Vortex pinning in Iron-based superconductors

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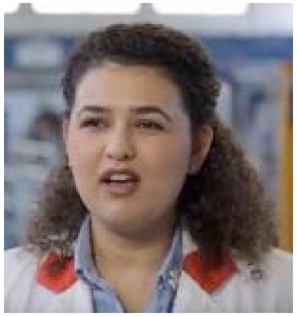
IUMRS-ICAM 2017

The 15th International Conference on Advanced Materials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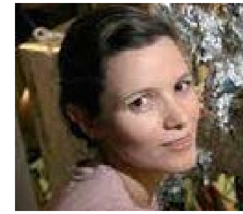
Marcin KONCZYKOWSKI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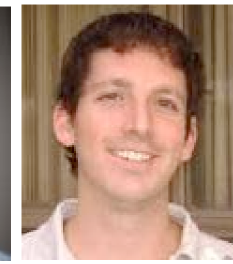
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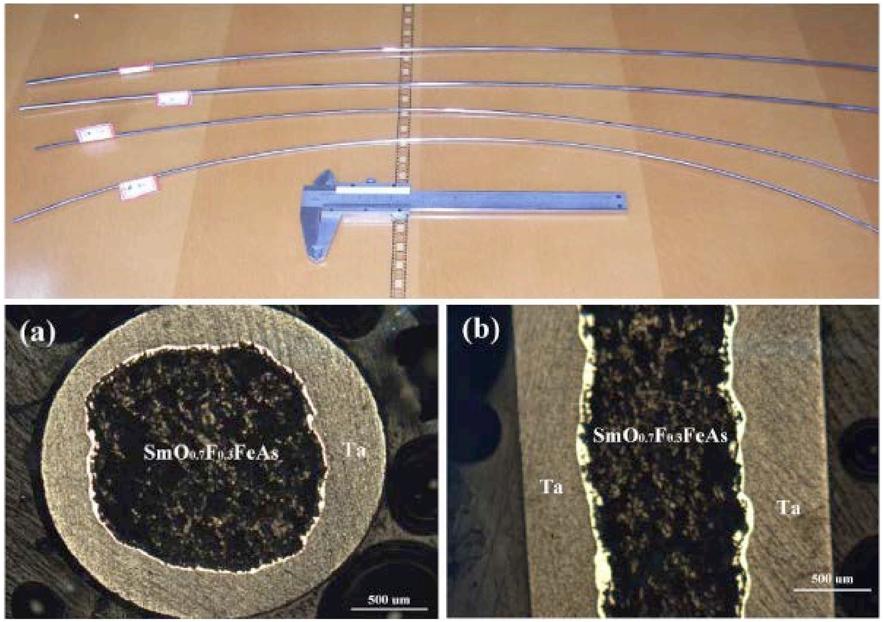
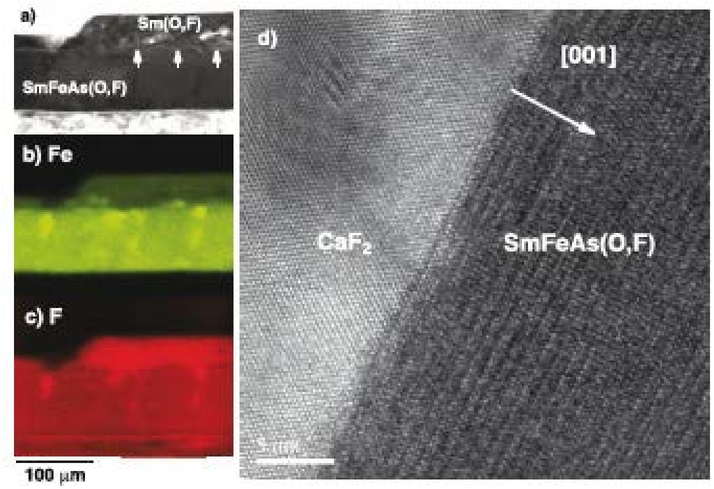
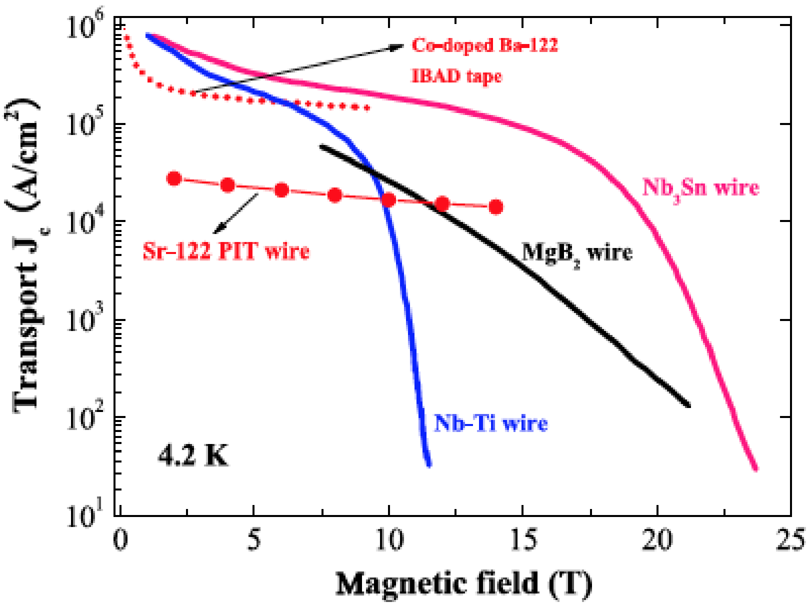


Ma Y W, Gao Z S, Qi Y P, Zhang X P, Wang L,Zhang Z Y and Wang D L 2009 Physica C **469** 651

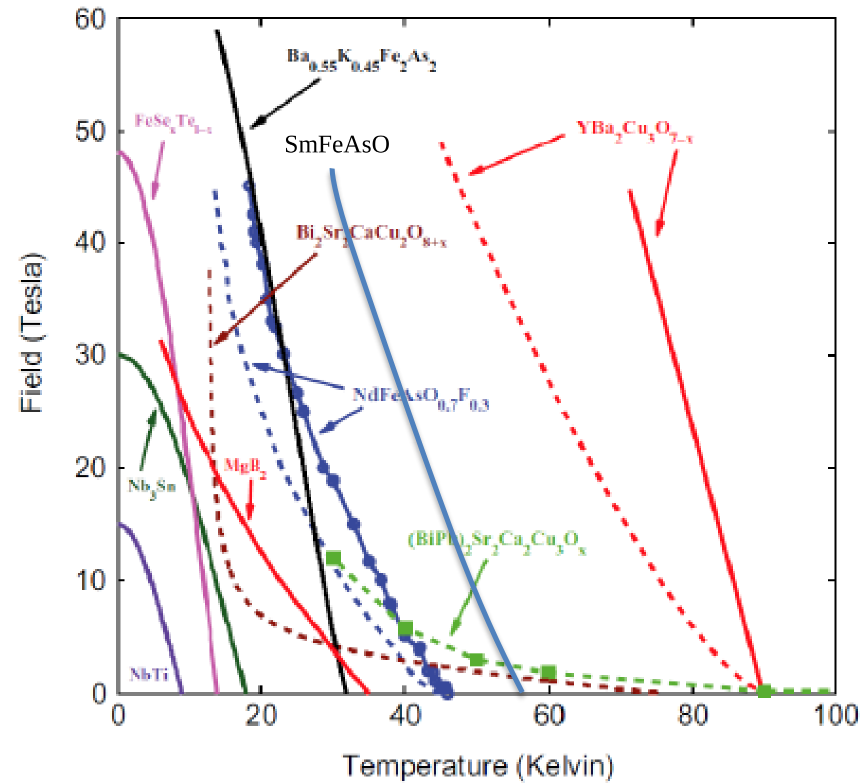


K. Iida et al., Scientific Reports 3:2139 (2013)

The critical current density in iron-based superconductors



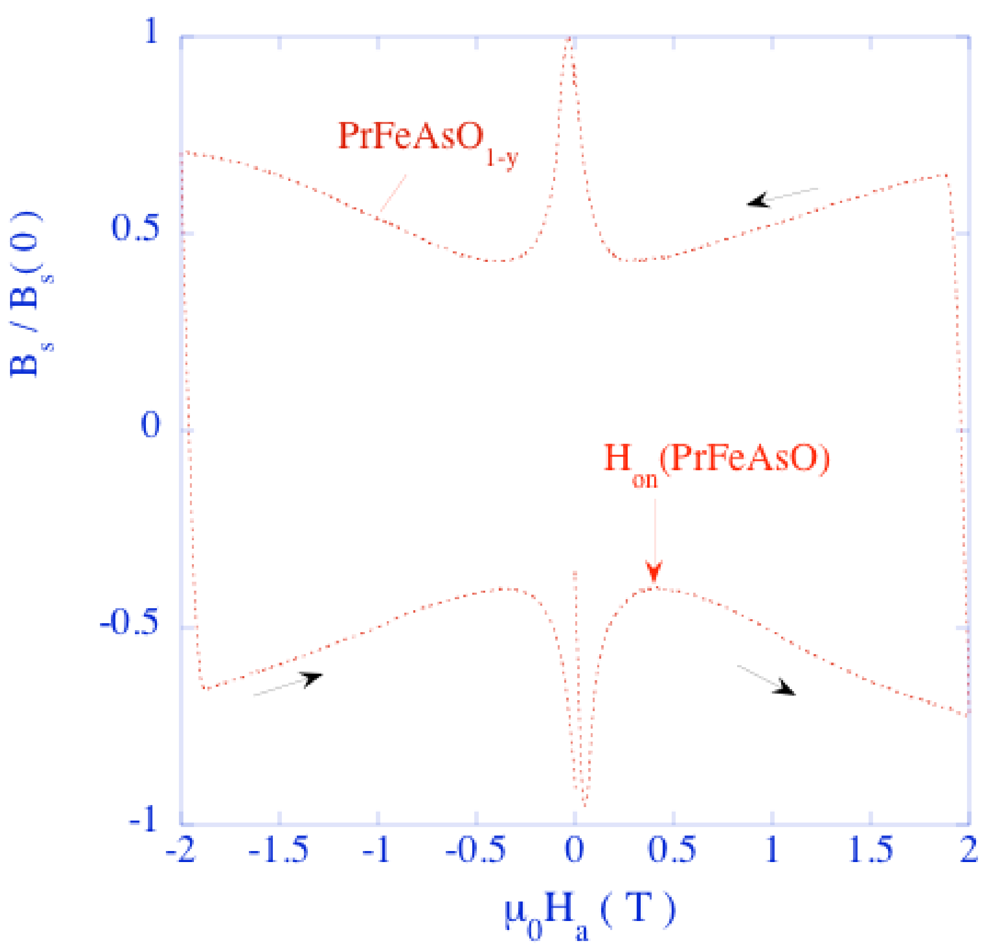
Yanwei Ma, Superconducting Science & Technology **25**, 113001 (2012)



A. Gurevich, Rep. Prog. in Physics **74**, 124501 (2011).

Trends ?
Limitations ?
Prospects ?

General behaviour of J_c of iron-based superconductors



C.J. van der Beek, G. Rizza, M. Konczykowski, P. Fertey, I. Monnet, Th. Klein, R. Okazaki, M. Ishikado, H. Kito, A. Iyo, H. Eisaki, S. Shamoto, M.E. Tillman, S. Bud'ko, P.C. Canfield, T. Shibauchi, Y. Matsuda, Phys. Rev. B **81**, 174517 (2010).

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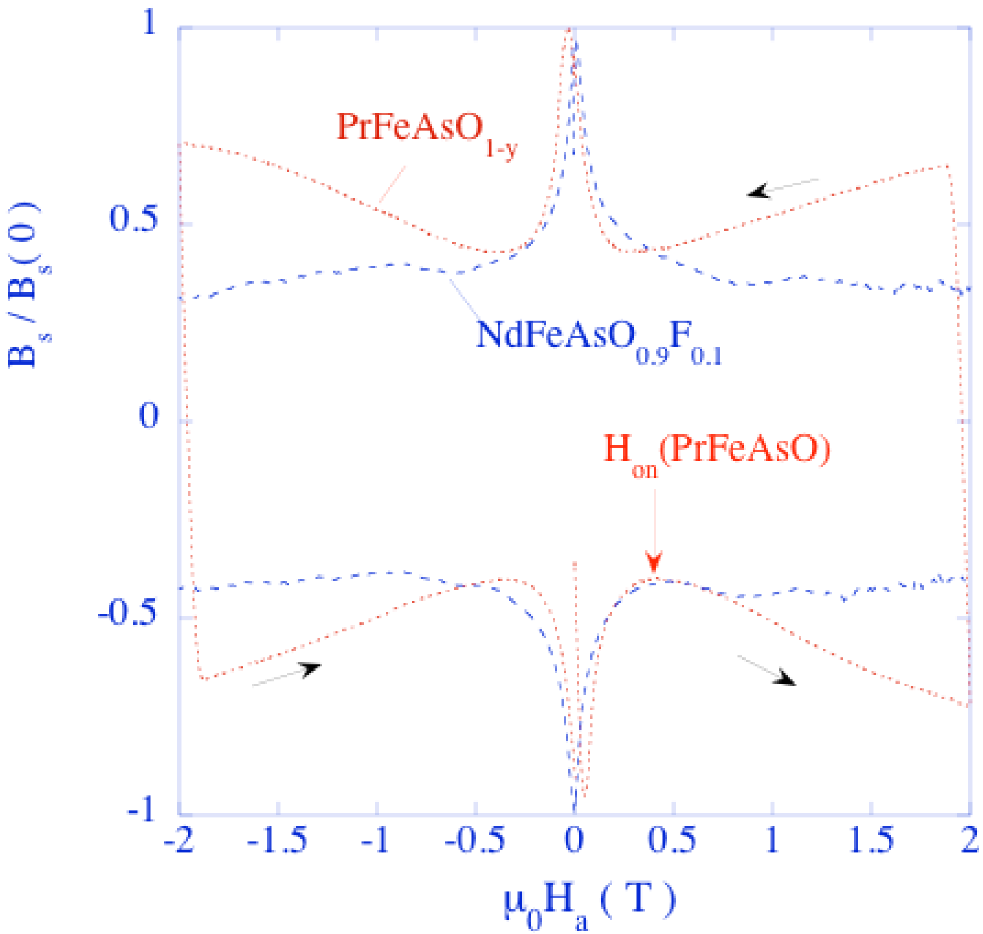

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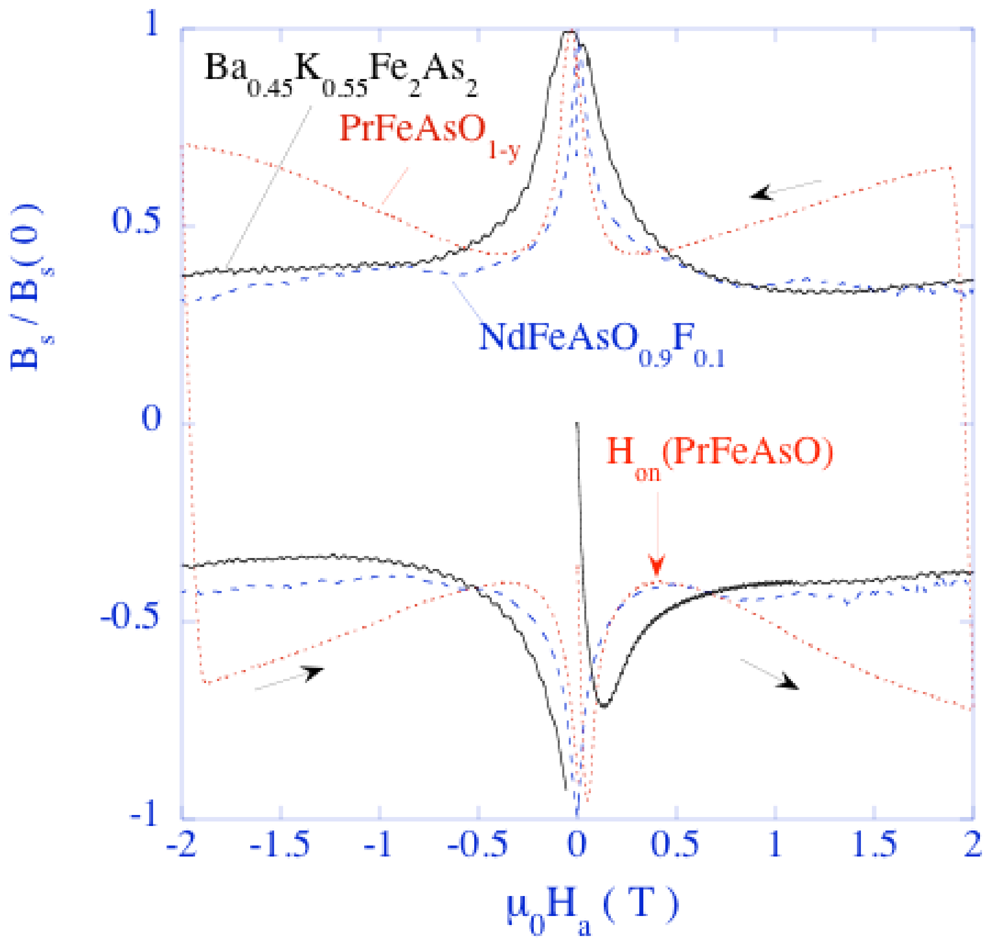

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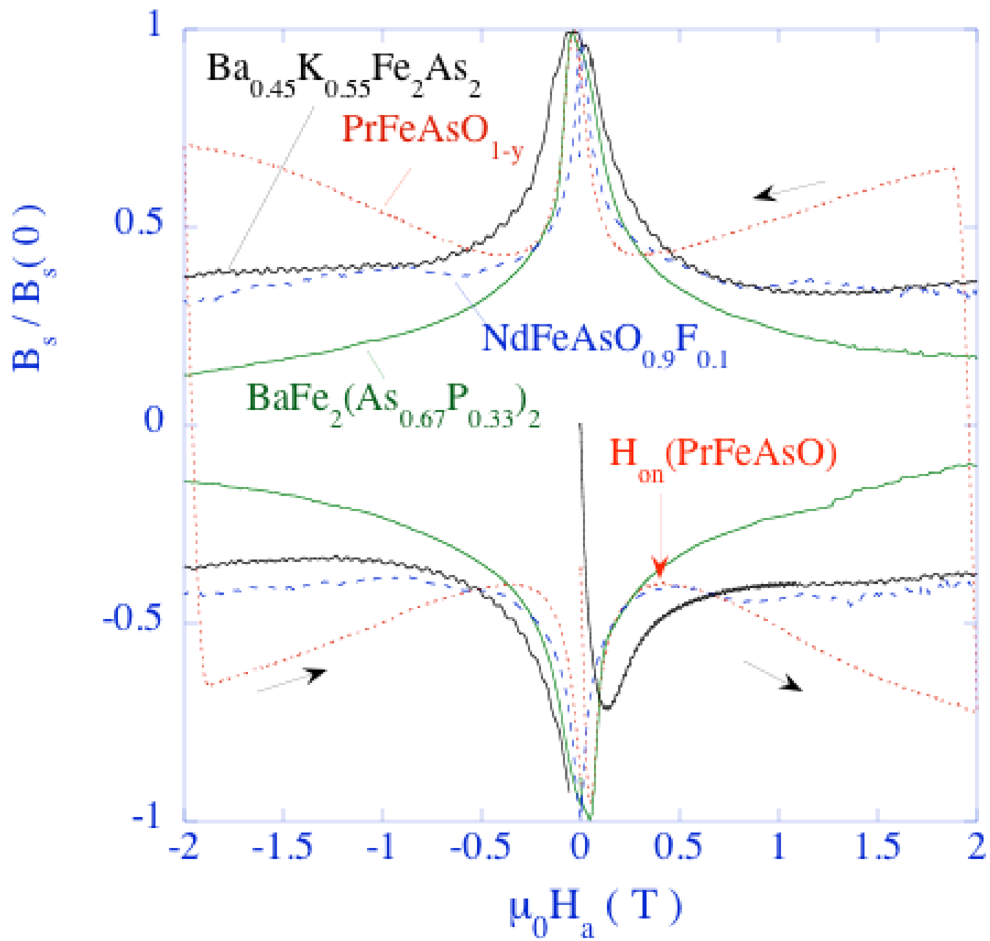

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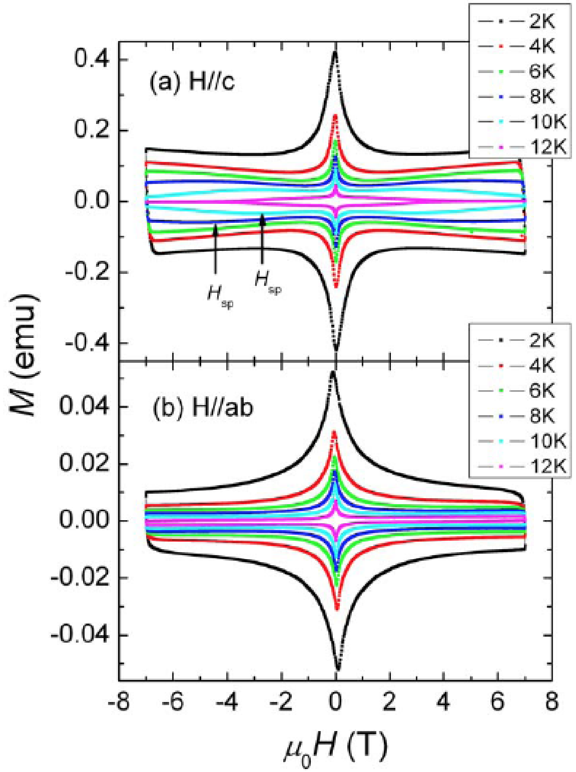
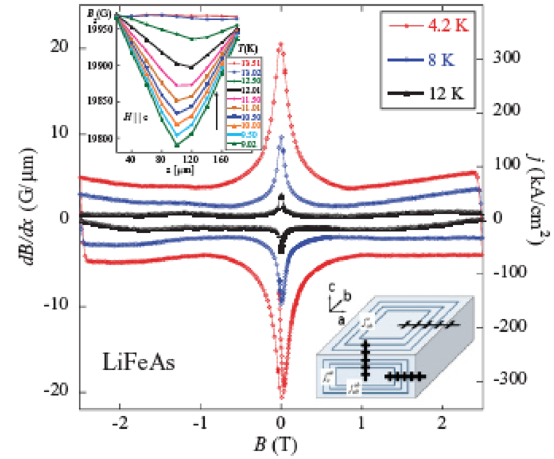
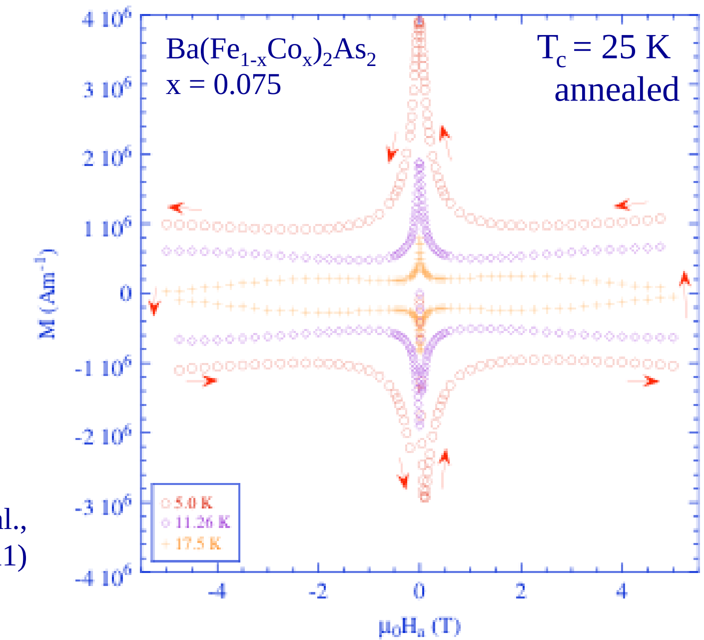


$Fe_{1.04}Se_{0.4}Te_{0.6}$
Liu, Kremer, and Lin



LiFeAs
Konczykowski et al.,
PRB **84**, 180514 (2011).

$Ba(Fe_{0.925}Co_{0.075})_2As_2$ crystal #2.1
Magnetization vs. Applied magnetic field



S. Demirdis et al.,
PRB **84**, 094517 (2011)

The critical current density in iron-based superconductors

Is there a pinning mechanism common to all iron-based superconductors ? Nature of the pinning centres ? Which pinning centres can do the job ?

Role of the defect charge ?

Role of multi-band character of superconductivity ?

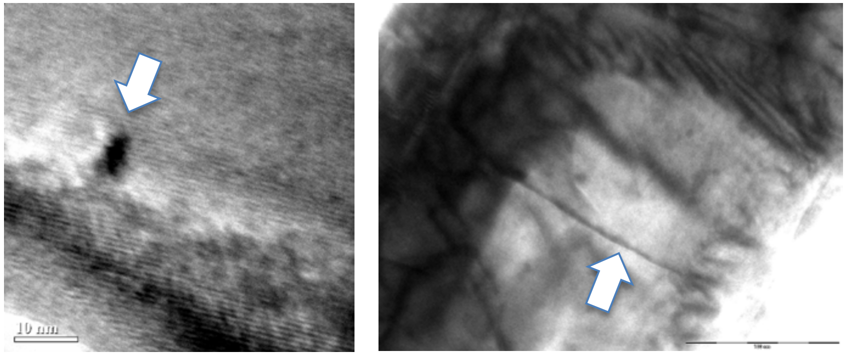
Relation with the phase diagram ? Charge carrier density ? Superfluid density ?

Role of order-parameter symmetry ?

Role of order parameter nodes ?

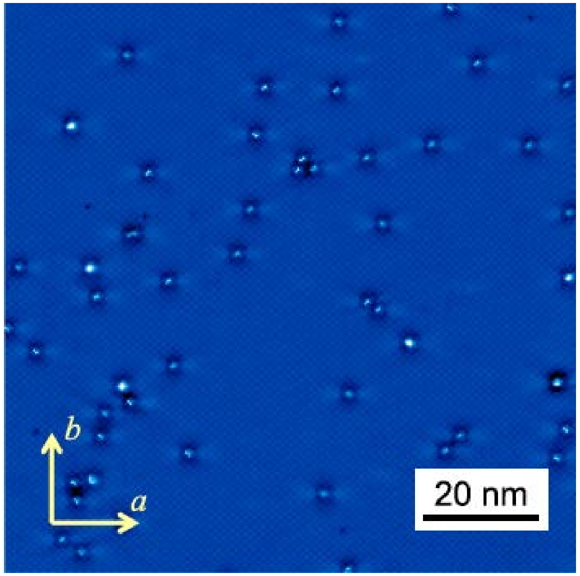
Can pinning be improved ?

Nature of the pinning centers

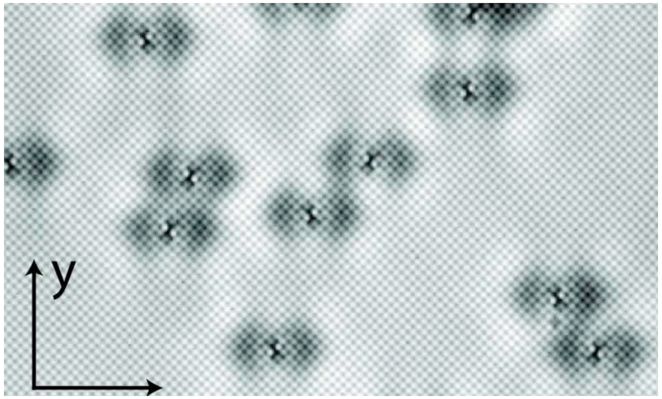


Single crystal $PrFeAsO_y$:
(a) nm-sized inclusion;
(b) Line dislocation

C.J. van der Beek et al., Phys. Rev. B **81**, 174517 (2010).



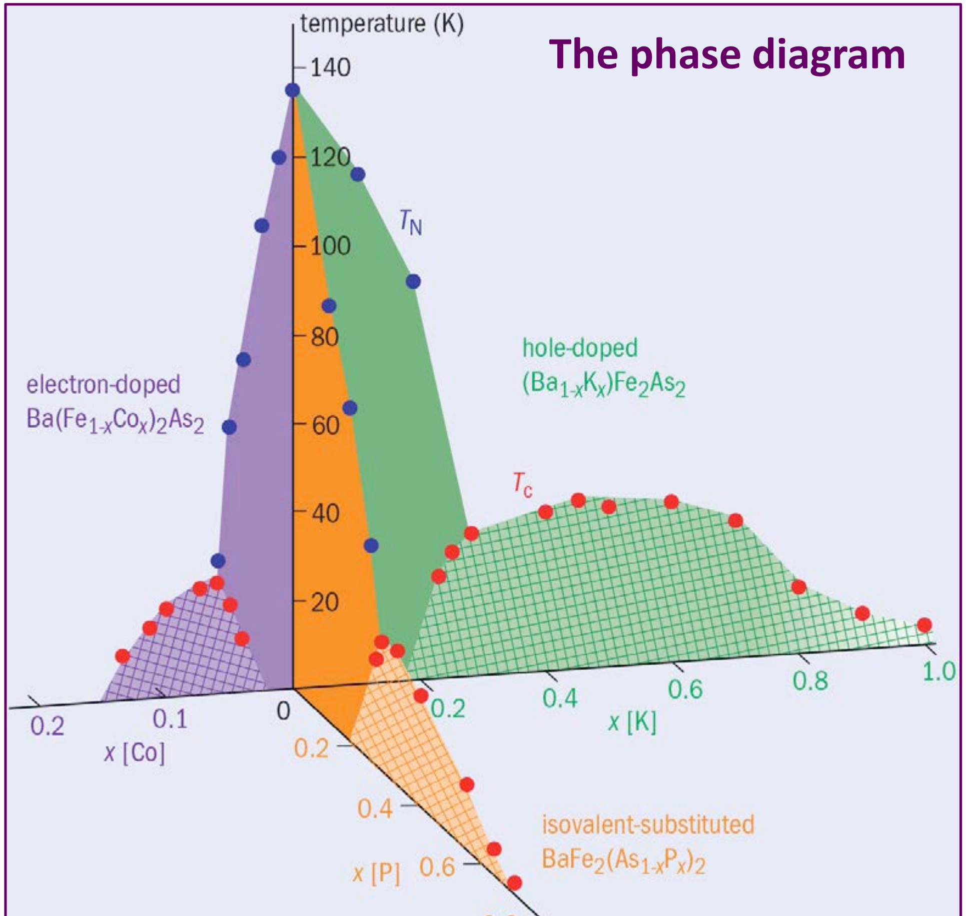
S. Kasahara et al., PNAS **111**, 16309 (2014)



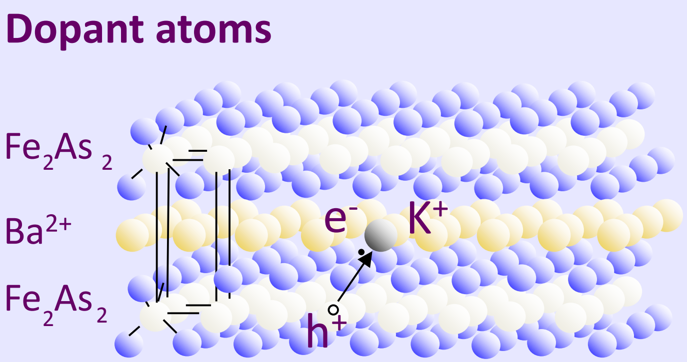
P.O. Sprau et al., Science **357**, 75-80 (2017)

Single crystal FeSe
Fe vacancies

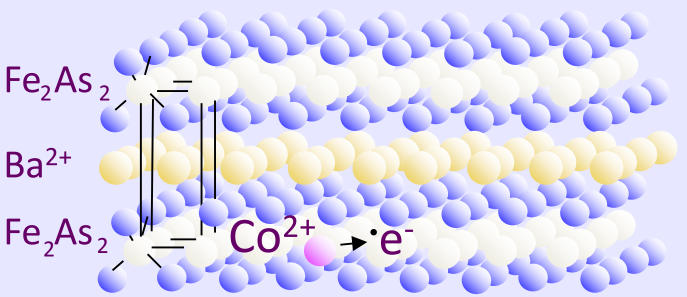
Nature of the pinning centers



H Aoki and H Hosono
Physics World February 2015



Doped $BaFe_2As_2$: $Ba_{1-x}K_xFe_2As_2$

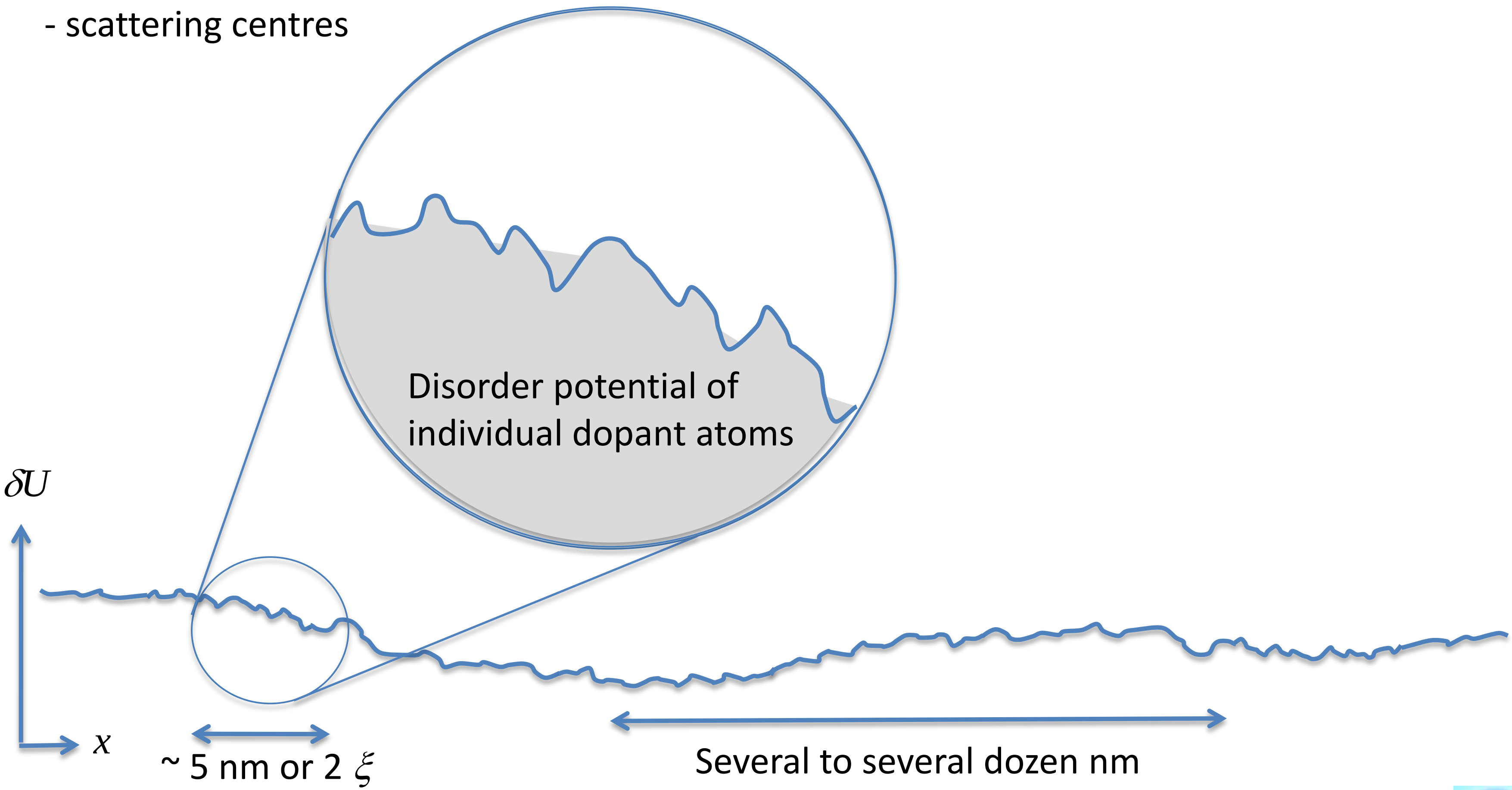


Doped $BaFe_2As_2$: $BaFe_{2-x}Co_xAs_2$

M. Rotter, M. Tegel, and D. Johrendt
Phys. Rev. Lett. **101** 107006 (2008)

Nature of the pinning centers

Dopant atoms:
- Local- and nm-scale T_c variations
- small voids
- scattering centres



IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
IUMRS-ICAM Keynote presentation A3-K30-001.

