

Is it easy to regularize a hypergraph with easy links?

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Abstract

A partition of a (hyper)graph is ε -homogeneous if the edge densities between almost all clusters are either at most ε or at least $1 - \varepsilon$. Suppose a 3-graph has the property that the link of every vertex has an ε -homogeneous partition of size $\text{poly}(1/\varepsilon)$. Does this guarantee that the 3-graph also has a small homogeneous partition? Terry and Wolf proved that such a 3-graph has an ε -homogeneous partition of size given by a *wowzer*-type function. Terry recently improved this to a double exponential bound, and conjectured that this bound is tight. Our first result in this paper disproves this conjecture by giving an improved (single) exponential bound, which is best possible. We further obtain an analogous result for k -graphs of all uniformities $k \geq 3$.

The above problem is part of a much broader programme which seeks to understand the conditions under which a (hyper)graph has small ε -regular partitions. While this problem is fairly well understood for graphs, the situation is (as always) much more involved already for 3-graphs. For example, it is natural to ask if one can strengthen our first result by only requiring each link to have ε -regular partitions of size $\text{poly}(1/\varepsilon)$. Our second result shows that surprisingly the answer is ‘no’, namely, a 3-graph might only have regular partitions of tower-type size, even though the link of every vertex has an ε -regular partition of polynomial size.

1 Introduction

Many important questions in extremal combinatorics are of a “local-to-global” nature: given local information about a certain discrete object, can we deduce something about its global structure? For example, extremal statements such as Turán’s theorem [43] or the Brown–Erdős–Sós conjecture [6] assert that if a (hyper)graph has no local portion that is too dense, then one can deduce a stronger bound on its global density.

When dealing with hypergraphs, a natural type of local condition that one can impose concerns the *links* of vertices. Here, given a k -uniform hypergraph H and a vertex $v \in V(H)$, the link $L(v)$ of v is the $(k-1)$ -uniform hypergraph on vertex set $V(H) \setminus \{v\}$ and edge set $\{S : S \cup \{v\} \in E(H)\}$. The collection of all links $\{L(v) : v \in V(H)\}$ provide a local view of the hypergraph H , and it is natural to ask which global properties can be deduced from this set of local views.

There are a number of well-known results and problems along these lines. For example, a famous result of Garland [22], which is critical to the study of high-dimensional expanders (see e.g. the survey [30]), roughly states that if all links are good spectral expanders, then the entire hypergraph is a good expander; see [30, Theorem 2.5] for the precise statement. In Turán theory, a statement of

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this type is given by a famous conjecture attributed to Erdős and Sós (see [21, Conjecture 1]), which states that if all links of a 3-uniform hypergraph are bipartite, then the hypergraph has edge density at most $\frac{1}{4}$. In Ramsey theory, a recent result of Fox and He [14] essentially completely resolves the question of what global information on the independence number of a 3-uniform hypergraph (henceforth 3-graph) can be deduced from the local information of forbidden configurations within its links.

In this paper, we study analogous questions that arise in the theory of graph and hypergraph regularity. A bipartite graph with parts A, B is said to be ε -regular if for all $X \subseteq A, Y \subseteq B$ with $|X| \geq \varepsilon|A|, |Y| \geq \varepsilon|B|$ it holds that $|d(X, Y) - d(A, B)| \leq \varepsilon$, where $d(X, Y) := e(X, Y)/(|X||Y|)$ denotes the edge density. The famous regularity lemma of Szemerédi [35] asserts that every graph has a vertex partition into parts V_1, \dots, V_k such that all but an ε -fraction of pairs of parts (V_i, V_j) define an ε -regular bipartite graph, and such that $k \leq K(\varepsilon)$ for some constant $K(\varepsilon)$ depending only on ε ; such a partition is called an ε -regular partition of size k . While Szemerédi's regularity lemma is of extraordinary importance in graph theory, theoretical computer science, number theory, and other areas of mathematics, its applicability is often limited by the terrible quantitative bounds it produces. Indeed, Szemerédi's proof showed that $K(\varepsilon)$ is at most a tower-type function¹ of $1/\varepsilon$, and a famous construction of Gowers [23] demonstrates that such tower-type bounds are necessary in the worst case. As such, there is a great deal of interest in proving more reasonable quantitative bounds on $K(\varepsilon)$ if one assumes that G has certain extra structure. Such assumptions can be global in nature (such as assuming that G is defined by semi-algebraic relations of bounded complexity [7, 16, 17]) or local in nature (such as assuming that G forbids a fixed induced bipartite pattern [2, 8, 18, 29]). In both of these cases, one can obtain an ε -regular partition with only $\text{poly}(1/\varepsilon)$ parts, a substantial improvement over the tower-type bound that is necessary without such assumptions. In this paper we focus on questions of this type in the setting of (hyper)graphs, but it is worth noting that similar questions have recently been studied in other areas such as arithmetic regularity in groups [11, 36, 40, 41].

In hypergraphs, the most natural extension of the notion of ε -regularity is now termed *weak ε -regularity*. We say that a tripartite 3-graph with parts A, B, C is weakly ε -regular if for all $X \subseteq A, Y \subseteq B, Z \subseteq C$ with $|X| \geq \varepsilon|A|, |Y| \geq \varepsilon|B|, |Z| \geq \varepsilon|C|$, we have

$$|d(X, Y, Z) - d(A, B, C)| \leq \varepsilon,$$

where $d(X, Y, Z) := e(X, Y, Z)/(|X||Y||Z|)$ denotes the edge density.

Extending Szemerédi's work, Chung [10] proved a regularity lemma for 3-graphs, which states that every 3-graph has a vertex partition into at most $K(\varepsilon)$ parts, such that all but an ε -fraction of the triples of parts define a weakly ε -regular tripartite 3-graph. Her proof again yields tower-type bounds on $K(\varepsilon)$, and it is easy to embed Gowers's example into a 3-graph to deduce that such tower-type bounds are necessary in the worst case. We remark that Chung's notion is now called *weak regularity* because it is too weak to be of use in most applications of the regularity method, such as the proof of the removal lemma; for such applications, more refined notions of hypergraph regularity had to be developed, and we refer to [24, 25, 34] for more information.

Following the pattern of local-to-global questions discussed above, it is natural to ask whether weak regularity of a 3-graph can be deduced from regularity of its links, and it is not hard to see that the answer is yes. Indeed, let H be a tripartite 3-graph with parts A, B, C , and suppose that every vertex $c \in C$ has a link² $L(c)$ which is an ε -regular bipartite graph between A and B . Note

¹We recall that the *tower function* is defined by $\text{twr}(0) = 1$ and $\text{twr}(x+1) = 2^{\text{twr}(x)}$ for $x \geq 0$.

²Strictly speaking, the link of a vertex $c \in C$ consists of a bipartite graph between A and B , plus isolated vertices

that for all $X \subseteq A, Y \subseteq B, Z \subseteq C$, we have

$$e_H(X, Y, Z) = \sum_{c \in Z} e_{L(c)}(X, Y),$$

simply by the definition of the link. As a consequence, the edge densities satisfy

$$d_H(X, Y, Z) = \frac{1}{|Z|} \sum_{c \in Z} d_{L(c)}(X, Y).$$

Now suppose that $|X| \geq \varepsilon|A|, |Y| \geq \varepsilon|B|, |Z| \geq \varepsilon|C|$. Then the assumption that $L(c)$ is ε -regular implies that $|d_{L(c)}(X, Y) - d_{L(c)}(A, B)| \leq \varepsilon$. Note too that $\frac{1}{|Z|} \sum_{c \in Z} d_{L(c)}(A, B) = d_H(A, B, Z)$, hence we conclude that

$$|d_H(X, Y, Z) - d_H(A, B, Z)| \leq \varepsilon.$$

If we now assume that every vertex $a \in A$ has an ε -regular link as well, we may run the same argument and deduce that $|d_H(A, B, Z) - d_H(A, B, C)| \leq \varepsilon$.

In other words, we have just proved that if all vertices³ of H have an ε -regular link, then H itself is weakly 2ε -regular. Of course, the utility of the regularity lemma is that it allows us to decompose *any* graph into ε -regular pieces, so the natural next question is as follows: if every vertex-link in H has a small regular partition, does this guarantee that H itself has a small weakly ε -regular partition?

Our first result answers this question very strongly in the negative, even if we require that the links have small regular partitions with a regularity parameter much smaller than ε .

Theorem 1.1. *Let $0 < \delta \leq \varepsilon$ such that ε is sufficiently small. Then for every $n \geq n_0(\delta)$, there is an n -vertex tripartite 3-graph H with the following properties.*

- For all $v \in V(H)$, the link $L_H(v)$ has a δ -regular partition with $O(\delta^{-8})$ parts.
- Every weakly ε -regular equipartition of H has at least $\text{twr}(\Omega(\log \frac{1}{\varepsilon}))$ parts.

In particular, as *every* 3-graph has a weakly ε -regular equipartition of tower-type size, Theorem 1.1 states that having small regular partitions of all links is essentially useless: it provides no extra benefit, in terms of the size of a weakly regular partition, than assuming no such information. We remark that by adapting ideas from [32] one can improve the lower bound to be of the form $\text{twr}(\text{poly}(\frac{1}{\varepsilon}))$; however, as we believe that the important issue is whether there is a sub-tower bound, we decided to stick with a simpler proof that gives only a logarithmic lower bound on the tower height.

However, our other main result is positive, and says that information about regular partitions of the links *is* useful, if we strengthen the notion of regularity. Namely, let us say that a bipartite graph with parts A, B is ε -homogeneous if $d(A, B) \in [0, \varepsilon] \cup [1 - \varepsilon, 1]$. It is easy to verify that homogeneity is a strictly stronger notion than regularity (up to a polynomial change in ε). Homogeneity for k -partite k -graphs is defined analogously; namely, a k -tuple of parts A_1, \dots, A_k is ε -homogeneous if $d(A_1, \dots, A_k) \in [0, \varepsilon] \cup [1 - \varepsilon, 1]$. For convenience, we focus on the k -partite setting, but we remark that this restriction is not essential and can be easily removed (see Remark 1.5 for details). Thus, for a k -partite k -graph H with parts A_1, \dots, A_k , we only consider vertex partitions which respect the

corresponding to every vertex in $C \setminus \{c\}$. But when working in the partite setting, it is more natural to delete these isolated vertices.

³In fact, we did not even need to use this assumption for vertices of B . On the other hand, only assuming that vertices in one part (say C) have regular links does not suffice; indeed, define a 3-graph by having half of the vertices of C be isolated and the other half form an edge with every pair in $A \times B$. This 3-graph is not ε -regular but every vertex in C has an ε -regular link.

partition into A_1, \dots, A_k . Such a partition, consisting of a partition \mathcal{P}_i of A_i for every $i \in [k]$, is said to be ε -homogeneous if the total sum of $|X_1| \cdots |X_k|$ over all k -tuples $(X_1, \dots, X_k) \in \mathcal{P}_1 \times \cdots \times \mathcal{P}_k$ which are not ε -homogeneous is at most $\varepsilon|A_1| \cdots |A_k|$.

Note that it is no longer the case that all graphs or k -graphs have an ε -homogeneous partition of bounded size; for example, a random k -partite k -graph of edge density $\frac{1}{2}$ does not have a $\frac{1}{4}$ -homogeneous partition into any bounded number of parts. However, our second main result demonstrates that if every link has a small homogeneous partition, then so does the hypergraph itself. Before stating this result precisely, we recall some of the history and known results on the question of which graphs and hypergraphs admit small homogeneous partitions.

