



ELSEVIER

Contents lists available at ScienceDirect

Journal of Combinatorial Theory,
Series B

www.elsevier.com/locate/jctb



Unavoidable hypergraphs



Matija Bucić^a, Nemanja Draganić^a, Benny Sudakov^{a,1},
Tuan Tran^{b,2}

^a Department of Mathematics, ETH, Zürich, Switzerland

^b Discrete Mathematics Group, Institute for Basic Science (IBS), Daejeon, Republic of Korea

ARTICLE INFO

Article history:

Received 25 November 2020

Available online xxxx

Keywords:

Unavoidable hypergraphs

Hypergraph Turan numbers

Sunflowers

ABSTRACT

The following very natural problem was raised by Chung and Erdős in the early 80's and has since been repeated a number of times. What is the minimum of the Turán number $ex(n, \mathcal{H})$ among all r -graphs \mathcal{H} with a fixed number of edges? Their actual focus was on an equivalent and perhaps even more natural question which asks what is the largest size of an r -graph that can not be avoided in any r -graph on n vertices and e edges?

In the original paper they resolve this question asymptotically for graphs, for most of the range of e . In a follow-up work Chung and Erdős resolve the 3-uniform case and raise the 4-uniform case as the natural next step. In this paper we make first progress on this problem in over 40 years by asymptotically resolving the 4-uniform case which gives us some indication on how the answer should behave in general.

© 2021 Elsevier Inc. All rights reserved.

E-mail addresses: matija.bucic@math.ethz.ch (M. Bucić), nemanja.draganic@math.ethz.ch (N. Draganić), benjamin.sudakov@math.ethz.ch (B. Sudakov), tuantran@ibs.re.kr (T. Tran).

¹ Research supported in part by SNSF grant 200021_196965.

² This work was supported by the Institute for Basic Science (IBS-R029-Y1).

<https://doi.org/10.1016/j.jctb.2021.06.010>

0095-8956/© 2021 Elsevier Inc. All rights reserved.

1. Introduction

The Turán number $\text{ex}(n, \mathcal{H})$ of an r -graph \mathcal{H} is the maximum number of edges in an r -graph on n vertices which does not contain a copy of \mathcal{F} as a subhypergraph. For ordinary graphs (the case $r = 2$), a rich theory has been developed (see [31]), initiated by the classical Turán's theorem [43] dating back to 1941. The problem of finding the numbers $\text{ex}(n, \mathcal{H})$ when $r > 2$ is notoriously difficult, and exact results are very rare (see surveys [30,32,40,42] and references therein).

The following very natural extremal question was raised by Chung and Erdős [8] almost 40 years ago. What is the minimum possible value of $\text{ex}(n, \mathcal{H})$ among r -graphs \mathcal{H} with a fixed number of edges? The focus of Chung and Erdős was on the equivalent inverse question which is perhaps even more natural. Namely, what is the largest size of an r -graph that we can not avoid in any r -graph on n vertices and e edges? This question was repeated multiple times over the years: it featured in a survey on Turán-type problems [30], in an Erdős open problem collection [7] and more recently in an open problem collection from AIM Workshop on Hypergraph Turán problems [36].

Following Chung and Erdős we call an r -graph \mathcal{H} as above (n, e) -unavoidable, so if every r -graph on n vertices and e edges contains a copy of \mathcal{H} . Their question now becomes to determine the maximum possible number of edges in an (n, e) -unavoidable r -graph. Let us denote the answer by $\text{un}_r(n, e)$. In the graph case, Chung and Erdős determined $\text{un}_2(n, e)$ up to a multiplicative factor for essentially the whole range. In a follow-up paper from 1987, Chung and Erdős [9] studied the 3-uniform case and identified the order of magnitude of $\text{un}_3(n, e)$ for essentially the whole range of e .³ In the same paper Chung and Erdős raise the 4-uniform case as the natural next step since the 3-uniform result fails to give a clear indication on how the answer should behave in general. In the present paper we resolve this question by determining $\text{un}_4(n, e)$ up to a multiplicative factor for essentially the whole range of e .

Theorem 1.1. *The following statements hold.*⁴

- (i) For $1 \leq e \leq n^2$, we have $\text{un}_4(n, e) \approx 1$.
- (ii) For $n^2 \leq e \leq n^3$, we have $\text{un}_4(n, e) \approx \min \left\{ (e/n^2)^{3/4}, (e/n)^{1/3} \right\}$.
- (iii) For $n^3 < e \ll \binom{n}{4}$, we have $\text{un}_4(n, e) \approx \min \left\{ e^{4/3}/n^{10/3}, \frac{e^{1/4} \log n}{\log \left(\binom{n}{4}/e \right)} \right\}$.

The optimal unavoidable hypergraphs, or in other words hypergraphs which minimise the Turán number, turn out to be certain combinations of sunflowers of different types. For this reason, it is essential for our proof of Theorem 1.1 to have a good understanding

³ Their argument unfortunately contains an error: the proof of [9, Lemma 6] is incorrect. We fill this gap in Section 5.

⁴ We stress that for us \ll means smaller by a (small enough) constant factor, see the end of Section 1 for details on the notation.

of the Turán numbers of sunflowers for a wide range of parameters. This turns out to be a well-studied problem in its own right.

1.1. Sunflowers

A family A_1, \dots, A_k of distinct sets is said to be a *sunflower* if there exists a *kernel* C contained in each of the A_i such that the *petals* $A_i \setminus C$ are disjoint. The original term for this concept was “ Δ -system”. The more recent term “sunflower” coined by Deza and Frankl [11] has recently become more prevalent. For $r, k \geq 1$, let $f_r(k)$ denote the smallest natural number with the property that any family of $f_r(k)$ sets of size r contains an (r -uniform) sunflower with k petals. The celebrated Erdős-Rado theorem [17] from 1960 asserts that $f_r(k)$ is finite; in fact Erdős and Rado gave the following bounds:

$$(k - 1)^r \leq f_r(k) \leq (k - 1)^r r! + 1. \tag{1}$$

They conjectured that for a fixed k the upper bound can be improved to $f_r(k) \leq O(k)^r$. Despite significant efforts, a solution to this conjecture remains elusive. The current record is $f_r(k) \leq O(k \log r)^r$, established by Bell, Chueluecha and Warnke [3], by slightly improving the $O(k \log(kr))^r$ bound given in 2019 by Rao [38], both of which are based upon a recent breakthrough on the problem due to Alweiss, Lovett, Wu and Zhang [2].

Some 43 years ago, Duke and Erdős [12] initiated the systematic investigation of a closely related problem. Denote by $Sf_r(t, k)$ the r -uniform sunflower with k petals, and kernel of size t . Duke and Erdős asked for the Turán number of $Sf_r(t, k)$. Over the years this problem has been reiterated several times [7,30] including in a recent collaborative “polymath” project [37]. The case $k = 2$ of the problem has received considerable attention [22,25,27,33,34,41], partly due to its huge impact in discrete geometry [26], communication complexity [39] and quantum computing [5]. Another case that has a rich history [13,15,16,19–21,24] is $t = 0$ (a matching of size k is forbidden); the optimal construction in this case is predicted by the Erdős Matching Conjecture. For fixed r, t and k with $1 \leq t \leq r - 1$ and $k \geq 3$ Frankl and Füredi [23, Conjecture 2.6] give a conjecture for the correct value of $\text{ex}(n, Sf_r(t, k))$ up to lower order terms, based on two natural candidates for near-optimal $Sf_r(t, k)$ -free r -graphs. They verify their conjecture for $r \geq 2t + 3$, but otherwise, with the exception of a few particular small cases, it remains open in general. If we are only interested in asymptotic results the answer of $\text{ex}(n, Sf_r(t, k)) \approx n^{\max\{r-t-1, t\}}$ was determined by Frankl and Füredi [22] and Füredi [29].

Another natural question is what happens if we want to find large sunflowers, in other words if we only fix the uniformity r and “type” of the sunflower, determined by its kernel size t , while allowing k to grow with n . Further motivation for this question is that it is easy to imagine that it could be very useful to know how big a sunflower of a fixed type we are guaranteed to be able to find in an r graph with n vertices and

e -edges. In particular, it is precisely the type of statement we require when studying the unavoidability problem of Chung and Erdős. In the graph case $r = 2$ the question simply asks for the Turán number of a (big) star and the answer is easily seen to be $\text{ex}(n, \text{Sf}_2(1, k)) \approx nk$. In contrast, the 3-uniform case is already non-trivial: Duke and Erdős [12] and Frankl [18] showed $\text{ex}(n, \text{Sf}_3(1, k)) \approx nk^2$ while $\text{ex}(n, \text{Sf}_3(2, k)) \approx n^2k$. Chung [6] even managed to determine the answer in the 3-uniform case up to lower order terms, while Chung and Frankl [10] determined $\text{ex}(n, \text{Sf}_3(1, k))$ precisely for large enough n . Chung and Erdős [9] wrote in their paper that results for such large sunflowers with uniformity higher than 3 are far from satisfactory. Here we make first progress in this direction, by solving asymptotically the 4-uniform case.

Theorem 1.2. *For $2 \leq k \leq n$ we have*

- (i) $\text{ex}(n, \text{Sf}_4(1, k)) \approx k^2n^2$,
- (ii) $\text{ex}(n, \text{Sf}_4(2, k)) \approx k^2n^2$ and
- (iii) $\text{ex}(n, \text{Sf}_4(3, k)) \approx kn^3$.

1.2. General proof strategy

Our proof strategy for determining $f_r(n, e)$ for most of the range is as follows. In order to show an upper bound $f_r(n, e) \leq D$ we need to show there is no r -graph with more than D edges which is contained in every r graph with n vertices and e edges. With this in mind we consider a number of, usually very structured, n -vertex r -graphs on e or more edges, and argue they can not have a common subhypergraph with more than D edges. The hypergraphs we use are often based on Steiner systems or modifications thereof. A major benefit of this approach is that our collection of hypergraphs often imposes major structural restrictions on possible common graphs which have close to D edges as well and tells us where to look for our optimal examples of unavoidable hypergraphs which we need in order to show matching lower bounds, by upper bounding their Turán numbers.

Organisation. In the following section we establish some preliminary results we will need later. In Section 3 we prove Theorem 1.2. In Section 4 we prove the first two parts of Theorem 1.1. In Section 5 we deal with the remaining regime. This section is split into several parts, in Section 5.1 we establish a number of 3-uniform results we will need for the lower bounds, which is proved in Section 5.2. We prove the upper bounds in Section 5.4. Finally, in Section 6 we make some final remarks and give a number of open problems and conjectures.

Notation. A *generalised star* is defined recursively as follows: $St_2(d)$ is the usual star S_d with d leaves, and $St_r(d_1, \dots, d_{r-1})$ is the r -graph in which all edges have a vertex v in common and upon removal of v from every edge we obtain d_1 copies of $St_{r-1}(d_2, \dots, d_{r-1})$.

Let G be an r -graph, and let $S \subseteq V(G)$ such that $1 \leq |S| \leq r - 1$. Then the *link graph*, denoted L_S , is the $(r - |S|)$ -graph on $V(G)$, whose edges are the sets T of size $r - |S|$ such that $S \cup T \in E(G)$. The *codegree* of S in G is defined as the number of edges of G which contain S . If the codegree of S is at least k , we say that S is *k-expanding*. We will refer to the immediate fact that in any k -uniform hypergraph the number of edges times the uniformity equals the sum of degrees over all vertices as the *handshaking lemma*.

For non-negative functions f and g we write either $f \lesssim g$ or $f = O(g)$ to mean there is a constant $C > 0$ such that $f(n) \leq Cg(n)$ for all n , we write $f \gtrsim g$ or $f = \Omega(g)$ to mean there is a constant $c > 0$ such that $f(n) \geq cg(n)$ for all n , we write $f \approx g$ to mean that $f \lesssim g$ and $f \gtrsim g$. To simplify the presentation we write $f \gg g$ or $g \ll f$ to mean that $f \geq Cg$ for a sufficiently large constant C ,⁵ which can be computed by analysing the argument. In particular, in this paper choosing $C = 2^{30}$ would be sufficient for all our arguments. All asymptotics are as $n \rightarrow \infty$ unless specified otherwise.

From now on whenever we say optimal unavoidable graph, we mean it has the largest number of edges up to a constant factor. Throughout the paper we omit floor and ceiling signs whenever they are not crucial, for the sake of clarity of presentation and since they would only, possibly, impact the constant factors.

2. Preliminaries

In this section we collect several simple results, that we use later on. The next two results will provide us with building blocks for examples of hypergraphs which will be useful both for proving lower bounds on Turán numbers of sunflowers needed for Theorem 1.2, as well as to force structure when proving upper bounds in Theorem 1.1. We include proofs for completeness.