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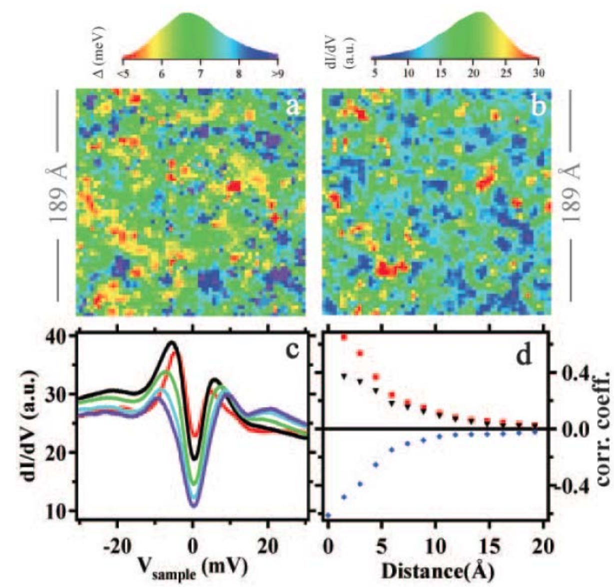
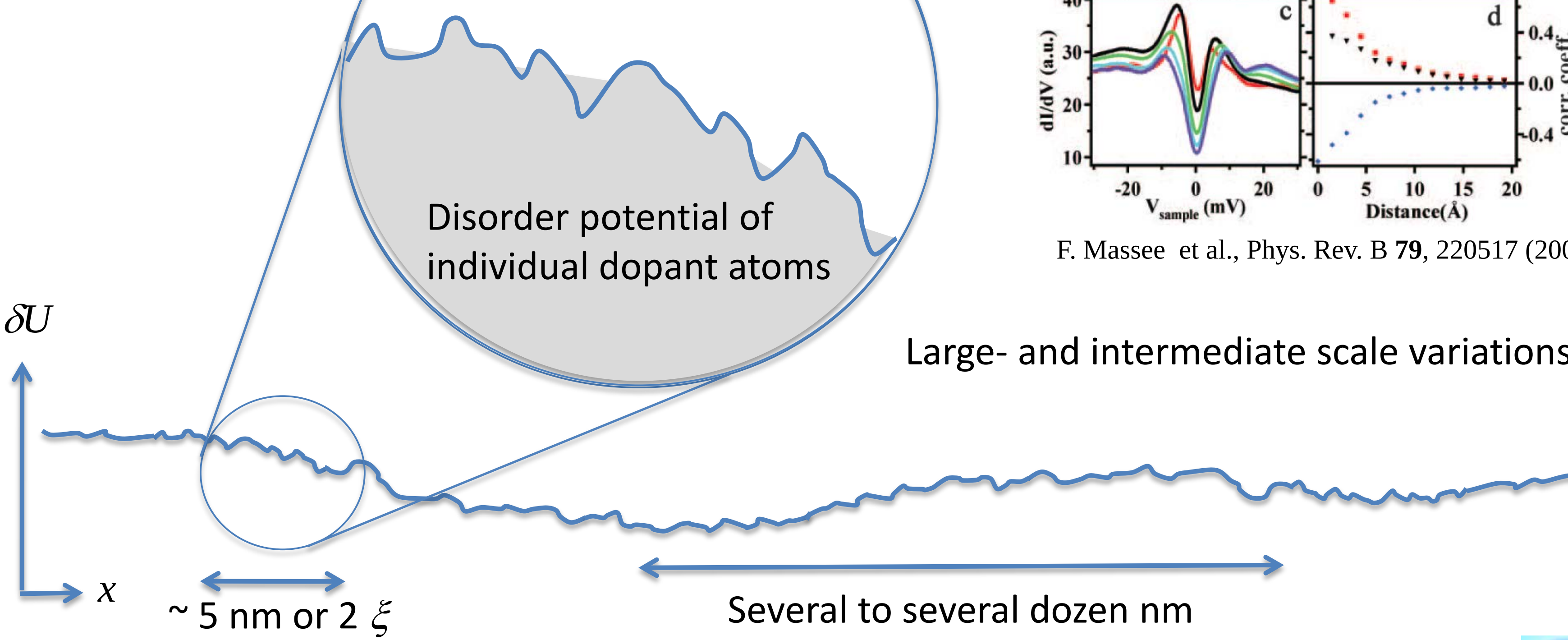
Gap maps in $Ba(Fe_{1-x}Co_x)_2As_2$



F. Massee et al., Phys. Rev. B **79**, 220517 (2009)



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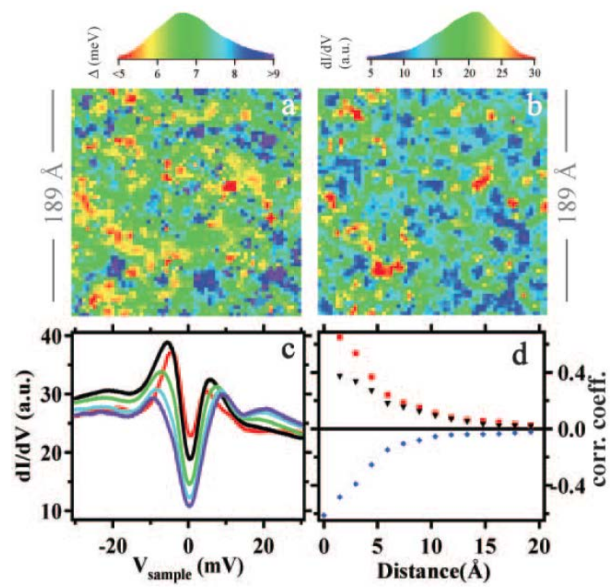
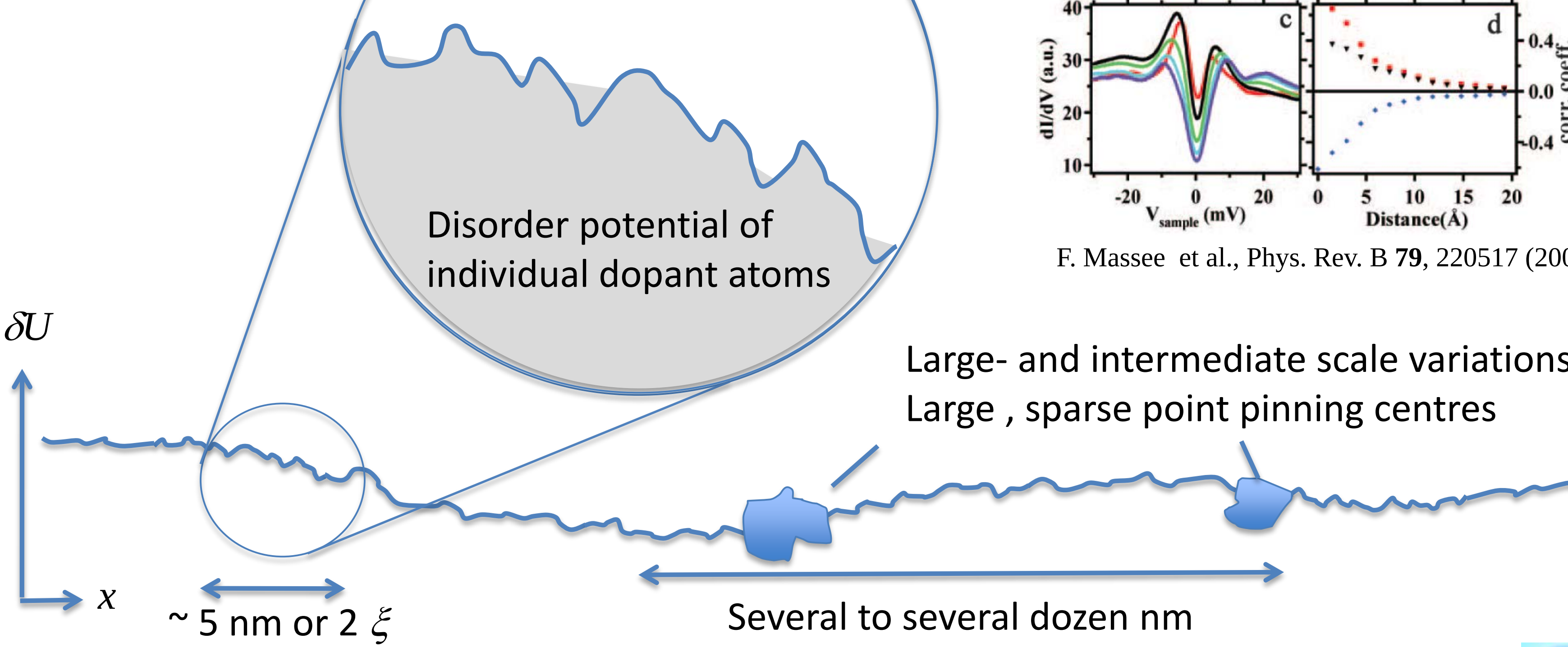


F. Massee et al., Phys. Rev. B **79**, 220517 (2009)



J_c of iron-based superconductors *example of $Ba(Fe_{0.93}Co_{0.07})_2As_2$…*

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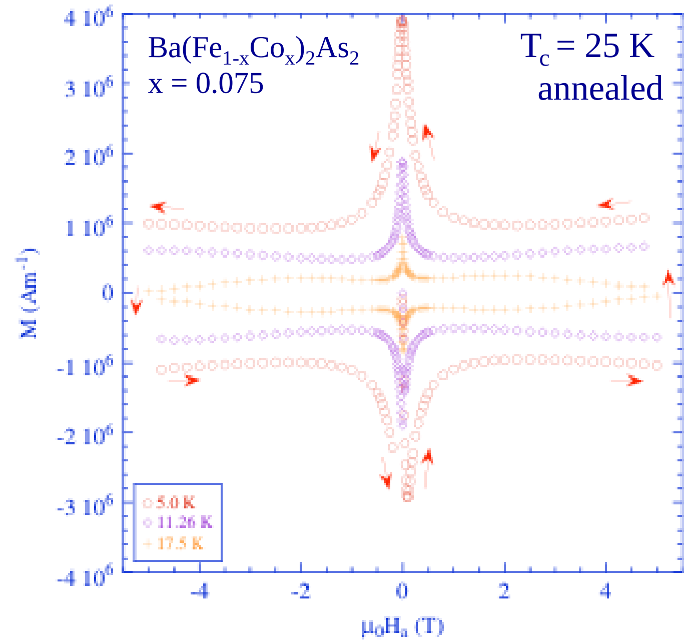

S. Demirdis et al., PRB **84**, 094517 (2011)

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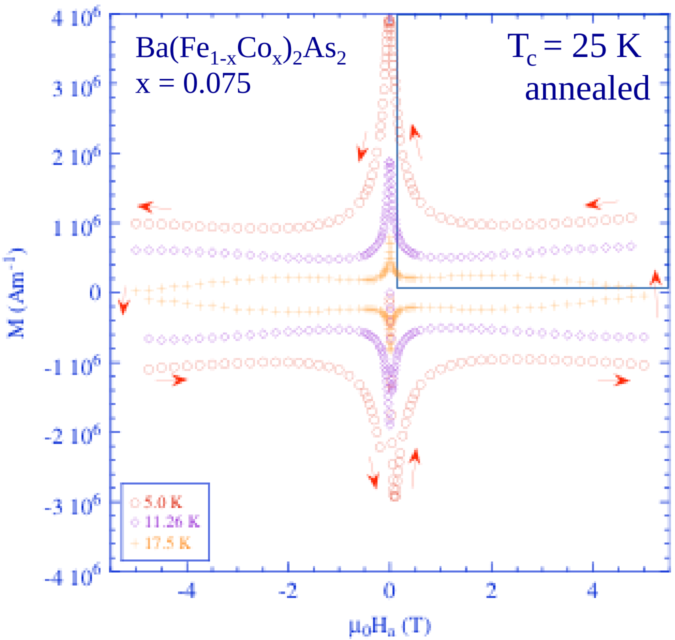

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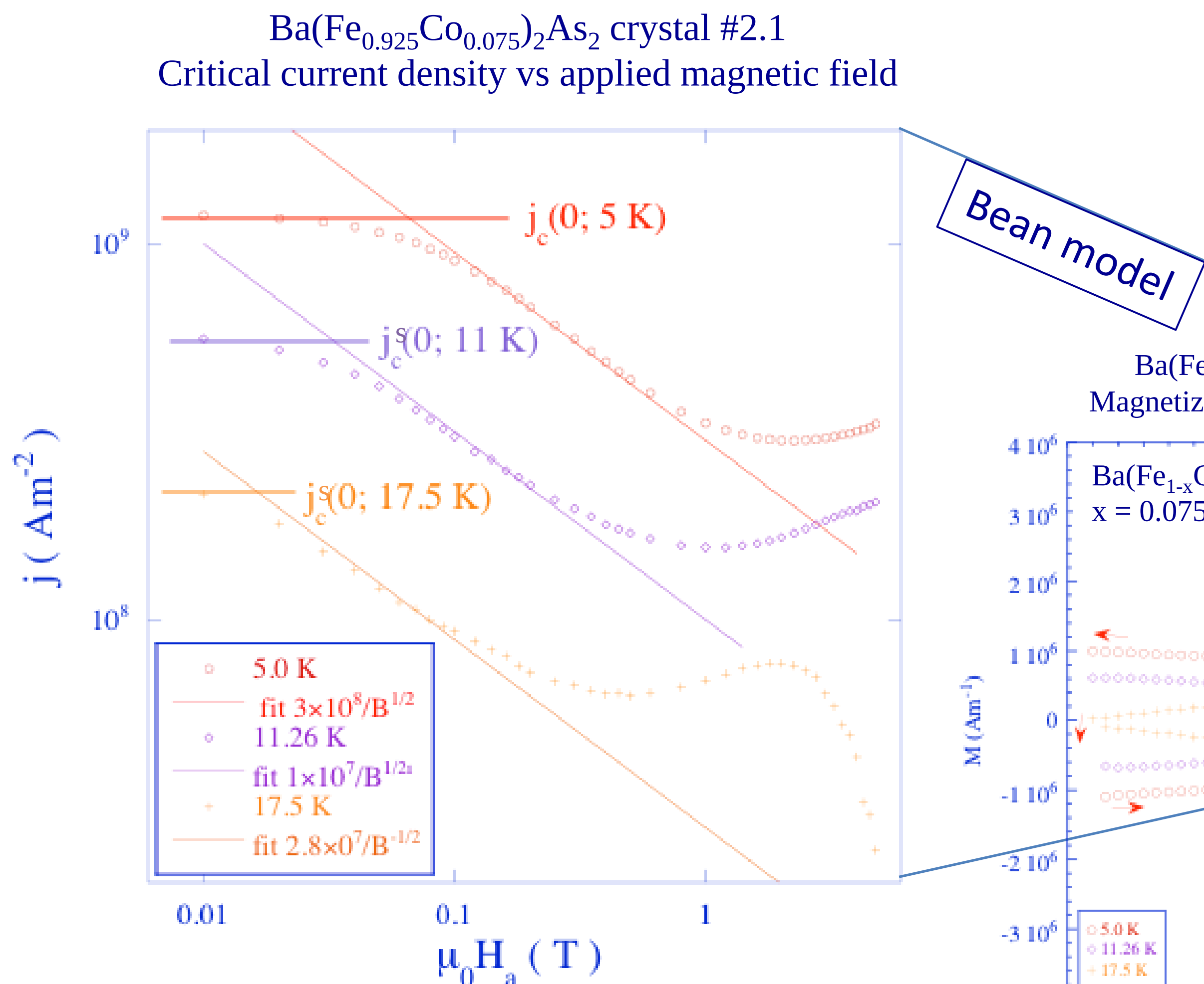

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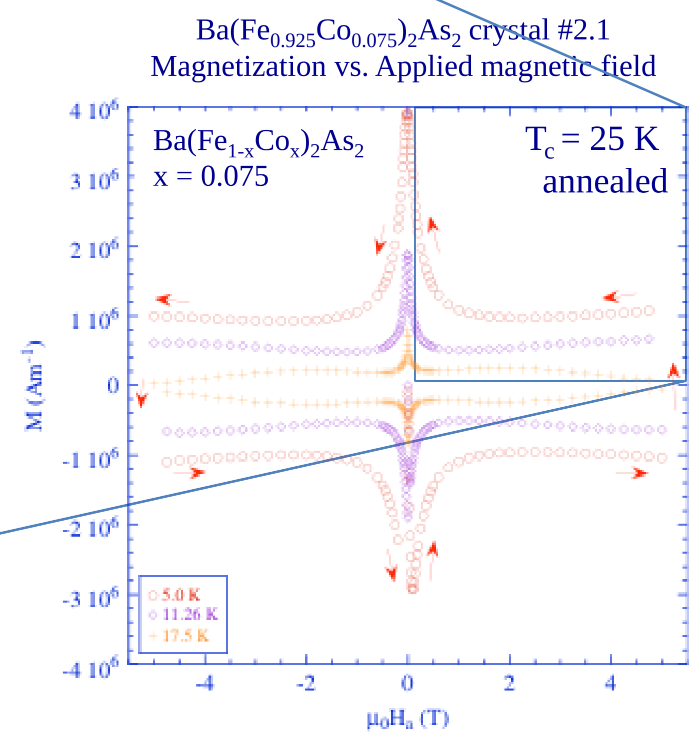


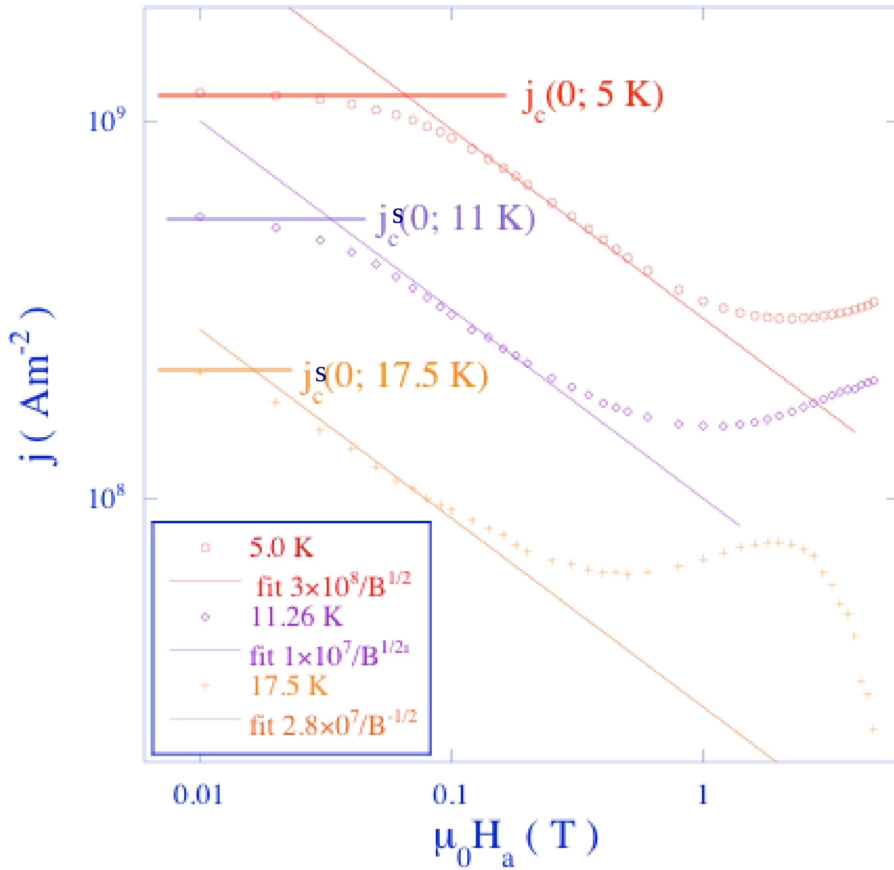
$j_c = j_c(0)\, f(b)\, g(t)$

example of $Ba(Fe_{0.93}Co_{0.07})_2As_2$…

$t = T / T_c$

$b = B / B_{c2}(T)$

Zero temperature, zero-field j_c : pinning mechanism, statistics



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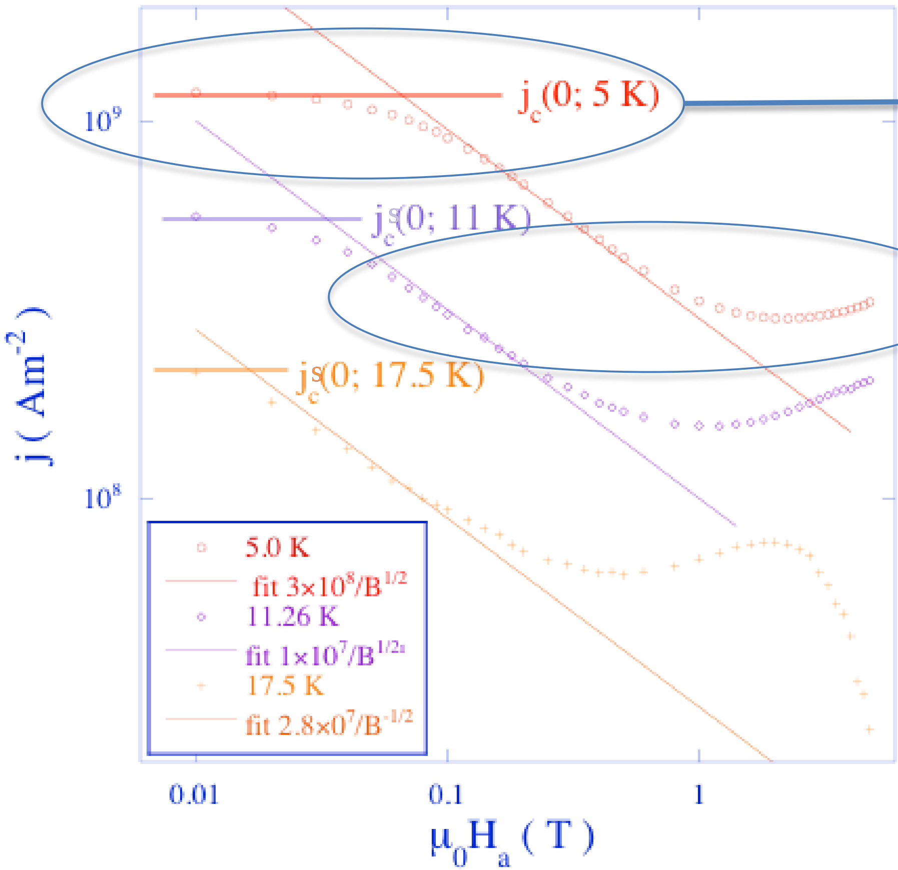

1, or a few × 10^9 Am^{-2} @ B = 0

a few × 10^8 Am^{-2} @ B ~ 1 T

S. Demirdis et al., PRB **84**, 094517 (2011)

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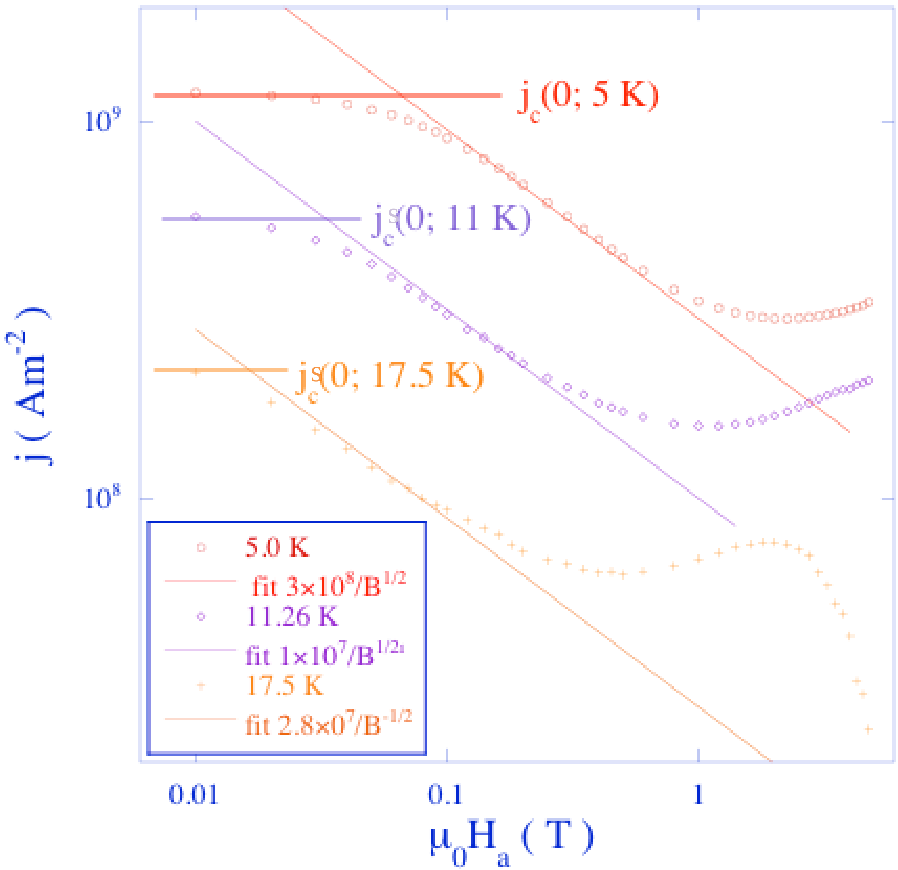

S. Demirdis et al., PRB **84**, 094517 (2011)

Field dependence :

- Statistics of pinning
- change in vortex lattice structure
- change in vortex structure

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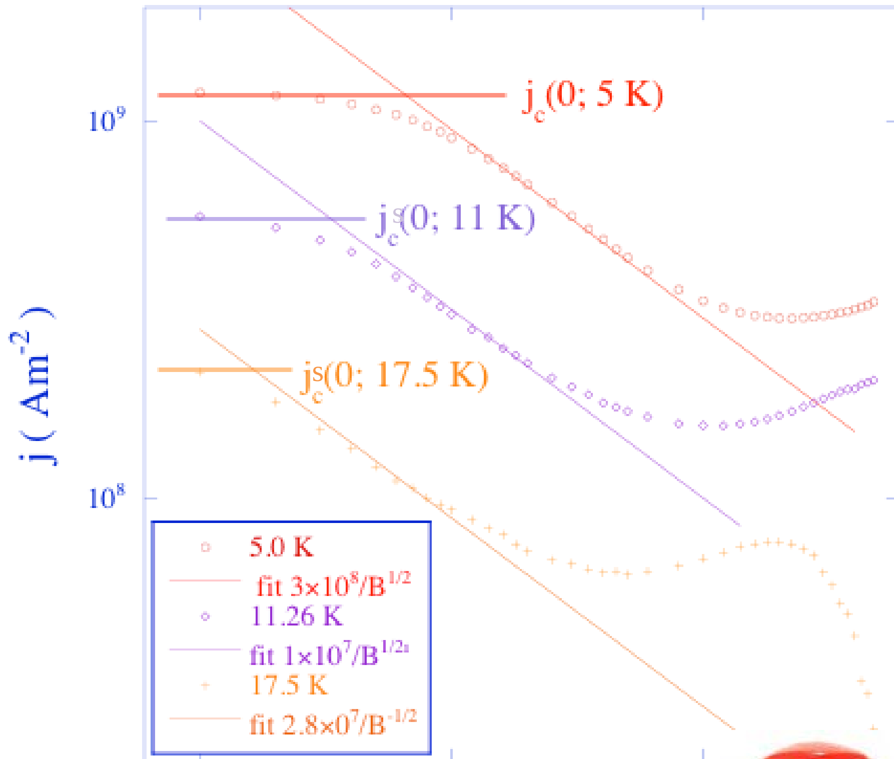

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Temperature dependence:

- thermal activation of quasiparticles: $\lambda(T)$
- decrease of the order parameter: $\xi(T)$
- multiple band effects
- thermal activation of vortices
- thermal smearing of the pin potential

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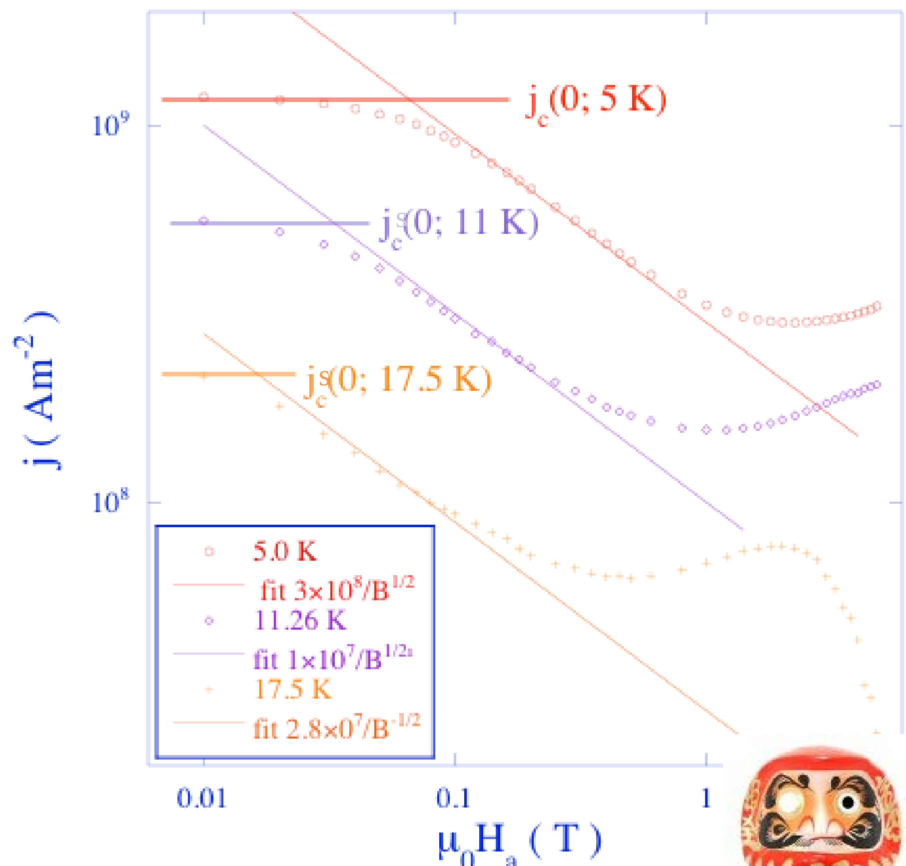

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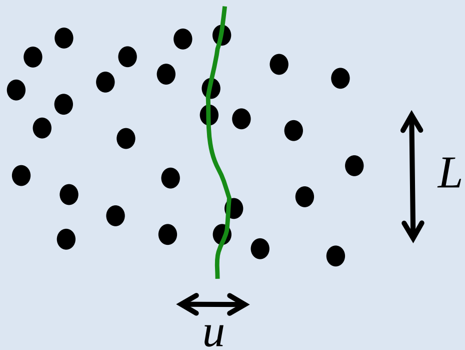
Nature of the pinning centres *$j_c(0)$: a question of magnitude*

Low fields / isolated vortices

Elastic energy loss ⇔ Pinning energy gain

$$\tilde{\varepsilon}_1 \frac{u^2}{L} = U_p$$



$\tilde{\varepsilon}_1 \simeq \varepsilon^2 \varepsilon_0 = \frac{\varepsilon^2 \Phi_0^2}{4\pi \mu_0 \lambda_{ab}^2}$ vortex line tension

U_p : pinning energy

n_i : pin density

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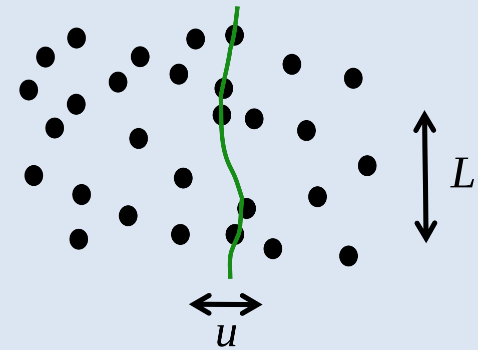

