

# A DEGREE VERSION OF THE HILTON–MILNER THEOREM

PETER FRANKL, JIE HAN, HAO HUANG, AND YI ZHAO

ABSTRACT. An intersecting family of sets is trivial if all of its members share a common element. Hilton and Milner proved a strong stability result for the celebrated Erdős–Ko–Rado theorem: when  $n > 2k$ , every non-trivial intersecting family of  $k$ -subsets of  $[n]$  has at most  $\binom{n-1}{k-1} - \binom{n-k-1}{k-1} + 1$  members. One extremal family  $\mathcal{HM}_{n,k}$  consists of a  $k$ -set  $S$  and all  $k$ -subsets of  $[n]$  containing a fixed element  $x \notin S$  and at least one element of  $S$ . We prove a degree version of the Hilton–Milner theorem: if  $n = \Omega(k^2)$  and  $\mathcal{F}$  is a non-trivial intersecting family of  $k$ -subsets of  $[n]$ , then  $\delta(\mathcal{F}) \leq \delta(\mathcal{HM}_{n,k})$ , where  $\delta(\mathcal{F})$  denotes the minimum (vertex) degree of  $\mathcal{F}$ . Our proof uses several fundamental results in extremal set theory, the concept of kernels, and a new variant of the Erdős–Ko–Rado theorem.

## 1. INTRODUCTION

A family  $\mathcal{F}$  of sets is called *intersecting* if for  $A \cap B \neq \emptyset$  for all  $A, B \in \mathcal{F}$ . A fundamental problem in extremal set theory is to study the properties of intersecting families. For positive integers  $k, n$ , let  $[n] = \{1, 2, \dots, n\}$  and  $\binom{V}{k}$  denote the family of all  $k$ -element subsets ( $k$ -subsets) of  $V$ . We call a family on  $V$   *$k$ -uniform* if it is a subfamily of  $\binom{V}{k}$ . A *full star* is a family that consists of all the  $k$ -subsets of  $[n]$  that contains a fixed element. We call an intersecting family  $\mathcal{F}$  *trivial* if it is a subfamily of a full star. The celebrated Erdős–Ko–Rado (EKR) theorem [3] states that, when  $n \geq 2k$ , every  $k$ -uniform intersecting family on  $[n]$  has at most  $\binom{n-1}{k-1}$  members, and the full star shows that the bound  $\binom{n-1}{k-1}$  is best possible. Hilton and Milner [14] proved the uniqueness of the extremal family in a stronger sense: if  $n > 2k$ , every non-trivial intersecting family of  $k$ -subsets of  $[n]$  has at most  $\binom{n-1}{k-1} - \binom{n-k-1}{k-1} + 1$  members. It is easy to see that the equality holds for the following family, denoted by  $\mathcal{HM}_{n,k}$ , which consists of a  $k$ -set  $S$  and all  $k$ -subsets of  $[n]$  containing a fixed element  $x \notin S$  and at least one vertex of  $S$ . For more results on intersecting families, see a recent survey by Frankl and Tokushige [10].

Given a family  $\mathcal{F}$  and  $x \in V(\mathcal{F})$ , we denote by  $\mathcal{F}(x)$  the subfamily of  $\mathcal{F}$  consisting of all the members of  $\mathcal{F}$  that contain  $x$ , i.e.,  $\mathcal{F}(x) := \{F \in \mathcal{F} : x \in F\}$ . Let  $d_{\mathcal{F}}(x) := |\mathcal{F}(x)|$  be the *degree* of  $x$ . Let  $\Delta(\mathcal{F}) := \max_x d_{\mathcal{F}}(x)$  and  $\delta(\mathcal{F}) := \min_x d_{\mathcal{F}}(x)$  denote the maximum and minimum degree of  $\mathcal{F}$ , respectively. There were extremal problems in set theory that considered the maximum or minimum degree of families satisfying certain properties. For example, Frankl [7] extended the Hilton–Milner theorem by giving sharp upper bounds on the size of intersecting families with certain maximum degree. Bollobás, Daykin, and Erdős [1] studied the minimum degree version of a well-known conjecture of Erdős [2] on matchings.

Huang and Zhao [15] recently proved a minimum degree version of the EKR theorem, which implies the original EKR theorem as a corollary. Indeed, they showed that if  $n > 2k$  and  $\mathcal{F}$  is a  $k$ -uniform intersecting family on  $[n]$ , then  $\delta(\mathcal{F}) \leq \binom{n-2}{k-2}$ , and the equality holds only if  $\mathcal{F}$  is a full star. Frankl and Tokushige [11] gave a different proof of this result for  $n \geq 3k$ . Generally speaking, a minimum degree condition forces the sets of a family to be distributed somewhat evenly and thus the size of a family that is required to satisfy a property might be smaller than the one without degree condition. Unless the extremal family is very regular, an extremal problem under the minimum degree condition seems harder than the original extremal problem because one cannot directly apply the *shifting method* (a powerful tool in extremal set theory).

