Evidence for line nodes in superconducting gap (*d*-wave superconductivity ?) of $(K,Na)Fe_2As_2$

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IFW-Dresden

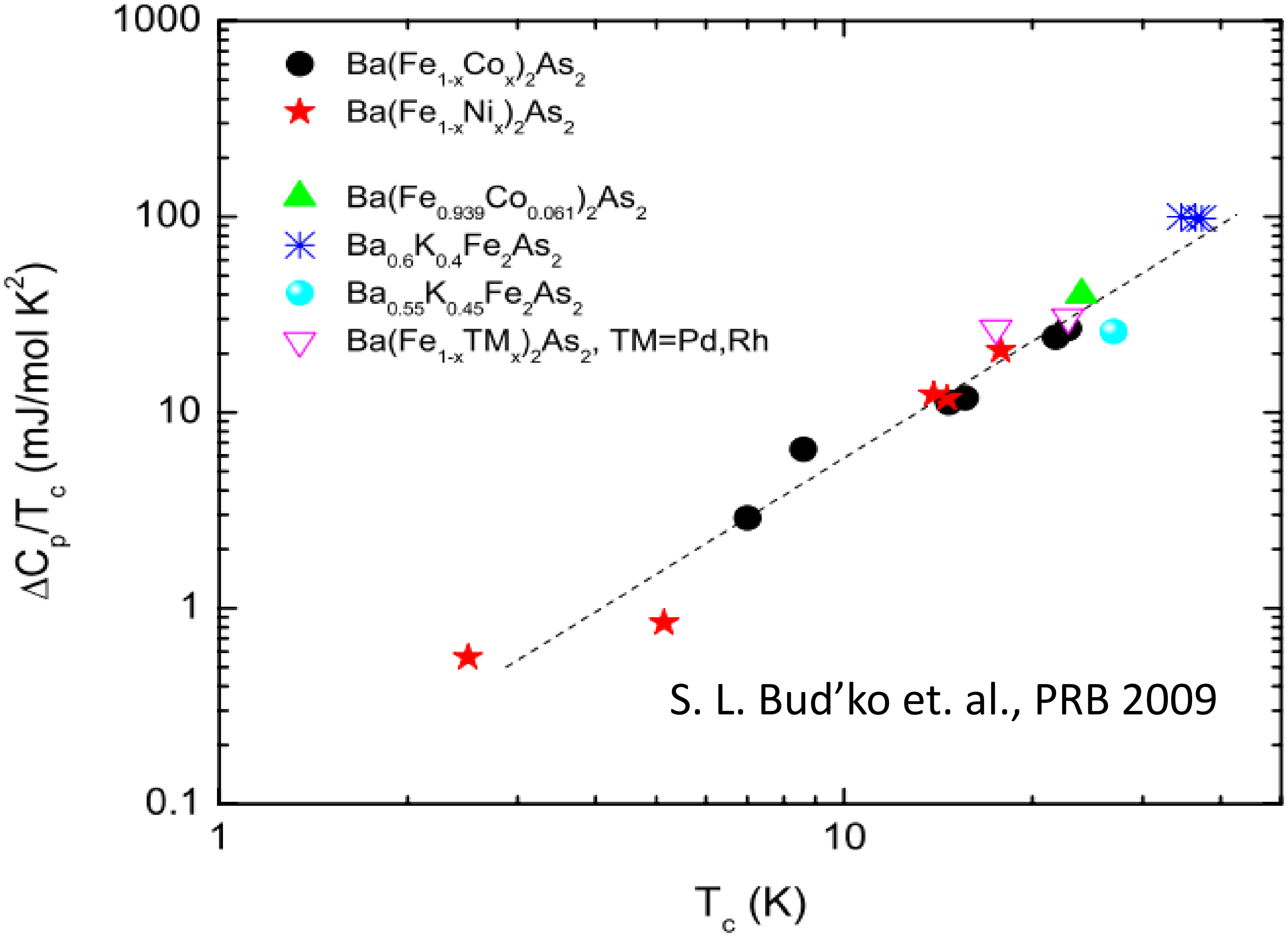
HTS-2013
Zvenigorod

Single crystals of $K_{1-x}Na_xFe_2As_2$:
S. Aswartham, I. Morozov, M. Roslova, S. Wurmehl

Experiment:
M. Abdel-Hafiez, O. Vakaliuk, D. Gruner, E. L. Green, M. Kumar, J. P. Vogt, A. Reifenberger, C. Enss, M. Hempel, R. Klingeler, A.U.B. Wolter, B. C. Hess, B. Holzapfel, J. Wosnitza, B. Büchner

Theory:
D. Efremov, S. Johnston, H. Rosner, S.-L. Drechsler, J. van den Brink

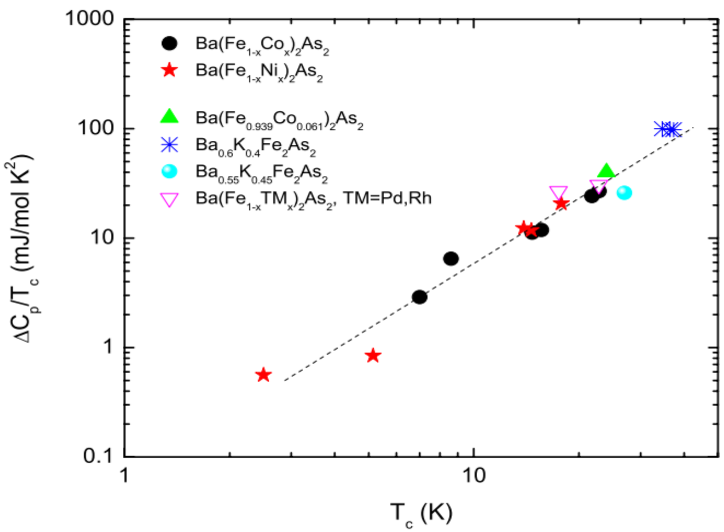
BNC scaling $\Delta C \propto T_c^3$



Empirical scaling holds for 122 iron-pnictides

BNC scaling is expected in the limit of strong pair-breaking within BCS theory for *d*-wave or *s*± SC gap