In the case of graphs, the answer has been well-understood for some time, and it turns out that the key notion is that of having *bounded VC-dimension*. We recall that the VC-dimension of a graph G is the largest integer d such that there exist distinct vertices $v_1, \dots, v_d \in V(G)$ with the property that for all $S \subseteq [d]$, there exists a vertex w_S which is adjacent to $\{v_i : i \in S\}$ and non-adjacent to $\{v_j : j \notin S\}$. Generally, the precise VC-dimension of a graph is not very important, and we are only interested in the property of having *bounded* VC-dimension, i.e. bounded by an absolute constant independent of the order of the graph. The property of having bounded VC-dimension turns out to be a deep and fundamental “low-complexity” notion for graphs, and a large number of works (e.g. [5, 15, 18, 19, 26, 27, 31]) have established that certain difficult problems become much more tractable when restricted to graphs of bounded VC-dimension.

In particular, VC-dimension is intimately connected with regular and homogeneous partitions. Indeed, it is well-known [2, 18, 29] that every graph with bounded VC-dimension has an ε -homogeneous (and hence $\text{poly}(\varepsilon)$ -regular) partition of size $(1/\varepsilon)^{O(1)}$. Moreover, this is an if and only if characterization in two distinct ways: first, a hereditary class of graphs admits homogeneous partitions of (any) bounded size if and only if it has bounded VC-dimension, which in turn happens if and only if it admits small ε -regular partitions (and otherwise tower-type bounds are required); see e.g. [3, 38] for details.

It is natural to ask for extensions of these characterizations to hypergraphs; for example, which classes of hypergraphs admit polynomially-sized regular partitions or polynomially-sized homogeneous partitions? Moreover, as hypergraph regularity is substantially subtler and more involved than graph regularity, there are additional questions that arise, such as characterizing hypergraphs which admit full regularity partitions of sub-wowzer type. For more information on these questions, and for recent progress, see e.g. [38, 39, 42]. In what follows, we focus on the existence and size of homogeneous partitions.

The first progress in this direction was due to Chernikov–Starchenko [8] and to Fox–Pach–Suk [18], who independently introduced a strong notion of bounded VC-dimension for hypergraphs, and proved that such hypergraphs admit ε -homogeneous partitions of size $\text{poly}(1/\varepsilon)$. More recently, Terry [38, Theorem 1.16] proved that this is an if and only if characterization in uniformity 3: a class of 3-graphs has bounded VC-dimension in this sense if and only if it admits polynomially-sized homogeneous partitions. However, in contrast to the graph case, the class of hypergraphs admitting homogeneous partitions of (some) bounded size is actually larger: it suffices for all links to have bounded VC-dimension. To state this precisely, we introduce the following definition [42].

Definition 1.2. Let $k \geq 3$ and let H be a k -graph. For distinct vertices $v_1, \dots, v_{k-2} \in V(H)$, their *link* $L(v_1, \dots, v_{k-2})$ is the graph on $V(H) \setminus \{v_1, \dots, v_{k-2}\}$ with edge set $\{xy : xyv_1 \dots v_{k-2} \in E(H)\}$. The *slicewise VC-dimension*⁴ of H is defined as the maximum VC-dimension of a link $L(v_1, \dots, v_{k-2})$ over all $v_1, \dots, v_{k-2} \in V(H)$.

⁴In this context, “slice” is a synonym for “link”. In [9], this quantity is called the *VC₁-dimension* of H .

That is, H has bounded slicewise VC-dimension if and only if all of its links have bounded VC-dimension. Chernikov and Towsner [9] proved that if H has bounded slicewise VC-dimension, then H admits an ε -homogeneous partition of bounded size (and in the case $k = 3$, this result was independently proved by Terry and Wolf [42]). Moreover, bounded slicewise VC-dimension turns out to be an if and only if characterization for when a hypergraph admits homogeneous partitions (see [42, Theorem 2.34] or [9, Theorem 7.1]) of any bounded size. The results of [9, 42], however, give very weak quantitative information on the number of parts in the resulting homogeneous partition: Chernikov and Towsner use infinitary techniques that give no bound at all, and Terry and Wolf use the hypergraph regularity lemma, and thus obtain wowzer-type bounds on the number of parts in the homogeneous partition of H .

These bounds were substantially improved by Terry, who gave a double-exponential upper bound [37, Theorem 1.4] in the case $k = 3$. Moreover, Terry proved a single-exponential lower bound [38, Theorem 6.8]; more precisely, she constructed a 3-graph with bounded slicewise VC-dimension which has no ε -homogeneous partitions with fewer than $2^{(1/\varepsilon)^{\Omega(1)}}$ parts. Terry writes that the main problem left open by her work is to close the gap between the single-exponential and double-exponential bounds, and she conjectured [37, 38] that the double-exponential upper bound is best possible.

Our second main theorem disproves Terry's conjecture, showing that the single-exponential bound is the truth.

Theorem 1.3. *Let H be a k -partite k -graph with bounded slicewise VC-dimension, and let $\varepsilon > 0$. Then H has an ε -homogeneous equipartition into $2^{(1/\varepsilon)^{O(1)}}$ parts.*

In addition to providing optimal bounds for this problem, Theorem 1.3 also gives a short and much simpler proof of the result of [9, 37, 42] that bounded slicewise VC-dimension implies the existence of homogeneous partitions.

In fact, we deduce Theorem 1.3 from the following result, which follows the theme introduced in Theorem 1.1; it states that if all links in H have homogeneous partitions of size r , then H itself has a homogeneous partition of size exponential in r . This immediately implies Theorem 1.3 since, as discussed above, all graphs of bounded VC-dimension have homogeneous partitions of polynomial size. Moreover, it nicely complements Theorem 1.1: knowing that all links have small regular partitions is essentially useless for finding a regular partition of H , but knowing that all links have small homogeneous partitions does yield a small homogeneous partition of H .

Theorem 1.4. *Let $\varepsilon \in (0, \frac{1}{2})$, let H be a k -partite k -graph with all parts of size n , and suppose that for all $v_1, \dots, v_{k-2} \in V(H)$ in distinct parts, the bipartite⁵ graph $L(v_1, \dots, v_{k-2})$ has an ε' -homogeneous partition of size at most r , where $\varepsilon' = c_k \varepsilon^6$ for a small enough constant $c_k > 0$ depending only on k . Then H has an ε -homogeneous equipartition into at most $2^{(r/\varepsilon)^{O(1)}}$ parts.*

Remark 1.5. In both Theorems 1.3 and 1.4, the statement for k -partite k -graphs immediately implies the corresponding result for general k -graphs.⁶ Indeed, given a k -graph H , we may pass to its k -partite cover \hat{H} , whose vertex set is k disjoint copies of $V(H)$ and whose edges are all transversal k -tuples corresponding to edges of H . It is easy to see that every link in \hat{H} is either empty or equal to the bipartite cover of a link in H , hence if all links in H have small homogeneous equipartitions, then the same holds for \hat{H} . We may then apply Theorem 1.4 to \hat{H} , obtaining k

⁵In the k -partite setting, when v_1, \dots, v_{k-2} come from distinct parts, we again delete the isolated vertices and view $L(v_1, \dots, v_{k-2})$ as a bipartite graph between the two parts not containing any of v_1, \dots, v_{k-2} .

⁶Here, the definition of an ε -homogeneous partition of a (general) k -graph includes k -tuples (X_1, \dots, X_k) where some of the X_i 's are equal; namely, the definition requires the sum of $|X_1| \dots |X_k|$ over all non- ε -homogeneous k -tuples of parts (X_1, \dots, X_k) (including those which repeat parts) to be at most $\varepsilon|V(H)|^k$.

different partitions of $V(H)$, one for each part of $V(\hat{H})$, each with at most $2^{(r/\varepsilon)^{O(1)}}$ parts. We now take the common refinement of these k partitions to obtain a partition of $V(H)$ whose number of parts is $(2^{(r/\varepsilon)^{O(1)}})^k = 2^{(r/\varepsilon)^{O(1)}}$. Finally, it is not hard to check that if the original equipartition of \hat{H} was ε -homogeneous, then the resulting partition of H is $\sqrt{\varepsilon}$ -homogeneous. This is actually an instance of a more general fact (a simple consequence of Markov's inequality), namely that any refinement of an ε -homogeneous partition is itself $\sqrt{\varepsilon}$ -homogeneous (see e.g. [37, Lemma 2.1]).

Remark 1.6. It is natural to ask for a version of Theorem 1.4 where we assume that all links of ℓ -tuples of vertices have small homogeneous partitions, for some $1 \leq \ell \leq k - 2$. However, it is not hard to check that this assumption is weakest for $\ell = k - 2$, in the following sense: If in a k -partite k -graph, the link of every ℓ -tuple has an ε'' -homogeneous partition of size r , then all but $\varepsilon' n^{k-2}$ of the $(k-2)$ -links have an ε' -homogeneous partition of size r , provided that $\varepsilon'' = \text{poly}(\varepsilon')$ is small enough. Indeed, this partition is simply the ε' -homogeneous partition of the link of the first ℓ vertices in the $(k-2)$ -tuple. The reason this works is that if a hypergraph has edge density very close to 0 or 1, then the same holds for the link of almost every vertex, so any given ℓ -tuple extends to only few $(k-2)$ -tuples for which the given partition is not ε' -homogeneous. Finally, our proof of Theorem 1.4 tolerates a small number of $(k-2)$ -tuples without an ε' -homogeneous partition of their link. Indeed, one only needs to adapt the proof of Lemma 2.2. To this end, one changes the definition of an i -good tuple $\mathbf{v} \cup \{x\}$ to require further that the link of \mathbf{v} has an ε' -homogeneous partition. The rest of the proof carries through essentially as is (with slightly different numbers). Summarizing, the analogue of Theorem 1.4 holds for ℓ -links, for any $1 \leq \ell < k - 2$.

1.1 Proof overview

We now briefly sketch the proofs of our main theorems, starting with the upper bound, Theorem 1.4. For this high-level discussion, we restrict our attention to 3-graphs, which already capture the heart of the problem.

Thus, let H be a 3-partite 3-graph with parts A, B, C , each of size n , and assume that the link of every vertex has a small ε -homogeneous equipartition, say of size $r = \text{poly}(1/\varepsilon)$ (the case of general r is no more complicated). It is not hard to show that the refinement of any homogeneous partition is again homogeneous (with only a polynomial loss in the parameters), so a natural approach is to simply take the common refinement of the homogeneous partitions of $L(c)$ over certain carefully chosen $c \in C$. This is essentially the approach taken by Terry [37], who first classifies the vertices in c according to the “structure” of the homogeneous partition of $L(c)$. However, it seems very difficult to follow such an approach without incurring double-exponential bounds: Terry loses one exponential in this classification by structure, and another exponential from needing to take the common refinement of all of these partitions. The key new idea in our approach is to begin with an “intermediate” partition, which is *not* a vertex partition, but rather a partition of $A \times B$ into a collection of (completely unstructured) bipartite graphs. By working with such partitions for much of the proof, we are able to maintain polynomial dependencies almost throughout, and only pay a single exponential at the end to take a common refinement. As discussed above, Terry [38] also proved a single-exponential lower bound for this problem, so this final step is in a sense unavoidable.

Namely, the first step is to partition $A \times B$ into bipartite graphs $E_1 \cup \dots \cup E_t$ with the following property: if (a, b) and (a', b') lie in the same class E_i of this partition, then they have *similar neighborhoods*, in the sense that the number of $c \in C$ such that $(a, b, c) \in E(H)$ but $(a', b', c) \notin E(H)$ (or vice versa) is at most εn . To define this partition, let us first fix some $(a, b) \in A \times B$, and consider the homogeneous partition of $L(a)$. The vertex b lies in some part, say B_i , of this partition. The key observation now is that for almost all $b' \in B_i$, the vertices b and b' have similar neighborhoods

in the graph $L(a)$, simply because they lie in the same part of a homogeneous partition: almost all $c \in C$ have the same edge relation to both b and b' . By the definition of the link $L(a)$, this immediately implies that (a, b) and (a, b') have similar neighborhoods in the sense above. As $|B_i| = n/r = \text{poly}(\varepsilon) \cdot n$, we conclude that there are $\text{poly}(\varepsilon) \cdot n$ choices of b' such that (a, b) and (a, b') have similar neighborhoods. By repeating the same argument, but now looking at the link $L(b')$ and considering the part containing a , we find that there are also $\text{poly}(\varepsilon) \cdot n$ choices of a' such that (a', b') and (a, b') have similar neighborhoods. In total, we find $\text{poly}(\varepsilon) \cdot n^2$ choices of (a', b') which have a similar neighborhood to (a, b) . At this point, it is straightforward to use random sampling to find a partition of (almost all of) $A \times B$ into $t = \text{poly}(1/\varepsilon)$ many bipartite graphs such that in each class (apart from a small exceptional class E_0), all pairs $(a, b), (a', b')$ have similar neighborhoods.

