

# High critical current density and vortex phase diagram of CaKFe<sub>4</sub>As<sub>4</sub> (1144) superconductors

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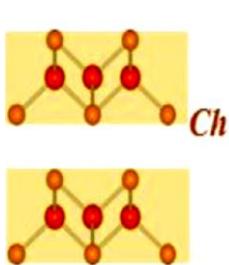
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# Iron based superconductors

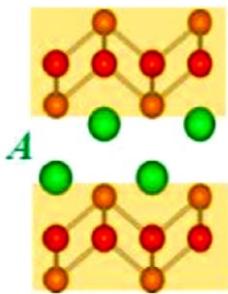
11



**FeCh**

Ch: Se, Te

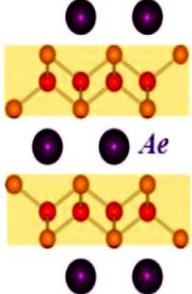
111



**AFePn**

A: Li, Na

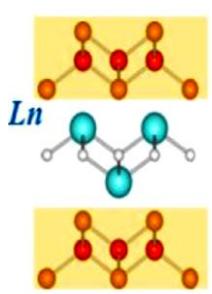
122



**AeFe<sub>2</sub>Pn<sub>2</sub>**

Ae: Ca, Sr, Ba, K, Eu & Pn:  
P, As)

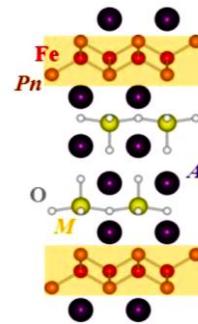
1111



**LnFePnO**

Ln: La, Ce, Sm... Ae: Ca, Sr &  
Pn: As, P

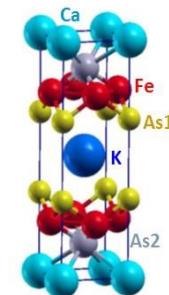
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**Ae<sub>4</sub>M<sub>2</sub>O<sub>6</sub>Fe<sub>2</sub>Pn<sub>2</sub>**

Ae: Ca, Sr, Ba M: Sc, V, Cr &  
Pn: P, As, Se

1144



**AeAFe<sub>4</sub>As<sub>4</sub>**

Ae: Ca, Sr A: K, Rb, Cs

$T_c^{max} = 13 \text{ K}$

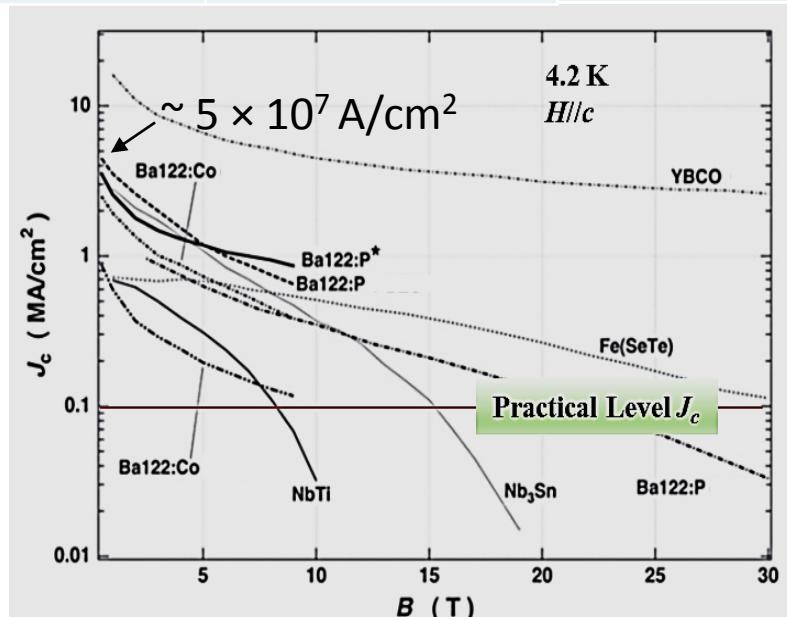
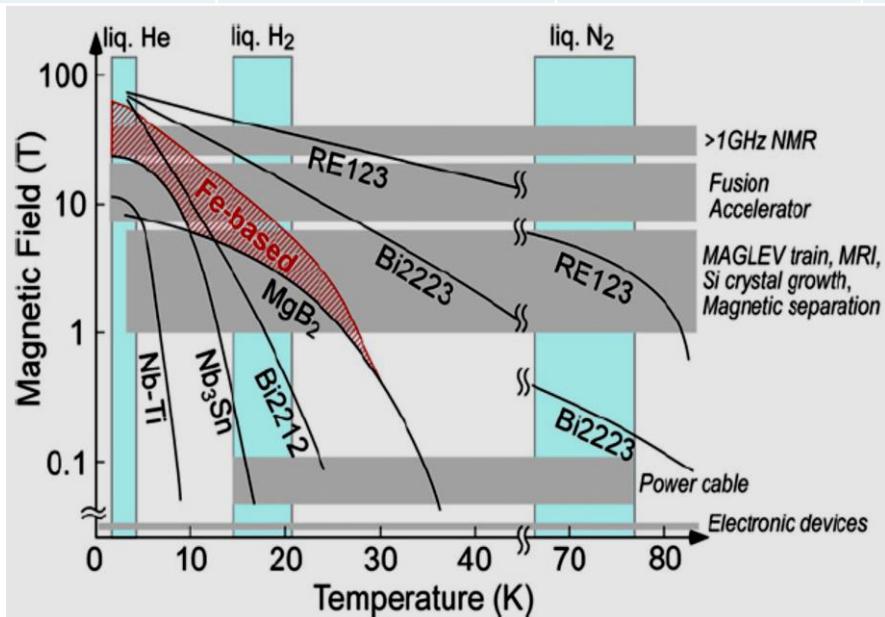
$T_c^{max} = 31 \text{ K}$

$T_c^{max} = 38 \text{ K}$

$T_c^{max} = 58 \text{ K}$

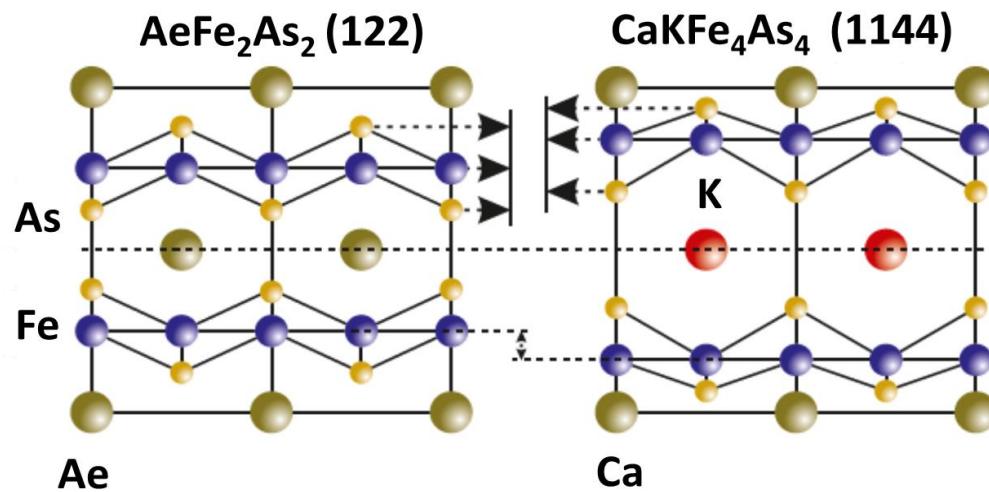
$T_c^{max} = 46 \text{ K}$

$T_c^{max} = 36 \text{ K}$



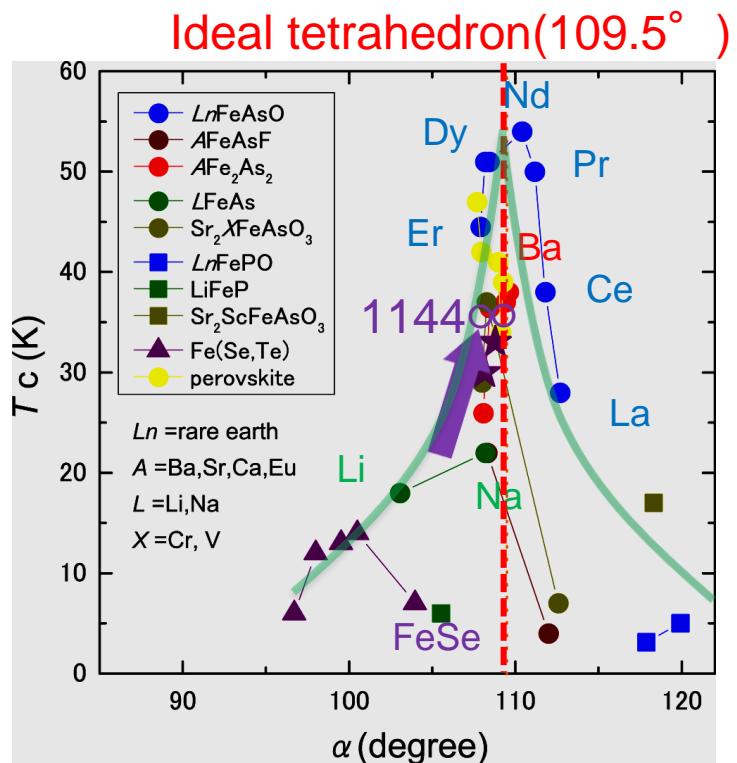
# Introduction about $\text{CaKFe}_4\text{As}_4$ (1144)

122	1144
Tetragonal	Tetragonal
I4/mmm	P4/mmm
$a = 3.9612 \text{ \AA}$	$a = 3.866 \text{ \AA}$
$c = 13.006 \text{ \AA}$	$c = 12.817 \text{ \AA}$
$d_{\text{Fe-As}} = 2.394 \text{ \AA}$	$d_{\text{Fe-As(1)}} = 2.408 \text{ \AA}$ $d_{\text{Fe-As(2)}} = 2.380 \text{ \AA}$
$\alpha_{\text{As(1)-Fe-As(1)}} = \alpha_{\text{As(2)-Fe-As(2)}} = 109.6^\circ$	$\alpha_{\text{As(1)-Fe-As(1)}} = 107.2^\circ$ $\alpha_{\text{As(2)-Fe-As(2)}} = 109.1^\circ$
$h_{\text{As(1)}} = h_{\text{As(2)}} = 1.346 \text{ \AA}$ (Anion height from Fe layer)	$h_{\text{As(1)}} = 1.429 \text{ \AA}$ $h_{\text{As(2)}} = 1.381 \text{ \AA}$