In this paper we study the minimum degree version of the Hilton–Milner theorem.

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**Theorem 1.** *Suppose  $k \geq 4$  and  $n \geq ck^2$ , where  $c = 30$  for  $k = 4, 5$  and  $c = 4$  for  $k \geq 6$ . If  $\mathcal{F} \subseteq \binom{[n]}{k}$  is a non-trivial intersecting family, then  $\delta(\mathcal{F}) \leq \delta(\mathcal{HM}_{n,k}) = \binom{n-2}{k-2} - \binom{n-k-2}{k-2}$ .*

Han and Kohayakawa [12] recently determined the maximum size of a non-trivial intersecting family that is not a subfamily of  $\mathcal{HM}_{n,k}$ . Later Kostochka and Mubayi [17] determined the maximum size of a non-trivial intersecting family that is not a subfamily of  $\mathcal{HM}_{n,k}$  or the extremal families given in [12] for sufficiently large  $n$ . Furthermore, Kostochka and Mubayi [17, Theorem 8] characterized *all* maximal intersecting 3-uniform families  $\mathcal{F}$  on  $[n]$  for  $n \geq 7$  and  $|\mathcal{F}| \geq 11$ . Using a different approach, Polcyn and Ruciński [18, Theorem 4] characterized *all* maximal intersecting 3-uniform families  $\mathcal{F}$  on  $[n]$  for  $n \geq 7$ , in particular, there are fifteen such families, including the full star and  $\mathcal{HM}_{n,3}$ . It is straightforward to check that all these families have minimum degree at most 3 – this gives the following proposition.

**Proposition 2.** *If  $n \geq 7$  and  $\mathcal{F} \subseteq \binom{[n]}{3}$  is a non-trivial intersecting family, then  $\delta(\mathcal{F}) \leq \delta(\mathcal{HM}_{n,3}) = 3$ .*

In order to Theorem 1, we prove a new variant of the EKR theorem, which is closely related to the EKR theorem for direct product given by Frankl [8].

**Theorem 3.** *Given integers  $k \geq 3$ ,  $\ell \geq 4$ , and  $m \geq k\ell$ , let  $T_1, T_2, T_3$  be three disjoint  $\ell$ -subsets of  $[m]$ . If  $\mathcal{F}$  is a  $k$ -uniform intersecting family on  $[m]$  such that every member intersects all of  $T_1, T_2, T_3$ , then  $|\mathcal{F}| \leq \ell^2 \binom{m-3}{k-3}$ .*

Theorem 3 becomes trivial when  $\ell = 1$  because every family  $\mathcal{F}$  of  $k$ -sets that intersect  $T_1, T_2, T_3$  is intersecting and satisfies  $|\mathcal{F}| \leq \binom{m-3}{k-3}$ . Our bound in Theorem 3 is asymptotically tight because a star with a center in  $T_1 \cup T_2 \cup T_3$  contains about  $\ell^2 \binom{m-3}{k-3}$   $k$ -sets that intersect  $T_1, T_2, T_3$ .

It is easy to derive the minimum degree version of the EKR theorem for sufficiently large  $n$  (the difficulty of the result in [15] was to derive the tight bound  $n \geq 2k + 1$ ). However, since  $\delta(\mathcal{HM}_{n,k}) \approx k \binom{n-3}{k-3}$  is significantly smaller than  $\binom{n-2}{k-2}$ , it is not easy to prove Theorem 1 for sufficiently large  $n$ .