As all pairs in a given part E_i have nearly the same neighborhood in C , we can now partition C into at most 2^t parts according to this information (and this is the only step where we pay an exponential). In this way, we obtain a homogeneous “vertex-edge” partition: we have partitioned C and $A \times B$ into parts, such that for almost all choices of a part in C and a part in $A \times B$, either almost all triples or almost none of the triples defined by these parts are edges of H . To convert this vertex-edge partition into a vertex partition of $A \cup B \cup C$, we simply repeat the argument above twice more, obtaining in turn partitions of $(A, B \times C)$ and of $(B, A \times C)$. Finally, it is not hard to show that the vertex partition of $A \cup B \cup C$ arising in this way is homogeneous, proving Theorem 1.4.

We now turn to discussing the proof of the lower bound, Theorem 1.1. The key idea here is a simple observation about the structure of Gowers’s [23] ingenious tower-type lower bound for Szemerédi’s regularity lemma. Namely, Gowers’s example can be viewed as an overlay of $t = \Theta(\log \frac{1}{\varepsilon})$ many bipartite graphs G_1, \dots, G_t , each of which is itself ε -regular (or, more precisely, has an ε -regular partition into a small number of parts). Nonetheless, these graphs interact in complicated ways, which causes their union to have no small ε -regular partition.

In our proof of Theorem 1.1, we leverage this observation as follows. We place the exact same graphs G_1, \dots, G_t on vertex set $A \cup B$. We also partition C into t parts C_1, \dots, C_t , and define a 3-graph by declaring that the link of each $c \in C_i$ is precisely the graph G_i , for all $1 \leq i \leq t$. By construction, all links of vertices in C have small ε -regular partitions. Moreover, this construction immediately implies that the link of every $a \in A$ is the union of t complete bipartite graphs, namely between $N_{G_i}(a)$ and C_i , for all i ; this structure readily yields a small ε -regular partition of $L(a)$, and the symmetric argument handles links of vertices in B . Finally, by modifying Gowers’s analysis of his construction, we show that the hypergraph H does not have any weakly ε -regular partitions into fewer than $\text{twr}(\Omega(\log \frac{1}{\varepsilon}))$ parts, proving Theorem 1.1.

Paper organization: We prove the upper bound Theorem 1.4 in Section 2, and the lower bound Theorem 1.1 in Section 3. We end in Section 4 with some concluding remarks and three tantalizing open problems, related to analogues of the Erdős–Hajnal conjecture, Rödl’s theorem, and the induced counting lemma. We omit floor and ceiling signs whenever these are not crucial.

2 Proof of Theorem 1.4

In this section we prove Theorem 1.4. Throughout this section, we assume for convenience that the number of vertices n is divisible by quantities determined by the other parameters. All proofs work without this assumption with very minor changes.

We need the following simple lemma, showing that an ε -homogeneous partition of a bipartite graph translates to a partition of almost all vertices on one of the sides so that any two vertices in the same part have almost the same neighborhood. We also require all parts, except for a small

exceptional set, to have the same size. Finally, for technical reasons it is important that we can specify the number of parts; namely, this number should be the same for all applications with the same parameters, rather than only being upper bounded by a function of these parameters.

Lemma 2.1. *Let $\gamma > 0$ and $r \in \mathbb{N}$, and set $q := \lceil (1 - \gamma) \frac{3r}{\gamma} \rceil$. Let G be a bipartite graph with parts X, Y of size n each, and suppose that G has an γ' -homogeneous partition $X = X_1 \cup \dots \cup X_s$ and $Y = Y_1 \cup \dots \cup Y_t$, where $s \leq r$ and $\gamma' := \frac{\gamma^3}{48}$. Then there is a partition $X = X'_0 \cup X'_1 \cup \dots \cup X'_q$ such that*

1. $|X'_1| = \dots = |X'_q|$ and $|X'_0| \leq \gamma n$;
2. for every $i \in [q]$ and $x, x' \in X'_i$, it holds that $|N_Y(x) \Delta N_Y(x')| \leq \gamma n$.

Proof. We say that $i \in [s]$ is *good* if the sum of $|Y_j|$ over $j \in [t]$ for which (X_i, Y_j) is not γ' -homogeneous is at most $\frac{\gamma^2}{16}n$. Otherwise X_i is *bad*. As the given partition is γ' -homogeneous, we get from Markov's inequality that $\sum_{X_i \text{ bad}} |X_i| \leq \frac{\gamma'^2 n^2}{\gamma'^2 n / 16} = \frac{\gamma^2 n^2}{3} = \frac{\gamma}{3}n$. Place all bad sets X_i into the exceptional set X'_0 (which we construct throughout the proof).

Observe that if (X_i, Y_j) is γ' -homogeneous, then the number of triples x, x', y such that $x, x' \in X_i$ and $y \in N_Y(x) \Delta N_Y(x')$ is at most $\gamma'|X_i|^2|Y_j|$. Indeed, if e.g. $d(X_i, Y_j) \geq 1 - \gamma'$ (the other case is symmetric), then the number of triples x, x', y containing a non-edge is at most $\gamma'|X_i|^2|Y_j|$.

Consider a good set X_i . Let \mathcal{T} be the set of triples x, x', y such that $x, x' \in X_i$, $y \in Y$ and $y \in N_Y(x) \Delta N_Y(x')$. By the above and the choice of γ' , we have $|\mathcal{T}| \leq (\frac{\gamma^2}{16} + \gamma')|X_i|^2n \leq \frac{\gamma^2}{12}|X_i|^2n$. Hence, there is $x_i \in X_i$ participating in at most $\frac{\gamma^2}{6}|X_i|n$ triples in \mathcal{T} . This means that the number of $x \in X_i$ with $|N_Y(x) \Delta N_Y(x_i)| \geq \frac{\gamma}{2}n$ is at most $\frac{\gamma}{3}|X_i|$. Move all of such elements x to X'_0 , and for every i , let X''_i denote the remaining elements of X_i . We now have that $|X'_0| \leq \frac{2\gamma}{3}n$. Also, this gives a partition X''_1, \dots, X''_s of $X \setminus X'_0$ such that for every $x \in X''_i$ it holds that $|N_Y(x) \Delta N_Y(x_i)| \leq \frac{\gamma}{2}n$. By the triangle inequality, $|N_Y(x) \Delta N_Y(x')| \leq \gamma n$ for all $x, x' \in X''_i$.

Now set $m := \frac{\gamma n}{3r}$ and split each X''_i into sets of size m and possibly one leftover set of size less than m . Move all leftover sets to X'_0 . Now $|X'_0| \leq \frac{2\gamma}{3}n + ms \leq \gamma n$, using $s \leq r$. This means that the number of parts of size m disjoint from X'_0 is at least $\frac{(1-\gamma)n}{m} = (1-\gamma)\frac{3r}{\gamma}$, and hence at least q . Move additional parts to X'_0 until the number of parts disjoint from X'_0 is exactly q . This gives the desired partition X'_0, X'_1, \dots, X'_q . Note that $|X'_0| = n - qm \leq n - (1-\gamma)\frac{3r}{\gamma} \cdot m = \gamma n$, as required. ■

The next lemma is the key step of the proof, yielding a partition of $A_1 \times \dots \times A_{k-1}$ into $(k-1)$ -partite $(k-1)$ -graphs, with the property that all $(k-1)$ -tuples in the same class have similar neighborhoods in A_k . This is, in a sense, a generalization of Lemma 2.1 to k -graphs, but, as discussed in Section 1.1, the main new insight is to partition $(k-1)$ -tuples of vertices, rather than vertices, in this step of the argument.

Lemma 2.2. *Let $\varepsilon > 0$, let H be a k -partite k -graph with parts A_1, \dots, A_k of size n each, and suppose that for every $(k-2)$ -tuple of vertices v_1, \dots, v_{k-2} in distinct parts, $L(v_1, \dots, v_{k-2})$ has an ε' -homogeneous partition of size at most r , where $\varepsilon' = \frac{1}{48}(\frac{\varepsilon}{6k})^3$. Then there is a partition $A_1 \times \dots \times A_{k-1} = E_0 \cup E_1 \cup \dots \cup E_t$ with $t \leq (r/\varepsilon)^{O(1)}$ such that $|E_0| \leq \varepsilon n^{k-1}$ and such that for every $1 \leq i \leq t$ and every $e, e' \in E_i$, it holds that $|N_{A_k}(e) \Delta N_{A_k}(e')| \leq \varepsilon n$.*

Proof. For each $i \in [k-1]$ and $(k-2)$ -tuple $\mathbf{v} \in \prod_{j \in [k-1] \setminus \{i\}} A_j$, apply Lemma 2.1 to the link of \mathbf{v} (which is a bipartite graph between A_i and A_k) with parameter $\gamma := \frac{\varepsilon}{6k}$ to obtain a partition $A_i = X_0^{(\mathbf{v})} \cup X_1^{(\mathbf{v})} \cup \dots \cup X_q^{(\mathbf{v})}$ such that $q = \lceil (1 - \frac{\varepsilon}{6k}) \frac{18kr}{\varepsilon} \rceil \leq \frac{18kr}{\varepsilon}$, $|X_0^{(\mathbf{v})}| \leq \gamma n$, $|X_1^{(\mathbf{v})}| = \dots = |X_q^{(\mathbf{v})}| \geq$

$\frac{(1-\gamma)n}{q}$, and for every $1 \leq \ell \leq q$ and $x, x' \in X_\ell^{(\mathbf{v})}$ it holds that $|N_{A_k}(\mathbf{v} \cup \{x\}) \Delta N_{A_k}(\mathbf{v} \cup \{x'\})| \leq \gamma n$. Note that due to the statement of Lemma 2.1, the number of parts q does not depend on \mathbf{v} . For $i \in [k-1]$, a tuple $e \in A_1 \times \cdots \times A_{k-1}$ is called *i-bad* if, writing $e = \mathbf{v} \cup \{x\}$ for $\mathbf{v} \in \prod_{j \in [k-1] \setminus \{i\}} A_j$ and $x \in A_i$, we have $x \in X_0^{(\mathbf{v})}$. Otherwise e is *i-good*. Note that there are at most γn^{k-1} *i-bad* tuples.

Next, given two *i-good* $(k-1)$ -tuples $e, e' \in A_1 \times \cdots \times A_{k-1}$, we call them *i-twins* if they arise from the same $\mathbf{v} \in \prod_{j \in [k-1] \setminus \{i\}} A_j$ and the same set $X_\ell^{(\mathbf{v})}$. More precisely, e, e' are *i-twins* if, when writing $e = \mathbf{v} \cup \{x\}, e' = \mathbf{v}' \cup \{x'\}$, we have that $\mathbf{v} = \mathbf{v}'$ and x, x' both lie in the same part $X_\ell^{(\mathbf{v})}$, for some $1 \leq \ell \leq q$. Note that if e, e' are *i-twins* then $|N_{A_k}(e) \Delta N_{A_k}(e')| \leq \gamma n$. Moreover, for each *i-good* tuple e , there are at least $\frac{(1-\gamma)n}{q}$ and at most $\frac{n}{q}$ tuples e' such that e, e' are *i-twins*.