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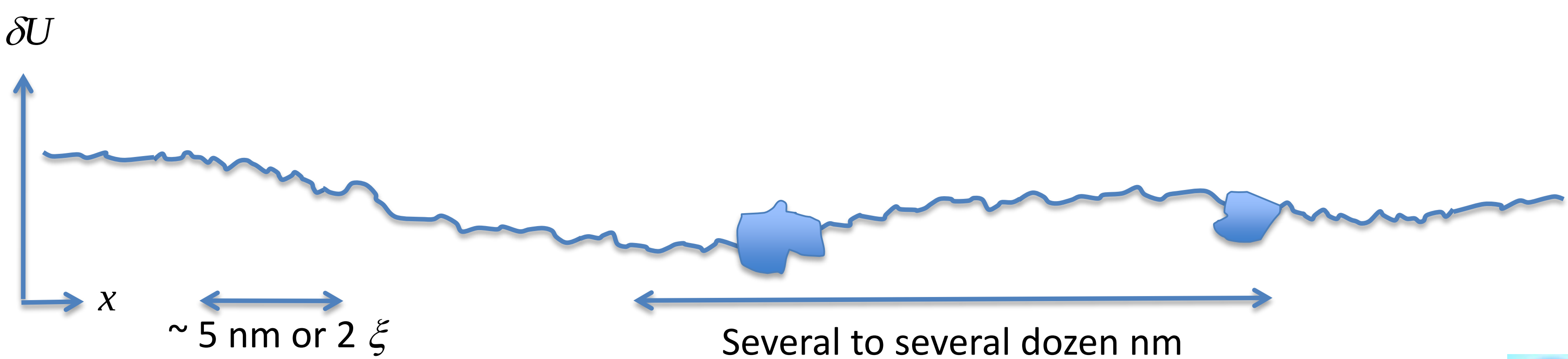

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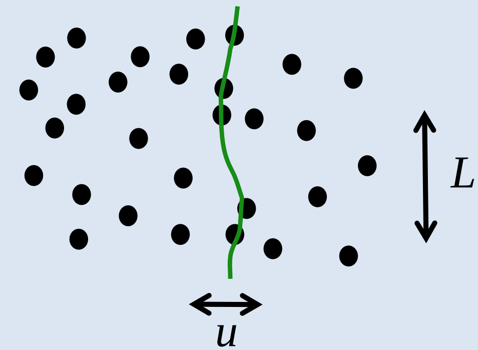

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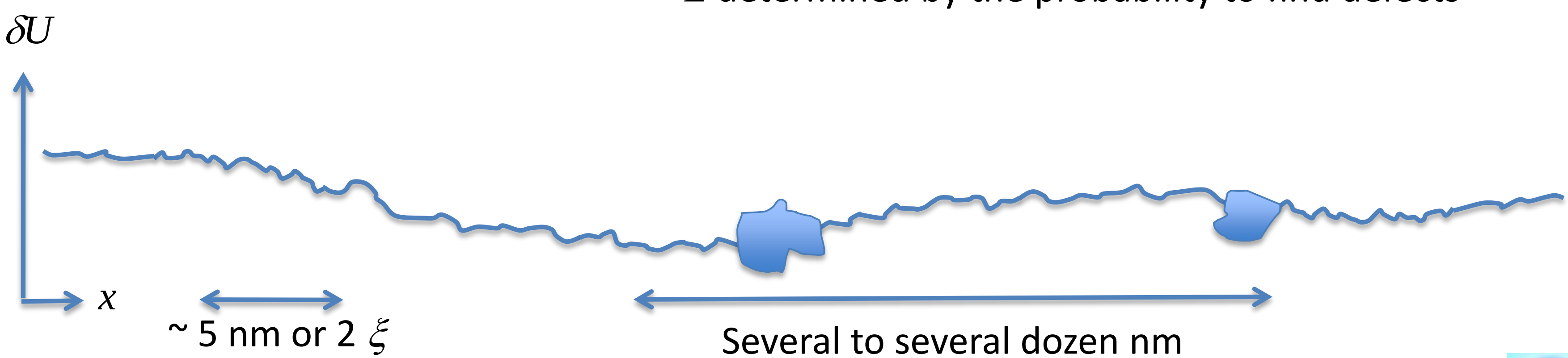
Fill all the (sparse) extended defects ($n_i << \xi^{-3}$) : $L = (\varepsilon_1 / \pi \tilde{n}_i U_p)^{1/2}$

L determined by the probability to find defects



IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
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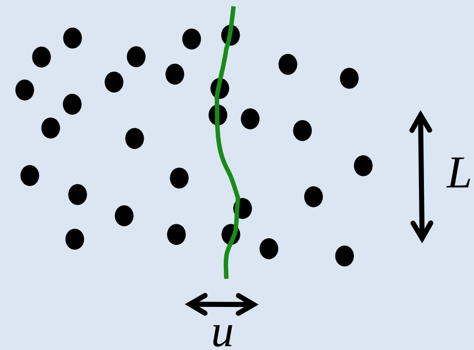

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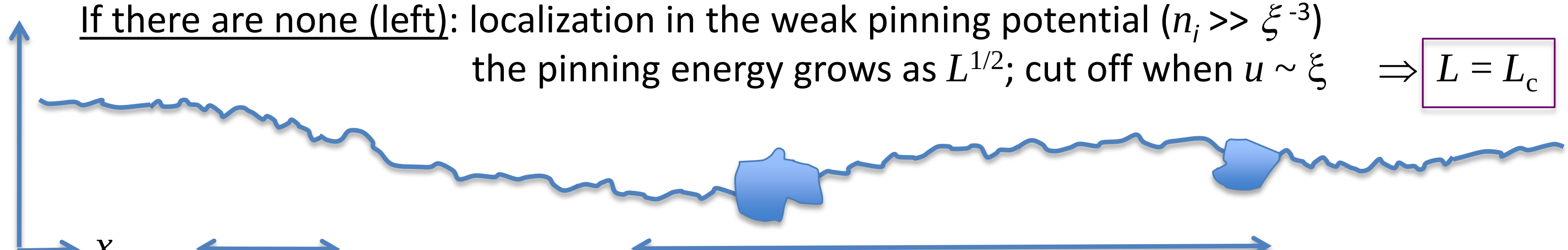
L determined by the probability to find defects

δU

If there are none (left): localization in the weak pinning potential ($n_i >> \xi^{-3}$)
the pinning energy grows as $L^{1/2}$; cut off when $u \sim \xi$ ⇒ $L = L_c$



x

~ 5 nm or 2 ξ

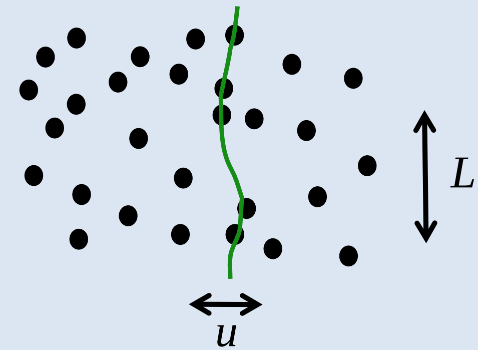
Several to several dozen nm

Nature of the pinning centres *$j_c(0)$: a question of magnitude*

Sparse, large defects ($n_i \ll \xi^3$): strong pinning

- Pinning force $F_p = \Phi_0 j_c$ from **direct sum** $\Sigma_i f_{p,i}$

$$j_c = 0.14 j_0 \varepsilon^{-1} n_i^{1/2} \left(\mathcal{D}_i^z \mathcal{F}(T)\right)^{3/2}$$

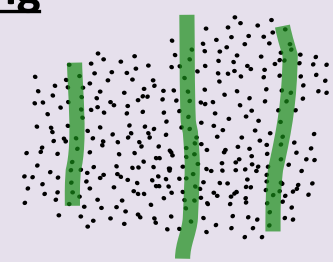


Atomic size, dense defects ($n_i \gg \xi^3$): weak, collective pinning

- Pinning force $F_p = (n_i \langle f_p^{\,2} \rangle / \xi^2 L_c)^{1/2}$ from **fluctuations** $\langle f_p^{\,2} \rangle^{1/2}$

$$j_c = j_0 \varepsilon^{-1} \delta^{2/3}$$

$$L_c = \varepsilon \xi \left(\frac{j_0}{j_c} \right)^{1/2}$$

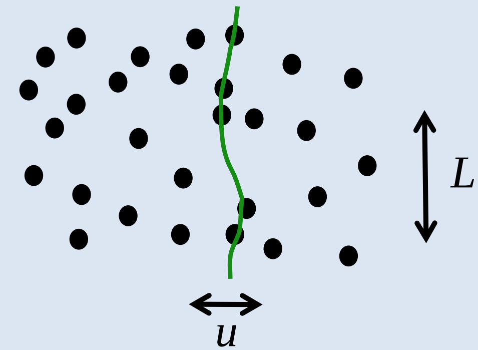


Nature of the pinning centres *$j_c(0)$: a question of magnitude*

Sparse, large defects ($n_i \ll \xi^3$): strong pinning

- Pinning force $F_p = \Phi_0 j_c$ from **direct sum** $\Sigma_i f_{p,i}$

$$j_c = 0.14 j_0 \varepsilon^{-1} n_i^{1/2} \left(\mathcal{D}_i^z \mathcal{F}(T)\right)^{3/2}$$



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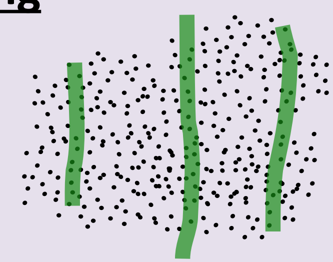
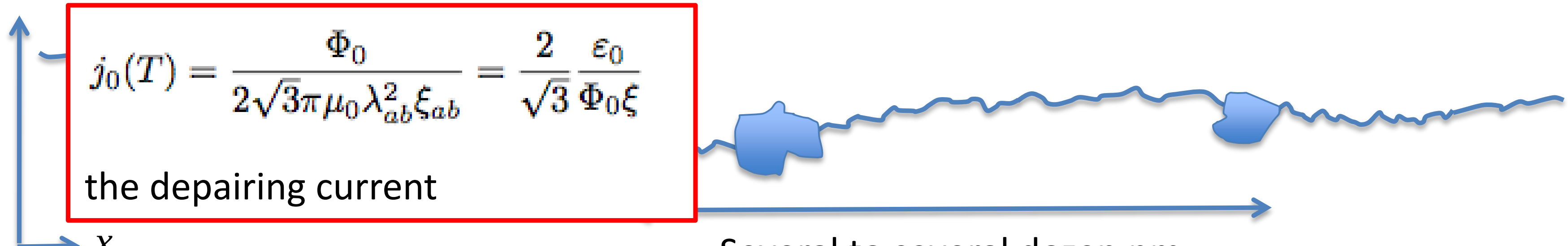


δU

$$j_0(T) = \frac{\Phi_0}{2\sqrt{3}\pi \mu_0 \lambda_{ab}^2 \xi_{ab}} = \frac{2}{\sqrt{3}} \frac{\varepsilon_0}{\Phi_0 \xi}$$

the depairing current



x

Several to several dozen nm

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
IUMRS-ICAM Keynote presentation A3-K30-001.

Depairing current and model critical currents in iron-based superconductors

1, or a few × 10^9 Am^{-2} @ B = 0

a few × 10^8 Am^{-2} @ B ~ 1T

$L_c \sim 13\,\xi$

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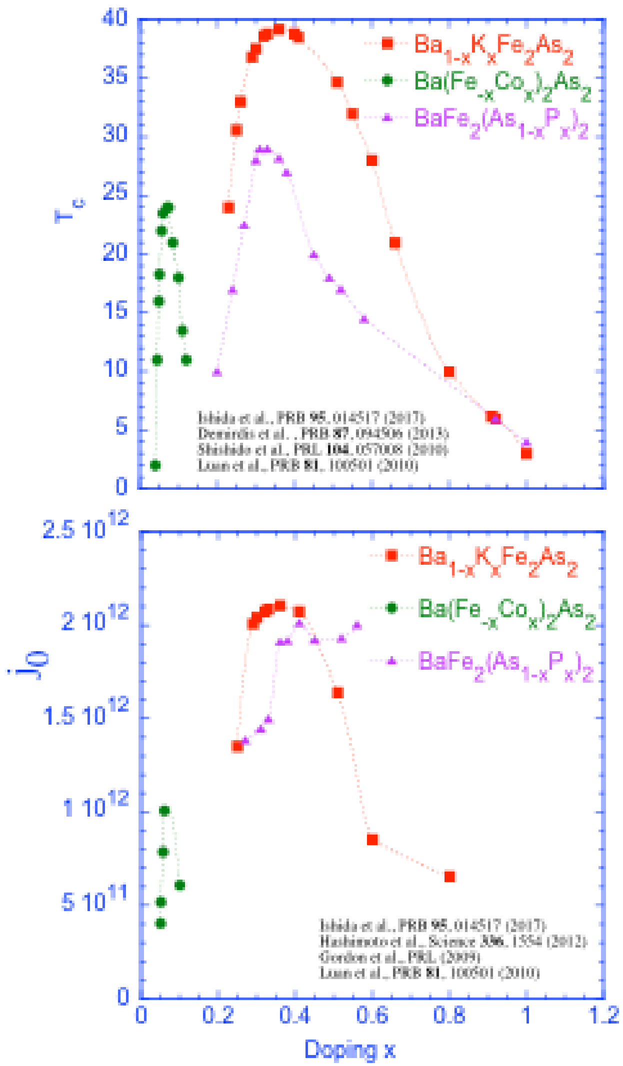

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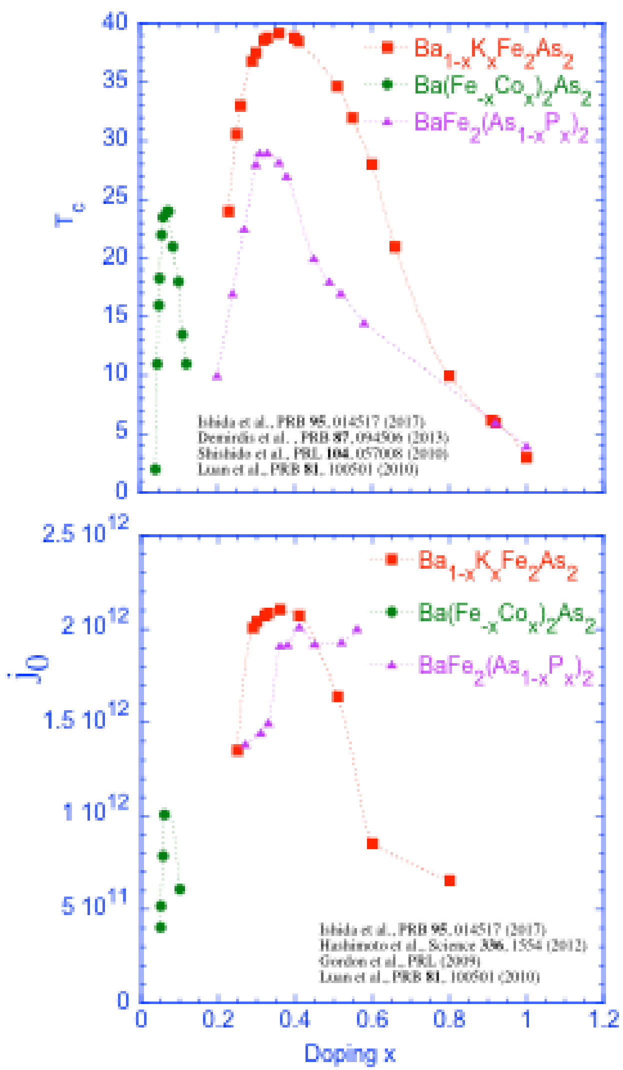

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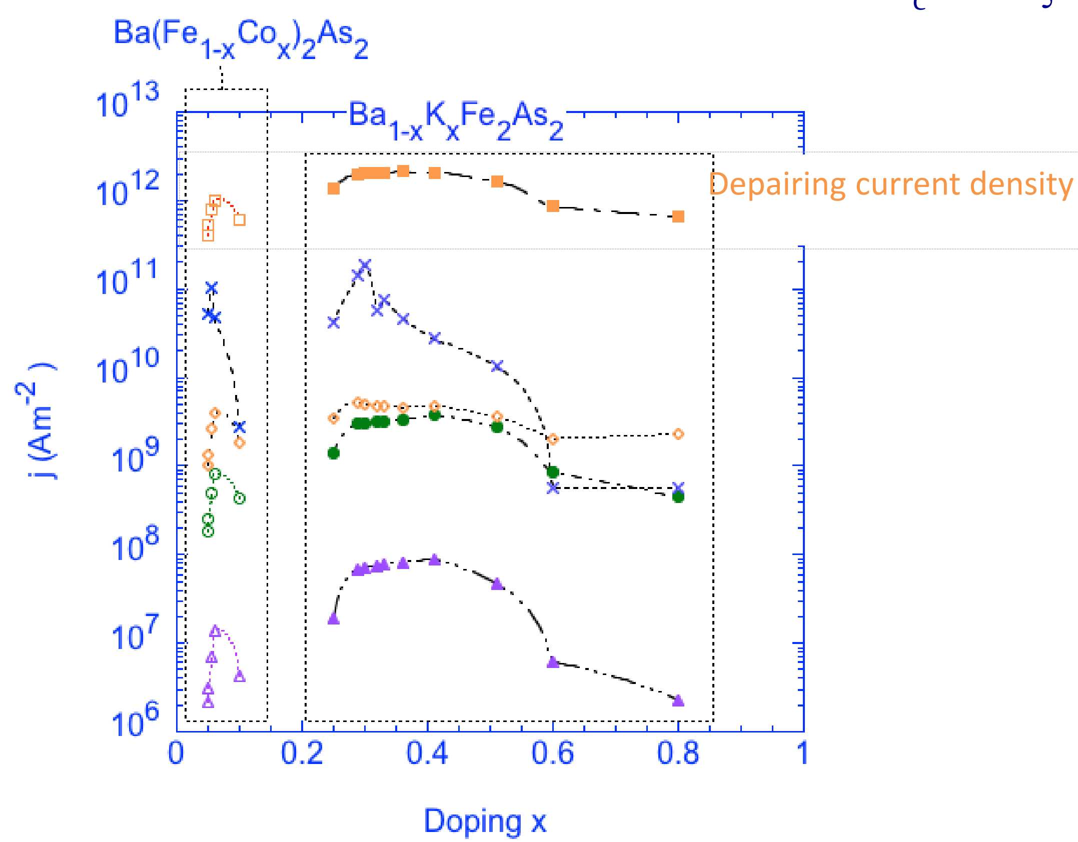

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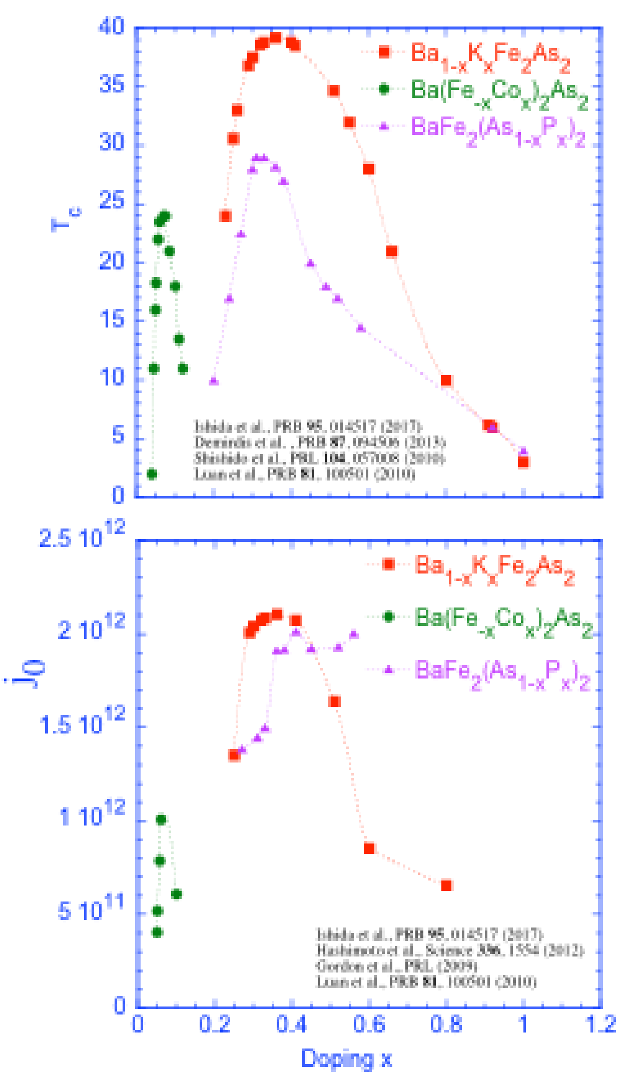

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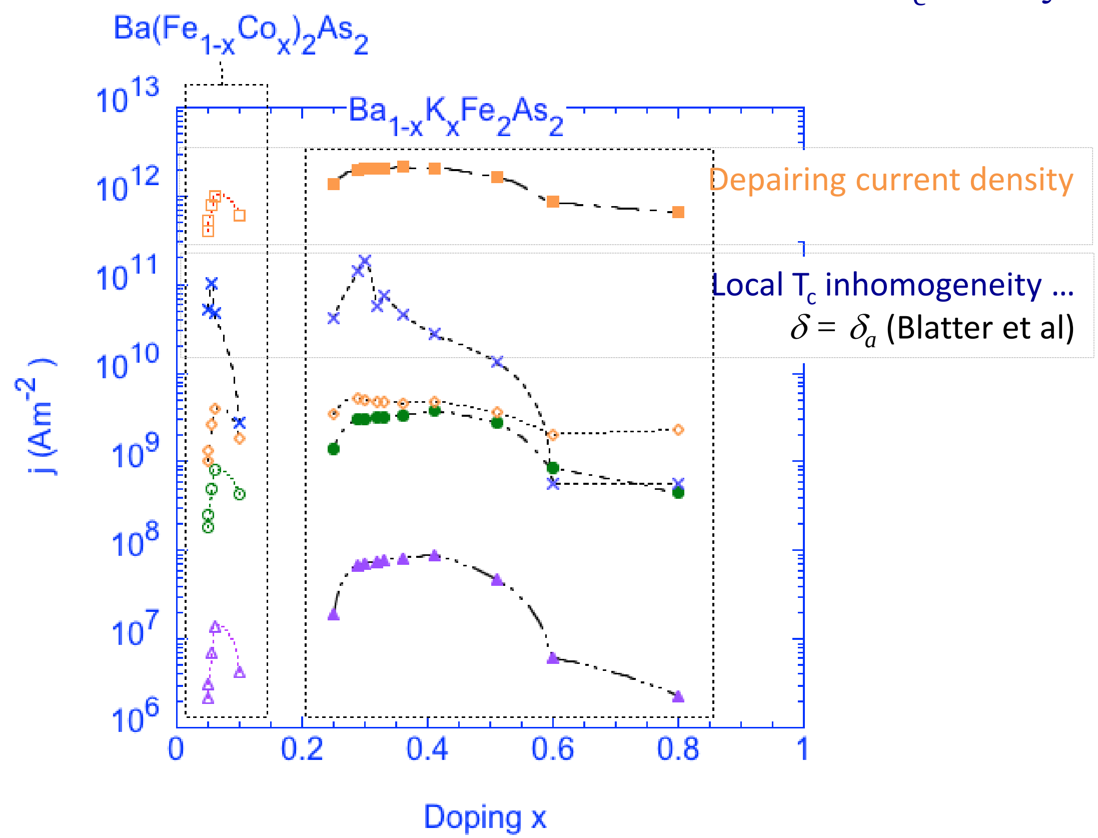

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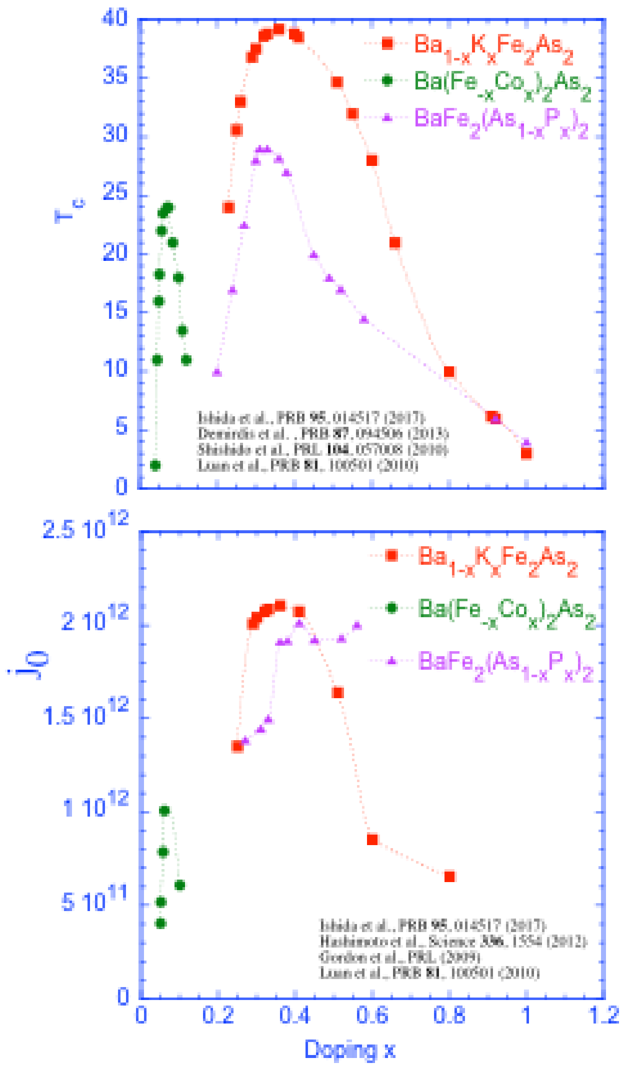

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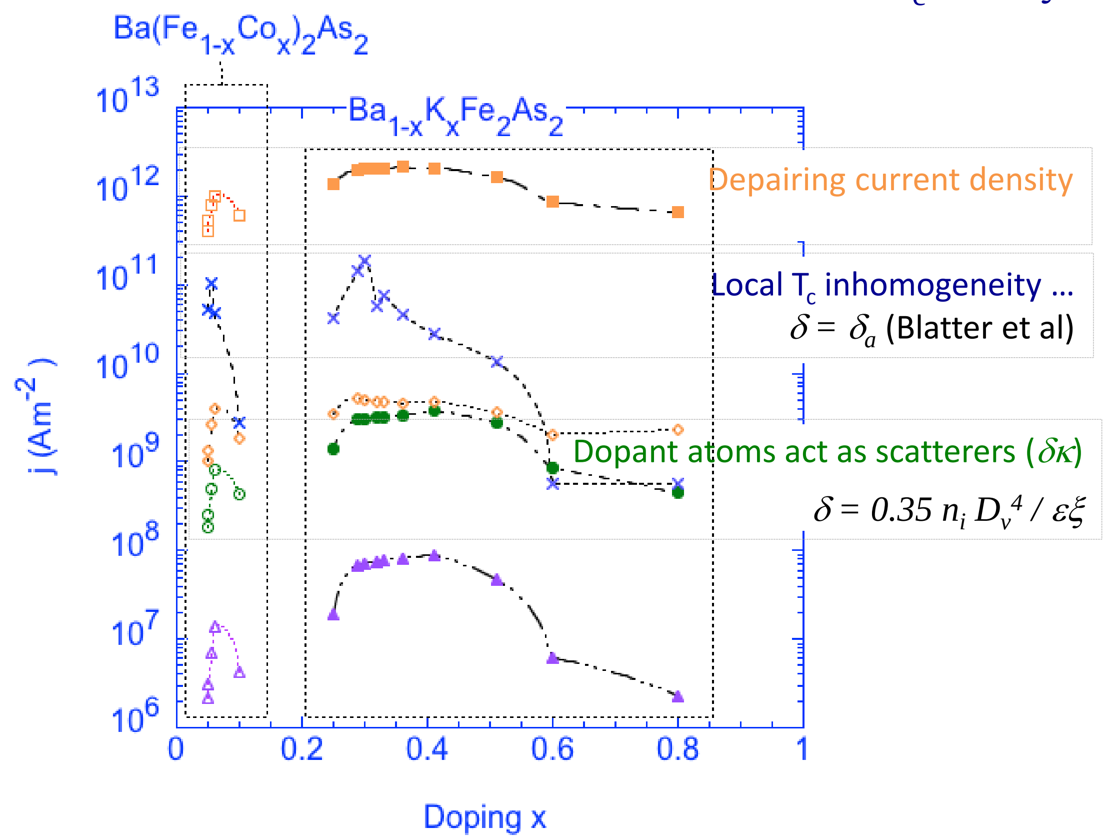

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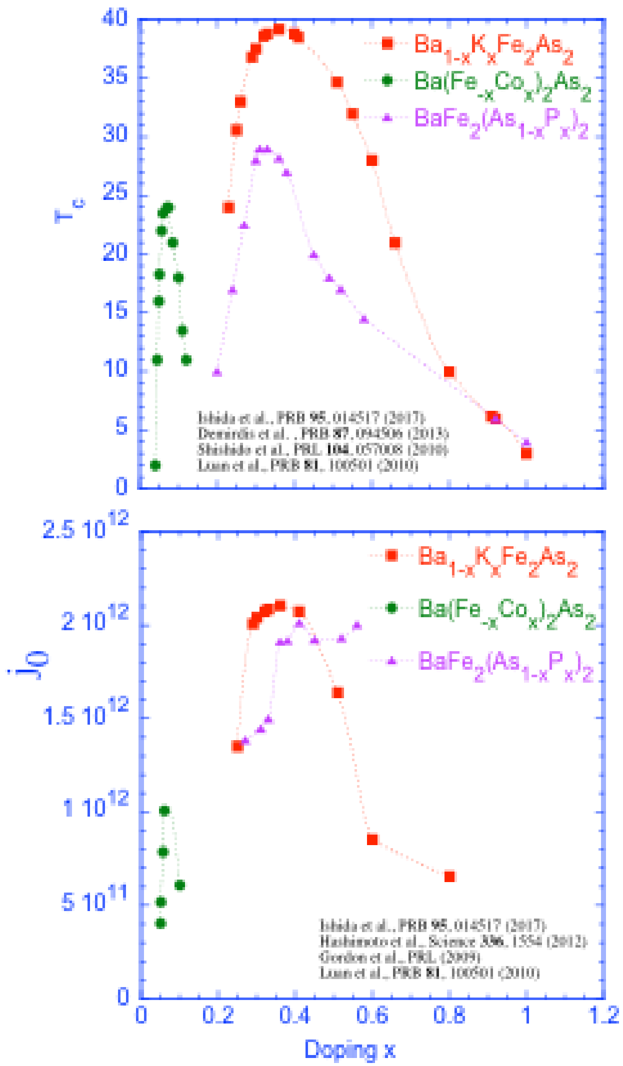

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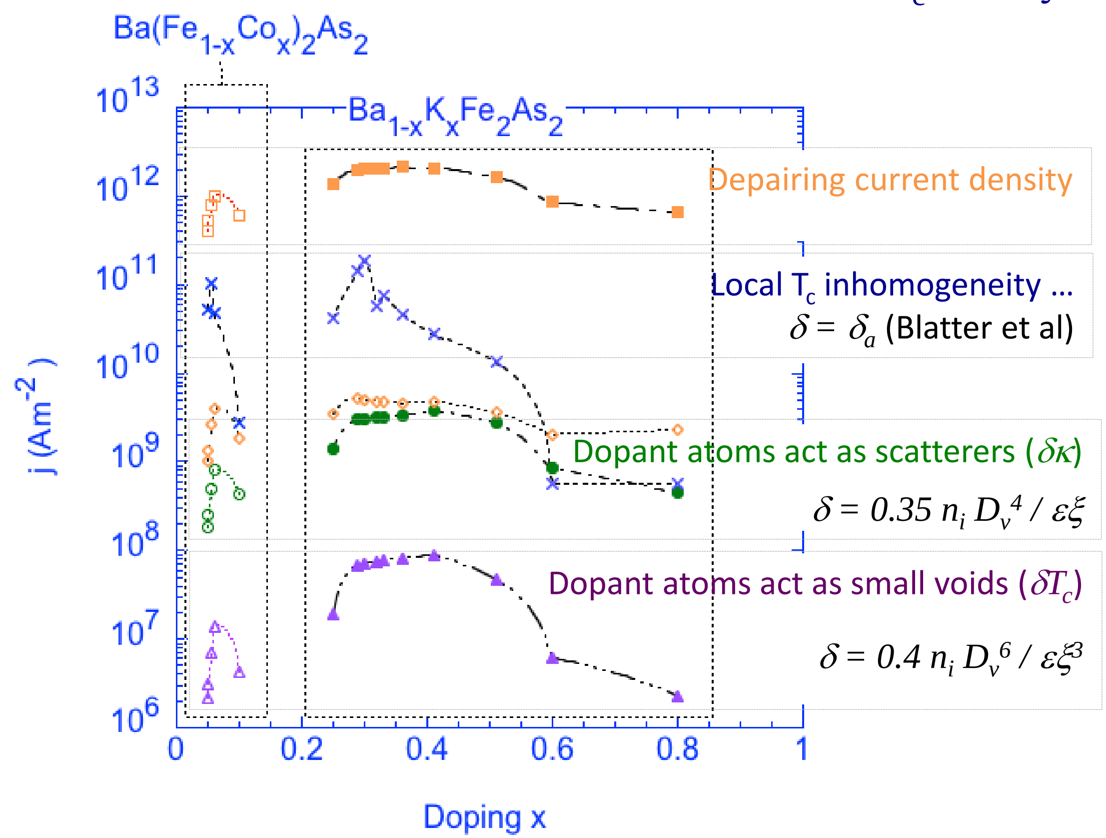

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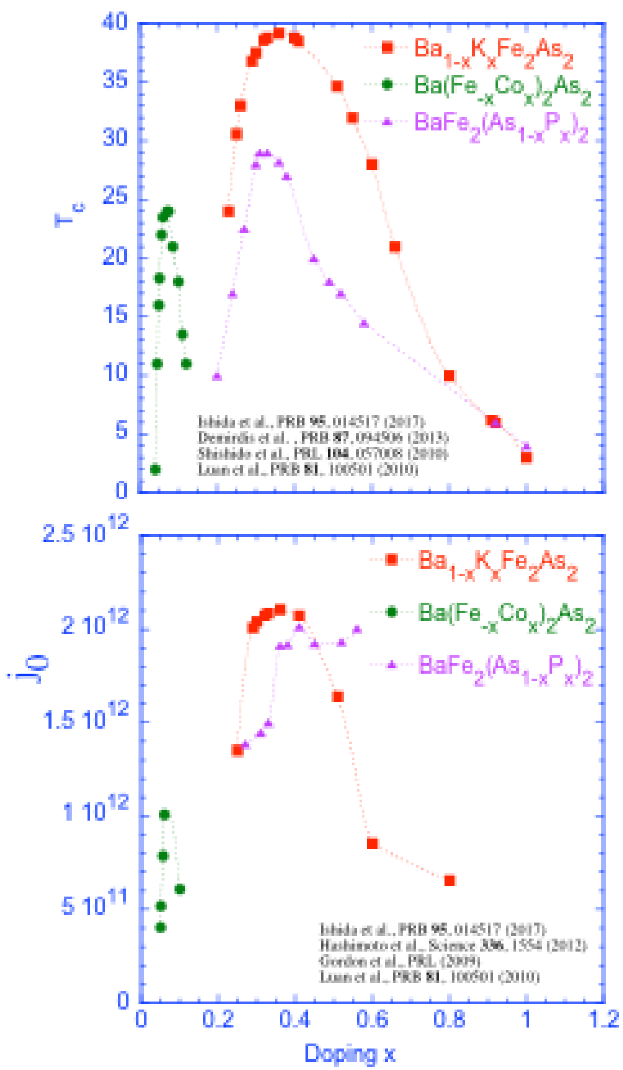