E. Pushkarov and K. Maki, Eur. Phys. J. B 4, 191 (1998)
L.A. Openov, Phys. Rev. B 69 224516 (2004)
V.G. Kogan Phys. Rev. B 80, 214532 (2009)

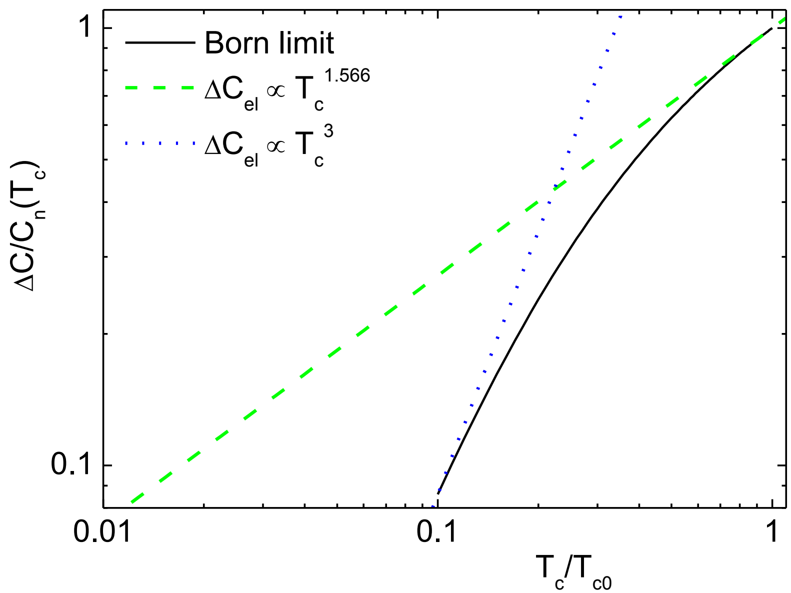


$$\Delta C = C_s - C_n = \frac{16\pi^4 k_B^4 N(0)\tau_+^2}{3\hbar^2(3\langle\Omega^4\rangle - 2)} T_c^3$$

strong pair-breaking at $T_c << T_{c0}$ for $<\Omega>=0$

T_{c0} – critical temperature in the clean limit

BNC scaling is expected in the limit of strong pair-breaking within BCS theory for *d*-wave or *s*± SC gap



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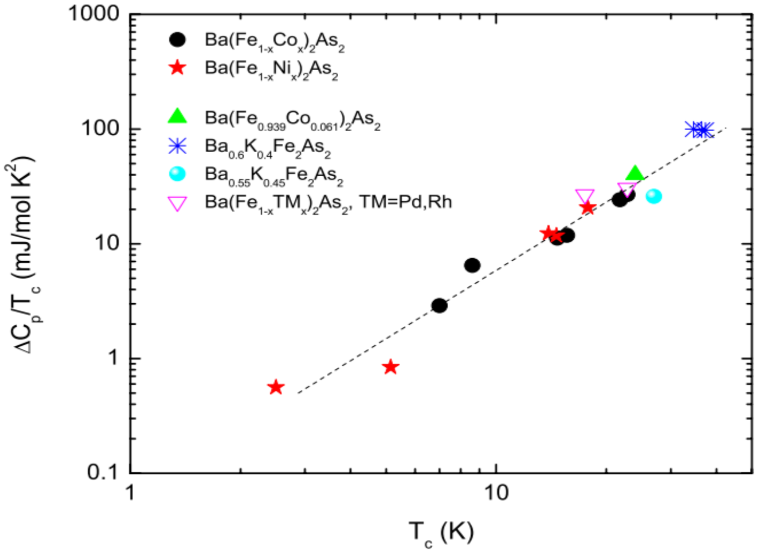
$$\Delta C = C_s - C_n = \frac{16\pi^4 k_B^4 N(0)\tau_+^2}{3\hbar^2(3\langle\Omega^4\rangle - 2)} T_c^3$$

strong pair-breaking when $T_c < 0.1T_{c0}$

T_{c0} > 400 K – critical temperature in the clean limit !

BNC scaling is expected for a quantum critical metal undergoing a pairing instability

J. Zaanen, Phys. Rev. B 80, 212502 (2009)



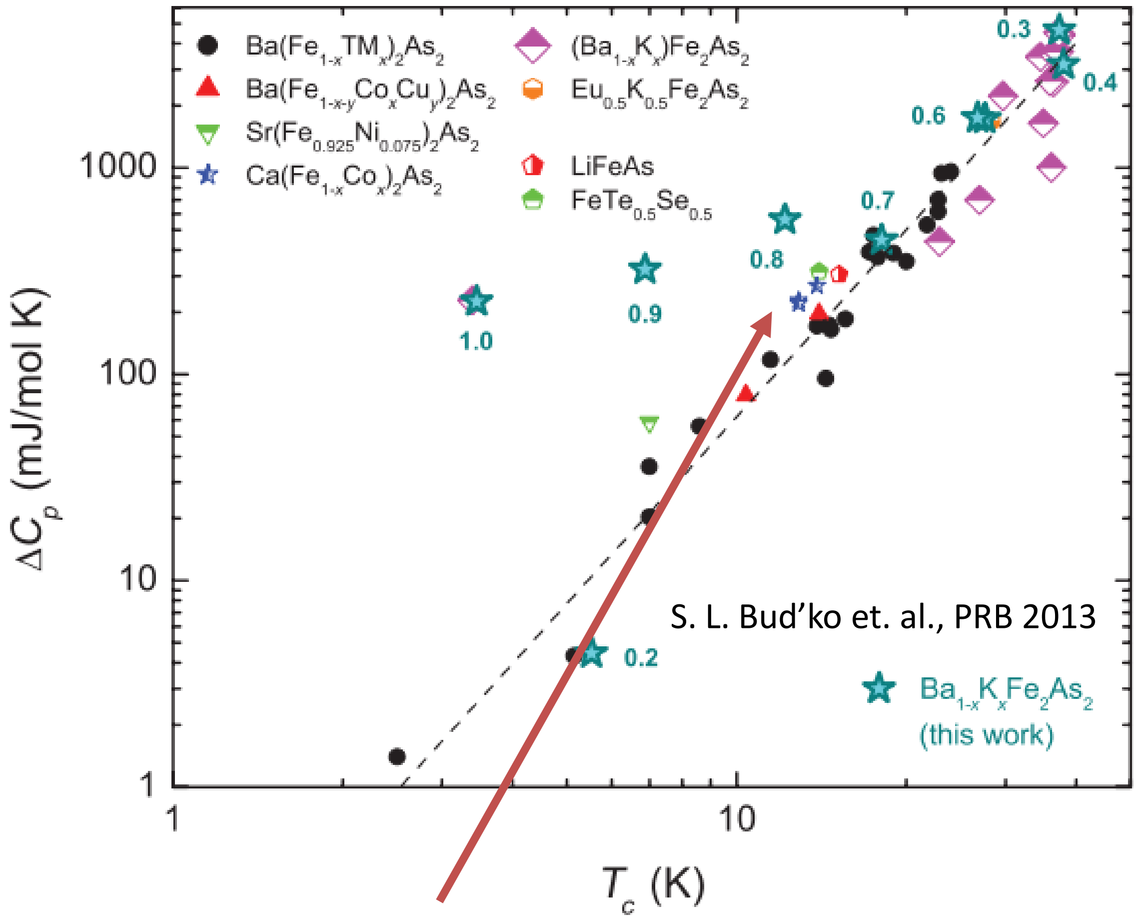
$$C_p = A_{cr}\left(\frac{T}{T_0}\right)^{d/z}$$