Additionally, let us say that two tuples $e, e_1 \in A_1 \times \cdots \times A_{k-1}$ are *chain twins* if there exists a sequence $e_1, e_2, \dots, e_k = e$ such that e_i, e_{i+1} are *i-twins* for each $1 \leq i \leq k-1$. Note that the choice of e_2, \dots, e_{k-1} is determined by e and e_1 , as e_i is obtained from e_1 by changing all coordinates $1, \dots, i-1$ to be as in e . Next, let us say that a tuple $e \in A_1 \times \cdots \times A_{k-1}$ is *excellent* if there are at least $(\frac{\gamma n}{q})^{k-1}$ choices of $e_1 \in A_1 \times \cdots \times A_{k-1}$ such that e and e_1 are chain twins. Our next claim shows that almost all tuples are excellent.

Claim 2.3. *There are at least $(1 - \frac{\varepsilon}{2})n^{k-1}$ excellent tuples $e \in A_1 \times \cdots \times A_{k-1}$.*

Proof. For the proof, we need to extend our definition of excellent tuples. For $0 \leq i \leq k-1$, we say that $e \in A_1 \times \cdots \times A_{k-1}$ is *i-excellent* if there are at least $(\frac{\gamma n}{q})^i$ choices of $e_1 \in A_1 \times \cdots \times A_{k-1}$ for which there is a sequence $e_1, \dots, e_i, e_{i+1} = e$ where e_j, e_{j+1} are *j-twins* for every $1 \leq j \leq i$. Note that, as above, such a sequence is uniquely determined by e_1 and the value of i . Moreover, in this terminology, an excellent tuple is the same as a $(k-1)$ -excellent tuple.

In order to prove the claim, we will show by induction on i that there are at least $(1 - 3i\gamma)n^{k-1}$ *i-excellent* tuples, for all $0 \leq i \leq k-1$. Note that the $i = k-1$ case suffices to prove the claim, as $1 - 3\gamma(k-1) \geq 1 - \frac{\varepsilon}{2}$. Moreover, the base case $i = 0$ of the induction is trivial, so we now turn to the inductive step.

As such, let $1 \leq i \leq k-1$, and let \mathcal{F} be the set of the $(i-1)$ -excellent tuples. By the induction hypothesis, $|\mathcal{F}| \geq (1 - 3(i-1)\gamma)n^{k-1}$. Let \mathcal{F}' be the set of all $e \in \mathcal{F}$ which are *i-good*. As there are in total at most γn^{k-1} *i-bad* tuples, we have that $|\mathcal{F}'| \geq |\mathcal{F}| - \gamma n^{k-1} \geq (1 - (3i-2)\gamma)n^{k-1}$. Every $e' \in \mathcal{F}'$ is *i-good*, hence has at least $\frac{(1-\gamma)n}{q}$ *i-twins*. Thus, the number of pairs (e, e') where $e' \in \mathcal{F}'$ and e, e' are *i-twins* is at least $|\mathcal{F}'| \cdot \frac{(1-\gamma)n}{q} \geq (1 - (3i-1)\gamma) \cdot \frac{n^k}{q}$. Let \mathcal{G} be the set of all $e \in A_1 \times \cdots \times A_{k-1}$ such that e has at least $\gamma \frac{n}{q}$ *i-twins* $e' \in \mathcal{F}'$. Using that each $e \in A_1 \times \cdots \times A_{k-1}$ has at most $\frac{n}{q}$ *i-twins*, we get

$$|\mathcal{G}| \geq \frac{(1 - (3i-1)\gamma) \cdot \frac{n^k}{q} - \frac{\gamma n^k}{q}}{\frac{n}{q}} = (1 - 3i\gamma)n^{k-1}.$$

To complete the proof of the claim, we show that every $e \in \mathcal{G}$ is *i-excellent*. Indeed, fix any $e \in \mathcal{G}$. Fix any $e' \in \mathcal{F}'$ such that e, e' are *i-twins*; there are at least $\frac{\gamma n}{q}$ choices for e' . As e' is $(i-1)$ -excellent, there are at least $(\frac{\gamma n}{q})^{i-1}$ choices for $e_1, \dots, e_{i-1}, e_i = e' \in A_1 \times \cdots \times A_{k-1}$ such that e_j, e_{j+1} are *j-twins* for every $1 \leq j \leq i-1$. Setting $e_{i+1} := e$, we get that e_j, e_{j+1} are *j-twins* for every $1 \leq j \leq i$. The total number of choices for e_1 is at least $(\frac{\gamma n}{q})^i$, hence e is indeed *i-excellent*. This completes the induction, and hence proves the claim by taking $i = k-1$. \blacksquare

Now let e be an excellent tuple, let e_1 be a chain twin of e , and let e_2, \dots, e_{k-1} be such that,

setting $e_k := e$, we have that e_i, e_{i+1} are i -twins for every $1 \leq i \leq k-1$. By the triangle inequality,

$$|N_{A_k}(e) \Delta N_{A_k}(e_1)| \leq \sum_{i=1}^{k-1} |N_{A_k}(e_{i+1}) \Delta N_{A_k}(e_i)| \leq (k-1)\gamma n \leq \frac{\varepsilon}{2}n.$$

As e is excellent, there are at least $(\frac{\gamma n}{q})^{k-1}$ choices for e_1 in the computation above. Therefore, there are at least $(\frac{\gamma n}{q})^{k-1}$ tuples $e' \in A_1 \times \cdots \times A_{k-1}$ such that $|N_{A_k}(e) \Delta N_{A_k}(e')| \leq \frac{\varepsilon}{2}n$.

Now sample tuples $f_1, \dots, f_t \in A_1 \times \cdots \times A_{k-1}$ uniformly at random and independently, where

$$t := \left(\frac{q}{\gamma}\right)^{k-1} \log\left(\frac{2}{\varepsilon}\right) = \left(\frac{r}{\varepsilon}\right)^{O(1)}.$$

For $i \in [t]$, let E_i be the set of $e \in A_1 \times \cdots \times A_{k-1}$ such that $|N_{A_k}(e) \Delta N_{A_k}(f_i)| \leq \frac{\varepsilon}{2}n$ (if this holds for multiple i , we break ties arbitrarily). Then by the triangle inequality, $|N_{A_k}(e) \Delta N_{A_k}(e')| \leq \varepsilon n$ for every $e, e' \in E_i$.

Moreover, for any fixed $e \in A_1 \times \cdots \times A_{k-1}$, we have that $e \in E_1 \cup \cdots \cup E_t$ if some f_i is a chain twin of e . In particular, if e is excellent, then

$$\mathbb{P}[e \notin E_1 \cup \cdots \cup E_t] \leq \left(1 - \left(\frac{\gamma}{q}\right)^{k-1}\right)^t \leq e^{-(\frac{\gamma}{q})^{k-1}t} \leq \frac{\varepsilon}{2}.$$

Moreover, by Claim 2.3, the number of excellent tuples is at least $(1 - \frac{\varepsilon}{2})n^{k-1}$. As a consequence, by linearity of expectation, we have that

$$\mathbb{E}[|E_1 \cup \cdots \cup E_t|] \geq \sum_{e \text{ excellent}} \mathbb{P}[e \in E_1 \cup \cdots \cup E_t] \geq \sum_{e \text{ excellent}} \left(1 - \frac{\varepsilon}{2}\right)^2 n^{k-1} \geq (1 - \varepsilon)n^{k-1}.$$

Hence, there is an outcome with $|E_1 \cup \cdots \cup E_t| \geq (1 - \varepsilon)n^{k-1}$, and setting $E_0 := (A_1 \times \cdots \times A_{k-1}) \setminus (E_1 \cup \cdots \cup E_t)$ completes the proof of Lemma 2.2. \blacksquare

The following lemma is a sort of converse to Lemma 2.1, stating that if a partition is not homogeneous, then there are many ‘‘witnesses’’ which witness this by having a large symmetric difference of their neighborhoods. It is an easy consequence of [18, Lemma 2.3], but we include a proof for completeness.

Lemma 2.4. *Let H be a k -partite k -graph with parts X_1, \dots, X_k of size n each. For $i \in [k]$, let \mathcal{P}_i be an equipartition of X_i into s parts, and suppose that $(\mathcal{P}_1, \dots, \mathcal{P}_k)$ is not ε -homogeneous. Then there are at least $\varepsilon^2(1 - \varepsilon)\frac{n^{k+1}}{s}$ pairs $e, e' \in X_1 \times \cdots \times X_k$ such that $|e \cap e'| = k-1$, $e \in E(H)$, $e' \notin E(H)$, and $e \Delta e'$ is contained in some part of \mathcal{P}_i for some $i \in [k]$.*

Proof. Fix a k -tuple $(Y_1, \dots, Y_k) \in \mathcal{P}_1 \times \cdots \times \mathcal{P}_k$ with $\varepsilon \leq d(Y_1, \dots, Y_k) \leq 1 - \varepsilon$. We claim that there are at least $\varepsilon(1 - \varepsilon)(\frac{n}{s})^{k+1}$ pairs $e, e' \in Y_1 \times \cdots \times Y_k$ with $|e \cap e'| = k-1$ and $e \in E(H)$, $e' \notin E(H)$. This suffices because the number of non- ε -homogeneous k -tuples (Y_1, \dots, Y_k) is at least εs^k .

To prove the above claim, sample vertices $u_i, v_i \in Y_i$ uniformly at random and independently, for each $i \in [k]$. For $0 \leq i \leq k$, let $e_i := (v_1, \dots, v_i, u_{i+1}, \dots, u_k)$. So $e_0 = (u_1, \dots, u_k)$ and $e_k = (v_1, \dots, v_k)$. Let us say that two k -tuples e, e' disagree if one of them is in $E(H)$ while the other is not. As the random tuples e_0, e_k are independent of one another, the probability that e_0, e_k disagree is at least $2\varepsilon(1 - \varepsilon)$, because $\varepsilon \leq d(Y_1, \dots, Y_k) \leq 1 - \varepsilon$. If this happens, then there is $1 \leq i \leq k$

such e_{i-1}, e_i disagree. Note that e_{i-1}, e_i differ only in the i th coordinate. Let t_i be the number of pairs $e, e' \in Y_1 \times \cdots \times Y_k$ such that e, e' differ only in the i th coordinate and $e \in E(H), e' \notin E(H)$. The probability that there exists $1 \leq i \leq k$ such that e_{i-1}, e_i disagree is at most

$$\sum_{i=1}^k \frac{2t_i}{|Y_1| \cdots |Y_k| \cdot |Y_i|} = \sum_{i=1}^k \frac{2t_i}{(n/s)^{k+1}}.$$

On the other hand, as explained above, this probability is at least $2\varepsilon(1-\varepsilon)$. It follows that $\sum_{i=1}^k t_i \geq \varepsilon(1-\varepsilon)(\frac{n}{s})^{k+1}$, proving our claim. \blacksquare

We now have all the tools needed to prove Theorem 1.4.

Proof of Theorem 1.4. We apply Lemma 2.2 k times with parameter $\frac{\varepsilon^2}{8k}$, each time with a different set X_i ($1 \leq i \leq k$) playing the role of A_k (with the other $k-1$ sets X_j playing the roles of A_1, \dots, A_{k-1}). This gives, for every $i \in [k]$, a partition $\prod_{j \in [k] \setminus \{i\}} X_j = E_0^{(i)} \cup E_1^{(i)} \cup \cdots \cup E_t^{(i)}$ such that $|E_0^{(i)}| \leq \frac{\varepsilon^2}{8k} n^{k-1}$, and such that for every $1 \leq j \leq t$ and $e, e' \in E_j^{(i)}$ it holds that $|N_{X_i}(e) \Delta N_{X_i}(e')| \leq \frac{\varepsilon^2}{8k} n$. Also, $t \leq (r/\varepsilon)^{O(1)}$.