J. Am. Chem. Soc. **138**, 3410 (2016)

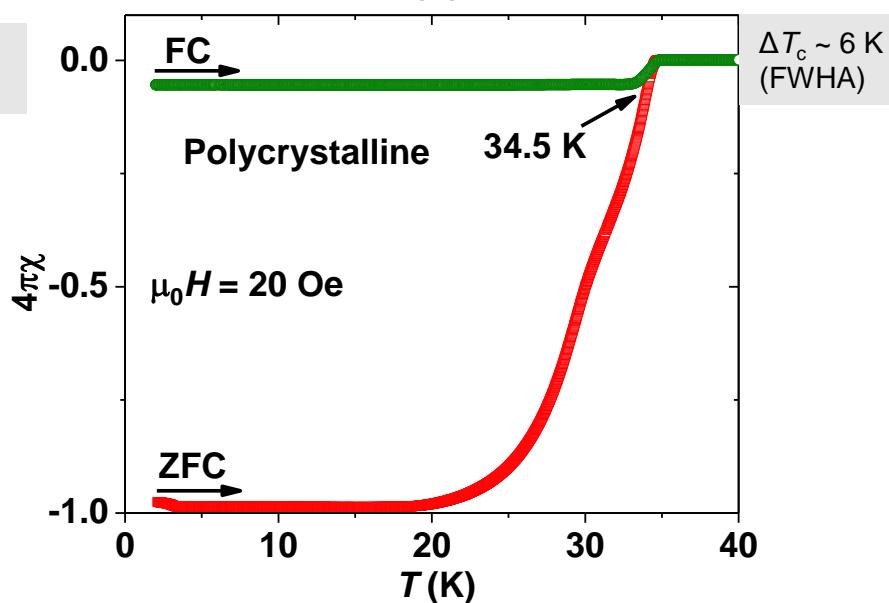
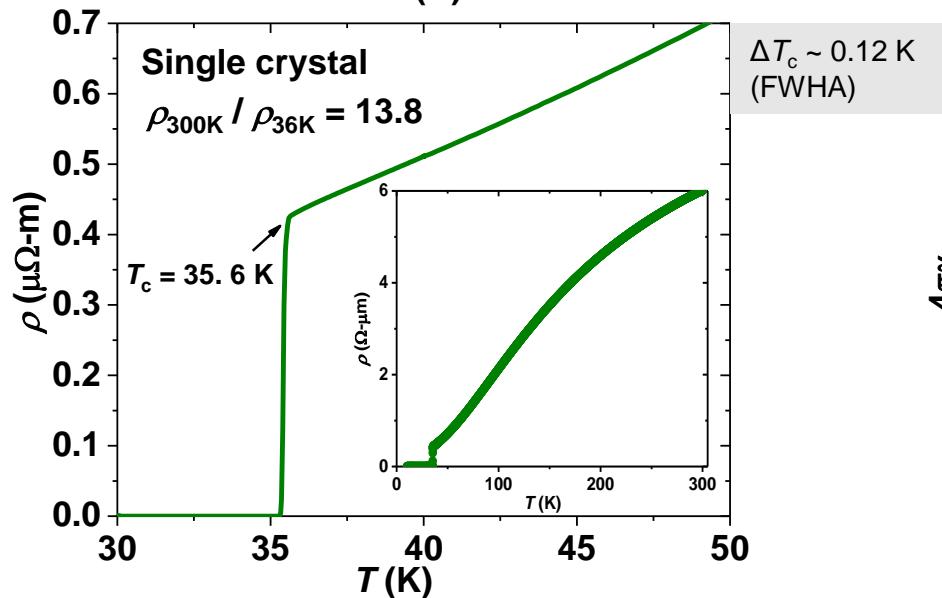
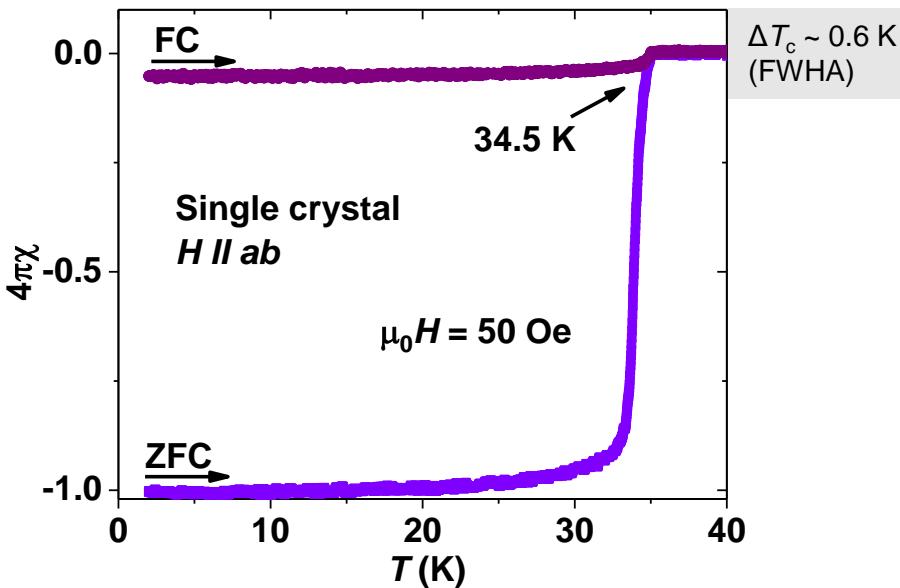
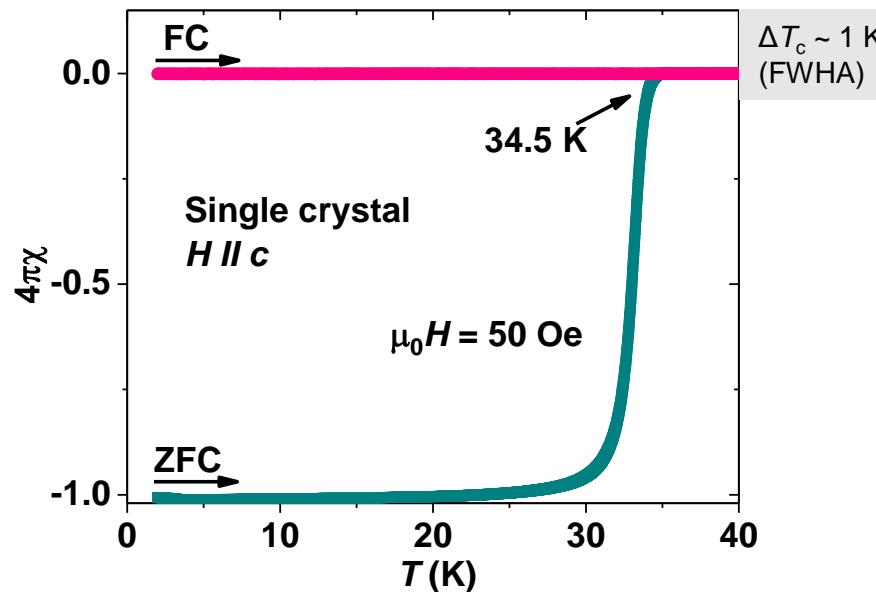
Phys. Rev. B **94**, 064501 (2016)



Sci. Technol. Adv. Mater. **16**, 033503 (2015)

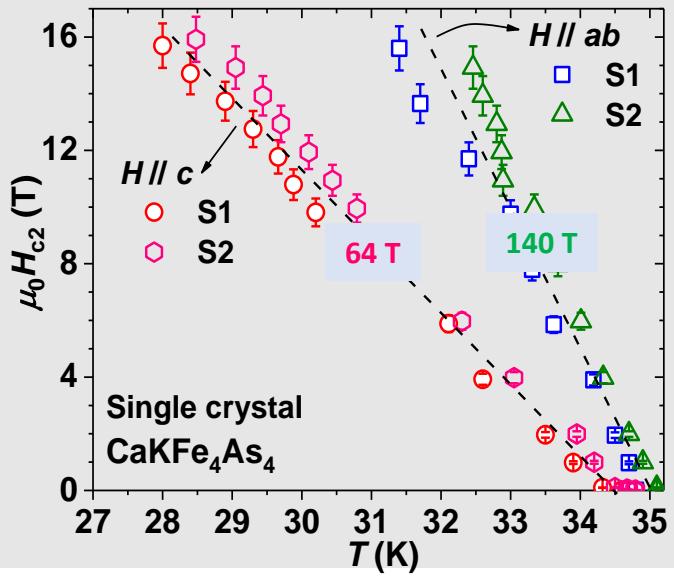
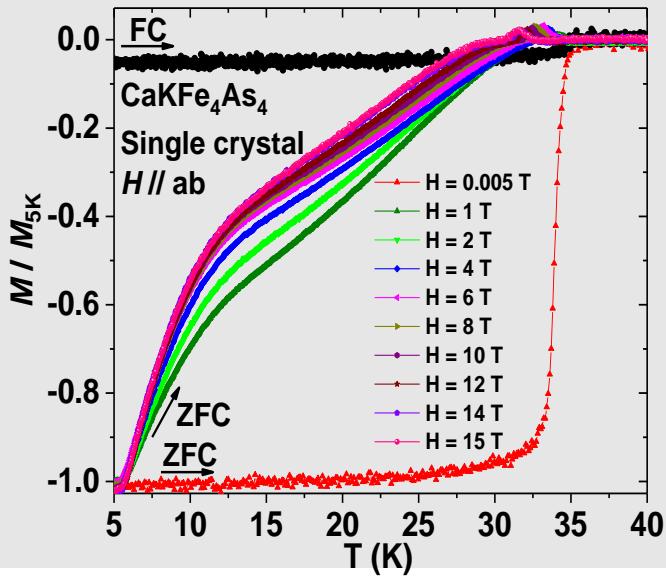
	$T_c$	$T_N$	$T_s$	SC
1111	~55K	~140K	~155K	Doping
122	~38K	~135K	~140K	Doping
1144	~35K	No	No	No doping

# Superconducting transition $T_c$ at 35 K in $\text{CaKFe}_4\text{As}_4$



- The sharp transition as well as perfect diamagnetism in ZFC demonstrate the high quality our single crystal and polycrystalline  $\text{CaKFe}_4\text{As}_4$  (1144).

# High upper critical field ( $H_{c2}$ ) higher than 100 T



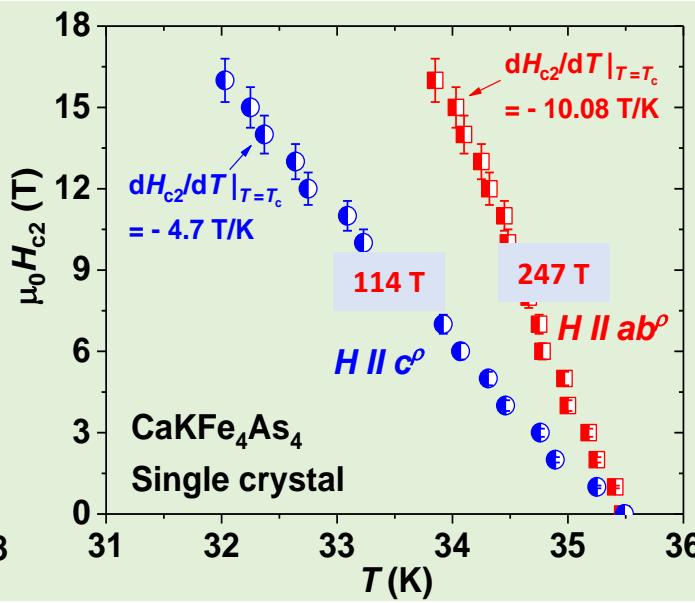
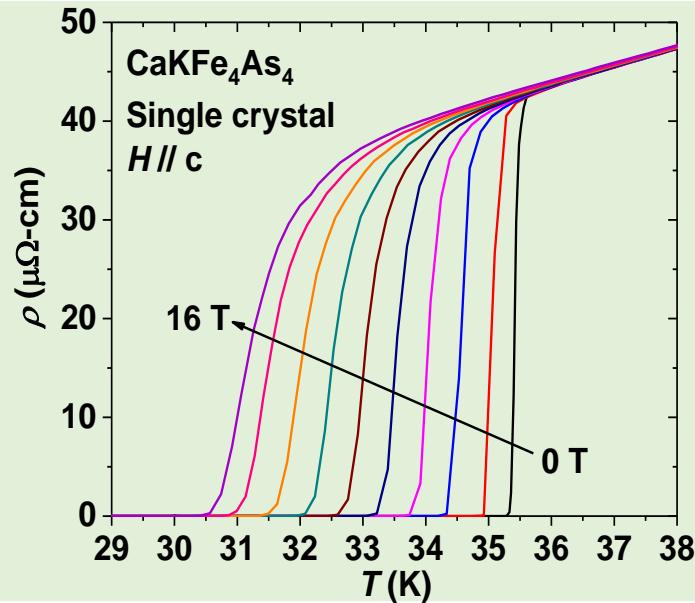
From Magnetic measurement

- The  $H_{c2}$  is calculated by WHH Model.

