

ARTICLE

# Codegree Conditions for Tiling Complete $k$ -Partite $k$ -Graphs and Loose Cycles

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## Abstract

Given two  $k$ -graphs ( $k$ -uniform hypergraphs)  $F$  and  $H$ , a perfect  $F$ -tiling (or  $F$ -factor) in  $H$  is a set of vertex-disjoint copies of  $F$  that together cover the vertex set of  $H$ . For all complete  $k$ -partite  $k$ -graphs  $K$ , Mycroft proved a minimum codegree condition that guarantees a  $K$ -factor in an  $n$ -vertex  $k$ -graph, which is tight up to an error term  $o(n)$ . In this paper we improve the error term in Mycroft's result to a sublinear term that relates to the Turán number of  $K$  when the differences of the sizes of the vertex classes of  $K$  are co-prime. Furthermore, we find a construction which shows that our improved codegree condition is asymptotically tight in infinitely many cases, thus disproving a conjecture of Mycroft. Finally, we determine exact minimum codegree conditions for tiling  $K^{(k)}(1, \dots, 1, 2)$  and tiling loose cycles, thus generalizing the results of Czygrinow, DeBiasio and Nagle, and of Czygrinow, respectively.

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## 1. Introduction

Given  $k \geq 2$ , a  $k$ -uniform hypergraph (for short,  $k$ -graph) is a pair  $H = (V, E)$ , where  $V$  is a finite vertex set and  $E$  is a family of  $k$ -element subsets of  $V$ . Given a  $k$ -graph  $H$  and a set  $S$  of  $d$  vertices in  $V(H)$ ,  $1 \leq d \leq k - 1$ , we let  $\deg_H(S)$  denote the number of edges of  $H$  containing  $S$ . The *minimum  $d$ -degree*  $\delta_d(H)$  of  $H$  is the minimum of  $\deg(S)$  over all  $d$ -subsets  $S$  of  $V(H)$ . Furthermore, the minimum 1-degree is usually referred to as the *minimum vertex degree* and the minimum  $(k - 1)$ -degree is referred to as the *minimum collective degree (codegree)*.

As a natural extension of matching problems, (hyper)graph *tiling* (alternatively called *packing*) has received much attention in the past two decades (see [23] for a survey). Given two (hyper)graphs  $F$  and  $H$ , a *perfect  $F$ -tiling*, or an  *$F$ -factor*, of  $H$  is a spanning subgraph of  $H$  that consists of vertex-disjoint copies of  $F$ . Here we are interested in minimum degree thresholds that force perfect packings in hypergraphs. Given a  $k$ -graph  $F$  and an integer  $n$  divisible by  $|F|$ , let  $\delta(n, F)$  be the smallest integer  $t$  such that every  $n$ -vertex  $k$ -graph  $H$  with  $\delta_{k-1}(H) \geq t$  contains a perfect  $F$ -tiling.

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Perfect tilings for graphs are well understood. In particular, extending the results of Hajnal and Szemerédi [10] and Alon and Yuster [1] (see also [21]), Kühn and Osthus [24] determined  $\delta(n, F)$  for all graphs  $F$ , up to an additive constant, for sufficiently large  $n$ .

Over the past few years there has been growing interest in obtaining degree conditions that force a perfect  $F$ -tiling in  $k$ -graphs for  $k \geq 3$ . In general, this appears to be much harder than the graph case (see a recent survey [34]). Let  $K_4^3$  be the complete 3-graph on four vertices, and let  $K_4^{3-}$  be the (unique) 3-graph on four vertices with three edges. Let  $C_2^3$  be the unique 3-graph on four vertices with two edges. Lo and Markström [26] proved that  $\delta(n, K_4^3) = (1 + o(1))3n/4$ , and independently Keevash and Mycroft [20] determined the exact value of  $\delta(n, K_4^3)$  for sufficiently large  $n$ . In [25] Lo and Markström proved that  $\delta(n, K_4^{3-}) = (1 + o(1))n/2$ . Very recently, Han Lo, Treglown and Zhao [13] determined  $\delta(n, K_4^{3-})$  exactly for large  $n$ . Kühn and Osthus [22] showed that  $\delta(n, C_2^3) = (1 + o(1))n/4$ , and Czygrinow, DeBiasio and Nagle [5] determined  $\delta(n, C_2^3)$  exactly for large  $n$ . Han and Zhao [16] determined the exact minimum vertex degree threshold for perfect  $C_2^3$ -tiling for large  $n$ . With more involved arguments, Han, Zang and Zhao [15] determined the minimum vertex degree threshold for perfect  $K$ -tiling asymptotically for all complete 3-partite 3-graphs  $K$ .

Mycroft [29] proved a general result on tiling  $k$ -partite  $k$ -graphs. To state his result, we need the following definitions. Let  $F$  be a  $k$ -graph on a vertex set  $U$  with at least one edge. A  $k$ -partite realization of  $F$  is a partition of  $U$  into vertex classes  $U_1, \dots, U_k$  so that for any  $e \in E(F)$  and  $1 \leq j \leq k$  we have  $|e \cap U_j| = 1$ . We say that  $F$  is  $k$ -partite if it admits a  $k$ -partite realization. Define

$$S(F) := \bigcup_{\chi} \{|U_1|, \dots, |U_k|\} \text{ and } \mathcal{D}(F) := \bigcup_{\chi} \{||U_i| - |U_j|| : i, j \in [k]\},$$

where in each case the union is taken over all  $k$ -partite realizations  $\chi$  of  $F$  into vertex classes  $U_1, \dots, U_k$  of  $F$ . Then  $\text{gcd}(F)$  is defined to be the greatest common divisor of the set  $\mathcal{D}(F)$  (if  $\mathcal{D}(F) = \{0\}$  then  $\text{gcd}(F)$  is undefined). We also define

$$\sigma(F) := \frac{\min_{S \in S(F)} S}{|V(F)|},$$

and thus in particular,  $\sigma(F) \leq 1/k$ . Mycroft [29] proved the following:

$$\delta(n, F) \leq \begin{cases} n/2 + o(n) & \text{if } S(F) = \{1\} \text{ or } \text{gcd}(S(F)) > 1, \\ \sigma(F)n + o(n) & \text{if } \text{gcd}(F) = 1, \\ \max\{\sigma(F)n, n/p\} + o(n) & \text{if } \text{gcd}(S(F)) = 1 \text{ and } \text{gcd}(F) = d > 1, \end{cases} \tag{1.1}$$

where  $p$  is the smallest prime factor of  $d$ . Moreover, Mycroft [29] showed that equality holds in (1.1) for all complete  $k$ -partite  $k$ -graphs  $F$ , as well as a wide class of other  $k$ -partite  $k$ -graphs. Furthermore, he conjectured that the error terms in (1.1) can be replaced with a (sufficiently large) constant that depends only on  $F$ .

**Conjecture 1.1** ([29]). *Let  $F$  be a  $k$ -partite  $k$ -graph. Then there exists a constant  $C$  such that the error term  $o(n)$  in (1.1) can be replaced with  $C$ .*

Let  $K^{(k)}(a_1, \dots, a_k)$  denote the complete  $k$ -partite  $k$ -graph with parts of size  $a_1, \dots, a_k$ . In this paper we always assume that  $a_1 \leq \dots \leq a_k$ . Thus  $\sigma(K^{(k)}(a_1, \dots, a_k)) = a_1/m$ , where  $m := a_1 + \dots + a_k$ . The well-known *space barrier* (Construction 2.1) shows that

$$\delta(n, K^{(k)}(a_1, \dots, a_k)) \geq \frac{a_1}{m}n. \tag{1.2}$$

This shows that the second line of (1.1) is asymptotically best possible when  $F = K^{(k)}(a_1, \dots, a_k)$  and  $\text{gcd}(F) = 1$ .

We first give a simple construction (Construction 2.2) that strengthens the space barrier. Applying this construction, we obtain the following proposition, whose part (i) shows that Conjecture 1.1 is false for all complete  $k$ -partite  $k$ -graphs  $K$  with  $\gcd(K) = 1$  and  $a_{k-1} \geq 2$ . Given two  $k$ -graphs  $F$  and  $H$ , we call  $H$   $F$ -free if  $H$  does not contain  $F$  as a subgraph. The well-known Turán number  $\text{ex}(n, F)$  is the maximum number of edges in an  $F$ -free  $k$ -graph on  $n$  vertices. Correspondingly, the codegree Turán number  $\text{coex}(n, F)$  is the maximum of the minimum codegree of an  $F$ -free  $k$ -graph on  $n$  vertices. Note that  $\text{coex}(n, F) \binom{n}{k-1} / k \leq \text{ex}(n, F)$  because an  $n$ -vertex  $k$ -graph  $H$  with  $\delta_{k-1}(H) \geq \text{coex}(n, F)$  has at least  $\text{coex}(n, F) \binom{n}{k-1} / k$  edges.

**Proposition 1.2.** *Let  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $a_1 \leq \dots \leq a_k$  and  $m = a_1 + \dots + a_k$ .*

- (i) *If  $a_{k-1} \geq 2$ , then  $\delta(n, K) \geq a_1 n / m + (1 - o(1)) \sqrt{(m - a_1)n / m}$ .*
- (ii) *If  $a_1 = 1$ , then*

$$\delta(n, K) \geq \frac{n}{m} + \text{coex}\left(\frac{m-1}{m}n + 1, K\right).$$

Our main result sharpens the second case of (1.1) by using the Turán number and the Frobenius number. Given integers  $0 \leq b_1 \leq \dots \leq b_k$  such that  $\gcd(b_1, \dots, b_k) = 1$ , the Frobenius number  $g(b_1, \dots, b_k)$  is the largest integer that cannot be expressed as  $\ell_1 b_1 + \dots + \ell_k b_k$  for any non-negative integers  $\ell_1, \dots, \ell_k$ .<sup>1</sup> By definition,  $g(b_1, \dots, b_k) = -1$  if some  $b_i = 1$ ; otherwise  $g(b_1, \dots, b_k) > 0$ . No general formula of  $g(b_1, \dots, b_k)$  is known, but it is known [7, 33] that  $g(b_1, \dots, b_k) \leq (b_k - 1)^2$ .

**Theorem 1.3.** *Let  $k \geq 3$  and  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $a_1 \leq \dots \leq a_k$ ,  $m = a_1 + \dots + a_k$  and  $\gcd(K) = 1$ . Let  $n \in m\mathbb{N}$  be sufficiently large. Suppose  $H$  is an  $n$ -vertex  $k$ -graph such that*

$$\delta_{k-1}(H) \geq \frac{a_1}{m}n + f(n) + C, \tag{1.3}$$

where

$$f(n) := \max_{1-C \leq i \leq 1} \text{ex}\left(\frac{m-a_1}{m}n + i, K\right) k \binom{\left(\frac{(m-a_1)}{m}n + i\right)^{-1}}{k-1}$$

and  $C = g(a_2 - a_1, \dots, a_k - a_1) + 1$ . Then  $H$  contains a  $K$ -factor.

A classical result of Erdős [6] states that, given integers  $k \geq 2$  and  $1 \leq a_1 \leq \dots \leq a_k$ , there exists  $c$  such that, for all sufficiently large  $n$ ,

$$\text{ex}(n, K^{(k)}(a_1, \dots, a_k)) \leq cn^{k-1/a_1 \dots a_{k-1}}. \tag{1.4}$$

This implies that  $f(n)$  in Theorem 1.3 is at most  $O(n^{1-1/a_1 \dots a_{k-1}})$ , which is smaller than the error term  $o(n)$  in (1.1). Due to Proposition 1.2(ii), the term  $f(n)$  in Theorem 1.3 would be asymptotically tight if  $a_1 = 1$  and  $\text{coex}(n, K) = (1 - o(1)) \text{ex}(n, K)k / \binom{n}{k-1}$  (i.e. the extremal  $k$ -graph of  $K$  is almost regular in terms of codegree). Mubayi [28] determined  $\text{ex}(n, K^{(k)}(1, \dots, 1, 2, t))$  asymptotically for all  $t \geq 2$ . Since the extremal  $k$ -graph in this case is almost regular in terms of codegree, we obtain a sharpened value of  $\delta(n, K^{(k)}(1, \dots, 1, 2, t))$ . Moreover, Mubayi [28] also determined the order of magnitude of  $\text{ex}(n, K^{(k)}(1, \dots, 1, s, t))$  for  $s \geq 3$  and  $t \geq (s - 1)! + 1$ . This gives the correct order of magnitude of the second term of  $\delta(n, K^{(k)}(1, \dots, 1, s, t))$  for  $s \geq 3$  and  $t \geq (s - 1)! + 1$  such that  $\gcd(s - 1, t - s) = 1$ .

<sup>1</sup>The usual definition of Frobenius numbers requires that all  $b_1, \dots, b_k$  are positive and distinct.

**Corollary 1.4.** *Let  $k \geq 3$ .*

(i) *For any  $t \geq 2$ ,*

$$\delta(n, K^{(k)}(1, \dots, 1, 2, t)) = \frac{n}{k+t} + (1 + o(1))\sqrt{\frac{(t-1)(k+t-1)}{k+t}}n.$$

(ii) *For any  $s \geq 3$  and  $t \geq (s-1)! + 1$  such that  $\gcd(s-1, t-s) = 1$ ,*

$$\delta(n, K^{(k)}(1, \dots, 1, s, t)) = \frac{n}{k+s+t-2} + \Theta(n^{1-1/s}).$$

If  $K := K^{(k)}(a_1, \dots, a_k)$  satisfies  $\gcd(K) = 1$  and  $a_{k-1} = 1$ , then  $a_k = 2$  and consequently  $K = K^{(k)}(1, \dots, 1, 2)$ . In this case  $\text{ex}(n, K) \leq \binom{n}{k-1}/k$ , because in a  $K$ -free  $k$ -graph, every  $(k-1)$ -set has degree at most 1. Moreover,  $C = g(0, \dots, 0, 1) + 1 = 0$  in this case. Theorem 1.3 thus gives that  $\delta(n, K) \leq n/(k+1) + 1$ . By a more careful analysis on the proof of Theorem 1.3, we are able to determine  $\delta(n, K^{(k)}(1, \dots, 1, 2))$  exactly (for sufficiently large  $n$ ).

**Theorem 1.5.** *Given  $k \geq 3$ , let  $n \in (k+1)\mathbb{Z}$  be sufficiently large. Then*

$$\delta(n, K^{(k)}(1, \dots, 1, 2)) = \begin{cases} \frac{n}{k+1} + 1 & \text{if } k-i \mid \binom{n'-i}{k-1-i} \text{ for all } 0 \leq i \leq k-2, \\ \frac{n}{k+1} & \text{otherwise,} \end{cases}$$

where  $n' = (kn/(k+1)) + 1$ .

A Steiner system  $S(t, k, n)$  is an  $n$ -vertex  $k$ -uniform hypergraph in which every set of  $t$  vertices has degree exactly 1. The divisibility conditions in Theorem 1.5 are necessary for the existence of  $S(k-1, k, n')$ . Our proof of Theorem 1.5 applies a recent breakthrough of Keevash [19], who showed that these divisibility conditions are also sufficient for the existence of a Steiner system  $S(k-1, k, n')$  for sufficiently large  $n'$ .

When  $k = 3$ , the divisibility conditions in Theorem 1.5 reduce to  $8 \mid n$ . Since  $K^{(3)}(1, 1, 2) = C_2^3$ , Theorem 1.5 gives the aforementioned result of Czygrinow, DeBiasio and Nagle [5]. When  $k$  is even, the divisibility conditions in Theorem 1.5 always fail, and consequently  $\delta(n, K) = n/(k+1)$ . To see this, letting  $i = k-2$ , we have  $k-i = 2$  and

$$\binom{n'-i}{k-1-i} = n' - k + 2 = \frac{kn}{k+1} - k + 3.$$

When  $k$  is even,  $kn/(k+1) - k + 3$  is odd and thus

$$k-i \nmid \binom{n'-i}{k-1-i}.$$

Our last result is on tiling loose cycles. For  $k \geq 3$  and  $s > 1$ , a loose cycle of length  $s$ , denoted  $C_s^k$ , is a  $k$ -graph with  $s(k-1)$  vertices  $1, \dots, s(k-1)$  and  $s$  edges  $\{j(k-1) + 1, \dots, j(k-1) + k\}$  for  $0 \leq j < s$ , where we regard  $s(k-1) + 1$  as 1. It is easy to see that  $\gcd(C_s^k) = 1$  unless  $s = k = 3$  (see Proposition 6.4). Rödl and Ruciński [30, Problem 3.15] asked for the value of  $\delta(n, C_s^3)$ . Mycroft [29] determined  $\delta(n, C_s^k)$  asymptotically for all  $s \geq 2$  and  $k \geq 3$ . Recently, Gao and Han [9] have shown that  $\delta(n, C_3^3) = n/6$  and independently Czygrinow [4] determined  $\delta(n, C_s^3)$  for all  $s \geq 3$ . By modifying the proof of Theorem 1.3, we determine the exact value of  $\delta(n, C_s^k)$  for  $k \geq 4$  and  $s \geq 2$ .

**Theorem 1.6.** *Given  $k \geq 4$  and  $s \geq 2$ , let  $n \in s(k - 1)\mathbb{N}$  be sufficiently large. Suppose  $H$  is an  $n$ -vertex  $k$ -graph such that*

$$\delta_{k-1}(H) \geq \frac{\lceil s/2 \rceil}{s(k-1)}n.$$

*Then  $H$  contains a  $C_s^k$ -factor.*

Construction 2.1 shows that the codegree condition in Theorem 1.6 is sharp.

The rest of the paper is organized as follows. We prove Proposition 1.2 and Corollary 1.4 in Section 2. Next we discuss proof ideas and give auxiliary lemmas and use them to prove Theorems 1.3, 1.5 and 1.6 in Section 3. We prove the auxiliary lemmas in Sections 4–6.

## 2. Proof of Theorem 1.4

The following well-known construction is often called the *space barrier* (for tiling problems). Given a  $k$ -graph  $F$ , let  $\tau(F)$  be the smallest size of a *vertex cover* of  $F$ , namely, a set that meets each edge of  $F$ . Trivially  $\tau(K^{(k)}(a_1, \dots, a_k)) = a_1$ . We also have  $\tau(C_s^k) \geq \lceil s/2 \rceil$  because  $C_s^k$  has  $s$  edges and every vertex of  $C_s^k$  has degree at most two.<sup>2</sup>

**Construction 2.1.** *Fix a  $k$ -graph  $F$  of  $m$  vertices. Let  $H_0 = (V, E)$  be an  $n$ -vertex  $k$ -graph such that  $V = A \cup B$  with  $|A| = \tau(F)n/m - 1$  and  $|B| = n - |A|$ , and  $E$  consists of all  $k$ -sets that intersect  $A$ . We have  $\delta_{k-1}(H_0) = |A| = \tau(F)n/m - 1$ .*

Since each copy of  $F$  in  $H_0$  contains at least  $\tau(F)$  vertices in  $A$ ,  $H_0$  does not contain a perfect  $F$ -tiling. We slightly strengthen Construction 2.1 as follows.