For $i \in [k]$, we define a partition \mathcal{P}_i of X_i as follows. For each $j \in [t]$, fix $e_j^{(i)} \in E_j^{(i)}$ and put $X_j^{(i)} := N_{X_i}(e_j^{(i)})$. Let \mathcal{P}'_i be the common refinement of the sets $X_1^{(i)}, \dots, X_t^{(i)}$. Note that $|\mathcal{P}'_i| \leq 2^t =: p$. Next, we refine \mathcal{P}'_i further to make the parts have the same size. To this end, partition each part of \mathcal{P}'_i into parts of size $m := \frac{\varepsilon^2 n}{8kp}$ and (possibly) an additional leftover part of size less than m . Let $X_0^{(i)}$ be the union of the leftover parts; so $|X_0^{(i)}| \leq \frac{\varepsilon^2}{8k} n$. Partition⁷ $X_0^{(i)}$ into parts of size m . The resulting partition is \mathcal{P}_i . Note that \mathcal{P}_i is an equipartition of size $s := \frac{n}{m} = \frac{8kp}{\varepsilon^2} \leq 2^{(r/\varepsilon)^{O(1)}}$.

We claim that $(\mathcal{P}_1, \dots, \mathcal{P}_k)$ is an ε -homogeneous partition of H . For the sake of contradiction, suppose otherwise. For $i \in [k]$, let T_i be the number of pairs of k -tuples $e, e' \in X_1 \times \cdots \times X_k$ such that there is $(X'_1, \dots, X'_k) \in \mathcal{P}_1 \times \cdots \times \mathcal{P}_k$ with $e, e' \in X'_1 \times \cdots \times X'_k$, $|e \cap e'| = k-1$, $e \Delta e' \subseteq X'_i$, $e \in E(H)$ and $e' \notin E(H)$. As we assumed that $(\mathcal{P}_1, \dots, \mathcal{P}_k)$ is not ε -homogeneous, Lemma 2.4 gives $T_1 + \cdots + T_k \geq \varepsilon^2(1-\varepsilon)\frac{n^{k+1}}{s}$. To get a contradiction, we now upper-bound each T_i . By symmetry, it suffices to consider T_k . Thus, we consider pairs e, e' with $e, e' \in X'_1 \times \cdots \times X'_k$ for some $(X'_1, \dots, X'_k) \in \mathcal{P}_1 \times \cdots \times \mathcal{P}_k$, $|e \cap e'| = k-1$, $e \Delta e' \subseteq X'_k$, $e \in E(H)$ and $e' \notin E(H)$. For $i \in [k-1]$, let x_i be the vertex of e, e' in X_i . The number of choices for e, e' where $(x_1, \dots, x_{k-1}) \in E_0^{(k)}$ is at most $|E_0^{(k)}| \cdot s \cdot (\frac{n}{s})^2 \leq \frac{\varepsilon^2}{8k} \cdot \frac{n^{k+1}}{s}$. Let now $j \in [t]$, and let us consider the case that $(x_1, \dots, x_{k-1}) \in E_j^{(k)}$. Recall that $|N_{X_k}(x_1, \dots, x_{k-1}) \Delta X_j^{(k)}| \leq \frac{\varepsilon^2}{8k} n$, where $X_j^{(k)} = N_{X_k}(e_j^{(k)})$ as above. This holds because (x_1, \dots, x_{k-1}) and $e_j^{(k)}$ both belong to $E_j^{(k)}$, and as $|N_{X_k}(f) \Delta N_{X_k}(f')| \leq \frac{\varepsilon^2}{8k} n$ for any two $f, f' \in E_j^{(k)}$. Also, by the definition of \mathcal{P}_k , each part of \mathcal{P}_k is contained either in $X_0^{(k)}$, or in $X_j^{(k)}$, or in $X_k \setminus X_j^{(k)}$ (because \mathcal{P}'_k is the common refinement of $X_1^{(k)}, \dots, X_t^{(k)}$). We handle these cases separately. First, as $|X_0^{(k)}| \leq \frac{\varepsilon^2}{8k} n$, the number of choices for e, e' where $e \Delta e' \subseteq X_0^{(k)}$ is at most $n^{k-1} \cdot \frac{\varepsilon^2}{8k} n \cdot \frac{n}{s} = \frac{\varepsilon^2}{8k} \cdot \frac{n^{k+1}}{s}$. Now consider the case that $e \Delta e'$ is contained in $X_j^{(k)}$ or in $X_k \setminus X_j^{(k)}$. As $|N_{X_k}(x_1, \dots, x_{k-1}) \Delta X_j^{(k)}| \leq \frac{\varepsilon^2}{8k} n$, the number of vertices $y' \in X_j^{(k)}$ with $(x_1, \dots, x_{k-1}, y') \notin E(H)$ is at most $\frac{\varepsilon^2}{8k} n$. Hence, the number of choices for e, e' where $e \Delta e' \subseteq X_j^{(k)}$ is at most $|E_j^{(k)}| \cdot \frac{\varepsilon^2}{8k} n \cdot \frac{n}{s} = |E_j^{(k)}| \cdot \frac{\varepsilon^2}{8k} \cdot \frac{n^2}{s}$. Similarly, the

⁷Here we use our assumption that n is divisible by quantities determined by the other parameters, and in particular is divisible by m .

number of vertices $y \in X_k \setminus X_j^{(k)}$ with $(x_1, \dots, x_{k-1}, y) \in E(H)$ is at most $\frac{\varepsilon^2}{8k}n$. Hence, the number of choices for e, e' where $e \triangle e' \subseteq X_k \setminus X_j^{(k)}$ is at most $|E_j^{(k)}| \cdot \frac{\varepsilon^2}{8k} \cdot \frac{n^2}{s}$. Collecting all terms, we get that

$$T_k \leq 2 \cdot \frac{\varepsilon^2}{8k} \cdot \frac{n^{k+1}}{s} + 2 \cdot \frac{\varepsilon^2}{8k} \cdot \frac{n^2}{s} \sum_{j=1}^t |E_j^{(k)}| \leq \frac{\varepsilon^2}{2k} \cdot \frac{n^{k+1}}{s}.$$

By symmetry, $T_1, \dots, T_{k-1} \leq \frac{\varepsilon^2}{2k} \cdot \frac{n^{k+1}}{s}$ as well, so $T_1 + \dots + T_k < \varepsilon^2(1 - \varepsilon) \frac{n^{k+1}}{s}$, a contradiction. ■

3 Proof of Theorem 1.1

Throughout this section, we fix $0 < \delta \leq \varepsilon$ with ε smaller than some implicit absolute constant, and also assume wherever needed that $n \geq n_0(\delta)$ is large enough. We will use the following lemma, which essentially appears in [23].

Lemma 3.1. *Let m, M be integers with $M \leq \max(e^{m/16}, 2)$. Then there are partitions $(X_i, Y_i)_{i=1, \dots, m}$ of $[M]$ having the following properties:*

1. *If $M \geq \log^3(8m^2)$, then $|X_i|, |Y_i| = \frac{M}{2} \pm M^{2/3}$ for every $1 \leq i \leq m$, and $|X_i \cap X_{i'}|, |X_i \cap Y_{i'}|, |Y_i \cap Y_{i'}| = \frac{M}{4} \pm M^{2/3}$ for every pair $1 \leq i \neq i' \leq m$.*
2. *Let $\zeta \leq 1/2$ and $\eta, \varepsilon > 0$ such that $(1 - \eta)(1 - 4\varepsilon) \geq 1 - \zeta + \zeta^2$. Let $\lambda_1, \dots, \lambda_M \in \mathbb{R}_{\geq 0}$ with $\sum_{i=1}^M \lambda_i = 1$, and suppose that $\lambda_i \leq 1 - \zeta$ for every $i \in [M]$. Then there are at least ηm indices $i \in [m]$ satisfying $\min\left(\sum_{j \in X_i} \lambda_j, \sum_{j \in Y_i} \lambda_j\right) > \varepsilon$.*

Item 2 of Lemma 3.1 follows immediately by combining Lemmas 3 and 5 in [23]. The desired partitions (X_i, Y_i) are chosen uniformly at random, and Item 1 is a simple property of random partitions. For completeness, we include the proof of Lemma 3.1 in Appendix A.

We now proceed with the proof of Theorem 1.1. We describe the construction used to establish the theorem in the following Section 3.1, and then analyze it in Section 3.2. As in [23], it is convenient to describe the construction as a weighted 3-graph. We will then transform this into an unweighted (“normal”) 3-graph via sampling.

3.1 The construction

We construct a weighted 3-partite 3-graph H with parts A, B, C , each of size n . We set $t := \lfloor \frac{1}{4} \log_7(\frac{1}{\varepsilon}) - 3 \rfloor$ and $s_0 = \lceil 4/\delta^4 \rceil$. Partition C into t equal parts C_1, \dots, C_t .

For an integer m , let $\phi(m) := \max(\lfloor e^{m/16} \rfloor, 2)$, and note that the conclusion of Lemma 3.1 holds for each $M \leq \phi(m)$. We now inductively define a sequence of integers m_0, m_1, \dots, m_t as follows. Set $m_0 = 1$. For each $1 \leq r \leq t$, if $m_{r-1} < s_0$ and $\phi(m_{r-1}) \geq s_0$ then set $m_r := m_{r-1} \cdot s_0$. Otherwise, set $m_r := m_{r-1} \cdot \phi(m_{r-1})$. Note that m_{r-1} divides m_r and $m_r > m_{r-1}$ (using that $\phi(m_{r-1}), s_0 \geq 2$). Also, $\frac{m_r}{m_{r-1}} \leq \phi(m_{r-1})$. To explain this somewhat unusual choice of a sequence, let us remark that we would generally like $m_r = m_{r-1} \cdot \phi(m_{r-1})$, as this enables us to apply Lemma 3.1 while also ensuring that m_r is exponentially larger than m_{r-1} , so as to obtain a tower-type bound in the end. However, if we have the sequence grow exponentially at every step, we may accidentally end up with a vertex whose link only has a δ -regular partition of size exponential in δ . In order to ensure that this doesn’t happen, we make sure to stunt the growth of the sequence at the critical step (around the value s_0),

thus ensuring a polynomial-sized δ -regular partition in all cases. See the proof of Lemma 3.4 for the precise details.

Next, let us identify each of A, B with $[n]$ in order to have an order on these sets. For $0 \leq r \leq t$, let \mathcal{A}_r be the partition of A into m_r equal-sized intervals (with respect to the vertex order), and similarly let \mathcal{B}_r be the partition of B into m_r equal-sized intervals. For each $1 \leq r \leq t$, \mathcal{A}_r refines \mathcal{A}_{r-1} because m_{r-1} divides m_r , and similarly for \mathcal{B}_r and \mathcal{B}_{r-1} .

Now we define 3-partite 3-graphs $H_1, \dots, H_t \subseteq A \times B \times C$. Fix $1 \leq r \leq t$ and let us write $\mathcal{A}_{r-1} = \{A_1, \dots, A_m\}$ and $\mathcal{B}_{r-1} = \{B_1, \dots, B_m\}$, where $m := m_{r-1}$. Put also $M := \frac{m_r}{m_{r-1}} \leq \phi(m_{r-1}) = \phi(m)$. For each $i \in [m]$, let $A_{i,1}, \dots, A_{i,M}$ (resp. $B_{i,1}, \dots, B_{i,M}$) be the parts of \mathcal{A}_r (resp. \mathcal{B}_r) contained in A_i (resp. B_i). Let $(X_i, Y_i)_{i=1}^m$ be the partitions of $[M]$ given by Lemma 3.1 (it is possible to invoke Lemma 3.1 because $M \leq \phi(m)$). Define a bipartite graph $G_r \subseteq A \times B$ as follows: For each pair $1 \leq i, j \leq m$, put into G_r all edges in $(\bigcup_{k \in X_j} A_{i,k}) \times (\bigcup_{k \in Y_i} B_{j,k})$ and $(\bigcup_{k \in Y_j} A_{i,k}) \times (\bigcup_{k \in X_i} B_{j,k})$. Now let $H_r = \{e \cup \{v\} : e \in E(G_r), v \in C_r\} = G_r \times C_r$. This completes the definition of H_r . Finally, let H be the weighted 3-graph $H := \sum_{r=1}^t 2^{-r} H_r$. Note that, as $\sum_{r=1}^t 2^{-r} \leq 1$, every edge of H has weight in $[0, 1]$.