Within Clean limit

$\xi_{\parallel c}, \xi_{\perp c} \sim 11-23 \text{ \AA} \ll \text{mean free path } (l \sim 125 \text{ \AA})$

- Very high  $H_{c2}$  more than 100 T is observed for  $\text{CaKFe}_4\text{As}_4$  (1144).

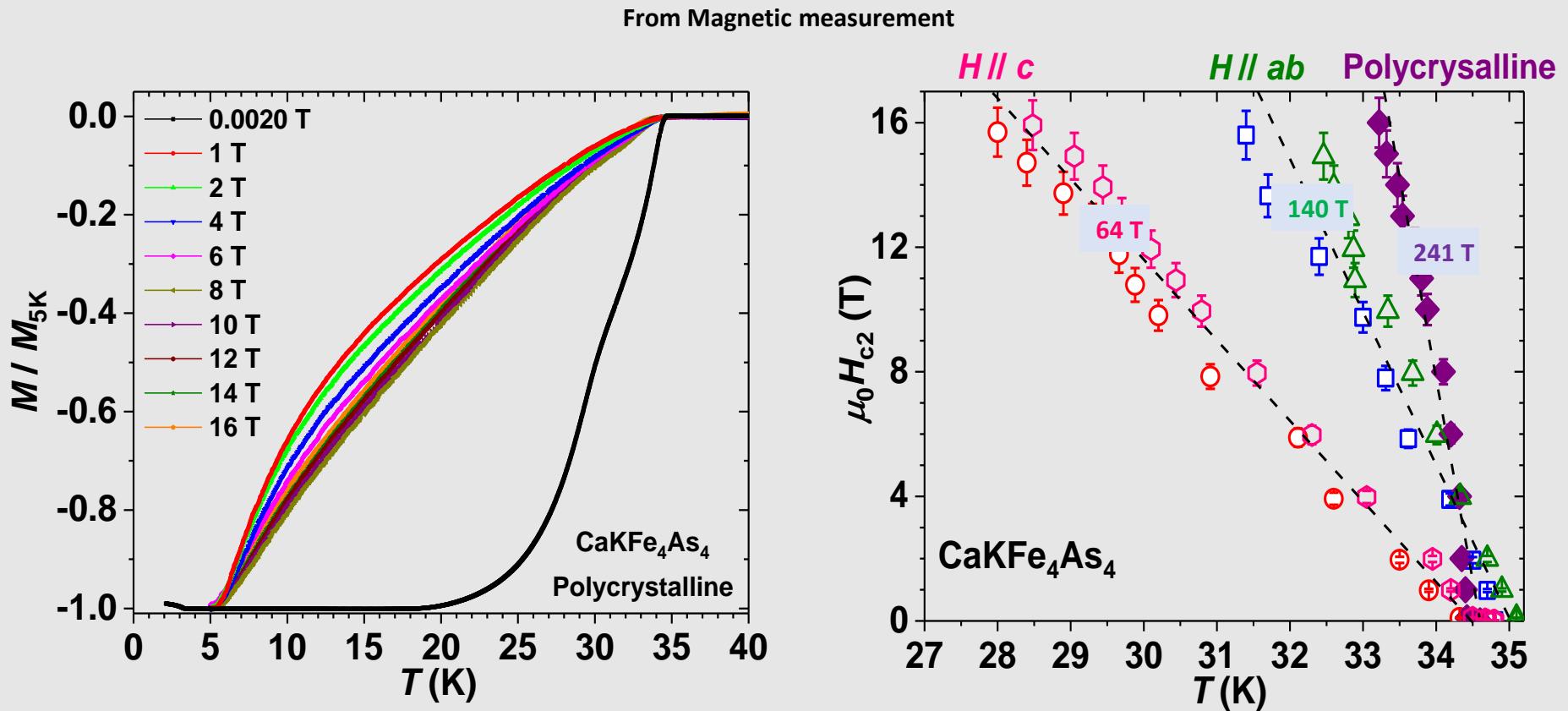


From Resistivity measurement

- 90% of the normal state resistivity is used to define  $H_{c2}$ .

- This  $H_{c2}$  value is very closed to the reported high value (304 T) in  $\text{NdFeAs(O,F)}$  (1111).

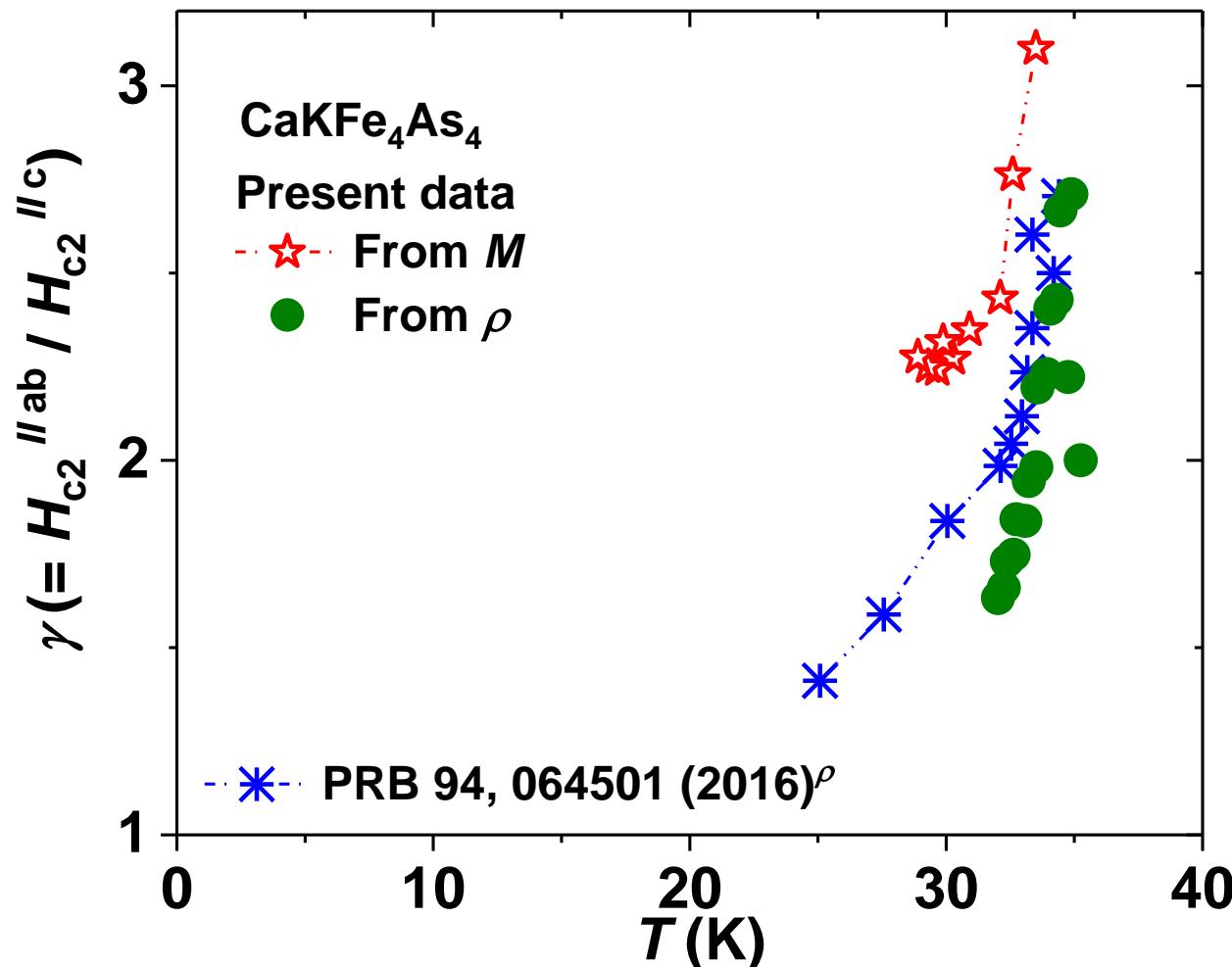
# Extremely high $H_{c2}$ of polycrystalline $\text{CaKFe}_4\text{As}_4$



$\text{CaKFe}_4\text{As}_4$	$dH_{c2}/dT$ ( $\text{T K}^{-1}$ )	$H_{c2}$ ( $\text{T}$ ) at 0 K
$H \parallel ab$ (Magnetization)	-5.7	140
$H \parallel c$ (Magnetization)	-2.6	64
Polycrystalline	-10.1	<u>241</u>
$H \parallel ab$ (Magneto-resistivity)	-10.08	<u>247</u>
$H \parallel c$ (Magneto-resistivity)	-4.7	114

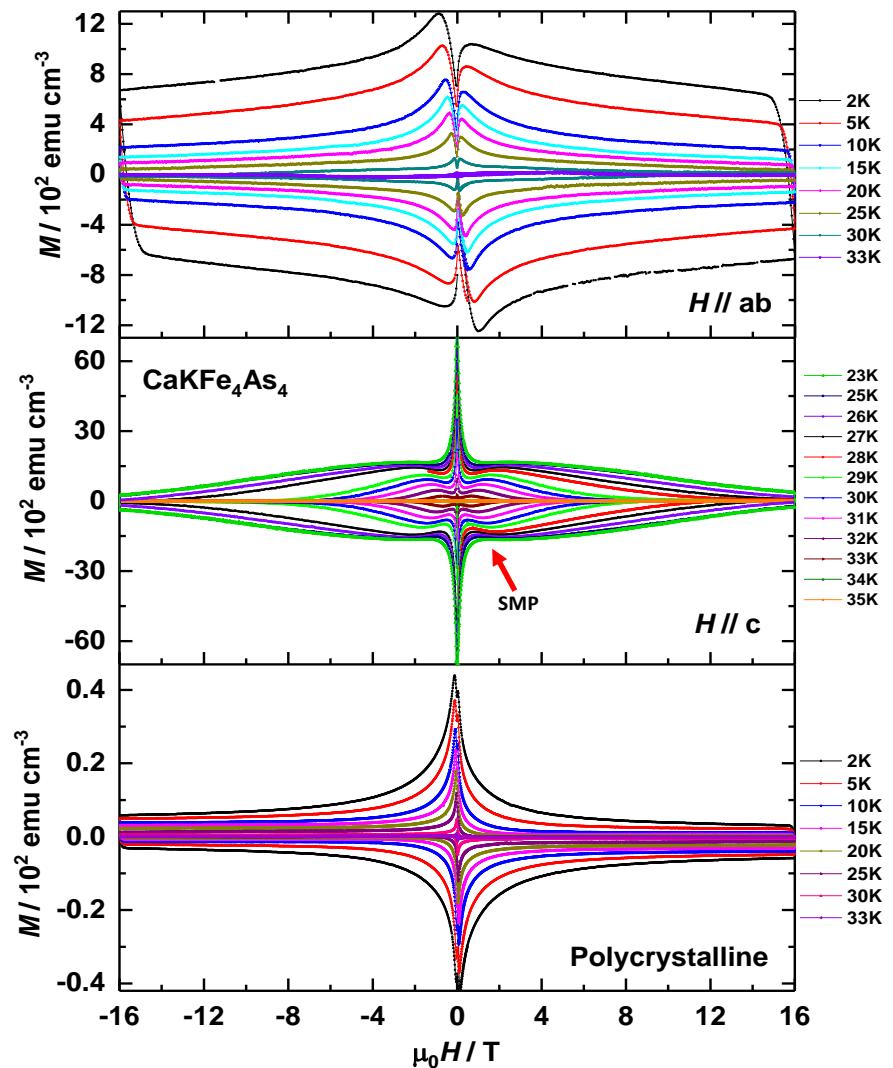
- ❖ High  $H_{c2}$  (more than 200 T) is also obtained in polycrystalline sample which is very good for magnetic application.