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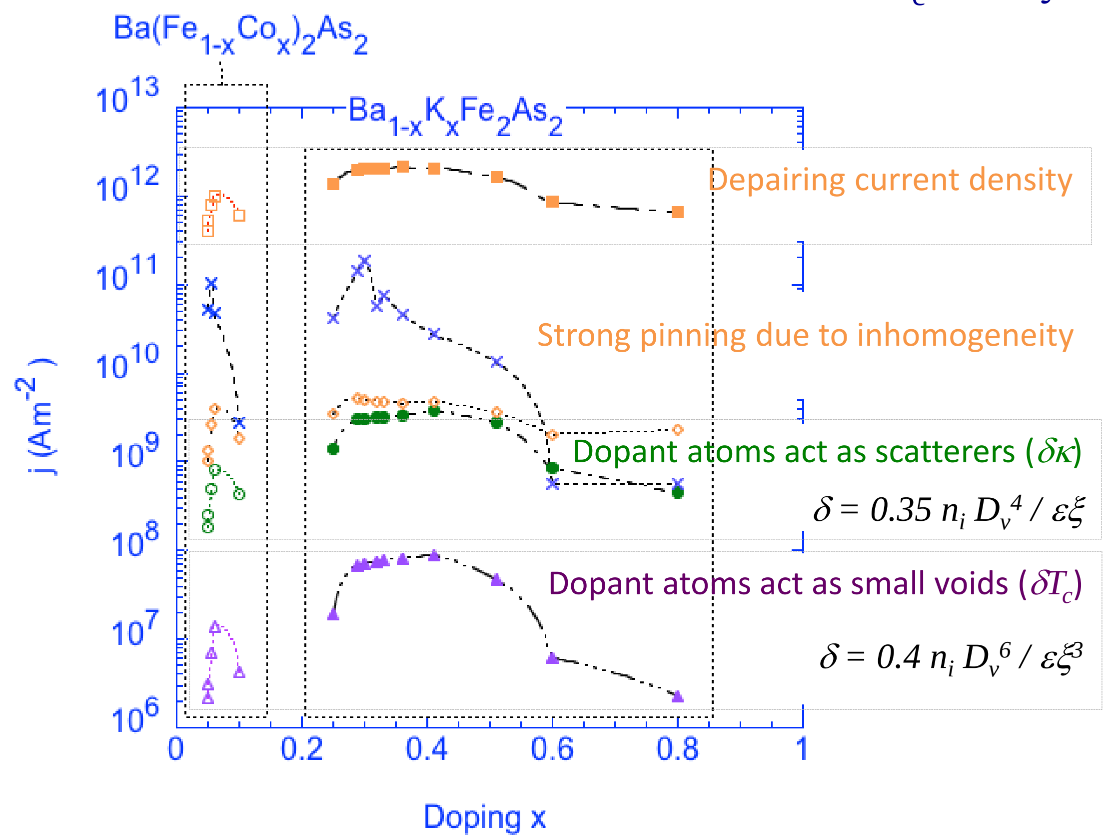

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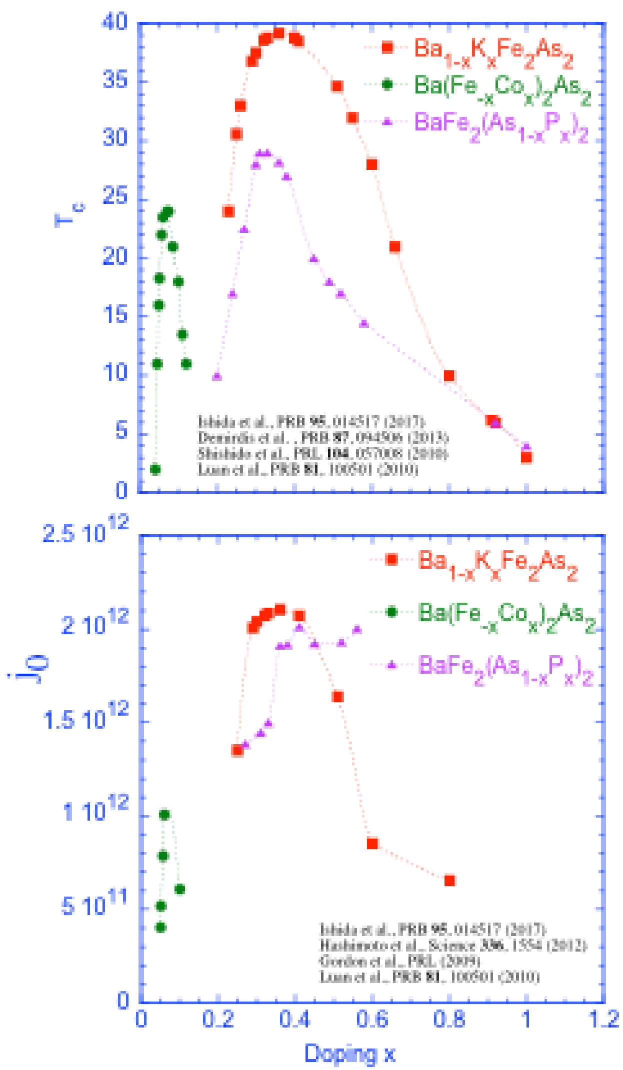

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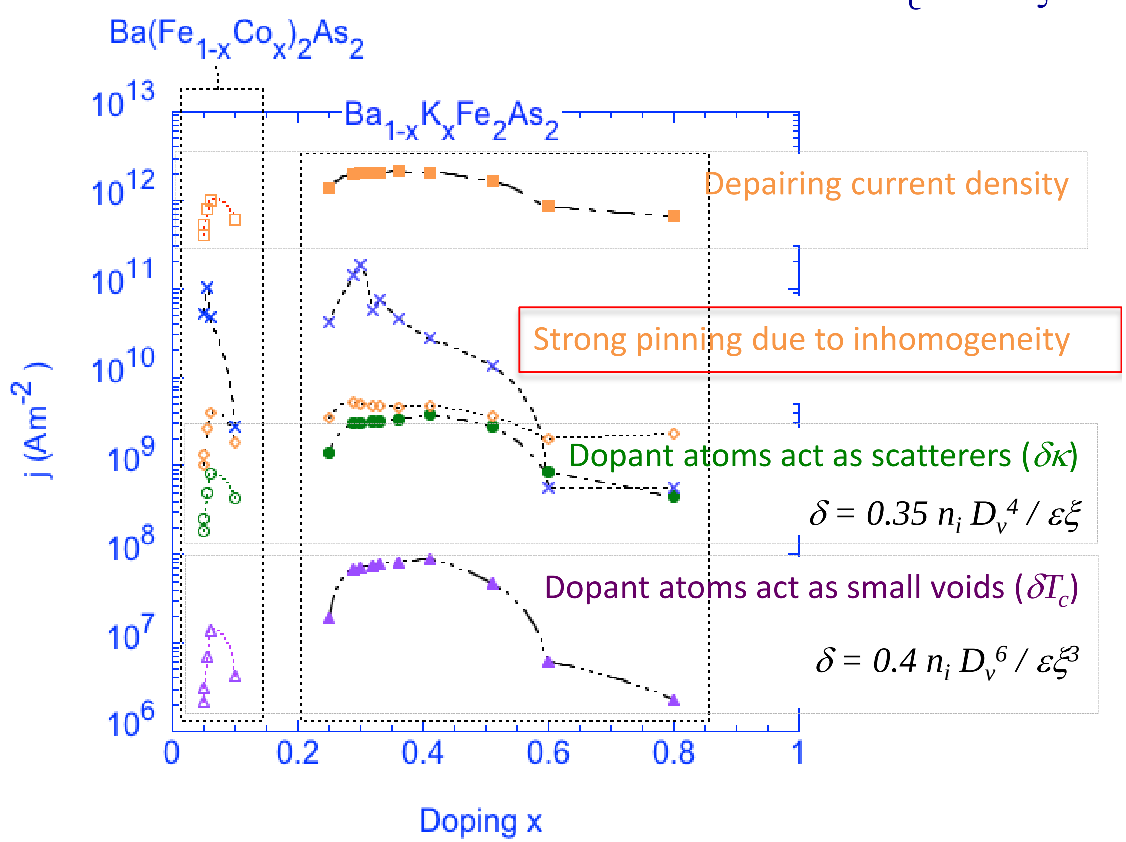
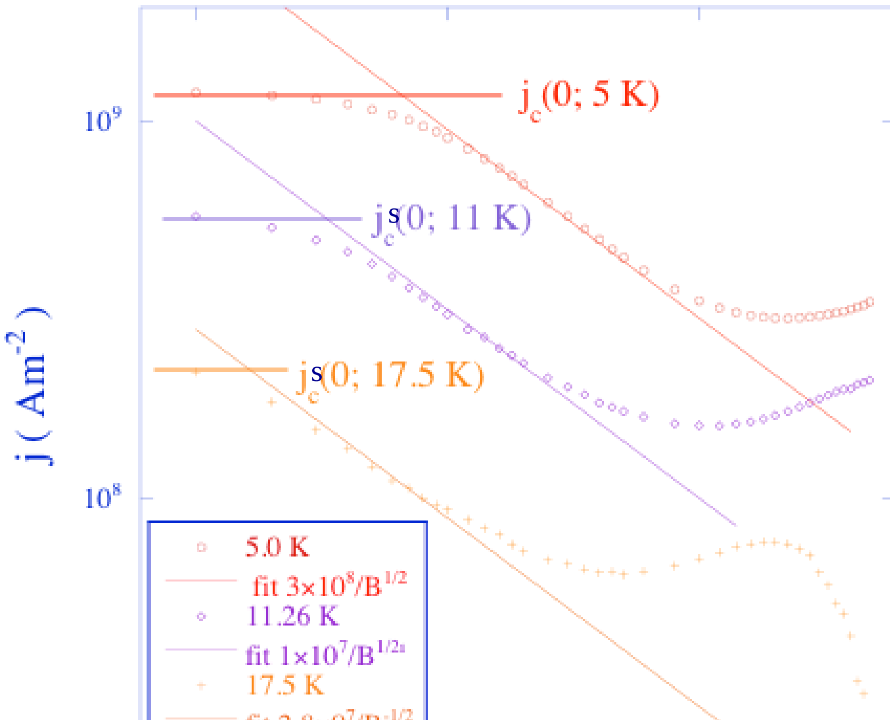


$j_c = j_c(0)\, f(b)\, g(t)$

example of $Ba(Fe_{0.93}Co_{0.07})_2As_2$…

$t = T / T_c$
$b = B / B_{c2}(T)$

Zero temperature, zero-field j_c : pinning mechanism, statistics



S. Demirdis et al., PRB **84**, 094517 (2011)

Field dependence :

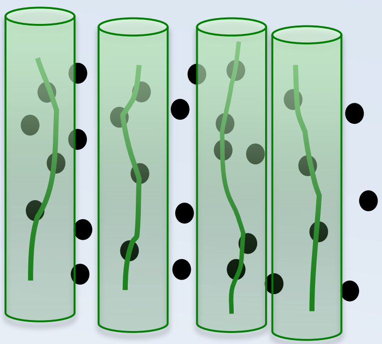
- Statistics of pinning
- change in vortex lattice structure
- change in vortex structure

Temperature dependence:

- thermal activation of quasiparticles: $\lambda(T)$
- decrease of the order parameter: $\xi(T)$
- multiple band effects
- thermal activation of vortices
- thermal smearing of the pin potential

Field dependence of the critical current density: statistics of pinning

Strong pinning $n_i << \xi^{-3}$



- F_p from direct sum $\Sigma_i f_{p,I}$
- # pins / vortex limited by vortex elasticity:
- Low B : ε_1 of individual vortex, $j_c \neq j_c(B)$
- High B : interaction with other vortices, $j_c \propto B^{-1/2}$

$$j_c^s(0) = \frac{f_p}{\sqrt{\pi}\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)^{1/2} \qquad (B < B^*)$$

$$j_c^s(B) = \frac{f_p}{\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)\left(\frac{\Phi_0}{B}\right)^{1/2} \qquad (B > B^*)$$

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Field dependence of the critical current density : statistics of pinning

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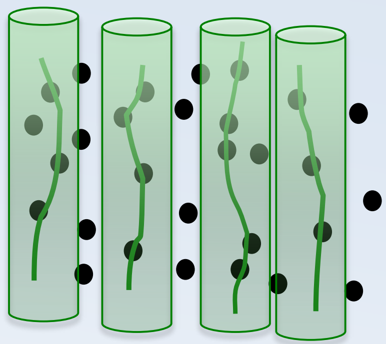

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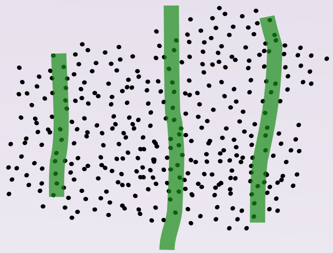
Weak ``collective'' pinning

$n_i >> \xi^{-3}$



A.I. Larkin, Yu. Ovchinnikov, JETP **31**, 784 (1970); JLTP **34**, 409 (1979).

G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

- $F_p = (n_i \langle f_p^2 \rangle / V_c)^{1/2}$ ~ 2nd moment of f_p
- correlation volume $V_c = R_c^2 L_c$:
- Low B: ε_1 of individual vortex

$V_c = L_c a_0^2$ $\quad j_c = j_0 \varepsilon^{-1} \delta^{2/3} \quad \neq j_c(B)$

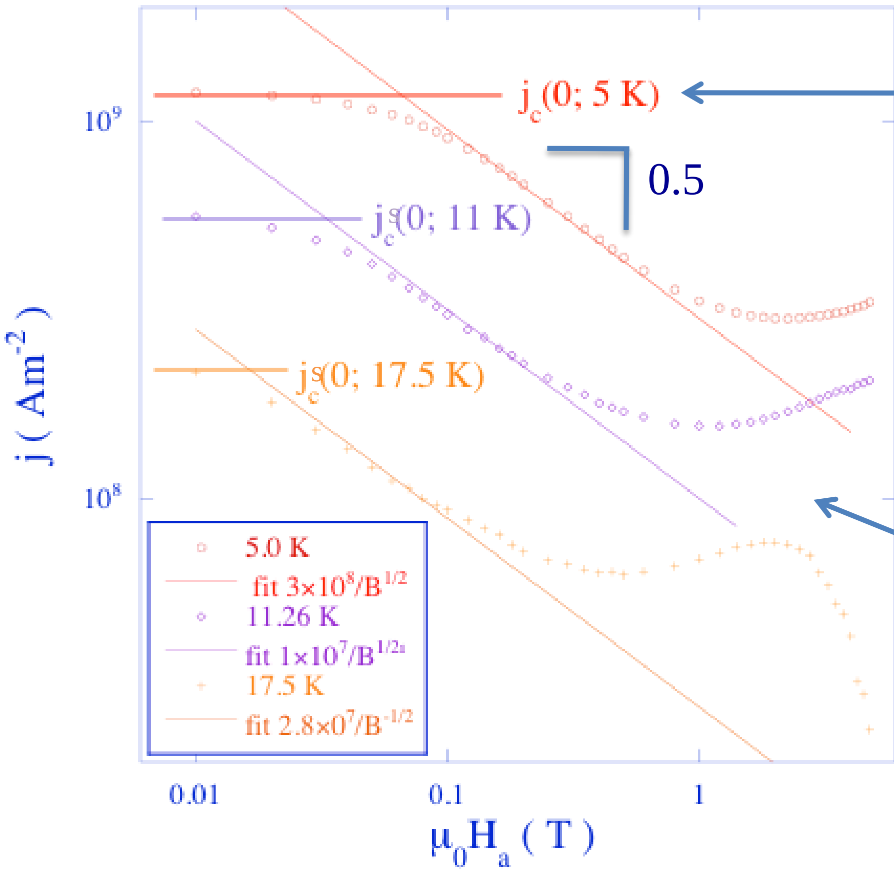
- $B > B_{sv} = 4\pi B_{c2}(j_c/j_0)$:

interaction with other vortices, $V_c = L_c R_c^2$

$$R_c = \left(\frac{\varepsilon_0 \xi}{2\Phi_0 j_c}\right)^{1/2} \qquad j_c \sim e^{-B/B_0}$$

J_c of iron-based superconductors *example of $Ba(Fe_{0.93}Co_{0.07})_2As_2$…*

$Ba(Fe_{0.925}Co_{0.075})_2As_2$ crystal #2.1
Critical current density vs applied magnetic field



S. Demirdis et al., PRB **84**, 094517 (2011)

Low B

Strong pinning by nm-scale sparse defects

$$j_c(0) = \frac{f_p}{\sqrt{\pi}\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)^{1/2} \quad (B < B^*)$$

$$j_c(B) = \frac{f_p}{\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)\left(\frac{\Phi_0}{B}\right)^{1/2} \quad (B > B^*)$$

Larger B

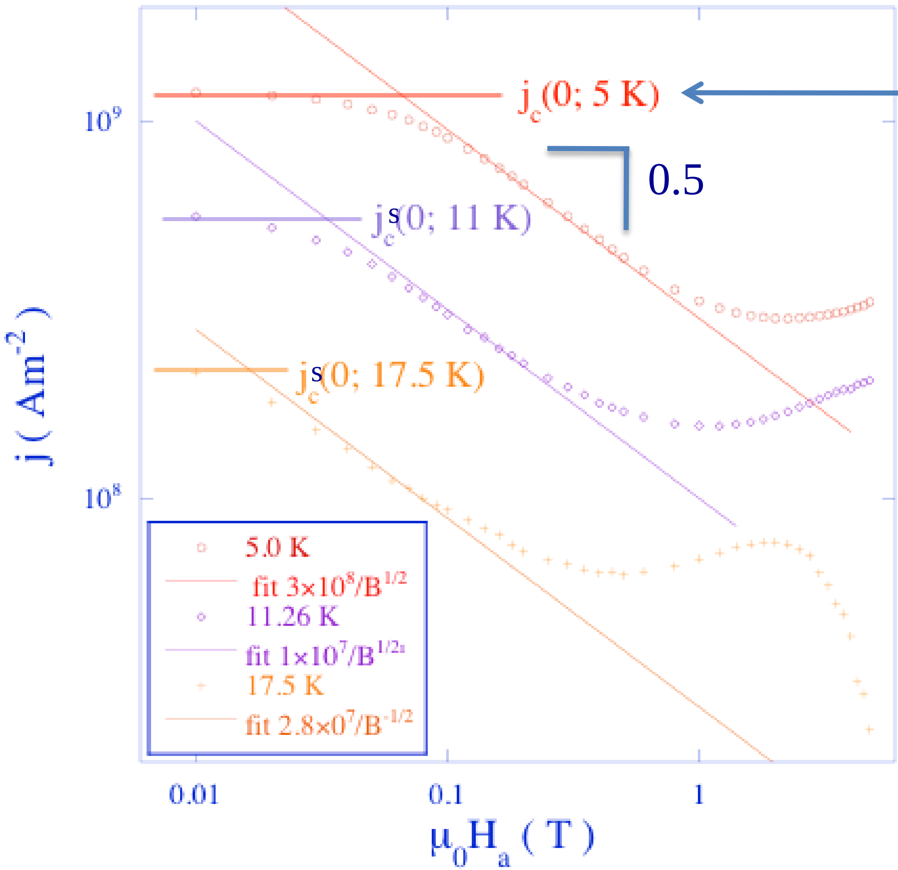
Weak collective pinning by dense,
atomic sized point-like impurities

$$j_c^{SV} = \frac{1}{\Phi_0}\left(\frac{n_i f_p^2}{\varepsilon_1}\right)^{2/3}\xi$$

Origin of strong pinning: the case for heterogeneity

Origin of strong pinning: the case for heterogeneity

$Ba(Fe_{0.925}Co_{0.075})_2As_2$ crystal #2.1
Critical current density vs applied magnetic field



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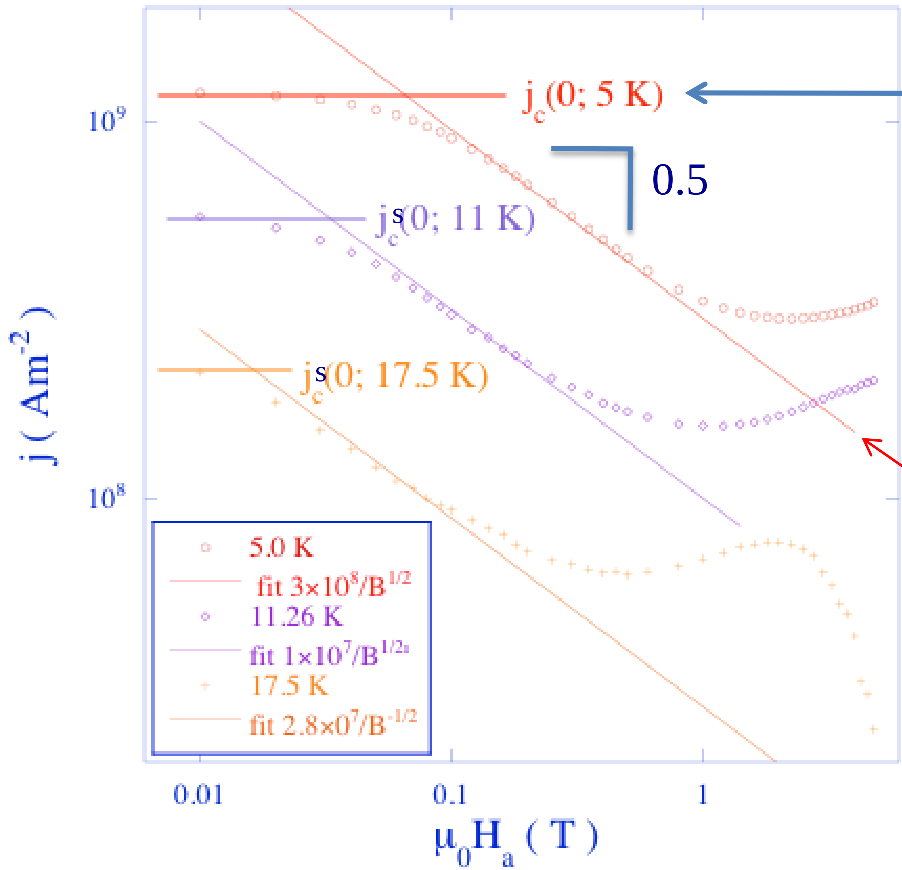

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Elementary pinning force of a single pin

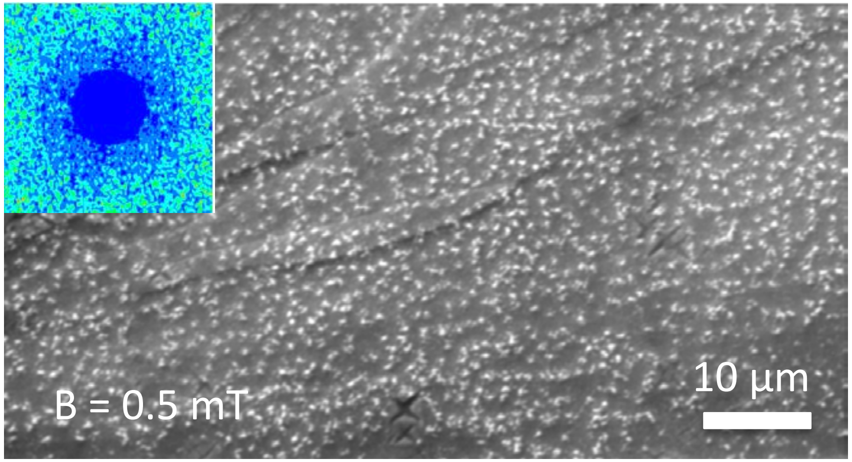
$$f_p \approx \pi\Phi_0^{3/2}\varepsilon\left[\frac{j_c^2(0)}{dj_c(B)/dB^{-1/2}}\right]$$

$$j_c(B) = \frac{f_p}{\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)\left(\frac{\Phi_0}{B}\right)^{1/2}$$

$f_p \sim 3\times10^{-13}$ N

$$\overline{\mathcal{L}} = \frac{f_{p,i}^{max}}{\Phi_0 j_c} = 100 \text{ nm}$$

Origin of strong pinning: the case for heterogeneity



Bitter decoration of single crystal $Ba(Fe_{0.9}Co_{0.1})_2As_2$
S. Demirdis et al., PRB 84, 094517 (2011)

Cf Eskildsen *et al.* (BD,SANS); Vinikov et al. (BD);
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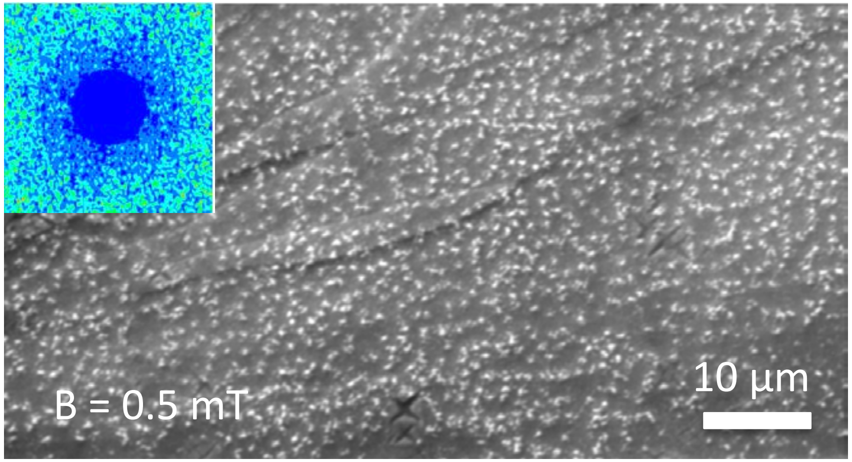

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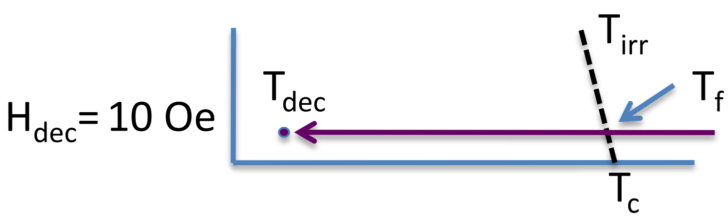

Vortex ensemble arrested at $T \sim 0.9\ T_c$

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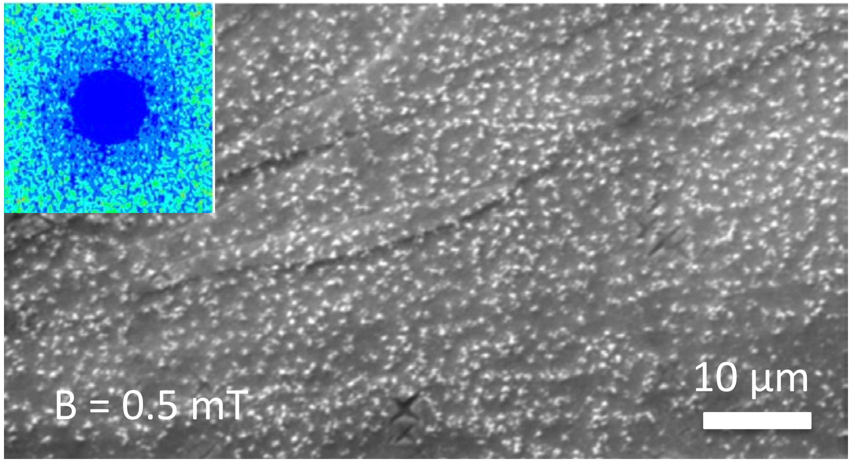

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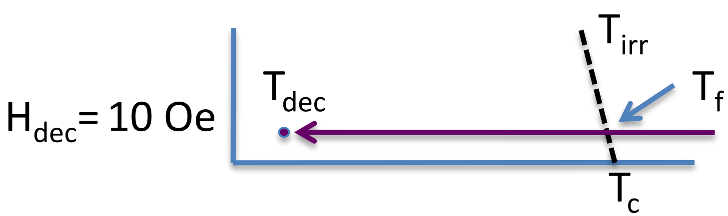
S. Demirdis et al., PRB 84, 094517 (2011)

$$\mathcal{E}^{i}_{int} = \sum_j \frac{\Phi_0^2}{2\pi\mu_0\lambda_{ab}^2} K_0\left(\frac{|r_{ij}|}{\lambda_{ab}}\right) = \sum_j 2\varepsilon_0 K_0\left(\frac{|r_{ij}|}{\lambda_{ab}}\right)$$



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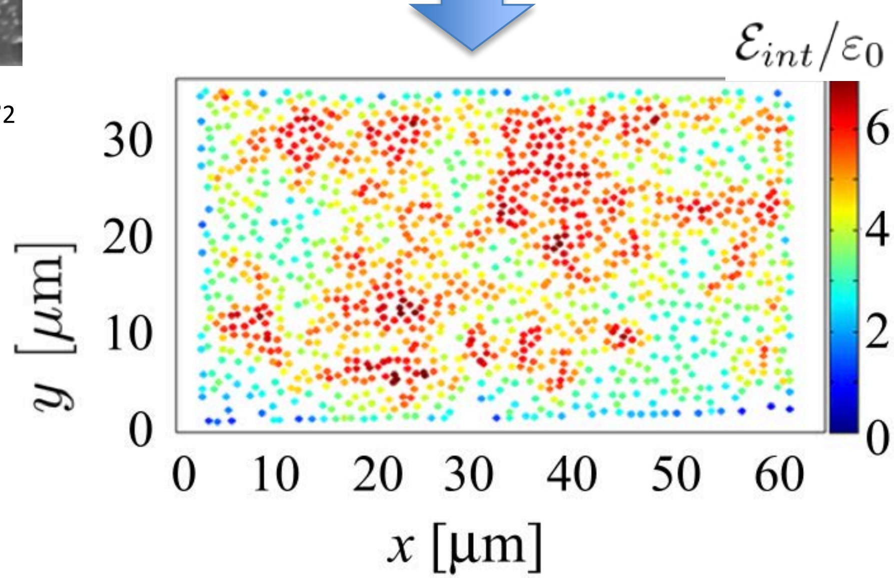

Vortex energies in single crystal $Ba(Fe_{0.9}Co_{0.1})_2As_2$

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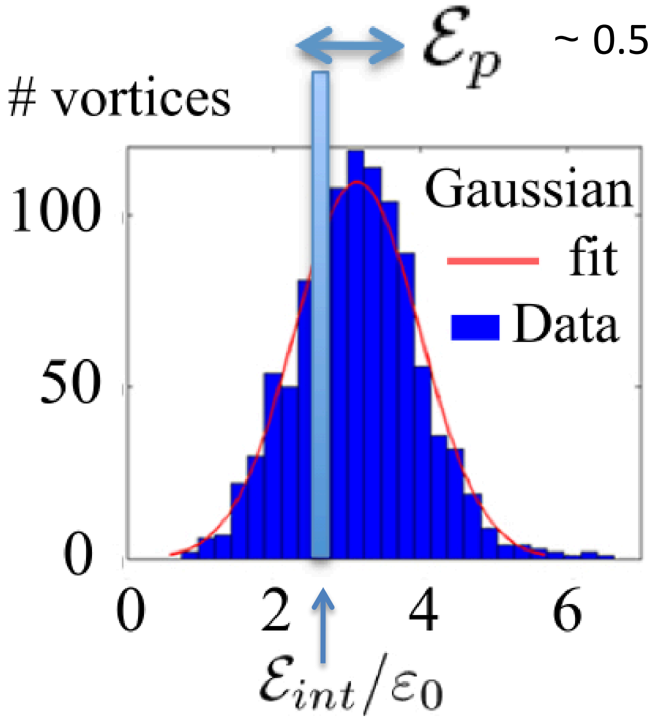
Origin of strong pinning: the case for heterogeneity

Vortex energies in single crystal $Ba(Fe_{0.9}Co_{0.1})_2As_2$

$\mathcal{E}_p$ ~ 0.5 ε_0! Half the vortex line energy!