**Construction 2.2.** *Let  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $a_1 \leq \dots \leq a_k$  and  $m = a_1 + \dots + a_k$ . Let  $H_1 = (V, E)$  be an  $n$ -vertex  $k$ -graph as follows. Let  $V = A \cup B$  such that  $|A| = a_1 n/m - 1$  and  $|B| = n - |A|$ . Let  $G$  be a  $k$ -graph on  $B$  which is  $K^{(k)}(b_1, b_2, \dots, b_k)$ -free for all  $1 \leq b_1 \leq \dots \leq b_k$  such that  $\sum_{i \in [k]} b_i = m - a_1 + 1$  and  $b_i \leq a_i$  for  $i \in [k]$ . Let  $E$  be the union of  $E(G)$  and the set of all  $k$ -tuples that intersect  $A$ , and thus  $\delta_{k-1}(H_0) = |A| + \delta_{k-1}(G) = a_1 n/m + \delta_{k-1}(G) - 1$ .*

In Construction 2.2, no  $m$ -set with at most  $a_1 - 1$  vertices in  $A$  spans a copy of  $K$ . Therefore each copy of  $K$  in  $H_0$  contains at least  $a_1$  vertices in  $A$  and consequently  $H_0$  does not contain a perfect  $K$ -tiling.

Now we give a construction of Mubayi [28]. Given  $t \geq 2$ , suppose that  $q$  is a prime number such that  $q \equiv 1 \pmod{t - 1}$ . Let  $n_0 = (q - 1)^2 / (t - 1)$ . Let  $\mathbf{F}$  be the  $q$ -element finite field, and let  $S$  be a (multiplicative) subgroup of  $\mathbf{F} \setminus \{0\}$  of order  $t - 1$ . We define a  $k$ -graph  $G_0$  whose vertex set consists of all equivalence classes in  $(\mathbf{F} \setminus \{0\}) \times (\mathbf{F} \setminus \{0\})$ , where  $(a, b) \sim (x, y)$  if there exists  $s \in S$  such that  $a = sx$  and  $b = sy$ . The class represented by  $(a, b)$  is denoted by  $\langle a, b \rangle$ . A set of  $k$  distinct classes  $\langle a_i, b_i \rangle$  ( $1 \leq i \leq k$ ) forms an edge in  $G_0$  if

$$\prod_{i=1}^k a_i + \prod_{i=1}^k b_i \in S.$$

It is easily observed that this relation is well-defined, and  $\delta_{k-1}(G_0) \geq q - k$ . Moreover, as shown in [28],  $G_0$  is  $K^{(k)}(1, \dots, 1, 2, t)$ -free.

<sup>2</sup>We also know  $\tau(C_s^k) \leq \lceil s/2 \rceil$  from Proposition 6.4.

To extend this construction, we use the fact that for any  $\varepsilon > 0$  and sufficiently large  $n$ , there exists a prime  $q$  such that  $q \equiv 1 \pmod{t-1}$  and  $n \leq (q-1)^2/(t-1) \leq (1+\varepsilon/3)n$  (see [17]). Let  $G_0$  be the  $k$ -graph on  $(q-1)^2/(t-1)$  vertices defined above. To obtain a  $K^{(k)}(1, \dots, 1, 2, t)$ -free  $k$ -graph  $G$  on  $n$  vertices, we delete a random set  $T$  of order  $(q-1)^2/(t-1) - n$  from  $G_0$  and let  $G := G_0 \setminus T$ . Since the expected value of the surviving codegree is at least  $(q-k)/(1+\varepsilon/3)$ , standard concentration results (e.g. Chernoff's bound) show that  $\delta_{k-1}(G) \geq (1-\varepsilon)\sqrt{(t-1)n}$  with positive probability. We summarize this construction together with the result on  $\text{ex}(n, K^{(k)}(1, \dots, 1, 2, t))$  from [28] in the following proposition.

**Proposition 2.3** ([28]). *For any  $t \geq 2$ , we have*

$$\text{coex}(n, K^{(k)}(1, \dots, 1, 2, t)) = (1 + o(1))\sqrt{(t-1)n},$$

and

$$\text{ex}(n, K^{(k)}(1, \dots, 1, 2, t)) = (1 + o(1))\frac{\sqrt{t-1}}{k!}n^{k-1/2}.$$

For integers  $s \geq 3$  and  $t \geq (s-1)! + 1$ , a more involved construction in [28] shows that there exists a  $K^{(k)}(1, \dots, 1, s, t)$ -free  $k$ -graph of order  $q^s - q^{s-1}$  for some prime number  $q$  with the desired minimum codegree. We omit the details of this construction and note that the construction can be extended to all sufficiently large  $n$  as above.

**Proposition 2.4** ([28]). *Given  $s \geq 3$  and  $t \geq (s-1)! + 1$ , we have  $\text{coex}(n, K^{(k)}(1, \dots, 1, s, t)) = \Theta(n^{1-1/s})$  and  $\text{ex}(n, K^{(k)}(1, \dots, 1, s, t)) = \Theta(n^{k-1/s})$ .*

**Proof of Proposition 1.2.** Assume  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $a_1 \leq \dots \leq a_k$ ,  $m = a_1 + \dots + a_k$  and  $a_{k-1} \geq 2$ . We will show that for any choice of  $b_1, b_2, \dots, b_k$  such that  $\sum_{i \in [k]} b_i = m - a_1 + 1$  and  $b_i \leq a_i$  for  $i \in [k]$ , we have  $b_{k-1} \geq 2$  (thus  $K^{(k)}(b_1, b_2, \dots, b_k)$  contains  $K^{(k)}(1, \dots, 1, 2, 2)$  as a subgraph). Then Proposition 1.2(i) follows from putting the  $k$ -graph  $G$  given by Proposition 2.3 with  $t = 2$  into Construction 2.2. To see why  $b_{k-1} \geq 2$ , first assume that  $a_1 = 1$ . In this case  $b_i = a_i$  for all  $i \in [k]$ . Since  $a_{k-1} \geq 2$ , we have  $b_{k-1} \geq 2$ . Second, assume that  $a_1 \geq 2$ . If  $b_{k-1} = 1$ , then  $b_1 = \dots = b_{k-1} = 1$  and consequently

$$\sum_{i \in [k]} a_i - \sum_{i \in [k]} b_i \geq (k-1)(a_1 - 1) > a_1 - 1,$$

a contradiction. Thus  $b_{k-1} \geq 2$ .

Proposition 1.2(ii) follows from Construction 2.2 immediately because  $a_1 = 1$  implies that  $a_i = b_i$  for  $i \in [k]$ . □

**Proof of Corollary 1.4.** The upper bounds in Corollary 1.4(i, ii) follow from Theorem 1.3 and the results on the Turán numbers from Propositions 2.3 and 2.4. The lower bounds follow from Proposition 1.2(ii) and the results on the codegree Turán numbers from Propositions 2.3 and 2.4. □

### 3. Proof ideas and lemmas

Mycroft's proofs [29] use the newly developed hypergraph blow-up lemma by Keevash [18]. Instead, our proofs include several new ingredients, which allow us to obtain a better bound via a much shorter proof. First, to obtain *exact* results, we separate the proof into a *non-extremal* case and an *extremal* case and deal with them separately. The proof of the non-extremal case utilizes

the *lattice-based absorbing method* developed recently by the second author [12], which builds on the *absorbing method* initiated by Rödl, Ruciński and Szemerédi [31]. In order to find an almost perfect  $K$ -tiling, we use the so-called *fractional homomorphic tiling*, which was used by Buß, Hàn and Schacht in [2], together with the weak regularity lemma for hypergraphs. Finally, we deal with the extremal case by careful analysis.

Now we give our lemmas. Throughout the paper, we write  $\alpha \ll \beta \ll \gamma$  to mean that we can choose the positive constants  $\alpha, \beta, \gamma$  from right to left. More precisely, there are increasing functions  $f$  and  $g$  such that, given  $\gamma$ , whenever we choose some  $\beta \leq f(\gamma)$  and  $\alpha \leq g(\beta)$ , the subsequent statement holds. Hierarchies of other lengths are defined similarly.

**Lemma 3.1 (Absorbing Lemma).** *Let  $k \geq 3$  and  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $a_1 \leq \dots \leq a_k$ ,  $m = a_1 + \dots + a_k$  and  $\gcd(K) = 1$ . Suppose  $\gamma' \ll \gamma \ll \rho$ ,  $1/m$  and  $n$  is sufficiently large. If  $H$  is an  $n$ -vertex  $k$ -graph such that  $\delta_{k-1}(H) \geq \rho n$ , then there exists a vertex set  $W \subseteq V(H)$  with  $|W| \leq \gamma n$  such that for any vertex set  $U \subseteq V(H) \setminus W$  with  $|U| \leq \gamma' n$  and  $|U| \in m\mathbb{Z}$ , both  $H[W]$  and  $H[U \cup W]$  contain  $K$ -factors.*

We say  $H$  is  $\xi$ -extremal if there exists a set  $B \subseteq V(H)$  of  $\lfloor (1 - \sigma(K))n \rfloor$  vertices such that  $e(B) \leq \xi \binom{|B|}{k}$ . In the following lemma we do not need the assumption  $\gcd(K) = 1$ , instead we assume that  $a_1 < a_k$  (which is necessary for  $\gcd(K) = 1$ ). Note that the  $a_1 = a_k$  (i.e.  $a_1 = \dots = a_k$ ) case has been solved in [9, Lemma 2.4].

**Lemma 3.2 (K-tiling Lemma).** *Let  $k \geq 3$  and  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $a_1 \leq \dots \leq a_k$ ,  $a_1 < a_k$ ,  $m = a_1 + \dots + a_k$ . For any  $\alpha, \gamma, \xi > 0$  such that  $\gamma \ll 1/m$  and  $\xi \geq 5bk^2\gamma$ , there exists an integer  $n_0$  such that the following holds. If  $H$  is a  $k$ -graph on  $n > n_0$  vertices with  $\delta_{k-1}(H) \geq (a_1/m - \gamma)n$ , then  $H$  has a  $K$ -tiling that covers all but at most  $\alpha n$  vertices unless  $H$  is  $\xi$ -extremal.*

Finally we give the extremal cases for Theorems 1.3, 1.5 and 1.6, respectively.

**Theorem 3.3.** *Given  $k \geq 3$ , let  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $a_1 \leq \dots \leq a_k$ ,  $m = a_1 + \dots + a_k$  and  $\gcd(K) = 1$ . Suppose  $1/n \ll \xi \ll 1/m$  and  $n \in m\mathbb{N}$ . If  $H$  is an  $n$ -vertex  $k$ -graph which is  $\xi$ -extremal and satisfies (1.3), then  $H$  contains a  $K$ -factor.*

**Theorem 3.4.** *Given  $k \geq 3$ , let  $1/n \ll \xi \ll 1/k$  such that  $n \in (k + 1)\mathbb{N}$ . Suppose  $H$  is an  $n$ -vertex  $k$ -graph that is  $\xi$ -extremal. Then  $H$  contains a  $K^{(k)}(1, \dots, 1, 2)$ -factor if either of the following holds:*

- (i)  $\delta_{k-1}(H) \geq n/(k + 1) + 1$ ,
- (ii)  $\delta_{k-1}(H) \geq n/(k + 1)$  and  $k - i \nmid \binom{n'-i}{k-1-i}$  for some  $0 \leq i \leq k - 2$  and  $n' = kn/(k + 1) + 1$ .

**Theorem 3.5.** *Given  $k \geq 4$  and  $s \geq 2$ , let  $1/n \ll \xi \ll 1/s, 1/k$  such that  $n \in s(k - 1)\mathbb{N}$ . Suppose  $H$  is an  $n$ -vertex  $k$ -graph with*

$$\delta_{k-1}(H) \geq \frac{\lceil s/2 \rceil}{s(k - 1)} n.$$

*If  $H$  is  $\xi$ -extremal, then  $H$  contains a  $C_s^k$ -factor.*

**Proofs of Theorems 1.3, 1.5 and 1.6.** We first prove Theorem 1.3. Let  $k \geq 3$  and  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $a_1 \leq \dots \leq a_k$ ,  $m = a_1 + \dots + a_k$  and  $\gcd(K) = 1$ . Suppose  $1/n \ll \gamma' \ll \gamma \ll \xi \ll 1/m$  and  $n \in m\mathbb{N}$ . Suppose  $H$  is an  $n$ -vertex  $k$ -graph satisfying (1.3). If  $H$  is  $\xi$ -extremal,

then  $H$  contains a  $K$ -factor by Theorem 3.3. Otherwise we apply Lemma 3.1 and find an absorbing set  $W$  in  $V(H)$  of size at most  $\gamma n$  which has the absorbing property. Let  $H' := H \setminus W$  and  $n' = |V(H')| \geq (1 - \gamma)n$ . Note that  $m \mid n'$ . If  $H'$  is  $(\xi/2)$ -extremal, then there exists a vertex subset  $B'$  in  $V(H')$  of order  $\lfloor (1 - \sigma(K))n' \rfloor$  such that

$$e_{H'}(B') \leq \frac{\xi}{2} \binom{|B'|}{k}.$$

Thus by adding to  $B'$  at most  $n - n' \leq \gamma n$  vertices, we get a set  $B$  of exactly  $\lfloor (1 - \sigma(K))n \rfloor$  vertices in  $V(H)$  with

$$e_H(B) \leq e_{H'}(B') + \gamma n \cdot \binom{n-1}{k-1} \leq \frac{\xi}{2} \binom{|B'|}{k} + k\gamma \binom{n}{k} \leq \xi \binom{|B|}{k}$$

because of the choice of  $\gamma$ . This means that  $H$  is  $\xi$ -extremal, a contradiction. We thus assume that  $H'$  is not  $(\xi/2)$ -extremal. By applying Lemma 3.2 on  $H'$  with  $\xi/2$  and  $\alpha = \gamma'$ , we obtain a  $K$ -tiling  $M$  that covers all but a set  $U$  of at most  $\gamma'n$  vertices. By the absorbing property of  $W$ ,  $H[W \cup U]$  contains a  $K$ -factor, and together with the  $K$ -tiling  $M$  we obtain a  $K$ -factor of  $H$ .

The proof of Theorem 1.6 is the same except that we replace  $K$  with  $C_s^k$  and Theorem 3.3 with Theorem 3.5 (here we apply Lemma 3.2 with the  $k$ -partite  $k$ -graph given by Proposition 6.4). Similarly, after replacing Theorem 3.3 with Theorem 3.4, the arguments above prove the upper bounds in Theorem 1.5. To see the lower bounds, we know  $\delta(n, K^{(k)}(1, \dots, 1, 2)) \geq n/(k + 1)$  from (1.2). Let  $n' = kn/(k + 1) + 1$ . If  $k - i \mid \binom{n-i}{k-1-i}$  for all  $0 \leq i \leq k - 2$ , then the result of Keevash [19] implies that the Steiner system  $S(k - 1, k, n')$  exists, in other words,  $\text{coex}(n', K^{(k)}(1, \dots, 1, 2)) = 1$ . Then the lower bound  $\delta(n, K^{(k)}(1, \dots, 1, 2)) \geq n/(k + 1) + 1$  follows from Proposition 1.2(ii).  $\square$

#### 4. Proof of the absorbing lemma

The following simple proposition will be useful.

**Proposition 4.1.** *Let  $H$  be a  $k$ -graph. If  $\delta_{k-1}(H) \geq xn$  for some  $0 \leq x \leq 1$ , then  $\delta_1(H) \geq x \binom{n-1}{k-1}$ .*

The following concepts were introduced by Lo and Markström [26]. Given a  $k$ -graph  $F$  of order  $m$ ,  $\beta > 0$ ,  $i \in \mathbb{N}$ , we say that two vertices  $u, v$  in a  $k$ -graph  $H$  on  $n$  vertices are  $(F, \beta, i)$ -reachable (in  $H$ ) if and only if there are at least  $\beta n^{im-1}$   $(im - 1)$ -sets  $W$  such that both  $H[\{u\} \cup W]$  and  $H[\{v\} \cup W]$  contain  $F$ -factors. A vertex set  $A$  is  $(F, \beta, i)$ -closed in  $H$  if every pair of vertices in  $A$  are  $(F, \beta, i)$ -reachable in  $H$ . For  $x \in V(H)$ , let  $\tilde{N}_{F,\beta,i}(x)$  be the set of vertices that are  $(F, \beta, i)$ -reachable to  $x$  in  $H$ .

We use the following lemma in [14] which gives us a partition  $\mathcal{P} = \{V_1, \dots, V_r\}$  on  $H$  such that, for any  $i \in [r]$ ,  $V_i$  is  $(F, \beta, 2^{c-1})$ -closed.