$\Delta C \propto T_c^3$ for three dimensional SC

$\Delta C \propto T_c^2$ for two dimensional SC

$z \sim 1$ and d is dimensionality of the space

BNC scaling $\Delta C \propto T_c^3$

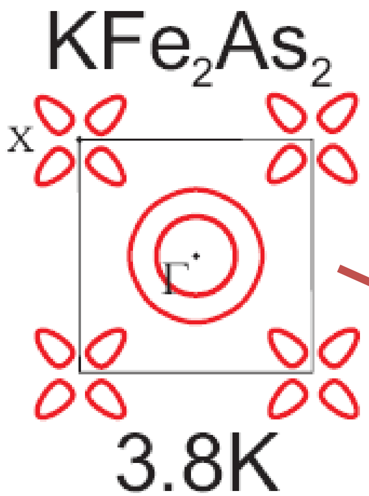


-deviation from the universal BNC curve for $K_xBa_{1-x}Fe_2As_2$ at **$x > 0.7$;**

-essential changes in superconducting state was expected

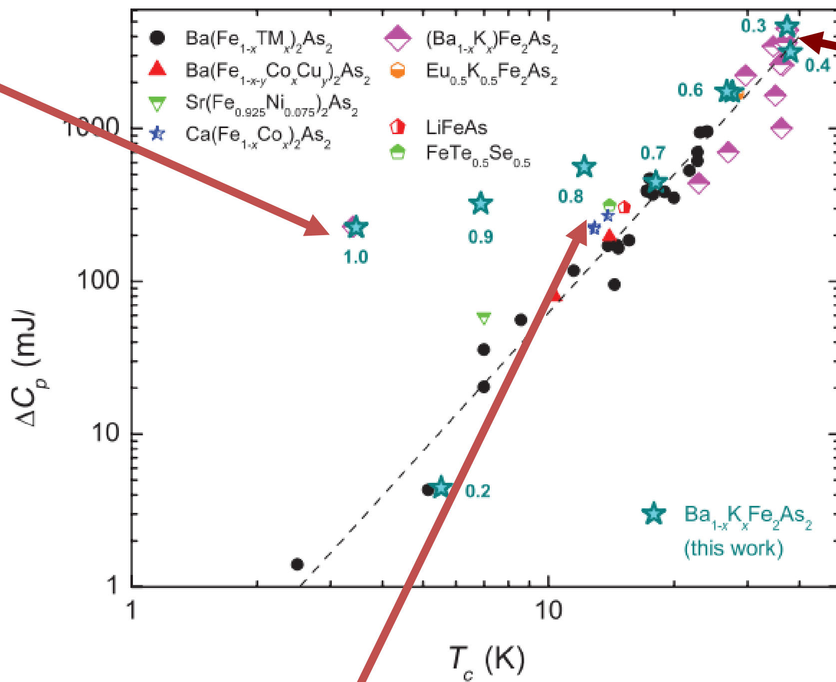
BNC scaling $\Delta C \propto T_c^3$

D. Evtushinsky at al., ARPES

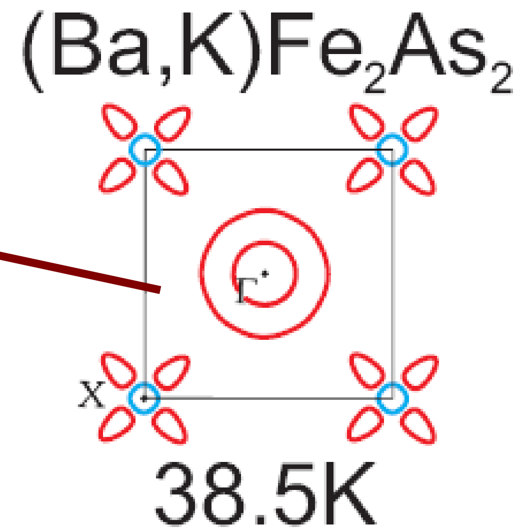


no el pockets
only h pockets
no nesting at Q=[π;π]
the gap symmetry?