Interaction energy in the triangular Abrikosov vortex lattice

S. Demirdis et al., PRB **84**, 094517 (2011)

Origin of strong pinning: the case for heterogeneity

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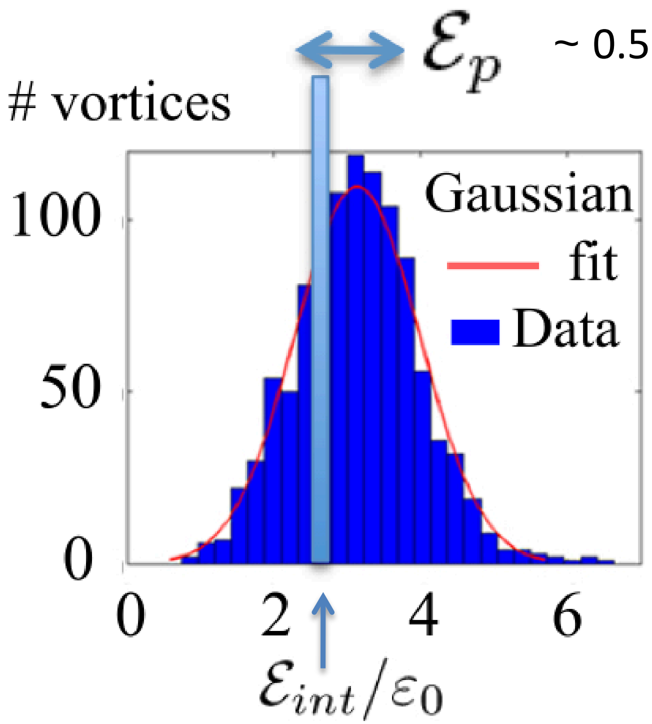

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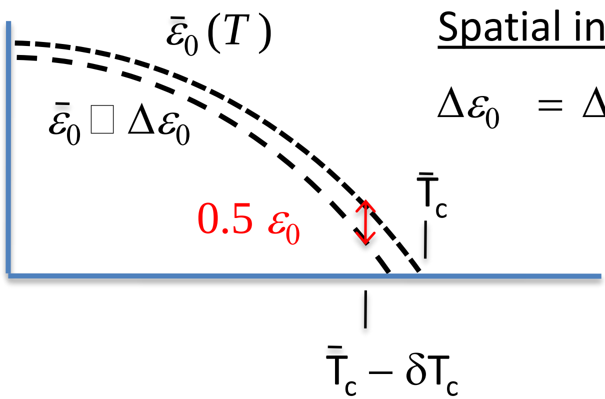


Spatial inhomogeneity

$\Delta\varepsilon_0 = \Delta[\varepsilon_0(r,0)(1-T_f/T_c)]$

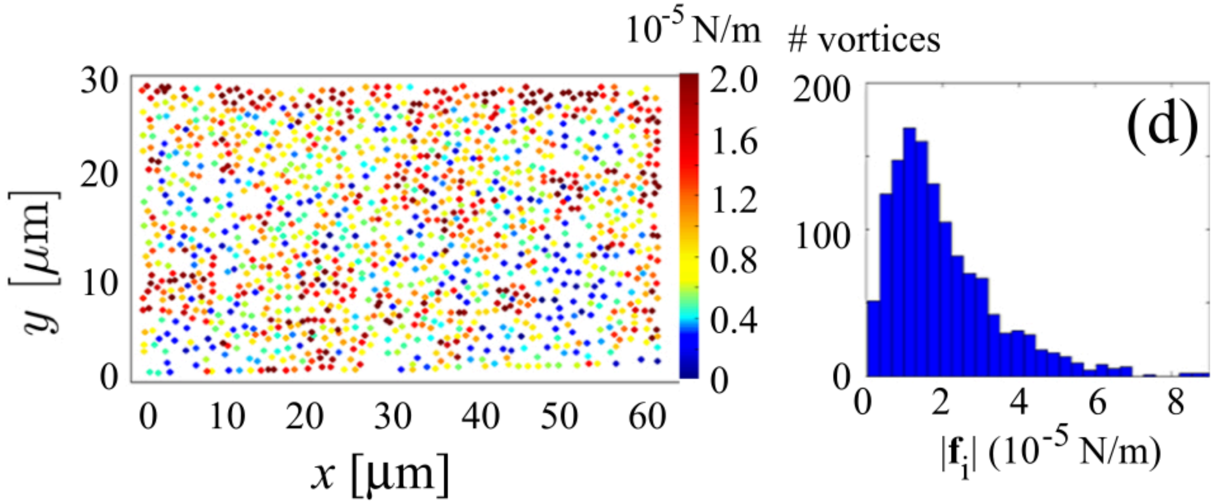
- Near T_c : $\Delta\varepsilon_0$ determined by ΔT_c

- Vortex ensemble arrested at $T \sim 0.95\ T_c$
- Consistent with spread of T_c in the crystal

S. Demirdis et al., PRB **84**, 094517 (2011)

Origin of strong pinning: the case for heterogeneity

Vortex pinning forces in single crystal $Ba(Fe_{0.9}Co_{0.1})_2As_2$



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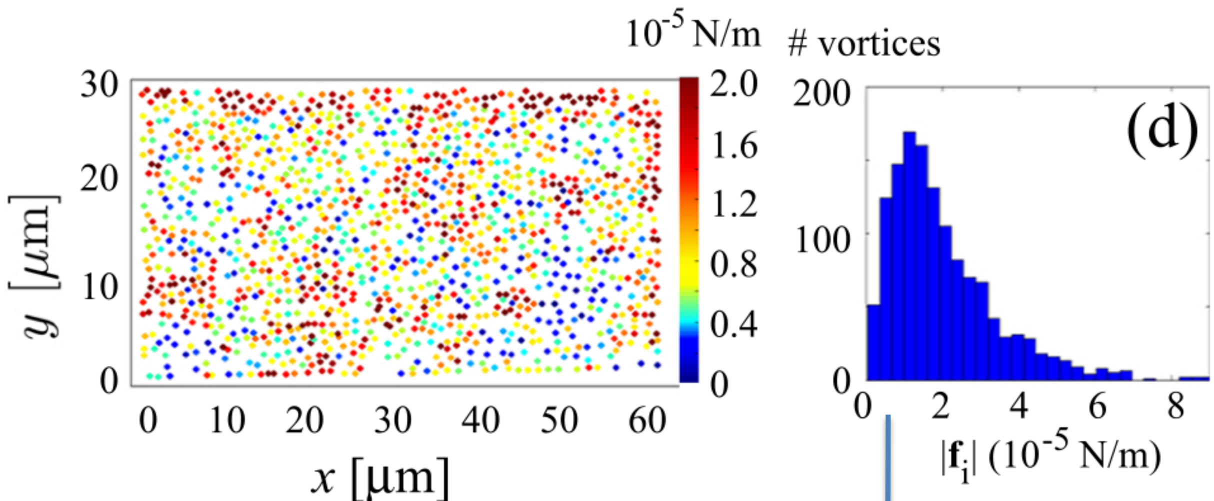


$|\mathbf{f}_i| \sim 5 - 10 \times 10^{-6}$ N/m Average Pinning force per vortex

$f_p \sim 3 \times 10^{-13}$ N Pinning force of a single pin

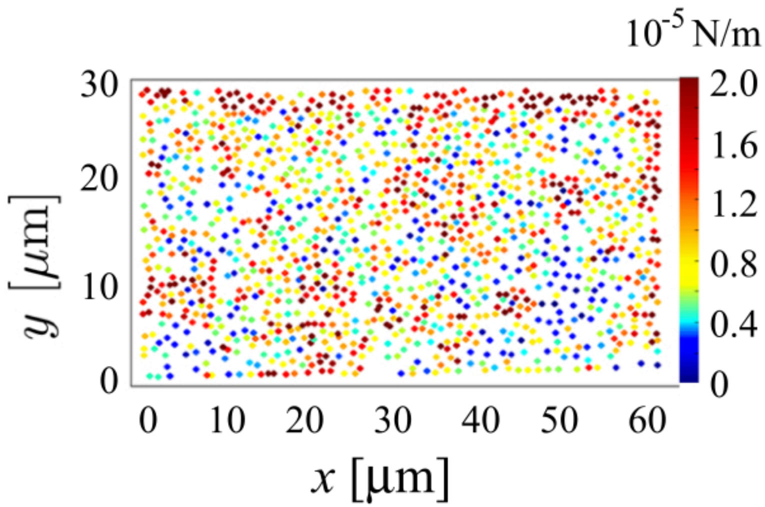
Distance between 2 pins ~ 30 - 60 nm | nm-scale disorder

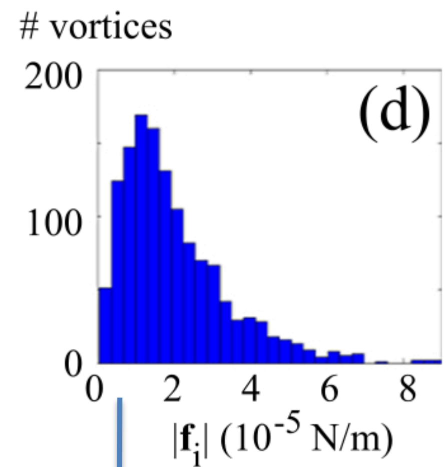
$$j_c(0) = \frac{f_p}{\sqrt{\pi}\Phi_0 \varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)^{1/2}$$

a few × 10^9 Am^{-2} @ B = 0

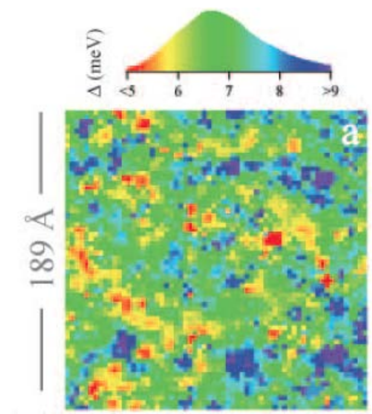
Origin of strong pinning: the case for heterogeneity

Vortex pinning forces in single crystal $Ba(Fe_{0.9}Co_{0.1})_2As_2$

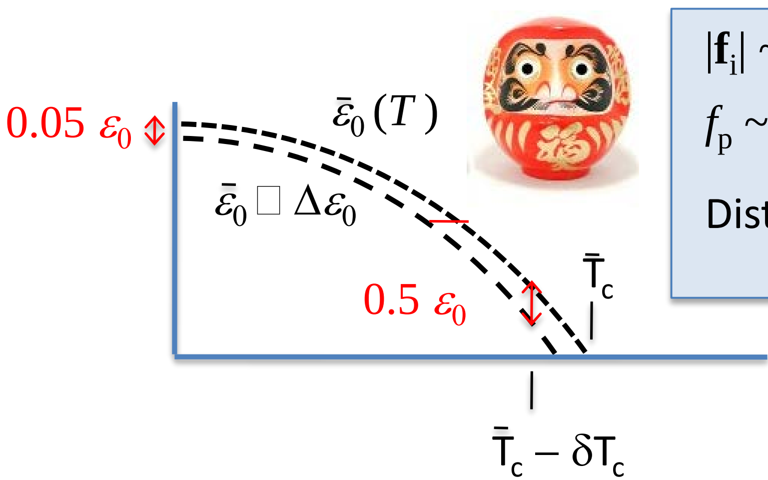




Gap maps



F. Massee et al., Phys. Rev. B **79**, 220517 (2009)



$|\mathbf{f}_i| \sim 5 - 10 \times 10^{-6}$ N/m Average Pinning force per vortex

$f_p \sim 3\times 10^{-13}$ N Pinning force of a single pin

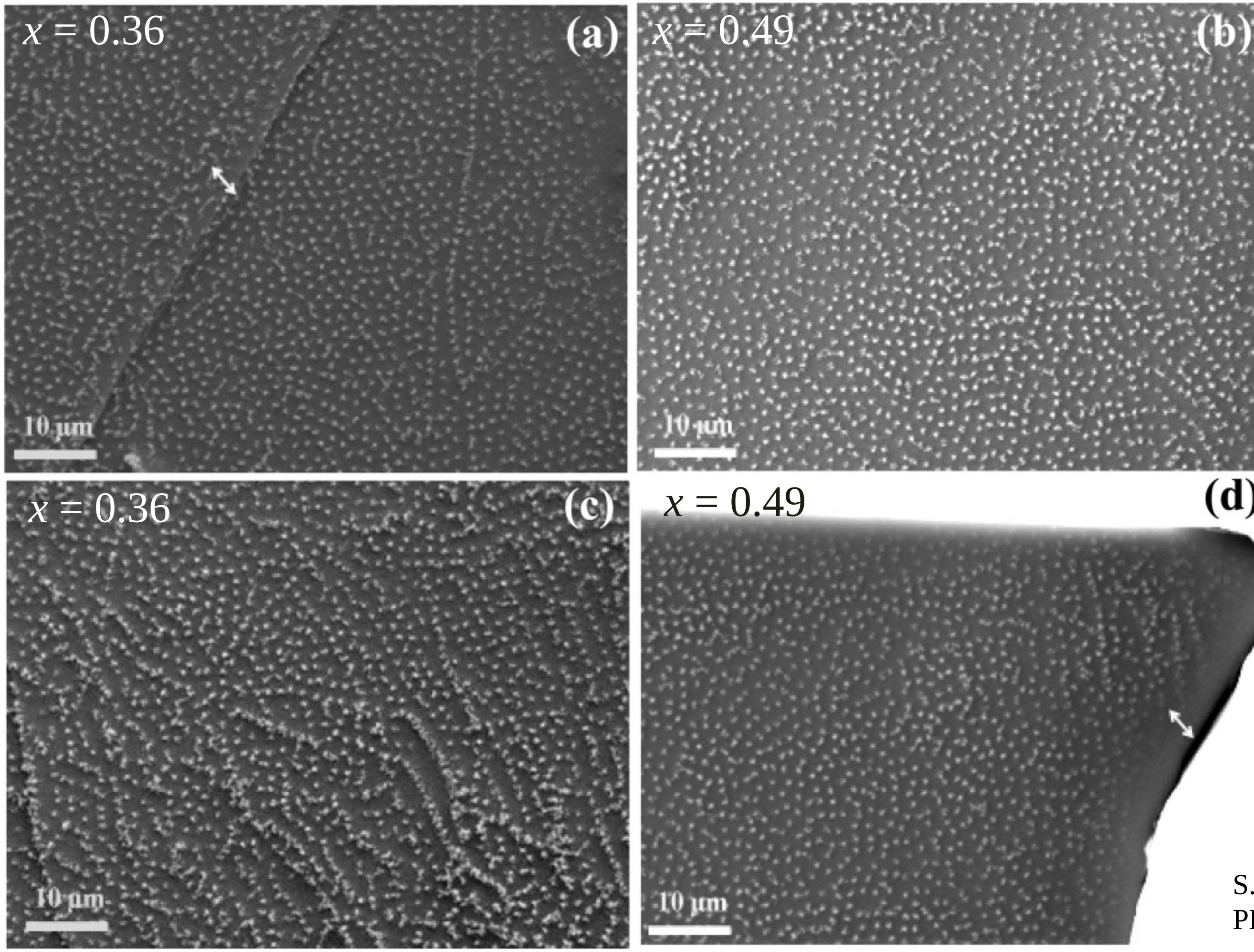
Distance between 2 pins ~ 30 - 60 nm | nm-scale disorder

$$j_c(0) = \frac{f_p}{\sqrt{\pi}\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)^{1/2}$$

a few × 10^9 Am^{-2} @ B = 0

Origin of strong pinning: the case for heterogeneity

Vortices in single crystal $BaFe_2(As_{1-x}P_x)_2$

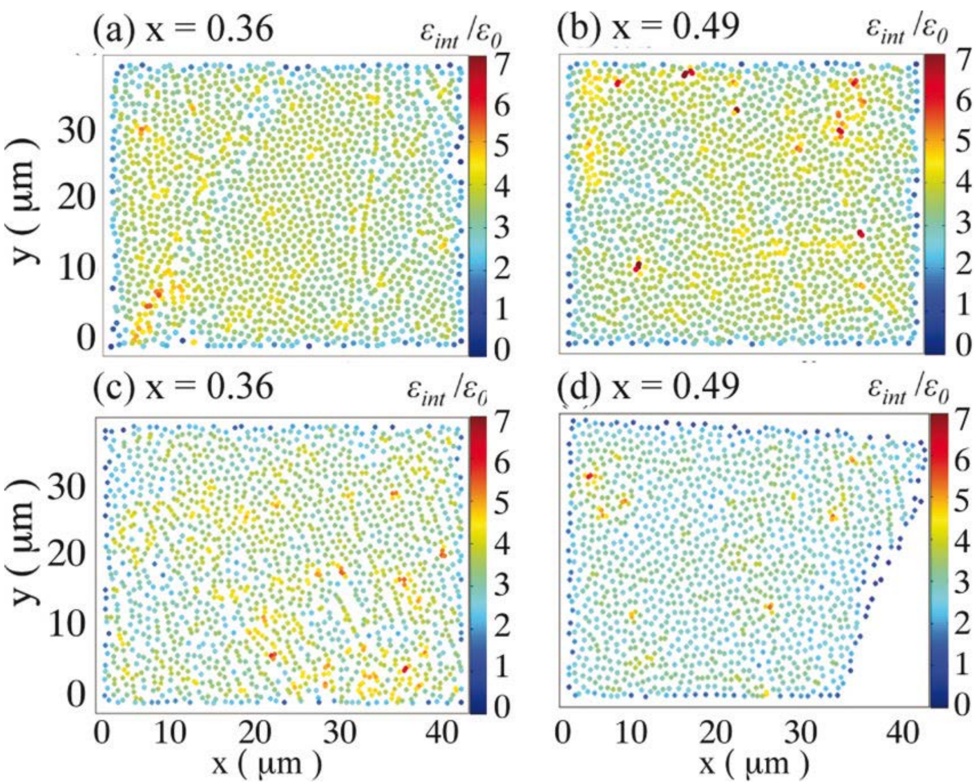


$T = 4.27$ K
$\mu_0 H = 2$ mT

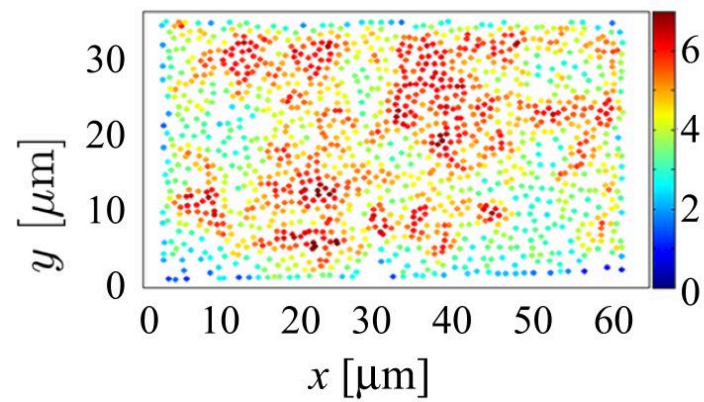
S. Demirdis et al.,
PRB **87**, 087506 (2013)

Origin of strong pinning: the case for heterogeneity

Vortex energies in single crystal $BaFe_2(As_{1-x}P_x)_2$



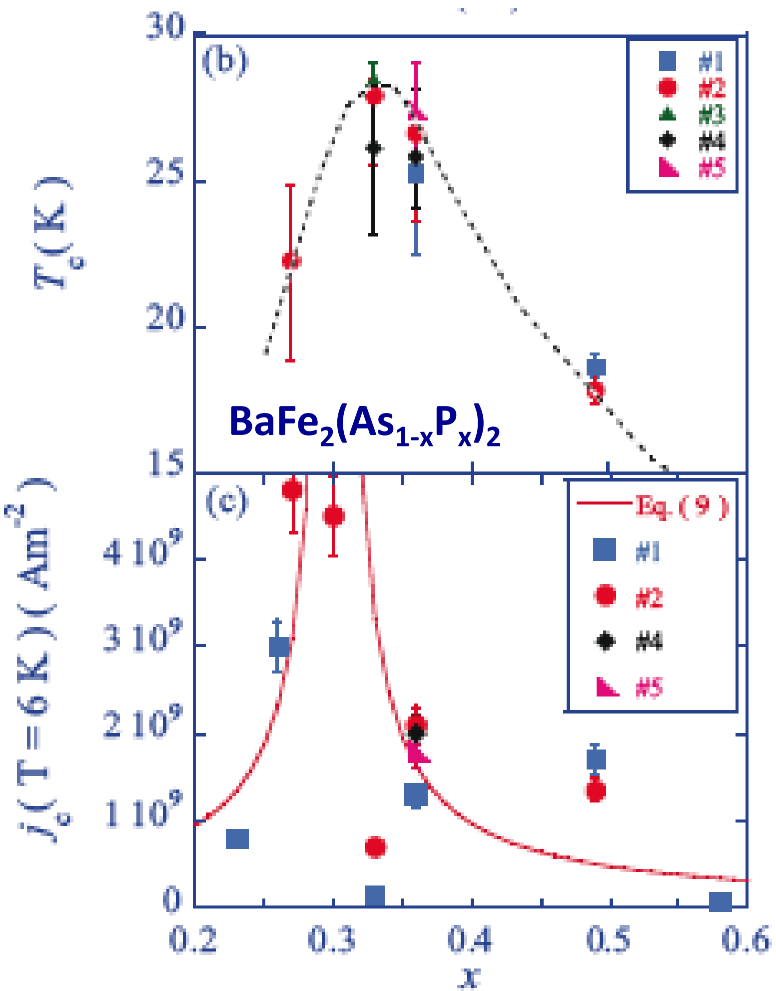
S. Demirdis et al.,
PRB **87**, 087506 (2013)



Vortex energies in $Ba(Fe_{0.9}Co_{0.1})_2As_2$

S. Demirdis et al., PRB **84**, 094517 (2011)

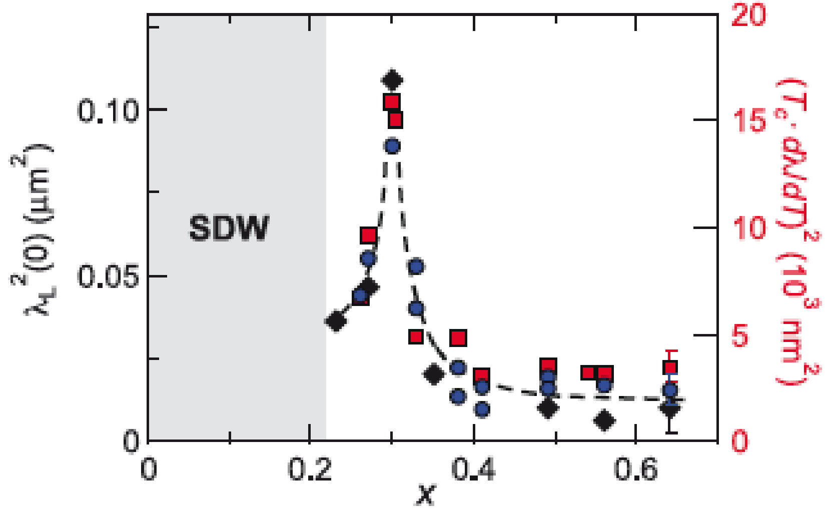
Origin of strong pinning: the case for heterogeneity



S. Demirdis et al., PRB **87**, 087506 (2013)

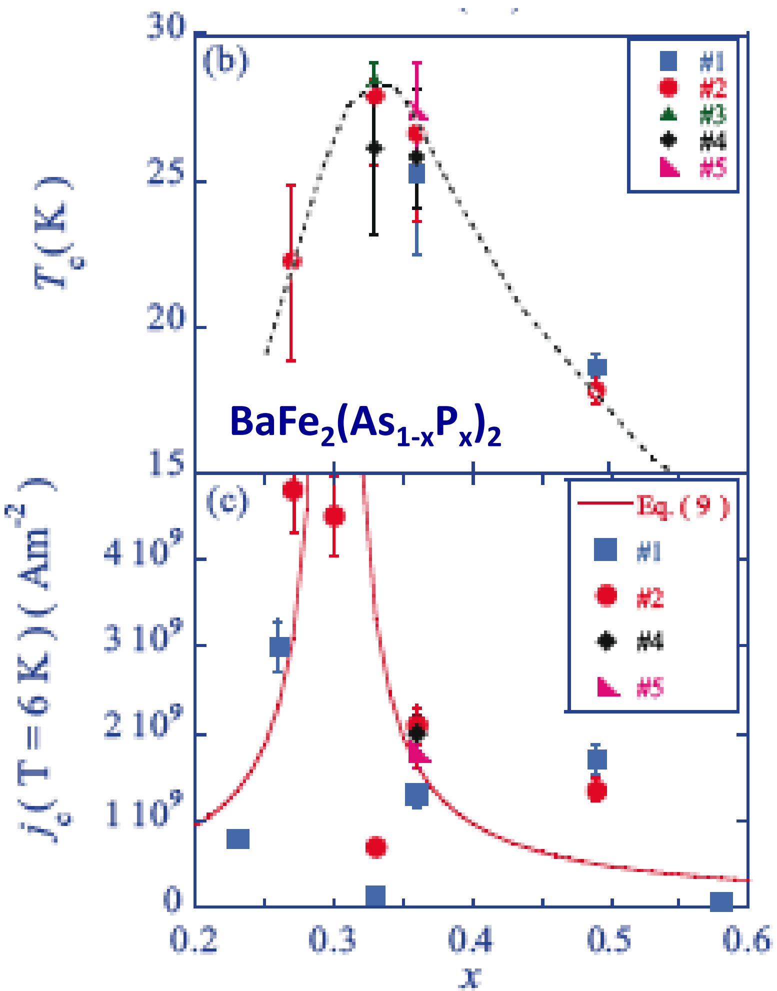
$$\langle f_p \rangle \sim \Delta\varepsilon_0 \sim \frac{\partial \varepsilon_0}{\partial \lambda_{ab}} \frac{\partial \lambda_{ab}}{\partial x} \Delta x$$

$$j_c(0) = \frac{f_p}{\Phi_0 \overline{\mathcal{L}}} = \pi^{1/2} \frac{f_p}{\Phi_0 \varepsilon_\lambda} \left(\frac{U_p n_i}{\varepsilon_0} \right)^{1/2}$$



K. Hashimoto et al., Science **336**, 1554 (2012)

Origin of strong pinning: the case for heterogeneity

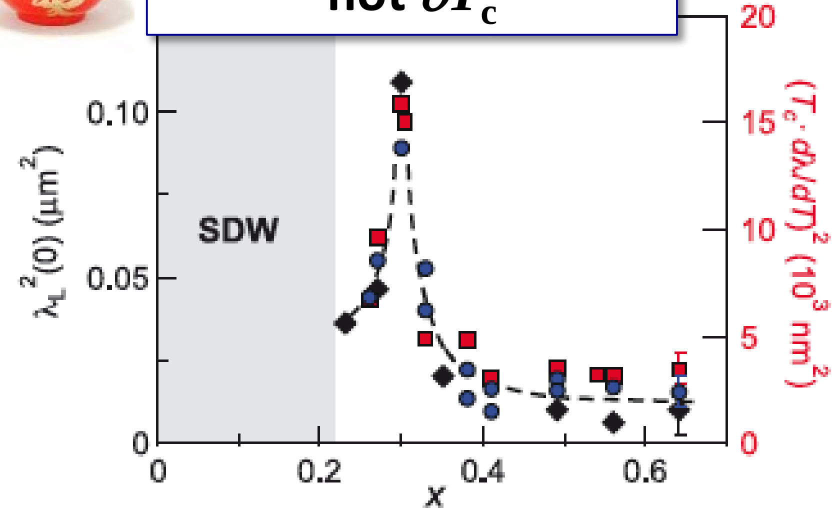


S. Demirdis et al., PRB **87**, 087506 (2013)

$$\langle f_p \rangle \sim \Delta\varepsilon_0 \sim \frac{\partial \varepsilon_0}{\partial \lambda_{ab}} \frac{\partial \lambda_{ab}}{\partial x} \Delta x$$

$$j_c(0) = \frac{\overline{f_p}}{\Phi_0 \overline{\mathcal{L}}} = \pi^{1/2} \frac{f_p}{\Phi_0 \varepsilon_\lambda} \left(\frac{U_p n_i}{\varepsilon_0} \right)^{1/2}$$

$\delta\lambda$ – pinning,
not δT_c

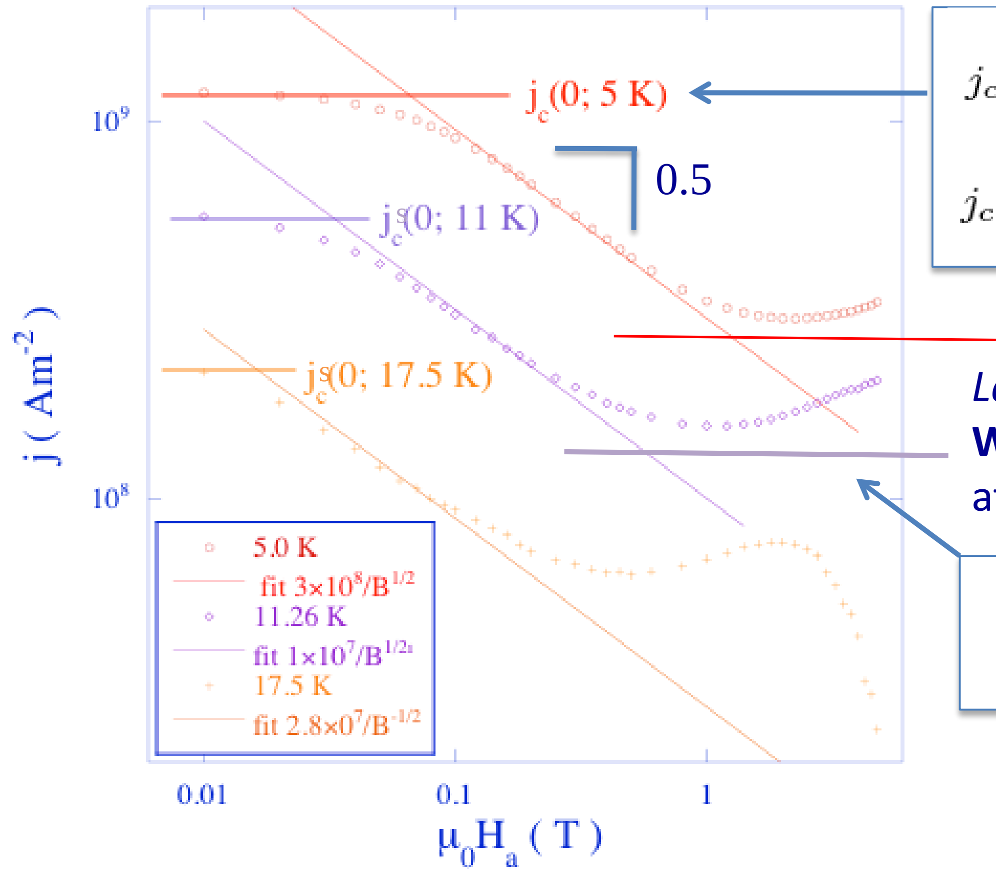


K. Hashimoto et al., Science **336**, 1554 (2012)

Origin of weak collective pinning: the case for quasiparticle scattering

Origin of weak collective pinning: the case for quasiparticle scattering

$Ba(Fe_{0.925}Co_{0.075})_2As_2$ crystal #2.1
Critical current density vs applied magnetic field



Low B

Strong pinning by nm-scale sparse defects

$$j_c(0) = \frac{f_p}{\sqrt{\pi}\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)^{1/2} \qquad (B < B^*)$$

$$j_c(B) = \frac{f_p}{\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)\left(\frac{\Phi_0}{B}\right)^{1/2} \qquad (B > B^*)$$

Larger B

Weak collective pinning by dense, atomic sized point-like impurities

$$j_c = j_0\varepsilon^{-1}\delta^{2/3} = \frac{1}{\Phi_0}\left(\frac{n_i f_p^2}{\varepsilon_1}\right)^{2/3}\xi$$

C.J. van der Beek et al., PRL **105**, 267002 (2010); PRB **81**, 174517 (2010).

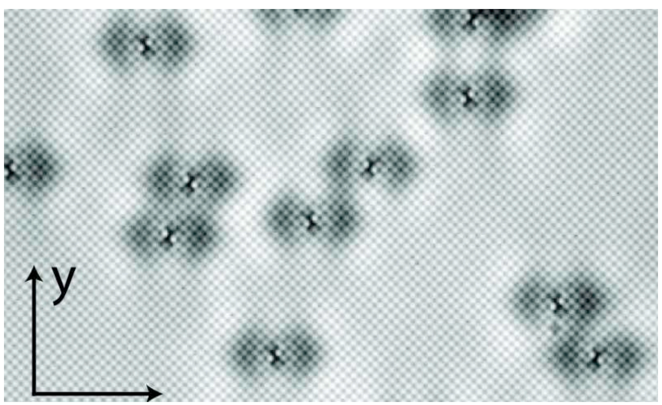
Origin of weak collective pinning: the case for quasiparticle scattering

$$j_c = j_0 \, \varepsilon^{-1} \delta^{2/3}$$

- Charged dopant atoms explain the weak pinning contribution to j_c
- If they are assumed to be responsible for quasiparticle scattering

$$\delta = 0.35 \, n_i \, D_v^4 / \varepsilon\xi \quad = \quad 0.35 \, n_i \, \sigma_{tr}^2 / \pi^2 \varepsilon\xi$$

$$\sigma_{tr} = \frac{4\pi^2}{k_F^2} \sin^2 \delta_0 \sim \pi D_v^2$$



P.O. Sprau et al., Science **357**, 75-80 (2017)

$$l = (n_i \, \sigma_{tr})^{-1}$$

Quasiparticle mean free path

- magnitude ✔
- doping dependence ✔

Origin of weak collective pinning: the case for quasiparticle scattering

Material	impurity	n_d (nm^{-3})	D_v (Å)	sin $\square_0$ = $2^{-1/2} k_F D_v$
$PrFeAsO_{0.9}$	(vacancy)	1.5	1.46	0.3(2)
$NdFeAsO_{0.9}F_{0.1}$	(F)	1.5	0.9	0.2
$Ba(Fe_{0.955}Ni_{0.45})_2As_2$	(Ni)	0.9	0.8	0.17
$Ba(Fe_{0.925}Co_{0.75})_2As_2$	(Co)	1.5	0.6	0.13
$Ba(Fe_{0.9}Co_{0.1})_2As_2$	(Co)	2	0.6	0.13
$Ba(Fe_{0.76}Ru_{0.24})_2As_2$	(Fe vacancy)	-	0.8	0.16
$Ba_{0.72}K_{0.28}Fe_2As_2$	(K)	2.8	0.7	0.1(4)
$Ba_{0.6}K_{0.4}Fe_2As_2$	(K)	4	0.8	0.2
$Ba_{0.45}K_{0.55}Fe_2As_2$	(K)	5.5	0.7	0.2

$k_F \sim 0.3$ Å^{-1}

$$\sigma_{tr} = \frac{4\pi^2}{k_F^2} \sin^2 \delta_0 \sim \pi D_v^2$$

$$l = (n_i \sigma_{tr})^{-1}$$

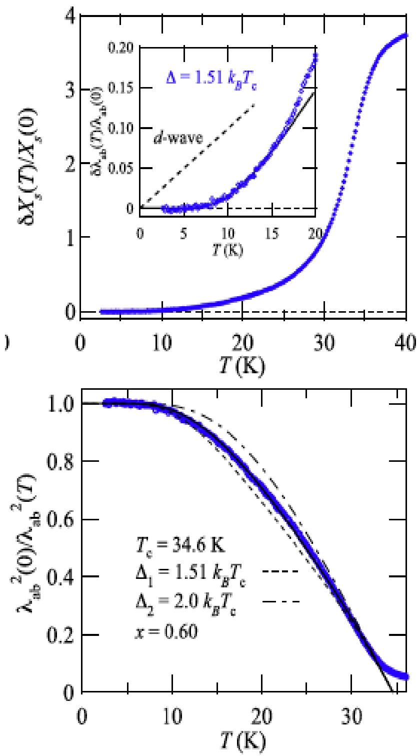
Quasiparticle mean free path

C.J. van der Beek et al., PRL **105**, 267002 (2010); PRB **81**, 174517 (2010).