**Lemma 4.2 (Lemma 6.3 of [14]).** *Let  $c, k, m \geq 2$  be integers and suppose  $1/n \ll \beta \ll \alpha \ll 1/c, \delta', 1/m$ . Let  $F$  be an  $m$ -vertex  $k$ -graph. Assume an  $n$ -vertex  $k$ -graph  $H$  satisfies  $|\tilde{N}_{F,\alpha,1}(v)| \geq \delta' n$  for any  $v \in V(H)$  and every set of  $c + 1$  vertices in  $V(H)$  contains two vertices that are  $(F, \alpha, 1)$ -reachable. Then we can find a partition  $\mathcal{P}$  of  $V(H)$  into  $V_1, \dots, V_r$  with  $r \leq \min\{c, 1/\delta'\}$  such that, for any  $i \in [r]$ ,  $|V_i| \geq (\delta' - \alpha)n$  and  $V_i$  is  $(F, \beta, 2^{c-1})$ -closed in  $H$ .*

Let  $\mathcal{P} = \{V_1, \dots, V_r\}$  be a vertex partition of  $H$ . The index vector  $\mathbf{i}_{\mathcal{P}}(S) \in \mathbb{Z}^r$  of a subset  $S \subset V$  with respect to  $\mathcal{P}$  is the vector whose coordinates are the sizes of the intersections of  $S$  with each part of  $\mathcal{P}$ , that is,  $\mathbf{i}_{\mathcal{P}}(S)_{V_i} = |S \cap V_i|$  for  $i \in [r]$ . We call a vector  $\mathbf{i} \in \mathbb{Z}^r$  an  $s$ -vector if all its



coordinates are non-negative and their sum is equal to  $s$ . Given a  $k$ -graph  $F$  of order  $m$  and  $\mu > 0$ , an  $m$ -vector  $\mathbf{v}$  is called a  $\mu$ -robust  $F$ -vector if there are at least  $\mu n^m$  copies  $C$  of  $F$  in  $H$  satisfying  $\mathbf{i}_{\mathcal{P}}(V(C)) = \mathbf{v}$ . Let  $I_{\mathcal{P},F}^{\mu}(H)$  be the set of all  $\mu$ -robust  $F$ -vectors. For  $j \in [r]$ , let  $\mathbf{u}_j \in \mathbb{Z}^r$  be the  $j$ th unit vector, namely,  $\mathbf{u}_j$  has 1 on the  $j$ th coordinate and 0 on other coordinates. A transferral is a vector of form  $\mathbf{u}_i - \mathbf{u}_j$  for some distinct  $i, j \in [r]$ . Let  $L_{\mathcal{P},F}^{\mu}(H)$  be the lattice (i.e. the additive subgroup) generated by  $I_{\mathcal{P},F}^{\mu}(H)$ .

To prove Lemma 3.1, our main tool is Lemma 4.2 together with the following results. The next proposition is a simple counting result that follows from (1.4).

**Proposition 4.3.** *Given integers  $k, r_0, a_1, \dots, a_k \in \mathbb{N}$ , suppose that  $1/n \ll \mu \ll \eta, 1/k, 1/r_0, 1/a_1, \dots, 1/a_k$ . Let  $H$  be a  $k$ -graph on  $n$  vertices with a vertex partition  $V_1 \cup \dots \cup V_r$  where  $r \leq r_0$ . Suppose  $i_1, \dots, i_k \in [r]$  and  $H$  contains at least  $\eta n^k$  edges  $e = \{v_1, \dots, v_k\}$  such that  $v_1 \in V_{i_1}, \dots, v_k \in V_{i_k}$ . Then  $H$  contains at least  $\mu n^{a_1 + \dots + a_k}$  copies of  $K^{(k)}(a_1, \dots, a_k)$  whose  $j$ th part is contained in  $V_{i_j}$  for all  $j \in [k]$ .*

We use the following result in [15], which says that  $V(H)$  is closed when all the transferrals of  $\mathcal{P}$  are present. We state it in a less general form, namely, we omit the trash set  $V_0$  in its original form.

**Lemma 4.4 (Lemma 3.9 of [15]).** *Let  $i_0, k, r_0 > 0$  be integers and let  $F$  be an  $m$ -vertex  $k$ -graph. Suppose  $1/n \ll 1/i_0, \beta' \ll \varepsilon, \beta, \mu$  such that  $i_0 \in \mathbb{Z}$ . Let  $H$  be a  $k$ -graph on  $n$  vertices with a partition  $\mathcal{P} = \{V_1, \dots, V_r\}$  such that  $r \leq r_0$  and for each  $j \in [r]$ ,  $|V_j| \geq \varepsilon n$  and  $V_j$  is  $(F, \beta, i_0)$ -closed in  $H$ . If  $\mathbf{u}_j - \mathbf{u}_l \in L_{\mathcal{P},F}^{\mu}(H)$  for all  $1 \leq j < l \leq r$ , then  $V(H)$  is  $(F, \beta', i_0)$ -closed in  $H$ .*

The following lemma of Lo and Markström provides the desired absorbing set when  $V(H)$  is closed.

**Lemma 4.5 (Lemma 1.1 of [26]).** *Let  $m$  and  $i$  be positive integers and let  $F$  be an  $m$ -vertex  $k$ -graph. Suppose  $1/n \ll \gamma' \ll \beta, 1/m, 1/i$  and  $H$  is an  $(F, \beta, i)$ -closed  $k$ -graph of order  $n$ . Then there exists a vertex set  $W \subseteq V(H)$  with  $|W| \leq \beta n$  such that for any vertex set  $U \subseteq V(H) \setminus W$  with  $|U| \leq \gamma' n$  and  $|U| \in m\mathbb{Z}$ , both  $H[W]$  and  $H[U \cup W]$  contain  $F$ -factors.*

We need another lemma from [26].

**Lemma 4.6 (Lemma 4.2 of [26]).** *Let  $k \geq 2$  be an integer and  $F$  be an  $m$ -vertex  $k$ -partite  $k$ -graph. Suppose  $1/n \ll \alpha \ll \gamma$ . For any  $k$ -graph  $H$  of order  $n$ , two vertices  $x, y \in V(H)$  are  $(F, \alpha, 1)$ -reachable to each other if the number of  $(k - 1)$ -sets  $S \in N(x) \cap N(y)$  with  $|N(S)| \geq \gamma n$  is at least  $\gamma^2 \binom{n}{k-1}$ .*

**Proof of Lemma 3.1.** Let  $k \geq 3$  and  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $a_1 \leq \dots \leq a_k, m = a_1 + \dots + a_k$  and  $\gcd(K) = 1$ . Given  $\rho > 0$ , we select other parameters as follows. We pick  $0 < \eta, \gamma \ll \rho$  such that  $(\lfloor 1/\rho \rfloor + 1)\rho > 1 + (\lfloor 1/\rho \rfloor + 1)^2\gamma$ . When applying Proposition 4.3 with  $r_0 = \lfloor 1/\rho \rfloor$  and  $\eta$ , we get  $0 < \mu \ll \eta$ . When applying Lemma 4.6, we get  $0 < \alpha \ll \gamma$ . When applying Lemma 4.2 with  $\alpha, c = \lfloor 1/\rho \rfloor$ , and  $\delta' = \rho - \gamma$ , we get  $\beta > 0$ . When applying Lemma 4.4 with  $i_0 = 2^{\lfloor 1/\rho \rfloor - 1}, r_0 = \lfloor 1/\rho \rfloor, \varepsilon = \rho - 2\gamma, \beta$ , and  $\mu$ , we get  $\beta'$  and an integer  $i_0'$ . Finally, when applying Lemma 4.5 with  $\beta'$  and  $i_0'$ , we get  $\gamma' > 0$ .

Let  $n$  be a sufficiently large integer and let  $H$  be a  $k$ -graph on  $n$  vertices such that  $\delta_{k-1}(H) \geq \rho n$ . By Proposition 4.1, we have  $\delta_1(H) \geq \rho \binom{n-1}{k-1}$ . First, for every  $v \in V(H)$ , let us bound  $|\tilde{N}_{K,\alpha,1}(v)|$  from below. Given any  $(k - 1)$ -set  $S$ , we have  $|N(S)| \geq \rho n$  because  $\delta_{k-1}(H) \geq \rho n$ . Then, by

Lemma 4.6, for any distinct  $u, v \in V(H)$ ,  $u \in \tilde{N}_{K,\alpha,1}(v)$  if  $|N(u) \cap N(v)| \geq \gamma^2 \binom{n}{k-1}$ . By double-counting, we have

$$\sum_{S \in N(v)} |N(S)| < |\tilde{N}_{K,\alpha,1}(v)| \cdot |N(v)| + n \cdot \gamma^2 \binom{n}{k-1}.$$

Note that  $|N(v)| \geq \delta_1(H) \geq \rho \binom{n-1}{k-1}$ . Together with  $\gamma \ll \rho$ , we get

$$|\tilde{N}_{K,\alpha,1}(v)| > \rho n - \frac{\gamma^2 n^k}{|N(v)|} \geq (\rho - \gamma)n. \tag{4.1}$$

Next we claim that every set of  $\lfloor 1/\rho \rfloor + 1$  vertices in  $V(H)$  contains two vertices that are  $(K, \alpha, 1)$ -reachable. Indeed, since  $\delta_1(H) \geq \rho \binom{n-1}{k-1}$ , the degree sum of any  $\lfloor 1/\rho \rfloor + 1$  vertices is at least  $(\lfloor 1/\rho \rfloor + 1)\rho \binom{n-1}{k-1}$ . By the definition of  $\gamma$ , we have

$$(\lfloor 1/\rho \rfloor + 1)\rho \binom{n-1}{k-1} > \left(1 + \binom{\lfloor 1/\rho \rfloor + 1}{2} \gamma\right) \binom{n}{k-1}.$$

By the Inclusion–Exclusion Principle, there exist  $u, v \in V(H)$  such that  $|N(u) \cap N(v)| \geq \gamma \binom{n}{k-1}$ , so they are  $(K, \alpha, 1)$ -reachable by Lemma 4.6.

By (4.1) and the above claim, we can apply Lemma 4.2 on  $H$  with the constants chosen at the beginning of the proof. So we get a partition  $\mathcal{P} = \{V_1, \dots, V_r\}$  of  $V(H)$  such that  $r \leq \min\{\lfloor 1/\rho \rfloor, 1/(\rho - \gamma)\} = \lfloor 1/\rho \rfloor$  and for any  $i \in [r]$ ,  $|V_i| \geq (\rho - 2\gamma)n$  and  $V_i$  is  $(K, \beta, 2^{c-1})$ -closed in  $H$ .

Now we show that  $\mathbf{u}_i - \mathbf{u}_j \in L_{\mathcal{P},K}^\mu(H)$  for all distinct  $i, j \in [r]$ . Without loss of generality, assume  $i = 1$  and  $j = 2$ . For any  $u \in V_1$  and  $v \in V_2$ , since  $\delta_{k-1}(H) \geq \rho n$ ,  $u$  and  $v$  are contained in at least  $\binom{n-2}{k-3} \rho n / (k-2)$  edges. Since there are  $\binom{k+r-1}{r-1}$   $k$ -vectors, by averaging, there exists a  $k$ -vector  $\mathbf{v}$  whose first two coordinates are positive and which is the index vector of at least

$$\frac{1}{\binom{k}{2}} \cdot \frac{|V_1||V_2| \binom{n-2}{k-3} \rho n / (k-2)}{\binom{k+r-1}{r-1}} > \eta n^k$$

edges (we divide by a factor of  $\binom{k}{2}$  because an edge may be counted at most  $\binom{k}{2}$  times because of its intersections with  $V_1$  and  $V_2$ ). Note that we can write  $\mathbf{v} = \mathbf{v}_1 + \mathbf{v}_2 + \dots + \mathbf{v}_k$  such that all  $\mathbf{v}_i \in \{\mathbf{u}_1, \dots, \mathbf{u}_r\}$ . Without loss of generality, assume that  $\mathbf{v}_1 = \mathbf{u}_1$  and  $\mathbf{v}_2 = \mathbf{u}_2$ .

We apply Proposition 4.3 with  $a_1, a_2, \dots, a_k$  and conclude that there are at least  $\mu n^m$  copies of  $K$  in  $H$  with index vector  $\mathbf{v}' = a_1 \mathbf{u}_1 + a_2 \mathbf{u}_2 + a_3 \mathbf{v}_3 + \dots + a_k \mathbf{v}_k$ . We then apply Proposition 4.3 again with  $a_2, a_1, \dots, a_k$  (with  $a_1, a_2$  exchanged) and conclude that there are at least  $\mu n^m$  copies of  $K$  in  $H$  with index vector  $\mathbf{v}'' = a_2 \mathbf{u}_1 + a_1 \mathbf{u}_2 + a_3 \mathbf{v}_3 + \dots + a_k \mathbf{v}_k$ . By definition, we have  $\mathbf{v}', \mathbf{v}'' \in L_{\mathcal{P},K}^\mu(H)$  and thus  $(a_1 - a_2)\mathbf{u}_1 + (a_2 - a_1)\mathbf{u}_2 = \mathbf{v}' - \mathbf{v}'' \in L_{\mathcal{P},K}^\mu(H)$ . By repeating the arguments for other permutations of  $a_1, a_2, \dots, a_k$ , we get that  $\mathbf{w}_i := (a_{i+1} - a_i)\mathbf{u}_1 + (a_i - a_{i+1})\mathbf{u}_2 \in L_{\mathcal{P},K}^\mu(H)$  for  $i = 1, 2, \dots, k-1$ . Recall that since  $\gcd(K) = 1$ , there exist  $\ell_1, \ell_2, \dots, \ell_{k-1} \in \mathbb{Z}$  such that

$$\ell_1(a_2 - a_1) + \ell_2(a_3 - a_2) + \dots + \ell_{k-1}(a_k - a_{k-1}) = 1.$$

Hence

$$\mathbf{u}_1 - \mathbf{u}_2 = \ell_1 \mathbf{w}_1 + \ell_2 \mathbf{w}_2 + \dots + \ell_{k-1} \mathbf{w}_{k-1} \in L_{\mathcal{P},K}^\mu(H)$$

and we are done.

Since  $\mathbf{u}_i - \mathbf{u}_j \in L_{\mathcal{P},K}^\mu(H)$  for all distinct  $i, j \in [r]$ , by Lemma 4.4, we conclude that  $V(H)$  is  $(K, \beta', i'_0)$ -closed. Thus the desired absorbing set is provided by Lemma 4.5.  $\square$

**5. Proof of the almost perfect tiling lemma**

For integers  $k \geq 2$  and  $1 \leq a_1 \leq a_2 \leq \dots \leq a_k$  with  $a_1 < a_k$ , let  $K := K^{(k)}(a_1, \dots, a_k)$ . Let  $m = |V(K)| = a_1 + \dots + a_k$  and  $\sigma(K) = a_1/m$ . Given an  $n$ -vertex  $k$ -graph  $H$  such that  $n$  is sufficiently large and  $\delta_{k-1}(H) \geq (\sigma(K) - o(1))n$ , we will show that either  $H$  has an almost perfect  $K$ -tiling, or  $H$  is  $\xi$ -extremal for some  $\xi > 0$ . Note that it suffices to consider the case when  $a_2 = a_3 = \dots = a_k$ . In fact, let  $K' := K^{(k)}((k-1)a_1, m - a_1, \dots, m - a_1)$  and note that  $\sigma(K) = \sigma(K') = a_1/m$ . Moreover, since  $K'$  has a perfect  $K$ -tiling, it suffices to find an almost perfect  $K'$ -tiling in  $H$ .

We thus consider  $K' := K^{(k)}(a, b, \dots, b)$  with  $a < b$  and call the vertex class of size  $a$  *small*, and those of size  $b$  *large*. Let  $m = a + (k-1)b$ . An  $\alpha$ -deficient  $K'$ -tiling of an  $n$ -vertex  $k$ -graph  $H$  is a  $K'$ -tiling of  $H$  that covers at least  $(1 - \alpha)n$  vertices. The following lemma allows a small number of  $(k-1)$ -subsets of  $V(H)$  to have low degree, and may find applications in other problems (e.g. in reduced hypergraphs after we apply the regularity lemma).

**Lemma 5.1.** *Fix integers  $k \geq 2$  and  $a < b$ ,  $0 < \gamma \ll 1/m$  and let  $K' := K^{(k)}(a, b, \dots, b)$ . For any  $\alpha > 0$  and  $\xi \geq 5bk^2\gamma$ , there exist  $\varepsilon > 0$  and an integer  $n_0$  such that the following holds. Suppose  $H$  is a  $k$ -graph on  $n > n_0$  vertices with  $\deg(S) \geq (\sigma(K') - \gamma)n$  for all but at most  $\varepsilon n^{k-1}$  sets  $S \in \binom{V(H)}{k-1}$ , then  $H$  has an  $\alpha$ -deficient  $K'$ -tiling or  $H$  is  $\xi$ -extremal.*

We will prove Lemma 5.1 by using the Weak Regularity Lemma for hypergraphs and the so-called fractional homomorphic tilings (introduced by Buß, Hàn and Schacht [2]).

**5.1 Weak regularity lemma**

Let  $H = (V, E)$  be a  $k$ -graph and let  $A_1, \dots, A_k$  be mutually disjoint non-empty subsets of  $V$ . We define  $e(A_1, \dots, A_k)$  to be the number of edges with one vertex in each  $A_i, i \in [k]$ , and the density of  $H$  with respect to  $(A_1, \dots, A_k)$  as

$$d(A_1, \dots, A_k) = \frac{e(A_1, \dots, A_k)}{|A_1| \cdots |A_k|}.$$

Given  $\varepsilon > 0$  and  $d \geq 0$ , we say a  $k$ -tuple  $(V_1, \dots, V_k)$  of mutually disjoint subsets  $V_1, \dots, V_k \subseteq V$  is  $(\varepsilon, d)$ -regular if

$$|d(A_1, \dots, A_k) - d| \leq \varepsilon$$

for all  $k$ -tuples of subsets  $A_i \subseteq V_i, i \in [k]$ , satisfying  $|A_i| \geq \varepsilon|V_i|$ . We say  $(V_1, \dots, V_k)$  is  $\varepsilon$ -regular if it is  $(\varepsilon, d)$ -regular for some  $d \geq 0$ . It is immediate from the definition that in an  $(\varepsilon, d)$ -regular  $k$ -tuple  $(V_1, \dots, V_k)$ , if  $V'_i \subset V_i$  has size  $|V'_i| \geq c|V_i|$  for some  $c \geq \varepsilon$ , then  $(V'_1, \dots, V'_k)$  is  $(\varepsilon/c, d)$ -regular.

The Weak Regularity Lemma (for hypergraphs) is a straightforward extension of Szemerédi’s regularity lemma for graphs [32].

**Theorem 5.2 (Weak Regularity Lemma).** *Given  $t_0 \geq 0$  and  $\varepsilon > 0$ , there exist  $T_0 = T_0(t_0, \varepsilon)$  and  $n_0 = n_0(t_0, \varepsilon)$  such that, for every  $k$ -graph  $H = (V, E)$  on  $n > n_0$  vertices, there exists a partition  $V = V_0 \cup V_1 \cup \dots \cup V_t$  such that:*

- (i)  $t_0 \leq t \leq T_0$ ,
- (ii)  $|V_1| = |V_2| = \dots = |V_t|$  and  $|V_0| \leq \varepsilon n$ ,
- (iii) for all but at most  $\varepsilon \binom{t}{k}$   $k$ -subsets  $\{i_1, \dots, i_k\} \subset [t]$ , the  $k$ -tuple  $(V_{i_1}, \dots, V_{i_k})$  is  $\varepsilon$ -regular.