Lemma 2.1 (*Partial Steiner Systems*). *Let $k > t > 0$ be fixed integers. For every n sufficiently large, there exists a k -graph $S(t, k, n)$ on n vertices such that every set of vertices of size t is contained in at most one edge, and the number of edges of $S(t, k, n)$ is at least $\Omega(n^t)$.*

Proof. Let X be an arbitrary k -subset of $[n]$. The number of k -sets which intersect X in i elements is $\binom{k}{i} \binom{n-k}{k-i}$. Thus the total number of k -sets which intersect X in at least t elements is $\sum_{i=t}^k \binom{k}{i} \binom{n-k}{k-i}$. It follows that there exists a k -graph G on $[n]$ such that:

- Any two edges of G intersect in at most $t - 1$ elements;
- $|E(G)| \geq \frac{\binom{n}{k}}{\sum_{i=t}^k \binom{k}{i} \binom{n-k}{k-i}} \gtrsim n^t$.

⁵ Note here that we are defining \gg , in a way which is more common in fields outside of combinatorics, namely $f \gg g$ does not mean $g = o(f)$ but is more similar to $g = O(f)$ with the exception that we are allowed to choose the constant in the big O as small as we like, as long as it remains fixed.

This completes the proof. \square

The above result as stated requires k to be fixed, however for certain applications we will want to relax this assumption. The following result is a special case where $t = 2$ and we allow $k \leq \sqrt{n/2}$. Here we say a hypergraph is linear if no two of its edges intersect in more than one vertex.

Lemma 2.2. *For $2 \leq k \leq \sqrt{n/2}$, there exists a linear k -graph on n vertices with at least $n^2/4k^2$ edges.*

Proof. By Chebyshev’s theorem, there is a prime p between $n/2k$ and n/k . Look at the affine plane \mathbb{F}_p^2 , and consider its subset $V = \{(x, y) \in \mathbb{F}_p^2 \mid 0 \leq x \leq k - 1, y \in \mathbb{F}_p\}$. The vertex set of our hypergraph will be V . Note that $|V| < n$. The edges are *partial lines* $L_{(x,y)}$, defined as follows for each $(x, y) \in \mathbb{F}_p^2$:

$$L_{(x,y)} = \{(0, x) + t(1, y) \mid 0 \leq t \leq k - 1\}.$$

Notice that for distinct pairs (x_1, y_1) and (x_2, y_2) the corresponding lines $L_{(x_1,y_1)}$ and $L_{(x_2,y_2)}$ intersect in at most one vertex, so our k -graph is linear, and has $p^2 \geq n^2/4k^2$ edges. \square

The following simple lemma will often come in useful.

Lemma 2.3. *Let G be a graph with at least $2k\ell$ edges and with no star S_k . Then G contains a matching of size ℓ .*

Proof. We find an ℓ -matching M in G as follows. Let $v \in V(G)$ be a non-isolated vertex, and take an arbitrary edge (u, v) incident with v and put it in M . Now delete all edges incident to u and v from G and repeat this procedure. If we found less than ℓ such edges, we deleted at most $2(\ell - 1)k$ edges in G , so there is an edge left which we can add to M . \square

The next auxiliary lemma is a generalisation of [8, Lemma 5] which will come in useful when looking at higher uniformities. We give a different proof, as it illustrates an idea which will be used a lot later on.

Lemma 2.4. *Any graph with n vertices and $e = 6sn \geq 6kn$ edges contains at least $\min\{s, \sqrt{sn/k}\}$ vertex-disjoint copies of the star S_k .*

Proof. Let $t = \min\{s, \sqrt{sn/k}\}$. If there are at least t vertices with degree at least $(t - 1)(k + 1) + k = t(k + 1) - 1$ then we can greedily find t vertex-disjoint copies of S_k . This means that by removing at most $t \cdot n \leq sn$ edges we get a graph with maximum degree less than $t(k + 1)$. Now let us take a maximal collection of vertex-disjoint S_k ’s. Unless

we are done there are at most $(t - 1)(k + 1)$ vertices spanned by these stars, so in total they touch less than $t^2(k + 1)^2 \leq 4t^2k^2 \leq 4sn$ edges. So upon removing them we are left with at least $sn \geq kn$ edges and can find another S_k . \square

3. Turán numbers of sunflowers

In this section we give the proof of Theorem 1.2.

3.1. 3-uniform case

We will need the following 3-uniform results, which were already established by Duke and Erdős [12] and Frankl [18]. We include our, somewhat simpler proofs, for completeness and to illustrate the ideas we will use in the 4-uniform case. There are only two different types of 3-uniform sunflowers, namely $Sf_3(1, k)$ and $Sf_3(2, k)$.

Lemma 3.1. *Let $2 \leq k \ll n$ we have $ex(n, Sf_3(1, k)) \approx k^2n$.*

Proof. For the lower bound, we split $[n]$ into disjoint sets: A of size $n - k \geq n/2$, and B of size k . Let our 3-graph consist of all edges with one vertex in A and two vertices in B . This 3-graph has $\Omega(k^2n)$ edges and is $Sf_3(1, k)$ -free. Indeed, if we can find a copy of $Sf_3(1, k)$ each of its edges contains two vertices in B , one of which is not the common vertex, so it uses at least $k + 1$ vertices of B , which has size k , a contradiction. This shows $ex(n, Sf_3(1, k)) = \Omega(k^2n)$.

For the upper bound, we will show that every 3-graph G with $4k^2n$ edges contains a copy of $Sf_3(1, k)$. Let G be such a 3-graph and suppose towards a contradiction that it does not contain an $Sf_3(1, k)$. For each $v \in V(G)$ let D_v denote the 2-graph on V whose edges are the $2k$ -expanding pairs Y such that $v \cup Y \in E(G)$. D_v does not contain matchings and stars of size k ; if D_v contained a k -matching then v and this matching would make an $Sf_3(1, k)$ in G ; if D_v contained a star of size k then we can greedily extend each edge of the star by a new vertex to obtain an $Sf_3(1, k)$, since the edges are $2k$ -expanding. Using Lemma 2.3 this implies that D_v can have at most $2k^2$ edges. The number of edges of G containing a $2k$ -expanding pair is upper bounded by $\sum_v |D_v| \leq 2k^2n$, so if we delete all such edges we are left with a 3-graph G' with at least $2k^2n$ edges with no $2k$ -expanding pairs of vertices. Now take a vertex v with degree at least $3|E(G')|/n \geq 4k^2$ in G' ; it cannot have a star of size $2k$ in its link graph, as then the pair v and centre of the star would be $2k$ -expanding. Using Lemma 2.3 this means there must be a k -matching in its link graph, which together with v forms an $Sf_3(1, k)$ in G , so we are done. \square

We now proceed to the second type of sunflowers.

Lemma 3.2. *For $2 \leq k \ll n$ we have $ex(n, Sf_3(2, k)) \approx kn^2$.*

Proof. To prove the lower bound, we consider the linear 3-graph $S(2, 3, n)$ on $[n]$ with $\Omega(n^2)$ edges, given by Lemma 2.1. Let G be a union of $k - 1$ random copies of $S(2, 3, n)$, where each copy is obtained by randomly permuting the vertices of $S(2, 3, n)$. Since each pair of vertices lies in at most one edge from each copy of $S(2, 3, n)$, G does not contain a copy of $Sf_3(2, k)$. A fixed triple is chosen with probability $\Omega(1/n)$ in a random copy of $S(2, 3, n)$, independently between our $k - 1$ copies. Thus the probability that a given triple is chosen in one of our $k - 1$ copies is at least $\Omega(k/n)$ so the expected number of chosen triples is $\Omega(kn^2)$, giving $\text{ex}(n, Sf_3(2, k)) = \Omega(kn^2)$.

We now turn to the upper bound. Let G be a 3-graph with kn^2 edges. By averaging, there must exist a pair of vertices belonging to at least k edges, which make a copy of $Sf_3(2, k)$ in G . \square

3.2. 4-uniform case

In this subsection we determine the behaviour of the Turán number of 4-uniform sunflowers, namely we prove Theorem 1.2. We begin with $Sf_4(1, k)$.

Lemma 3.3. *For $2 \leq k \ll n$ we have $\text{ex}(n, Sf_4(1, k)) \approx k^2n^2$.*

Proof. We consider the lower bound first. We split the n vertices into disjoint sets A of size $n - k \geq n/2$ and B of size k . Let G be the 4-graph consisting of edges which have two vertices in each of A and B , so in total G has $\approx k^2n^2$ edges. Note that G is $Sf_4(1, k)$ -free. Indeed, if we can find a copy of $Sf_4(1, k)$ each of its edges contains two vertices in B , one of which is not the common vertex, so it uses at least $k + 1$ vertices of B , which has size k , a contradiction.

For the upper bound, we will show that every 4-graph G with $e \gg k^2n^2$ edges contains a copy of $Sf_4(1, k)$. Let G be such a 4-graph and suppose it does not contain a copy of $Sf_4(1, k)$. For each $v \in V(G)$, let D_v denote the set of $3k$ -expanding triples Y such that $v \cup Y \in E(G)$. So D_v is a 3-graph. If some D_v has at least $e/(2n) \gg k^2n$ edges then by Lemma 3.1 we can find an $Sf_3(1, k)$ in D_v and greedily extend it to an $Sf_4(1, k)$ in G , so we may assume that each D_v has at most $e/(2n)$ edges. The number of edges of G containing a $3k$ -expanding triple is upper bounded by $\sum_v |D_v| \leq e/2$ so if we delete all such edges we are left with a 4-graph G' with at least $e/2$ edges and no $3k$ -expanding triple of vertices.

Now look at pairs of vertices which are $18k^2$ -expanding. Any such pair has no star of size $3k$ in its link graph as that would give a $3k$ -expanding triple, so by Lemma 2.3 it has a matching of size $3k$. If we can find a star of size k formed by the $18k^2$ -expanding pairs, then using the matchings we found in the link graphs we can once again greedily extend it into a copy of $Sf_4(1, k)$. Hence, the total number of $18k^2$ -expanding pairs is at most kn . They can lie in at most $3k^2n^2$ different edges (since the third vertex we can choose in n many ways but the fourth in at most $3k$, because there are no $3k$ -expanding triples). Deleting all such edges from G' we obtain G'' with at least $e/4 \geq 18k^2n^2$ edges,

without $18k^2$ -expanding pairs, which is a contradiction (since by density G'' must have an $18k^2$ -expanding pair). \square

Remark. By induction this easily extends to higher uniformities, giving $\text{ex}(n, Sf_r(1, k)) \approx_r k^2 n^{r-2}$. We now turn to the second type of 4-uniform sunflowers, namely $Sf_4(2, k)$.

Lemma 3.4. For $2 \leq k \ll n$ we have $\text{ex}(n, Sf_4(2, k)) \approx k^2 n^2$.

Proof. We prove a lower bound first. Let us say that a (2-)graph G is *good* if it has at most $2k$ vertices and each of its edges is contained in a copy of K_4 . If we can show that there exists m edge disjoint copies of good graphs G_1, \dots, G_m on the same vertex set $[n]$, with at least $\Theta(n^2 k^2)$ copies of K_4 in total among G_1, \dots, G_m , then we would be done. Indeed, we can construct a 4-graph H on $[n]$ by putting a 4-edge in H for any 4 vertices which induce a copy of K_4 in one of G_1, \dots, G_m ; this 4-graph has at least $\Theta(n^2 k^2)$ edges, and by assumption each vertex pair P in $[n]$ is an edge of at most one graph G_i , and therefore all the 4-edges in H which contain P contain only vertices from G_i of which there are at most $2k$, so no pair can be the centre of a sunflower $Sf_4(2, k)$ which has $2k + 2$ vertices.

Now we show the existence of such G_1, \dots, G_m , for $m = \frac{n^2}{48k^2}$. We choose $2k$ vertices uniformly at random, with repetition from $[n]$ and choose G_1 to be the complete graph on these $2k$ vertices. Suppose we obtained graphs G_1, \dots, G_i , where $i < m$. Choose again a set of uniformly random $2k$ vertices, and choose G_{i+1} to be the complete graph on these vertices from which we remove all the edges in G_1, \dots, G_i and after this we remove all edges not participating in a K_4 .