S. L. Bud'ko et. al., PRB 2013



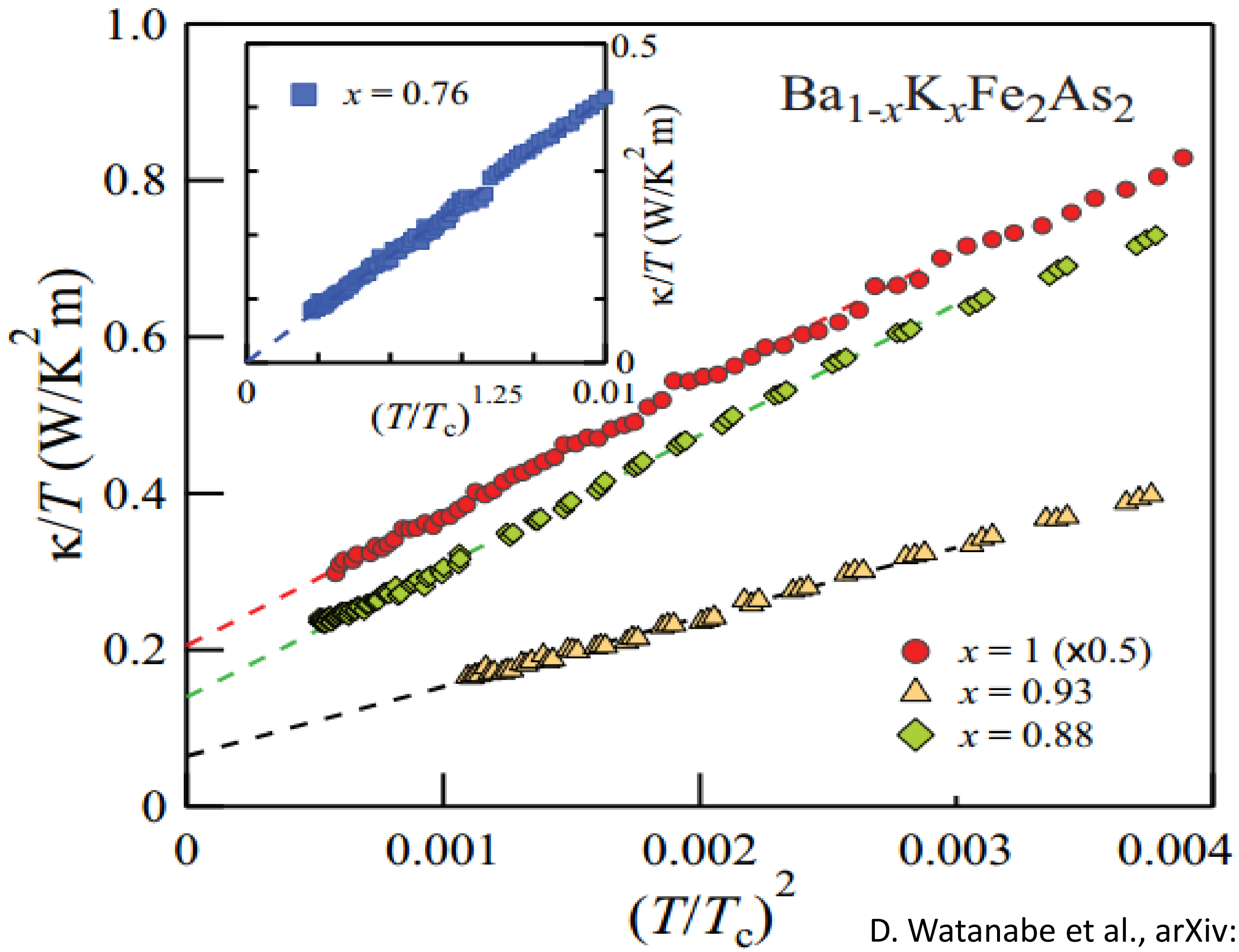
D. Evtushinsky at al., ARPES



nesting between el and h pockets is responsible for s± SC

- disappearance of electron pocket at **x > 0.7**

Thermal conductivity

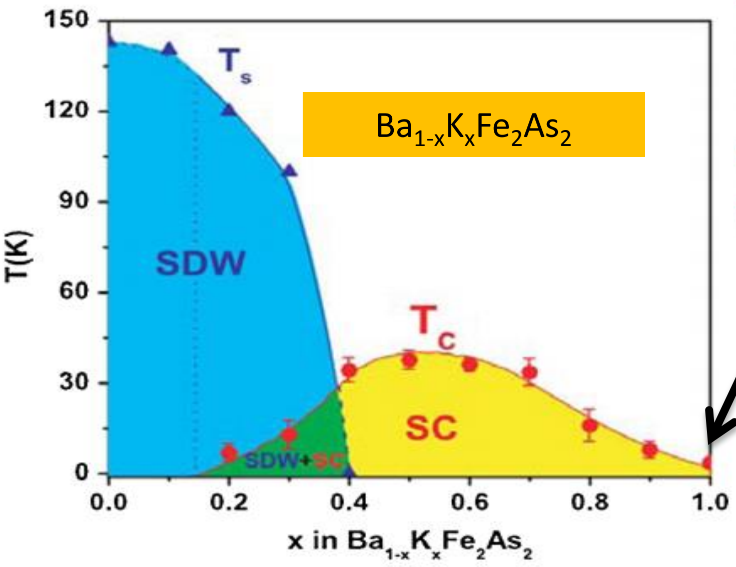


D. Watanabe et al., arXiv: 1307.3408v1

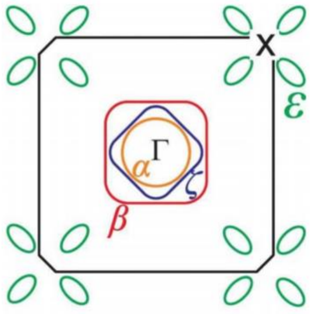
- Residual contribution to thermal conductivity
- nodes in the SC gap of $K_xBa_{1-x}Fe_2As_2$ at x > 0.7
- Non universal behavior -> s± gap with accidental nods ?