The partition given in Theorem 5.2 is called an  $\varepsilon$ -regular partition of  $H$ . Given an  $\varepsilon$ -regular partition  $\mathcal{Q}$  of  $H$  and  $d \geq 0$ , we refer to  $V_i, i \in [t]$  as *clusters* and define the *cluster hypergraph*

$R = R(\varepsilon, d, \mathcal{Q})$  with vertex set  $[t]$  in which  $\{i_1, \dots, i_k\} \subset [t]$  is an edge if and only if  $(V_{i_1}, \dots, V_{i_k})$  is  $\varepsilon$ -regular and  $d(V_{i_1}, \dots, V_{i_k}) \geq d$ .

The following corollary shows that the cluster hypergraph inherits the minimum codegree of the original hypergraph. The proof is standard and very similar to that of [11, Proposition 16], so we omit the proof.

**Corollary 5.3** ([11]). *Suppose  $1/t_0 \ll \varepsilon \ll c, d, 1/k$ . Then there exist  $T$  and  $n_1$  such that the following holds. Let  $H$  be a  $k$ -graph on  $n > n_1$  vertices such that  $\deg_H(S) \geq cn$  for all but at most  $\varepsilon n^{k-1}$   $(k-1)$ -sets  $S$ . Then  $H$  has an  $\varepsilon$ -regular partition  $\mathcal{Q} = \{V_0, V_1, \dots, V_t\}$  with  $t_0 \leq t \leq T$  such that in the cluster hypergraph  $R = R(\varepsilon, d, \mathcal{Q})$ , all but at most  $\sqrt{\varepsilon} t^{k-1}$   $(k-1)$ -subsets  $S$  of  $[t]$  satisfy  $\deg_R(S) \geq (c - d - 5\sqrt{\varepsilon})t$ .*

**5.2 Fractional  $\text{hom}(K')$ -tiling**

Let  $K' := K^{(k)}(a, b, \dots, b)$  with  $a < b$ . To obtain a large  $K'$ -tiling in the hypergraph  $H$ , we consider weighted homomorphisms from  $K'$  into the cluster hypergraph  $R$ . For this purpose, we extend a definition introduced by Buř, Hàn and Schacht [2] for 3-graphs.<sup>3</sup>

**Definition.** Given a  $k$ -graph  $H$ , a function  $h : V(H) \times E(H) \rightarrow [0, 1]$  is called a fractional  $\text{hom}(K')$ -tiling of  $H$  if

- (1)  $h(v, e) = 0$  if  $v \notin e$ ,
- (2)  $h(v) = \sum_{e \in E(H)} h(v, e) \leq 1$ ,
- (3) for each  $e \in E(H)$  there exists a labelling  $e = v_1 \dots v_k$  such that

$$h(v_1, e) \leq \dots \leq h(v_k, e) \quad \text{and} \quad \frac{h(v_1, e)}{a_1} \geq \dots \geq \frac{h(v_k, e)}{a_k}$$

By  $h_{\min}$  we denote the smallest non-zero value of  $h(v, e)$  (and set  $h_{\min} = \infty$  if  $h \equiv 0$ ). For  $e = v_1 \dots v_k$ , we write  $h(v_1, \dots, v_k) = (h(v_1, e), \dots, h(v_k, e))$  and  $h(e) = \sum_{i \in [k]} h(v_i, e)$ . The sum over all values is the weight  $w(h)$  of  $h$ :

$$w(h) = \sum_{(v,e) \in V(H) \times E(H)} h(v, e).$$

Assume that  $V(K') = A_1 \cup \dots \cup A_k$  with  $|A_1| = a$  and  $|A_2| = \dots = |A_k| = b$ , and  $m = a + (k-1)b$ .

**Fact 5.4.** There is a fractional  $\text{hom}(K')$ -tiling of  $K'$  such that  $w(h) = m$  and  $h_{\min} = b^{1-k}$ .

**Proof.** For each edge  $e = v_1 \dots v_k$  of  $K'$  with  $v_i \in A_i$  for  $i \in [k]$ , we assign weight

$$h(v_1, \dots, v_k) = \left( \frac{1}{b^{k-1}}, \frac{1}{ab^{k-2}}, \dots, \frac{1}{ab^{k-2}} \right).$$

Then  $h(e) = m/(ab^{k-1})$  and consequently  $w(h) = m$ . □

In the rest of the proof, we will refer to the weight assignment in Fact 5.4 as the *standard weights*.

Let  $\widehat{K}'$  be a  $k$ -graph obtained from  $K'$  by adding  $k-1$  new vertices and a new edge that consists of the  $k-1$  new vertices and a vertex from a large vertex class of  $K'$ .

<sup>3</sup>As noted by a referee, we could also use Farkas's lemma here (see [3]).

**Proposition 5.5.** *There is a fractional hom  $(K')$ -tiling of  $\widehat{K}'$  such that  $w(h) \geq m + 1/(ab^{k-1})$  and  $h_{\min} = b^{1-k}$ .*

**Proof.** Assume  $V(K') = A_1 \cup \dots \cup A_k$  with  $|A_1| = a$  and  $|A_i| = b$  for  $2 \leq i \leq k$ . Let  $u_1, \dots, u_{k-1}$  be the vertices of  $\widehat{K}'$  not in  $V(K')$  and let  $e = \{v, u_1, \dots, u_{k-1}\}$  be the edge of  $\widehat{K}'$  not in  $E(K')$ , where  $v \in A_j$  for some  $j > 1$ . Fix any edge  $e_1 = x_1 \dots x_k$  of  $K'$  with  $x_i \in A_i$  for  $i \in [k]$  such that  $x_j = v$ . We assign the weight

$$h(v, u_1, \dots, u_{k-1}) = \left( \frac{1}{ab^{k-2}}, \frac{1}{a^2b^{k-3}}, \dots, \frac{1}{a^2b^{k-3}} \right).$$

to  $e$  and the standard weight to all the edges of  $K'$  except for  $e_1$ . Moreover, set  $e_1$  as unweighted. Since  $\sum_{e' \in E(K')} h(e') = m - m/(ab^{k-1})$  and  $h(e) = m/(a^2b^{k-2})$ , we have  $h_{\min} = b^{1-k}$  and

$$w(h) = m - \frac{m}{ab^{k-1}} + \frac{m}{a^2b^{k-2}} = m + \frac{1}{ab^{k-1}} \frac{m(b-a)}{a} \geq m + \frac{1}{ab^{k-1}}. \quad \square$$

The following proposition says that a fractional hom  $(K')$ -tiling in the cluster hypergraph can be converted to an integer  $K'$ -tiling in the original hypergraph. It is almost the same as [15, Proposition 4.4], which covers the  $k = 3$  case, so we omit its proof.

**Proposition 5.6.** *Suppose  $\varepsilon, \phi > 0$ ,  $d \geq 2\varepsilon/\phi$  and  $t > 0$  is an integer, and  $n$  is sufficiently large. Let  $H$  be a  $k$ -graph on  $n$  vertices with an  $(\varepsilon, t)$ -regular partition  $\mathcal{Q}$  and a cluster hypergraph  $\mathcal{R} = \mathcal{R}(\varepsilon, d, \mathcal{Q})$ . Suppose there is a fractional hom  $(K')$ -tiling  $h$  of  $\mathcal{R}$  with  $h_{\min} \geq \phi$ . Then there exists a  $K'$ -tiling of  $H$  that covers at least  $(1 - 2b\varepsilon/\phi)w(h)n/t$  vertices.  $\square$*

### 5.3 Proof of the $K'$ -tiling lemma (lemma 5.1)

**Proposition 5.7.** *For all  $0 < \rho \leq 1/2$  and all  $\xi, \beta, \delta, \varepsilon > 0$  the following holds. Suppose there exists an  $n_0$  such that, for every  $k$ -graph  $H$  on  $n > n_0$  vertices satisfying  $\deg(S) \geq \rho n$  for all but at most  $\varepsilon n^{k-1}$   $(k-1)$ -sets  $S$ , either  $H$  has a  $\beta$ -deficient  $K'$ -tiling or  $H$  is  $\xi$ -extremal. Then every  $k$ -graph  $H'$  on  $n' > n_0$  vertices with  $\deg(S) \geq (\rho - \delta)n'$  for all but at most  $\varepsilon(n')^{k-1}$   $(k-1)$ -sets  $S$  has a  $(\beta + 2\delta m)$ -deficient  $K'$ -tiling or is  $\xi$ -extremal.*

**Proof.** Suppose we are given a  $k$ -graph  $H'$  on  $n' > n_0$  vertices with  $\deg(S) \geq (\rho - \delta)n'$  for all but at most  $\varepsilon(n')^{k-1}$   $(k-1)$ -sets  $S$ . By adding a set  $A$  of  $2\delta n'$  new vertices to  $H'$  and adding to  $E(H)$  all  $k$ -subsets of  $V(H') \cup A$  that intersect  $A$ , we obtain a new hypergraph  $H$  on  $n = n' + 2\delta n'$  vertices. All  $(k-1)$ -subsets of  $V(H)$  that intersect  $A$  have degree  $n - k + 1$ . All but at most  $\varepsilon(n')^{k-1}$   $(k-1)$ -subsets  $S$  of  $V(H')$  satisfy

$$\deg(S) \geq (\rho - \delta)n' + 2\delta n' = \rho n' + \delta n' = \rho n - 2\rho\delta n' + \delta n' \geq \rho n$$

because  $\rho \leq 1/2$ . By assumption, either  $H$  has a  $\beta$ -deficient  $K'$ -tiling, or  $H$  is  $\xi$ -extremal. If  $H$  has a  $\beta$ -deficient  $K'$ -tiling, then by removing all the  $K'$ -copies that intersect  $A$ , we obtain a  $(\beta + 2\delta m)$ -deficient  $K'$ -tiling of  $H'$ . Otherwise  $H$  is  $\xi$ -extremal, namely, there exists a set  $B \subseteq V(H)$  of  $\lfloor (1 - \sigma(K'))n \rfloor$  vertices such that  $e(B) \leq \xi \binom{|B|}{k}$ . We can assume that  $A \cap B = \emptyset$  – otherwise we swap the vertices in  $A \cap B$  with the same number of vertices in  $V \setminus (A \cup B)$  and  $e(B)$  will not increase. By averaging, there exists a subset  $B' \subseteq B \subseteq V(H')$  of order exactly  $\lfloor (1 - \sigma(K'))n' \rfloor$  such that  $e(B') \leq \xi \binom{|B'|}{k}$ . Thus,  $H'$  is  $\xi$ -extremal.  $\square$

Now we are ready to prove Lemma 5.1.

**Proof of Lemma 5.1.** Fix positive integers  $a < b$  and  $k \geq 2$ , and a real number  $0 < \gamma \ll 1/m$ . Let  $m := a + (k - 1)b$  and  $\sigma := \sigma(K') = a/m$ . Trivially the lemma works when  $\alpha \geq 1$  or  $\xi \geq 1$ . Assume to the contrary that there exist  $\alpha \in (0, 1), \xi \in [5bk^2\gamma, 1)$  such that for all  $\varepsilon_0 > 0$  and integers  $n_0$ , Lemma 5.1 fails, namely, there is a  $k$ -graph  $H$  on  $n > n_0$  vertices which satisfies  $\deg(S) \geq (\sigma - \gamma)n$  for all but at most  $\varepsilon_0 n^{k-1}$   $(k - 1)$ -sets  $S$  but which does not contain an  $\alpha$ -deficient  $K'$ -tiling and is not  $\xi$ -extremal. Let  $\Gamma$  be the set of such pairs  $(\alpha, \xi)$ . Define  $f(\alpha, \xi) = \alpha + \gamma\alpha^2\xi$ , and let  $f_0$  be the supremum of  $f(\alpha, \xi)$  among all  $(\alpha, \xi) \in \Gamma$ .

Let  $\eta = \gamma^2 f_0^2 / 32$ . By the definition of  $f_0$ , there exists a pair  $(\alpha_0, \xi_0) \in \Gamma$  such that  $f_0 - \eta \leq f(\alpha_0, \xi_0) \leq f_0$ . Moreover, since  $1 + \gamma\alpha_0\xi_0 \leq 2$ , we have that  $\alpha_0 \geq (f_0 - \eta)/2 \geq f_0/4$ . Let  $d = (\gamma\alpha_0)^2 / (4m)$ . Since  $f(\alpha_0, \xi_0) \geq f_0 - \eta$ , we have

$$f(\alpha_0 + (\gamma\alpha_0)^2, \xi_0 - 5d) > \alpha_0 + (\gamma\alpha_0)^2 + \gamma\alpha_0^2(\xi_0 - 5d) \geq f_0 - \eta + \gamma\alpha_0^2(\gamma - 5d) \geq f_0$$

by  $d \leq \gamma^2 \leq \gamma/10$  and  $\eta = \gamma^2 f_0^2 / 32 \leq \gamma^2 \alpha_0^2 / 2$ . This means that  $(\alpha_0 + (\gamma\alpha_0)^2, \xi_0 - 5d) \notin \Gamma$ , that is, there exist  $\varepsilon_* > 0$  and  $n_* \in \mathbb{N}$  such that, for every  $k$ -graph  $H$  on  $n > n_*$  vertices satisfying  $\deg(S) \geq (\sigma - \gamma)n$  for all but at most  $\varepsilon_* n^{k-1}$   $(k - 1)$ -sets  $S$ ,  $H$  has an  $(\alpha_0 + (\gamma\alpha_0)^2)$ -deficient  $K'$ -tiling or is  $(\xi_0 - 5d)$ -extremal. Since  $\sigma < 1/k \leq 1/2$ , we can apply Proposition 5.7 with parameters  $\delta = 2d$  and  $\sqrt{\varepsilon}$  and derive that

(†) for every  $k$ -graph  $H'$  on  $n > n_*$  vertices satisfying  $\deg(S) \geq (\sigma - \gamma - 2d)n$  for all but at most  $\varepsilon_* n^{k-1}$   $(k - 1)$ -sets  $S$ , either  $H'$  has an  $(\alpha_0 + (\gamma\alpha_0)^2 + 4dm)$ -deficient  $K'$ -tiling, or it is  $(\xi_0 - 5d)$ -extremal.

Let  $\varepsilon > 0$  be such that  $\varepsilon \leq \min\{\varepsilon_*^2, d^k, (1/k - \sigma)/3, d/(2b^k)\}$  and  $\varepsilon \ll c, d, 1/k$  as required by Corollary 5.3. Let  $n_1$  and  $T$  be the parameters returned by Corollary 5.3 with inputs  $c = \sigma - \gamma, \varepsilon, d, k$  and sufficiently large  $t_0$  (in particular,  $t_0 > n_*$ ).

Let  $H$  be a  $k$ -graph on  $n \geq n_1$  vertices which satisfies  $\deg(S) \geq (\sigma - \gamma)n$  for all but at most  $\varepsilon n^{k-1}$   $(k - 1)$ -sets  $S$ . Our goal is to show that either  $H$  contains an  $\alpha_0$ -deficient  $K'$ -tiling or  $H$  is  $\xi_0$ -extremal. This implies that  $(\alpha_0, \xi_0) \notin \Gamma$ , contradicting the definition of  $(\alpha_0, \xi_0)$ . Let us apply Corollary 5.3 to  $H$  with the constants chosen above and obtain a cluster hypergraph  $R = R(\varepsilon, d, \mathcal{Q})$  on  $t \geq t_0$  vertices such that the number of  $(k - 1)$ -subsets  $S \subseteq V(R)$  violating

$$\deg_R(S) \geq (\sigma - \gamma - d - 5\sqrt{\varepsilon})t \geq (\sigma - \gamma - 2d)t$$

is at most  $\sqrt{\varepsilon}t^{k-1} \leq \varepsilon_* t^{k-1}$ . Let  $N$  be the number of vertices in each cluster except  $V_0$  and thus  $(1 - \varepsilon)(n/t) \leq N \leq n/t$ .

Note that the reduced  $k$ -graph  $R$  satisfies the assumption of (†). If  $R$  is  $(\xi_0 - 5d)$ -extremal, then there exists a vertex set  $B \subseteq V(R)$  of order  $\lfloor (1 - \sigma)t \rfloor$  such that  $e(B) \leq (\xi_0 - 5d) \binom{|B|}{k}$ . Let  $B' \subseteq V(H)$  be the union of the clusters in  $B$ . By regularity, we have

$$e(B') \leq e(B) \cdot N^k + \binom{t}{k} \cdot d \cdot N^k + \varepsilon \binom{t}{k} \cdot N^k + t \binom{N}{2} \binom{n-2}{k-2},$$

where the right-hand side bounds the number of edges from regular  $k$ -tuples with high density, edges from regular  $k$ -tuples with low density, edges from irregular  $k$ -tuples and edges that lie in at most  $k - 1$  clusters. Since  $e(B) \leq (\xi_0 - 5d) \binom{|B|}{k}$  and  $1/t \leq \varepsilon$ , we get

$$\begin{aligned} e(B') &\leq (\xi_0 - 5d) \binom{|B|}{k} N^k + (d + \varepsilon) \binom{t}{k} \left(\frac{n}{t}\right)^k + t \binom{n/t}{2} \binom{n-2}{k-2} \\ &\leq (\xi_0 - 5d) \binom{|B'|}{k} + (d + 2\varepsilon) \binom{n}{k}. \end{aligned}$$

Note that

$$|B'| = \lfloor (1 - \sigma)t \rfloor N \geq (1 - \sigma)(1 - \varepsilon)n - N \geq (1 - \sigma - 2\varepsilon)n.$$

On the other hand,  $|B'| \leq (1 - \sigma)n$  implies that  $|B'| \leq \lfloor (1 - \sigma)n \rfloor$ . By adding at most  $2\varepsilon n$  vertices of  $V \setminus B'$  to  $B'$ , we obtain a subset  $B'' \subseteq V(H)$  of size exactly  $\lfloor (1 - \sigma)n \rfloor$ , with  $e(B'') \leq e(B') + 2\varepsilon n \binom{n-1}{k-1} \leq e(B') + 2k\varepsilon \binom{n}{k}$ . Since  $\sigma < 1/k$  and  $\varepsilon \leq (1/k - \sigma)/3$ , we have

$$\binom{|B'|}{k} \geq \binom{(1 - \sigma - 2\varepsilon)n}{k} \geq (1 - \sigma - 2\varepsilon)^k \binom{n}{k} - O(n^{k-1}) \geq \left(1 - \frac{1}{k}\right)^k \binom{n}{k}.$$

Since  $(1 - 1/k)^k \geq 1/4$  for  $k \geq 2$ , it follows that

$$\binom{|B'|}{k} \geq \frac{1}{4} \binom{n}{k},$$

and consequently

$$e(B'') \leq (\xi_0 - 5d) \binom{|B'|}{k} + (d + 2\varepsilon + 2k\varepsilon) \binom{n}{k} \leq (\xi_0 - 5d + 4(d + 2\varepsilon + 2k\varepsilon)) \binom{|B'|}{k} \leq \xi_0 \binom{|B'|}{k}$$

by  $\varepsilon \leq d^k$ . Hence  $H$  is  $\xi_0$ -extremal, and we are done.