Notice that for each graph G_i , with $i \in [m]$, the expected number of K_4 's is at least

$$\binom{2k}{4} (1 - 6i \cdot (2k/n)^2) \cdot \frac{1}{2} \geq \Theta(k^4),$$

since probability that 4 randomly sampled vertices are different is at least $1 - 6/n \geq 1/2$ and by a union bound the probability that one of its 6 edges already got chosen in some G_1, \dots, G_i is at most $6i \cdot (2k/n)^2 \leq 1/2$. So the total expected number of K_4 's among G_1, \dots, G_m is by linearity of expectation at least $m \cdot \Theta(k^4) = \Theta(n^2 k^2)$ and we are done.

For the upper bound, there must be a vertex v with degree $\gg k^2 n$ in any graph on $\gg k^2 n^2$ edges, so we can find an $Sf_3(1, k)$ in its link graph, by Lemma 3.1, which together with v forms a copy of $Sf_4(2, k)$. \square

Finally, we deal with the third and last kind, namely $Sf_4(3, k)$.

Lemma 3.5. For $2 \leq k \ll n$ we have $\text{ex}(n, Sf_4(3, k)) \approx kn^3$.

Proof. For the lower bound, we take a 4-graph G which is a union of $k - 1$ random copies of a 4-graph $S(3, 4, n)$ on n vertices with $\Omega(n^3)$ edges, given by Lemma 2.1. A

single triple of vertices lies in at most one edge for each copy so in total in at most $k - 1$ edges; this means there is no $Sf_4(3, k)$ in G . Each fixed quadruple is an edge of G with probability $\Omega(1/n)$, independently between different choices. Thus the probability that a quadruple is chosen in G is at least $\Omega(k/n)$, so the expected number of chosen triples is at least $\Omega(kn^3)$. Therefore, $\text{ex}(n, Sf_4(3, k)) \geq \Omega(kn^3)$.

Let G be a 4-graph on n vertices with kn^3 edges. By the pigeonhole principle there is a triple of vertices belonging to at least k edges, which makes an $Sf_4(3, k)$. This shows $\text{ex}(n, Sf_4(3, k)) \leq kn^3$. \square

The above three results establish Theorem 1.2 when $k \ll n$. This shows that $\text{ex}(n, Sf_4(i, k)) \approx n^4$ for any $k = cn$ for some small enough constant c . The bound in the remaining range, namely when $k \geq cn$, is immediate since $Sf_4(i, k) \subseteq Sf_4(i, k')$ for any $k \leq k'$ in the case of lower bounds and by the trivial bound $\text{ex}(n, Sf_4(i, k)) \leq \binom{n}{4}$ in the case of upper bounds, since we are only interested in bounds up to constant factor.

4. Unavoidability, sparse regimes

In this section we prove Theorem 1.1 for $e \ll n^3$, so for the majority of the first two regimes. We note that in order to prove Theorem 1.1 it is sufficient to prove it for the regimes $e \ll n^2, n^2 \ll e \ll n^3$ and $n^3 \ll e \ll n^4$ since in the remaining cases $e \approx n^2, e \approx n^3$ the bounds of the regimes match (up to a constant factor) and $\text{un}_4(n, e)$ is monotone in e . We begin with the sparsest regime $e \ll n^2$, which is quite simple to handle but illustrates the general approach.

Theorem 4.1. *For $1 \leq e \ll n^2$, we have $\text{un}_4(n, e) = 1$.*

Proof. Starting with the upper bound, let \mathcal{H} be an (n, e) -unavoidable 4-graph where $e \leq cn^2$ for some sufficiently small constant $c > 0$. This means it is contained in any 4-graph on n vertices with at least e edges and our task is to show that it must consist of only one edge. To see this, observe that the 4-graph $S(2, 4, n)$, given by Lemma 2.1, has $\Omega(n^2) \geq e$ edges so it must contain \mathcal{H} as a subgraph. This forces \mathcal{H} to be linear. Similarly, the n -vertex 4-graph which consists of all edges which contain two fixed vertices has $\Omega(n^2) \geq e$ edges so also has \mathcal{H} as a subgraph. This forces any two edges of \mathcal{H} to intersect in at least 2 vertices. Since \mathcal{H} must also be linear this means it can have at most 1 edge.

The lower bound is immediate, since any n -vertex graph with e edges contains an edge ($e \geq 1$) so a single edge graph is (n, e) -unavoidable showing $\text{un}_4(n, e) \geq 1$. \square

We now turn to the upper bound for the second regime.

Theorem 4.2. *For $n^2 \ll e \ll n^3$ we have $\text{un}_4(n, e) \lesssim \min\{(e/n^2)^{3/4}, (e/n)^{1/3}\}$.*

Proof. Let H be an (n, e) -unavoidable 4-graph and let $k = c\sqrt{e}/n$, for $c > 0$ large enough. This means that any n -vertex 4-graph with at least $\Omega(k^2n^2)$ edges must contain H (by choosing c large enough, since $e = n^2k^2/c^2$). Note that the regime bounds imply $1 \ll k \ll \sqrt{n}$. To show the bound it suffices to show that $|E(H)| \leq \min\{2k^{3/2}, (k^2n)^{1/3}\}$. In order to do this, we will consider a number of examples of 4-graphs with more than e edges. Each of them will reveal some additional information on how H should look like and allow us to conclude it can't have more than the claimed number of edges.

- The 4-graph $S(3, 4, n)$, given by Lemma 2.1, has $\Omega(n^3) \geq e$ edges. So it forces H to have no two edges intersecting in three vertices.
- The graph with one special vertex contained in all of $\binom{n-1}{3}$ possible edges implies that all edges of H must contain a common vertex, say v . Let H_3 be the link graph of v (so a 3-graph).
- We take the graph obtained from an n -vertex linear k -graph by taking every 4-subset of every edge in this k -graph as an edge. Note that by Lemma 2.2, since $k \ll \sqrt{n}$, we can find such a 4-graph with $\Omega(k^2n^2)$ edges. This implies that H_3 splits into components of size at most k each, since v is contained in all 4-edges and by construction any two 4-edges which intersect in more than one vertex belong to a single k -edge of our starting linear k -graph.
- Let us take the hypergraph with sets of vertices V_1 of size k and V_2 of size $n - k$ such that we choose any pair of vertices in V_1 and any pair of vertices in V_2 and join them in an edge. This 4-graph has $\Omega(k^2n^2)$ edges. Since every edge has at least two vertices in V_1 this means every edge of H_3 must have at least one vertex in V_1 ; in other words, H_3 has a cover of size at most k , so we fix such a cover and denote it by C . Consequently, H_3 has at most k components.
- Let us take a set S of $2k^2 \ll n$ vertices and split them into k^2 pairs. We join each of these k^2 pairs with every pair among the $n - |S|$ vertices outside of S into a 4-edge. This gives us an n vertex 4-graph with $\Omega(k^2n^2)$ edges, so we must be able to find a copy of H inside it. If v is embedded inside S and we let w be its pair, then v and w belong to each edge of H . We claim this implies that H has at most k edges. To see this observe first that every edge of H_3 contains w , so H_3 only has a single component. By the third point we know it consists of at most k vertices. We further know, by the first point, that if we remove w we get a matching, since otherwise we would have two edges of H which intersect in 3 vertices. This implies H has at most k edges and we are done. So, v must be embedded outside of S . If a vertex of C is in S then it participates in at most one edge of H (since we know each such edge contains the vertex of C , its pair in S and v and there is only one edge of H containing any triple of vertices), so such vertices contribute at most k edges. If we remove these edges from H we know that in the remaining 4-graph upon removing v and the vertex of C from an edge we obtain one of our pairs in S .

Since we removed at most $k \ll \min\{k^{3/2}, (k^2n)^{1/3}\}$ edges, so at most a constant proportion of edges in H , we may assume we started with H in which such edges did not exist. Putting together the observations so far we know that H has a fixed vertex v in all edges, its link graph is the 3-graph H_3 which consists of at most k vertex-disjoint copies of a subhypergraph of $Sf_3(1, k)$, whose centres are vertices of C and whose petals upon removal of the centre vertices give a matching M (our pairing of vertices in S) which in total has size at most k^2 . The following two further examples provide us with one of the desired bounds each.

- Let V_1 induce k disjoint copies of $K_{\sqrt{k}, \sqrt{k}}$, we extend each edge of this graph into 4-edges by adding every possible pair of the remaining vertices (the set of which we denote by V_2). Since $|V_1| = 2k^{3/2} \ll n$ if we set $|V_2| = n - |V_1|$ this 4-graph will have n vertices and $\Omega(k^2n^2)$ edges, so contains H . Let us consider the edges of M containing a vertex embedded in V_1 . There can be at most $2k^{3/2}$ such edges since $|V_1| = 2k^{3/2}$, so upon deleting all corresponding edges of H we are left with a subgraph of H in which v and C got embedded into V_1 (or we are left with an empty graph). But this implies $|C| \leq 2\sqrt{k}$, so again there are at most $2k^{3/2}$ edges of H remaining (since we know that if we fix a vertex from C , in addition to v , their link graph is a matching of size at most k). It follows that $|E(H)| \leq 4k^{3/2}$ giving us the first part of the result.
- Take a set V_1 of $(k^2n)^{1/3} \ll n$ vertices and let V_2 be the set of remaining vertices. We make a 4-graph by taking any triple in V_1 and a single vertex in V_2 . This gives us $\Omega(k^2n^2)$ edges and implies $|E(H)| \leq (k^2n)^{1/3}$ since among every pair of vertices in M at least one must be in V_1 .

This completes the proof. \square

The rest of this section is devoted to the upper bound part of the following theorem, as the lower bound follows from Theorem 4.2. Analysing the above proof narrows down the possibilities for an optimal unavoidable graph significantly, leading us to $St_4(\sqrt{k}, k, 1)$ as a natural candidate for an optimal unavoidable graph. This indeed turns out to be the case as a consequence of the following result.

Theorem 4.3. For $2 \leq k \leq n^{2/3}$ we have $\text{ex}(n, St_4(\sqrt{k}, k, 1)) \approx \max\{k^2n^2, k^{9/2}n\}$.

Before proving this result let's see why it gives the desired lower bound for the unavoidability problem. We want to show that there is an (n, e) -unavoidable 4-graph with $\gtrsim \min\{(e/n^2)^{3/4}, (e/n)^{1/3}\}$ edges, for any $n^2 \ll e \ll n^3$. To do this we choose k as large as possible, so that $e \gg \max\{k^2n^2, k^{9/2}n\}$, which means that $k \gtrsim \min\{(e/n^2)^{1/2}, (e/n)^{2/9}\}$. By our choice of k the above theorem applies and tells us that any 4-graph with n vertices and e edges contains $St_4(\sqrt{k}, k, 1)$, i.e. it is (n, e) -unavoidable. This implies there is an (n, e) -unavoidable 4-graph with $k^{3/2} \gtrsim \min\{(e/n^2)^{3/4}, (e/n)^{1/3}\}$ edges, as desired.

So, combining Theorem 4.3 and Theorem 4.2 we obtain the desired result for the middle range.

Theorem 4.4. For $n^2 \ll e \ll n^3$, we have $un_4(n, e) \approx \min \{ (e/n^2)^{3/4}, (e/n)^{1/3} \}$.

Let us now turn to the proof of Theorem 4.3. For the upper bound our task is to show that any 4-graph G on n vertices with $e \gg \max\{k^2n^2, k^{9/2}n\}$ edges contains a copy of $St_4(\sqrt{k}, k, 1)$. To this end, note that by the pigeonhole principle, the link graph L_v of some vertex $v \in V(G)$ must have $e/n \gg \max\{k^2n, k^{9/2}\}$ triples. If L_v contains \sqrt{k} vertex-disjoint copies of $Sf_3(1, k)$, then we are done. Unfortunately, a 3-graph on n vertices with $\gg \max\{k^2n, k^{9/2}\}$ edges may not have more than one vertex-disjoint copy $Sf_3(1, k)$, let alone \sqrt{k} copies. For example, the 3-graph consisting of all triples containing a fixed vertex has $\binom{n-1}{2}$ edges (which is large enough when $k \ll n^{4/9}$), and it clearly does not contain two disjoint copies of $Sf_3(1, k)$. As the next result shows, one can remedy the situation by imposing a boundedness condition on the codegrees.

Lemma 4.5. Let $k \geq 2$. Every n -vertex 3-graph with at least $e \gg \max\{k^2n, k^{9/2}\}$ edges, in which every pair of vertices has codegree at most $3k^{3/2}$, contains \sqrt{k} vertex-disjoint copies of $Sf_3(1, k)$.