For most of the proof, we shall work with the weighted 3-graph H . Consequently, we need to introduce the weighted analogues of the basic notions of link, density, and regularity. For $v \in A$, the link $L_H(v)$ is defined as the weighted graph on $B \times C$ where $e \in B \times C$ has weight $H(e \cup \{v\})$. The link of a vertex in B or C is defined analogously. For $A' \subseteq A, B' \subseteq B, C' \subseteq C$, the density of (A', B', C') is defined as $d_H(A', B', C') = \frac{1}{|A'||B'||C'|} \sum_{e \in A' \times B' \times C'} H(e)$. Weak regularity for weighted 3-graphs is defined analogously to the unweighted case.

3.2 The analysis

Throughout this section, we use the same notation as in Section 3.1. We begin with the following lemma, showing that if m_{r-1} is large enough, then the graph G_r is δ -regular.

Lemma 3.2. *Let $1 \leq r \leq t$ such that $m_{r-1} \geq s_0$. Then the graph G_r is δ -regular.*

For the proof of Lemma 3.2, we need the following fact from [1].

Lemma 3.3 ([1, Lemma 3.2]). *Let G be a bipartite graph with parts A, B of size n each. Let d be the density of G and let $2n^{-1/4} < \delta < \frac{1}{16}$. Suppose that*

1. *For all but at most $\frac{1}{8}\delta^4 n$ of the vertices $x \in B$, it holds that $|d_G(x) - dn| \leq \delta^4 n$;*
2. *For every $B' \subseteq B$ with $|B'| \geq \delta n$, it holds that $\sum_{x,y \in B'} (|N_G(x) \cap N_G(y)| - d^2 n) < \frac{\delta^3}{2} n |B'|^2$.*

Then G is δ -regular.

Proof of Lemma 3.2. We will show that Conditions 1–2 in Lemma 3.3 are satisfied. As in Section 3.1, write $m := m_{r-1}$, $M := \frac{m_r}{m_{r-1}}$, $\mathcal{A}_{r-1} = \{A_1, \dots, A_m\}$ and $\mathcal{B}_{r-1} = \{B_1, \dots, B_m\}$, and for each $i \in [m]$ let $A_{i,1}, \dots, A_{i,M}$ (resp. $B_{i,1}, \dots, B_{i,M}$) be the parts of \mathcal{A}_r (resp. \mathcal{B}_r) contained in A_i (resp. B_i). Let also $(X_i, Y_i)_{i=1}^m$ be the partitions of $[M]$ given by Lemma 3.1. Note that by the assumption of Lemma 3.2, we have $m \geq s_0$ and therefore $M = \phi(m) = \lfloor e^{m/16} \rfloor \geq e^{\Omega(s_0)}$. This also implies that $M \geq \log^3(8m^2)$ (as we assumed that ε is at most some absolute constant, hence s_0 is at least some large constant), so we may apply Item 1 of Lemma 3.1.

First, fix any $x \in B$ and let us consider the degree of x in G_r . Let $j \in [m]$ such that $x \in B_j$. Fix any $1 \leq i \leq m$ and consider the edges between x and A_i . For convenience, set $A_i^{(1)} = \bigcup_{k \in X_j} A_{i,k}$,

$A_i^{(2)} = \bigcup_{k \in Y_j} A_{i,k}$, $B_j^{(1)} = \bigcup_{k \in X_i} B_{j,k}$, $B_j^{(2)} = \bigcup_{k \in Y_i} B_{j,k}$. By definition, G_r has all edges in $A_i^{(1)} \times B_j^{(1)}$ and $A_i^{(2)} \times B_j^{(2)}$ and no other edges between A_i and B_j . By Item 1 of Lemma 3.1, $|X_i|, |Y_i|, |X_j|, |Y_j| = \frac{M}{2} \pm M^{2/3}$. This means that each of the sets $A_i^{(1)}, A_i^{(2)}$ has size $(\frac{1}{2} \pm M^{-1/3})|A_i|$. Therefore, the number of edges between x and A_i is $(\frac{1}{2} \pm M^{-1/3})|A_i|$. As this is true for every $1 \leq i \leq m$, it follows that $d_{G_r}(x) = (\frac{1}{2} \pm M^{-1/3})n = (\frac{1}{2} \pm \frac{\delta^4}{2})n$, using that $M \geq e^{\Omega(s_0)}$. It follows that the density d of G_r is $\frac{1}{2} \pm \frac{\delta^4}{2}$, and that for every $x \in B$ we have $|d_G(x) - dn| \leq \delta^4 n$.

Now we consider Item 2 in Lemma 3.3. Fix any $B' \subseteq B$ with $|B'| \geq \delta n$. For convenience, put $f(x, y) := |N_{G_r}(x) \cap N_{G_r}(y)| - d^2 n$ for $x, y \in B'$, and let $S := \sum_{x, y \in B'} f(x, y)$. The pairs x, y belonging to the same part of \mathcal{B}_{r-1} contribute at most $|B'| \cdot \frac{n}{m} \cdot n = |B'| \frac{n^2}{m} \leq \frac{\delta^3}{4} n |B'|^2$ to S , using that $m \geq s_0$ and $|B'| \geq \delta n$. Now consider the pairs x, y belonging to different parts of \mathcal{B}_{r-1} . So fix $1 \leq j \neq j' \leq m$ such that $x \in B_j, y \in B_{j'}$. Fix any $1 \leq i \leq m$. As before, put $B_j^{(1)} = \bigcup_{k \in X_i} B_{j,k}$, $B_j^{(2)} = \bigcup_{k \in Y_i} B_{j,k}$ and similarly $B_{j'}^{(1)} = \bigcup_{k \in X_i} B_{j',k}$, $B_{j'}^{(2)} = \bigcup_{k \in Y_i} B_{j',k}$. Let $a, a' \in \{1, 2\}$ such that $x \in B_j^{(a)}$ and $y \in B_{j'}^{(a')}$. By the definition of G_r , the common neighborhood of x, y in A_i is $\bigcup_{k \in Z} A_{i,k}$, where

$$Z := \begin{cases} X_i \cap X_{i'} & a = 1, a' = 1, \\ X_i \cap Y_{i'} & a = 1, a' = 2, \\ Y_i \cap X_{i'} & a = 2, a' = 1, \\ Y_i \cap Y_{i'} & a = 2, a' = 2. \end{cases}$$

By Item 1 of Lemma 3.1, in all cases we have $|Z| = \frac{M}{4} \pm M^{2/3}$. This means that the common neighborhood of x, y in A_i has size $(\frac{1}{4} \pm M^{-1/3})|A_i|$. Summing over all $1 \leq i \leq m$, we get that $|N_{G_r}(x) \cap N_{G_r}(y)| \leq (\frac{1}{4} + M^{-1/3})n$ and therefore $f(x, y) \leq (\frac{1}{4} + M^{-1/3})n - (\frac{1}{2} - M^{-1/3})^2 n \leq \frac{\delta^3}{4} n$, using that $M \geq e^{\Omega(s_0)}$. It follows that $S \leq \frac{\delta^3}{4} n |B'|^2 + \frac{\delta^3}{4} n |B'|^2 = \frac{\delta^3}{2} n |B'|^2$. Hence, both items of Lemma 3.3 hold, implying that G_r is δ -regular. ■

Given Lemma 3.2, it is now straightforward to show that all links in H have small δ -regular partitions.

Lemma 3.4. *For every $v \in V(H)$, the link $L_H(v)$ of v has a δ -regular partition of size $O(\delta^{-8})$.*

Proof. Suppose first that $v \in C$, and let $1 \leq r \leq t$ such that $v \in C_r$. Note that $L_H(v) = 2^{-r} \cdot G_r$. We consider two cases. If $m_{r-1} \geq s_0$ then by Lemma 3.2, G_r , and hence also $L_H(v) = 2^{-r} \cdot G_r$, is δ -regular, meaning that (A, B) is a (trivial) δ -regular partition of $L_H(v)$. Now suppose that $m_{r-1} < s_0$. Then, by the definition of the sequence m_0, \dots, m_t , we have $m_r \leq m_{r-1} \cdot s_0 \leq s_0^2$ (it is here that we crucially use the definition of the sequence, making sure that m_r is not exponentially larger than s_0). Thus, the partitions $\mathcal{A}_r, \mathcal{B}_r$ have size at most $s_0^2 \leq 17/\delta^8$. Observe that for each $A' \in \mathcal{A}_r, B' \in \mathcal{B}_r$, (A', B', C_r) is a complete or empty 3-partite 3-graph. This means that in H , either all edges in (A', B', C_r) have weight 2^{-r} , or all such edges have weight 0. Hence, $(\mathcal{A}_r, \mathcal{B}_r)$ is a δ -regular partition of $L_H(v)$.

Next, suppose that $v \in A \cup B$. By symmetry, it suffices to handle the case that $v \in A$. For $1 \leq r \leq t$, let $N_r \subseteq B$ denote the neighborhood of v in the graph G_r . By the definition of H_r and H , all edges in $N_r \times C_r$ have weight 2^{-r} in $L_H(v)$, while all edges in $(B \setminus N_r) \times C_r$ have weight 0 in $L_H(v)$. Let B_1, \dots, B_s be the atoms of the Venn diagram of N_1, \dots, N_t , and note that $s \leq 2^t \leq \frac{1}{\varepsilon} \leq \frac{1}{\delta}$. Then for each $1 \leq i \leq s$ and $1 \leq r \leq t$, all edges in (B_i, C_r) have the same weight in $L_H(v)$. It follows that $(\{B_1, \dots, B_s\}, \{C_1, \dots, C_t\})$ is a δ -regular partition of $L_H(v)$, as required. ■

The final step is showing that H has no weakly ε -regular partitions with fewer than a tower-type number of parts. This step also follows the work of Gowers, so we recall some notation and ideas from [23]. For two sets P, A and a real number β , we write $P \subset_\beta A$ if $|P \cap A| \geq (1 - \beta)|P|$, or equivalently if $|P \setminus A| \leq \beta|P|$. For $\beta = 0$, this is simply the usual subset relation. If P_1, \dots, P_k and A_1, \dots, A_m are two partitions of the same set, we say that the partition $\{P_1, \dots, P_k\}$ β -refines $\{A_1, \dots, A_m\}$ if, for all but at most βk indices $s \in [k]$, there exists some $i \in [m]$ such that $P_s \subset_\beta A_i$. For $\beta = 0$, this is precisely the standard notion of refinement of partitions. We also remark that as long as $\beta < \frac{1}{2}$, there can be no ambiguity: if $P_s \subset_\beta A_i$, then $P_s \not\subset_\beta A_j$ for any $j \neq i$. We will ensure that $\beta < \frac{1}{2}$ in all that follows.

Lemma 3.5. *Let $P_1, \dots, P_k, Q_1, \dots, Q_k, R_1, \dots, R_k$ be partitions of A, B, C , respectively, and suppose that all parts have the same size up to a factor of two. Suppose that all but εk^3 of the triples (P_a, Q_b, R_c) are weakly ε -regular in H . Suppose that $\varepsilon^{1/4} \leq \beta \leq \frac{1}{72}$. If (P_1, \dots, P_k) and (Q_1, \dots, Q_k) β -refine \mathcal{A}_{r-1} and \mathcal{B}_{r-1} , respectively, then they (7β) -refine $\mathcal{A}_r, \mathcal{B}_r$, respectively.*

We stress that in the statement of this lemma, we do not care about how the partition (R_1, \dots, R_k) interacts with the given partition (C_1, \dots, C_t) of C ; all that matters is the fact that (P_1, \dots, P_k) and (Q_1, \dots, Q_k) roughly refine \mathcal{A}_{r-1} and \mathcal{B}_{r-1} .