We thus assume that  $R$  is not  $(\xi_0 - 5d)$ -extremal. By  $(\dagger)$ ,  $R$  has an  $(\alpha_0 + (\gamma\alpha_0)^2 + 4dm)$ -deficient  $K'$ -tiling. Let  $\mathcal{K}$  be a largest  $K'$ -tiling of  $R$ , and let  $U$  be the set of vertices in  $R$  not covered by  $\mathcal{K}$ . Then  $|U| \leq (\alpha_0 + (\gamma\alpha_0)^2 + 4dm)t$ . Let  $q := |\mathcal{K}|$ .

Now assume that  $H$  contains no  $\alpha_0$ -deficient  $K'$ -tiling. The following proposition shows that there is no fractional hom  $(K')$ -tiling of  $R$  whose weight is substantially larger than  $(1 - \alpha_0)t$ .

**Claim 5.8.** *If  $h$  is a fractional hom  $(K')$ -tiling of  $R$  with  $h_{\min} \geq b^{1-k}$ , then  $w(h) \leq (1 - \alpha_0 + 2b^k\varepsilon)t \leq qm + 3(\gamma\alpha_0)^2t$ .*

**Proof.** We first observe that  $H$  contains an  $\alpha_0$ -deficient  $K'$ -tiling if there is a fractional hom  $(K')$ -tiling  $h$  of  $R$  with  $h_{\min} \geq b^{1-k}$  and  $w(h) \geq (1 - \alpha_0 + 2b^k\varepsilon)t$ . This indeed follows from Proposition 5.6 because  $2b^k\varepsilon \leq d = (\gamma\alpha_0)^2/(4m) < \alpha_0$  and

$$\left(1 - \frac{2b\varepsilon}{b^{1-k}}\right) w(h) \frac{n}{t} \geq (1 - 2b^k\varepsilon)(1 - \alpha_0 + 2b^k\varepsilon)t \frac{n}{t} > (1 - \alpha_0)n.$$

It remains to show that  $qm + 3(\gamma\alpha_0)^2t \geq (1 - \alpha_0 + 2b^k\varepsilon)t$ . Since  $|U| \leq (\alpha_0 + (\gamma\alpha_0)^2 + 4dm)t$  and  $|U| + qm = t$ , we have

$$qm + 3(\gamma\alpha_0)^2t \geq t - (\alpha_0 + (\gamma\alpha_0)^2 + 4dm)t + 3(\gamma\alpha_0)^2t \geq (1 - \alpha_0 + 2b^k\varepsilon)t$$

because  $4dm = (\gamma\alpha_0)^2$  and  $2b^k\varepsilon < (\gamma\alpha_0)^2$ . □

We claim the following for  $|U|$ :

$$|U| \geq \frac{\alpha_0}{2}t \quad \text{and} \quad e(U) \leq \frac{\gamma}{k} \binom{|U|}{k}. \tag{5.1}$$

Indeed, if  $|U| < \alpha_0 t/2$ , then by applying Fact 5.4 to each member of  $\mathcal{K}$ , we obtain a fractional hom  $(K')$ -tiling  $h$  of  $R$  with  $h_{\min} = b^{1-k}$  and weight  $w(h) = (1 - \alpha_0/2)t > (1 - \alpha_0 + 2b^k\varepsilon)t$ . This contradicts Claim 5.8. If  $e(U) \geq \gamma \binom{|U|}{k}/k$ , then since  $|U| \geq \alpha_0 t/2$  and  $t$  is sufficiently large, we can apply (1.4) to find a copy of  $K'$  in  $U$ , contradicting the maximality of  $\mathcal{K}$ .

Let  $D$  be the set of vertices  $v \in V(R) \setminus U$  such that

$$\left| N(v) \cap \binom{U}{k-1} \right| \geq \gamma \binom{|U|}{k-1}.$$

Let  $\mathcal{K}_1 \subseteq \mathcal{K}$  be the set of copies of  $K'$  that contain at least  $a + 1$  vertices from  $D$ . Let  $\mathcal{K}_2 \subseteq \mathcal{K}$  be the set of copies of  $K'$  that contain exactly  $a$  vertices from  $D$ . Let  $\mathcal{K}_3 \subseteq \mathcal{K}$  be the set of copies of  $K'$  that contain at most  $a - 1$  vertices from  $D$ .

**Claim 5.9.**

$$|\mathcal{K}_1| < \frac{\gamma}{m(k-1)^2} |U| < \frac{\gamma}{m(k-1)^2} t.$$

**Proof.** Suppose instead that

$$|\mathcal{K}_1| \geq \frac{\gamma}{m(k-1)^2} |U|.$$

Let  $K_1, \dots, K_\ell$  be distinct members of  $\mathcal{K}_1$ , where

$$\ell = \left\lceil \frac{\gamma |U|}{m(k-1)^2} \right\rceil.$$

For each  $j \leq \ell$ , since  $|V(K_j) \cap D| \geq a + 1$ , we can find a vertex  $v_j \in D$  from a large vertex class of  $K_j$ . Since

$$\gamma \binom{|U|}{k-1} > \frac{\gamma |U|}{m(k-1)} \binom{|U|-1}{k-2} > (\ell - 1)(k-1) \binom{|U|-1}{k-2},$$

we can greedily pick disjoint  $(k - 1)$ -sets  $S_1, \dots, S_\ell$  from  $U$  such that  $S_j \in N(v_j)$ . Thus, for each  $j \leq \ell$ , by Proposition 5.5, we get a fractional hom  $(K')$ -tiling  $h^j$  of  $R[V(K_j) \cup S_j]$  such that  $w(h^j) \geq m + 1/(ab^{k-1})$  and  $h_{\min}^j \geq b^{1-k}$ . We assign the standard weight to other members of  $\mathcal{K}$  and thus obtain a fractional hom  $(K')$ -tiling  $h$  of  $R$  with  $h_{\min} \geq b^{1-k}$  and weight

$$w(h) \geq qm + \frac{\gamma |U|}{m(k-1)^2} \frac{1}{ab^{k-1}} \geq qm + \frac{\gamma \alpha_0 t}{2m(k-1)^2 ab^{k-1}} > qm + 3(\gamma \alpha_0)^2 t,$$

where we used (5.1) and that  $\gamma$  is small. This contradicts Claim 5.8. □

We now find an upper bound for  $|\mathcal{K}_3|$ . First, by the definitions of  $\mathcal{K}_1, \mathcal{K}_2, \mathcal{K}_3$  and  $e(U) \leq \gamma \binom{|U|}{k}/k$ , we have

$$\begin{aligned} \sum_{S \in \binom{U}{k-1}} \deg(S) &\leq (m|\mathcal{K}_1| + a|\mathcal{K}_2| + (a-1)|\mathcal{K}_3|) \binom{|U|}{k-1} + qm\gamma \binom{|U|}{k-1} + \gamma \binom{|U|}{k} \\ &\leq aq \binom{|U|}{k-1} + ((m-a)|\mathcal{K}_1| - |\mathcal{K}_3|) \binom{|U|}{k-1} + \gamma \binom{|U|}{k-1} t, \end{aligned}$$

where the second inequality follows from  $|\mathcal{K}_1| + |\mathcal{K}_2| + |\mathcal{K}_3| = q$  and  $qm + |U| = t$ . Second, the degree condition of  $R$  implies that

$$\sum_{S \in \binom{U}{k-1}} \deg(S) \geq \left( \binom{|U|}{k-1} - \sqrt{\varepsilon} t^{k-1} \right) (\sigma - \gamma - 2d)t.$$



Since  $|U| \geq \alpha_0 t/2$  and  $\varepsilon \leq d^k \leq (\gamma \alpha_0)^{2k}$ , we have

$$\sqrt{\varepsilon} t^{k-1} \leq (\gamma \alpha_0)^k \left(\frac{2|U|}{\alpha_0}\right)^{k-1} \leq \gamma \binom{|U|}{k-1}$$

as  $\gamma \leq 1/(2k)$  and  $|U|$  is sufficiently large. It follows that

$$\sum_{S \in \binom{U}{k-1}} \deg(S) \geq \left(\binom{|U|}{k-1} - \gamma \binom{|U|}{k-1}\right) \left(\frac{a}{m} - (\gamma + 2d)\right) t \geq \binom{|U|}{k-1} a q - 2\gamma \binom{|U|}{k-1} t,$$

where the last inequality holds because  $2d \leq \gamma(m - a)/m$  and  $qm \leq t$ . Comparing the upper and lower bounds for  $\sum_{S \in \binom{U}{k-1}} \deg(S)$  gives

$$|\mathcal{K}_3| \leq (m - a)|\mathcal{K}_1| + 3\gamma t.$$

By Claim 5.9, it follows that

$$|\mathcal{K}_1| + |\mathcal{K}_3| \leq |\mathcal{K}_1| + (m - a)|\mathcal{K}_1| + 3\gamma t \leq 4\gamma t. \tag{5.2}$$

Thus we have  $|\mathcal{K}_2| \geq q - 4\gamma t$ .

Let  $A$  be the union of  $U$  and the vertices covered by  $\mathcal{K}_2$  but not in  $D$ . Then

$$|A| \geq |U| + (m - a)(q - 4\gamma t) \geq (1 - \sigma)t - 4(m - a)\gamma t \geq \left(1 - \frac{1}{k}\right)t \tag{5.3}$$

because  $\gamma$  is small. We claim that we can find a set  $\mathcal{M}$  of  $\ell'$  disjoint edges in  $A$ , where  $\ell' = \lceil \gamma|U|/(km^2) \rceil$ . Indeed, by deleting some vertices or adding at most  $4(m - a)\gamma t$  vertices from  $V(R) \setminus A$  to  $A$ , we can obtain a set  $A'$  of size exactly  $\lfloor (1 - \sigma)t \rfloor$ . Since  $R$  is not  $(\xi_0 - 5d)$ -extremal, we have that  $e(A') \geq (\xi_0 - 5d) \binom{|A'|}{k}$ . If  $|A| > \lfloor (1 - \sigma)t \rfloor$ , then as

$$e(A') \geq (\xi_0 - 5d) \binom{|A'|}{k} > (\ell' - 1)k \binom{|A'| - 1}{k - 1},$$

we can find the desired  $\mathcal{M}$  in  $A' \subseteq A$ . Otherwise, for  $|A| \leq \lfloor (1 - \sigma)t \rfloor$ , by (5.3), it follows that

$$\begin{aligned} e(A) &\geq e(A') - 4(m - a)\gamma t \cdot \binom{|A| - 1}{k - 1} \\ &\geq (\xi_0 - 5d) \binom{|A'|}{k} - 4(m - a)\gamma \frac{|A|}{1 - 1/k} \binom{|A| - 1}{k - 1} \\ &\geq (\xi_0 - 5d - 4bk^2\gamma) \binom{|A|}{k} \\ &> \gamma \binom{|A|}{k} \\ &> (\ell' - 1)k \binom{|A| - 1}{k - 1} \end{aligned}$$

because  $\xi_0 \geq 5bk^2\gamma$  and  $5d < \gamma$ . Thus we can greedily find the desired  $\mathcal{M}$  in  $A$ .

Let  $K_1, \dots, K_p$  denote the members of  $\mathcal{K}_2$  that intersect the edges of  $\mathcal{M}$ , where  $p \leq k\ell'$ . For each  $j \in [p]$ , suppose  $V(K_j) \cap D = \{v_{j,1}, \dots, v_{j,a}\}$ . For each  $j \in [p]$  and  $i \in [a]$ , we claim that we can greedily find disjoint copies  $K'_{j,i}$  of complete  $(k - 1)$ -partite  $(k - 1)$ -graphs  $K^{(k-1)}(b, \dots, b)$  in  $N(v_{j,i}) \cap \binom{U}{k-1}$ . Indeed, during the process, at most  $pa(k - 1)b + k\ell'$  vertices of  $U$  are occupied and the number of  $(k - 1)$ -subsets of  $U$  intersecting these vertices is at most

$$(pa(k - 1)b + k\ell') \binom{|U| - 1}{k - 2} \leq amk\ell' \binom{|U| - 1}{k - 2} \leq \frac{k - 1}{k} \gamma \binom{|U|}{k - 1}$$

because  $\ell' \leq \gamma|U|/(km^2) + 1$ ,  $ak < m$ , and  $|U|$  is sufficiently large. Thus, since

$$\left| N(v_{j,i}) \cap \binom{U}{k-1} \right| - \frac{k-1}{k} \gamma \binom{|U|}{k-1} \geq \gamma \binom{|U|}{k-1} - \frac{k-1}{k} \gamma \binom{|U|}{k-1} = \frac{\gamma}{k} \binom{|U|}{k-1},$$

we can apply (1.4) to find the desired  $K'_{j,i}$  for all  $v_{j,i}$ .

For each  $j \in [p]$  and  $i \in [a]$ ,  $R[V(K'_{j,i}) \cup \{v_{j,i}\}]$  spans a copy of  $K^{(k)}(1, b, \dots, b)$ . We now assign the weight  $(1/b^{k-1}, 1/(ab^{k-2}), \dots, 1/(ab^{k-2}))$  to each edge of this  $K^{(k)}(1, b, \dots, b)$  such that the weight of  $v_{j,i}$  is  $1/b^{k-1}$ . The total weight of  $R[V(K'_{j,i}) \cup \{v_{j,i}\}]$  is thus  $1 + b(k-1)/a = m/a$ . Next we assign the standard weight to each member of  $\mathcal{K} \setminus \{K_1, \dots, K_p\}$ . Finally, we assign weight  $(1, \dots, 1)$  to all the edges of  $\mathcal{M}$ . This gives a fractional hom  $(K')$ -tiling  $h$  with  $h_{\min} = b^{1-k}$  and weight

$$w(h) = pa \frac{m}{a} + (q-p)m + k\ell' \geq qm + \frac{\gamma|U|}{m^2} \geq qm + \frac{\gamma\alpha_0 t}{2m^2} > qm + 3(\gamma\alpha_0)^2 t,$$

where we used (5.1) and that the assumption  $\gamma$  is small. This contradicts Claim 5.8 and completes our proof. □

### 6. The extremal case

In this section we prove Theorems 3.3, 3.4 and 3.5. We first give some notation. Given two disjoint vertex sets  $X$  and  $Y$  and two integers  $i, j \geq 0$ , a set  $S \subset X \cup Y$  is called an  $X^i Y^j$ -set if  $|S \cap X| = i$  and  $|S \cap Y| = j$ . When  $X, Y$  are two disjoint subsets of  $V(H)$  and  $i + j = k$ , we let  $H(X^i Y^j)$  denote the family of all edges of  $H$  that are  $X^i Y^j$ -sets, and let  $e_H(X^i Y^j) = |H(X^i Y^j)|$  (the subscript may be omitted if it is clear from the context). We use  $\bar{e}_H(X^i Y^{k-i})$  to denote the number of non-edges among  $X^i Y^{k-i}$ -sets. Given a set  $L \subseteq X \cup Y$  with  $|L \cap X| = l_1 \leq i$  and  $|L \cap Y| = l_2 \leq k - i$ , we define  $\text{deg}(L, X^i Y^{k-i})$  as the number of edges in  $H(X^i Y^{k-i})$  that contain  $L$ , and

$$\overline{\text{deg}}(L, X^i Y^{k-i}) = \binom{|X| - l_1}{i - l_1} \binom{|Y| - l_2}{k - i - l_2} - \text{deg}(L, X^i Y^{k-i}).$$

Our earlier notation  $\text{deg}(S, R)$  may be viewed as  $\text{deg}(S, S^{|S|}(R \setminus S)^{k-|S|})$ .

#### 6.1 Tools and a general set-up

The following lemma deals with a special (ideal) case of Theorem 3.3. We postpone its proof to the end of this section.

**Lemma 6.1.** *Let  $K := K^{(k)}(a_1, \dots, a_k)$  with  $m := a_1 + \dots + a_k$ . Suppose  $1/n \ll \rho \ll 1/m$  and  $n \in m\mathbb{Z}$ . Suppose  $H$  is a  $k$ -graph on  $n$  vertices with a partition of  $V(H) = X \cup Y$  such that  $a_1|Y| = (m - a_1)|X|$ . Furthermore, assume that*

- for every vertex  $v \in X$ ,  $\overline{\text{deg}}(v, Y) \leq \rho \binom{|Y|}{k-1}$ ,
- for every vertex  $u \in Y$ ,  $\overline{\text{deg}}(u, XY^{k-1}) \leq \rho \binom{|Y|}{k-1}$ .

Then  $H$  contains a  $K$ -factor.

We use the following simple fact in the proof.

**Fact 6.2.** Let  $t, m, n \in \mathbb{N}$  and  $F$  be an  $m$ -vertex  $k$ -partite  $k$ -graph. Let  $H$  be an  $n$ -vertex  $k$ -graph with maximum vertex degree  $\Delta$  and  $e(H) > (t - 1)m\Delta + \text{ex}(n', F)$ , where  $n' = n - (t - 1)m$ . Then  $H$  contains an  $F$ -tiling of size  $t$ .

**Proof.** Assume to the contrary that the largest  $F$ -tiling  $M$  in  $H$  has size at most  $t - 1$ . Let  $V'$  be a set of  $(t - 1)m$  vertices containing  $V(M)$ . Therefore,  $V(H) \setminus V'$  spans no copy of  $F$  and thus spans at most  $\text{ex}(n', F)$  edges. So we have  $e(H) \leq (t - 1)m\Delta + \text{ex}(n', F)$ , a contradiction.  $\square$

Now we start with a general set-up and prove some estimates. Assume that  $k \geq 3, a_1 \leq \dots \leq a_k$  and  $m = a_1 + \dots + a_k$ . Suppose  $1/n \ll \xi \ll 1/m$  such that  $n \in m\mathbb{N}$ . Let  $H$  be a  $k$ -graph on  $V$  of  $n$  vertices such that  $\delta_{k-1}(H) \geq a_1 n/m$ . Furthermore, assume that there is a set  $B \subseteq V(H)$ , such that  $|B| = (m - a_1)n/m$  and  $e(B) \leq \xi \binom{|B|}{k}$ . Let  $A = V \setminus B$ . Then  $|A| = a_1 n/m$ . Note that we only require  $\delta_{k-1}(H) \geq a_1 n/m$ , so we can use the estimates in all proofs.