Proof. Assume first that there exist vertices $v_1, \dots, v_{\sqrt{k}}$ with degree at least $18k^3$. Since there are no pairs of vertices with codegree larger than $3k^{3/2}$, we know that the link graph of any v_i does not contain a star of size $3k^{3/2}$, so by Lemma 2.3 it must contain a matching of size $3k^{3/2}$. Now assume we have found $i - 1$ disjoint copies of $Sf_3(1, k)$ centred at v_1, \dots, v_{i-1} and not using any other v_j 's. Let us consider a matching of size $3k^{3/2}$ in the link graph of v_i . At most $\sqrt{k} + 2(i - 1)k < 2k^{3/2}$ of the pairs in the matching already contain a vertex from either $\{v_i, \dots, v_{\sqrt{k}}\}$ or belonging to one of our $(i - 1)$ already found copies of $Sf_3(1, k)$'s. The remaining pairs make a matching of size at least k in the link graph of v_i while avoiding $\{v_1, \dots, v_{\sqrt{k}}\}$ as well as any already used vertex. This gives us a new $Sf_3(1, k)$ centred at v_i which is disjoint from the previous ones. After repeating \sqrt{k} many times we get the desired \sqrt{k} vertex-disjoint copies of $Sf_3(1, k)$.

So we may assume there are less than \sqrt{k} vertices with degree at least $18k^3$. Each such vertex belongs to at most $3k^{3/2}n$ edges (the second vertex we can choose in n ways and then third in $3k^{3/2}$ ways since codegrees are at most $3k^{3/2}$). Thus in total there are at most $3k^2n$ edges containing a vertex with degree at least $18k^3$. We delete these edges and are left with at least $e/2$ edges.

Suppose we have found $i - 1$ vertex-disjoint copies of $Sf_3(1, k)$ in the remaining 3-graph, where $1 \leq i \leq \sqrt{k}$. There are at most $(i - 1)(2k + 1) \cdot 18k^3 < 54k^{9/2}$ edges which contains a vertex from one of these copies. Removing these edges, we are left with at least $e/4 \gg k^2n$ edges. Thus Lemma 3.1 applies giving us a new $Sf_3(1, k)$. This way we obtain \sqrt{k} vertex-disjoint copies of $Sf_3(1, k)$. \square

We are now ready to finish our analysis of the middle range by proving Theorem 4.3.

Proof of Theorem 4.3. The lower bound follows from Theorem 4.2.

Turning to the upper bound, set $m \gg \max\{k^2n, k^{9/2}\}$ and let G be an n -vertex 4-graph with at least nm edges. Suppose to the contrary that G has no copies of $St_4(\sqrt{k}, k, 1)$.

Let us first consider the case that there are at most $nm/2$ edges containing a $3k^{3/2}$ -expanding triple in G . Remove all these edges to obtain a 4-graph G' with at least $nm/2$ edges in which there is no $3k^{3/2}$ -expanding triple. By the handshaking lemma, we can find a vertex x in G' of degree at least $2m$. If we look at the 3-graph G_x obtained by removing x from all these edges we know it has at least $2m$ edges, additionally we know that no pair of vertices is $3k^{3/2}$ -expanding in G_x as such pair together with x would give a $3k^{3/2}$ -expanding triple. So all codegrees in G_x are at most $3k^{3/2}$ and Lemma 4.5 applies, giving us \sqrt{k} vertex-disjoint copies of $Sf_3(1, k)$ which together with x make a copy of $St_4(\sqrt{k}, k, 1)$, a contradiction.

Therefore, there are at least $nm/2$ edges which contain a $3k^{3/2}$ -expanding triple. For any $v \in V(G)$ let D_v denote the 3-graph consisting of triples X such that $v \cup X \in E(G)$ and X is $3k^{3/2}$ -expanding. Note that we have $\sum_{v \in V(G)} |D_v| \geq nm/2$ since each edge of G , containing a $3k^{3/2}$ -expanding triple, contributes at least 1 to this sum. Hence, there exists a vertex x with $|D_x| \geq m/2$.

Claim 1. *There is no star of size \sqrt{k} consisting of $3k^{3/2}$ -expanding pairs in the 3-graph D_x .*

Proof. Suppose to the contrary that we can find distinct vertices $v_0, \dots, v_{\sqrt{k}}$ such that $\{v_0, v_i\}$ makes a $3k^{3/2}$ -expanding pair for all $1 \leq i \leq \sqrt{k}$. We know that $\{v_0, v_i\}$ completes into an edge of D_x in at least $3k^{3/2}$ different ways, so we can greedily find k vertices v_{i1}, \dots, v_{ik} such that $\{v_0, v_i, v_{ij}\} \in E(D_x)$ and all v_i, v_{ij} are distinct, for all $1 \leq i \leq \sqrt{k}$ and $1 \leq j \leq k$. The last part is due to the fact that we choose at most $1 + \sqrt{k} + k^{3/2} < 2k^{3/2}$ vertices in total and each pair completed an edge in at least $3k^{3/2}$ ways so we always have an unused vertex to choose for our v_{ij} 's.

Now since each $\{v_0, v_i, v_{ij}\} \in E(D_x)$ and is in particular expanding, we can extend it into an edge of G in $3k^{3/2}$ ways so again greedily we obtain $St_4(\sqrt{k}, k, 1)$ as it contains $1 + \sqrt{k} + 2k^{3/2} < 3k^{3/2}$ vertices so we always have a new vertex to choose to extend $\{v_0, v_i, v_{ij}\}$. This is a contradiction. \square

For $y \neq x$, let D_{xy} denote the set of pairs X such that $y \cup X \in E(D_x)$ and X is $3k^{3/2}$ -expanding in D_x .

Claim 2. *For every $y \neq x$, one has $|D_{xy}| \leq 6k^{3/2}n$.*

Proof. Suppose to the contrary that $|D_{xy}| \geq 6k^{3/2}n$ for some $y \neq x$. According to Lemma 2.4 (with $s = k^{3/2}$), the graph D_{xy} contains $\min\{k^{3/2}, \frac{\sqrt{k^{3/2}n}}{k}\} \geq \sqrt{k}$ (using $n \geq k^{3/2}$) vertex-disjoint copies of S_k . Label the edges of these stars by $e_1, e_2, \dots, e_{k^{3/2}}$.

As $y \cup e_i$ is a $3k^{3/2}$ -expanding triple for every i , we can greedily find distinct vertices $v_1, \dots, v_{k^{3/2}} \in V(G) \setminus \bigcup_j e_j$ such that $y \cup e_1 \cup v_1, \dots, y \cup e_{k^{3/2}} \cup v_{k^{3/2}}$ are edges of G . This yields a copy of $St_4(\sqrt{k}, k, 1)$, a contradiction. \square

Claim 3. *There are at most \sqrt{k} vertices y having $|D_{xy}| \geq 6k^2$.*

Proof. Suppose otherwise and let $v_1, \dots, v_{\sqrt{k}}$ denote vertices with $|D_{xv_i}| \geq 6k^2$. Since by Claim 1 there are no stars of size \sqrt{k} in D_{xv_i} we know by Lemma 2.3 that there must be a matching of size $3k^{3/2}$ in D_{xv_i} . Now assume for some $i \leq \sqrt{k}$ we have found $i - 1$ vertex-disjoint copies of $Sf_3(1, k)$ centred at v_1, \dots, v_{i-1} which do not use vertices from $\{v_i, \dots, v_{\sqrt{k}}\}$. We know there is a matching of size $3k^{3/2}$ in D_{xv_i} , at most $\sqrt{k} + 2k^{3/2}$ of the pairs in the matching use a vertex which already belongs to one of our $Sf_3(1, k)$'s so we can still find a k -matching in D_{xv_i} , avoiding any already used vertices. This gives us a new $Sf_3(1, k)$ centred at v_i disjoint from the previous ones and we may repeat this \sqrt{k} many times. Finally, these copies of $Sf_3(1, k)$ when joined with x make a copy of $St_4(\sqrt{k}, k, 1)$ which is a contradiction. \square

Finally, it follows from Claims 2 and 3 that the number of edges in D_x containing a $3k^{3/2}$ -expanding pair is at most $\sum_y |D_{xy}| \leq \sqrt{k} \cdot 6k^{3/2}n + n \cdot 6k^2 \leq m/4$. Deleting all such edges we are left with $m/4$ edges of D_x such that no pair of vertices is $3k^{3/2}$ -expanding. Lemma 4.5 implies we can find \sqrt{k} disjoint copies of $Sf_3(1, k)$ which together with x gives us a $St_4(\sqrt{k}, k, 1)$, a contradiction. This completes the proof. \square

5. Unavoidability, the dense regime

In this section we deal with the last regime, when $e \gg n^3$. Note once again that by monotonicity of $un_4(n, e)$ and combining it with Theorem 4.4 this will imply the result for $e \approx n^3$ as well.

For the majority of the regime the optimal unavoidable 4-graphs turn out to be based on generalised stars. Specifically, for $e = kn^3$ they will be disjoint unions of $St_4((n/k)^{1/3}, (n/k)^{1/3}, k)$ of suitable size. Unfortunately, in this regime upper bounds do not force as much structure as they do in the previous section, so we begin with the lower bounds. With this in mind our first goal is to determine $ex(n, St_4(d_1, d_2, d_3))$ for $d_1 = d_2 = (n/k)^{1/3}$ and $d_3 = k$ (although our methods should allow one to answer this question in general as well).

In order to find a copy of $St_4(d_1, d_2, d_3)$ in a graph we will either find d_1 vertex-disjoint copies of $St_3(d_2, d_3)$ inside the link graph of a vertex or find $St_3(d_1, d_2)$ consisting of so called expanding triples, namely triples of vertices which belong to many edges of our graph. In the former case we are done immediately, in the latter we can use the expansion of the triples to greedily extend each edge of our $St_3(d_1, d_2)$ using d_3 new vertices. To find disjoint copies of $St_3(d_2, d_3)$ or $St_4(d_1, d_2, d_3)$ we can simply remove any already used vertex from the graph and argue that the remainder still contains enough edges

to find a new copy. Unfortunately, as we have already seen in the previous section this approach fails to provide enough stars in most cases. A way around this is to embed the leaves of all our stars (since there are many of them) among vertices with low degrees, the 3rd layer vertices among vertices with only slightly higher degree and so on. This approach requires very good understanding of Turán numbers of 3-uniform generalised stars and their unions which we give in the following section.

In the subsequent section we show the desired bounds for our 4-uniform case. Interestingly, towards the end of the range, as e approaches $\binom{n}{4}$, generalised stars stop being the optimal examples and are replaced with (disjoint unions) of complete 4-partite graphs, which we will find through a combination of the Kővári-Sós-Turán theorem and a similar embedding trick where we embed largest parts of our already found r -partite graphs into vertices with low degree, in order to be able to find many disjoint copies.

5.1. Turán numbers of 3-uniform generalised stars

In this section we will give a number of upper bounds on Turán numbers of generalised stars, and their disjoint unions. The first two results determine these Turán numbers up to constant factors and we prove them in full generality since we find them interesting in their own right. The subsequent three lemmas allow us to do even better (find our stars in graphs with even less edges) if we know certain additional properties of our graph or give us more control where in the graph we can find our stars. We do not state these in full generality, but rather for the cases which arise naturally in the proof of our 4-uniform result.

The following lemma, which generalises Lemma 3.1, determines the Turán number of any 3-uniform generalised star, up to a constant factor.

Theorem 5.1. *For every positive integers n, h and k , we have*

$$\text{ex}(n, St_3(h, k)) \lesssim \max\{kn^2, h^2k^2n\}.$$

Proof. Let G be a 3-graph with $e \gg \max\{kn^2, h^2k^2n\}$ edges. We want to find h vertex-disjoint copies of S_k in the link graph of some vertex. Let D_v be the subgraph of the link graph of v consisting of pairs Y for which $v \cup Y$ is an edge of G and Y is $3hk$ -expanding.

If at least $e/2$ edges in G contain a pair which is $3hk$ -expanding then there exists a D_v of size at least $e/(2n)$, as $\sum_{v \in V} |D_v| \geq e/2$. If D_v contains an S_h , then since it consists of $3hk$ -expanding edges, we would be done by greedily extending it into a copy of $St_3(h, k)$, since $3hk \geq hk + h + 1 = |St_3(h, k)|$. Hence, we suppose there is no S_h in D_v , i.e. every vertex has degree at most h in D_v . Take a maximal collection of disjoint k -stars in D_v . If this collection consists of at least h stars, they together with v make $St_3(h, k)$ and we are done, so let us assume towards a contradiction that there are less than h of them. So the union of the stars in this collection has at most $hk + h \leq 2hk$ vertices, which participate in at most $2hk \cdot h \leq e/(4n)$ edges of D_v , since we have shown that degree

of any vertex is at most h . This means that among the remaining at least $e/(4n) \geq kn$ edges in D_v we can find a new S_k , contradicting maximality of our collection.