Possible gap symmetry of KFe_2As_2

No electron-like pockets

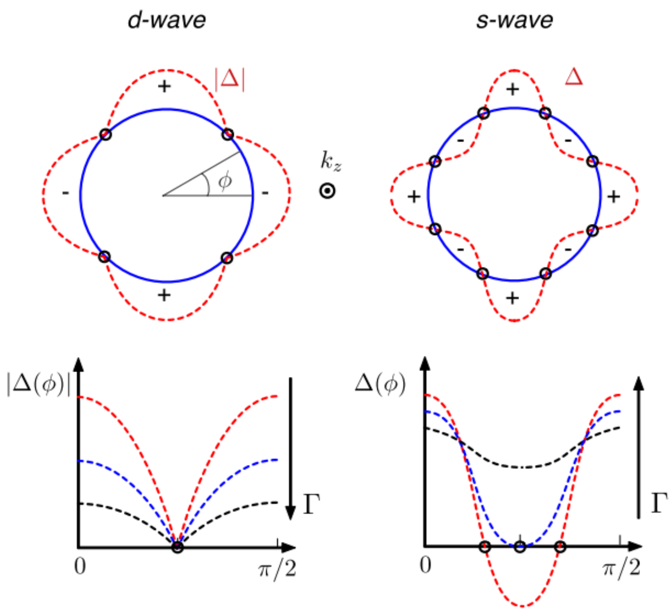


Johrendt *et al.,* (2009), H. Chen et *et al.*, 2009



K. Hashimoto, et al, PRB 2010

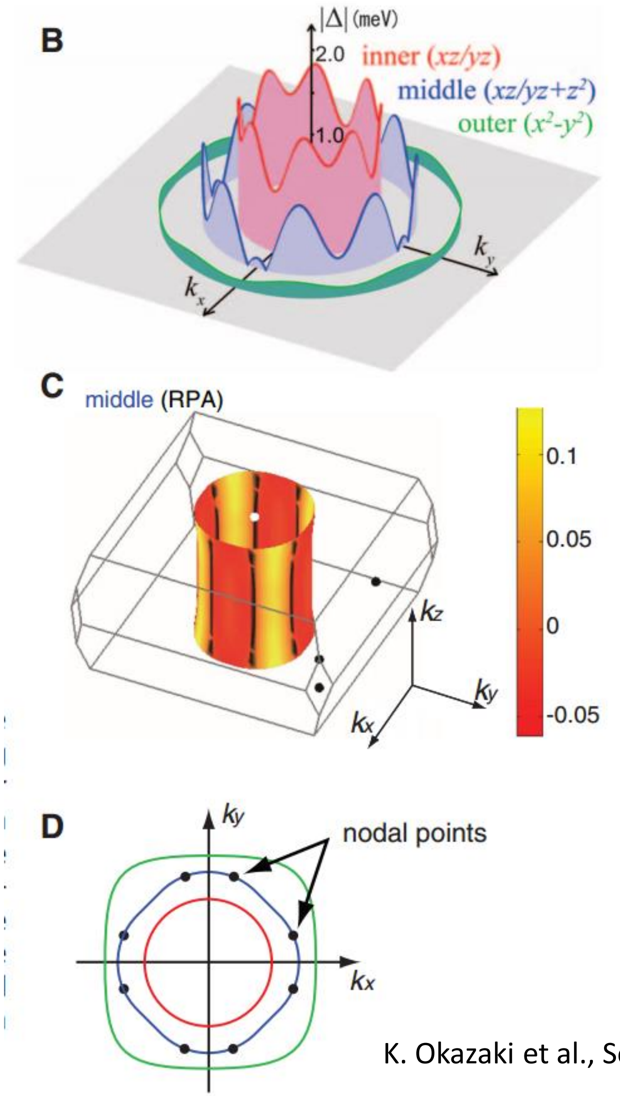
Overdoped



J-Ph Reid et al., Supercond. Sci. Technol. (2012)

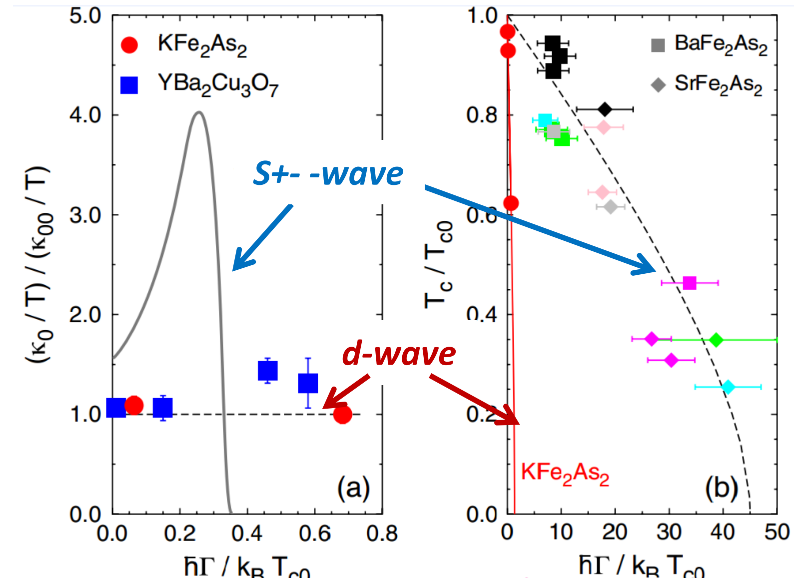
***s*± with accidental nodes or *d* – wave ?**

Superconductivity of KFe_2As_2: s_{+-} accidental nodes or d – wave ?



K. Okazaki et al., Science (2012)

J-Ph Reid et al., PRL (2012)