# Low anisotropy ( $\gamma$ ) of single crystal $\text{CaKFe}_4\text{As}_4$

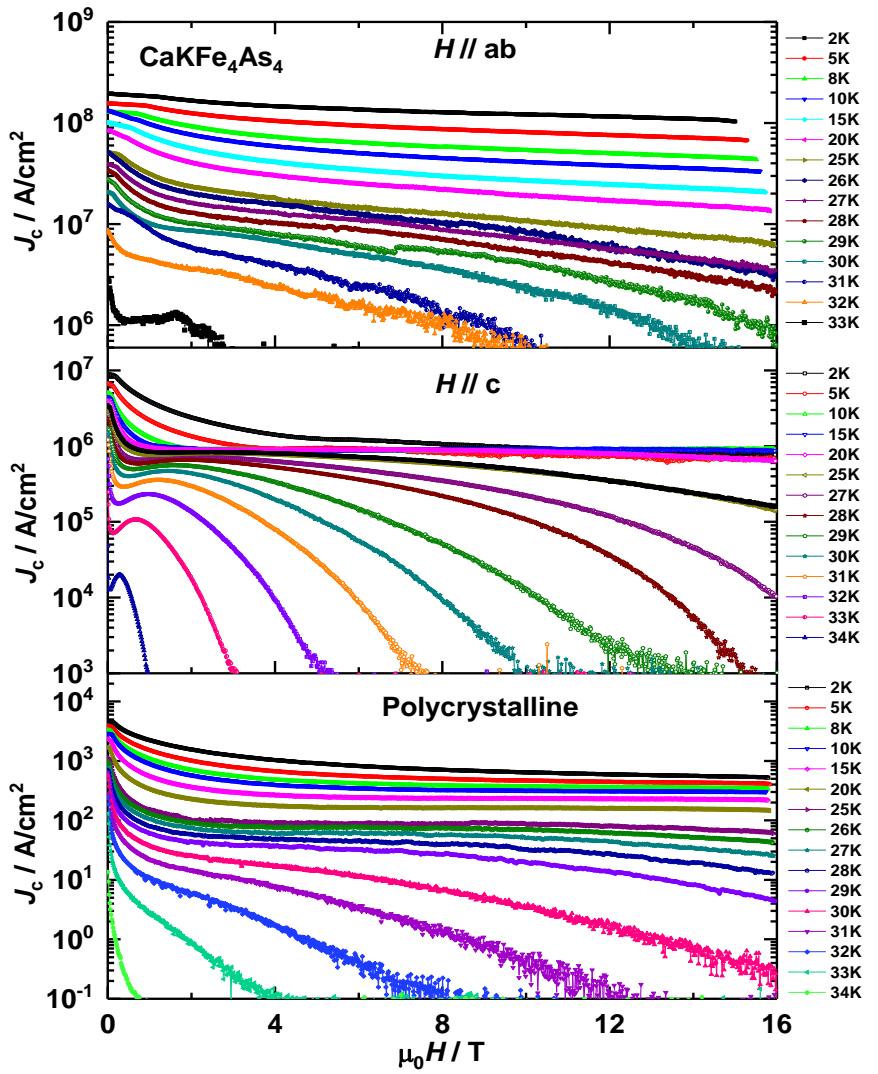


- ❖ Low Anisotropy ( $\gamma$ ) is observed from magnetization and resistivity measurements.
- ❖ This anisotropy value is similar to that of other categories of iron based superconductors such as 122, 111, 11.

# High critical current density $J_c$ of $\text{CaKFe}_4\text{As}_4$

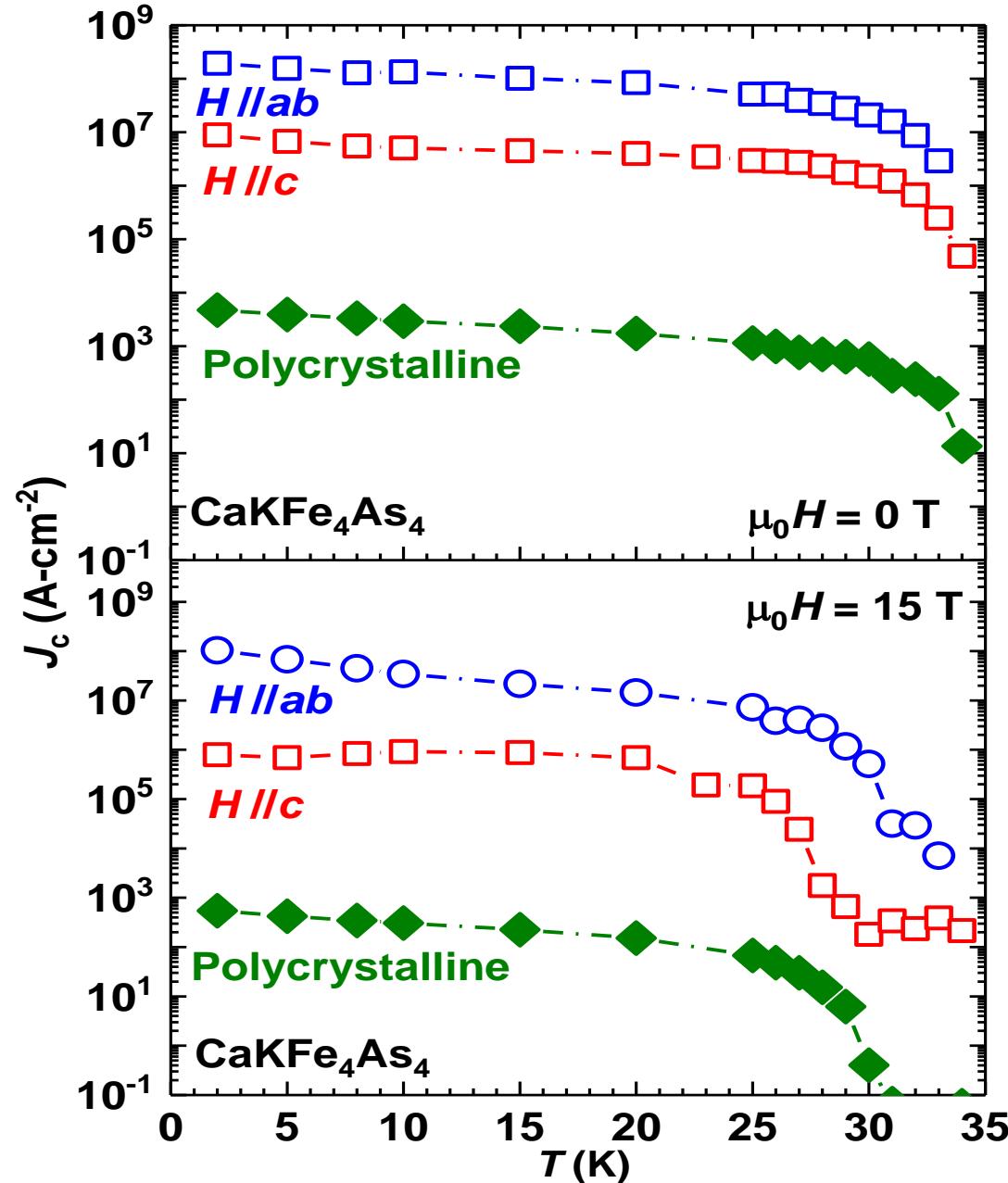


- ❖ Second magnetization peak (SMP) (Fishtail effect) is observed only in  $H \parallel c$ .
- ❖  $J_c$  is extracted using the Bean model,  $J_c = 20 \Delta M / a(1-a/3b)$  or  $30 \Delta M/d$ ,  $a$  and  $b$  are the sample width or  $d$  is diameter of the disk shaped sample.



Singh et al. (Submitted) (2017)

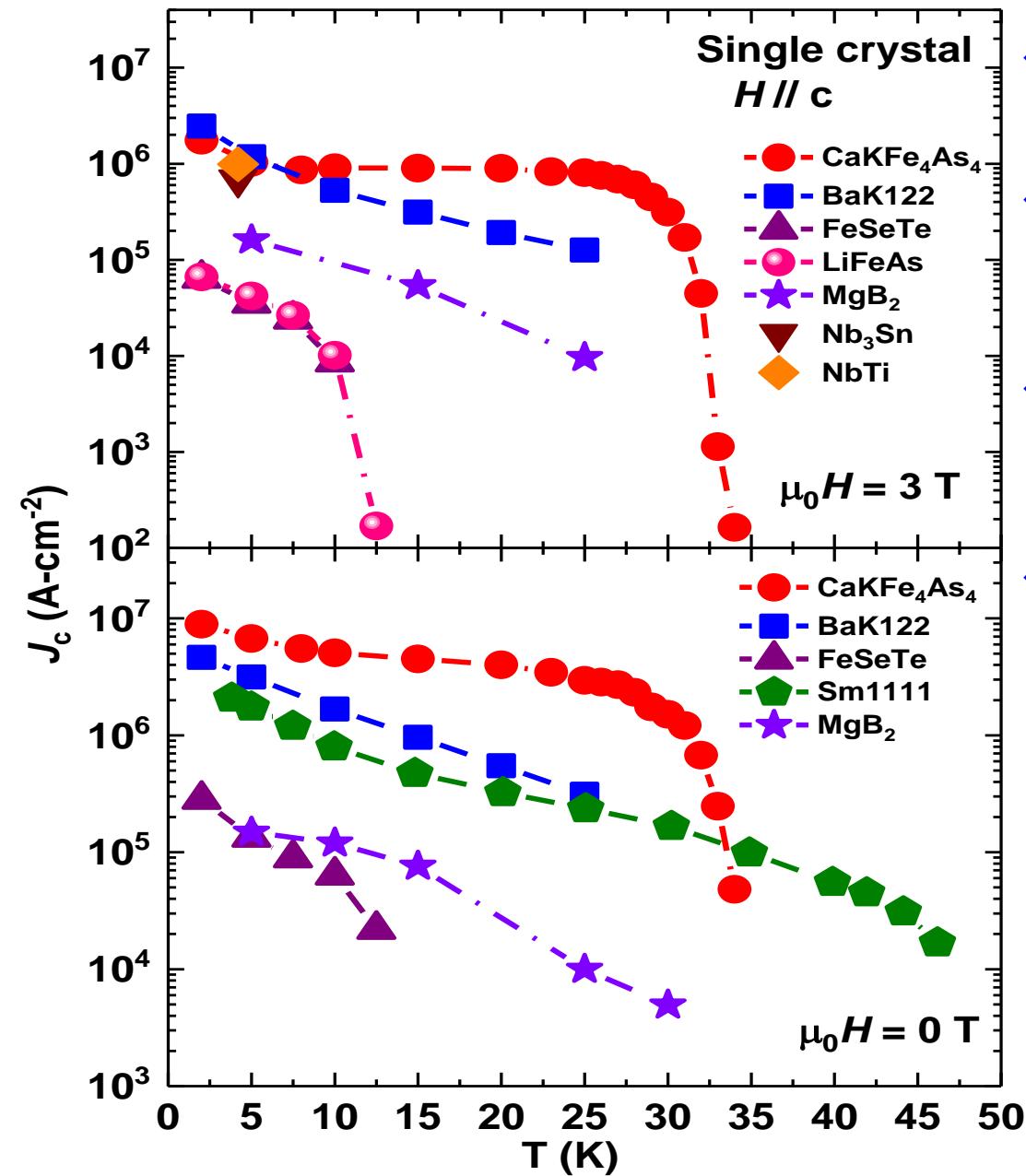
# High and magnetic independent $J_c$ of $\text{CaKFe}_4\text{As}_4$