So we may assume that G contains at most $e/2$ edges containing a $3hk$ -expanding pair; removing all such edges we obtain a graph G' in which there is no $3hk$ -expanding pair of vertices. We can find a vertex with degree at least e/n and once again keep finding k -stars in its link graph for as long as we have less than h of them. At any point we have at most hk vertices and they have degree at most $3hk$ in the link graph of the found vertex (since we removed all edges containing a $3hk$ -expanding pair), so they always touch at most $3h^2k^2 \leq e/(4n)$ edges, hence we have at least $e/(4n) \geq kn$ other edges, and we can find a new S_k , as desired. \square

Remark. One can show the bound in the proposition is tight, up to a constant factor, provided $2 \leq k \leq n/h$. Indeed, Lemma 3.2 gives the first term, and taking $n/(hk)$ disjoint copies of the complete 3-graph on hk vertices gives the second. Note also that, since $|St_3(h, k)| > hk$, when $hk > n$ we can never find a copy of $St_3(h, k)$ in a graph on n vertices, hence the largest $St_3(h, k)$ -free graph is complete; this completes the picture on Turán numbers of generalised 3-uniform stars (case $k = 1$ being Lemma 3.1).

The next result shows that if $|E(G)| \gg \max\{kn^2, h^2k^2n\}$ then not only G contains a copy of $St_3(h, k)$, as guaranteed by the above proposition, but it contains many disjoint copies of them. After the proof we make a few remarks about the optimality of the given result, which the reader might want to read beforehand, since one might find this helpful to understand where the parameters come from.

Theorem 5.2. *Every 3-graph on n vertices with $e \gg sn^2$ edges, with $s \geq \max\{k, h^2k^2/n\}$, contains at least $t = \min\{s, \sqrt{sn}/h, s^{1/3}n^{2/3}/(hk)\}$ vertex-disjoint copies of $St_3(h, k)$.*

Proof. Let G be a 3-graph on n vertices with e edges. Set $L_2 = e/(3ht)$ and $L_3 = e/(3hkt)$. We call a star $St_3(h, k)$ in G *well-behaved* if its h second layer vertices have degrees at most L_2 and its hk third layer vertices have degrees at most L_3 . Suppose we have found a collection of less than t vertex-disjoint well-behaved generalised stars $St_3(h, k)$. The used vertices touch at most $t \cdot \binom{n}{2} + ht \cdot L_2 + hkt \cdot L_3 \leq \frac{3}{4}e$ edges. We call this set of edges R .

Our goal now is to show that we can find a new well-behaved star $St_3(h, k)$ in G among the vertices which are not contained in any of the previous stars. Let A denote the set of vertices with degree at least L_2 , B the set of vertices with degrees between L_3 and L_2 and C the set of vertices with degree at most L_3 . Note that $|A \cup B| \leq 9ht + 9hkt \leq 18hkt$. Furthermore, there exists a subset $F \subseteq E(G) \setminus R$ such that every edge in F contains the exact same number of vertices in A , as well as in B , and in C , and we have $|F| \geq \frac{1}{10} \cdot \frac{1}{4}e \gg sn^2$, since there are⁶ $\binom{3+2}{2} = 10$ different types of edges according to how many vertices they have in each of the sets A, B and C . We distinguish four cases.

⁶ The number of non-negative integer solutions to $x_1 + x_2 + x_3 = 3$.

Case (i). The edges in F have no vertices in C .

We have $|F| \leq \binom{|A \cup B|}{3} \lesssim (hkt)^3 \leq sn^2 \ll |F|$, a contradiction.

Case (ii). All three vertices of each edge in F are in C .

We can find a copy of $St_3(h, k)$ using only the edges in F by Theorem 5.1, since $s \geq \max\{k, h^2k^2/n\}$ and $|F| \gg sn^2$. As all its vertices are in C the star is well-behaved.

Case (iii). All edges of F have exactly two vertices in C .

There must exist a vertex in $A \cup B$ of degree at least $\frac{|F|}{|A \cup B|} \geq \frac{|F|}{18hkt} \gg \frac{sn^2}{hkt}$. Hence, we can use Lemma 2.4 to find h vertex-disjoint copies of S_k in its link graph. To see why the lemma gives this, note that for $s' = sn/(hkt)$ we have $\min\{s', \sqrt{s'n}/k\} \geq h$ and $s' \geq k$. Indeed, we have

$$\frac{s'}{h} = \frac{\sqrt{sn}}{hk} \cdot \frac{\sqrt{sn}}{ht} \geq 1, \quad \frac{\sqrt{s'n}}{hk} = t \cdot \sqrt{\frac{sn^2}{(hkt)^3}} \geq t \geq 1 \quad \text{and}$$

$$\frac{s'}{k} = \frac{s}{k} \cdot \frac{s^{1/3}n^{2/3}}{hkt} \cdot \frac{n^{1/3}}{s^{1/3}} \geq 1,$$

where we used $s \geq h^2k^2/n$ and $t \leq \sqrt{sn}/h$ in the first inequality, $t \leq s^{1/3}n^{2/3}/hk$ in the second and last inequalities, where we also used $n \geq s \geq k$. This yields a copy of $St_3(h, k)$ with all second and third layer vertices in C , so the copy is well-behaved.

Case (iv). Each edge in F has exactly one vertex in C .

Let \mathcal{P} be the set of $sn^2/(hkt)^2$ -expanding pairs of vertices in $A \cup B$. The total number of edges in F which do not contain a pair in \mathcal{P} is less than $\binom{|A \cup B|}{2} \cdot sn^2/(hkt)^2 \leq 9 \cdot 18sn^2 \leq |F|/2$. The remaining, at least $|F|/2$ edges each contain a pair from \mathcal{P} and each such pair can belong to at most n edges, so $|\mathcal{P}| \geq |F|/(2n) \gg sn$. Since at most $\binom{|A|}{2} \leq \binom{9ht}{2} < 41sn$ pairs have both vertices in A , there are at least $18sn$ pairs in \mathcal{P} with at least one vertex in B . This means that there is a vertex in $A \cup B$ having at least $18sn/|A \cup B| \geq sn/(hkt) \geq h$ neighbours (with respect to \mathcal{P}) in B , so we find a copy of S_h in \mathcal{P} with leaves in B . Since the pairs in \mathcal{P} have degrees at least $sn^2/(hkt)^2 \geq hkt \geq hk$ (using $t \leq s^{1/3}n^{2/3}/hk$), we can greedily extend this S_h into a copy of $St_3(h, k)$, which is well-behaved since every edge in S_h had at most one vertex in A and exactly two in $A \cup B$ so the third vertex of any edge containing it must be in C , by the case assumption. \square

Remark. This result is again best possible in a number of ways. We need the bound on s in order to be able to find even a single star, since Theorem 5.1 is tight, as explained by the remark below it. The actual number of stars we find is also optimal: the bound $t \leq s$ follows by taking $K_{s,n,n}$, $t \leq \sqrt{sn}/h$ by taking $K_{\sqrt{sn}, \sqrt{sn}, n}$ (note that $\sqrt{sn} \leq n$) and $t \leq s^{1/3}n^{2/3}/(hk)$ by taking the complete graph on $s^{1/3}n^{2/3} \leq n$ vertices.

The following lemmas arise as parts of our argument bounding $\text{ex}(n, St_4(d, d, k))$, where $d = (n/k)^{1/3}$, in the following subsection. They are either strengthenings of the above bounds or allow us more control over where we find vertices of our 3-uniform stars.

Lemma 5.3. *Let H be a 3-graph on n vertices with $e \gg kn^2$ edges. If every pair of vertices belongs to less than $3kd^2$ edges of H , then H contains d vertex-disjoint copies of $St_3(d, k)$, where $d = (n/k)^{1/3}$.*

Proof. We first show that for any vertex w of degree at least $7kn$ in H , there is an $St_3(d, k)$ centred at w . Observe first that the link graph L_w does not contain a star of size $3kd^2$, as otherwise the centre of this star and w make a pair of too high codegree. This means that in the link graph of w we can find d vertex-disjoint copies of S_k , again by a greedy procedure. Indeed in every step we have used at most $2kd$ vertices, each having degree at most $3kd^2$ in L_w , so in total they touch at most $6k^2d^3 = 6kn$ edges, and we can find the new S_k among the remaining nk edges. This gives us the desired $St_3(d, k)$ centred at w .

Let A be the set of vertices with degree larger than $ed/(8n) \gg nkd$ and B the set of vertices with degree at most this. Since we have e edges in total this implies $|A| \leq 24n/d$. This in turn implies that there can be at most $\binom{|A|}{2} \cdot 3kd^2 \leq e/3$ edges with at least 2 vertices in A , so we can remove them to get a subgraph $H' \subseteq H$ in which every vertex has at most one vertex in A and $|E(H')| \geq 2e/3 \gg kn^2$.

Let us first assume there are at least $e/3$ edges with all vertices in B . Taking a maximal collection of vertex-disjoint $St_3(d, k)$ using only such edges, either we are done (if we have found d of them) or have used at most $2kd^2$ vertices, each with degree at most $ed/(8n)$. So in total, currently used vertices touch at most $2kd^2 \cdot ed/(8n) = e/4$ edges of H' . Upon removing them we are left with at least $e/12 \gg kn^2$ edges with all vertices in B and disjoint from the set of already used vertices. In particular, there is still a vertex of degree at least $7kn$ and we can use the observation from the beginning of the proof to find an additional $St_3(d, k)$, a contradiction.

So we may assume there are at least $e/3$ edges with one vertex in A and 2 in B . Now take a maximal collection of vertex-disjoint copies of $St_3(d, k)$ with centres in A and remaining vertices in B . Either we are done or we have used at most d vertices from A and $2kd^2$ vertices in B . The former have degrees at most $n \cdot 3kd^2$ (second vertex we may choose in n many ways, but for the final we are restricted by the codegree assumption) so touch at most $d \cdot n \cdot 3kd^2 = 3n^2 \leq e/24$ edges. The latter have degrees at most $ed/(8n)$, by definition of B , so touch at most $2kd^2 \cdot ed/(8n) = e/4$ edges. Hence, upon removing all these edges we are left with at least $e/24 \geq 7kn^2$ of our edges, all of which are disjoint from the set of already used vertices. This means there is a vertex in A with degree at least $7kn$, so once again using our initial observation we find an additional $St_3(d, k)$, a contradiction. \square

The following lemma allows us to find many copies of 3-uniform stars with an added restriction that its leaves should avoid a relatively small subset of vertices, provided the edges of our graph have at least one vertex in this small subset. The choice of parameters might seem a bit arbitrary, but it arises from our intended application of the lemma in the 4-uniform case.

Lemma 5.4. *Let n, k and t be positive integers with $t \leq \min\{k, \sqrt{d}\}$, where $d = (n/k)^{1/3}$. Let H be an n -vertex 3-graph with $e \gg \frac{n^3}{td^2}$ edges. Let $C \subseteq V(H)$ such that $|C| \leq 16nt/d$ and assume that every edge of H has precisely one vertex in C . Then H contains d vertex-disjoint copies of $St_3(d, k)$ whose leaves lie outside of C .*

Proof. Let $D = V(H) \setminus C$. Suppose there exists a set X of d vertices in D with degree at least

$$\delta := \frac{ed}{8n} \gg \frac{n^2}{dt} = \frac{nd^2k}{t} \geq \max\{nd^2, ntdk\} \tag{2}$$

where in the last inequality we used the assumption on t . We delete from H any edge containing two vertices in X . We deleted at most

$$d^2|C| \leq 16ntd \ll \frac{\delta}{k}$$

such edges, using (2). Hence, vertices in X after deletion still have degree at least $\frac{\delta}{2}$. We now show how to find d vertex-disjoint copies of $St_3(d, k)$ with centres in X , 2nd layer vertices in C and leaves in $D \setminus X$. We construct them as follows. We pick a vertex from X and look inside its link graph for copies of stars S_k with centres in C , leaves in $D \setminus X$ and not using any already used vertices. If we find d of them we proceed to the next vertex of X , otherwise we stop. If we did not stop by the time we considered all vertices of X , we have found our desired structure. So we may assume that we do stop at some point when considering $x \in X$. At this point we have used at most d^2 vertices from C and $kd^2 + d \leq 2kd^2$ vertices from D (the first term being the contribution of $D \setminus X$ and the second of X). In the link graph L_x (note that this graph consists of edges with one vertex in C and one in D), already used vertices from C touch at most $d^2 \cdot n \leq \delta/8$ edges in total, using (2). Furthermore, used vertices from D touch at most

$$2kd^2|C| \leq 32ntdk \leq \frac{\delta}{8}$$

edges in total, using (2). So removing all edges touching these forbidden, already used, vertices we are left with at least

$$\frac{\delta}{4} \geq \frac{16ntk}{d} \geq k|C|$$

edges in L_x , avoiding all already used vertices. Hence, we find another appropriate S_k , a contradiction.