- The same scattering determines the low temperature $\lambda(T)$

Correlation between vortex pinning and λ(T)

Electron doped $PrFeAsO_{1-y}$

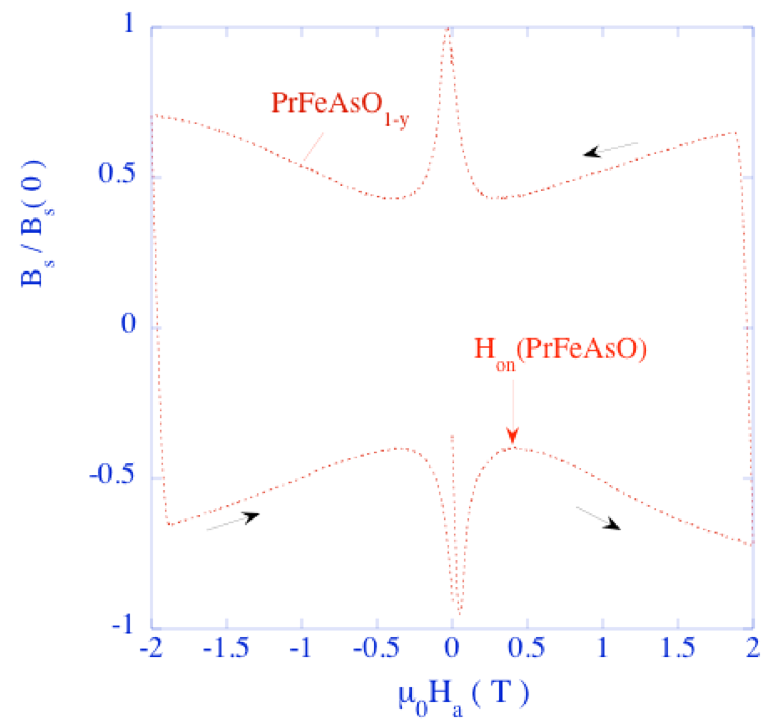


$\delta\lambda/\lambda \sim \sqrt{\pi\Delta/2k_BT}\, e^{-\Delta/k_BT}$
$\sim T^2$

K. Hashimoto et al., PRL **102**, 171002 (2009);

R. Gordon et al., PRB **79**, 100506 (2009).

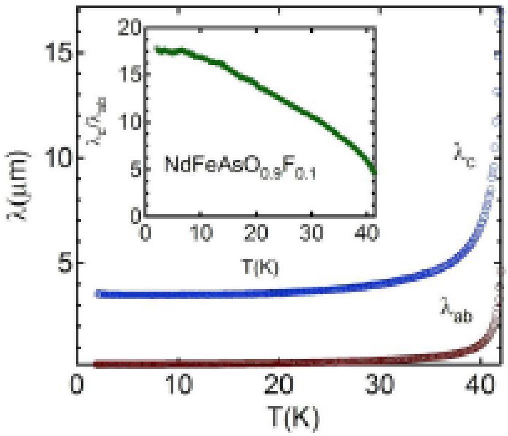
- Vortex pinning in the mixed state
- Critical current density j_c

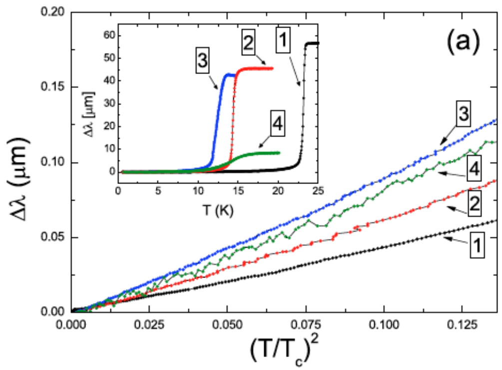


Correlation between vortex pinning and λ(T)

Electron doped $NdFeAsO_{1-x}F_x$

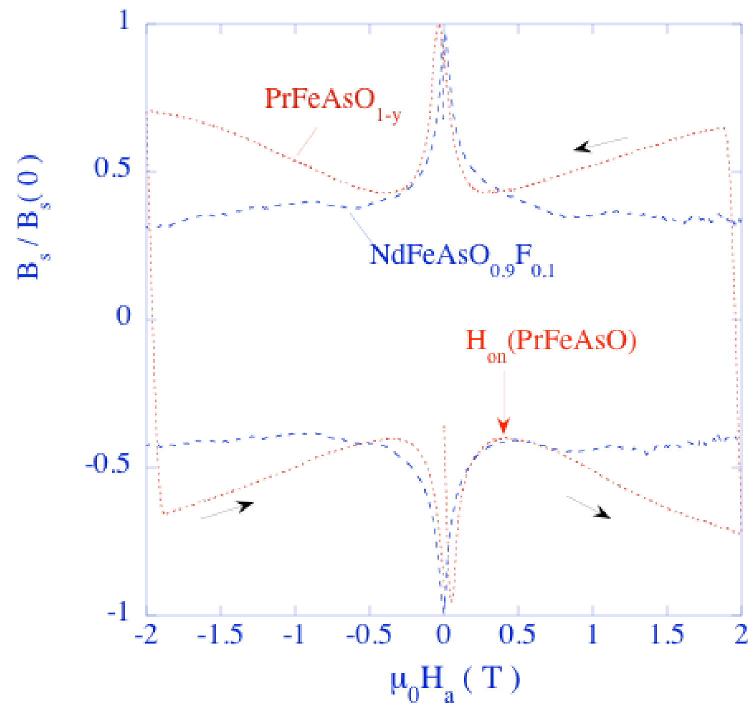
$\delta\lambda/\lambda \sim T^2$





R. T. Gordon, H. Kim, M. A. Tanatar, R. Prozorov, and V. G. Kogan, Phys. Rev. B **81**, 180501 (2010)

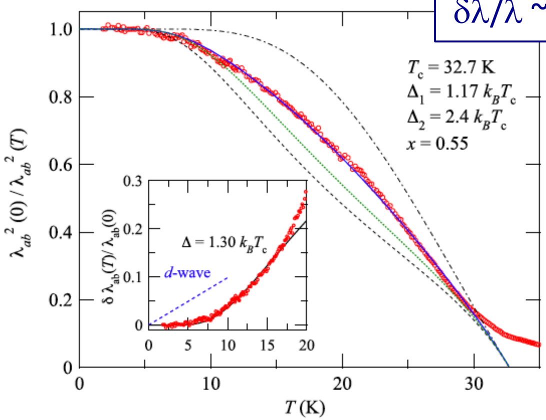
- Vortex pinning in the mixed state
- Critical current density j_c



Correlation between vortex pinning and λ(T)

Hole doped $Ba_{0.45}K_{0.55}Fe_2As_2$

$\delta\lambda/\lambda \sim \sqrt{\pi\Delta/2k_BT}\, e^{-\Delta/k_BT}$



K. Hashimoto et al., Phys. Rev. Lett. **102**, 207001 (2009).

- Vortex pinning in the mixed state
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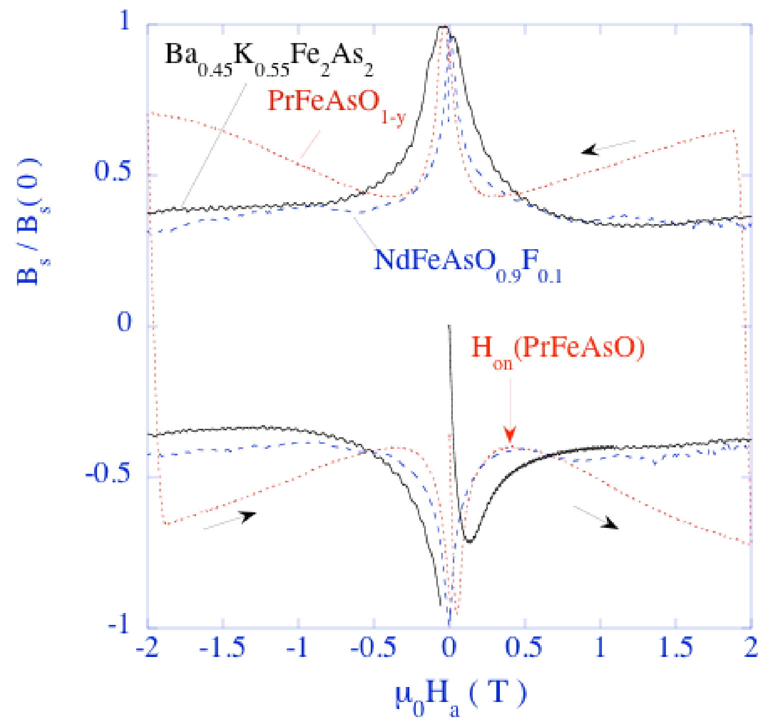

Correlation between vortex pinning and λ(T)

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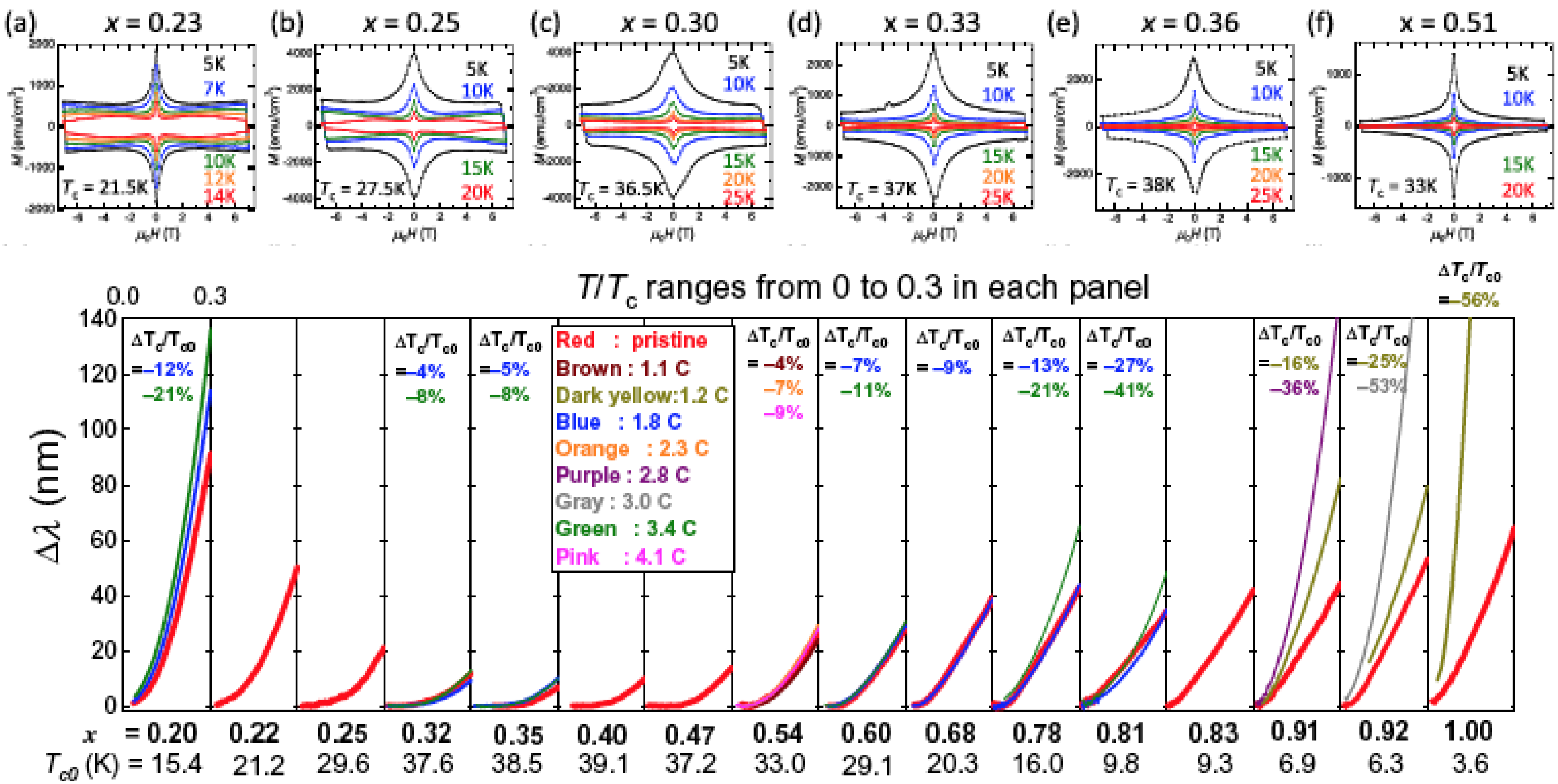
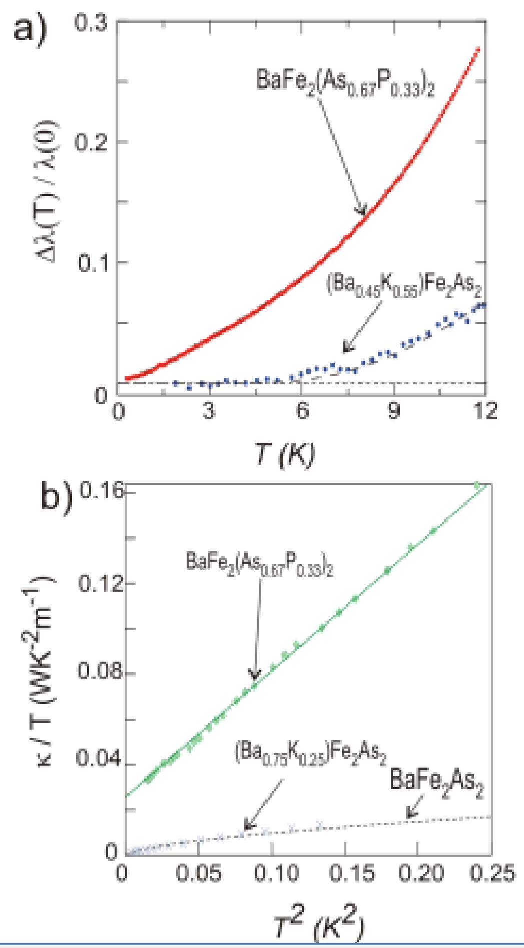
Shigeyuki Ishida et al., Phys. Rev. **B** 95, 014517 (2017)



Kyuil Cho et al., Scientific Advances 2e:160807 (2016)

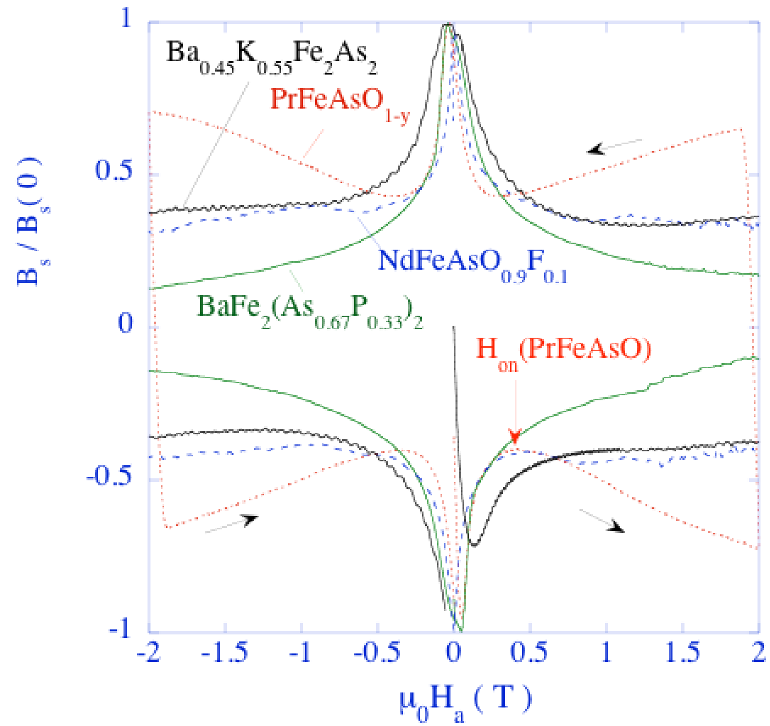
Correlation between vortex pinning and λ(T)

Isovalently substituted $BaFe_2(As_{1-x}P_x)_2$

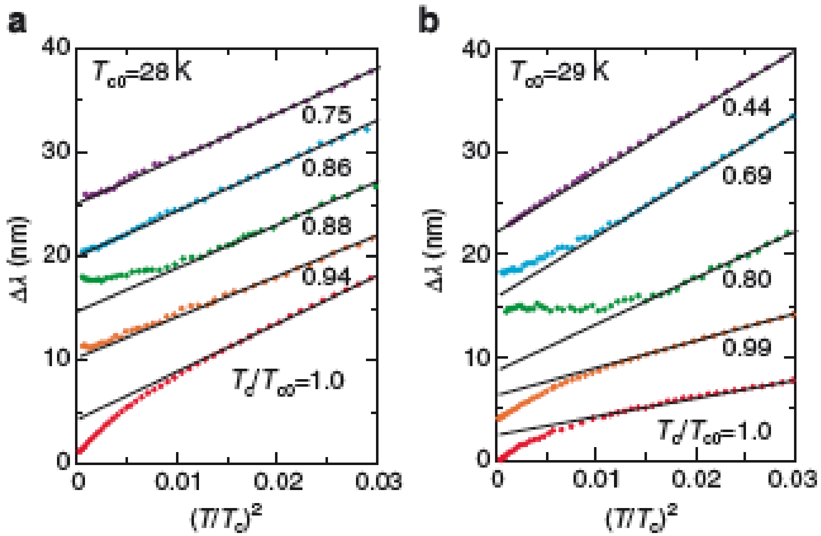


Shigeru Kasahara, Phys. Rev. B **81,** 220501R (2010)

- Vortex pinning in the mixed state
- Critical current density j_c



Low T Electron irradiation of isovalently substituted $BaFe_2 (As_{1-x}P_x)_2$



Pelletron Facility At LSI

http://emir.in2p3.fr/LSI

Lifting of gap nodes by quasiparticle scattering
Y. Mizukami et al., Nature Communications **5**:5657 (2014)

Point defects
(Frenkel pairs)

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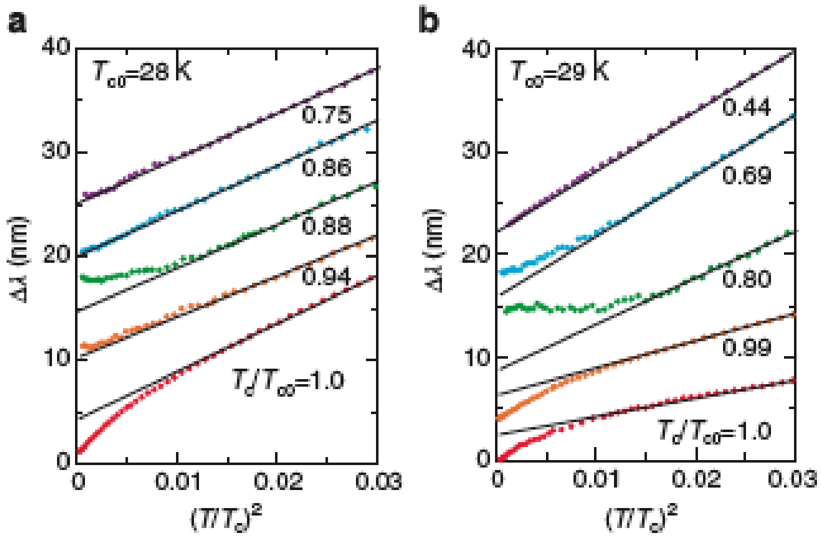

SIRIUS

Pelletron Facility At LSI

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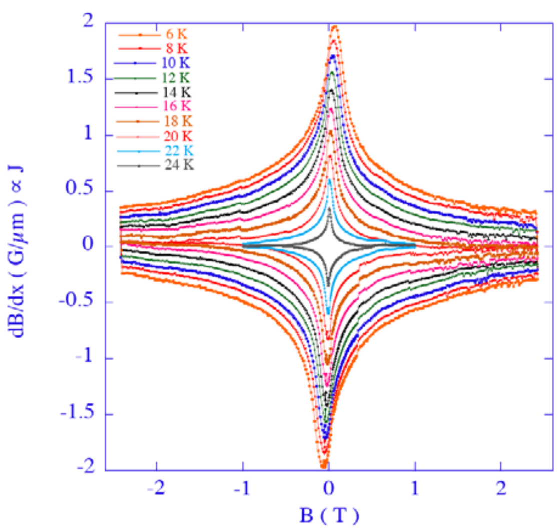
Lifting of gap nodes by quasiparticle scattering
Y. Mizukami et al., Nature Communications **5**:5657 (2014)



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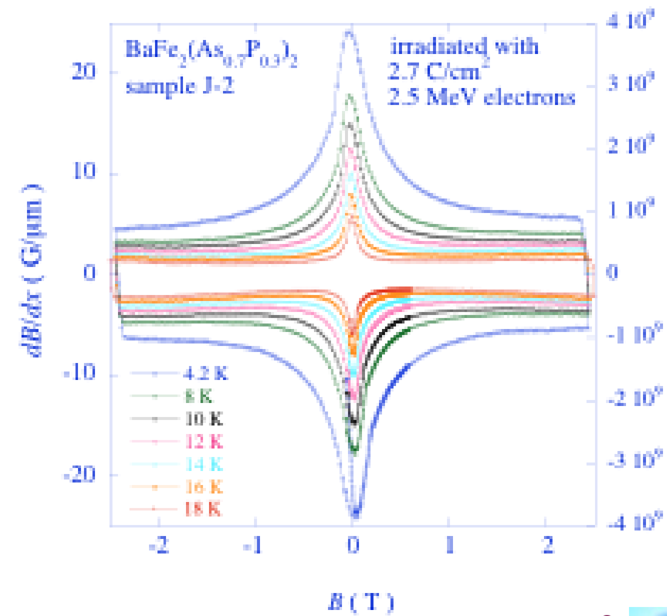

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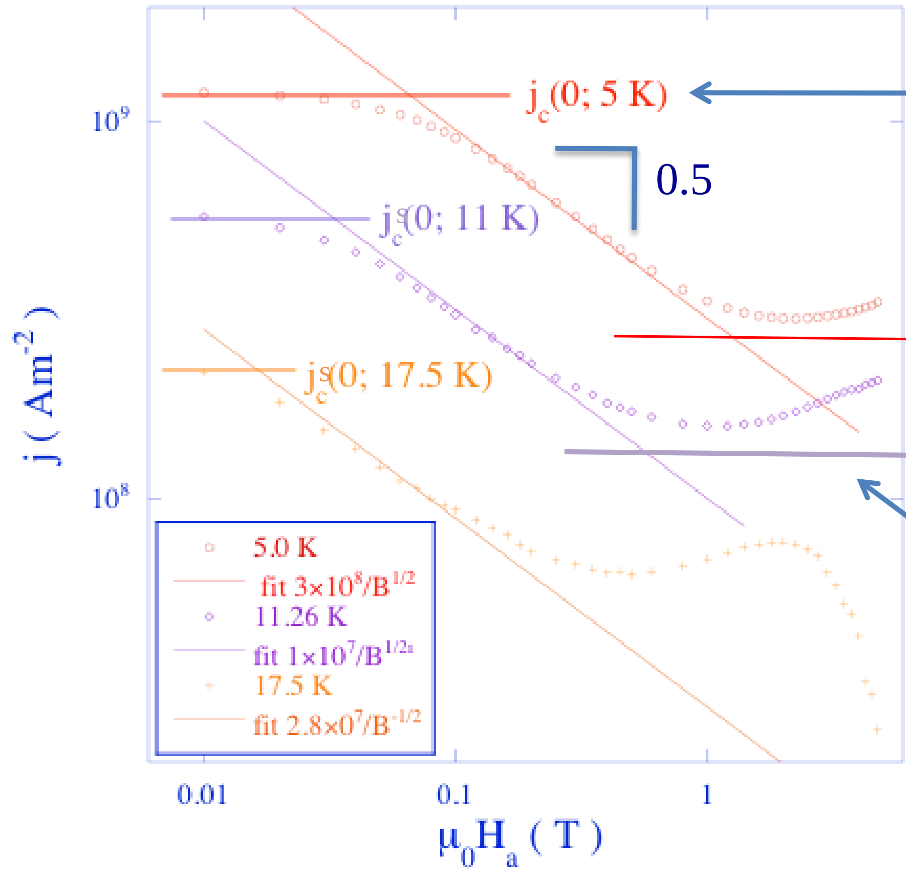

Low B

Strong pinning by nm-scale sparse defects

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$$j_c(B) = \frac{f_p}{\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)\left(\frac{\Phi_0}{B}\right)^{1/2} \qquad (B > B^*)$$

Larger B

Weak collective pinning by dense, atomic sized point-like impurities

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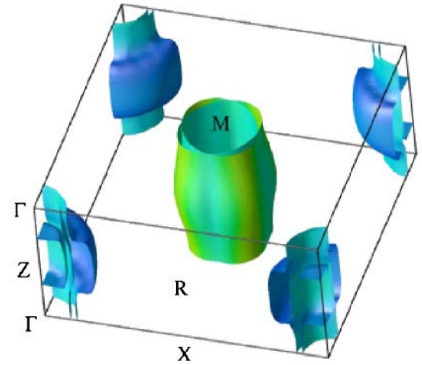
C.J. van der Beek et al., PRL **105**, 267002 (2010); PRB **81**, 174517 (2010).

Multiple band superconductivity and j_c

Multiple band superconductivity and j_c



H. Ding et al., EPL 83, 47001 (2008)

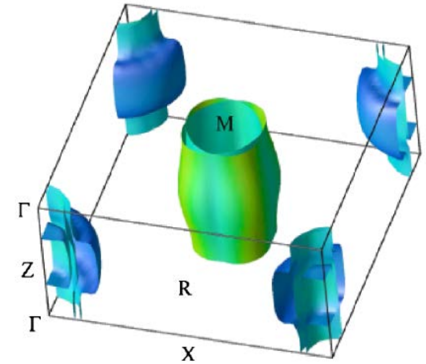
D.J. Singh and M.H. Du, PRL 100 , 237003 (2008)

Different values of Δ and $N(0)$ on different bands

Penetration depth determined by superfluid density / DOS

Coherence length determined by the gap amplitude (and the DOS)

Multiple band superconductivity and j_c



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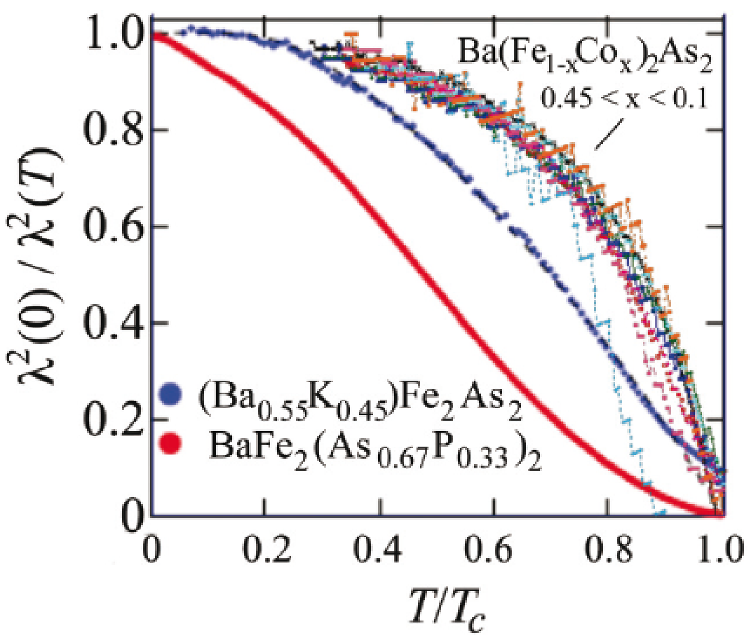
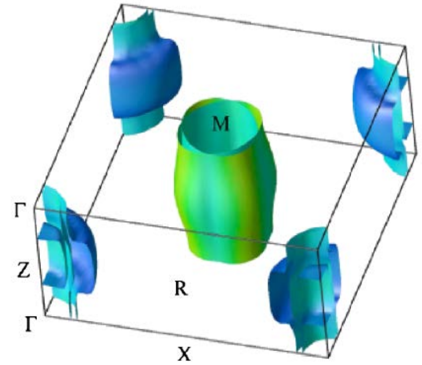


Multiple band superconductivity and j_c



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Different values of Δ and $N(0)$ on different bands

Penetration depth determined by superfluid density / DOS

Coherence length determined by the gap amplitude (and the DOS)

Single band superconductivity : anisotropy ratio $\varepsilon \equiv (m/M)^{1/2} < 1$

$$\varepsilon = \lambda_{ab}/\lambda_c = \xi_c/\xi_{ab} \qquad \varepsilon = B_{c2}^{\|c}/ B_{c2}^{\|ab}$$

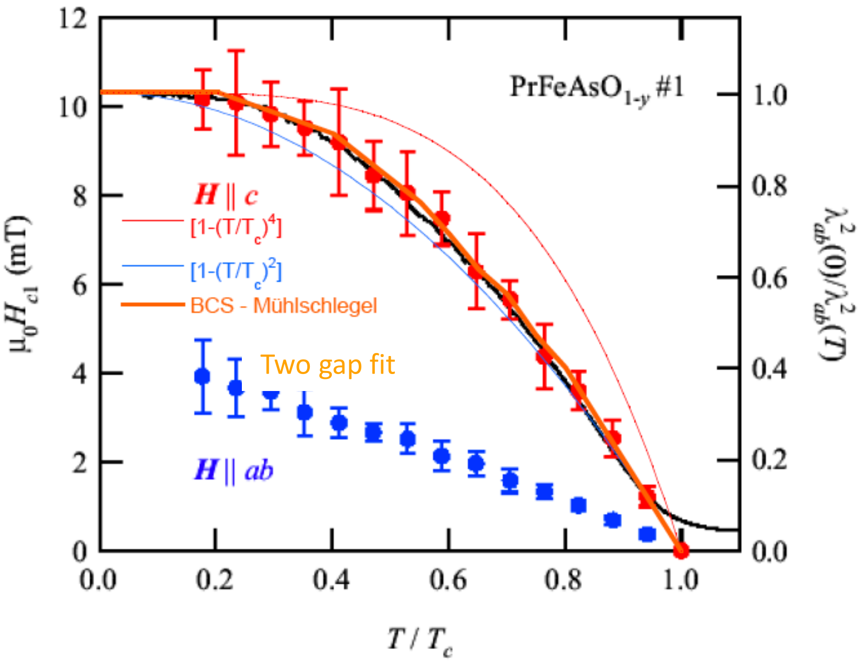
Multiband superconductivity : different anisotropy ratios

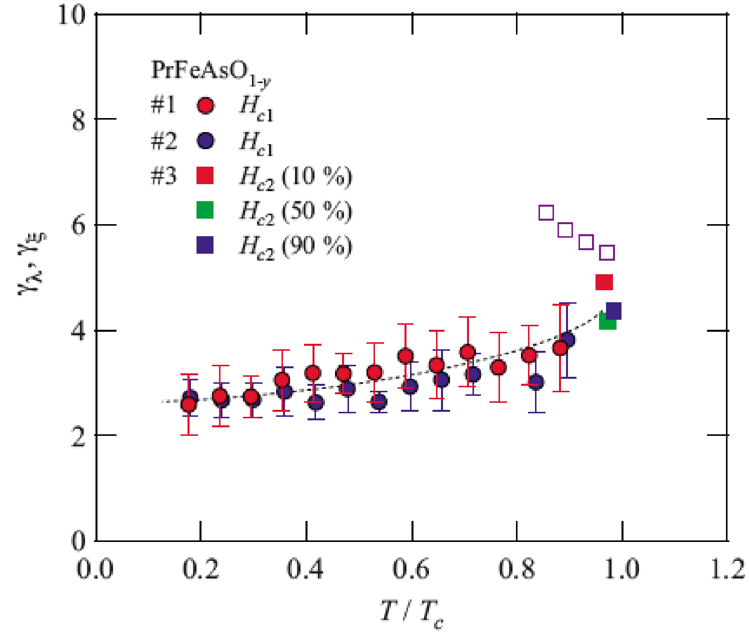
$$\varepsilon_\lambda = \lambda_{ab}/\lambda_c \sim \frac{\langle v_{F,c}\rangle}{\langle v_{F,ab}\rangle} \qquad \varepsilon_\lambda = \frac{B_{c1}^{\|ab} \ln\kappa_{ab}}{B_{c1}^{\|c} \ln\kappa_c}$$

$$\kappa_{ab} = (\lambda_{ab}\lambda_c/\xi_{ab}\xi_c)^{1/2}$$

$$\varepsilon_\xi = \xi_c/\xi_{ab} \sim \frac{\langle v_{F,c}\rangle}{\langle v_{F,ab}\rangle}\frac{\langle \Delta_{ab}\rangle}{\langle \Delta_c\rangle} \qquad \varepsilon_\xi = B_{c2}^{\|c}/ B_{c2}^{\|ab}$$

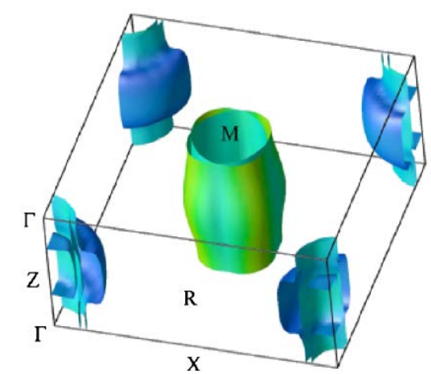
$PrFeAsO_{1-y}$: B_{c1} and B_{c2}





$$\gamma_\lambda = \varepsilon_\lambda^{-1} = \lambda_c/\lambda_{ab} = \frac{B_{c1}^{\|c}\ln\kappa_c}{B_{c1}^{\|ab}\ln\kappa_{ab}} \sim \frac{\langle v_{F,ab}\rangle}{\langle v_{F,c}\rangle}$$

$$\gamma_\xi = \varepsilon_\xi^{-1} = \xi_{ab}/\xi_c \sim B_{c2}^{\|ab}/B_{c2}^{\|c} \sim \frac{\langle v_{F,ab}\rangle}{\langle v_{F,c}\rangle}\frac{\langle\Delta_c\rangle}{\langle\Delta_{ab}\rangle}$$

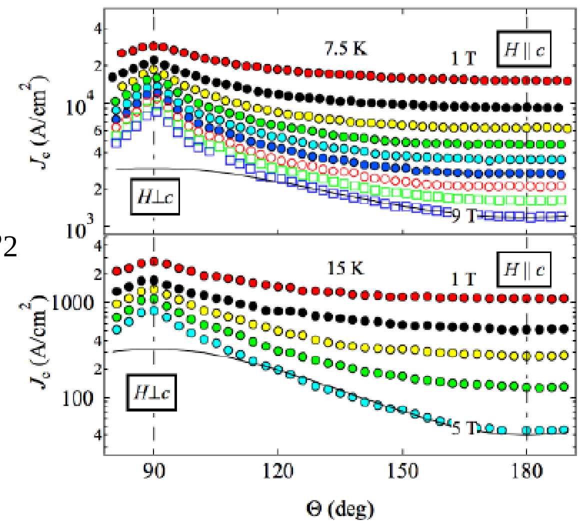


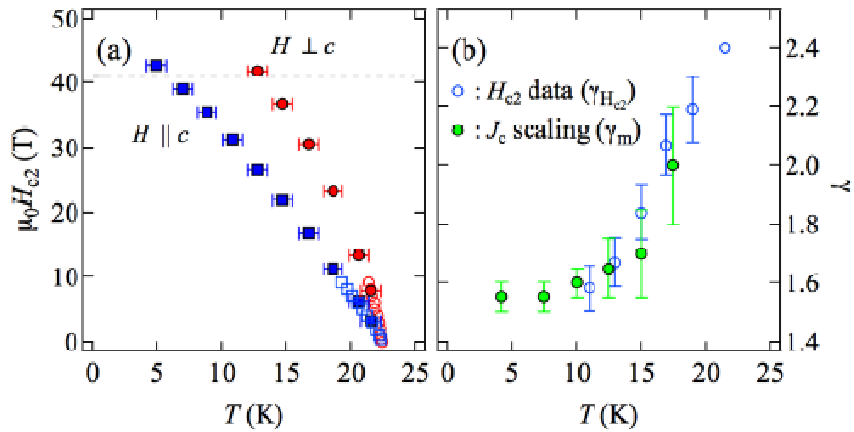
R. Okazaki et al., Phys. Rev. B **79**, 064520 (2009).