Our proof of Theorem 1 applies several fundamental results in extremal set theory as well as Theorem 3. The following is an outline of our proof. Let  $\mathcal{F}$  be a non-trivial intersecting family such that  $\delta(\mathcal{F}) > \delta(\mathcal{HM}_{n,k})$ . For every  $u \in [n]$ , we obtain a lower bound for  $|\mathcal{F} \setminus \mathcal{F}(u)|$  by applying the assumption on  $\delta(\mathcal{F})$  and the Frankl–Wilson theorem [5, 19] on the maximum size of  $t$ -intersecting families. If  $k = 4, 5$ , then we derive a contradiction by considering the *kernel* of  $\mathcal{F}$  (a concept introduced by Frankl [6]). When  $k \geq 6$ , we separate two cases based on  $\Delta(\mathcal{F})$ . When  $\Delta(\mathcal{F})$  is large, assume that  $|\mathcal{F}(u)| = \Delta(\mathcal{F})$  and let  $\mathcal{F}_2 := \mathcal{F} \setminus \mathcal{F}(u)$ . A result of Frankl [9] implies that  $\mathcal{F}_2$  contains three edges  $E_i := \{u\} \cup T_i$ ,  $i \in [3]$ , where  $T_1, T_2, T_3$  are pairwise disjoint. Since  $\mathcal{F}_2$  is intersecting and every member of  $\mathcal{F}_2$  meets each of  $T_1, T_2, T_3$ , Theorem 3 gives an upper bound on  $|\mathcal{F}_2|$ , which contradicts the lower bound that we derived earlier. When  $\Delta(\mathcal{F})$  is small, we apply the aforementioned result of Frankl [7] to obtain an upper bound on  $|\mathcal{F}|$ , which contradicts the assumption on  $\delta(\mathcal{F})$ .

## 2. TOOLS

**2.1. Results that we need.** Given a positive integer  $t$ , a family  $\mathcal{F}$  of sets is called  *$t$ -intersecting* if  $|A \cap B| \geq t$  for all  $A, B \in \mathcal{F}$ . A  $t$ -intersecting EKR theorem was proved in [3] for sufficiently large  $n$ . Later Frankl [5] (for  $t \geq 15$ ) and Wilson [19] (for all  $t$ ) determined the exact threshold for  $n$ .

**Theorem 4.** [5, 19] *Let  $n \geq (t+1)(k-t+1)$  and let  $\mathcal{F}$  be a  $k$ -uniform  $t$ -intersecting families on  $[n]$ . Then  $|\mathcal{F}| \leq \binom{n-t}{k-t}$ .*

As mentioned in Section 1, Frankl [7] determined the maximum possible size of an intersecting family under a maximum degree condition.

**Theorem 5.** [7] *Suppose  $n > 2k$ ,  $3 \leq i \leq k+1$ ,  $\mathcal{F} \subseteq \binom{[n]}{k}$  is intersecting. If  $\Delta(\mathcal{F}) \leq \binom{n-1}{k-1} - \binom{n-i}{k-1}$ , then  $|\mathcal{F}| \leq \binom{n-1}{k-1} - \binom{n-i}{k-1} + \binom{n-i}{k-i+1}$ .*

Given a  $k$ -uniform family  $\mathcal{F}$ , a *matching of size  $s$*  is a collection of  $s$  vertex-disjoint sets of  $\mathcal{F}$ . A well-known conjecture of Erdős [2] states that if  $n \geq (s+1)k$  and  $\mathcal{F} \subseteq \binom{[n]}{k}$  satisfies  $|\mathcal{F}| > \max\{\binom{n}{k} - \binom{n-s}{k}, \binom{k(s+1)-1}{k}\}$ , then  $\mathcal{F}$  contains a matching of size  $s+1$ . Frankl [9] verified this conjecture for  $n \geq (2s+1)k - s$ .

**Theorem 6.** [9] Let  $n \geq (2s+1)k - s$  and let  $\mathcal{F} \subseteq \binom{[n]}{k}$ . If  $|\mathcal{F}| > \binom{n}{k} - \binom{n-s}{k}$ , then  $\mathcal{F}$  contains a matching of size  $s+1$ .

Frankl [8] proved an EKR theorem for direct products.

**Theorem 7.** [8] Suppose  $n = n_1 + \dots + n_d$  and  $k = k_1 + \dots + k_d$ , where  $n_i \geq k_i$  are positive integers. Let  $X_1 \cup \dots \cup X_d$  be a partition of  $[n]$  with  $|X_i| = n_i$ , and

$$\mathcal{H} = \left\{ F \in \binom{[n]}{k} : |F \cap X_i| = k_i \text{ for } i = 1, \dots, d \right\}.$$

If  $n_i \geq 2k_i$  for all  $i$  and  $\mathcal{F} \subseteq \mathcal{H}$  is intersecting, then

$$\frac{|\mathcal{F}|}{|\mathcal{H}|} \leq \max_i \frac{k_i}{n_i}.$$

Note that the  $d = 1$  case of Theorem 7 is the EKR theorem.