So we may assume that there are at most d vertices in D with degree at least δ . These vertices participate in at most

$$dn^2 = \frac{n^3}{kd^2} \leq \frac{e}{4}$$

edges (using $t \leq k$); we delete them and are left with a graph H' with at least $\frac{3e}{4}$ edges such that all vertices in D have degree at most δ in H' . Let us take a maximal collection of vertex-disjoint copies of $St_3(d, k)$ with centres in C . If we are not done, the centres touch at most $dn^2 \leq \frac{e}{4}$ edges, while the other used vertices touch at most $2kd^2 \cdot \delta = \frac{e}{4}$ edges (since they all belong to D so touch at most δ edges). So there are at least $e/4$ edges which do not touch any of the used vertices. Let H'' be the graph consisting of these edges. Now it is enough to find another $St_3(d, k)$ in H'' , with its centre in C . Note that there is a vertex in C of degree at least

$$\frac{e}{4|C|} \geq \frac{6n^2}{dt^2} = 6n \cdot \frac{kd^2}{t^2}$$

in H'' . Applying Lemma 2.4 with $s := \frac{kd^2}{t^2}$, which we can since $s \geq kd \geq k$ (using $t \leq \sqrt{d}$), we find $\min\{s, \sqrt{sn}/k\} \geq \min\{kd, d^2\} \geq d$ (using $n = kd^3$ and $t \leq \sqrt{d}$ in the second term) disjoint stars S_k in the link graph of this vertex, completing the proof. \square

The final lemma for the 3-uniform case is the following. It is similar in spirit to the above one, except that it works with smaller sets and only finds a single star. While the above lemma will be used to embed a number of stars within the link graph of a fixed vertex, the following one will be used to find the star making the first three layers of the generalized stars that we will consider in the next subsection.

Lemma 5.5. *Let n, k and t be positive integers with $t \leq \min\{k, \sqrt{d}\}$, where $d = (n/k)^{1/3}$. Let H be a 3-graph on vertex set $B \cup C$ where B and C are disjoint, $|B| \leq 16td^2$ and $|C| \leq 16td^2k$. If H has $e \gg kn^2$ edges then it contains a copy of $St_3(d, d)$ whose leaves all lie in C .*

Proof. There are at most

$$\binom{|B|}{3} \leq 2^{12}t^3d^6 \leq 2^{12}k^3(n/k)^2 \leq \frac{e}{4}$$

edges within B . If we have $e/4$ edges living completely in C then by Theorem 5.1, since

$$e/4 \geq 2^8n^2 \geq \max\{d|C|^2, d^4|C|\},$$

where we used $t^2 \leq d$ for the first term and $t \leq k$ for the second, we can find a copy of $St_3(d, d)$ consisting of these edges, so in particular having all leaves in C , as desired. So we may assume there are at least $e/2$ edges containing vertices from both B and C . Let H' be the subgraph consisting of such edges.

A pair of vertices in H is said to be a B -pair if it contains at least one vertex in B . There are at most

$$|B| \cdot (|B| + |C|) \leq 2^9 t^2 d^4 k \leq 2^9 d^4 k^3 = 2^9 kn^2/d^2 \leq e/(12d^2)$$

B -pairs. We say a B -pair is C -expanding if it extends into an edge of H' using a vertex from C in at least $3d^2$ many ways. This means there are at most $e/4$ edges which contain a non- C -expanding B -pair. The remaining, at least $e/4$, edges only contain C -expanding B -pairs. Each of these edges can be split into a B -pair, which must be C -expanding and a vertex in C . Hence, there needs to be at least

$$\frac{e}{4|C|} \geq \frac{kn^2}{td^2k} = \frac{k}{t} \cdot \frac{n}{d^3k} \cdot dn \geq dn$$

C -expanding B pairs. Hence, we can find a star of size d made of such pairs and since each of them extends to at least $3d^2 \geq |St_3(d, d)|$ edges using a vertex in C , we find our desired star by a greedy procedure. \square

5.2. Optimal 4-uniform unavoidable graphs

We finally have all the 3-uniform results our hearts might desire, we proceed to the 4-uniform case.

We begin by determining the Turán number of a single copy of our unavoidable generalised 4-uniform star. The proof is relatively simple since we did most of the legwork in the previous section.

Lemma 5.6. *For $1 \leq k \leq n$ one has $ex(n, St_4(d, d, k)) \lesssim kn^3$, where $d = (n/k)^{1/3}$.*

Proof. For ease of notation, set $St = St_4(d, d, k)$. Let G be an n -vertex 4-graph with $e \gg kn^3$ edges. We say a triple of vertices X is *expanding* in G if it is $3kd^2$ -expanding.

Claim. *If at least $e/2 \gg kn^3$ edges contain an expanding triple, then G contains St .*

Proof. Let $D_v := \{X \subseteq V(G)^3 \mid X \cup v \in E(G), X \text{ is expanding}\}$. We have $\sum_v |D_v| \geq e/2$, since every edge containing an expanding triple contributes at least one to the sum on the left. This implies that there exists a vertex v with $|D_v| \geq e/(2n)$. Now, if there exists a vertex w with degree at least $6dn$ in D_v then we can find d vertex-disjoint copies of the star of size d within the link graph of w in D_v , by Lemma 2.4 and using that $n = d^3k \geq d^3$. Adding w to these edges gives us an $St_3(d, d)$ within D_v (so consisting of

expanding triples). This in turn implies we are done by greedily extending it to a copy of St . So we may assume every vertex has degree at most $6dn$ in D_v .

Theorem 5.1 tells us that we can find at least one $St_3(d, k)$ in any 3-graph with $e/(4n) \gg kn^2$ edges (using that $n = d^3k \geq d^2k$ so that $d^2k^2n \leq kn^2$). Suppose we have found $t < d$ vertex-disjoint copies of $St_3(d, k)$ in D_v ; they span at most $3kd^2$ vertices, each having degree at most $6dn$ in D_v . Hence, these vertices are incident to at most $18n^2$ edges, so if we remove all of them, we are left with at least $e/(4n)$ edges. Now, Theorem 5.1 implies that we can find another disjoint $St_3(d, k)$. Therefore, we can find at least d vertex-disjoint copies of $St_3(d, k)$ inside D_v , which together with v give us a copy of St . \square

By the claim we may assume there are at most $e/2$ edges containing an expanding triple, so after deleting them we are left with a subgraph G' with at least $e/2 \gg kn^3$ edges, with no expanding triples. Take a vertex of maximum degree; it has degree at least $e/n \gg kn^2$ and in its link graph no pair of vertices belongs to more than $3kd^2$ edges since there is no expanding triple. So Lemma 5.3 implies the result. \square

The following result gives us our optimal unavoidable 4-graphs.

Theorem 5.7. *In any 4-graph G on n vertices with $e \gg kn^3$ edges, one can find $t = \min\{k, d^{1/4}\}$ vertex-disjoint copies of $St_4(d, d, k)$, where $d = (n/k)^{1/3}$.*

Proof. Set $L_2 = \frac{e}{4td}$, $L_3 = \frac{e}{4td^2}$ and $L_4 = \frac{e}{4td^2k}$. We partition $V(G)$ into level sets according to their degrees

$$\begin{aligned} A &:= \{v \mid d(v) > L_2\}, \\ B &:= \{v \mid L_3 < d(v) \leq L_2\}, \\ C &:= \{v \mid L_4 < d(v) \leq L_3\} \text{ and} \\ D &:= \{v \mid d(v) \leq L_4\}. \end{aligned}$$

Let $St := St_4(d, d, k)$. A generalised star St in G is said to be *well-behaved* if its second layer vertices are embedded among vertices with degree at most L_2 (i.e. vertices in $B \cup C \cup D$), the third layer vertices in vertices of degree at most L_3 (i.e. vertices in $C \cup D$), and the fourth layer vertices in vertices of degree at most L_4 (i.e. vertices in D). Let us consider a maximal collection of vertex-disjoint well-behaved generalised stars St . If we found less than t stars then already used vertices touch at most $t \cdot \binom{n}{3} + td \cdot L_2 + td^2 \cdot L_3 + td^2k \cdot L_4 \leq \frac{7}{8}e$ edges. So there are at least $e/8$ edges disjoint from any previously used edges and our task is to show we can embed an additional well-behaved St using these edges.

Handshaking lemma gives us:

$$|A| \leq 4e/L_2 = 16td,$$

$$|B| \leq 4e/L_3 = 16td^2 \text{ and}$$

$$|C| \leq 4e/L_4 = 16td^2k.$$

This implies $|A \cup B| \leq 32td^2$ and $|A \cup B \cup C| \leq 48td^2k$. Hence the total number of edges with at least 2 vertices in A , or at least 3 vertices in $A \cup B$, or all 4 vertices in $A \cup B \cup C$ is upper bounded by

$$\begin{aligned} & \binom{|A|}{2} \binom{n}{2} + \binom{|A \cup B|}{3} n + \binom{|A \cup B \cup C|}{4} \\ & \leq 2^6 t^2 d^2 n^2 + 2^{10} t^3 d^6 n + 2^{19} t^4 d^8 k^4 \\ & \leq 2^6 d^{5/2} n^2 + 2^{10} k^3 d^6 n + 2^{19} d^9 k^4 \\ & \leq 2^6 n^3 k + 2^{10} n^3 k + 2^{19} n^3 k \leq 2^{20} kn^3 \leq e/16, \end{aligned}$$

where we used $t^4 \leq d$ and $t \leq k$ in the second inequality and $n = kd^3$ in the third. In particular, there are at least $e/16$ remaining edges (which do not touch used vertices) such that they have at least 1 vertex in D , at least 2 vertices in $C \cup D$ and at least 3 vertices in $B \cup C \cup D$. Furthermore, there exists a subset F of these edges of size $|F| \geq (e/16)/35 \gg kn^3$ which all have the same number of vertices in each of A, B, C and D , since there are $\binom{4+3}{3} = 35$ different types of edges according to how many vertices they have in each of the sets A, B, C and D . We distinguish several cases depending on how many vertices our edges in F have in D .

Case (i). All edges in F have 4 vertices in D .

Any St we find in this case is well-behaved so we are done by Lemma 5.6.

Case (iii). All edges in F have exactly 3 vertices in D .

There is a vertex v in $A \cup B \cup C$ of degree at least $\frac{|F|}{|A \cup B \cup C|} \gg \frac{kn^3}{td^2k} = n^2dk/t$. Using Theorem 5.2 (with $s := dk/t$ and $h := d$ so that $s \geq k$ and $ns = k^2d^4/t \geq h^2k^2$), we get at least d vertex-disjoint copies of $St_3(d, k)$, since

$$s \geq d, \quad \frac{\sqrt{sn}}{h} = \frac{kd}{\sqrt{t}} \geq d \quad \text{and} \quad \frac{s^{1/3}n^{2/3}}{hk} = (d^4/t)^{1/3} \geq d.$$

Together with v , this gives a desired well-behaved copy of St .

Case (iii). All edges in F have exactly 2 vertices in D .

There can be at most $|A||B|\binom{n}{2} \leq 128t^2n^3/k < |F|$ edges in F with 1 vertex in A and 1 in B . Hence our edges either have exactly 2 vertices in B and 2 in D , or at least 1 vertex in C .

Subcase (a). All edges in F have 2 vertices in B and 2 in D .

Given a vertex set S , a pair of vertices in S is called an S - S pair.

Denote by \mathcal{P} the set of B - B pairs with at least $|F|/|B|^2 \geq 3nkd^2$

⁷ The number of non-negative integer solutions to $x_1 + x_2 + x_3 + x_4 = 4$.

pairs in their link graph. Since there are $\binom{|B|}{2}$ different B - B pairs, ones outside of \mathcal{P} belong to at most $\binom{|B|}{2} \cdot |F|/|B|^2 \leq |F|/2$ edges. Hence, the remaining $|F|/2$ edges have their B - B pair belonging to \mathcal{P} . Each $B - B$ pair can extend into an edge in at most $\binom{|D|}{2}$ many ways. Hence,

$$|\mathcal{P}| \geq \frac{|F|}{2} / \binom{|D|}{2} \geq 16kn \geq d|B|.$$

Therefore, \mathcal{P} contains a star of size d . We embed vertex-disjoint stars S_k into the link graphs of the leaves of our star in \mathcal{P} , dealing with one leaf at a time and moving to the next one when we found d stars S_k inside its link. Unless we are done, we have used at most $2kd^2$ vertices which can touch at most $2kd^2 \cdot n$ many D - D pairs within the current link graph. Thus we still have at least $nk d^2 \geq kn$ many D - D pairs in the link graph, disjoint from any already used vertices, which means we can find another S_k , as desired.