Critical current anisotropy ?

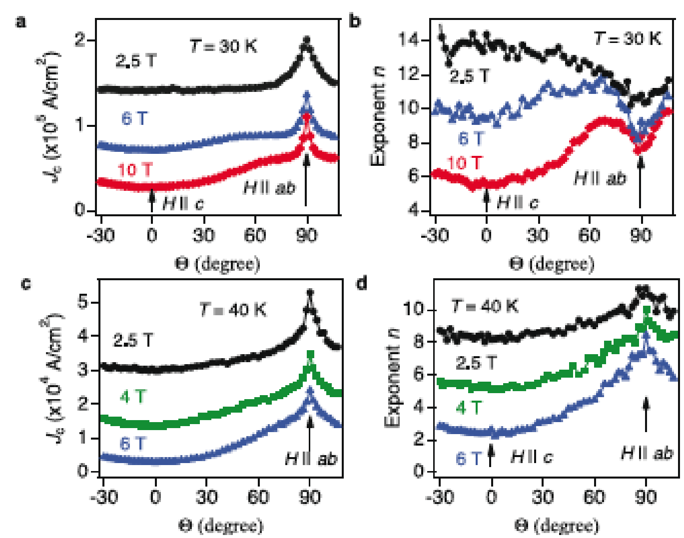
J. Hänisch *et al.*, IEEE Trans. Appl. Superc. **21** (2010) 2887.

$Ba(Fe_{0.9}Co_{0.1})_2As_2$
Thin films

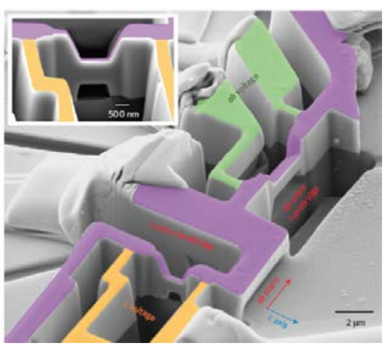




K. Iida et al., Scientific Reports 3:2139 (2013)



Ph. Moll et al.,
nature Materials **9**, 628 (2010)

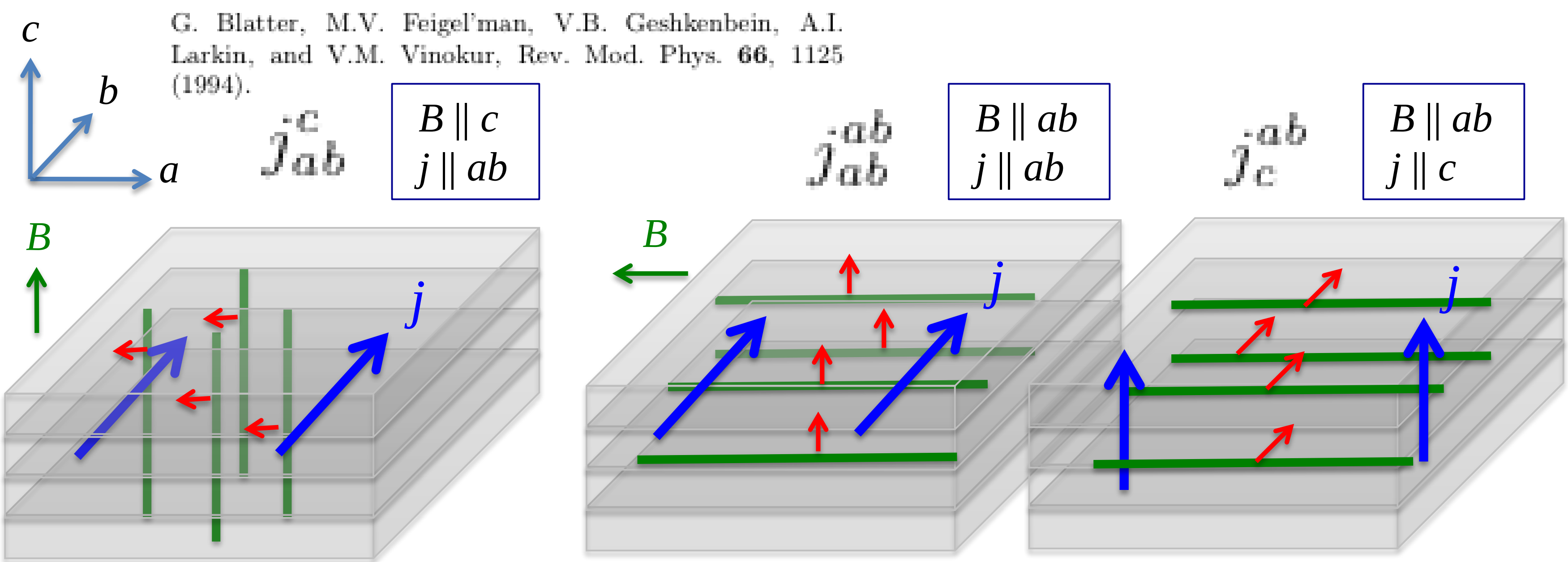


$SmFeAsO_{0.75}F_{0.25}$

SmFeAs(O,F)

Anisotropy of the critical current : 3 independent j_c's

G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, and V.M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).



(hard motion) (easy motion)

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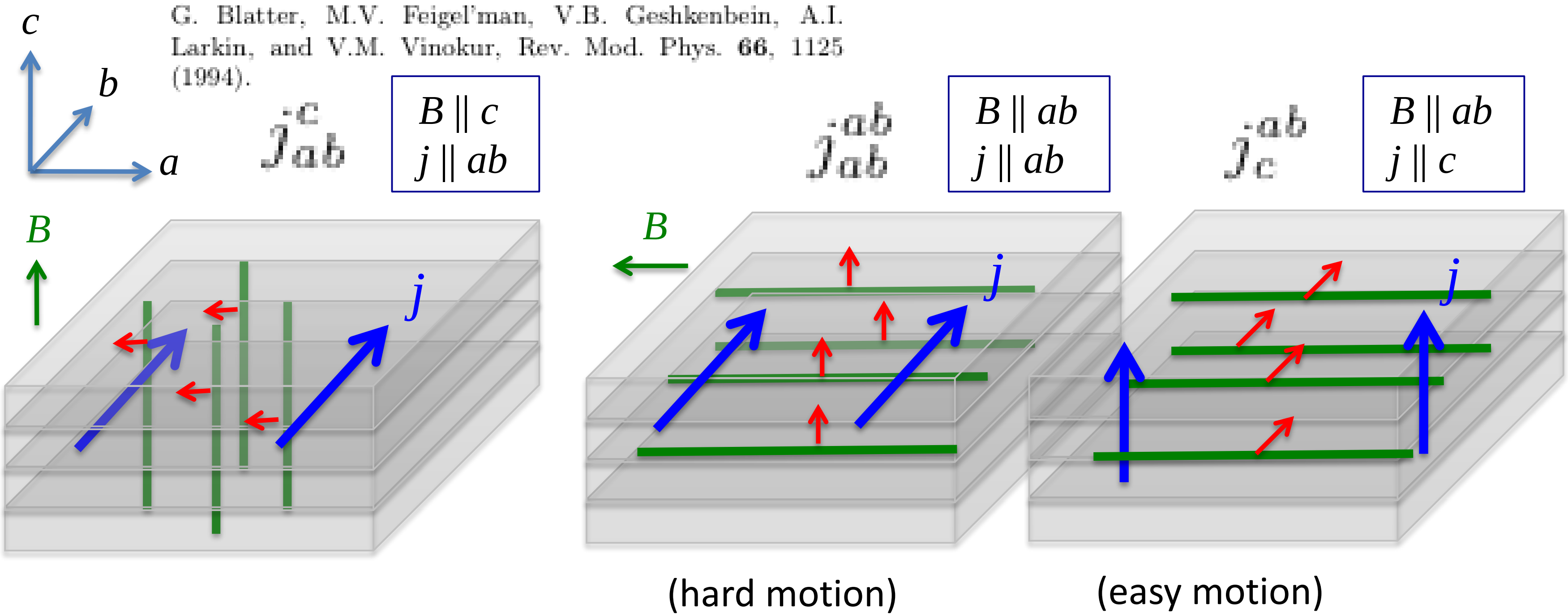
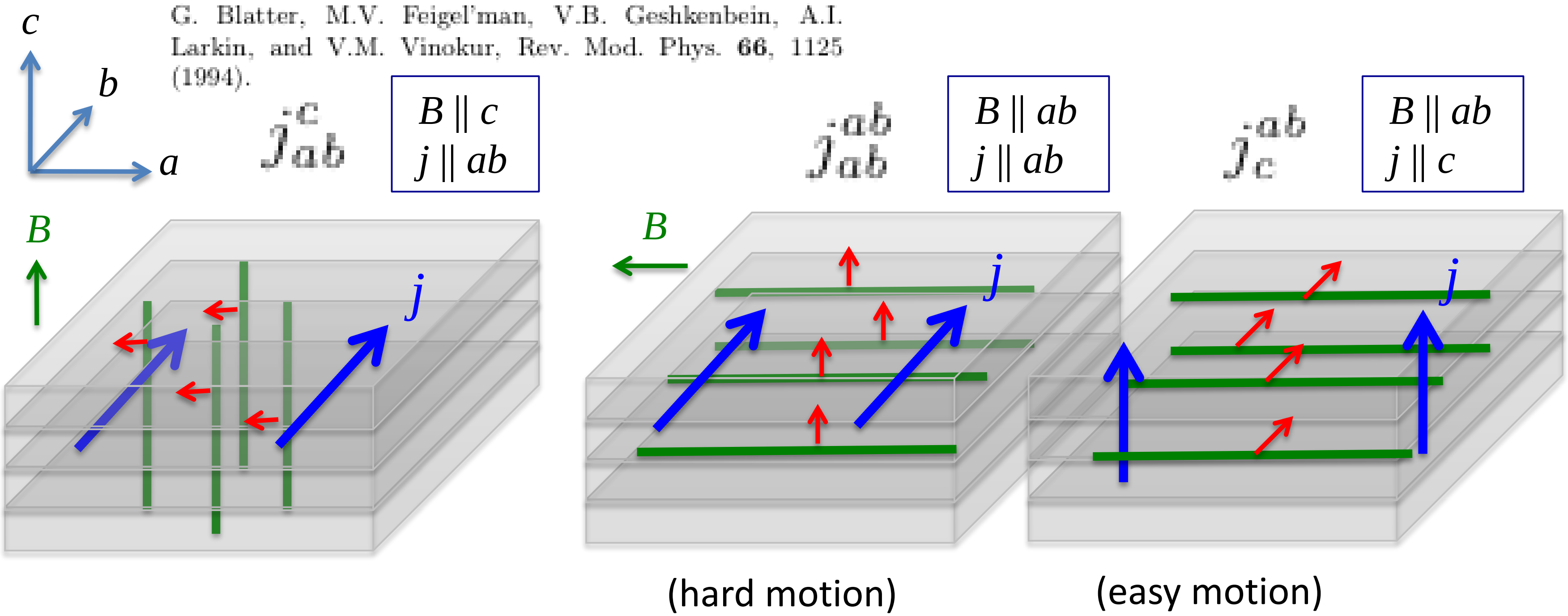


1. Strong pinning : 1D (single vortex) and 3D
2. 1D collective pinning

Anisotropy of the critical current: 3 independent j_c's

G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, and V.M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

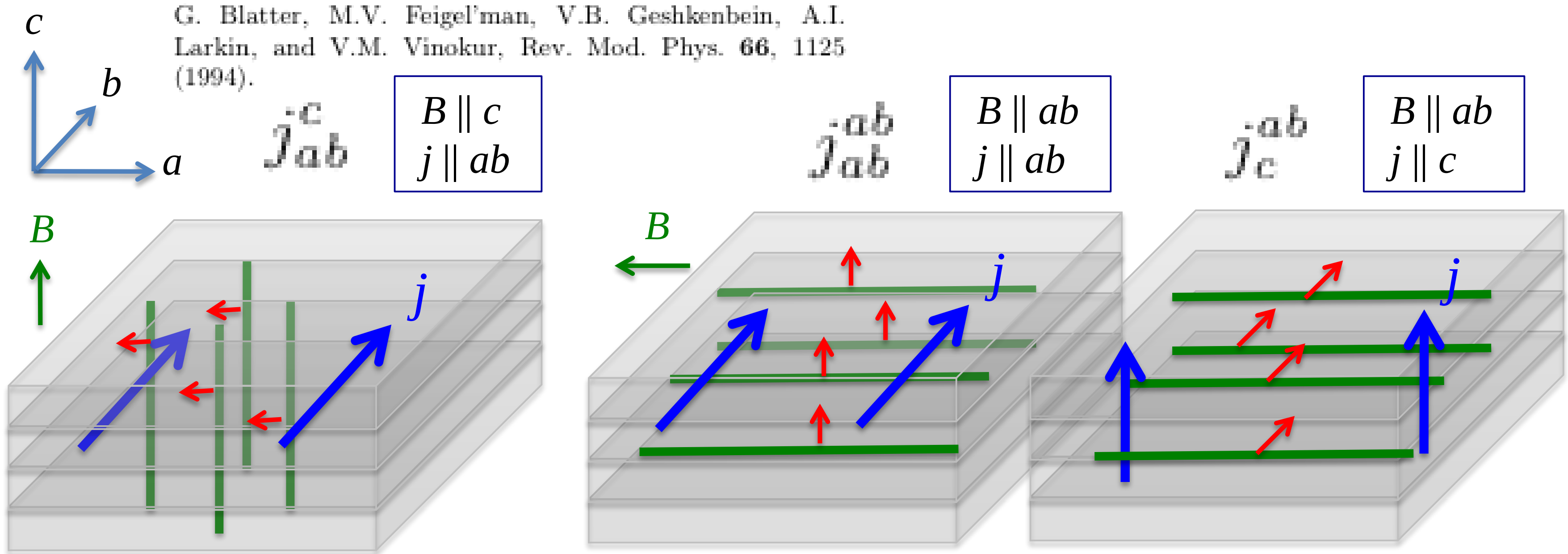


1. Strong pinning : 1D (single vortex) and 3D
2. 1D collective pinning

a. Anisotropy of f_p
b. Anisotropy of U_p
c. Anisotropy of vortex line tension ε_1
d. Anisotropy of c_{44}, c_{66}

C.J. van der Beek, M. Konczykowski, R. Prozorov, Superc. Sci. Techn. **25** (2012) 084010

Anisotropy of the critical current: 3 independent j_c's



(hard motion) (easy motion)

1. Strong pinning : 1D (single vortex) and 3D
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a. Anisotropy of f_p
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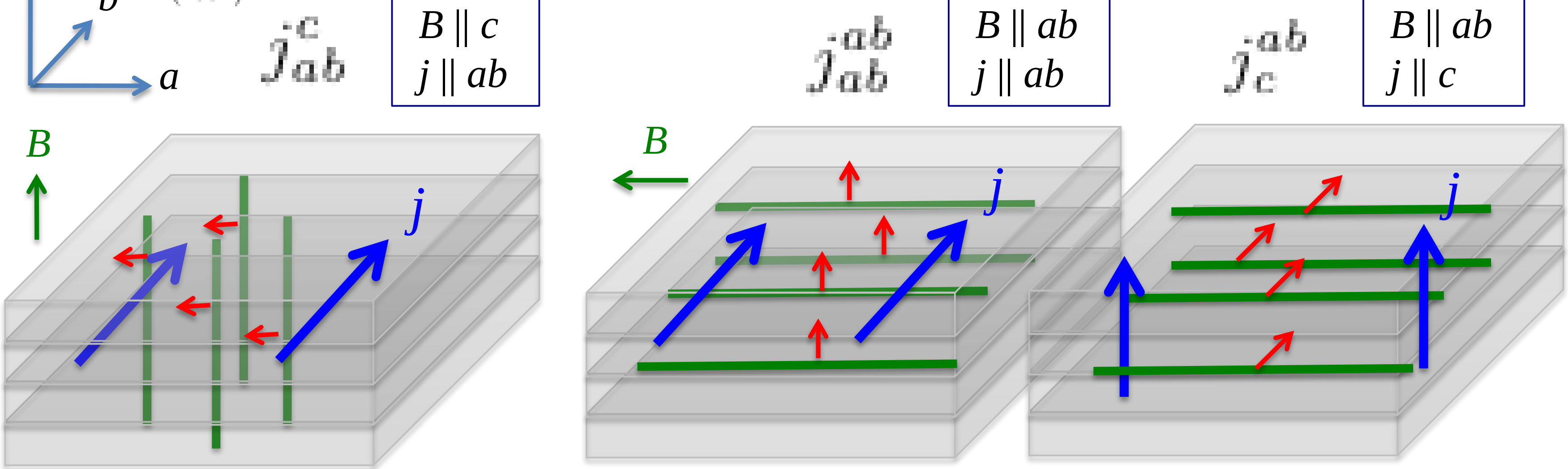
Simplest model : ε_{λ} ‾ ε_{ξ}

C.J. van der Beek, M. Konczykowski, R. Prozorov, Superc. Sci. Techn. **25** (2012) 084010

Anisotropy of the critical current: 1D collective pinning

$$j_c^{SV} = \frac{1}{\Phi_0}\left(\frac{n_i f_p^2}{\varepsilon_1}\right)^{2/3}\xi$$

G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, and V.M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).



(hard motion) (easy motion)

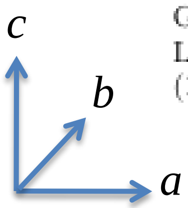
Single band	$j_{ab}^{c} = j_{SV}$	$j_{ab}^{ab} = j_{ab}^{c}$	$j_{c}^{ab} = \varepsilon j_{ab}^{c}$
Multiband	$j_{ab}^{c} = j_{SV}$	$j_{ab}^{ab} = \left(\frac{\varepsilon_\lambda}{\varepsilon_\xi}\right)^{7/3} j_{SV}$	$j_{c}^{ab} = \left(\frac{\varepsilon_\lambda^{5/3}}{\varepsilon_\xi^{2/3}}\right) j_{SV}$

C.J. van der Beek, M. Konczykowski, R. Prozorov, Superc. Sci. Techn. **25** (2012) 084010

Anisotropy of the critical current: strong pinning

$L = (\varepsilon_1 / \pi n_i U_p)^{1/2}$

$j_c = f_p / \Phi_0 L$



G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, and V.M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

j_{ab}^{c} | $B \parallel c$, $j \parallel ab$

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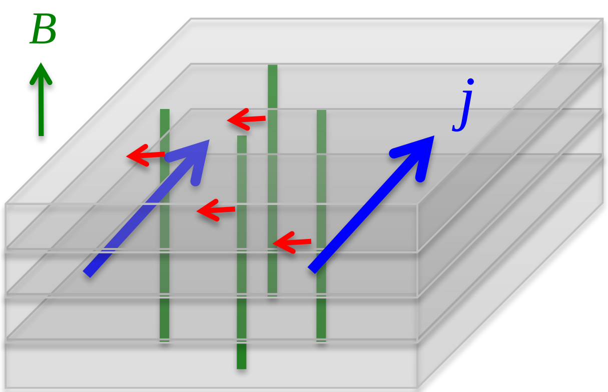
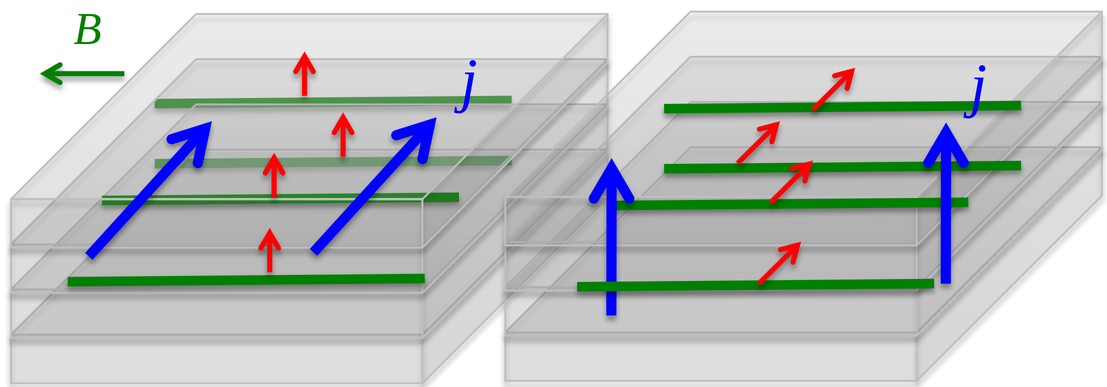
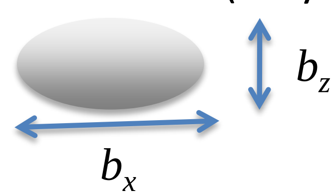




(hard motion)

(easy motion)

1. Anisotropy of f_p : ε_b
2. Anisotropy of vortex line tension ε_1



Multiband: $j_{ab}{}^{c} = j_s{}^{c}$

$$j_{ab}^{ab} = \frac{\varepsilon_\lambda^2}{\varepsilon_b^{3/2} \varepsilon_\xi} j_s^c$$

$$j_{c}^{ab} = \frac{\varepsilon_\lambda^2}{\varepsilon_b^{3/2}} j_s^c$$

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Anisotropy of the critical current: strong pinning

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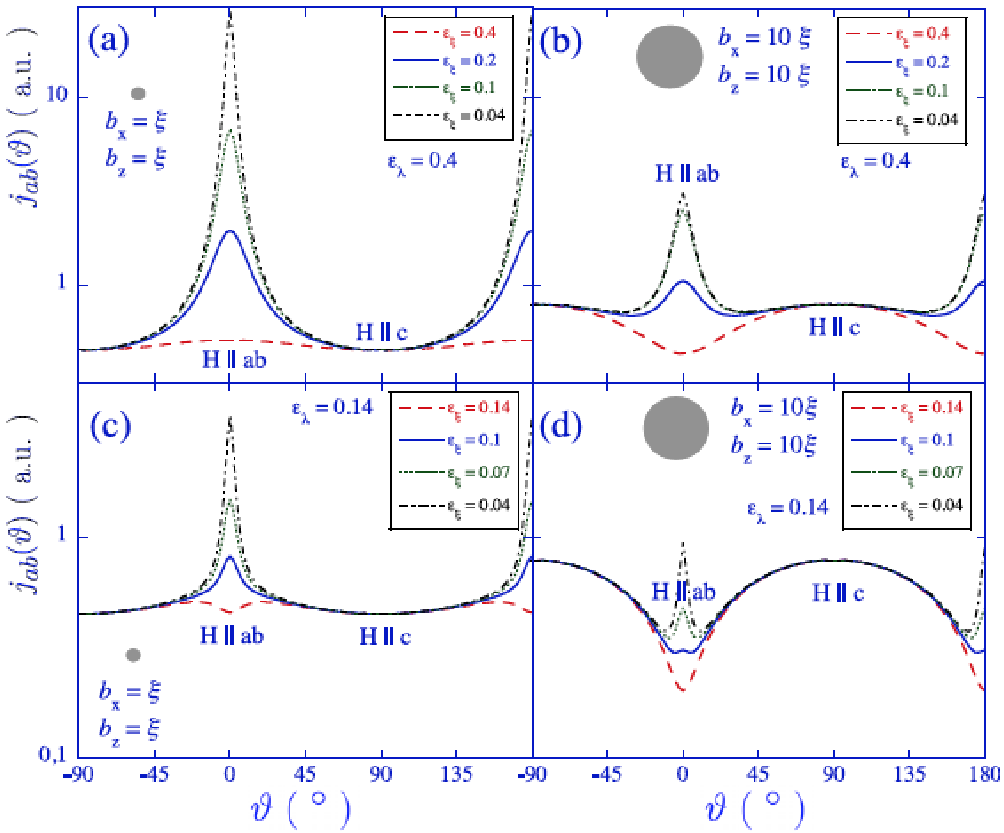

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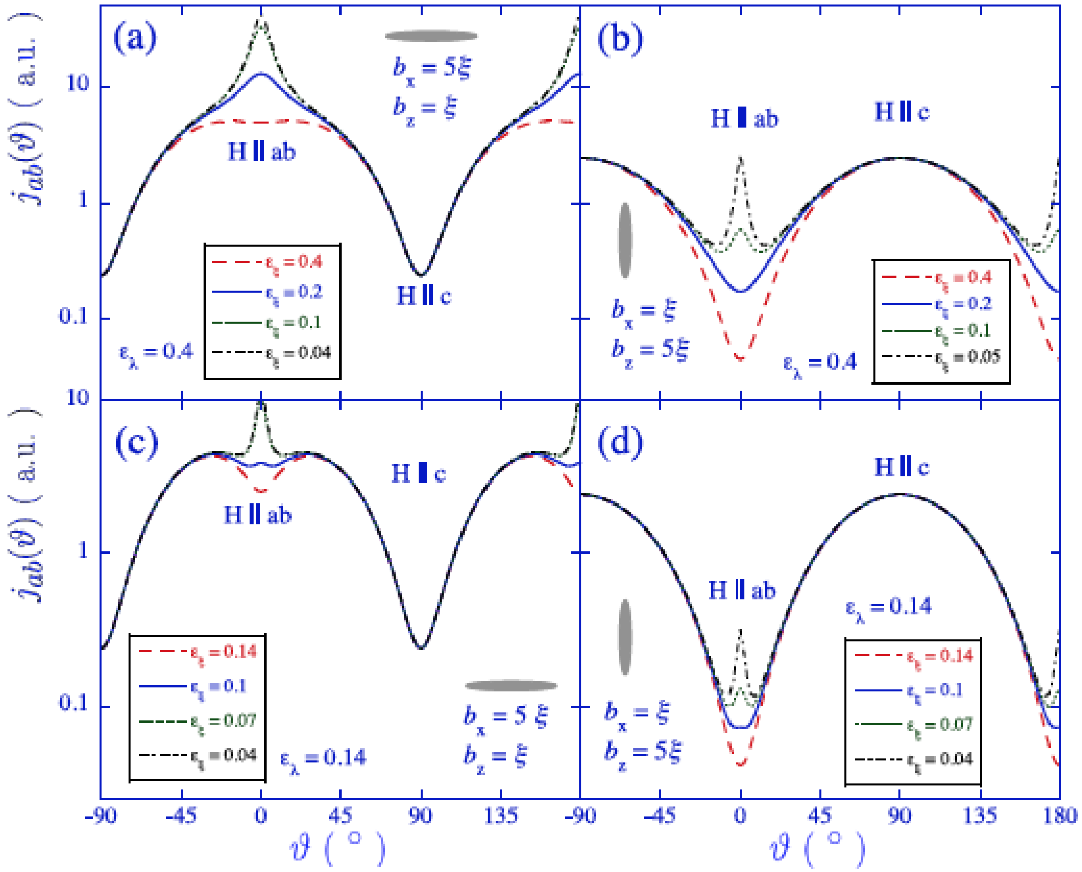

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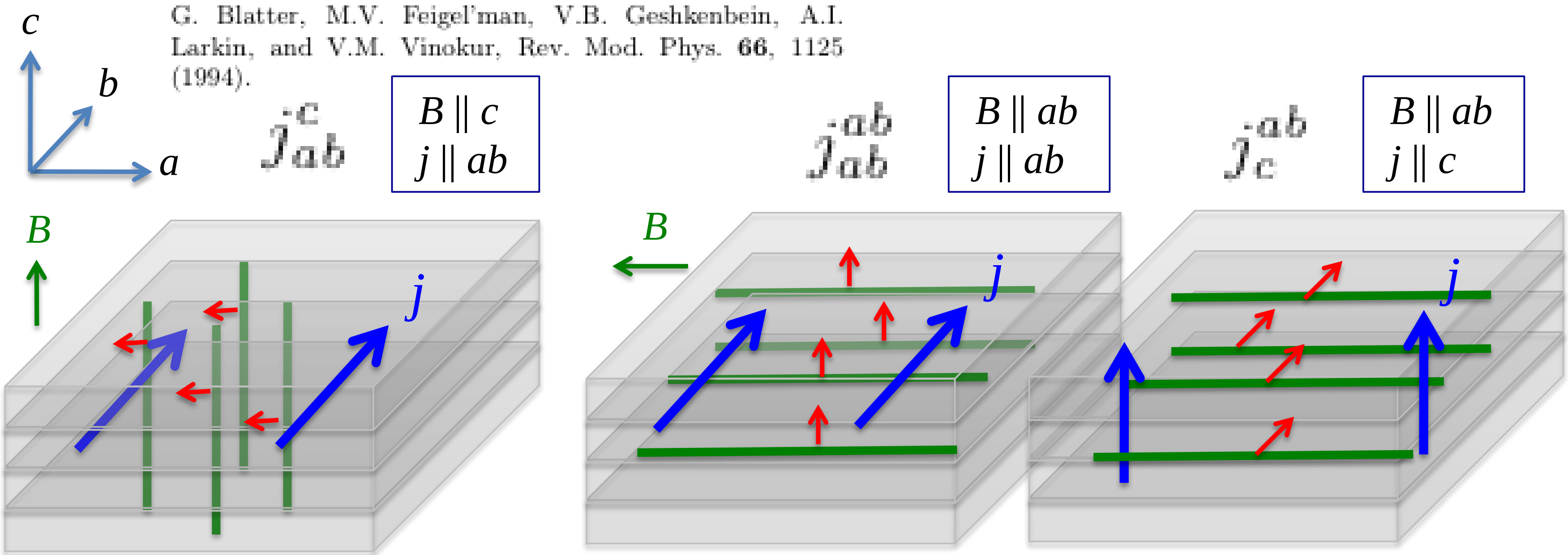
In all cases:

G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, and V.M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).