Proof of Lemma 3.5. We prove the statement for A ; the statement for B is completely analogous. As before, write $\mathcal{A}_{r-1} = \{A_1, \dots, A_m\}$ and $\mathcal{A}_r = \{A_{i,j} : i \in [m], j \in [M]\}$, where $m = m_{r-1}$ and $M := \frac{m_r}{m_{r-1}}$. Fix some P_s , and suppose that $P_s \subset_\beta A_i$ for some $i \in [m]$. Suppose that there is no $j \in [M]$ such that $P_s \subset_{7\beta} A_{i,j}$. For each $j \in [M]$, let $\mu_j := |P_s \cap A_{i,j}| / |P_s|$. Note that

$$\mu := \sum_{j=1}^M \mu_j = \sum_{j=1}^M \frac{|P_s \cap A_{i,j}|}{|P_s|} = \frac{|P_s \cap A_i|}{|P_s|} \geq 1 - \beta,$$

since $P_s \subset_\beta A_i$. Additionally, $\mu_j \leq 1 - 7\beta$ for every $j \in [M]$ by the assumption that there is no j with $P_s \subset_{7\beta} A_{i,j}$. Now set $\lambda_j := \mu_j / \mu$, so that $\sum_{j=1}^M \lambda_j = 1$ and $\lambda_j \leq \frac{\mu_j}{1-\beta} \leq \frac{1-7\beta}{1-\beta} \leq 1 - 6\beta$ for every $j \in [M]$. By Item 2 of Lemma 3.1 with $\zeta := 6\beta$, $\eta := 5\beta$ and 2ε in place of ε (the condition $(1 - \eta)(1 - 8\varepsilon) \geq 1 - \zeta + \zeta^2$ in Lemma 3.1 holds since $\beta \leq \frac{1}{72}$ and $\varepsilon \leq \frac{\beta}{16}$), we get that there is $I \subseteq [m]$ with $|I| \geq 5\beta m$, such that for every $h \in I$ we have

$$\min \left(\sum_{j \in X_h} \lambda_j, \sum_{j \in Y_h} \lambda_j \right) > 2\varepsilon. \quad (3.1)$$

Recall that for at least $(1 - \beta)k$ choices of $u \in [k]$, there is some $h \in [m]$ such that $Q_u \subset_\beta B_h$. We claim that for at least βk of the indices $u \in [k]$, there is $h \in I$ with $Q_u \subset_\beta B_h$. Indeed, suppose otherwise. Then for all but $2\beta k$ of the indices $u \in [k]$, it holds that $|Q_u \cap B_h| \geq (1 - \beta)|Q_u|$ for some $h \in [m] \setminus I$. Also, we have $|Q_u| \leq \frac{2n}{k}$ for every $u \in [k]$ by the assumption that the sizes of the parts Q_1, \dots, Q_k differ by at most a factor of 2. It follows that

$$n = \sum_{u=1}^k |Q_u| \leq 2\beta k \cdot \frac{2n}{k} + \frac{1}{1-\beta} \sum_{h \in [m] \setminus I} |B_h| = 4\beta n + \frac{1}{1-\beta} (m - |I|) \cdot \frac{n}{m} \leq 4\beta n + \frac{1-5\beta}{1-\beta} n < n,$$

a contradiction. This proves our claim.

Now fix any $u \in [k]$ such that $Q_u \subset_{\beta} B_h$ for some $h \in I$ (there are at least βk choices for u by the above). Let $V_X := P_s \cap \bigcup_{j \in X_h} A_{i,j}$, $V_Y := P_s \cap \bigcup_{j \in Y_h} A_{i,j}$, and similarly $W_X := Q_u \cap \bigcup_{j \in X_i} B_{h,j}$, $W_Y := Q_u \cap \bigcup_{j \in Y_i} B_{h,j}$. By construction and (3.1), we have that

$$\min(|V_X|, |V_Y|) = \min \left(\sum_{j \in X_h} \mu_j, \sum_{j \in Y_h} \mu_j \right) \cdot |P_s| \geq \min \left(\sum_{j \in X_h} \lambda_j, \sum_{j \in Y_h} \lambda_j \right) \cdot (1 - \beta) \cdot |P_s| \geq \varepsilon |P_s|.$$

Additionally, W_X and W_Y are disjoint subsets of Q_u with $|W_X \cup W_Y| \geq (1 - \beta)|Q_u|$, hence $\max(|W_X|, |W_Y|) \geq (1 - \beta)|Q_u|/2 \geq \varepsilon|Q_u|$. Suppose that $|W_X| \geq \varepsilon|Q_u|$; the other case is handled symmetrically.

In the graph G_r , we have that (V_X, W_X) is a complete pair, whereas (V_Y, W_X) is empty. This implies that $d_H(V_X, W_X, C_r) = 2^{-r}$ and $d_H(V_Y, W_X, C_r) = 0$. For $\ell \in [k]$, let us say that ℓ is *r-small* if $|R_\ell \cap C_r| < \varepsilon|R_\ell|$, where we recall that R_1, \dots, R_k is the given partition of C . We say that ℓ is *r-large* if it is not *r-small*. We have

$$|C_r| = \sum_{\ell \text{ r-large}} |R_\ell \cap C_r| + \sum_{\ell \text{ r-small}} |R_\ell \cap C_r| < \sum_{\ell \text{ r-large}} |R_\ell \cap C_r| + \sum_{\ell=1}^t \varepsilon|R_\ell| = \sum_{\ell \text{ r-large}} |R_\ell \cap C_r| + \varepsilon|C|.$$

Using that $|C_r| = |C|/t$, we get

$$\sum_{\ell \text{ r-large}} |R_\ell \cap C_r| > \frac{|C|}{t} - \varepsilon|C| \geq \frac{|C|}{2t},$$

where we used that $\varepsilon < 1/(2t)$, which holds because $t \leq \log \frac{1}{\varepsilon}$ and as ε is assumed small enough.

On the other hand, since all parts R_ℓ have the same size up to a factor of two, we have that

$$\sum_{\ell \text{ r-large}} |R_\ell \cap C_r| \leq \sum_{\ell \text{ r-large}} |R_\ell| \leq \frac{2|C|}{k} \cdot |\{\ell \in [k] : \ell \text{ is r-large}\}|.$$

Combining these two inequalities, and using that $\sqrt{\varepsilon} < 1/(4t)$ (again since ε is sufficiently small), we find that

$$|\{\ell \in [k] : \ell \text{ is r-large}\}| \geq \frac{k}{4t} > \sqrt{\varepsilon}k.$$

The final observation is that if ℓ is *r-large*, then the triple (P_s, Q_u, R_ℓ) is not weakly ε -regular. Indeed, we have that

$$d_H(V_X, W_X, R_\ell \cap C_r) - d_H(V_Y, W_X, R_\ell \cap C_r) = 2^{-r} \geq 2^{-t} > \varepsilon,$$

while the sets $V_X, V_Y, W_X, R_\ell \cap C_r$ are subsets of P_s, P_s, Q_u, R_ℓ , respectively, each with at least an ε -fraction of the vertices of the corresponding set.

Recall that this argument worked for each of at least βk choices for u , and at least $\sqrt{\varepsilon}k$ choices for ℓ . Therefore, under the assumption that $P_s \subset_{\beta} A_i$ but there is no j such that $P_s \subset_{7\beta} A_{i,j}$, we find that there are at least $\beta\sqrt{\varepsilon} \cdot k^2$ choices of $(u, \ell) \in [k]^2$ for which the triple (P_s, Q_u, R_ℓ) is not weakly ε -regular. This can happen for at most βk values of s , because the given partitions $(P_i, Q_i, R_i)_{i=1,\dots,k}$ are weakly ε -regular, and as $\beta > \varepsilon^{1/4}$. Also, at most βk choices of s do not satisfy $P_s \subset_{\beta} A_i$ for any i . Hence, we conclude that $\{P_1, \dots, P_k\}$ does indeed (7β) -refine \mathcal{A}_r . \blacksquare

It is now a simple matter to complete the proof of Theorem 1.1.

Proof of Theorem 1.1. Let H be the weighted 3-partite 3-graph defined in Section 3.1. By Lemma 3.4, every link $L_H(v)$ in H has a δ -regular partition of size $O(\delta^{-8})$. Next, we show that every weakly ε -regular equipartition of H has size at least $\text{twr}(\Omega(\log \frac{1}{\varepsilon}))$. So fix such an equipartition, given by partitions $P_1, \dots, P_k, Q_1, \dots, Q_k, R_1, \dots, R_k$ of A, B, C , respectively. Setting $\beta_r := 7^r \varepsilon^{1/4}$, we claim that for $0 \leq r \leq t$, the partitions (P_1, \dots, P_k) and (Q_1, \dots, Q_k) β_r -refine \mathcal{A}_r and \mathcal{B}_r , respectively. Indeed, this follows by induction on r : the base case $r = 0$ is trivial, and the induction step is given by Lemma 3.5. By the choice of $t = \frac{1}{4} \log_7(\frac{1}{\varepsilon}) - 3$, we get that $\beta_r < \frac{1}{72}$ for every r , as required by Lemma 3.5. It is easy to see that if an equipartition \mathcal{P} β -refines an equipartition \mathcal{A} for $\beta < \frac{1}{2}$, then $|\mathcal{P}| \geq |\mathcal{A}|/2$. Hence, $k \geq m_t/2$. Now, observe that $m_t \geq \text{twr}(\Omega(\log \frac{1}{\varepsilon}))$. Indeed, by the definition of the sequence m_0, \dots, m_t , we have $m_r = m_{r-1} \cdot \phi(m_{r-1})$ for all but at most one choice of r . Also, for all but $O(1)$ choices of r , we have $\phi(m_{r-1}) = \lfloor e^{m_{r-1}/16} \rfloor$, meaning that m_r is exponential in m_{r-1} . It is easy to see that this implies that $m_t \geq \text{twr}(\Omega(t))$, as required.

So far we proved Theorem 1.1 for weighted 3-graphs. To obtain a (non-weighted) 3-graph, we let H^* be the 3-partite 3-graph on A, B, C obtained by sampling each edge $e \in A \times B \times C$ with probability $H(e)$, where $H(e)$ is the weight of e in H . Using a Chernoff-type bound (e.g. Lemma A.1), it is easy to see that with high probability the following holds:

- For all $X \subseteq A, Y \subseteq B, Z \subseteq C$ with $|X|, |Y|, |Z| = \Omega(n)$, it holds that $|d_{H^*}(X, Y, Z) - d_H(X, Y, Z)| = o(1)$.
- For all $v \in A$ and $Y \subseteq B, Z \subseteq C$ with $|Y|, |Z| = \Omega(n)$, $|d_{L_{H^*}(v)}(Y, Z) - d_{L_H(v)}(Y, Z)| = o(1)$, and the analogous statement holds for $v \in B$ and $v \in C$.

Consequently, H^* satisfies the assertion of the theorem with ε, δ replaced with $\varepsilon/2, 2\delta$, respectively. ■

4 Concluding remarks

In this section we record three corollaries of our results, none of which we believe to be quantitatively optimal. It would be very interesting to improve the quantitative aspects of any of them. We restrict our attention to 3-graphs, but the corollaries and questions have natural analogues in all higher uniformities.

Proposition 4.1. *For every $D \geq 1$ and $\varepsilon > 0$ there exists $\delta > 0$ such that the following holds. Let H be a 3-partite 3-graph, and suppose that H has slicewise VC-dimension at most D . If H is weakly δ -regular, then $d(H) \in [0, \varepsilon] \cup [1 - \varepsilon, 1]$.*

In other words, if H is both weakly δ -regular and of bounded slicewise VC-dimension, then H must be almost empty or almost complete. Proposition 4.1 follows immediately from Theorem 1.3, as the latter implies that H has a ε -homogeneous partition into at most $2^{\text{poly}(1/\varepsilon)}$ parts. If H is weakly δ -regular for $\delta < 2^{-\text{poly}(1/\varepsilon)}$, then in fact the density of each of these ε -homogeneous triples must be very close to the global density of H , implying that H itself is very sparse or very dense.

This argument shows that we may take δ to depend single-exponentially on ε in Proposition 4.1. However, we conjecture that this bound can be improved to polynomial.