Subcase (b). All edges have at least 1 vertex in C and exactly 2 vertices in D .

There is a vertex $v \in A \cup B \cup C$ which appears in at least $\frac{|F|}{|A \cup B \cup C|} \gg \frac{kn^3}{td^2k} = n^3/(td^2)$ edges with the remaining vertices being one in C and two in D . By Lemma 5.4 (note that $|C| \leq 16td^2k = 16nt/d$), the link graph of v contains d vertex-disjoint copies of $St_3(d, k)$ whose leaves lie in D .

Case (iv). All edges in F have exactly 1 vertex in D .

Let \mathcal{T} denote the collection of all triples in $A \cup B \cup C$ of codegree at least

$$\frac{|F|}{|A \cup B \cup C|^3} \geq \frac{3kn^3}{(td^2k)^3} = \frac{3kd^3}{t^3} \geq 3kd^2.$$

Triples from $A \cup B \cup C$ outside \mathcal{T} belong to at most $\binom{|A \cup B \cup C|}{3} \cdot \frac{|F|}{|A \cup B \cup C|^3} \leq |F|/2$ edges, so at least half of the edges in F contain a triple in \mathcal{T} , and so $|\mathcal{T}| \geq |F|/(2n) \gg kn^2$. As there are at most

$$|A| \cdot \binom{|A \cup B \cup C|}{2} \leq 2^{16}t^3d^5k^2 \leq 2^{16}d^6k^2 = 2^{16}n^2 \leq |\mathcal{T}|/2$$

triples with a vertex in A , we can remove them to obtain a collection \mathcal{T}' of triples in $B \cup C$ such that $|\mathcal{T}'| \gg kn^2$. Now, if we find a well-behaved $St_3(d, d)$ within \mathcal{T}' (meaning that the second and third layer of vertices are embedded in $B \cup C$ and C respectively) then we are done by greedily extending it and choosing distinct vertices in D for 4-th layer vertices of St , which we can

since each triple has codegree at least $3kd^2$. The existence of such $St_3(d, d)$ is guaranteed by Lemma 5.5. \square

Finally, the optimal unavoidable 4-graphs at the very end of the range are of a very different flavour.

Theorem 5.8. *Every n -vertex 4-graph with $e \geq n^{4-1/216}$ edges contains $\frac{1}{24}(e/n)^{1/4}$ vertex-disjoint copies of the complete 4-partite 4-graph $K_4(s, s, s, t)$, where $s = \frac{1}{12} \left(\frac{\log n}{\log(n^4/e)} \right)^{1/3}$ and $t = n^{1/4}$.*

As the proof is an easy consequence of the well-known Kővári-Sós-Turán theorem and is very similar to its 3-uniform analogue ([9, Theorem 8]), we defer it to the appendix.

5.3. Lower bounds

Let us now deduce the lower bound of the last regime of the unavoidability problem, i.e. we show the lower bound in Theorem 1.1 (iii). Note first that if $e \leq n^{4-\varepsilon}$ for any $\varepsilon > 0$ we know $\frac{e^{1/4} \log n}{\log\binom{n}{4}/e} \approx e^{1/4}$. In particular, for $n^3 \ll e \leq n^{4-1/216}$, we can use Theorem 5.7 with $k \gtrsim e/n^3$, to conclude there is an (n, e) -unavoidable 4-graph with

$$\min\{k, (n/k)^{1/12}\} \cdot (n/k)^{2/3} k = \min\{n^{2/3} k^{4/3}, n^{3/4} k^{1/4}\} \gtrsim \min\{e^{4/3}/n^{10/3}, e^{1/4}\}$$

edges, showing the desired bound.

Similarly for $n^{4-1/216} \leq e \ll n^4$, Theorem 5.8 provides us with an (n, e) -unavoidable graph with

$$\gtrsim (e/n)^{1/4} \frac{\log n}{\log(n^4/e)} n^{1/4} \gtrsim \frac{e^{1/4} \log n}{\log\binom{n}{4}/e}$$

edges, as desired.

5.4. Upper bounds

The results of the previous sections complete the picture in terms of lower bounds on $\text{un}_4(n, e)$. Let us now turn to the upper bounds. They turn out to be much simpler than in the previous case, largely thanks to the following easy counting lemma from [9].

Lemma 5.9. *If an r -graph H on p vertices with q edges is (n, e) -unavoidable then*

$$q < \frac{p \log n}{\log\binom{n}{r}/e}.$$

The following result, together with monotonicity of $\text{un}_4(n, e)$ establishes the upper bounds for Theorem 1.1 (iii) and completes its proof.

Theorem 5.10.

- (i) For $n^3 \ll e \ll n^{40/13}$ we have $\text{un}_4(n, e) \lesssim e^{4/3}/n^{10/3}$.
- (ii) For $n^{40/13} \ll e \leq \binom{n}{4}$ we have $\text{un}_4(n, e) \lesssim \frac{e^{1/4} \log n}{\log \binom{n}{4}/e}$.

Proof of Theorem 5.10. (i) Let H be an (n, e) -unavoidable graph. Let $t = 3(e/n)^{1/3}$. Take n/t disjoint copies of a 4-uniform clique on t vertices. In total this gives us $\frac{n}{t} \binom{t}{4} > e$ edges so this graph must contain H as a subgraph. In particular, every connected component of H has size at most t . Now take another graph with a set V_1 of $50e/n^3 \leq n/2$ vertices and a set V_2 of $n/2$ vertices and we pick all edges having one vertex in V_1 and three in V_2 ; this graph has more than e edges, so it must contain H as a subgraph. This implies H can have at most $50e/n^3$ connected components. In turn this implies H has at most $50te/n^3 = 150e^{4/3}/n^{10/3}$ vertices. Now Lemma 5.9 implies H has at most $\frac{13}{12}|V(H)|$ edges, which completes the proof.

(ii) Let H be an (n, e) -unavoidable graph. Take a 4-uniform clique on $m = 3e^{1/4}$ vertices; it has $\binom{m}{4} > e$ edges so must contain H , hence H has at most m vertices. The claimed upper bound again follows from Lemma 5.9. \square

6. Concluding remarks and open problems

In this paper we resolve a question of Chung and Erdős which asks to determine the order of magnitude of $\text{un}_4(n, e)$ defined as the maximum number of edges in a 4-graph G which is contained in every 4-graph on n vertices and $e \ll \binom{n}{4}$ edges. The most immediate open question is to answer their question for any uniformity.

Question 6.1 (*Chung and Erdős, 1983*). What is the order of magnitude of $\text{un}_r(n, e)$ for any r ?

From our result the answer is now known for $r \leq 4$ and $e \ll \binom{n}{4}$. In addition, our methods and certain further partial results give some indication about how the answer should behave for larger uniformities as well. For example, it seems likely that in general there are $\lceil \frac{r}{2} \rceil + 1$ different regimes. The first one, when $e \ll n^{\lfloor \frac{r}{2} \rfloor}$ always has an easy answer of $\text{un}_r(n, e) = 1$ and the following regimes are $n^i \ll e \ll n^{i+1}$ where $\lfloor \frac{r}{2} \rfloor \leq i \leq r - 1$. In each regime (with the exception of $i = (r - 1)/2$ and $i = r - 1$) there are two competing bounds, which arise from the fact there are two sunflowers $Sf_r(t, 2)$ with $\text{ex}(n, Sf_r(t, 2)) \approx n^i$. Our answer in the second regime for the 4-uniform case turned out to be a bit surprising and is in fact in-between the two natural guesses, so we are not willing to conjecture the correct value of the turning point for general uniformity.

In the last regime, $i = r - 1$, the upper bound given by Theorem 5.10 generalises easily and seems to give the correct answer for all uniformities (as long as $e \ll n^r$).

Conjecture 6.2. For any $r \geq 2$ and $\varepsilon > 0$, provided $n^{r-1} \ll e \ll n^{r-\varepsilon}$ we have

$$\text{un}_r(n, e) \approx \min\{e^{\frac{r}{r-1}}/n^{r-1+\frac{1}{r-1}}, e^{\frac{1}{r}}\}.$$

Here, even the optimal unavoidable r -graphs seem to be clear, namely they should consist of an appropriate number of copies of $St_r((n/k)^{1/(r-1)}, \dots, (n/k)^{1/(r-1)}, k)$, however bounding their Turán numbers seems to be highly non-trivial. The assumption $e \ll n^{r-\varepsilon}$ was made since it is not hard to generalise Theorem 5.8 (we do so in the Appendix) and hence determine $\text{un}_r(n, e)$ for all $n^{r-\varepsilon} \ll e \ll n^r$ for some $\varepsilon > 0$.

The main stumbling block for extending our methods to higher uniformities is the fact that Turán numbers of sunflowers $\text{ex}(n, Sf_r(t, k))$ are not very well understood when $r \geq 5$ and k is allowed to depend on n , as pointed out by Chung and Erdős in [9]. The main reason being that these sunflowers represent main building blocks for all our examples, across most of the range. On this front, the appropriate generalisation of Theorem 1.2 seems to be as follows.

Conjecture 6.3. For every fixed $r \geq 5$ and $t < r$ one has $\text{ex}(n, Sf_r(t, k)) \approx k^{\min\{t+1, r-t\}} n^{\max\{r-t-1, t\}}$.

This would generalise a result of Frankl and Füredi [22] and Füredi [29] (who solve it when k is a constant) and the question may be attributed to Chung and Erdős. One can generalise our constructions from Section 3 to show the lower bound part, and some methods for upper bounds also generalise. We can prove this conjecture for several more uniformities, although even in the case $r = 5$ we needed additional ideas.

Since generalised stars seem to be optimal unavoidable graphs, as long as $e \ll n^{r-1}$, (at which point their unions take over) the following seems to be the key problem one needs to resolve in order to answer Question 6.1.

Question 6.4. Let r be fixed. Determine the order of magnitude of $\text{ex}(n, St_r(d_1, \dots, d_{r-1}))$, where d_i 's are allowed to depend on n .

One can read out the answer for $r = 3$ from Theorem 5.1 and we believe our methods suffice to also solve it for $r = 4$. Yet for higher uniformities even the case in which we keep the d_i 's fixed, which is yet another generalisation of the result of Frankl and Füredi [22] and Füredi [29] on Turán numbers of sunflowers with fixed uniformity and number of petals, seems potentially interesting.

Both Conjecture 6.2 and Question 6.4 are examples of an interesting general question. Turán numbers of both graphs and hypergraphs are well-studied, but in most cases one is only interested in Turán numbers of a graph of fixed size. For many classical examples one can ask what happens if the fixed size restriction is removed. This can be very useful in a

number of situations, perhaps the most ubiquitous being the Kővári-Sós-Turán theorem [35] which is often used to find complete bipartite graphs of order even comparable to that of the underlying graph. For some additional examples see [1,14,28]. It definitely seems there is plenty of potential for interesting future work in this direction.

So far we have avoided discussing the assumption $e \ll n^4$ in Theorem 1.1, mostly following in line of Chung and Erdős. In fact we can replace this condition in Theorem 1.1 with $e \leq \binom{n}{4} - n^{1+c}$ for any $c > 0$ (it requires choosing s and t slightly differently in Theorem 5.8). The problem seems to change significantly at this point and attains a very different flavour. Even the graph case, which was raised by Chung and Erdős in 1983 has only recently been resolved in [4] and it suggests that around this point the optimal extremal examples seem to become (pseudo)random graphs in place of the complete r -partite graphs and the answer changes. Given that even the graph case turned out to be somewhat involved and relies on completely different ideas, we leave this open for future research.

Question 6.5. For $r \geq 3$ determine the order of magnitude of $\text{un}_r(n, e)$ when $e = (1 - o(1))\binom{n}{r}$.

Another natural follow-up question is to determine how optimal (up to a constant factor) (n, e) -unavoidable r -graphs look like. It is entirely possible to answer this question without answering Question 6.1, since one can potentially force the structure of an optimal unavoidable graph similarly as in Theorem 4.2 (as was demonstrated by Chung and Erdős in the 3-uniform case). At the very least we believe that optimal unavoidable graphs should be (close to) generalised stars as long as e is not too close to $\binom{n}{4}$. Towards the end of the range the situation becomes blurry, as at least for part of the range, both copies of complete r -partite graphs and generalised stars are simultaneously optimal.