- ❖ The critical current density ( $J_c$ ) is quite temperature stable up to 15 T magnetic field.
- ❖ Highest  $J_c$  ( $>100 \text{ MA/cm}^2$ ) at 15 T is obtained for  $\text{CaKFe}_4\text{As}_4$  (1144).

*Rev. Modern. Phys.* **36**, 31 (1964)

# Highest critical current density $J_c$ of $\text{CaKFe}_4\text{As}_4$



- ❖ All compared samples are single crystals for  $H \parallel c$ .
- ❖ Generally, the most of superconducting single crystal shows the highest  $T_c$  for  $H \parallel c$ .
- ❖ The obtained  $J_c$  of  $\text{CaKFe}_4\text{As}_4$  are much more stable with respect to magnetic field.
- ❖ In-field  $J_c$  values of 1144 are higher than the previously reported ones, including those for 122-type compounds and also conventionally alloy superconducting wires Nb-Ti,  $\text{Nb}_3\text{Sn}$  and  $\text{MgB}_2$ .

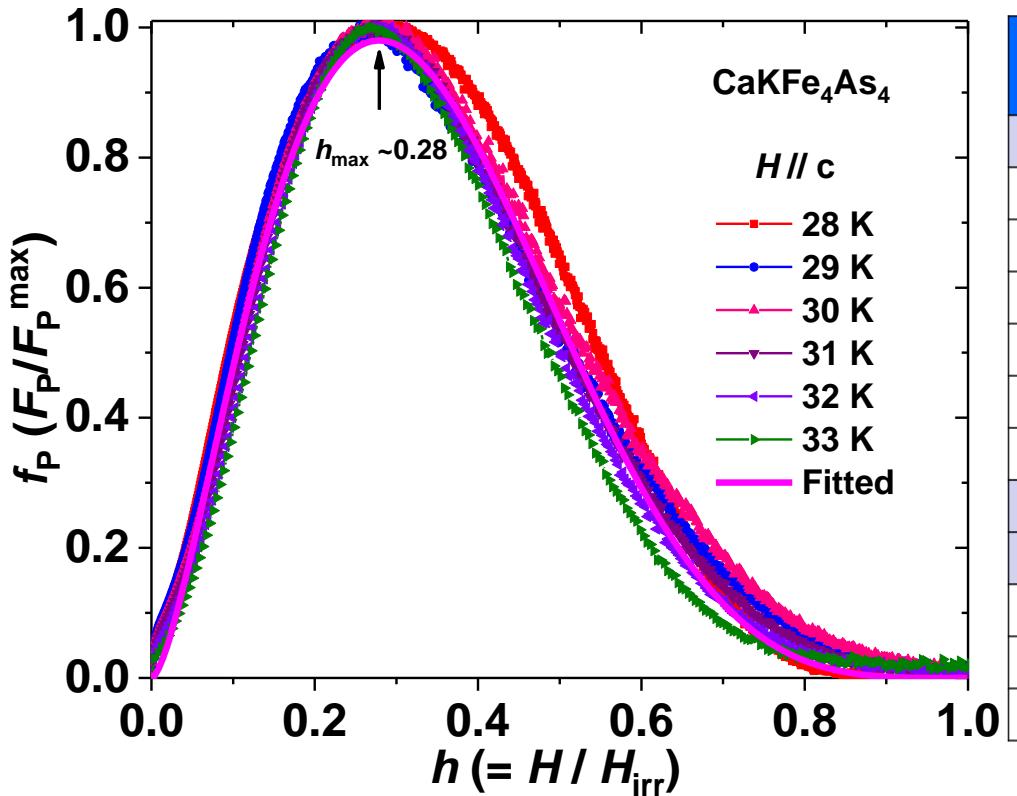
*Appl. Phys. Lett.* **93**, 142506 (2008)

*Phys. Rev. B* **80**, 8 (2009)

*Phys. Rev. B* **83**, 094502 (2011)

*Supercond. Sci. Tech.* **14**, R115 (2001)

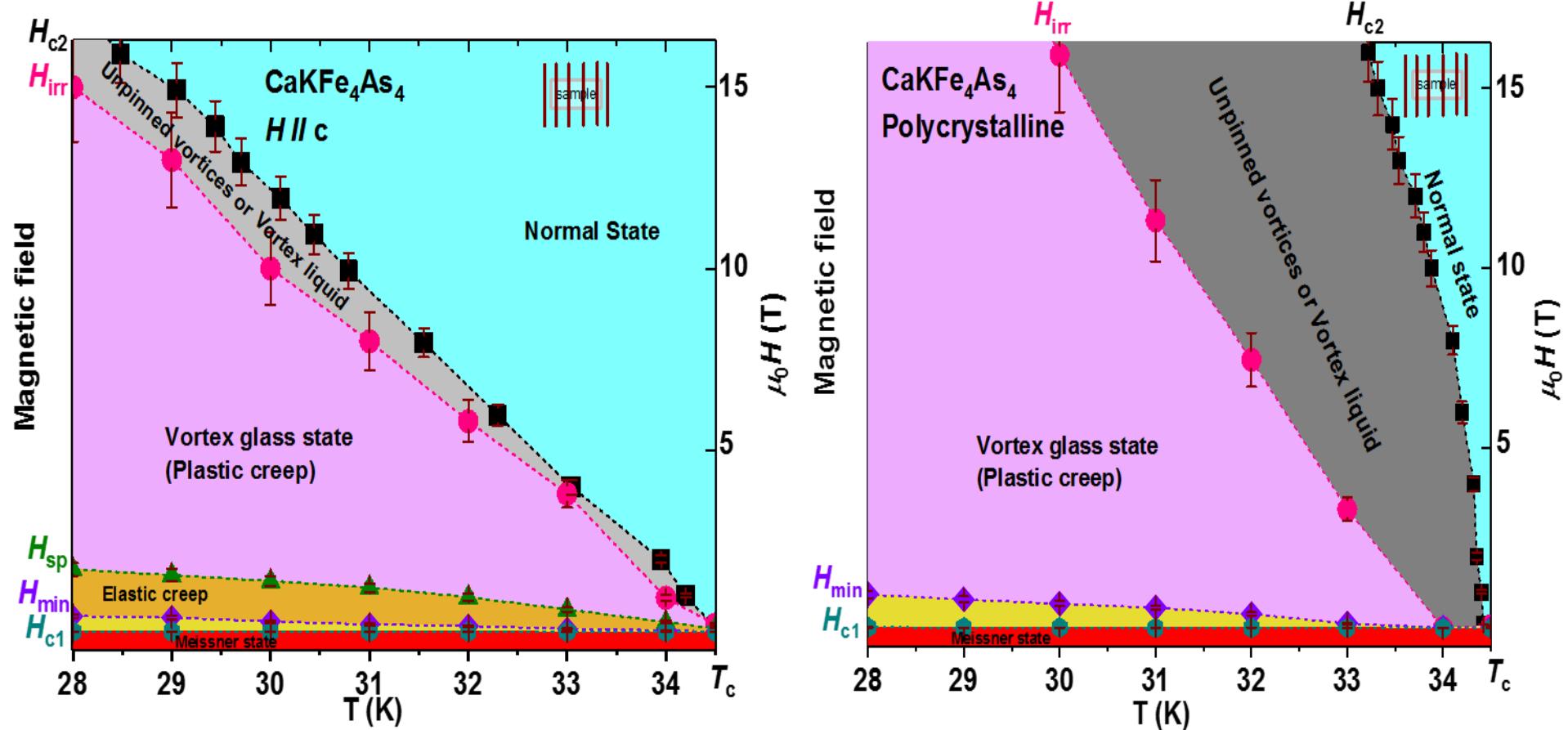
# Vortex pinning force of CaKFe<sub>4</sub>As<sub>4</sub> (1144)



Single crystal	p	q	$h_{\max} = p / (p+q)$	Peak position
CaKFe <sub>4</sub> As <sub>4</sub>	1.43	3.61	0.28	0.28
Ba <sub>0.6</sub> K <sub>0.4</sub> Fe <sub>2</sub> As <sub>2</sub>	1	2	0.33	0.33
Ba <sub>0.68</sub> K <sub>0.32</sub> Fe <sub>2</sub> As <sub>2</sub>				0.43
BaFe <sub>1.8</sub> Co <sub>0.2</sub> As <sub>2</sub>	1.67	2	0.45	0.45
BaFe <sub>1.85</sub> Co <sub>0.15</sub> As <sub>2</sub>				0.37
BaFe <sub>1.29</sub> Ru <sub>0.71</sub> As <sub>2</sub>	1.95	2.5	0.44	0.45
BaFe <sub>1.91</sub> Ni <sub>0.09</sub> As <sub>2</sub>				0.32
FeTe <sub>0.7</sub> Se <sub>0.3</sub>				0.27
FeTe <sub>0.6</sub> Se <sub>0.4</sub>	1.54	3.8	0.28	0.28
K <sub>x</sub> Fe <sub>2-y</sub> Se <sub>2</sub>	0.86	1.83	0.32	0.33
YBa <sub>2</sub> Cu <sub>3</sub> O <sub>7</sub>	2	4	0.33	0.33
NdBa <sub>2</sub> Cu <sub>3</sub> O <sub>7-d</sub>	1.48	2.23	0.45	0.45