(hard motion) (easy motion)

Multiband

Collective pinning : $j_c = (n_i \langle f_p^2 \rangle / V_c)^{1/2} / B$

$j_{ab}^{ab}/j_{c}^{ab} = 1/\varepsilon_\xi.$

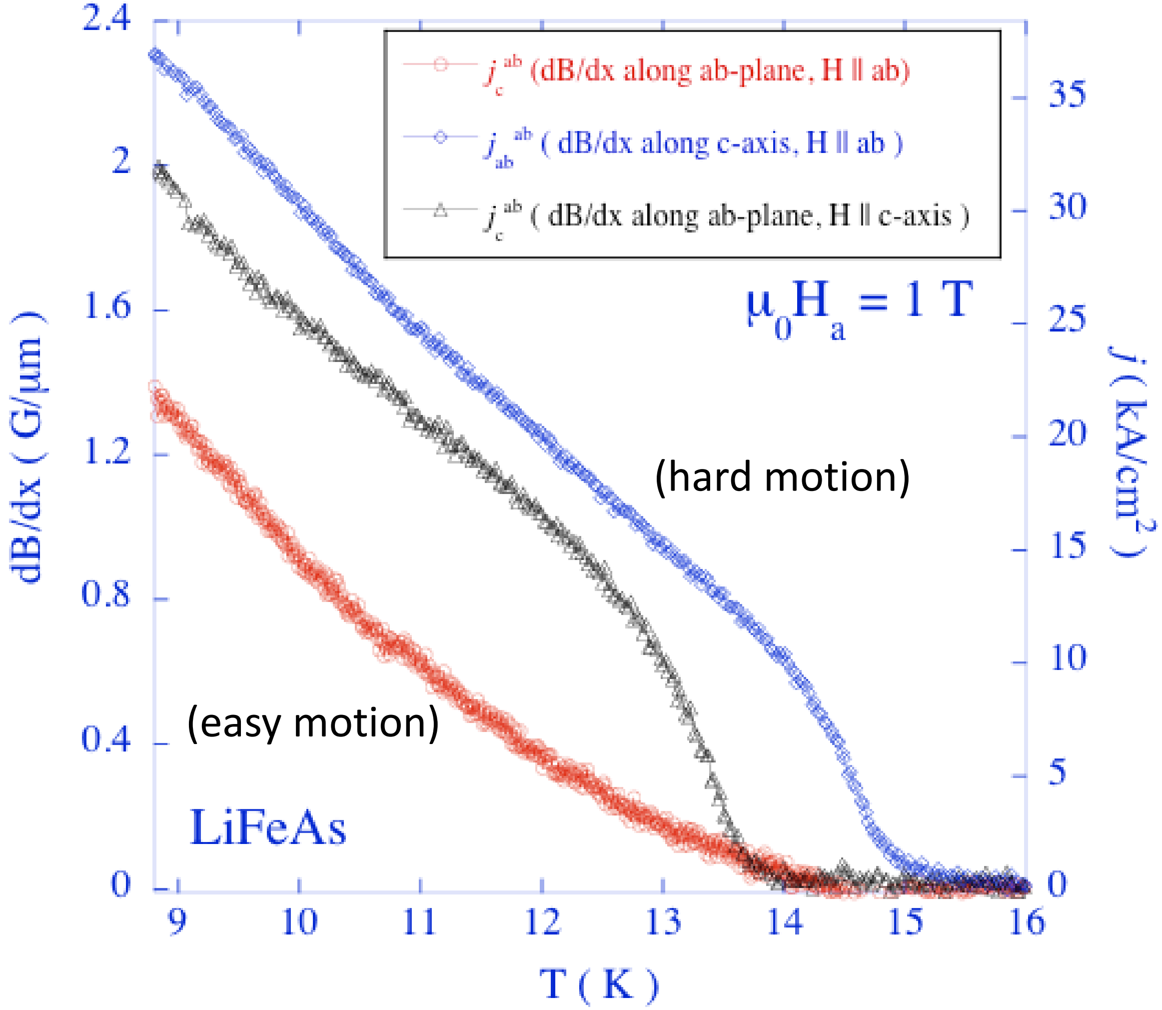
Strong pinning : $j_c = f_p / \Phi_0 L$

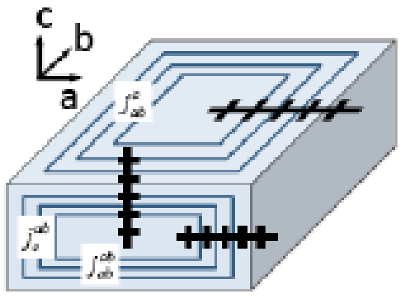
The anisotropy of the elementary pinning force

C.J. van der Beek, M. Konczykowski, R. Prozorov, Superc. Sci. Techn. **25** (2012) 084010

Vortex pinning in LiFeAs: T dependence of trapped flux

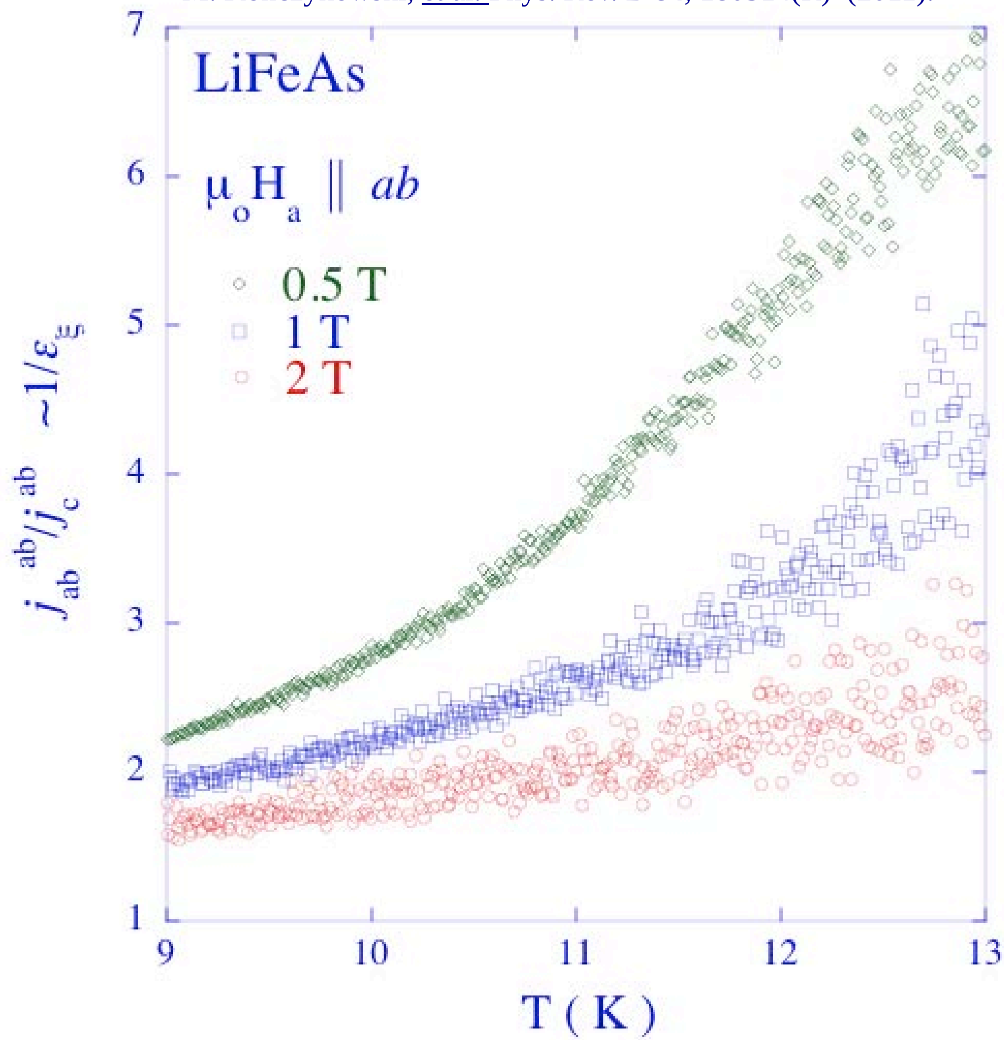
M. Konczykowski, et al. Phys. Rev. B **84**, 180514(R) (2011).





j_c anisotropy in LiFeAs

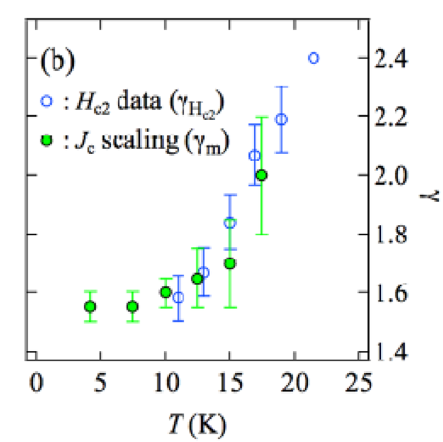
M. Konczykowski, et al. Phys. Rev. B **84**, 180514(R) (2011).



$$j_{ab}^{ab}/j_c^{ab} = 1/\varepsilon_\xi.$$

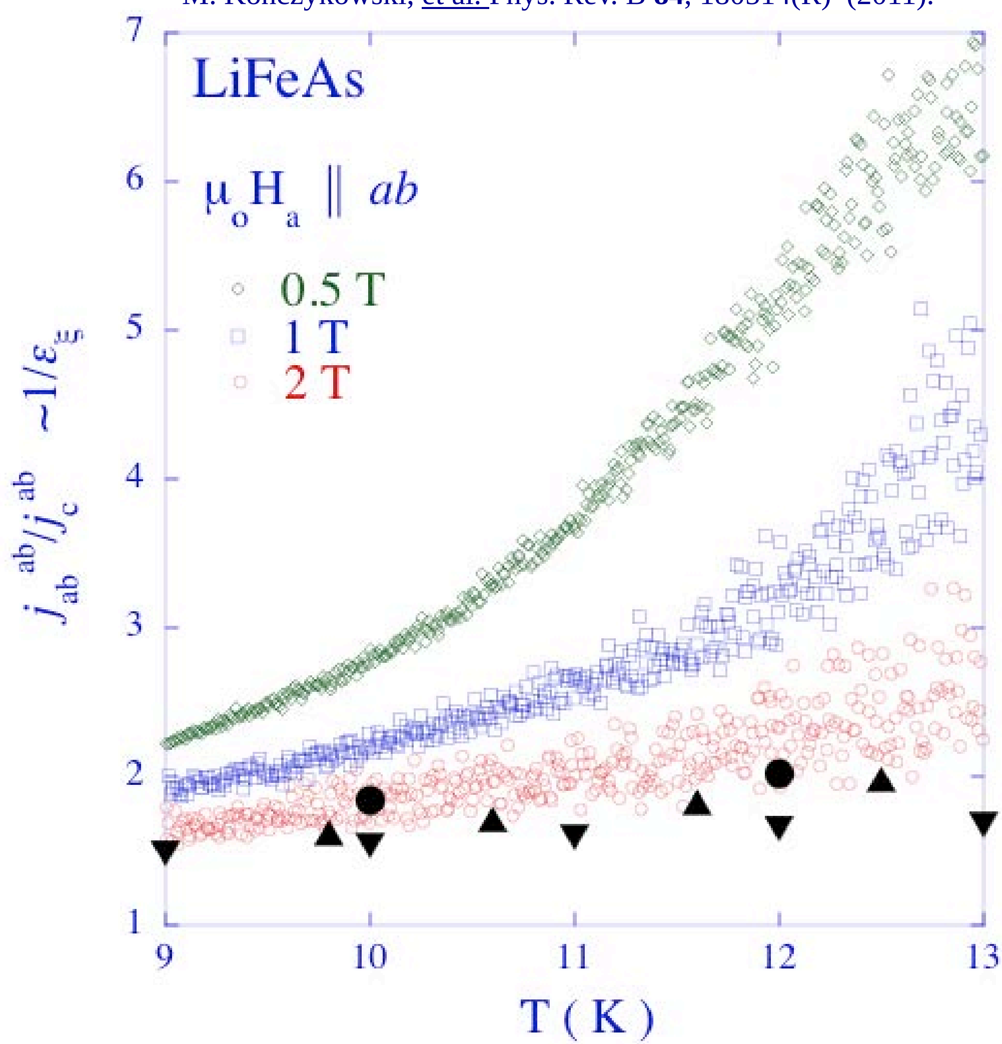
viz $Ba(Fe_{0.9}Co_{0.1})_2As_2$ Thin films

J. Hänisch *et al.*, IEEE Trans. Appl. Superc. **21** (2010) 2887.



j_c anisotropy in LiFeAs (and other iron-based superconductors)

M. Konczykowski, et al. Phys. Rev. B **84**, 180514(R) (2011).



$$j_{ab}^{ab}/j_c^{ab} = 1/\varepsilon_\xi.$$

▲ K. Cho *et al.* , PRB **83**, 060502(R) (2011).
▼ N. Kurita *et al.*, J. Phys. Soc. Japan 80, 013706 (2011)
● S. Khim *et al.* , Phys. Rev B **84**, 104502 (2011).

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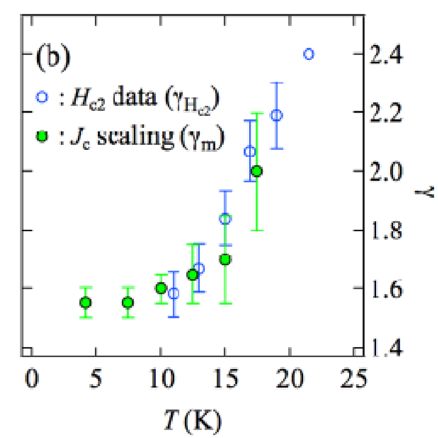
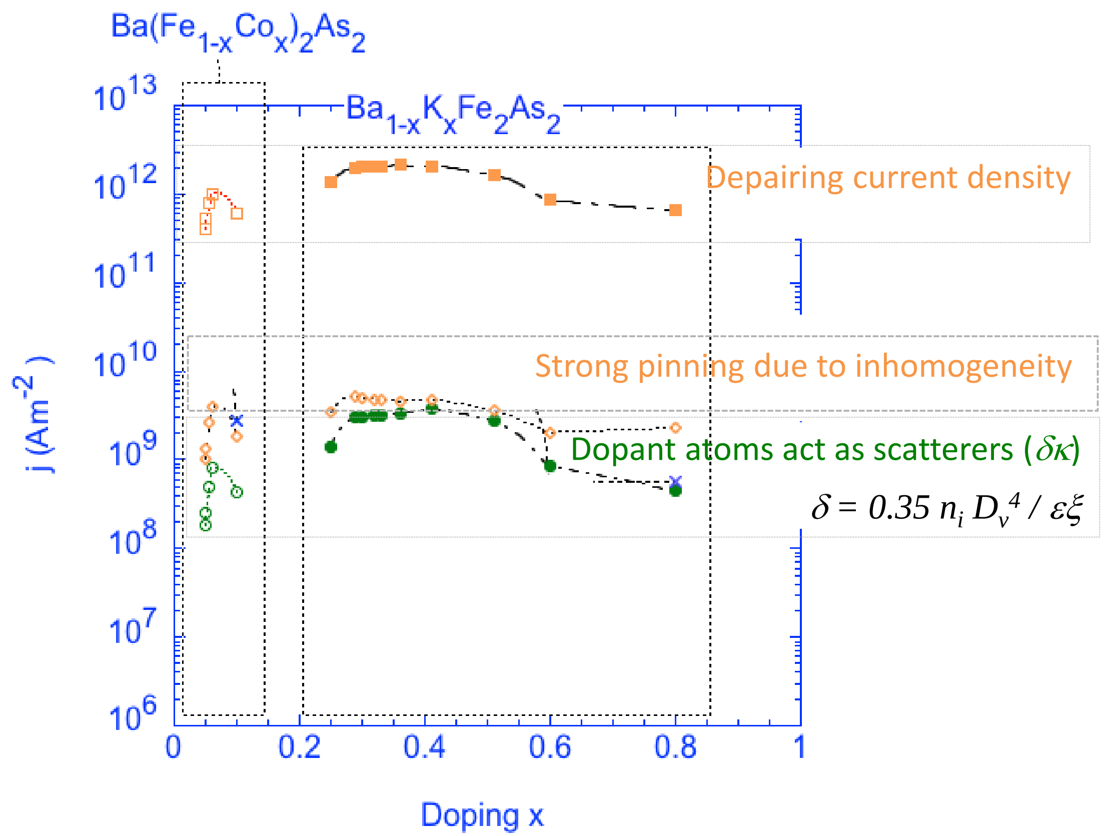
Thin films

J. Hänisch *et al.*, IEEE Trans. Appl. Superc. **21** (2010) 2887.

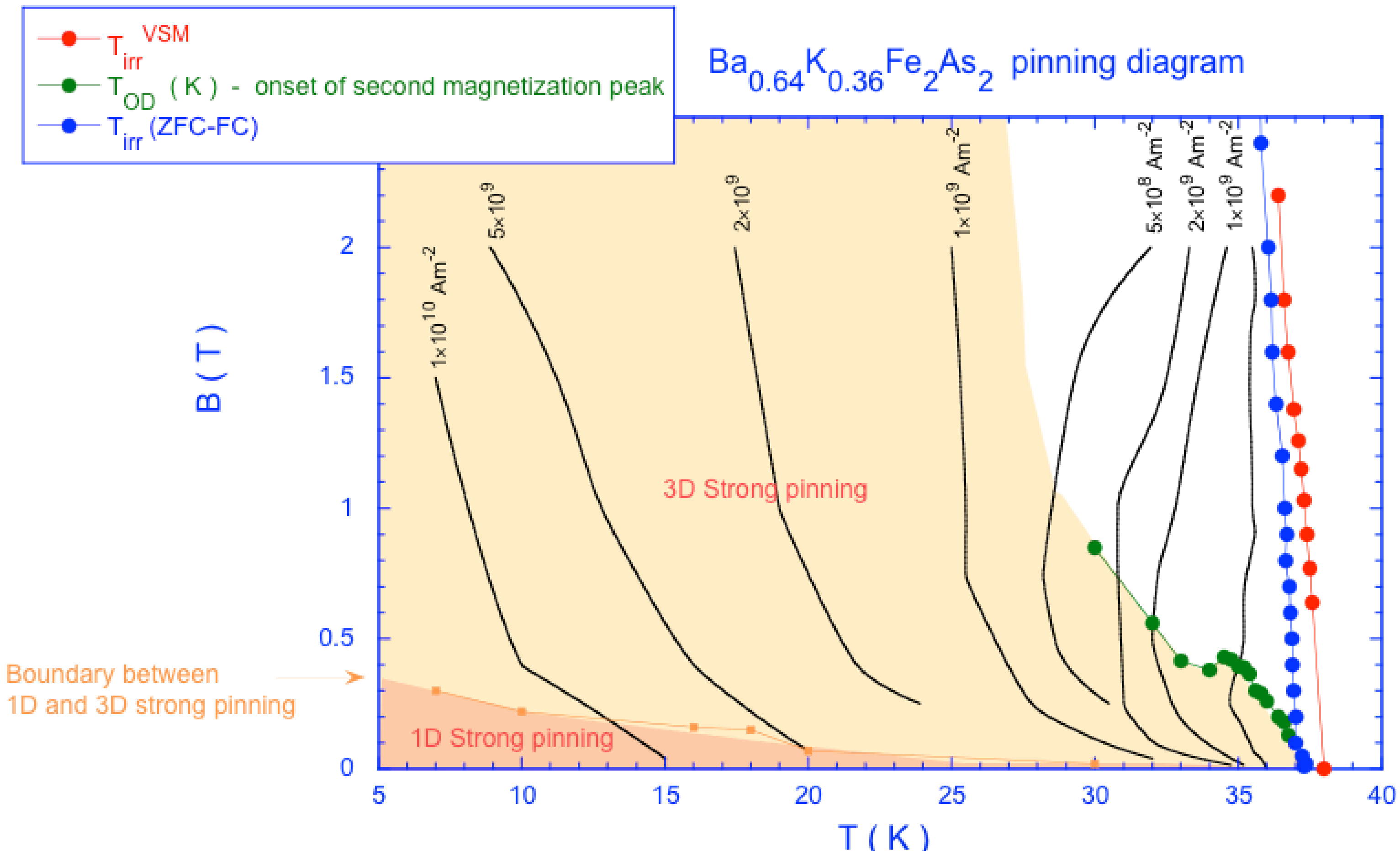


Prospects for improvement

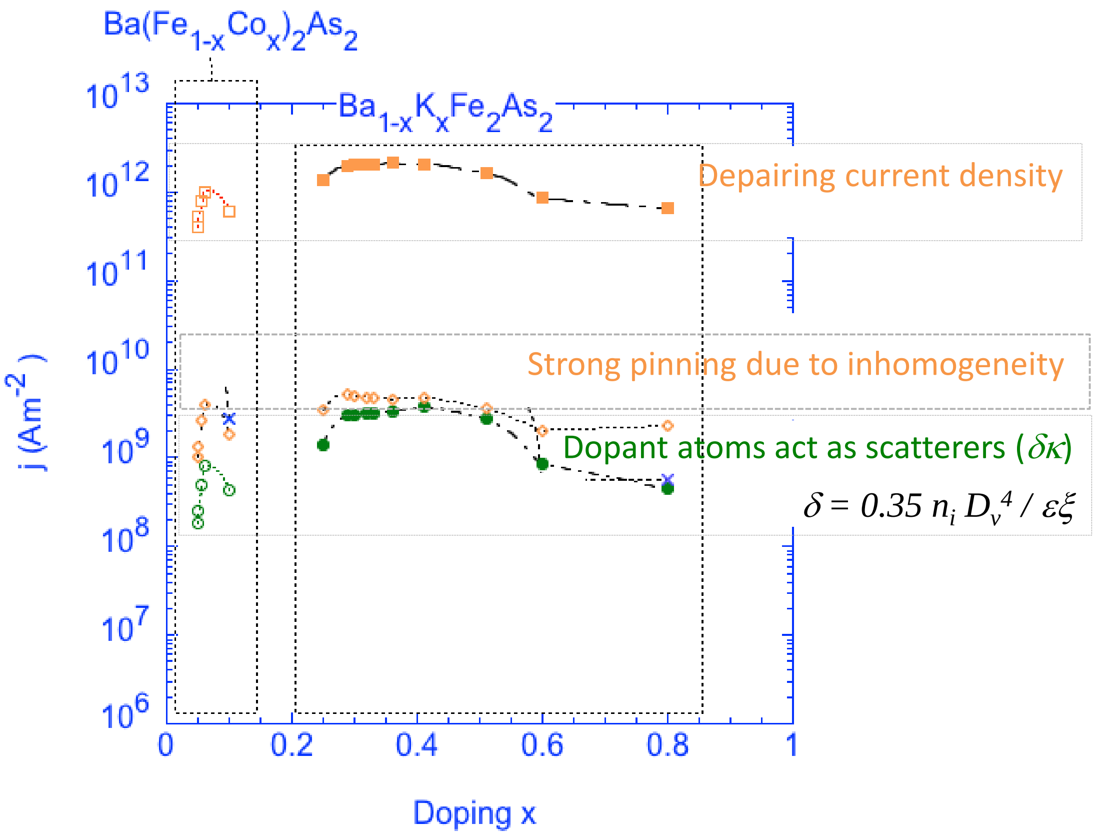


Pinning in optimally-doped $Ba_{1-x}K_xAs_2Fe_2$

- Strong pinning below B_{sp} : chemical disorder
- Weak pinning around B_{sp}: dopant atoms, Fe vacancies



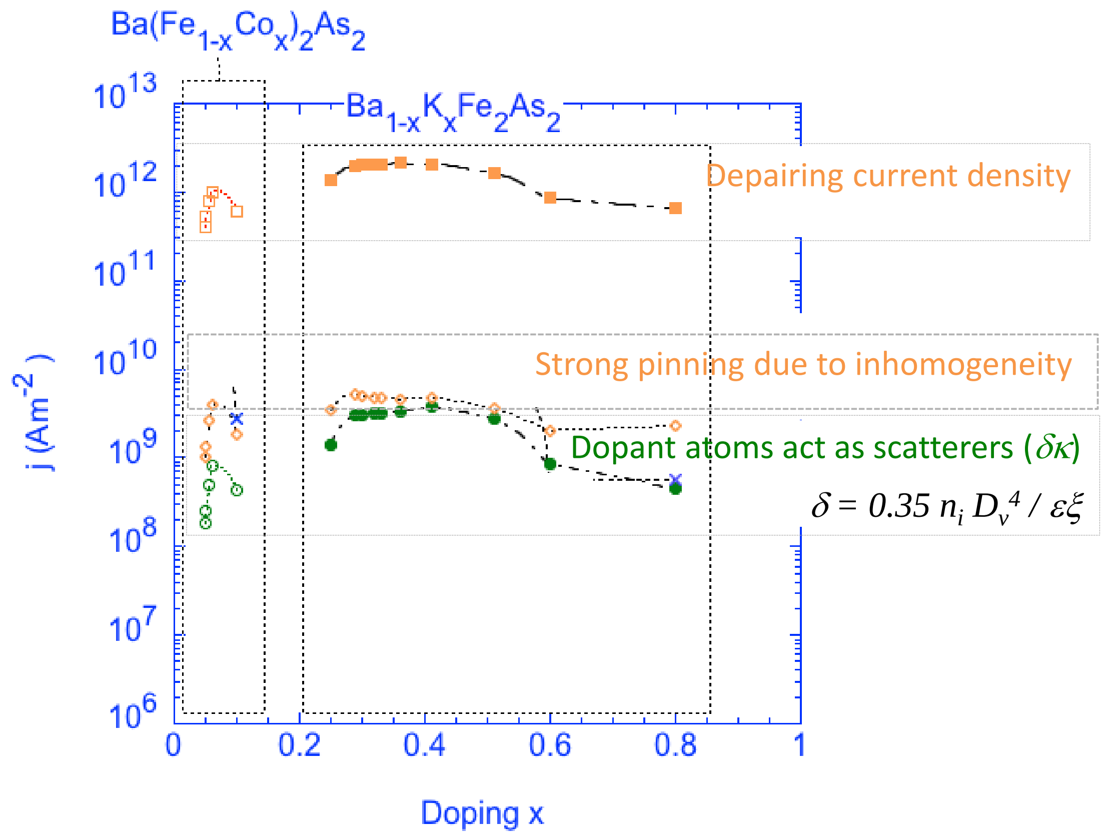
Prospects for improvement



~ $YBa_2Cu_3O_7$

~ 0.1 × (j_c of $YBa_2Cu_3O_7$)

Prospects for improvement

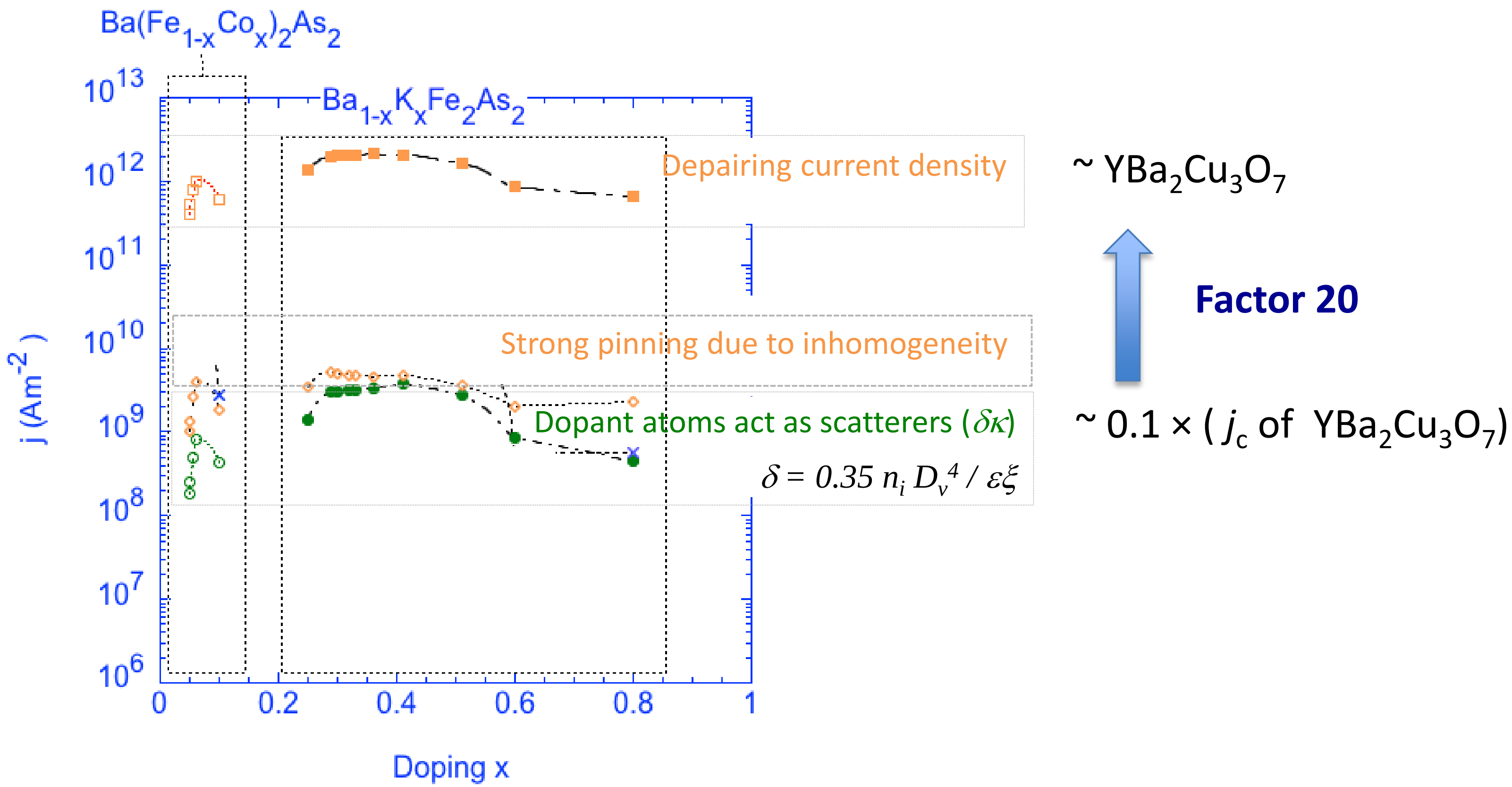


~ $YBa_2Cu_3O_7$

Factor 20

~ 0.1 × (j_c of $YBa_2Cu_3O_7$)

Prospects for improvement



- 122 type compounds most promising because of high B_{c2}, smaller anisotropy, less creepy
- 1111 type compounds : high T_c
- FeSe
- tailoring of defects might yield almost isotropic j_c

Take-home:

Pinning in Iron-based superconductors:

- It's (mainly) the dopant atoms
- Magnitude: follows depairing current
- Low B : strong pinning by nm-scale heterogeneity
- Intermediate B : collective pinning

$\delta\kappa$ mechanism - Charged dopants / vacancies

Multiple band superconductivity and j_c :

- Supplementary anisotropy in j_c appears
- j_c anisotropy for field || ab directly probes coherence length anisotropy
- Beware the T – dependence (and we haven't even talked about creep…)

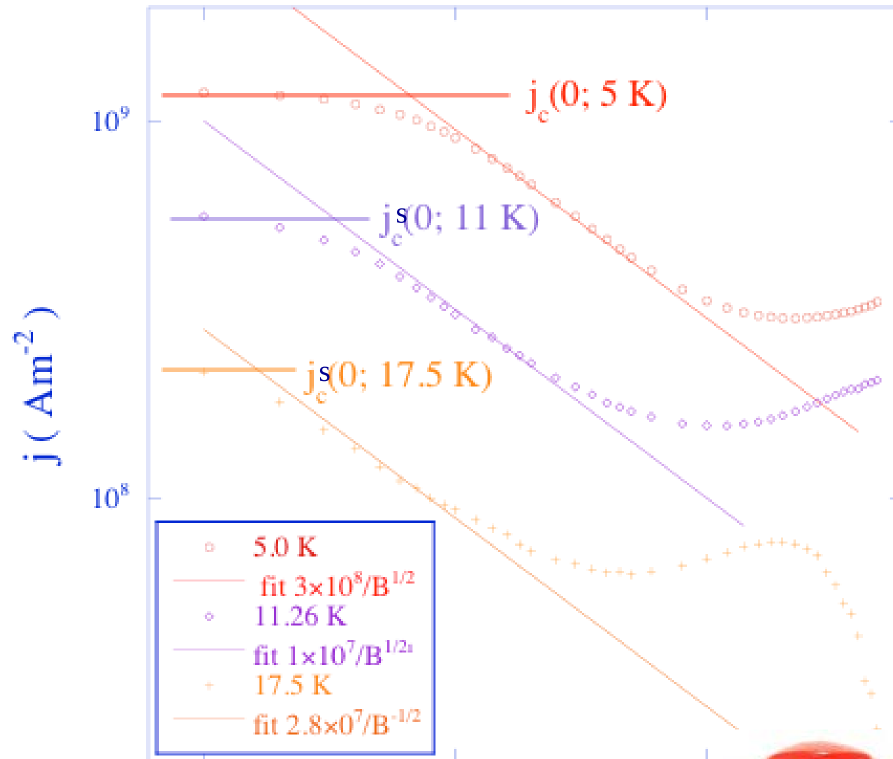
$$j_c = j_c(0)\, f(b)\, g(t)$$

example of $Ba(Fe_{0.93}Co_{0.07})_2As_2$…

$t = T / T_c$

$b = B / B_{c2}(T)$

Zero temperature, zero-field j_c : pinning mechanism, statistics



S. Demirdis et al., PRB **84**, 094517 (2011)

Field dependence:

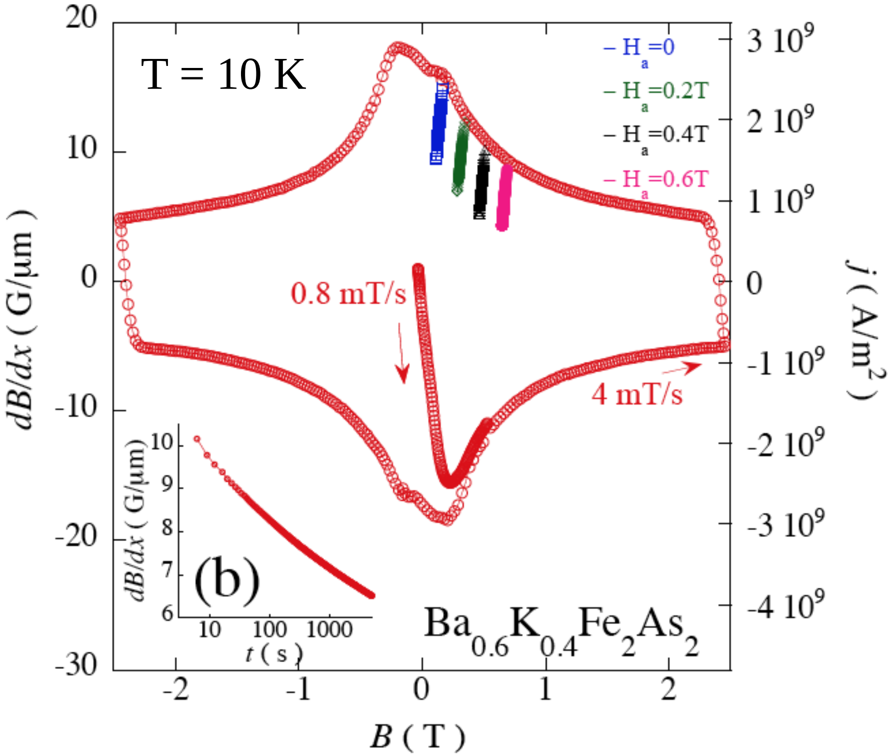
- Statistics of pinning
- change in vortex lattice structure
- change in vortex structure

Temperature dependence:

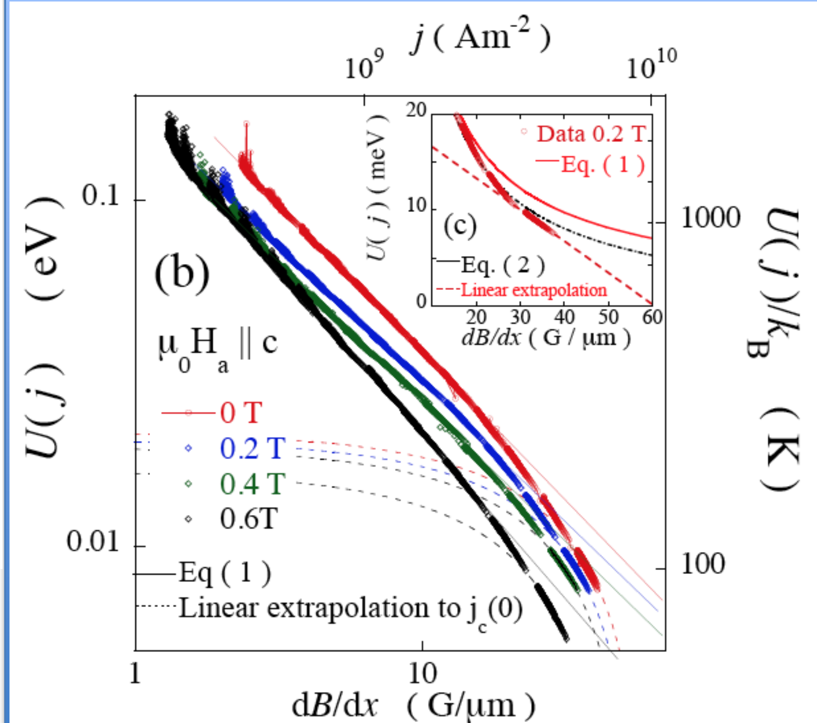
- thermal activation of quasiparticles: $\lambda(T)$
- decrease of the order parameter: $\xi(T)$
- multiple band effects
- thermal activation of vortices
- thermal smearing of the pin potential

Thermal activation and creep

Thermal activation and creep



Activation barrier vs current density



- Creep is of nucleation type
- Weak pins determine creep rate

Thermal activation and creep