**2.2. Kernels of intersecting families.** Frankl introduced the concept of *kernels* (and called them *bases*) for intersecting families in [6]. Given  $\mathcal{F} \subseteq \binom{V}{k}$ , a set  $S \subseteq V$  is called a *cover* of  $\mathcal{F}$  if  $S \cap A \neq \emptyset$  for all  $A \in \mathcal{F}$ . For example, if  $\mathcal{F}$  is intersecting, then every member of  $\mathcal{F}$  is a cover. Given an intersecting family  $\mathcal{F}$ , we define its *kernel*  $\mathcal{K}$  as

$$\mathcal{K} := \{S : S \text{ is a cover of } \mathcal{F} \text{ and any } S' \subsetneq S \text{ is not a cover of } \mathcal{F}\}.$$

An intersecting family  $\mathcal{F}$  is called *maximal* if  $\mathcal{F} \cup \{G\}$  is not intersecting for any  $k$ -set  $G \notin \mathcal{F}$ . Note that, when proving Theorem 1, we may assume that  $\mathcal{F}$  is maximal because otherwise we can add more  $k$ -sets to  $\mathcal{F}$  such that the resulting intersecting family is still non-trivial and satisfies the minimum degree condition. We observe the following fact on the kernels.

**Fact 8.** If  $n \geq 2k$  and  $\mathcal{F} \in \binom{[n]}{k}$  is a maximal intersecting family, then  $\mathcal{K}$  is also intersecting.

*Proof.* Suppose there are  $K_1, K_2 \in \mathcal{K}$  such that  $K_1 \cap K_2 = \emptyset$ . Since  $n \geq 2k$ , we can find two disjoint  $k$ -sets  $F_1, F_2$  on  $[n]$  such that  $K_i \subseteq F_i$  for  $i = 1, 2$ . For  $i = 1, 2$ , since  $K_i$  is a cover of  $\mathcal{F}$ ,  $F_i$  intersects all members of  $\mathcal{F}$ . Since  $\mathcal{F}$  is maximal, we derive that  $F_1, F_2 \in \mathcal{F}$ . This contradicts the assumption that  $F_1, F_2$  are disjoint.  $\square$

For  $i \in [k]$ , let  $\mathcal{K}_i := \mathcal{K} \cap \binom{[n]}{i}$ . If an intersecting family  $\mathcal{F}$  is non-trivial, then  $\mathcal{K}_1 = \emptyset$ . Below we prove an upper bound for  $|\mathcal{K}_i|$ ,  $3 \leq i \leq k$ , where the  $i = k$  case was given by Erdős and Lovász [4].

**Lemma 9.** For  $3 \leq i \leq k$ , we have  $|\mathcal{K}_i| \leq k^i$ .

In order to prove Lemma 9, We use a result of Håstad, Jukna, and Pudlák [13, Lemma 3.4]. Given a family  $\mathcal{F}$ , the *cover number* of  $\mathcal{F}$ , denoted by  $\tau(\mathcal{F})$ , is the size of the smallest cover of  $\mathcal{F}$ .

**Lemma 10.** [13] If  $\mathcal{F}$  is an  $i$ -uniform family with  $|\mathcal{F}| > k^i$ , then there exists a set  $Y$  such that  $\tau(\mathcal{F}_Y) \geq k+1$ , where  $\mathcal{F}_Y := \{F \setminus Y : F \in \mathcal{F}, F \supseteq Y\}$ .

*Proof of Lemma 9.* Suppose  $|\mathcal{K}_i| > k^i$  for some  $3 \leq i \leq k$ . Then by Lemma 10, there exists a set  $Y$  such that  $\tau((\mathcal{K}_i)_Y) \geq k+1$ . In particular,  $(\mathcal{K}_i)_Y$  is nonempty, namely, there exists  $K \in \mathcal{K}_i$  such that  $Y \subsetneq K$ . By the definition of  $\mathcal{K}$ , this implies that  $Y$  is not a cover of  $\mathcal{F}$ , so there exists  $F \in \mathcal{F}$  such that  $F \cap Y = \emptyset$ . Since each member of  $\mathcal{K}_i$  is a cover of  $\mathcal{F}$ , each of them intersects  $F$ . This implies that  $\tau((\mathcal{K}_i)_Y) \leq |F| = k$ , a contradiction.  $\square$

### 3. PROOF OF THEOREM 3

In this section we derive Theorem 3 from Theorem 6.