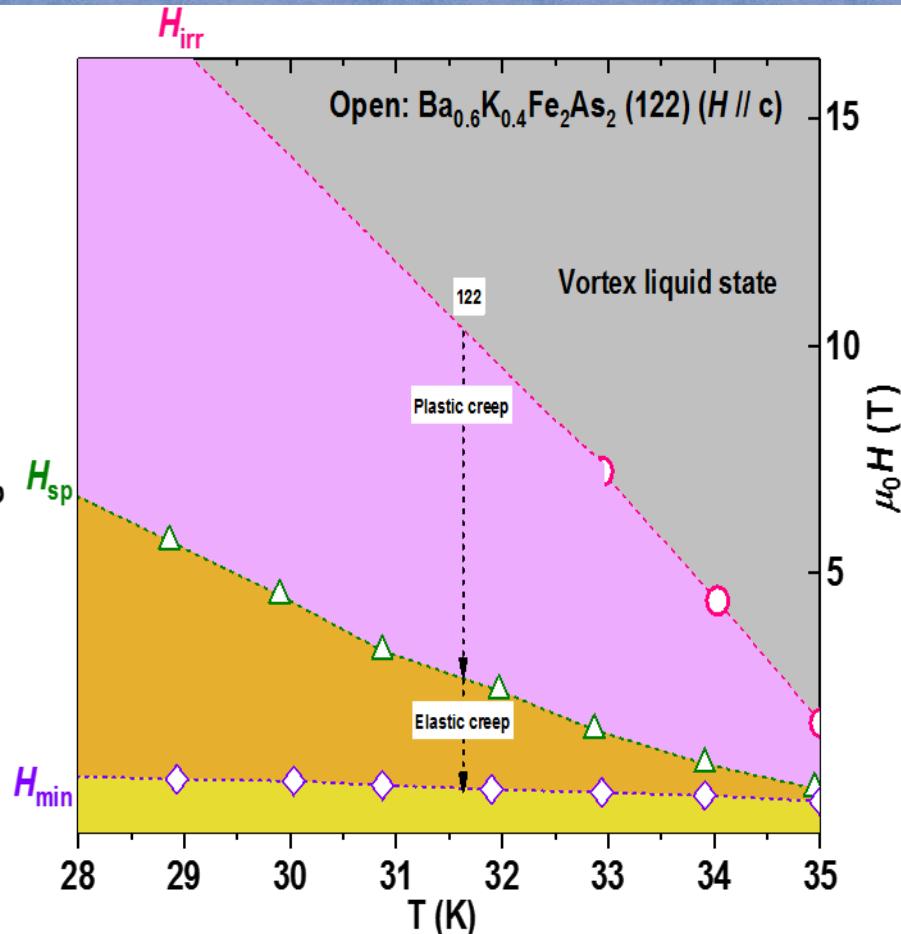
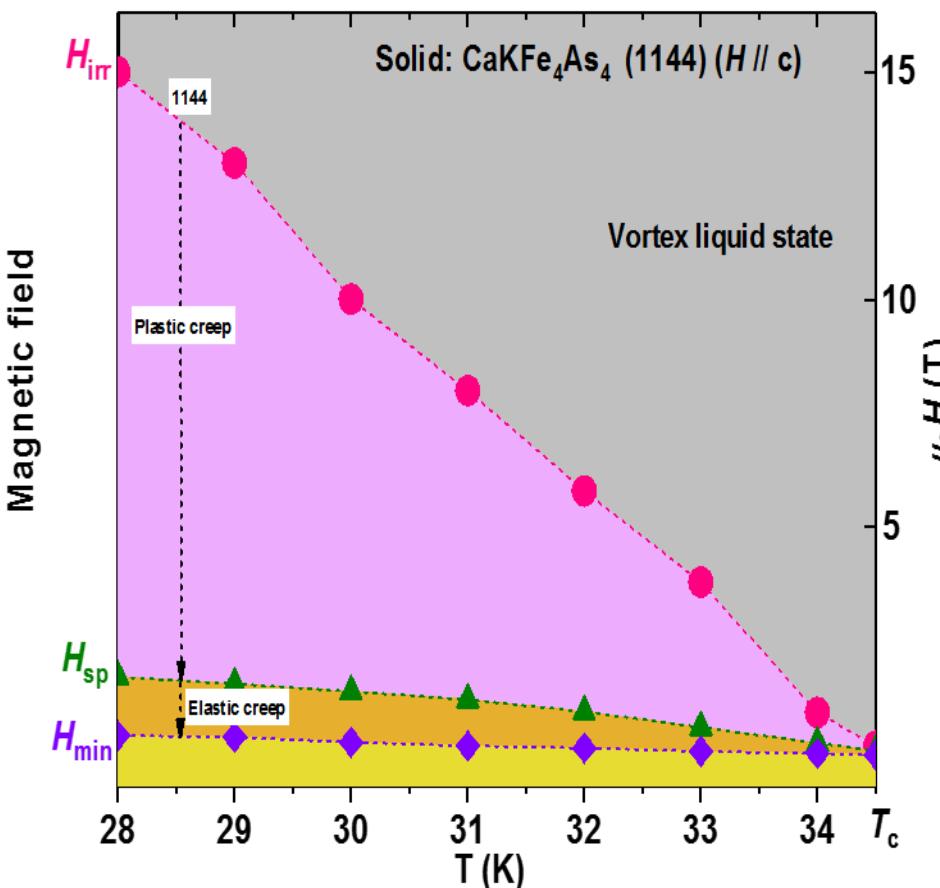
- ❖  $F_P = \mu_0 H \times J_c$ .
- ❖ According to the Dew-Hughes model, the normalized  $f^P = F^P / F_{\max}^P = Ah^p(1 - h)^q$ , here  $p$  and  $q$  values depend on the origin of pinning mechanism and  $h = H / H_{\text{irr}}$ .
- ❖ **Vortex pinning in 1144 is by a mixture of the surface and the point core pinning of the normal centres.**

# Vortex phase diagram of $\text{CaKFe}_4\text{As}_4$ (1144)



- ❖  $H_{sp}$  locating at the peak of  $J-H$  graph depict the threshold field at vortex elastic pinning change to plastic pinning.
- ❖ It suggest that the pinning force is larger in  $H \parallel c$  compared to polycrystalline sample.

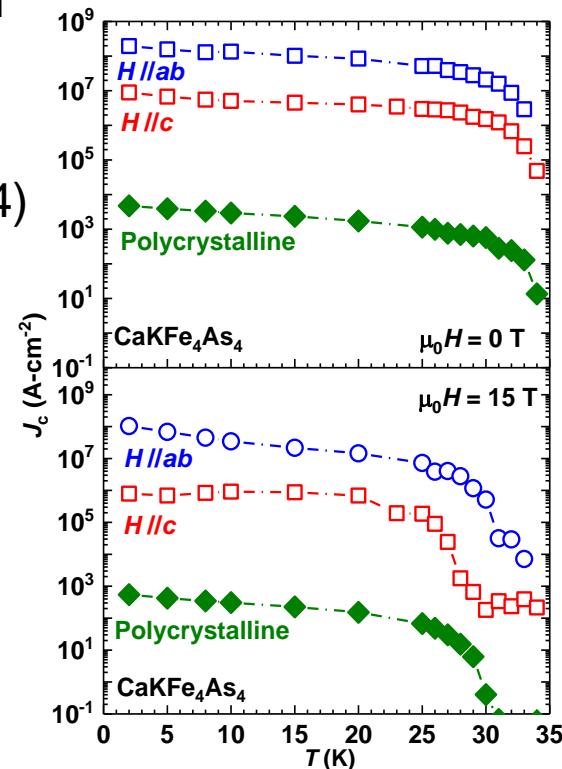
# Vortex phase diagram of 1144 and 122



- ❖ The vortex phase diagram of 1144 ( $T_c = 35$  K) is almost same as 122 ( $T_c = 38$  K).
- ❖  $H_{\text{sp}}$  locating at the peak of  $J-H$  graph in 1144 is lower than that in 122.
- ❖ Different temperature dependence of the characteristic fields for 1144 and 122 might be due to different strength of the pinning mechanism.

# Conclusions

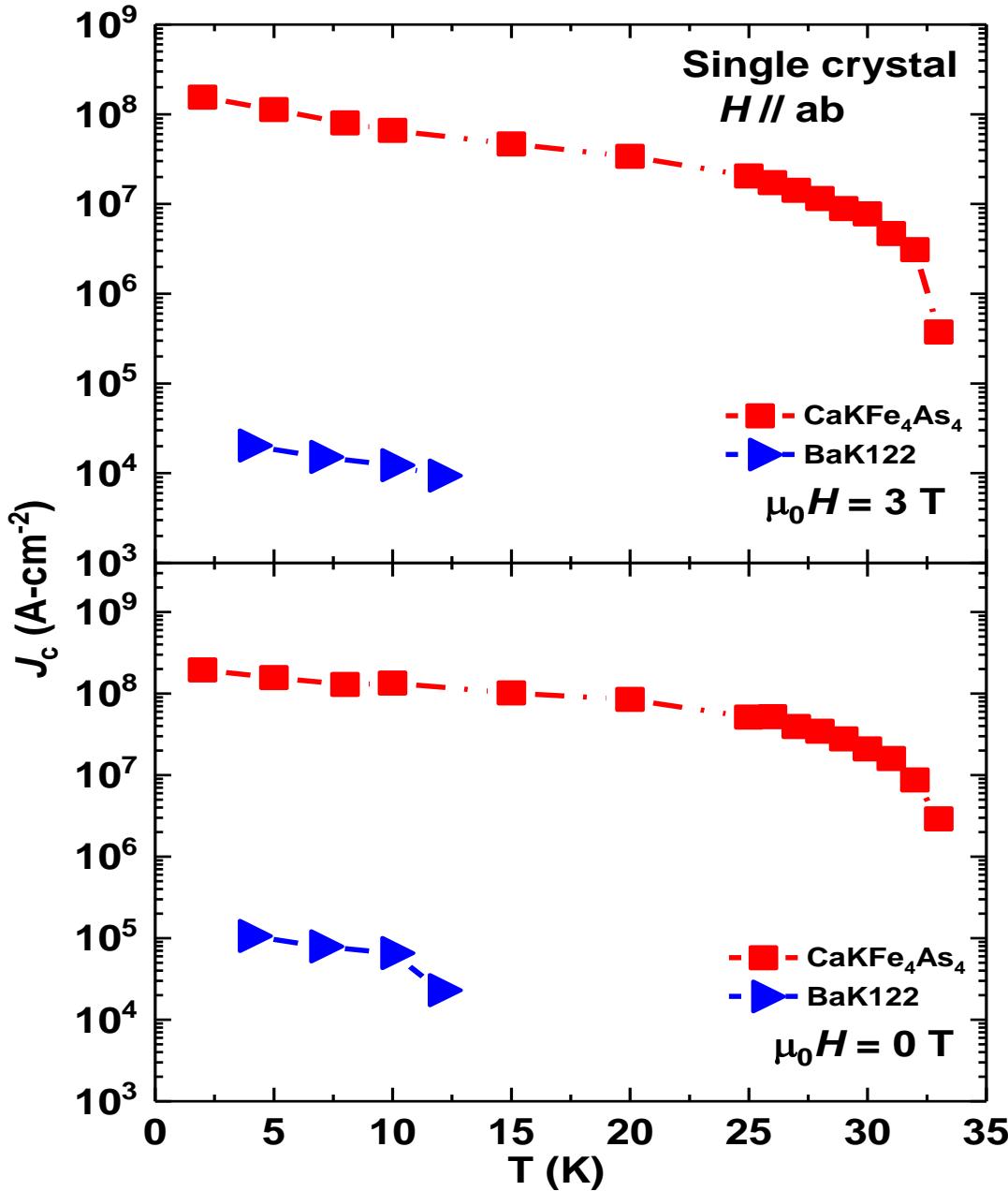
- CaKFe<sub>4</sub>As<sub>4</sub> (1144) could be a extremely high potential candidate for the superconducting application.
- New family of Fe based superconductors (CaKFe<sub>4</sub>As<sub>4</sub>; 1144) have:
  - $T_c \sim 35$  K
  - Highest  $J_c \sim 2 \times 10^8$  A/cm<sup>2</sup> at 5 K and self field (>100 times higher than other superconductors.)
  - High upper critical field  $H_{c2} \sim 250$  T
  - Almost magnetic field independent of  $J_c$  up to 15 T
- The existence of both surface and the point core pinning of the normal centres in place of single pinning mechanism.
- CaKFe<sub>4</sub>As<sub>4</sub> (1144) could be a good candidate for superconducting wires and tapes.