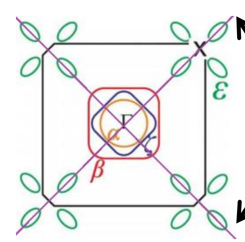


$$\Gamma = \frac{e_{el}^2 \rho_0 v_f^2 \gamma_n}{2(k_b \pi)^2}$$

Disorder independent Thermal conductivity

T_c unusually sensitivity to disorder

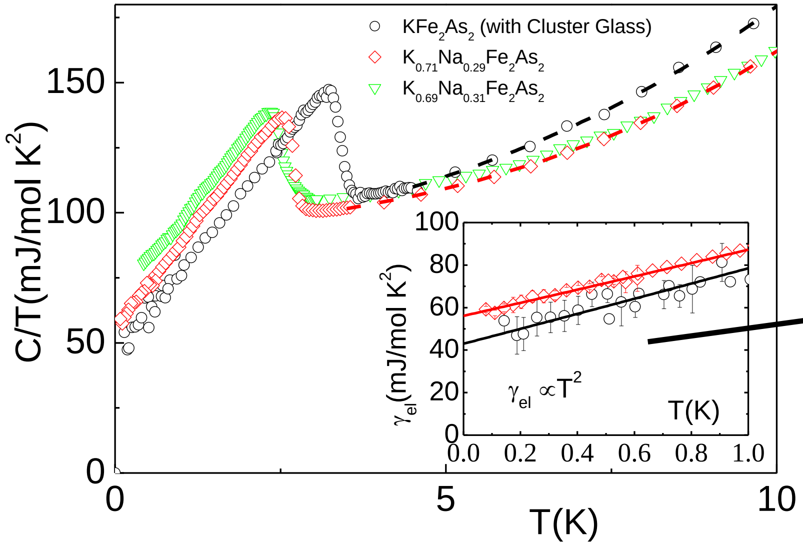
$$\Gamma_{cr} / T_{c0} \approx 0.9$$



possible nodal directions

K. Hashimoto, et al, PRB 2010

Disorder independent *line nodes* in the gap of $K_{1-x}Na_xFe_2As_2$



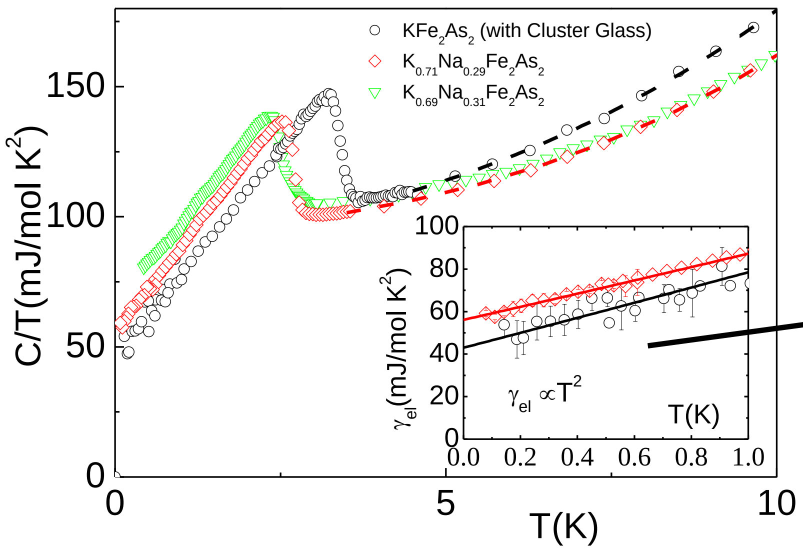
$\gamma_{\rm el} \propto \alpha_{\rm sc} T^2$

$$\alpha_{\rm sc}({\rm mJ/mol\ K^3}) \approx 0.283 \frac{\varkappa \gamma_{\rm el}({\rm mJ/mol\ K^2})}{\Delta_0({\rm meV})}$$

line nods in SC gap

M. Abdel-Hafiez, V. Grinenko et al, PRB(R) 2013

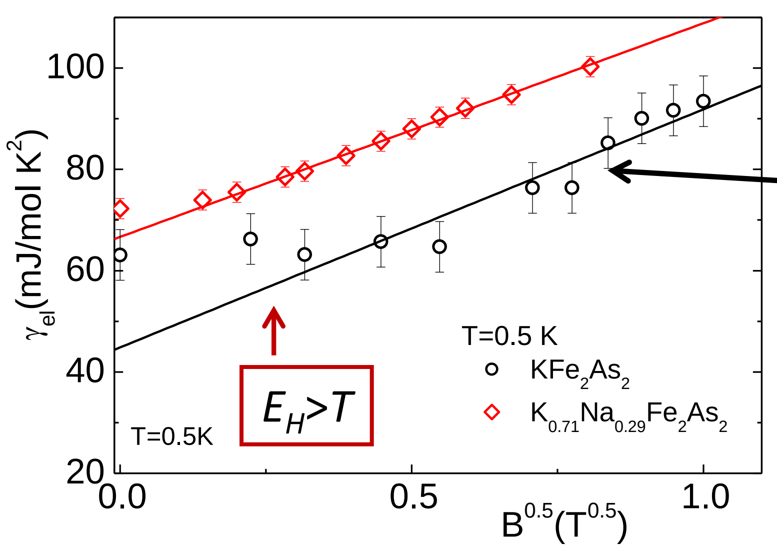
Disorder independent *line nodes* in the gap of $K_{1-x}Na_xFe_2As_2$



$$\gamma_{el} \propto \alpha_{sc} T^2$$

$$\alpha_{sc}(\text{mJ/mol K}^3) \approx 0.283 \frac{\varkappa\gamma_{el}(\text{mJ/mol K}^2)}{\Delta_0(\text{meV})}$$

B$^{0.5}$ dependence of specific heat due to Doppler shift of electrons in magnetic field



$$C(T,H) \approx \frac{2TE_H}{\pi v_f v_\Delta}\left(\frac{\pi^2}{3}M_1 + \frac{7\pi^4}{15}P(0)\frac{T^2}{E_H^2}\right)$$

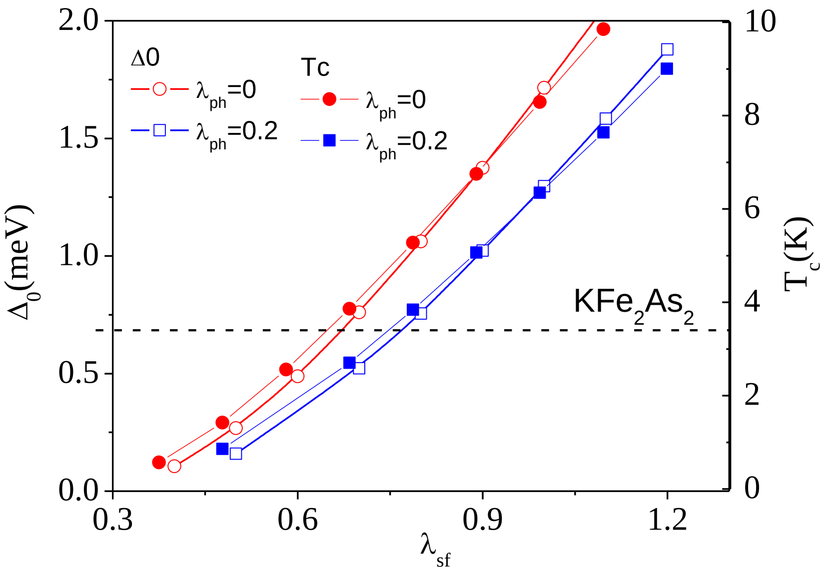
$$E_H = \hbar v_F (\pi B/\Phi_0)^{0.5}$$

$$\Delta_0^{exp} \sim 0.4 \text{ - } 0.7 \text{ meV}$$

M. Abdel-Hafiez, V. Grinenko et al, PRB(R) 2013

consistent with single-band d-wave

KFe2As2 : a two-dimensional effective single-band d-wave superconductor?