*Proof of Theorem 3.* Let  $\mathcal{F}_r$  consist of all the subsets of  $\mathcal{F}$  that intersect with  $T_1 \cup T_2 \cup T_3$  in exactly  $r$  elements. Then  $\mathcal{F} = \mathcal{F}_3 \cup \mathcal{F}_4 \cup \dots \cup \mathcal{F}_k$ . Let  $X_1 = T_1$ ,  $X_2 = T_2$ ,  $X_3 = T_3$ ,  $X_4 = [m] \setminus (T_1 \cup T_2 \cup T_3)$ , and  $k_1 = k_2 = k_3 = 1$ ,  $k_4 = k - 3$ . Since  $m \geq k\ell$ , we have  $1/\ell \geq (k-3)/(m-3\ell)$ . Since  $\ell \geq 2$ , we can apply Theorem 6 to conclude that

$$|\mathcal{F}_3| \leq \ell^3 \binom{m-3\ell}{k-3} \cdot \frac{1}{\ell} = \ell^2 \binom{m-3\ell}{k-3}.$$

Note that a set  $S \in \mathcal{F}_4$  intersects  $T_1, T_2, T_3$  with either 1, 1, 2 or 1, 2, 1 or 2, 1, 1 elements. We partition  $\mathcal{F}_4$  into three subfamilies accordingly. Our assumption implies

$$\frac{k-4}{m-3\ell} \leq \frac{2}{\ell} \leq \frac{1}{2}.$$

We can apply Theorem 6 to each subfamily of  $\mathcal{F}_4$  and obtain that

$$|\mathcal{F}_4| \leq 3 \binom{\ell}{2} \ell^2 \binom{m-3\ell}{k-4} \cdot \frac{2}{\ell} = 3(\ell-1) \ell^2 \binom{m-3\ell}{k-4}.$$

Finally, for  $5 \leq r \leq k$ , we claim that  $|\mathcal{F}_r| \leq \ell^2 \binom{3\ell-3}{r-3} \binom{m-3\ell}{k-r}$ . Indeed, let  $X_1 = T_1 \cup T_2 \cup T_3$ ,  $X_2 = [m] \setminus X_1$ ,  $k_1 = r$  and  $k_2 = k - r$ . Note that  $|X_2| = m - 3\ell \geq 2(k - r)$  and  $r/(3\ell) \geq (k - r)/(m - 3\ell)$ . If  $|X_1| = 3\ell \geq 2r$ , then Theorem 6 gives that

$$|\mathcal{F}_r| \leq \binom{3\ell-1}{r-1} \binom{m-3\ell}{k-r} < \ell^2 \binom{3\ell-3}{r-3} \binom{m-3\ell}{k-r}.$$

When  $3\ell \leq 2r$ , we have  $r \geq 6$  because  $\ell \geq 4$ . Hence,

$$\binom{3\ell}{r} < \frac{(3\ell)^3}{r(r-1)(r-2)} \binom{3\ell-3}{r-3} \leq \frac{18\ell^2}{(r-1)(r-2)} \binom{3\ell-3}{r-3} < \ell^2 \binom{3\ell-3}{r-3},$$

and the trivial bound on  $|\mathcal{F}_r|$  gives that

$$|\mathcal{F}_r| \leq \binom{3\ell}{r} \binom{m-3\ell}{k-r} < \ell^2 \binom{3\ell-3}{r-3} \binom{m-3\ell}{k-r}$$

as claimed. Summing up the bounds for  $|\mathcal{F}_3|, |\mathcal{F}_4|$  and  $|\mathcal{F}_r|$  for  $r \geq 5$ , we have

$$\begin{aligned} |\mathcal{F}| &= |\mathcal{F}_3| + |\mathcal{F}_4| + \sum_{r=5}^k |\mathcal{F}_r| \\ &\leq \ell^2 \binom{m-3\ell}{k-3} + 3(\ell-1) \ell^2 \binom{m-3\ell}{k-4} + \ell^2 \sum_{r=5}^k \binom{3\ell-3}{r-3} \binom{m-3\ell}{k-r} = \ell^2 \binom{m-3\ell}{k-3}, \end{aligned}$$

because  $\binom{m-3\ell}{k-3} = \sum_{i=0}^{k-3} \binom{m-3\ell}{k-3-i} \binom{3\ell-3}{i}$ . □

#### 4. PROOF OF THEOREM 1

We start with some simple estimates. First, for  $n \geq ck^2$ ,  $c \geq 1$  and  $1 \leq t \leq k-1$ , we have

$$\begin{aligned} \frac{\binom{n-2k+t-1}{k-2}}{\binom{n-t-1}{k-2}} &= \frac{(n-2k+t-1) \cdots (n-3k+t+2)}{(n-t-1) \cdots (n-t-k+2)} \geq \left(1 - \frac{2k-2t}{n-t-k+2}\right)^{k-2} \\ &\geq 1 - \frac{2(k-t)(k-2)}{n-t-k+2} \geq \frac{c-2}{c}. \end{aligned} \tag{4.1}$$