Let  $\varepsilon_1 = \xi^{1/7}, \varepsilon_2 = \xi^{1/3}$  and  $\varepsilon_3 = 2\xi^{2/3}$ . We now define

$$A' := \left\{ v \in V : \overline{\text{deg}}(v, B) \leq \varepsilon_2 \binom{|B|}{k-1} \right\},$$

$$B' := \left\{ v \in V : \text{deg}(v, B) \leq \varepsilon_1 \binom{|B|}{k-1} \right\}, \quad V_0 := V \setminus (A' \cup B').$$

**Claim 6.3.**  $\{|A \setminus A'|, |B \setminus B'|, |A' \setminus A|, |B' \setminus B|\} \leq \varepsilon_3 |B|$  and  $|V_0| \leq 2\varepsilon_3 |B|$ .

**Proof.** First assume that  $|B \setminus B'| > \varepsilon_3 |B|$ . By the definition of  $B'$ , we get that

$$e(B) > \frac{1}{k} \varepsilon_1 \binom{|B|}{k-1} \cdot \varepsilon_3 |B| > 2\xi \binom{|B|}{k},$$

which contradicts  $e(B) \leq \xi \binom{|B|}{k}$ .

Second, assume that  $|A \setminus A'| > \varepsilon_3 |B|$ . Then by the definition of  $A'$ , for any vertex  $v \notin A'$ , we have that  $\overline{\text{deg}}(v, B) > \varepsilon_2 \binom{|B|}{k-1}$ . So we get

$$\overline{e}(AB^{k-1}) > \varepsilon_3 |B| \cdot \varepsilon_2 \binom{|B|}{k-1} = 2\xi |B| \binom{|B|}{k-1}.$$

Together with  $e(B) \leq \xi \binom{|B|}{k}$ , this implies that

$$\begin{aligned} \sum_{S \in \binom{B}{k-1}} \overline{\text{deg}}(S) &= k\overline{e}(B) + \overline{e}(AB^{k-1}) \\ &> k(1 - \xi) \binom{|B|}{k} + 2\xi |B| \binom{|B|}{k-1} \\ &= ((1 - \xi)(|B| - k + 1) + 2\xi |B|) \binom{|B|}{k-1} \\ &> |B| \binom{|B|}{k-1}. \end{aligned}$$

where the last inequality holds because  $n$  is large enough. By the pigeonhole principle, there exists a set  $S \in \binom{B}{k-1}$ , such that  $\overline{\text{deg}}(S) > |B| = (m - a_1)n/m$ , contradicting  $\delta_{k-1}(H) \geq a_1 n/m$ .

Consequently

$$\begin{aligned} |A' \setminus A| &= |A' \cap B| \leq |B \setminus B'| \leq \varepsilon_3|B|, \\ |B' \setminus B| &= |A \cap B'| \leq |A \setminus A'| \leq \varepsilon_3|B|, \\ |V_0| &\leq |A \setminus A'| + |B \setminus B'| \leq \varepsilon_3|B| + \varepsilon_3|B| = 2\varepsilon_3|B|. \end{aligned} \quad \square$$

Note that by  $|B \setminus B'| \leq \varepsilon_3|B|$  we have

$$\deg(w, B') \geq \deg(w, B) - |B \setminus B'| \binom{|B|}{k-2} \geq \frac{\varepsilon_1}{2} \binom{|B'|}{k-1} \quad \text{for any vertex } w \in V_0, \tag{6.1}$$

and by  $|B' \setminus B| \leq \varepsilon_3|B|$  we have

$$\overline{\deg}(v, B') \leq \overline{\deg}(v, B) + |B' \setminus B| \binom{|B'|}{k-2} \leq 2\varepsilon_2 \binom{|B'|}{k-1} \quad \text{for any vertex } v \in A' \tag{6.2}$$

and

$$\deg(v, B') \leq \deg(v, B) + |B' \setminus B| \binom{|B'|}{k-2} \leq 2\varepsilon_1 \binom{|B'|}{k-1} \quad \text{for any vertex } v \in B'. \tag{6.3}$$

Moreover, for any  $(k-1)$ -set  $S \subseteq B'$ , by

$$\deg(S, A') + \deg(S, B') + \deg(S, V_0) \geq \delta_{k-1}(H) \quad \text{and} \quad \overline{\deg}(S, A') = |A'| - \deg(S, A'),$$

we have

$$\overline{\deg}(S, A') \leq |A'| - \delta_{k-1}(H) + \deg(S, B') + \deg(S, V_0) \leq \deg(S, B') + 3\varepsilon_3|B|,$$

where we used

$$\deg(S, V_0) \leq |V_0| \leq 2\varepsilon_3|B|, \quad |A'| \leq \frac{a_1}{m}n + \varepsilon_3|B| \quad \text{and} \quad \delta_{k-1}(H) \geq \frac{a_1}{m}n.$$

Furthermore, for any  $v \in B'$ , by (6.3), we have

$$\sum_{S: v \in S \in \binom{B'}{k-1}} \deg(S, B') = (k-1) \deg(v, B') \leq 2(k-1)\varepsilon_1 \binom{|B'|}{k-1}.$$

Putting these together gives that, for any  $v \in B'$ ,

$$\overline{\deg}(v, A' B'^{k-1}) = \sum_S \overline{\deg}(S, A') \leq \sum_S \deg(S, B') + 3\varepsilon_3|B| \binom{|B'| - 1}{k-2} \leq 2k\varepsilon_1 \binom{|B'|}{k-1}, \tag{6.4}$$

where the sums are on  $S$  such that  $v \in S \in \binom{B'}{k-1}$ . Let  $\mathcal{B}$  be the set of  $(k-1)$ -sets  $S \subseteq B'$  such that  $\overline{\deg}_H(S, A') > \sqrt{2\varepsilon_2}|A'|$ . By (6.2), we have that  $\overline{e}_H(A' B'^{k-1}) \leq 2\varepsilon_2|A'| \binom{|B'|}{k-1}$  and thus

$$|\mathcal{B}| \leq \sqrt{2\varepsilon_2} \binom{|B'|}{k-1}. \tag{6.5}$$

In all three proofs we will define  $\varepsilon_1, \varepsilon_2, \varepsilon_3$  and  $A', B', V_0$  in the same way and thus Claim 6.3 and (6.1)–(6.5) hold.

**6.2 Proof of Theorem 3.3**

Assume that  $k \geq 3$ ,  $a_1 \leq \dots \leq a_k$  and  $m = a_1 + \dots + a_k$ . Let  $K := K^{(k)}(a_1, \dots, a_k)$  such that  $\gcd(K) = 1$ . Suppose  $1/n \ll \xi \ll 1/m$  such that  $n \in m\mathbb{N}$ . Assume  $H$  is a  $\xi$ -extremal  $k$ -graph on

$n$  vertices that satisfies (1.3). Let  $B$  be a set of  $(m - a_1)n/m$  vertices such that  $e(B) \leq \xi \binom{|B|}{k}$ . Let  $A = V \setminus B$ . Define  $\varepsilon_1, \varepsilon_2, \varepsilon_3, A', B', V_0$  as in Section 1.1 and thus Claim 6.3 and (6.1)–(6.5) hold.

In the following proof we will build four vertex-disjoint  $K$ -tilings  $\mathcal{K}_1, \mathcal{K}_2, \mathcal{K}_3, \mathcal{K}_4$ , whose union is a  $K$ -factor of  $H$ . The ideal case is when  $(m - a_1)|A'| = a_1|B'|$  and  $V_0 = \emptyset$  – in this case we apply Lemma 6.1 to obtain a  $K$ -factor of  $H$  such that each copy of  $K$  has  $a_1$  vertices in  $A'$  and  $m - a_1$  vertices in  $B'$ . So the purpose of the  $K$ -tilings  $\mathcal{K}_1, \mathcal{K}_2, \mathcal{K}_3$  is to cover the vertices of  $V_0$  and adjust the sizes of  $A'$  and  $B'$  so that we can apply Lemma 6.1 (and obtain  $\mathcal{K}_4$ ) after  $\mathcal{K}_1, \mathcal{K}_2, \mathcal{K}_3$  are removed. More precisely, we cover the vertices of  $V_0$  by  $\mathcal{K}_2$  and let

$$q := |B'| - |B| = \frac{a_1}{m}n - |A'| - |V_0|$$

denote the *discrepancy* between the current and ideal sizes of  $B'$ . If  $q > 0$ , then we apply the minimum codegree condition to find copies of  $K$  from  $B'$ . Since removing a copy of  $K$  from  $B'$  reduces the discrepancy by  $a_1$ , we cannot reduce the discrepancy to zero unless  $a_1$  divides  $q$ . Therefore we remove enough copies of  $K$  from  $B'$  (denoted by  $\mathcal{K}_1$ ) such that the discrepancy is less than or equal to  $-C$ . This allows us to apply the definition of Frobenius numbers and remove more copies of  $K$  (denoted by  $\mathcal{K}_3$ ) to ‘increase’ the discrepancy to zero.

**The  $K$ -tilings  $\mathcal{K}_1, \mathcal{K}_2$ .** Our goal is to find  $K$ -tilings  $\mathcal{K}_1, \mathcal{K}_2$  such that  $V_0 \subseteq V(\mathcal{K}_2)$ ,

$$|\mathcal{K}_1| + |\mathcal{K}_2| \leq 4\varepsilon_3|B|, \tag{6.6}$$

$$-2a_1\varepsilon_3|B| \leq q_1 \leq -C, \tag{6.7}$$

where

$$q_1 := \frac{a_1}{m}|V \setminus V(\mathcal{K}_1 \cup \mathcal{K}_2)| - |A' \setminus V(\mathcal{K}_1 \cup \mathcal{K}_2)|.$$

When  $q \leq -C$ , let  $\mathcal{K}_1 = \emptyset$ . When  $q \geq 1 - C$ ,  $\mathcal{K}_1$  consists of  $q + C$  copies of  $K$  obtained from  $H[B']$  as follows.<sup>4</sup> Note that

$$\delta_{k-1}(H[B']) \geq \delta_{k-1}(H) - |A'| - |V_0| \geq q + C + f(n)$$

by (1.3) and the definition of  $q$ . We claim that

$$\frac{f(n)}{k} \binom{|B'|}{k-1} \geq \text{ex}(|B'| - (q + C - 1)m, K). \tag{6.8}$$

Indeed, when  $q \geq 1$ , we have

$$|B'| \geq |B| + 1 \quad \text{and} \quad \binom{|B'|}{k-1} \geq \binom{|B| + 1}{k-1}.$$

Since

$$f(n) \geq k \text{ex}(|B| + 1, K) / \binom{|B| + 1}{k-1},$$

it follows that

$$\frac{f(n)}{k} \binom{|B'|}{k-1} \geq \text{ex}(|B| + 1, K).$$

Since

$$|B| + 1 = |B'| - q + 1 \geq |B'| - (q + C - 1)m,$$

<sup>4</sup>It suffices to find  $\lceil (q + C)/a_1 \rceil$  copies of  $K$ , but since Fact 6.2 provides (at least)  $q + C$  copies, we choose to use all of them to simplify later calculations.

(6.8) follows from the monotonicity of the Turán number. When  $q \leq 0$ , we have  $|B| - C < |B'| \leq |B|$ . The definition of  $f(n)$  implies that

$$\frac{f(n)}{k} \binom{|B'|}{k-1} \geq \text{ex}(|B'|, K).$$

Again, (6.8) follows from the monotonicity of the Turán number.

By (6.8), we have

$$\begin{aligned} e_H(B') &\geq \frac{\delta_{k-1}(H[B'])}{k} \binom{|B'|}{k-1} \\ &\geq \frac{q+C}{k} \binom{|B'|}{k-1} + \text{ex}(|B'| - (q+C-1)m, K) \\ &> (q+C-1)m \cdot 2\varepsilon_1 \binom{|B'|}{k-1} + \text{ex}(|B'| - (q+C-1)m, K). \end{aligned}$$

By (6.3), we can apply Fact 6.2 to obtain  $q + C$  vertex-disjoint copies of  $K$  in  $H[B']$ , denoted by  $\mathcal{K}_1$ .

Next we choose a  $K$ -tiling  $\mathcal{K}_2$  such that each copy of  $K$  contains  $a_1 - 1$  vertices in  $A'$ , one vertex in  $V_0$  and  $m - a_1$  vertices in  $B'$ . By (6.1) and (6.5) we derive that, for any vertex  $w \in V_0$ ,

$$|N(w, B') \setminus \mathcal{B}| \geq \frac{\varepsilon_1}{2} \binom{|B'|}{k-1} - \sqrt{2\varepsilon_2} \binom{|B'|}{k-1} \geq \frac{\varepsilon_1}{3} \binom{|B'|}{k-1}$$

by the choice of  $\varepsilon_1$  and  $\varepsilon_2$ . Let  $V_0 = \{w_1, \dots, w_{|V_0|}\}$ . For each  $w_i$ , by (1.4) we can find a copy  $T_i$  of  $K^{(k-1)}(a_2, \dots, a_k)$  in (the  $(k-1)$ -graph)  $N(w, B') \setminus \mathcal{B}$  such that these copies are vertex-disjoint, and are also vertex-disjoint from  $V(\mathcal{K}_1)$ . This is possible because the number of vertices in  $B'$  that we need to avoid is at most

$$|V(\mathcal{K}_1)| + (m - a_1)|V_0| \leq (\varepsilon_3|B| + C) \cdot m + (m - a_1)\varepsilon_3|B| \leq 2m\varepsilon_3|B|,$$

and so we have

$$|N(w, B') \setminus \mathcal{B}| - 2m\varepsilon_3|B| \binom{|B'|}{k-2} \geq \frac{\varepsilon_1}{3} \binom{|B'|}{k-1} - 2m\varepsilon_3|B| \binom{|B'|}{k-2} \geq \frac{\varepsilon_1}{4} \binom{|B'|}{k-1}.$$

Thus, (1.4) implies the existence of the desired  $T_i$ . Note that each  $\{w_i\} \cup T_i$  spans a copy of  $K^{(k)}(1, a_2, \dots, a_k)$  in  $H$ . To obtain copies of  $K$ , we extend each of them (one by one) by adding  $a_1 - 1$  vertices from  $A'$ . Note that each such vertex from  $A'$  needs to be the common neighbour of  $a' := \prod_{2 \leq i \leq k} a_i$   $(k-1)$ -sets, which is possible since by our choice, these  $(k-1)$ -sets are not in  $\mathcal{B}$ , and thus they have at least  $(1 - a'\sqrt{2\varepsilon_2})|A'|$  common neighbours in  $A'$ . Since  $(1 - a'\sqrt{2\varepsilon_2})|A'| > (a_1 - 1)|V_0|$ , we can greedily extend each  $\{w_i\} \cup T_i$  into a copy of  $K$ . Denote the resulting  $K$ -tiling by  $\mathcal{K}_2$ .

By definition, we have  $|\mathcal{K}_1| \leq |q| + C$  and  $|\mathcal{K}_2| = |V_0|$ . The result in [7] (see also [33]) mentioned in Section 1 implies that  $C \leq (a_k - a_1)^2$ . By Claim 6.3,  $|\mathcal{K}_1| + |\mathcal{K}_2| \leq \varepsilon_3|B| + C + 2\varepsilon_3|B| \leq 4\varepsilon_3|B|$ , i.e. (6.6) holds. Let  $A_1$  and  $B_1$  be the sets of vertices in  $A'$  and  $B'$  not covered by  $\mathcal{K}_1 \cup \mathcal{K}_2$ , respectively, and  $V_1 := A_1 \cup B_1$ . So  $q_1 = (a_1/m)|V_1| - |A_1|$ . Note that  $|A_1| = |A'| - (a_1 - 1)|V_0|$  and  $|V_1| = n - m|\mathcal{K}_1| - m|V_0|$ . So we have

$$q_1 = \frac{a_1}{m}n - a_1|\mathcal{K}_1| - |V_0| - |A'| = q - a_1|\mathcal{K}_1| \leq q - |\mathcal{K}_1|.$$

Recall that  $|\mathcal{K}_1| = q + C$  if  $q \geq 1 - C$  and  $|\mathcal{K}_1| = 0$  if  $q \leq -C$ . So in both cases we get  $q_1 \leq q - |\mathcal{K}_1| \leq -C$ . Moreover, by  $-\varepsilon_3|B| \leq q \leq \varepsilon_3|B|$  and the fact that  $n$  is sufficiently large, we have  $q_1 = q - a_1|\mathcal{K}_1| \geq q - a_1|q + C| \geq -2a_1\varepsilon_3|B|$ . So (6.7) holds.

**The  $K$ -tiling  $\mathcal{K}_3$ .** Next we build our  $K$ -tiling  $\mathcal{K}_3$ . Since  $-q_1 \geq C > g(a_2 - a_1, a_3 - a_1, \dots, a_k - a_1)$  and  $\text{gcd}(a_2 - a_1, a_3 - a_1, \dots, a_k - a_1) = 1$ , there exist non-negative integers  $\ell_1, \dots, \ell_{k-1}$  such

that

$$\ell_1(a_2 - a_1) + \ell_2(a_3 - a_1) + \dots + \ell_{k-1}(a_k - a_1) = -q_1$$

(here we let  $\ell_i = 0$  if  $a_i - a_1 = 0$ ). For each  $i \in [k - 1]$ , we pick  $\ell_i$  vertex-disjoint copies of  $K$  each with  $a_{i+1}$  vertices in  $A_1$  and  $m - a_{i+1}$  vertices in  $B_1$  such that all copies of  $K$  are vertex-disjoint. Let  $\mathcal{K}_3$  denote the set of copies of  $K$ . Note that we can choose these desired copies of  $K$  by Proposition 4.3 and the fact that  $H(A_1B_1^{k-1})$  is dense (see (6.9)). By the definition of  $\mathcal{K}_3$ , we have  $|\mathcal{K}_3| = \sum_{i \in [k-1]} \ell_i$  and

$$\begin{aligned} \frac{a_1}{m} |V_1 \setminus V(\mathcal{K}_3)| - |A_1 \setminus V(\mathcal{K}_3)| &= \frac{a_1}{m} (|V_1| - m|\mathcal{K}_3|) - (|A_1| - |V(\mathcal{K}_3) \cap A_1|) \\ &= q_1 + (|V(\mathcal{K}_3) \cap A_1| - a_1|\mathcal{K}_3|) \\ &= q_1 + \sum_{i \in [k-1]} \ell_i(a_{i+1} - a_1) = 0. \end{aligned}$$

Let  $A_2 = A_1 \setminus V(\mathcal{K}_3)$  and  $B_2 = B_1 \setminus V(\mathcal{K}_3)$ . So we have

$$\frac{a_1}{m} (|A_2| + |B_2|) = |A_2|,$$

that is,  $(m - a_1)|A_2| = a_1|B_2|$ .