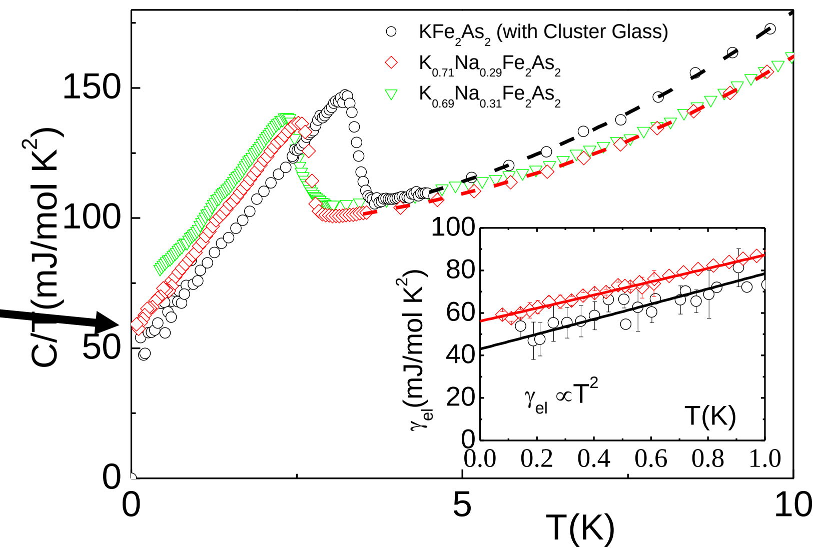
M. Abdel-Hafiez, V. Grinenko et al, PRB(R) 2013

Eliashberg theory for *d*-wave consistent with evaluated gap value:

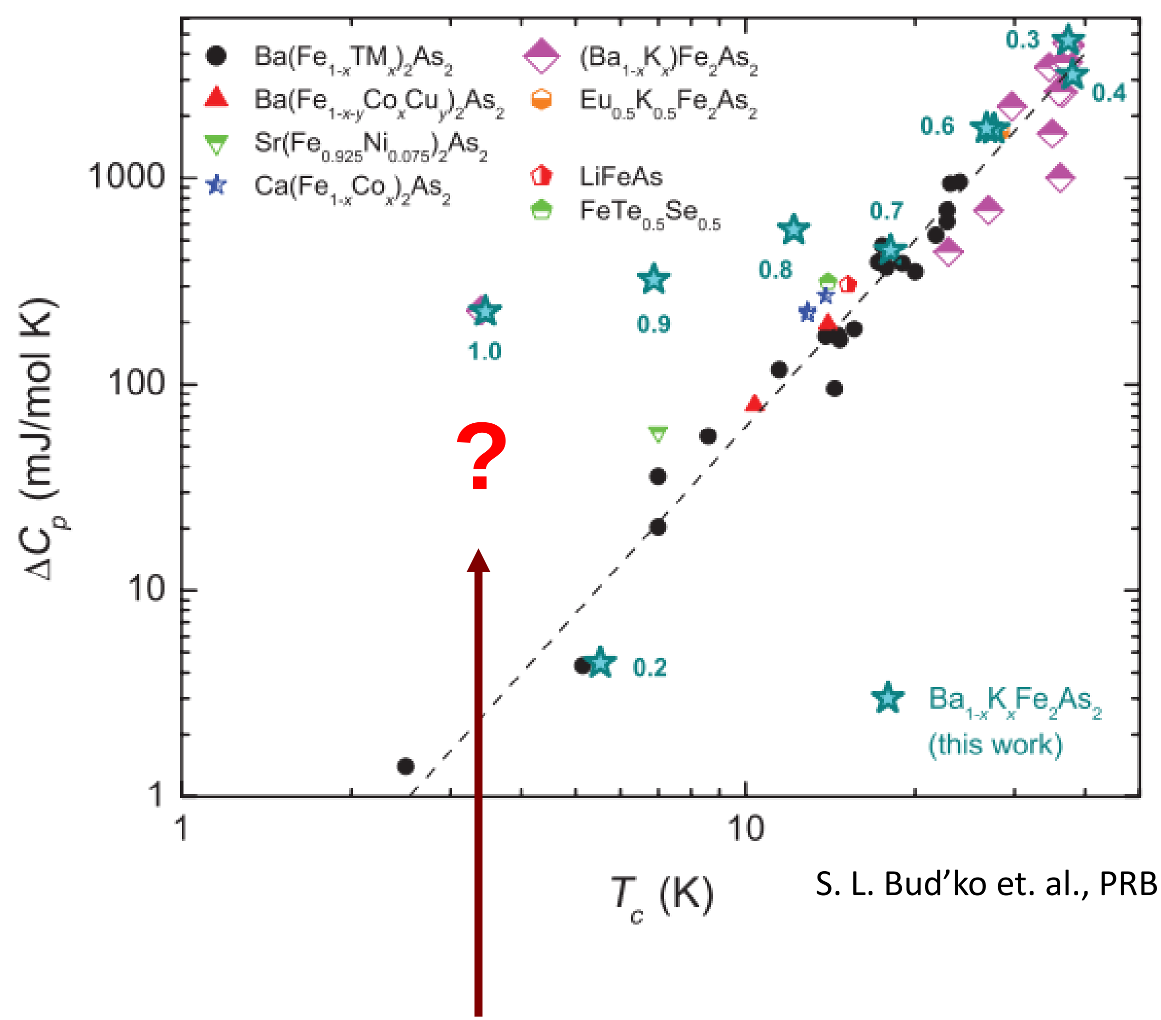
$$\Delta_0^{exp} \sim 0.4 - 0.7 \text{ meV}$$

Unusually larger residual electronic specific heat

Unpaired electrons are related to the pair-breaking du to disorder?