Similarly, one can show that  $\binom{n-k-2}{k-3} \geq \frac{c-1}{c} \binom{n-3}{k-3}$ . Second, if  $\delta(\mathcal{F}) > \binom{n-2}{k-2} - \binom{n-k-2}{k-2}$ , then we have

$$\begin{aligned} |\mathcal{F}| &> \frac{n}{k} \left( \binom{n-2}{k-2} - \binom{n-k-2}{k-2} \right) > n \binom{n-k-2}{k-3} \\ &\geq \frac{(c-1)n}{c} \binom{n-3}{k-3} > \frac{(c-1)}{c} (k-2) \binom{n-2}{k-2}. \end{aligned} \tag{4.2}$$

**Lemma 11.** *Suppose  $k \geq 4$  and  $n \geq 4k^2$ ,  $\mathcal{F} \subseteq \binom{[n]}{k}$  is a non-trivial intersecting family such that  $\delta(\mathcal{F}) > \delta(\mathcal{HM}_{n,k}) = \binom{n-2}{k-2} - \binom{n-k-2}{k-2}$ . Then for any  $u \in [n]$ ,*

- (i) there exists  $E, E' \in \mathcal{F}$  such that  $u \notin E \cup E'$  and  $|E \cap E'| = 1$ ;  
(ii)  $|\mathcal{F} \setminus \mathcal{F}(u)| > \frac{k-2}{2} \binom{n-2}{k-2}$ .

*Proof.* Given  $u \in [n]$ , write  $\mathcal{F}_1 = \mathcal{F}(u)$  and  $\mathcal{F}_2 = \mathcal{F} \setminus \mathcal{F}_1$ . If  $|\mathcal{F}_2| = 1$ , then  $\mathcal{F} \subseteq \mathcal{HM}_{n,k}$ , and thus  $\delta(\mathcal{F}) \leq \delta(\mathcal{HM}_{n,k})$ , a contradiction. So assume that  $|\mathcal{F}_2| \geq 2$ .

Let  $t = \min |E \cap E'|$  among all distinct  $E, E' \in \mathcal{F}_2$ . Obviously  $1 \leq t \leq k-1$ , and  $\mathcal{F}_2$  is a  $t$ -intersecting family on  $[2, n]$ . Then since  $n > 4k^2 \geq (k-t+1)(t+1) + 1$ , we get  $|\mathcal{F}_2| \leq \binom{n-t-1}{k-t}$  by Theorem 4. Note that there exist  $E, E' \in \mathcal{F}_2$  such that  $|E \cap E'| = t$ . Since every set in  $\mathcal{F}_1$  must intersect both  $E$  and  $E'$ , for every  $x \notin E \cup E' \cup \{u\}$ , we have

$$|\mathcal{F}_1(x)| \leq \binom{n-2}{k-2} - 2 \binom{n-k-2}{k-2} + \binom{n-2k+t-2}{k-2}. \quad (4.3)$$

Let  $X = [n] \setminus (E \cup E' \cup \{u\})$  and thus  $|X| = n-1 - (2k-t)$ . Suppose  $x \in X$  attains the minimum degree in  $\mathcal{F}_2$  among all elements of  $X$ . Since  $|\mathcal{F}(x)| = |\mathcal{F}_1(x)| + |\mathcal{F}_2(x)| > \delta(\mathcal{HM}_{n,k})$ , by (4.3) we have

$$|\mathcal{F}_2(x)| > \binom{n-k-2}{k-2} - \binom{n-2k+t-2}{k-2}.$$

By the definition of  $x$  we get

$$\begin{aligned} |\mathcal{F}_2| &> \frac{|X|}{k-t} \left( \binom{n-k-2}{k-2} - \binom{n-2k+t-2}{k-2} \right) \geq \frac{|X|(k-t)}{k-t} \binom{n-2k+t-2}{k-3} \\ &= (k-2) \binom{n-2k+t-1}{k-2}, \end{aligned}$$

where the factor  $k-t$  comes from the fact that every member  $F \in \mathcal{F}_2$  is counted at most  $k-t$  times – because  $|F \cap E_1| \geq t$ . By (4.1) with  $c = 4$  and  $k \geq 4$ , we get

$$|\mathcal{F}_2| > \frac{k-2}{2} \binom{n-t-1}{k-2} \geq \binom{n-t-1}{k-2},$$

which, together with  $|\mathcal{F}_2| \leq \binom{n-t-1}{k-t}$ , implies that  $t = 1$ , so (i) holds. Since  $t = 1$ , the first inequality above gives (ii).  $\square$