Note that  $|\mathcal{K}_3| = \sum_{i \in [k-1]} \ell_i \leq -q_1 \leq 2a_1\varepsilon_3|B|$  by (6.7). Together with (6.6) and Claim 6.3, we have

$$|B_2| \geq |B'| - |V(\mathcal{K}_1 \cup \mathcal{K}_2)| - m|\mathcal{K}_3| \geq |B'| - 4m\varepsilon_3|B| - 2a_1m\varepsilon_3|B| > (1 - \varepsilon_1)|B'|.$$

Hence, for every vertex  $v \in A_2$ , by (6.2),

$$\overline{\text{deg}}(v, B_2) \leq \overline{\text{deg}}(v, B') \leq 2\varepsilon_2 \binom{|B'|}{k-1} \leq 2\varepsilon_2 \binom{(1/(1 - \varepsilon_1))|B_2|}{k-1} < \varepsilon_1 \binom{|B_2|}{k-1}.$$

By (6.4) and  $|B_2| \geq (1 - \varepsilon_1)|B'|$ , for every  $v \in B_2$  we have

$$\overline{\text{deg}}(v, A_2B_2^{k-1}) \leq \overline{\text{deg}}(v, A'B'^{k-1}) \leq 2k\varepsilon_1 \binom{|B'|}{k-1} \leq 3k\varepsilon_1 \binom{|B_2|}{k-1}. \tag{6.9}$$

**The  $K$ -tiling  $\mathcal{K}_4$ .** Finally, we apply Lemma 6.1 with  $X = A_2$ ,  $Y = B_2$  and  $\rho = 3k\varepsilon_1$  and get a  $K$ -factor  $\mathcal{K}_4$  on  $A_2 \cup B_2$ .

So  $\mathcal{K}_1 \cup \mathcal{K}_2 \cup \mathcal{K}_3 \cup \mathcal{K}_4$  is a  $K$ -factor of  $H$ . This concludes the proof of Theorem 3.3.

**6.3 Proof of Theorem 3.4**

As mentioned in Section 1, (1.3) reduces to  $\delta_{k-1}(H) \geq n/(k + 1) + 1$  when  $K = K^{(k)}(1, \dots, 1, 2)$ . Thus Theorem 3.4 follows from Theorem 3.3 if condition (i) holds. Now assume condition (ii), that is,  $\delta_{k-1}(H) \geq n/(k + 1)$  and  $k - i \nmid \binom{n-i}{k-1-i}$  for some  $0 \leq i \leq k - 2$  and  $n' = kn/(k + 1) + 1$ . The proof closely follows the proof of Theorem 3.3 (with  $C = 0$ ) and the only difference is the existence of  $\mathcal{K}_1$  when  $q = |B'| - |B| \geq 1$ . Note that  $\delta_{k-1}(H[B']) \geq q$ . Since  $\text{ex}(n, K^{(k)}(1, \dots, 1, 2)) \leq \binom{n}{k-1}/k$ , when  $q \geq 2$  we can find  $q$  copies of  $K^{(k)}(1, \dots, 1, 2)$  in  $B'$  by Fact 6.2. Otherwise  $q = 1$ , i.e.  $|B'| = n'$ . Assume to the contrary that  $H[B']$  is  $K^{(k)}(1, \dots, 1, 2)$ -free, that is, any  $k - 1$  vertices in  $B'$  have degree at most 1 in  $B'$ . Then by  $\delta_{k-1}(H[B']) \geq 1$  we derive that any  $k - 1$  vertices in  $B'$  have degree exactly 1 in  $B'$ . This means that a Steiner system  $S(k - 1, k, n')$  exists, contradicting the divisibility conditions.

**6.4 Proof of Theorem 3.5**

Recall that a loose cycle  $C_s^k$  has a vertex set  $[s(k-1)]$  and  $s$  edges  $\{\{j(k-1)+1, \dots, j(k-1)+k\} \text{ for } 0 \leq j < s\}$ , where we treat  $s(k-1)+1$  as 1. When  $s=2, 3$ ,  $C_s^k$  has a unique  $k$ -partite realization:  $C_2^k \subset K^{(k)}(1, 1, 2, \dots, 2)$  and  $C_3^k \subset K^{(k)}(2, 2, 2, 3, \dots, 3)$ . When  $s \geq 4$ , we 3-colour the vertices  $j(k-1)+1$ ,  $0 \leq j < s$  (these are the vertices of degree two) with  $\lfloor s/2 \rfloor$  red vertices,  $\lfloor s/2 \rfloor - 1$  blue vertices and the remaining one or two vertices green. We complete the  $k$ -colouring of  $C_s^k$  by colouring the  $k-2$  uncoloured vertices of each edge of  $C_s^k$  with the  $k-2$  colours not used to colour the two vertices of degree two. In this colouring, there are  $\lfloor s/2 \rfloor$  red vertices,  $\lfloor s/2 \rfloor + 1$  blue vertices,  $s-1$  or  $s-2$  green vertices, and  $s$  vertices in other colour classes. Furthermore, since each vertex in  $C_s^k$  has degree at most 2, in any  $k$ -colouring of  $C_s^k$ , each colour class has size at least  $\lfloor s/2 \rfloor$ . Thus,

$$\sigma(C_s^k) = \frac{\lfloor s/2 \rfloor}{s(k-1)}.$$

We summarize the above arguments into a proposition.

**Proposition 6.4.** *For any  $k \geq 4$  and  $s \geq 2$  we have*

$$\sigma(C_s^k) = \frac{\lfloor s/2 \rfloor}{s(k-1)}.$$

Moreover, there exists a  $k$ -partite realization of  $C_s^k$ , in which the smallest part is of size  $\lfloor s/2 \rfloor$  and there is a part of size  $\lfloor s/2 \rfloor + 1$ . In particular,  $\text{gcd}(C_s^k) = 1$ . □

In order to prove Theorem 3.5, we use upper bounds for  $\text{ex}(n, P_2^k)$  and  $\text{ex}(n, C_2^k)$  from [8]. Note that the results in [8] are in the language of extremal set theory, but it is easy to formalize the results for our purpose: a  $k$ -graph is  $C_2^k$ -free if and only if the size of the intersection of any two edges is not 2; a  $k$ -graph is  $P_2^k$ -free if and only if the size of the intersection of any two edges is not 1.

**Theorem 6.5 ([8]).** *For  $k \geq 4$ , there exists a constant  $d_k$  such that  $\text{ex}(n, C_2^k) \leq d_k n^{\max\{2, k-3\}}$  and  $\text{ex}(n, P_2^k) \leq \binom{n-2}{k-2}$ .*

**Proof of Theorem 3.5.** Let  $K^{(k)}(a_1, \dots, a_k)$  be a  $k$ -partite realization of  $C_s^k$  such that  $a_1 = \lfloor s/2 \rfloor$  and  $a_{k'} = \lfloor s/2 \rfloor + 1$  for some  $k' \in [k]$ . Then we have that  $\text{gcd}(K^{(k)}(a_1, \dots, a_k)) = 1$  and  $C = g(a_2 - a_1, \dots, a_k - a_1) + 1 = 0$ . Let  $m = s(k-1)$ . Suppose  $1/n \ll \xi \ll 1/m$ . Assume  $H$  is an  $n$ -vertex  $k$ -graph which is  $\xi$ -extremal and  $\delta_{k-1}(H) \geq a_1 n/m$ . Define  $\varepsilon_1, \varepsilon_2, \varepsilon_3, A', B', V_0$  as in Section 1.1 and thus Claim 6.3 and (6.1)–(6.5) hold.

The proof follows that of Theorem 3.3 by constructing  $C_s^k$ -tilings  $\mathcal{K}_1, \mathcal{K}_2, \mathcal{K}_3$  and  $\mathcal{K}_4$ , whose union forms a perfect  $C_s^k$ -tiling of  $H$ . We will only show the first step, the existence of  $\mathcal{K}_1, \mathcal{K}_2$ , because it is the only part different from that in the proof of Theorem 3.3.

Here we need a stronger control on the ‘good’  $(k-1)$ -sets in  $B'$ , that is, every vertex in  $B'$  is in many such good  $(k-1)$ -sets (note that this is stronger than  $\mathcal{B}$ , for which we only have control of the total number of ‘bad’ sets). Let  $G$  be the  $(k-1)$ -graph on  $B'$  whose edges are all  $(k-1)$ -sets  $S \subseteq B'$  such that  $\overline{\text{deg}}_H(S, A') < \sqrt{2k\varepsilon_1}|A'|$ . We claim that

$$\delta_1(G) \geq (1 - m\sqrt{2k\varepsilon_1}) \binom{|B'| - 1}{k-2}, \quad \text{and thus } \bar{e}(G) \leq m\sqrt{2k\varepsilon_1} \binom{|B'|}{k-1}. \tag{6.10}$$



Suppose instead that some vertex  $v \in B'$  satisfies  $\overline{\deg}_G(v) > m\sqrt{2k\varepsilon_1} \binom{|B'| - 1}{k - 2}$ . Since every non-neighbour  $S'$  of  $v$  in  $G$  satisfies  $\overline{\deg}_H(S' \cup \{v\}, A') \geq \sqrt{2k\varepsilon_1}|A'|$ , we have

$$\overline{\deg}_H(v, A'B'^{k-1}) > m\sqrt{2k\varepsilon_1} \binom{|B'| - 1}{k - 2} \sqrt{2k\varepsilon_1}|A'| > 2k\varepsilon_1 \binom{|B'|}{k - 1},$$

where we used  $m|A'| > |B'|$ . This contradicts (6.4).

**The  $K$ -tilings  $\mathcal{K}_1, \mathcal{K}_2$ .** Assume that  $q = |B'| - (m - a_1)n/m$ . As in the proof of Theorem 3.3, our goal is to find  $C_s^k$ -tilings  $\mathcal{K}_1, \mathcal{K}_2$  such that  $V_0 \subseteq V(\mathcal{K}_2)$ , and (6.6) and (6.7) hold (with  $C = 0$ ).

We first construct a  $C_s^k$ -tiling  $\mathcal{K}_1$  such that  $|\mathcal{K}_1| = \max\{q, 0\}$  and each copy of  $C_s^k$  in  $\mathcal{K}_1$  contains exactly  $m - a_1 + 1$  vertices in  $B'$ . Let  $\mathcal{K}_1 = \emptyset$  if  $q \leq 0$ . Then assume  $q \geq 1$  and note that  $\delta_{k-1}(H[B']) \geq q$ . Thus

$$e_H(B') \geq \frac{1}{k} \delta_{k-1}(H[B']) \binom{|B'|}{k - 1} \geq \frac{q}{k} \binom{|B'|}{k - 1} > (q - 1)m \cdot 2\varepsilon_1 \binom{|B'|}{k - 1} + \frac{q}{2k} \binom{|B'|}{k - 1}.$$

Since  $k \geq 4$ , by Theorem 6.5, we know that

$$\text{ex}(|B'|, C_2^k) \leq \frac{q}{2k} \binom{|B'|}{k - 1} \quad \text{and} \quad \text{ex}(|B'|, P_2^k) \leq \frac{q}{2k} \binom{|B'|}{k - 1}.$$

First, assume  $s = 2$ . Note that if  $s = 2$ , then  $a_1 = 1$ , i.e.  $m - a_1 + 1 = m$ . By (6.3) and Fact 6.2,  $H[B']$  contains a set of  $q$  vertex-disjoint copies of  $C_2^k$ . Denote it by  $\mathcal{K}_1$  and we are done. Second, assume  $s \geq 3$ , and then by (6.3) and Fact 6.2,  $H[B']$  contains a collection of  $q$  vertex-disjoint copies of  $P_2^k$  denoted by  $Q_1, \dots, Q_q$ .

For each  $i \in [q]$ , we extend  $Q_i$  (or only one edge of  $Q_i$ ) to a copy of  $C_s^k$  such that all copies of  $C_s^k$  are vertex-disjoint and each copy contains exactly  $m - a_1 + 1$  vertices in  $B'$ . Indeed, for  $i \in [q]$ , let  $E_1, E_s$  be the two edges in  $Q_i$ . If  $s$  is even, let  $Q'_i = Q_i$  and pick  $u \in E_1 \setminus E_s, u' \in E_s \setminus E_1$ ; if  $s$  is odd, let  $Q'_i = E_1$  and let  $u, u'$  be two distinct vertices from  $Q'_i$ . Let  $s' = 2\lceil s/2 \rceil$ . We pick vertex sets  $S_2, \dots, S_{s'-1}$  of size  $k - 2$ , and vertices  $u_3, u_5, \dots, u_{s'-3}$  from the unused vertices in  $B'$  such that the  $(k - 1)$ -sets

$$\begin{aligned} F_2 &:= S_2 \cup \{u\}, & F_{s'-1} &:= S_{s'-1} \cup \{u'\}, \\ F_{2j-1} &:= S_{2j-1} \cup \{u_{2j-1}\}, & F_{2j} &:= S_{2j} \cup \{u_{2j-1}\} \quad \text{for } 2 \leq j \leq (s' - 2)/2 \end{aligned}$$

are in  $E(G)$ . This is possible by (6.10) (we pick an edge that contains  $u$ , an edge that contains  $u'$  and then some copies of  $P_2^{k-1}$  such that all these are vertex-disjoint and vertex-disjoint from other existing vertices). Then, for each  $2 \leq j \leq s'/2$ , pick  $u_{2j-2} \in N_H(F_{2j-2}) \cap N_H(F_{2j-1}) \cap A'$ , which is possible since  $F_i \in E(G)$  and thus  $\overline{\deg}_H(F_i, A') < \sqrt{2k\varepsilon_1}|A'|$ . Note that  $Q'_i \cup \bigcup_{2 \leq j \leq s'-1} S_j \cup \{u_2, \dots, u_{s'-2}\}$  spans a loose cycle of length  $s' - 1$  if  $s$  is odd and  $s'$  if  $s$  is even, that is, it spans a copy of  $C_s^k$ . Moreover, each such copy contains exactly  $s'/2 - 1 = a_1 - 1$  vertices in  $A'$ , and thus exactly  $m - a_1 + 1$  vertices in  $B'$ .

Next we choose a  $K$ -tiling  $\mathcal{K}_2$  such that each copy of  $K$  contains  $a_1 - 1$  vertices in  $A'$ , one vertex in  $V_0$  and  $m - a_1$  vertices in  $B'$ . This can be done by the same argument as in the proof of Theorem 3.3.

By definition, we have  $|\mathcal{K}_1| \leq |q|$  and  $|\mathcal{K}_2| = |V_0|$ . By Claim 6.3,  $|\mathcal{K}_1| + |\mathcal{K}_2| \leq |q| + |V_0| \leq 4\varepsilon_3|B|$ , i.e. (6.6) holds. Let  $A_1$  and  $B_1$  be the sets of vertices in  $A'$  and  $B'$  not covered by  $\mathcal{K}_1 \cup \mathcal{K}_2$ , respectively. Let  $V_1 := A_1 \cup B_1$ . Let

$$q_1 = \frac{a_1}{m} |V_1| - |A_1|.$$

Recall that if  $s = 2$ , then  $a_1 = 1$ . Therefore for any  $s \geq 2$ , by the definitions of  $A_1, B_1$ , we have  $|A_1| = |A'| - (a_1 - 1)|\mathcal{K}_1| - (a_1 - 1)|V_0|$  and  $|V_1| = n - m|\mathcal{K}_1| - m|V_0|$ . Together with  $q = a_1n/m - (|A'| + |V_0|)$ , we get

$$q_1 = \frac{a_1}{m}n - |\mathcal{K}_1| - |V_0| - |A'| = q - |\mathcal{K}_1| = q - \max\{0, q\} \leq 0.$$

Since  $-\varepsilon_3|B| \leq q \leq \varepsilon_3|B|$ , we get  $q_1 = q - \max\{0, q\} \geq -|q| \geq -2a_1\varepsilon_3|B|$ . Thus (6.7) holds. The rest of the proof is similar to the above and is omitted.  $\square$

**6.5 Proof of Lemma 6.1**

In this subsection we prove Lemma 6.1 by following the proof of [16, Lemma 4.4], which proves the case when  $K = K^{(3)}(1, 1, 2)$ .

We need the following result of Lu and Székely [27, Theorem 3].

**Theorem 6.6 ([27]).** *Let  $F$  be a  $k$ -graph in which each edge intersects at most  $d$  other edges. If  $H$  is an  $n$ -vertex  $k$ -graph such that  $|V(F)|$  divides  $n$  and*

$$\delta_1(H) \geq \left(1 - \frac{1}{e(d+1+xk^2)}\right) \binom{n-1}{k-1},$$

where  $e = 2.718\dots$  and  $x = |E(F)|/|V(F)|$ , then  $H$  contains an  $F$ -factor.

**Proof of Lemma 6.1.** Let  $t = |X|/a_1$ . Let  $\mathcal{G}$  be the  $(k-1)$ -graph on  $Y$  whose edges are all  $(k-1)$ -sets  $S \subseteq Y$  such that  $\overline{\text{deg}}_H(S, X) < \sqrt{\rho}t$ . First we claim that

$$\delta_1(\mathcal{G}) \geq (1 - m\sqrt{\rho}) \binom{|Y|-1}{k-2}, \tag{6.11}$$

and consequently

$$\overline{e}(\mathcal{G}) \leq m\sqrt{\rho} \binom{|Y|}{k-1}. \tag{6.12}$$

Suppose instead that some vertex  $v \in Y$  satisfies

$$\overline{\text{deg}}_{\mathcal{G}}(v) > m\sqrt{\rho} \binom{|Y|-1}{k-2}.$$

Since every non-neighbour  $S'$  of  $v$  in  $\mathcal{G}$  satisfies  $\overline{\text{deg}}_H(S' \cup \{v\}, X) \geq \sqrt{\rho}t$ , we have

$$\overline{\text{deg}}_H(v, XY^{k-1}) > m\sqrt{\rho} \binom{|Y|-1}{k-2} \sqrt{\rho}t.$$

Since  $|Y| = (m - a_1)t$ , we have

$$\overline{\text{deg}}_H(v, XY^{k-1}) > m\rho \frac{|Y|}{m - a_1} \binom{|Y|-1}{k-2} > \rho \binom{|Y|}{k-1},$$

contradicting our assumption.