Acknowledgments

We are grateful to the anonymous referees for their careful reading of the paper and a number of useful suggestions.

Appendix A. Large complete r -partite subgraphs of dense r -graphs

In this section we provide a proof of (a generalisation of) Theorem 5.8.

The proof is based on Kővári-Sós-Turán theorem [35], for hypergraphs. Since the sizes of the r -partite graphs we want to find grow with the number of vertices we need to go through the standard proof with care. The starting point is the graph case.

Theorem A.1 (Kővári, Sós and Turán [35]). *If $G = (A \cup B, E)$ is a bipartite graph and for some integers s and t we have*

$$t \binom{|A|}{s} < |B| \binom{|E|/|B|}{s}$$

then G contains a complete bipartite graph $K_{s,t}$ with the vertex class of size s embedded in A .

We will apply the following in the not so dense case.

Lemma A.2. *Let n, r and s be positive integers with $r \geq 2$ and $n \geq 2^{(4s)^{r-1}}$. Let V_1, \dots, V_r be sets of size n and M be a subset of $V_1 \times \dots \times V_r$ with $|M| \geq n^{r-1}/(4s)^{r-1}$. Then there exists $A_1 \times \dots \times A_r \subset M$ such that $|A_i| = s$ for every $1 \leq i < r$ and $|A_r| = \sqrt{n}$.*

Proof. We prove Lemma A.2 by induction on r . The base case $r = 2$ follows from Theorem A.1 since

$$\sqrt{n} \binom{n}{s} < n \binom{n^{1-1/(4s)}}{s}.$$

Here we used the fact that $\binom{n}{s} / \binom{m}{s} \leq (\frac{n}{m-s})^s \leq (\frac{2n}{m})^s$ provided $m \geq 2s$.

Assume that the statement holds for $r-1$. Consider the bipartite graph $G = (A \cup B, M)$ in which $A = V_1$ and $B = V_2 \times \dots \times V_r$. Since

$$n^{r-1-1/(4s)^{r-2}} \binom{n}{s} < n^{r-1} \binom{n^{1-1/(4s)^{r-1}}}{s}$$

for $n \geq 2^{(4s)^{r-1}}$, there exists $A_1 \times M' \subset M$ with $|A_1| = s$ and $|M'| = n^{r-1-1/(4s)^{r-2}}$. By appealing to the induction hypothesis, we conclude M' contains $A_2 \times \dots \times A_r$ such that $|A_i| = s$ for every $2 \leq i \leq r-1$ and $|A_r| = \sqrt{n}$. This completes the proof of Lemma A.2. \square

We now show a similar bound for a number of copies of r -partite graphs.

Theorem A.3. *Every n -vertex r -graph G with $e \geq n^{r-1}/6^{r-1}$ edges contains $\frac{1}{6r}(e/n)^{1/r}$ vertex-disjoint copies of the complete r -partite r -graph $K_r(s, \dots, s, t)$, where $s = \frac{1}{12} \left(\frac{\log n}{\log(n^r/e)} \right)^{1/(r-1)}$ and $t = n^{1/r}$.*

Proof. A vertex of G is called *expanding* if its degree is at least $re^{1-1/r}$. By the handshaking lemma, there are at most $e^{1/r}$ expanding vertices. Let k denote the maximum number of vertex-disjoint copies of $K_r(s, \dots, s, t)$ that can be embedded in G , whereas in each copy the r -th vertex class consists of t non-expanding vertices. Suppose to the contrary that $k < \frac{1}{6r}(e/n)^{1/r}$.

The number of edges containing some used vertices is at most $k(r-1)s \cdot \binom{n}{r-1} + kt \cdot re^{1-1/r} \leq e/3$ assuming $e \geq n^{r-1/r}$. Moreover, the number of edges within the set

of expanding vertices is at most $\binom{e^{1/r}}{r} \leq e/6$. Therefore, by removing those edges we obtain a subhypergraph H with $e/2$ edges such that any edge of H contains at least one non-expanding vertex, and the edges of H don't touch used vertices. Let V_1, \dots, V_{r-1} be $r - 1$ copies of $V(G)$, and V_r be a copy of the set of non-expanding vertices. Denote by M the set of r -tuples (v_1, \dots, v_r) in $V_1 \times \dots \times V_r$ such that $\{v_1, \dots, v_r\}$ is an edge of H . Clearly, $|M| \geq |E(H)| \geq e/2 \geq n^{r-1}/(4s)^{r-1}$.⁸ Lemma A.2 implies that there exists a set $A_1 \times \dots \times A_r \subset M$ satisfying $|A_1| = \dots = |A_{r-1}| = s$ and $|A_r| = \sqrt{n} \geq t$. The sets A_1, \dots, A_r are disjoint, for the edges of H consist of distinct vertices. Hence H contains a copy of $K_r(s, \dots, s, t)$ in which the r -th vertex class is embedded in the set of non-expanding vertices, a contradiction to the maximality of k . \square

References

- [1] N. Alon, R. Yuster, The Turán number of sparse spanning graphs, *J. Comb. Theory, Ser. B* 103 (3) (2013) 337–343.
- [2] R. Alweiss, S. Lovett, K. Wu, J. Zhang, Improved bounds for the sunflower lemma, arXiv preprint arXiv:1908.08483.
- [3] T. Bell, S. Chueluecha, L. Warnke, Note on sunflowers, *Discrete Math.* 344 (2021).
- [4] M. Bucić, N. Draganić, B. Sudakov, Universal and unavoidable graphs, *Comb. Probab. Comput.* (2021), <https://doi.org/10.1017/S0963548321000110>, in press.
- [5] H. Buhrman, R. Cleve, A. Wigderson, Quantum vs. classical communication and computation, in: *Proceedings of 30th STOC, 1998*, pp. 63–68.
- [6] F.R.K. Chung, Unavoidable stars in 3-graphs, *J. Comb. Theory, Ser. A* 35 (3) (1983) 252–262.
- [7] F.R.K. Chung, Open problems of Paul Erdős in graph theory, *J. Graph Theory* 25 (1) (1997) 3–36.
- [8] F.R.K. Chung, P. Erdős, On unavoidable graphs, *Combinatorica* 3 (2) (1983) 167–176.
- [9] F.R.K. Chung, P. Erdős, On unavoidable hypergraphs, *J. Graph Theory* 11 (2) (1987) 251–263.
- [10] F.R.K. Chung, P. Frankl, The maximum number of edges in a 3-graph not containing a given star, *Graphs Comb.* 3 (1987) 111–126.
- [11] M. Deza, P. Frankl, Every large set of equidistant $(0, +1, -1)$ -vectors forms a sunflower, *Combinatorica* 1 (3) (1981) 225–231.
- [12] R.A. Duke, P. Erdős, Systems of finite sets having a common intersection, in: *Proceedings, 8th SE Conf. Combinatorics, Graph Theory and Computing, 1977*, pp. 247–252.
- [13] P. Erdős, A problem on independent r -tuples, *Ann. Univ. Sci. Budapest.* 8 (1965) 93–95.
- [14] P. Erdős, On a theorem of Rademacher–Turán, *Ill. J. Math.* 6 (1962) 122–127.
- [15] P. Erdős, T. Gallai, On the minimal number of vertices representing the edges of a graph, *Publ. Math. Inst. Hungar. Acad. Sci.* 6 (1961) 181–203.
- [16] P. Erdős, C. Ko, R. Rado, Intersection theorems for systems of finite sets, *Q. J. Math.* 12 (1961) 313–320.
- [17] P. Erdős, R. Rado, Intersection theorems for systems of sets, *J. Lond. Math. Soc.* 35 (1960) 85–90.
- [18] P. Frankl, An extremal problem for 3-graphs, *Acta Math. Acad. Sci. Hung.* 32 (1978) 157–160.
- [19] P. Frankl, Improved bounds for Erdős' matching conjecture, *J. Comb. Theory, Ser. A* 120 (2013) 1068–1072.
- [20] P. Frankl, On the maximum number of edges in a hypergraph with given matching number, *Discrete Appl. Math.* 216 (2017) 562–581.
- [21] P. Frankl, Proof of the Erdős matching conjecture in a new range, *Isr. J. Math.* 222 (2017) 421–430.
- [22] P. Frankl, Z. Füredi, Forbidding just one intersection, *J. Comb. Theory, Ser. A* 39 (1985) 160–176.
- [23] P. Frankl, Exact solution of some Turán-type problems, *J. Comb. Theory, Ser. A* 45 (1987) 226–262.
- [24] P. Frankl, A. Kupavskii, The Erdős Matching Conjecture and concentration inequalities, arXiv preprint arXiv:1806.08855.

⁸ Notice that $e/2 \geq n^{r-1}/(4s)^{r-1}$ provided $s \leq \frac{1}{6} \left(\frac{\log n}{\log(n^r/e)} \right)^{1/(r-1)}$, while $n \geq 2^{(4s)^{r-1}}$ for $s \leq \frac{1}{4} (\log n)^{1/(r-1)}$. Furthermore, for $e \geq n^{1-1/6^{r-1}}$ we have $\frac{1}{6} \left(\frac{\log n}{\log(n^r/e)} \right)^{1/(r-1)} \geq 1$.

- [25] P. Frankl, V. Rödl, Forbidden intersections, *Trans. Am. Math. Soc.* 300 (1987) 259–286.
- [26] P. Frankl, V. Rödl, A partition property of simplices in euclidean space, *J. Am. Math. Soc.* 3 (1990) 1–7.
- [27] P. Frankl, R.M. Wilson, Intersection theorems with geometric consequences, *Combinatorica* 1 (1981) 357–368.
- [28] Z. Füredi, D.S. Gunderson, Extremal numbers for odd cycles, *Comb. Probab. Comput.* 24 (2015) 641–645.
- [29] Z. Füredi, On finite set-systems whose every intersection is a kernel of a star, *Discrete Math.* 47 (1983) 129–132.
- [30] Z. Füredi, Turán type problems, in: *Surveys in Combinatorics, 199*, Guildford, 1991, in: *London Math. Soc. Lecture Note Ser.*, vol. 166, Cambridge Univ. Press, Cambridge, 1991, pp. 253–300.
- [31] Z. Füredi, M. Simonovits, The history of degenerate (bipartite) extremal graph problems, in: *Erdős Centennial*, in: *Bolyai Soc. Math. Stud.*, vol. 25, János Bolyai Math. Soc., Budapest, 2013, pp. 169–264.
- [32] P. Keevash, Hypergraph Turán problems, in: *Surveys in Combinatorics 2011*, in: *London Math. Soc. Lecture Note Ser.*, vol. 392, Cambridge Univ. Press, Cambridge, 2011, pp. 83–139.
- [33] P. Keevash, E. Long, Frankl-Rödl-type theorems for codes and permutations, *Trans. Am. Math. Soc.* 369 (2017) 1147–1162.
- [34] P. Keevash, E. Long, Forbidden vector-valued intersections, *Proc. Lond. Math. Soc.* 121 (2020) 702–742.
- [35] P. Kövári, V. Sós, P. Turán, On a Problem of K. Zarankiewicz, *Colloquium Mathematicum*, vol. 3, Polska Akademia Nauk, 1954, pp. 50–57.
- [36] D. Mubayi, O. Pikhurko, B. Sudakov, Turán problem: some open questions, available online at <https://homepages.warwick.ac.uk/~maskat/Papers/TuranQuestions.pdf>.
- [37] Polymath10: the Erdős Rado delta system conjecture, available online at <https://gilkalai.wordpress.com/2015/11/03/polymath10-the-erdos-rado-delta-system-conjecture/>.
- [38] A. Rao, Coding for sunflowers, *Discrete Anal.* (2020), arXiv preprint arXiv:1909.04774.
- [39] J. Sgall, Bounds on pairs of families with restricted intersections, *Combinatorica* 19 (1999) 555–566.
- [40] A. Sidorenko, What we know and what we do not know about Turán numbers, *Graphs Comb.* 11 (2) (1995) 179–199.
- [41] V.T. Sós, Some remarks on the connection of graph theory, finite geometry and block designs, in: *Proc. Coll. Int. Teorie Combinatorie, Accad. Naz. Lincei, Roma, 1973*, pp. 223–233.
- [42] B. Sudakov, Recent developments in extremal combinatorics: Ramsey and Turán type problems, in: *Proceedings of the International Congress of Mathematicians, vol. IV*, Hindustan Book Agency, New Delhi, 2010, pp. 2579–2606.
- [43] P. Turán, On an extremal problem in graph theory, *Mat. Fiz. Lapok* 48 (1941) 436–452.