*Proof of Theorem 1.* First assume that  $k \geq 6$  and  $n \geq 4k^2$ . Suppose  $\mathcal{F} \subseteq \binom{[n]}{k}$  is a non-trivial intersecting family such that  $\delta(\mathcal{F}) > \delta(\mathcal{HM}_{n,k}) = \binom{n-2}{k-2} - \binom{n-k-2}{k-2}$ . Suppose  $u \in [n]$  attains the maximum degree of  $\mathcal{F}$  and write  $\mathcal{F}' := \mathcal{F} \setminus \mathcal{F}(u)$ . If  $|\mathcal{F}(u)| > \binom{n-1}{k-1} - \binom{n-3}{k-3}$ , then by Theorem 6, the  $(k-1)$ -uniform family  $\{E \setminus \{u\} : E \in \mathcal{F}(u)\}$  contains a matching  $\mathcal{M} = \{T_1, T_2, T_3\}$  of size 3. Every member of  $\mathcal{F}'$  must intersect each of  $T_1, T_2, T_3$ . By Theorem 3, we have  $|\mathcal{F}'| \leq (k-1)^2 \binom{n-4}{k-3}$ . On the other hand, Lemma 11 Part (ii) implies that  $|\mathcal{F}'| > \frac{k-2}{2} \binom{n-2}{k-2} = \frac{n-2}{2} \binom{n-3}{k-3} > 2(k-1)^2 \binom{n-3}{k-3}$  because  $n \geq 4k^2 \geq 4(k-1)^2 + 2$ . This gives a contradiction.

We thus assume that  $|\Delta(\mathcal{F})| \leq \binom{n-1}{k-1} - \binom{n-3}{k-1}$ . By Theorem 5,

$$|\mathcal{F}| \leq \binom{n-1}{k-1} - \binom{n-3}{k-1} + \binom{n-3}{k-2} = \frac{3n-2k-2}{n-2} \binom{n-2}{k-2} \leq 3 \binom{n-2}{k-2}.$$

Since  $\delta(\mathcal{F}) > \binom{n-2}{k-2} - \binom{n-k-2}{k-2}$ , by (4.2), we have  $|\mathcal{F}| > \frac{3}{4}(k-2) \binom{n-2}{k-2}$ . The upper and lower bounds for  $|\mathcal{F}|$  together imply  $k < 6$ , a contradiction.

Now assume that  $k = 4, 5$  and  $n \geq 30k^2$ . By Lemma 11 Part (i) for any  $u \in [n]$ , there exists  $E, E' \in \mathcal{F}$  such that  $u \notin E \cup E'$  and  $|E \cap E'| = 1$ . Since  $\mathcal{F}$  is intersecting, each member of  $\mathcal{F}$  is a cover of  $\mathcal{F}$  and thus contains as a subset a minimal cover, which is a member of the kernel  $\mathcal{K}$ . Thus  $|\mathcal{F}| \leq \sum_{i=1}^k |\mathcal{K}_i| \binom{n-i}{k-i}$ . We know  $\mathcal{K}_1 = \emptyset$  because  $\mathcal{F}$  is non-trivial. By Lemma 9,

$$|\mathcal{F}| \leq |\mathcal{K}_2| \binom{n-2}{k-2} + \sum_{i=3}^k k^i \binom{n-i}{k-i}.$$

Since  $n \geq 30k^2$ , for any  $3 \leq i \leq k$ , we have

$$k^{i-2} \binom{n-i}{k-i} = \binom{n-2}{k-2} \cdot k^{i-2} \cdot \frac{k-2}{n-2} \cdot \frac{k-3}{n-3} \cdots \frac{k-i+1}{n-i+1} \leq \binom{n-2}{k-2} \frac{1}{30^{i-2}}.$$

Thus

$$|\mathcal{F}| \leq |\mathcal{K}_2| \binom{n-2}{k-2} + k^2 \binom{n-2}{k-2} \sum_{i=3}^k \frac{1}{30^{i-2}} \leq \binom{n-2}{k-2} \left( |\mathcal{K}_2| + \frac{k^2}{29} \right).$$

On the other hand, by (4.2), we have  $|\mathcal{F}| > \frac{29}{30}(k-2) \binom{n-2}{k-2} > \frac{28}{29}(k-2) \binom{n-2}{k-2}$ . So we get  $28(k-2) < 29|\mathcal{K}_2| + k^2 \leq 29|\mathcal{K}_2| + 25$ . Together with  $4 \leq k \leq 5$ , this implies that  $|\mathcal{K}_2| \geq k-2 \geq 2$ . Assume that  $uv, uv' \in \mathcal{K}_2$ . Clearly any  $E \in \mathcal{F}$  not containing  $u$  must contain both  $v$  and  $v'$ , i.e., any  $E, E' \in \mathcal{F}$  not containing  $u$  satisfy that  $|E \cap E'| \geq 2$ , contradicting Lemma 11 Part (i). This completes the proof of Theorem 1.  $\square$

## 5. CONCLUDING REMARKS

The main question arising from our work is whether Theorem 1 holds for all  $n \geq 2k+1$ . Proposition 2 confirms this for  $k=3$ . Another question is whether the following generalization of Theorems 3 and 6 is true. We say a family  $\mathcal{H}$  of sets has the *EKR property* if the largest intersecting subfamily of  $\mathcal{H}$  is trivial.