Singh et al. (Submitted) (2017)



# Highest critical current density $J_c$ of $\text{CaKFe}_4\text{As}_4$



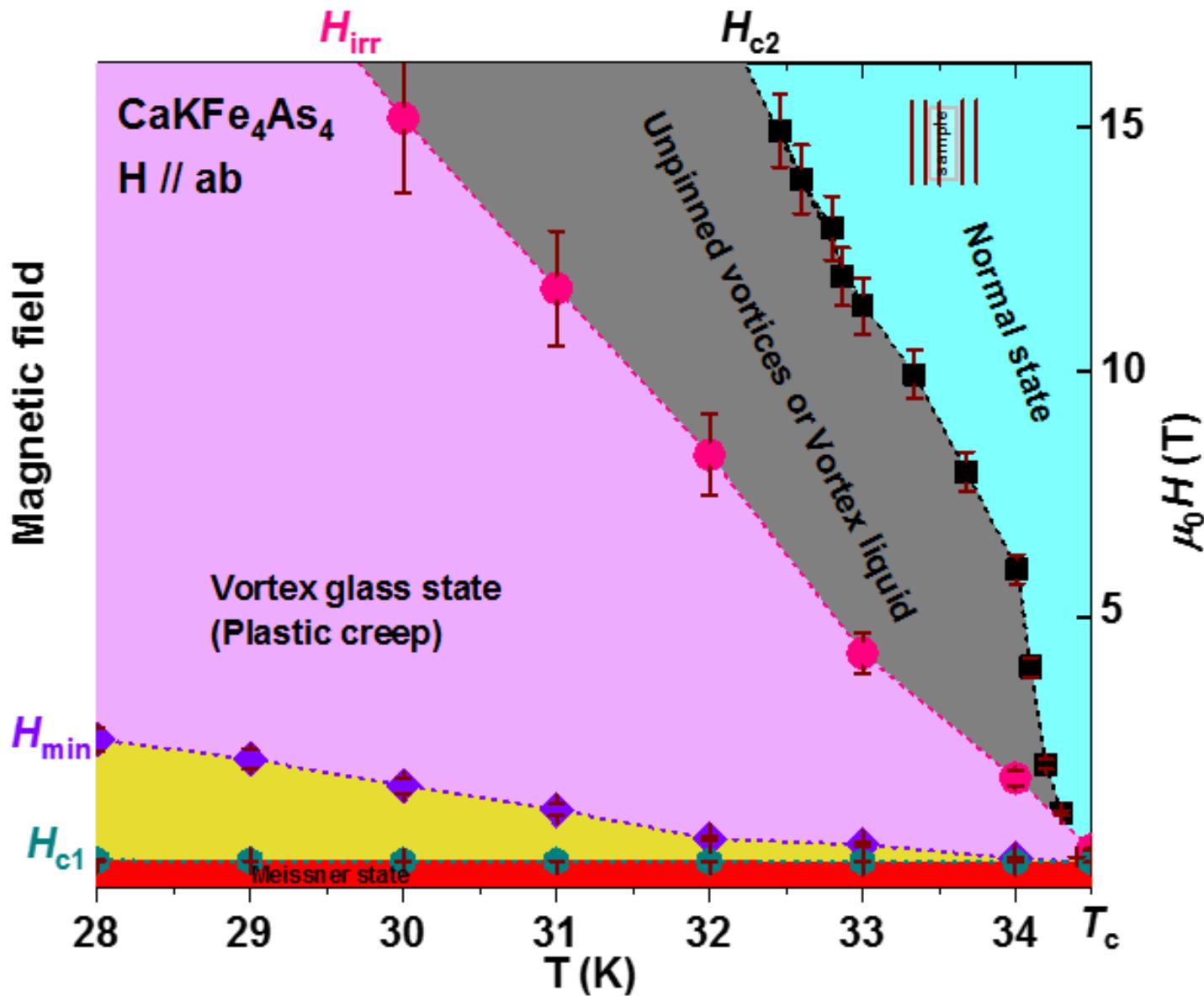
- ❖ All compared samples are single crystals ( $H \parallel ab$ ).
- ❖ The obtained  $J_c$  of  $\text{CaKFe}_4\text{As}_4$  are much more stable with respect to magnetic field.
- ❖  $J_c$  values of 1144 for  $H \parallel ab$  are extremely higher than the previously reported ones, including those for 122-type compounds.
- ❖ For 1144, only one order of  $J_c$  magnitude is different between  $H \parallel c$  and  $H \parallel ab$  i.e. very low  $J_c$  anisotropic nature.

*Appl. Phys. Lett.* **93**, 142506 (2008)

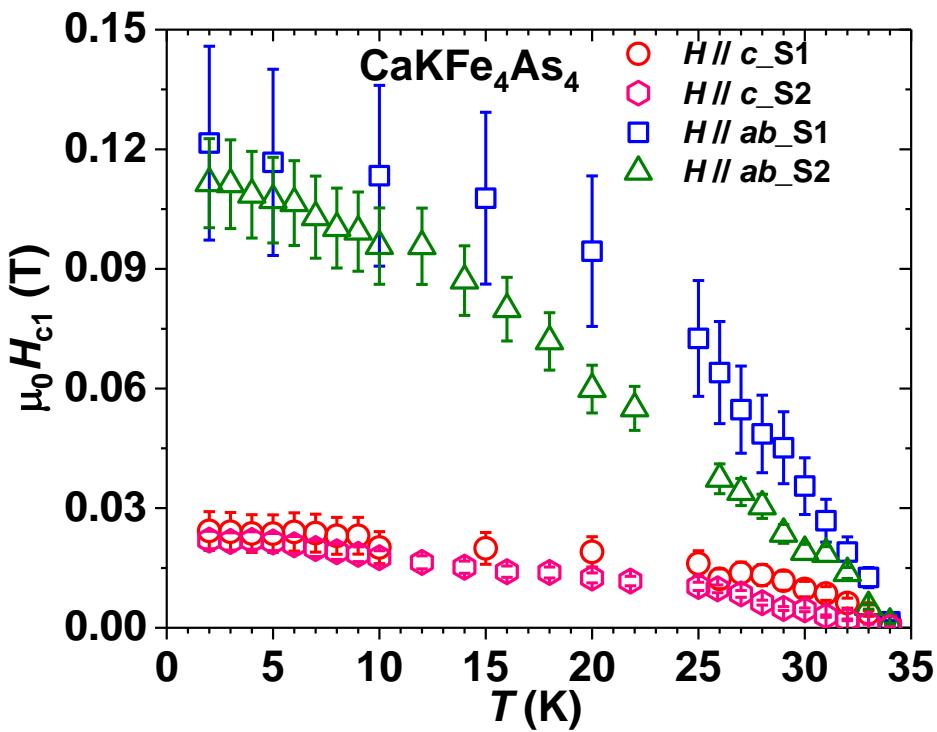
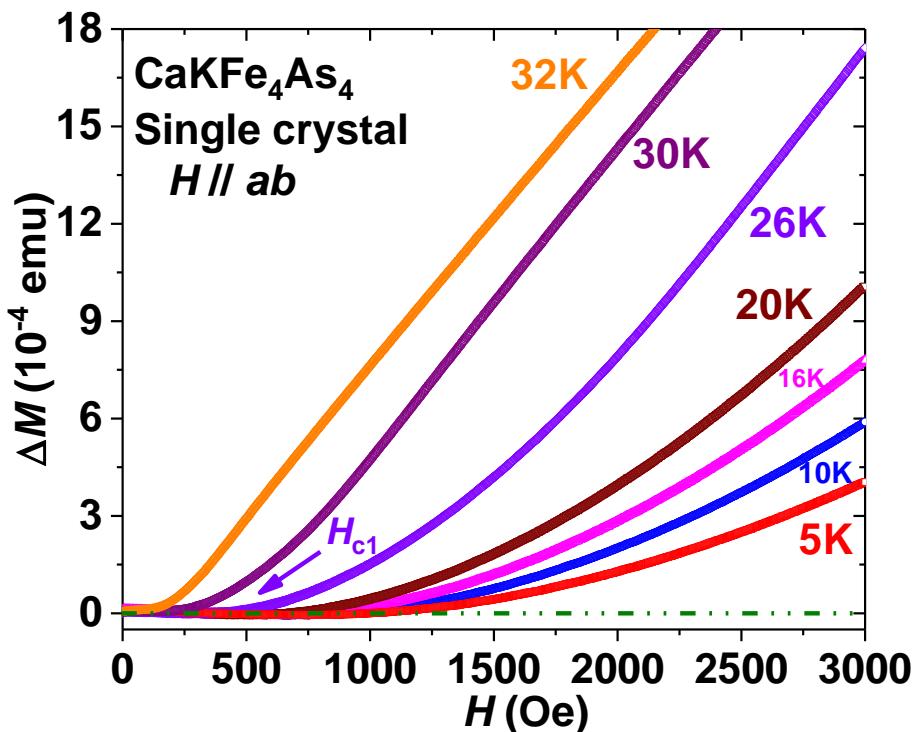
*Supercond. Sci. Tech.* **26**, 015009 (2013)

*Supercond. Sci. Tech.* **14**, R115 (2001)

Singh et al. (Submitted) (2017)