Let  $Q$  be an  $(m - a_1)$ -subset of  $Y$ . We call  $Q$  *good* (otherwise *bad*) if every  $(k-1)$ -subset of  $Q$  is an edge of  $\mathcal{G}$ , that is,  $Q$  spans a *clique* of size  $m - a_1$  in  $\mathcal{G}$ . Furthermore, we say  $Q$  is *suitable* for a vertex  $x \in X$  if  $x \cup T \in E(H)$  for every  $(k-1)$ -set  $T \subset Q$ . Note that if an  $(m - a_1)$ -set is good, by the definition of  $\mathcal{G}$  it is suitable for at least  $(1 - \binom{m-a_1}{k-1} \sqrt{\rho})t$  vertices of  $X$ .

**Claim 6.7.** *For any  $x \in X$ , at least  $(1 - \rho^{1/4}) \binom{|Y|}{m-a_1} (m - a_1)$ -subsets of  $Y$  are good and suitable for  $x$ .*

**Proof.** First, by the degree condition of  $H$ , i.e. for any  $x \in X$ , the number of  $(m - a_1)$ -sets in  $Y$  that are not suitable for  $x$  is at most

$$\rho \binom{|Y|}{k-1} \binom{|Y| - k + 1}{m - a_1 - k + 1} \leq \sqrt{\rho} \binom{|Y|}{m - a_1}.$$

Second, by (6.12), at most

$$\bar{e}(\mathcal{G}) \binom{|Y| - k + 1}{m - a_1 - k + 1} \leq m \sqrt{\rho} \binom{|Y|}{k-1} \binom{|Y| - k + 1}{m - a_1 - k + 1} \leq \frac{1}{2} \rho^{1/4} \binom{|Y|}{m - a_1}$$

$(m - a_1)$ -subsets of  $Y$  contain a non-edge of  $\mathcal{G}$ . Since  $\rho^{1/2} + \frac{1}{2} \rho^{1/4} \leq \rho^{1/4}$ , the claim follows.  $\square$

Let  $\mathcal{F}_0$  be the set of good  $(m - a_1)$ -sets in  $Y$ . We will pick a family of disjoint good  $(m - a_1)$ -sets in  $Y$  such that, for any  $x \in X$ , many members of this family are suitable for  $x$ . To achieve this, we pick a family  $\mathcal{F}$  by selecting each member of  $\mathcal{F}_0$  randomly and independently with probability

$$p = 4 \binom{m - a_1}{k-1} \sqrt{\rho} |Y| / \binom{|Y|}{m - a_1}.$$

Then  $|\mathcal{F}|$  follows the binomial distribution  $B(|\mathcal{F}_0|, p)$  with expectation

$$\mathbb{E}(|\mathcal{F}|) = p |\mathcal{F}_0| \leq p \binom{|Y|}{m - a_1}.$$

Furthermore, for every  $x \in X$ , let  $f(x)$  denote the number of members of  $\mathcal{F}$  that are suitable for  $x$ . Then  $f(x)$  follows the binomial distribution  $B(N, p)$  with  $N \geq (1 - \rho^{1/4}) \binom{|Y|}{m - a_1}$  by Claim 6.7. Hence  $\mathbb{E}(f(x)) \geq p(1 - \rho^{1/4}) \binom{|Y|}{m - a_1}$ . Since there are at most

$$\binom{|Y|}{m - a_1} \cdot (m - a_1) \cdot \binom{|Y| - 1}{m - a_1 - 1}$$

pairs of intersecting  $(m - a_1)$ -sets in  $Y$ , the expected number of intersecting pairs of  $(m - a_1)$ -sets in  $\mathcal{F}$  is at most

$$p^2 \binom{|Y|}{m - a_1} \cdot (m - a_1) \cdot \binom{|Y| - 1}{m - a_1 - 1} = 16 \binom{m - a_1}{k-1}^2 (m - a_1)^2 \rho |Y|.$$

By Chernoff's bound (the first two properties) and Markov's bound (the last one), we can find a family  $\mathcal{F}$  of good  $(m - a_1)$ -subsets of  $Y$  that satisfies

•

$$|\mathcal{F}| \leq 2p \binom{|Y|}{m - a_1} \leq 8 \binom{m - a_1}{k-1} \sqrt{\rho} |Y|,$$

• for any vertex  $x \in X$ , at least

$$\frac{p}{2} (1 - \rho^{1/4}) \binom{|Y|}{m - a_1} = 2 \binom{m - a_1}{k-1} (1 - \rho^{1/4}) \sqrt{\rho} |Y|$$

members of  $\mathcal{F}$  are suitable for  $x$ .

• the number of intersecting pairs of  $(m - a_1)$ -sets in  $\mathcal{F}$  is at most

$$32 \binom{m - a_1}{k-1}^2 (m - a_1)^2 \rho |Y|.$$

After deleting one  $(m - a_1)$ -set from each of the intersecting pairs from  $\mathcal{F}$ , we obtain a family  $\mathcal{F}' \subseteq \mathcal{F}$  consisting of at most  $8 \binom{m - a_1}{k-1} \sqrt{\rho} |Y|$  disjoint good  $(m - a_1)$ -subsets of  $Y$ , and for each  $x \in X$ , at least

$$2 \binom{m - a_1}{k - 1} (1 - \rho^{1/4}) \sqrt{\rho} |Y| - 32 \binom{m - a_1}{k - 1}^2 (m - a_1)^2 \rho |Y| \geq \binom{m - a_1}{k - 1} \sqrt{\rho} |Y| \tag{6.13}$$

members of  $\mathcal{F}'$  are suitable for  $x$ .

Denote  $\mathcal{F}'$  by  $\{Q_1, Q_2, \dots, Q_q\}$  for some  $q \leq 8 \binom{m - a_1}{k - 1} \sqrt{\rho} |Y|$ . Let  $Y_1 = Y \setminus V(\mathcal{F}')$  and  $\mathcal{G}' = \mathcal{G}[Y_1]$ . Then  $|Y_1| = |Y| - (m - a_1)q$ . Since  $\overline{\deg}_{\mathcal{G}'}(v) \leq \overline{\deg}_{\mathcal{G}}(v)$  for every  $v \in Y_1$ , we have, by (6.11),

$$\delta_1(\mathcal{G}') \geq \binom{|Y_1| - 1}{k - 2} - m \sqrt{\rho} \binom{|Y| - 1}{k - 2} \geq (1 - 2m \sqrt{\rho}) \binom{|Y_1| - 1}{k - 2}.$$

By the choice of  $\rho$  and Theorem 6.6,  $\mathcal{G}'$  contains a perfect tiling  $\{Q_{q+1}, \dots, Q_t\}$  such that each  $Q_i$  is a clique on  $m - a_1$  vertices for  $q + 1 \leq i \leq t$ .

Consider the bipartite graph  $\Gamma$  between  $X$  and  $\mathcal{Q} := \{Q_1, Q_2, \dots, Q_t\}$  such that  $x \in X$  and  $Q_i \in \mathcal{Q}$  are adjacent if and only if  $Q_i$  is suitable for  $x$ . For every  $i \in [t]$ , since each  $Q_i$  is a clique in  $\mathcal{G}$ , we have  $\deg_{\Gamma}(Q_i) \geq |X| - \binom{m - a_1}{k - 1} \sqrt{\rho} t$  by the definition of  $\mathcal{G}$ . Let  $\mathcal{Q}' = \{Q_{q+1}, \dots, Q_t\}$  and  $X_0$  be the set of  $x \in X$  such that  $\deg_{\Gamma}(x, \mathcal{Q}') \leq |\mathcal{Q}'|/2$ . Then

$$|X_0| \frac{|\mathcal{Q}'|}{2} \leq \sum_{x \in X} \overline{\deg}_{\Gamma}(x, \mathcal{Q}') \leq \binom{m - a_1}{k - 1} \sqrt{\rho} t \cdot |\mathcal{Q}'|,$$

which implies that

$$|X_0| \leq 2 \binom{m - a_1}{k - 1} \sqrt{\rho} t = 2 \binom{m - a_1}{k - 1} \sqrt{\rho} \frac{|Y|}{m - a_1} \leq \binom{m - a_1}{k - 1} \sqrt{\rho} |Y| \quad (\text{since } m - a_1 \geq 2).$$

We now find a perfect tiling of  $K^{(2)}(1, a_1)$  in  $\Gamma$  such that the centre of each  $K^{(2)}(1, a_1)$  is in  $\mathcal{Q}$ .

**Step 1.** Each  $x \in X_0$  is matched to some  $Q_i, i \in [q]$  that is suitable for  $x$ . This is possible because of (6.13) and  $|X_0| \leq \binom{m - a_1}{k - 1} \sqrt{\rho} |Y|$ .

**Step 2.** Each  $Q_i, i \in [q]$  is matched with  $a_1 - 1$  or  $a_1$  more vertices in  $X \setminus X_0$ . This is possible because  $\deg_{\Gamma}(Q_i) \geq |X| - \binom{m - a_1}{k - 1} \sqrt{\rho} t \geq |X_0| + a_1 q$ . Thus, all  $Q_i, i \in [q]$  are covered by vertex-disjoint copies of  $K^{(2)}(1, a_1)$ .

**Step 3.** Let  $X'$  be the set of uncovered vertices in  $X$  and note that  $|X'| = a_1 t - a_1 q = a_1 |\mathcal{Q}'|$ . Partition  $X'$  arbitrarily into  $X_1, \dots, X_{a_1}$  each of size  $|\mathcal{Q}'|$ . Note that for each  $i \in [a_1]$ , we have for all  $x \in X_i, \deg_{\Gamma}(x, \mathcal{Q}') > |\mathcal{Q}'|/2$  and for all  $Q_j \in \mathcal{Q}', \deg_{\Gamma}(Q_j, X_i) \geq |X_i| - \binom{m - a_1}{k - 1} \sqrt{\rho} t \geq |X_i|/2$ . So the Marriage Theorem provides a perfect matching in each  $\Gamma[X_i, \mathcal{Q}'], i \in [a_1]$  and thus we get a perfect tiling of  $K^{(2)}(1, a_1)$  on  $X' \cup \mathcal{Q}'$  in  $\Gamma$ .

The perfect tiling of  $K^{(2)}(1, a_1)$  in  $\Gamma$  gives rise to the desired  $K$ -factor in  $H$ . □

### 7. Concluding remarks

In this paper we study the minimum codegree threshold  $\delta(n, K)$  for tiling complete  $k$ -partite  $k$ -graphs  $K$  perfectly when  $\gcd(K) = 1$ . By Proposition 1.2,

$$\delta(n, K) \geq \frac{n}{m} + \text{coex} \left( \frac{m - 1}{m} n + 1, K \right) \quad \text{when } a_1 = 1.$$

In view of this and Theorem 1.3, it would be interesting to know if one can replace the second term in (1.3) with a term similar to  $\text{coex}((m - a_1)n/m + 1, K)$ . Moreover, it would be interesting to know if  $\text{ex}(n, K) / \binom{n}{k - 1}$  (or  $\text{coex}(n, K)$ ) is monotone on  $n$  so that the maximization in (1.3) could be avoided.

Following the notation in [29], we call  $k$ -partite  $k$ -graphs satisfying the three lines of (1.1) type 0, type 1 and type  $d$ , respectively. For complete  $k$ -partite  $k$ -graphs  $K$  of type  $d$  for an even  $d \geq 0$ , a simple application of the absorbing method together with Lemma 3.2 implies that  $\delta(n, K) = n/2 + o(n)$ , which gives a re-proof of the result of Mycroft [29] without using the hypergraph blow-up lemma. We think that further sharpening is possible via careful analysis of the extremal case, to which we shall return in the near future.

Suppose  $K := K^{(k)}(a_1, \dots, a_k)$ . When  $K$  is type 1 (namely,  $\gcd(K) = 1$ ), Proposition 1.2 and Theorem 1.5 settle Conjecture 1.1 (either negatively or positively). Now we give a construction showing that Conjecture 1.1 is false for many other complete  $k$ -partite  $k$ -graphs, for which we need to recall a construction by Mycroft [29]. Fix a prime number  $p$ . Let  $\mathbf{u}_i \in \mathbb{Z}_p^p$  be the unit vector whose  $i$ th coordinate is one. For  $1 \leq i < p$ , let  $\mathbf{v}_i = \mathbf{u}_i + (i - 1)\mathbf{u}_p$ . Let  $L$  be the (proper) sub-lattice of  $\mathbb{Z}_p^p$  generated by  $\mathbf{v}_1, \dots, \mathbf{v}_{p-1}$ . The following property was proved in [29, Section 2].

(†) For any vector  $\mathbf{v} \in \mathbb{Z}_p^p$ , there exists precisely one  $i \in [p]$  such that  $\mathbf{v} + \mathbf{u}_i \in L$ .

Let  $\mathcal{P} = \{V_1, V_2, \dots, V_p\}$  be a partition of  $V$  such that  $|V_1| + |V_2| + \dots + |V_p| = n$ ,  $|V_i| = n/p \pm 1$  for  $i \in [p]$  and  $\mathbf{i}_{\mathcal{P}}(V) \notin L \pmod p$  (recall that  $\mathbf{i}_{\mathcal{P}}(S)$  is the vector of  $\mathbb{Z}^p$  whose  $i$ th coordinate is  $|S \cap V_i|$ ). Let  $H_p$  be the  $k$ -graph on  $V$  whose edges are  $k$ -sets  $e$  such that  $\mathbf{i}_{\mathcal{P}}(e) \in L \pmod p$ . Observe that (†) implies that  $\delta_{k-1}(H_p) \geq n/p - k$ .

**Proposition 7.1** ([29]). *Suppose that  $K$  is a complete  $k$ -partite  $k$ -graph of type  $d$  for some  $d \neq 1$ . Let  $p$  be the smallest prime factor of  $d$  (thus  $p = 2$  when  $d = 0$ ). Then  $H_p$  contains no  $K$ -factor.*

Using  $H_p$  and the construction behind Proposition 2.3, we disprove Conjecture 1.1 for many complete  $k$ -partite  $k$ -graphs of type  $d \neq 1$ .

**Proposition 7.2.** *Let  $K := K^{(k)}(a_1, \dots, a_k)$  be type  $d \neq 1$  and let  $p$  be the smallest prime factor of  $d$ . Then Conjecture 1.1 is false for  $K$  if  $a_{k-2} \geq p + 1$ .*

**Proof.** Let  $n \in (a_1 + \dots + a_k)\mathbb{Z}$  and let  $G$  be an  $n$ -vertex  $K^{(k)}(1, \dots, 1, 2, 2)$ -free  $k$ -graph with  $\delta_{k-1}(G) = (1 - o(1))\sqrt{n}$  provided by Proposition 2.3. We first take a copy of the  $n$ -vertex  $k$ -graph  $H_p$  under a vertex partition  $V_1, V_2, \dots, V_p$ . Then we take a random permutation of  $V(G)$  and then add  $E(G)$  on top of  $H_p$ . Denote the resulting graph by  $H$ . By standard concentration results, we have  $\delta_{k-1}(H) \geq n/p + (1 - o(1))\sqrt{n}/p$ . We claim that

(‡) every copy of  $K$  in  $H$  has each of its vertex classes completely in  $V_i$  for some  $i \in [p]$ .

Suppose instead that there exist distinct  $i_1, i_2 \in [p]$  and a copy of  $K$  in  $H$  with vertex classes  $U_1, \dots, U_k$  such that  $U_l \cap V_{i_1} \neq \emptyset$  and  $U_l \cap V_{i_2} \neq \emptyset$  for some  $l \in [k]$ . For  $i \in [k] \setminus \{l\}$ , let  $C_i = U_i \cap V_j$  such that  $|U_i \cap V_j| \geq |U_i \cap V_{j'}|$  for all  $j' \in [p]$  (if more than one  $j$  satisfies this, choose any of them). Since  $a_k \geq a_{k-1} \geq a_{k-2} \geq p + 1$ , by the pigeonhole principle, we have  $|C_i| \geq 2$  for any  $i \in \{k - 2, k - 1, k\} \setminus \{l\}$ . Thus both  $(U_l \cap V_{i_1}) \cup \bigcup_{j \neq l} C_j$  and  $(U_l \cap V_{i_2}) \cup \bigcup_{j \neq l} C_j$  contain  $K^{(k)}(1, \dots, 1, 2, 2)$  as a subgraph such that a vertex class of size one is placed in  $U_l \cap V_{i_1}$  and  $U_l \cap V_{i_2}$ , respectively. Since  $G$  is  $K^{(k)}(1, \dots, 1, 2, 2)$ -free, both copies of  $K^{(k)}(1, \dots, 1, 2, 2)$  contain an edge in  $H_p$ . The index vectors of these two edges can be written as  $\mathbf{v} + \mathbf{u}_{i_1}$  and  $\mathbf{v} + \mathbf{u}_{i_2}$  for some  $\mathbf{v}$ , contradicting (†).

Since  $G$  is  $K$ -free, each copy  $K_1$  of  $K$  in  $H$  must contain some edge  $e$  in  $H_p$ . Since  $K$  is a blow-up of  $e$ , (‡) implies that  $\mathbf{i}_{\mathcal{P}}(e') = \mathbf{i}_{\mathcal{P}}(e) \in L \pmod p$  for all  $e' \in E(K_1)$ . Thus, all copies of  $K$  in  $H$  are actually in  $H_p$ . Therefore,  $H$  has no  $K$ -factor by Proposition 7.1. □

When  $K = K^{(k)}(a_1, \dots, a_k)$  is type  $d \neq 1$ , Proposition 7.2 leaves out the following unsettled cases for complete  $k$ -partite  $k$ -graphs in Conjecture 1.1:  $K^{(k)}(2, \dots, 2, 2s, 2t)$  for  $t \geq s \geq 1$  (type 0), and  $K^{(k)}(a_1, \dots, a_1, a_{k-1}, a_k)$  (type  $d \geq 2$ ). To see how to derive the second case, we note that if  $K$  is type  $d \geq 2$  and  $p$  is the smallest prime factor of  $d$ , then  $a_1 \geq 1$  and  $a_{k-2} \leq p$  force that  $a_1 = a_{k-2}$ .

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