**Conjecture 12.** *Suppose  $n = n_1 + \cdots + n_d$  and  $k \geq k_1 + \cdots + k_d$ , where  $n_i > k_i \geq 0$  are integers. Let  $X_1 \cup \cdots \cup X_d$  be a partition of  $[n]$  with  $|X_i| = n_i$ , and*

$$\mathcal{H} := \left\{ F \subseteq \binom{[n]}{k} : |F \cap X_i| \geq k_i \text{ for } i = 1, \dots, d \right\}.$$

*If  $n_i \geq 2k_i$  for all  $i$  and  $n_i > k - \sum_{j=1}^d k_j + k_i$  for all but at most one  $i \in [d]$  such that  $k_i > 0$ , then  $\mathcal{H}$  has the EKR property.*

The assumptions on  $n_i$  cannot be relaxed for the following reasons. If  $n_i < 2k_i$  for some  $i$ , then  $\mathcal{H}$  itself is intersecting and  $|\mathcal{H}(x)| < |\mathcal{H}|$  for any  $x \in [n]$ . If  $n_i \leq k - \sum_{j=1}^d k_j + k_i$  for distinct  $i_1, i_2$  such that  $k_{i_1}, k_{i_2} > 0$ , then for any  $x \in [n]$ , the union of  $\mathcal{H}(x)$  and  $\{F \in \mathcal{H} : X_{i_1} \subseteq F \text{ or } X_{i_2} \subseteq F\}$  is a larger intersecting family than  $\mathcal{H}(x)$ .

When  $k = k_1 + \cdots + k_d$ , Conjecture 12 follows from Theorem 7, in particular, the  $d=1$  case is the EKR theorem. A recent result of Katona [16] confirms Conjecture 12 for the case  $d=2$  and  $n_1, n_2 \geq 9(k - \min\{k_1, k_2\})^2$ . We can prove Conjecture 12 in the following case.

**Theorem 13.** *Given positive integers  $d \leq k$ ,  $2 \leq t_1 \leq t_2 \leq \cdots \leq t_d$  with  $t_2 \geq k-d+2$ , there exists  $n_0$  such that the followings holds for all  $n \geq n_0$ . If  $T_1, \dots, T_d$  are disjoint subsets of  $[n]$  such that  $|T_i| = t_i$  for all  $i$ , then*

$$\mathcal{H} := \left\{ F \subseteq \binom{[n]}{k} : |F \cap T_i| \geq 1 \text{ for } i = 1, \dots, d \right\}$$

*has the EKR property.*

We omit the proof of Theorem 13 here because the purpose of this paper is to prove Theorem 1. Moreover, when  $d=3$  and  $t_1 = t_2 = t_3 = k-1$ , our  $n_0$  is  $\Omega(k^4)$  so we cannot replace Theorem 3 by Theorem 13 in our main proof. Nevertheless, it would be interesting to know the smallest  $n_0$  such that Theorem 13 holds.

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ALFRÉD RÉNYI INSTITUTE OF MATHEMATICS, P.O.BOX 127, H-1364 BUDAPEST, HUNGARY  
*E-mail address*, Peter Frankl: [peter.frankl@gmail.com](mailto:peter.frankl@gmail.com)

INSTITUTO DE MATEMÁTICA E ESTATÍSTICA, UNIVERSIDADE DE SÃO PAULO, RUA DO MATÃO 1010, 05508-090, SÃO PAULO, BRAZIL  
*E-mail address*, Jie Han: [jhan@ime.usp.br](mailto:jhan@ime.usp.br)

DEPARTMENT OF MATH AND CS, EMORY UNIVERSITY, ATLANTA, GA 30322  
*E-mail address*, Hao Huang: [hao.huang@emory.edu](mailto:hao.huang@emory.edu)

DEPARTMENT OF MATHEMATICS AND STATISTICS, GEORGIA STATE UNIVERSITY, ATLANTA, GA 30303  
*E-mail address*, Yi Zhao: [yzhao6@gsu.edu](mailto:yzhao6@gsu.edu)