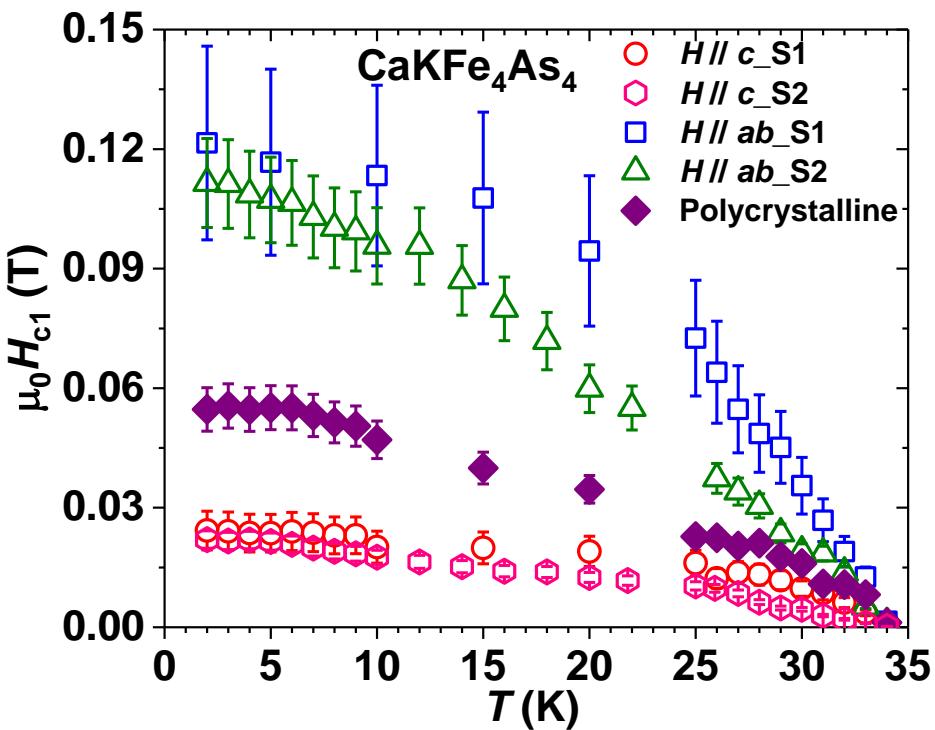
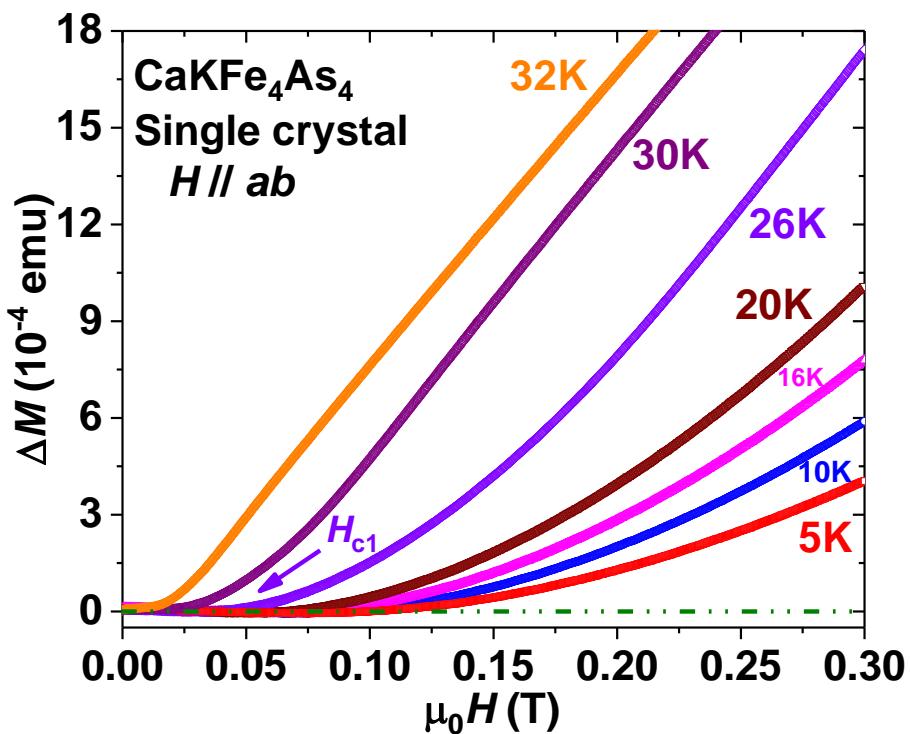


# Meissner state ( $H_{c1}$ ) of single crystal CaKFe<sub>4</sub>As<sub>4</sub> (1144)

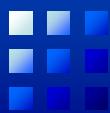


- ❖ The calculated  $H_{c1}$  is corrected by demagnetization factor (N~0.99).
- ❖ High  $H_{c1}$ (~1200 Oe) for  $H \parallel ab$ .
- ❖ S1 and S2 are two crystals from same batch.

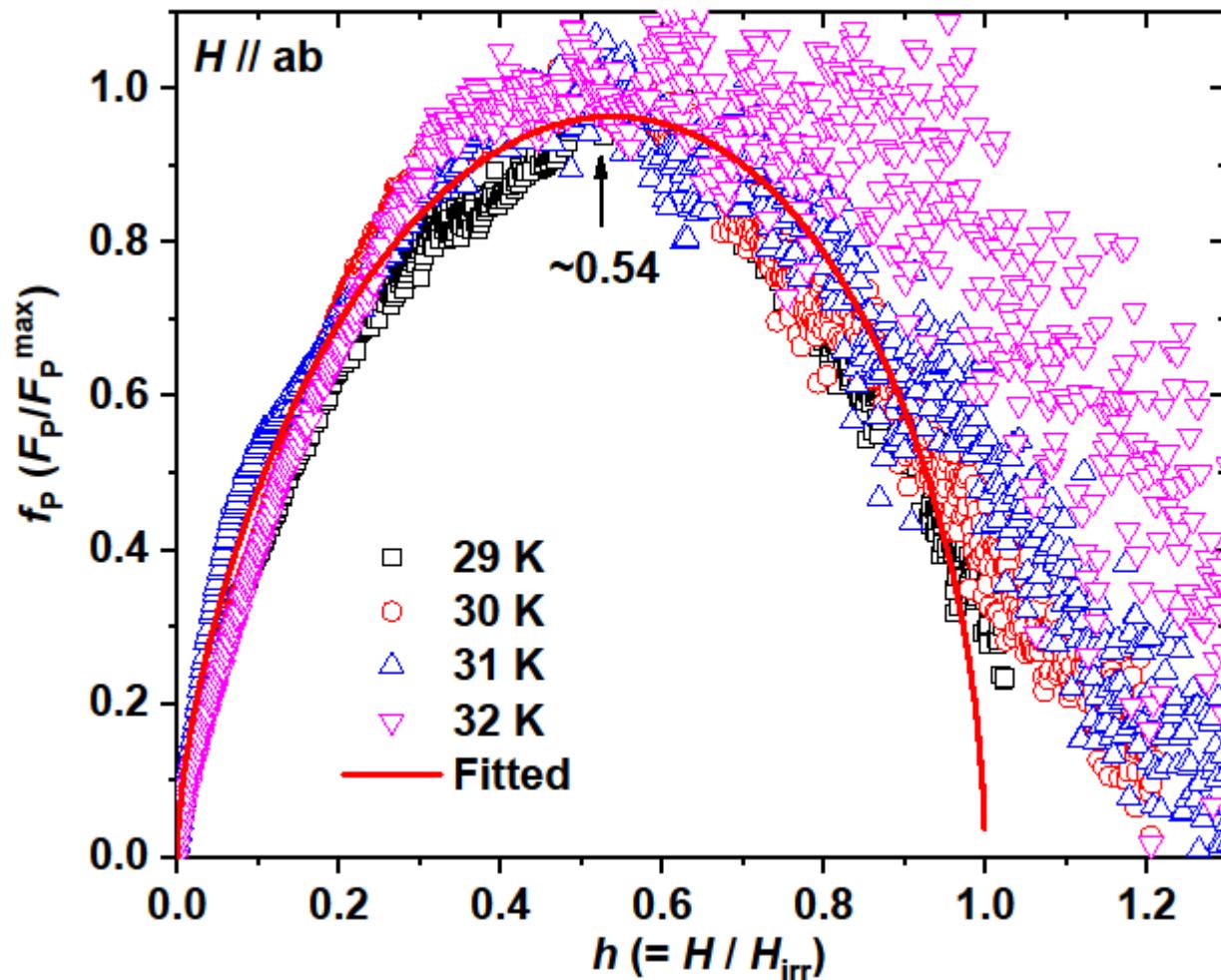
# Meissner state ( $H_{c1}$ ) of single & polycrystalline 1144

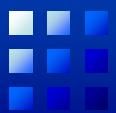


- ❖ High  $H_{c1}$ (~1200 Oe) at 2 K for  $H \parallel ab$ .
- ❖ The calculated  $H_{c1}$  is corrected by demagnetization factor (N~0.99).
- ❖  $H_{c1}$  for polycrystalline lies between for that of  $H \parallel c$  and  $H \parallel ab$ , indicating that grains are orientated in both directions.

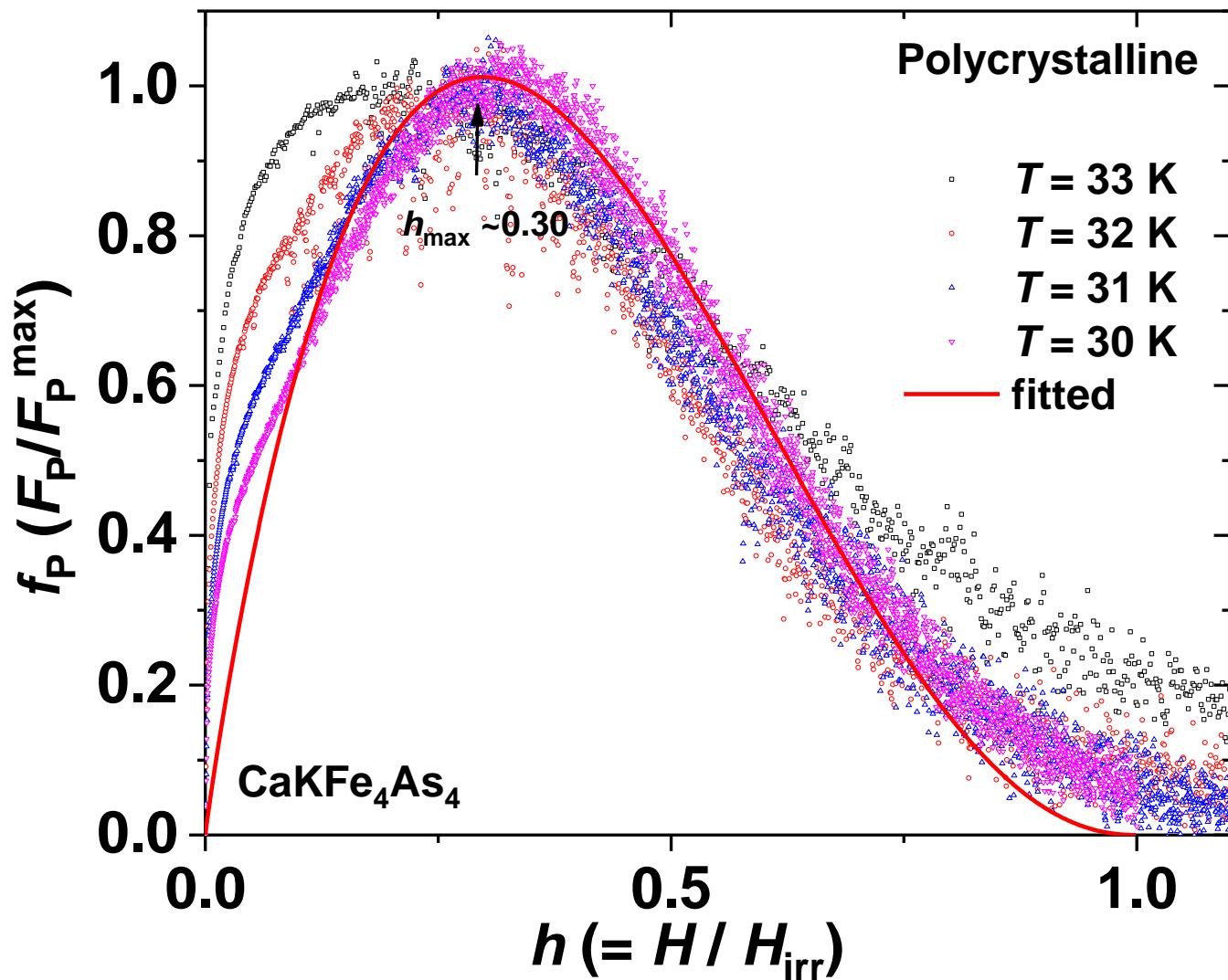


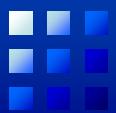
# B par to ab





# Polycrystalline





# Polycrystalline

