 1**,  $\mathcal{M}_H$  is a minor obstruction for the class of matroids of branchwidth  $f(r) \cdot k \cdot \log(k+1) - 1$ . From  $(\star)$ , we have:

$$\begin{aligned} \lambda &:= \lambda(E_X, E_Y) = r(E_X) + r(E_Y) - r(\mathcal{M}_H) + 1 \\ &= \delta(E(H_X), E(H[Y])) - \sigma(H_X) - \sigma(H[Y]) + \sigma(H) + 1 \\ &\leq \delta(E(H_X), E(H[Y])) \\ &\leq |E_C| = 2r - 2 \\ &\leq f(r) \cdot k \cdot \log(k+1) - 1. \end{aligned}$$

Thus, by **Proposition 5**, either  $|E_X| \leq g(\lambda)$  or  $|E_Y| \leq g(\lambda)$ . Since  $g$  is non-decreasing, either  $|E(H_X)| \leq g(2r - 2)$  or  $|E(H[Y])| \leq g(2r - 2)$ . This directly implies that for any  $(2r - 2)$ -edge-protrusion  $Z$  of  $H$ ,  $G[Z \cup N_G(Z)]$  has at most  $g(2r - 2)$  edges. Therefore  $Z$ 's extension is also at most  $g(2r - 2)$  and the claim follows.  $\diamond$

Combining the above claim, **Observation 2**, and **Theorem 3**, we infer that either  $H$  contains a  $\theta_r$ -model  $M$  with at most  $f(r) \cdot \log k$  edges, or it contains a minor with minimum degree at least  $\frac{1}{r-1} \cdot 2^{\frac{f(r) \log k - 5r}{4r(2g(2r-2)+1)}} \geq k(r+1) - 1$ . If the second case is true, then by **Corollary 3**  $H$  contains  $k \cdot \theta_r$  as a minor, which proves the inductive step. Because  $M$  is 2-connected, we obtain that  $|V(M)| \leq |E(M)|$ . Therefore,  $|V(M)| \leq |E(M)| \leq f(r) \cdot \log k$  and we can bound the treewidth of the graph  $G' = G \setminus V(M)$  as follows:

$$\begin{aligned} \mathbf{tw}(G') &\geq \mathbf{tw}(G) - |V(M)| \\ &\geq f(r) \cdot k \cdot \log(k+1) - f(r) \cdot \log k \\ &\geq f(r) \cdot k \cdot \log k - f(r) \cdot \log k \\ &= f(r) \cdot (k - 1) \cdot \log k. \end{aligned}$$

Then, from the induction hypothesis,  $G'$  contains a  $(k-1)\cdot\theta_r$ -model  $M'$  and obviously  $M \cup M'$  is a  $k \cdot \theta_r$ -model of  $G$ , which concludes our proof.  $\square$

Theorem 5 implies that for every fixed  $r$ , it holds that every graph excluding  $k \cdot \theta_r$  as a minor has treewidth  $O(k \cdot \log k)$ . We conclude with a lemma indicating that this bound is tight up to the constants hidden in the  $O$ -notation.

**Lemma 8.** *For every integer  $r \geq 2$ , there exist an  $n$ -vertex graph  $G$  and an integer  $k$  such that  $\mathbf{tw}(G) = \Omega(k \cdot \log k)$  and  $G$  does not contain  $k \cdot \theta_r$  as a minor.*

*Proof.* Let  $G$  be a (big enough)  $n$ -vertex 3-regular Ramanujan graph  $G$  (see [Mor94]). Such a graph has girth at least  $c \cdot \log n$  for some universal constant  $c$  (see [BB90]) and satisfies  $\mathbf{tw}(G) = \Omega(n)$  (cf. [BEM<sup>+</sup>04, Corollary 1]). Let  $k$  be the minimum integer such that  $n < k \cdot c \cdot \log n$ . Notice that  $n = \Omega(k \cdot \log k)$ , and thus  $\mathbf{tw}(G) = \Omega(k \cdot \log k)$ . We will show that  $k \cdot \theta_r$  is not a minor of  $G$ . Suppose for contradiction that  $G$  contains  $k$  vertex-disjoint subgraphs  $H_1, \dots, H_k$ , each of which is a model of  $\theta_r$ . As the girth of  $G$  is at least  $c \cdot \log n$ , the same holds for every  $H_i$ . As  $r \geq 2$ ,  $H_i$  contains at least one cycle of length at least  $c \cdot \log n$ . Therefore  $G$  should contain at least  $k \cdot c \cdot \log n$  vertices. This implies that  $|V(G)| \geq k \cdot c \cdot \log n > n$ , a contradiction.  $\square$

## 6 Concluding remarks

In this paper, we introduced the concept of  $H$ -girth and proved that for every  $r \in \mathbb{N}_{\geq 2}$ , a large  $\theta_r$ -girth forces an exponentially large clique minor. This extends the results of Kühn and Osthus related to the usual notion of girth. We also gave a variant of our result where the minimum degree is replaced by a connectivity measure. As an application of our result, we optimally improved (up to a constant factor) the upper-bound on the treewidth of graphs excluding  $k \cdot \theta_r$  as a minor. A first question is whether our lower-bound on the clique minor size can be improved.

Let us now state more general questions spawned by this work. A natural line of research is to investigate the  $H$ -girth parameter for different instantiations of  $H$ . An interesting problem in this direction could be to characterize the graphs  $H$  for which our results (Theorem 1 and Theorem 2) can be extended.

From its definition, the  $H$ -girth is related to the minor relation. An other direction of research would be to extend the parameter of  $H$ -girth to other containment relations. One could consider, for a fixed graph  $H$ , the minimum size of an induced subgraph that can be contracted to  $H$ , or the minimum size of a subdivision of  $H$  in a graph. The first one of these parameters is related to induced minors and the second one to topological minors.

As the usual notion of girth appears in various contexts in graph theory, we wonder for which graphs  $H$  the results related to girth can be extended to the  $H$ -girth or to the two aforementioned variants.

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