Conjecture 4.2. *We may take $\delta = \varepsilon^{O(1)}$ in Proposition 4.1.*

A useful perspective on Conjecture 4.2 has to do with embedding induced sub(hyper)graphs, which we now discuss. Let B be a bipartite graph. We say that B is a *bipartitely induced subgraph* of

a graph G if G contains an induced subgraph isomorphic to some supergraph of B , obtained by only adding new edges in the two parts of B , without adding or removing any edges across the bipartition. It is not hard to see that G has bounded VC-dimension if and only if there is some fixed B which is not a bipartitely induced subgraph of G .

This immediately implies that a 3-graph H has bounded slicewise VC-dimension if and only if it avoids T as a tripartitely induced subhypergraph, where T is some tripartite 3-graph one of whose three parts is a singleton. In this language, we see that Proposition 4.1 can be viewed as an induced embedding lemma: in contrapositive, it says that if H is weakly δ -regular and has edge density bounded away from 0 and 1, then H contains a tripartitely induced copy of any fixed tripartite T one of whose parts is a singleton. One motivation for Conjecture 4.2 is that most embedding lemmas that one encounters can be proved with polynomial dependencies. Moreover, one could try to prove such an induced embedding lemma by first proving a counting lemma with two-sided error bounds, and then applying inclusion-exclusion. However, an unusual feature of this problem is that this corresponding counting lemma is simply false: it is well-known (see e.g. [13, 28]) that weak δ -regularity is too weak to support a counting lemma (with two-sided error bounds) for any T that is not linear, and hence proving Conjecture 4.2 would require a completely different technique. Additionally, in most settings when one can prove a counting lemma, it holds in any “orientation”: namely, we should be able to embed the three parts of T into the three parts of H according to any bijection $[3] \rightarrow [3]$. However, a simple example shows that this is not true for Proposition 4.1. Namely, consider the 3-partite 3-graph H on parts A, B, C obtained as follows: each vertex $c \in C$ picks uniformly random subsets $A_c \subseteq A, B_c \subseteq B$, and then $E(H) = \{(a, b, c) : c \in C, a \in A_c, b \in B_c\}$. With high probability H is weakly $o(1)$ -regular and has density $\frac{1}{4} + o(1)$. But if we let T be the 3-graph on $\{x, y_1, y_2, z_1, z_2\}$ with edge set $E(T) = \{(x, y_1, z_1), (x, y_2, z_2)\}$, then it is easy to see that H contains no tripartitely induced copy of T for which $x \in C$. This is not a contradiction to Proposition 4.1, as there *are* induced copies of T with $x \in A \cup B$, but this example demonstrates another subtle feature of this unusual induced counting lemma, and shows why proving Conjecture 4.2 may be more challenging than proving other similar-looking induced embedding lemmas.

Another natural statement that follows directly from Theorem 1.3, and which also suggests an avenue for attacking Conjecture 4.2, is the following partite hypergraph analogue of Rödl’s theorem [33] on induced F -free graphs. To make the analogy clearer, we continue using the language of forbidden tripartitely induced subgraphs, rather than discussing bounded slicewise VC-dimension.

Proposition 4.3. *Let T be a tripartite 3-graph one of whose parts is a singleton. For every $\varepsilon > 0$, there exists $\delta > 0$ such that the following holds. If H is a 3-partite 3-graph on parts $V_1 \cup V_2 \cup V_3$, each of size n , and if H contains no tripartitely induced copy of T , then there exist $V'_i \subseteq V_i$ with $|V'_i| \geq \delta n$ such that $d(V'_1, V'_2, V'_3) \in [0, \varepsilon] \cup [1 - \varepsilon, 1]$.*

Indeed, Proposition 4.3 follows immediately from Theorem 1.3, as we may take (V'_1, V'_2, V'_3) to be any ε -homogeneous triple from the ε -homogeneous partition of H . In particular, Theorem 1.3 implies that we may take $\delta \geq 2^{-\text{poly}(1/\varepsilon)}$ in Proposition 4.3. We conjecture that this dependence can also be improved to polynomial.

Conjecture 4.4. *We may take $\delta = \varepsilon^{O(1)}$ in Proposition 4.3.*

Note that Conjecture 4.4 would immediately imply Conjecture 4.2. Moreover, it is an appealing statement for other reasons; for example, Conjecture 4.4 would imply the Erdős–Hajnal conjecture for 3-partite 3-graphs with no tripartitely induced copy of T . That is, assuming Conjecture 4.4, a standard argument (see e.g. [20, Conjecture 7.1]) shows that if H has no tripartitely induced copy of T , then there exist $V''_i \subseteq V_i$ such that $|V''_i| = n^{\Omega(1)}$, and such that the triple (V''_1, V''_2, V''_3) is

either complete or empty. We remark that one must work in this tripartite setting in order to obtain such an Erdős–Hajnal-type result: [12, Theorem 1.2] implies that there exist H with no tripartitely induced copy of T and with no clique or independent set of size greater than $\Theta(\log n)$.

Nonetheless, we are still able to prove an analogue of Rödl’s theorem [33] in the non-partite setting, as follows.

Proposition 4.5. *Let T be a tripartite 3-graph one of whose parts is a singleton. For every $\varepsilon > 0$, there exists $\delta > 0$ such that the following holds. If H is a 3-graph with no tripartitely induced copy of T , then there exists $U \subseteq V(H)$ with $|U| \geq \delta|V(H)|$ such that $d(U) \in [0, \varepsilon] \cup [1 - \varepsilon, 1]$.*

The deduction of Proposition 4.5 is relatively standard, so we only sketch it. First, by Theorem 1.3 and Remark 1.5, we can find an ε -homogeneous partition of H , as the assumption that there is no tripartitely induced copy of T implies that all links have bounded VC-dimension. We now use Turán’s theorem for hypergraphs to pass to a large number of parts containing no non-homogeneous triples, and then apply Ramsey’s theorem for hypergraphs to pass to yet another subset in which either all triples have density at most ε , or all triples have density at least $1 - \varepsilon$. The union of these parts is then the desired set U .

The proof sketched above shows that δ can be taken to depend triple-exponentially on ε (one exponential from the application of Theorem 1.4, then two more from the application of the 3-uniform Ramsey theorem). We are uncertain about the true dependence.

Problem 4.6. *What is the optimal dependence of δ on ε in Proposition 4.5?*

Acknowledgments: Part of this work was conducted while the authors were visiting the SwissMAP research center at Les Diablerets. We thank them for their welcome and for providing an excellent working environment. We also thank Artem Chernikov and the anonymous referees for helpful comments on an earlier version of this paper.

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A Proof of Lemma 3.1

We will need Hoeffding's inequality (see [4, Theorem A.1.4]):

Lemma A.1 (Hoeffding's inequality). *Let $Z \sim \text{Bin}(n, p)$. Then*

$$\mathbb{P}[Z \geq np + t], \mathbb{P}[Z \leq np - t] \leq e^{-2t^2/n}.$$

Proof of Lemma 3.1. We choose each partition (X_i, Y_i) , $1 \leq i \leq m$, randomly, by including each element of $[M]$ into one of the sets X_i, Y_i with probability $\frac{1}{2}$, independently of all other choices. Thus both $|X_i|$ and $|Y_i|$ are distributed as $\text{Bin}(M, \frac{1}{2})$, and in particular $\mathbb{E}[|X_i|] = \mathbb{E}[|Y_i|] = \frac{M}{2}$. By Lemma A.1, the probability that $||X_i| - \frac{M}{2}| \geq M^{2/3}$ is at most $2e^{-2M^{1/3}}$. Similarly, fixing $1 \leq i < i' \leq m$, each of $|X_i \cap X_{i'}|, |X_i \cap Y_{i'}|, |Y_i \cap X_{i'}|, |Y_i \cap Y_{i'}|$ has expected value $\frac{M}{4}$, and by Lemma A.1, the probability that it deviates from its expectation by more than $M^{2/3}$ is at most $2e^{-2M^{1/3}}$. There are $4\binom{m}{2}$ such events (4 per each pair $1 \leq i < i' \leq m$). By taking the union bound over all $1 \leq i \leq m$ (for the first statement) and $1 \leq i < i' \leq m$ (for the second statement), we get that the probability that Item 1 fails is at most $(m + 4\binom{m}{2}) \cdot 2e^{-2M^{1/3}} \leq 2m^2 \cdot 2e^{-2M^{1/3}} \leq \frac{1}{2}$, where the inequality holds if $M \geq \log^3(8m^2)$. Thus, Item 1 holds with probability at least $\frac{1}{2}$.

Now consider Item 2. For distinct $j, j' \in [M]$, let $z_{j,j'}$ be the number of indices i for which j, j' are on the same side of the partition (X_i, Y_i) . Let \mathcal{A} be the event that $z_{j,j'} \leq \frac{3m}{4}$ for all j, j' . We claim that $\mathbb{P}[\mathcal{A}] > \frac{1}{2}$. Indeed, fixing j, j' , we have $z_{j,j'} \sim \text{Bin}(m, \frac{1}{2})$. By Lemma A.1, $\mathbb{P}[z_{j,j'} \geq 3m/4] \leq e^{-2 \cdot (1/4)^2 m} = e^{-m/8}$. By the union bound over j, j' , the probability that \mathcal{A} fails is at most $\binom{M}{2} \cdot e^{-m/8} < \frac{1}{2}$, using that $M \leq e^{m/16}$.

We conclude that with positive probability, Item 1 and \mathcal{A} hold. Now we show that \mathcal{A} implies Item 2. Put $g_i(\lambda) := \left| \sum_{j \in X_i} \lambda_j - \sum_{j \in Y_i} \lambda_j \right|$. We have

$$\begin{aligned} \sum_{i=1}^m g_i(\lambda)^2 &= \sum_{i=1}^m \left[\sum_{j=1}^M \lambda_j^2 + \sum_{j, j' \in \binom{X_i}{2} \cup \binom{Y_i}{2}} 2\lambda_j \lambda_{j'} - \sum_{j \in X_i, j' \in Y_i} 2\lambda_j \lambda_{j'} \right] \\ &= m \sum_{j=1}^M \lambda_j^2 + \sum_{j, j' \in \binom{M}{2}} (4z_{j,j'} - 2m) \lambda_j \lambda_{j'} \leq m \left(\sum_{j=1}^M \lambda_j^2 + \sum_{j, j' \in \binom{M}{2}} \lambda_j \lambda_{j'} \right) \\ &= \frac{m}{2} \left(\sum_{j=1}^M \lambda_j^2 + \left(\sum_{j=1}^M \lambda_j \right)^2 \right) = \frac{m}{2} \left(\sum_{j=1}^M \lambda_j^2 + 1 \right), \end{aligned}$$

where the inequality uses that \mathcal{A} happened. Convexity implies that under the constraints $0 \leq \lambda_j \leq 1 - \zeta$ for every j and $\sum_{j=1}^M \lambda_j = 1$, the function $\sum_{j=1}^M \lambda_j^2$ is maximized when some λ_j equals $1 - \zeta$ and another λ_j equals ζ . Hence, $\sum_{j=1}^M \lambda_j^2 \leq (1 - \zeta)^2 + \zeta^2 = 1 - 2\zeta + 2\zeta^2$. Plugging this into the above, we get that $\sum_{i=1}^m g_i(\lambda)^2 \leq m(1 - \zeta + \zeta^2) \leq m(1 - \eta)(1 - 4\epsilon)$. Hence, the number of $1 \leq i \leq m$ with $g_i(\lambda)^2 \geq 1 - 4\epsilon$ is at most $(1 - \eta)m$. If $g_i(\lambda)^2 < 1 - 4\epsilon$ then $g_i(\lambda) < 1 - 2\epsilon$, which can only happen if $\min(\sum_{j \in X_i} \lambda_j, \sum_{j \in Y_i} \lambda_j) > \epsilon$. This proves that Item 2 in the lemma holds. \blacksquare