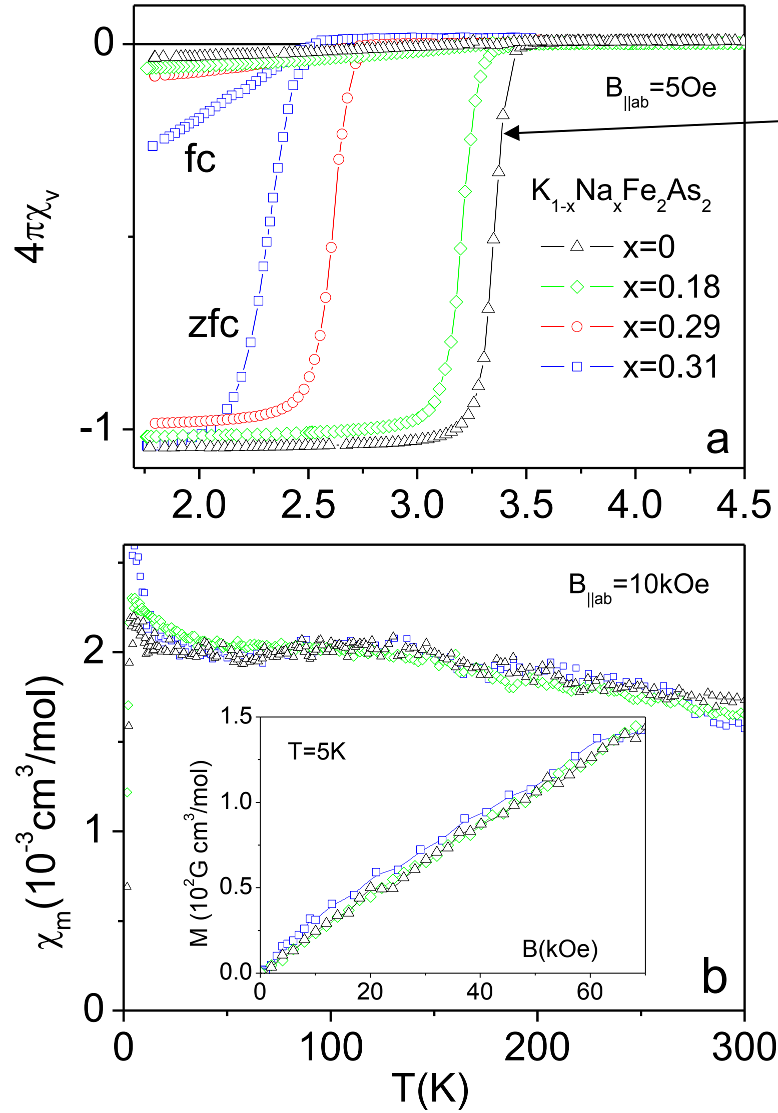
Superconducting specific heat jump ΔC for $K_{1-x}Na_xFe_2As_2$



S. L. Bud'ko et. al., PRB 2013

We fix the hole doping and vary amount of disorder induced by Na doping

Magnetic susceptibility $K_{1-x}Na_xFe_2As$

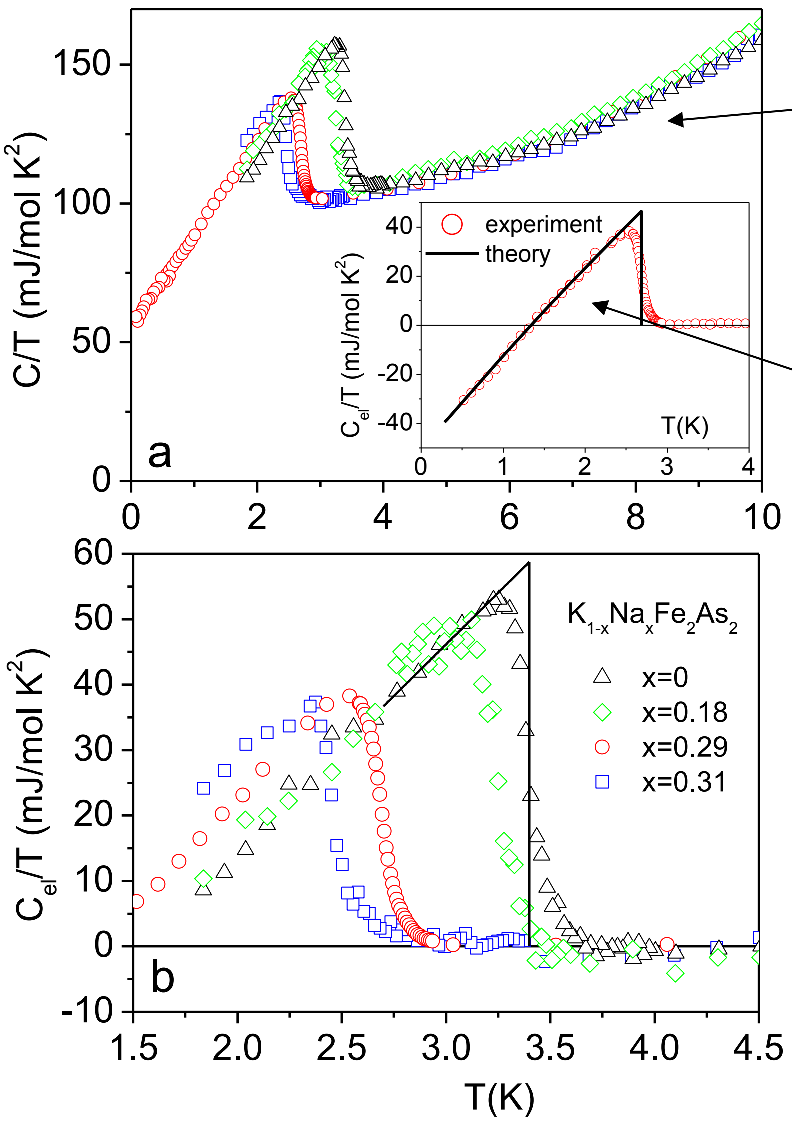


nearly parallel shift of the zfc curve with Na doping -> homogenous Na distribution

nearly *T*-independent below 100K
–> Pauli susceptibility;
independent on Na doping
-> Na doping does not change density of state;
Na is nonmagnetic impurity

V.Grinenko et al., arXiv:1308.2201

Specific heat of $K_{1-x}Na_xFe_2As$

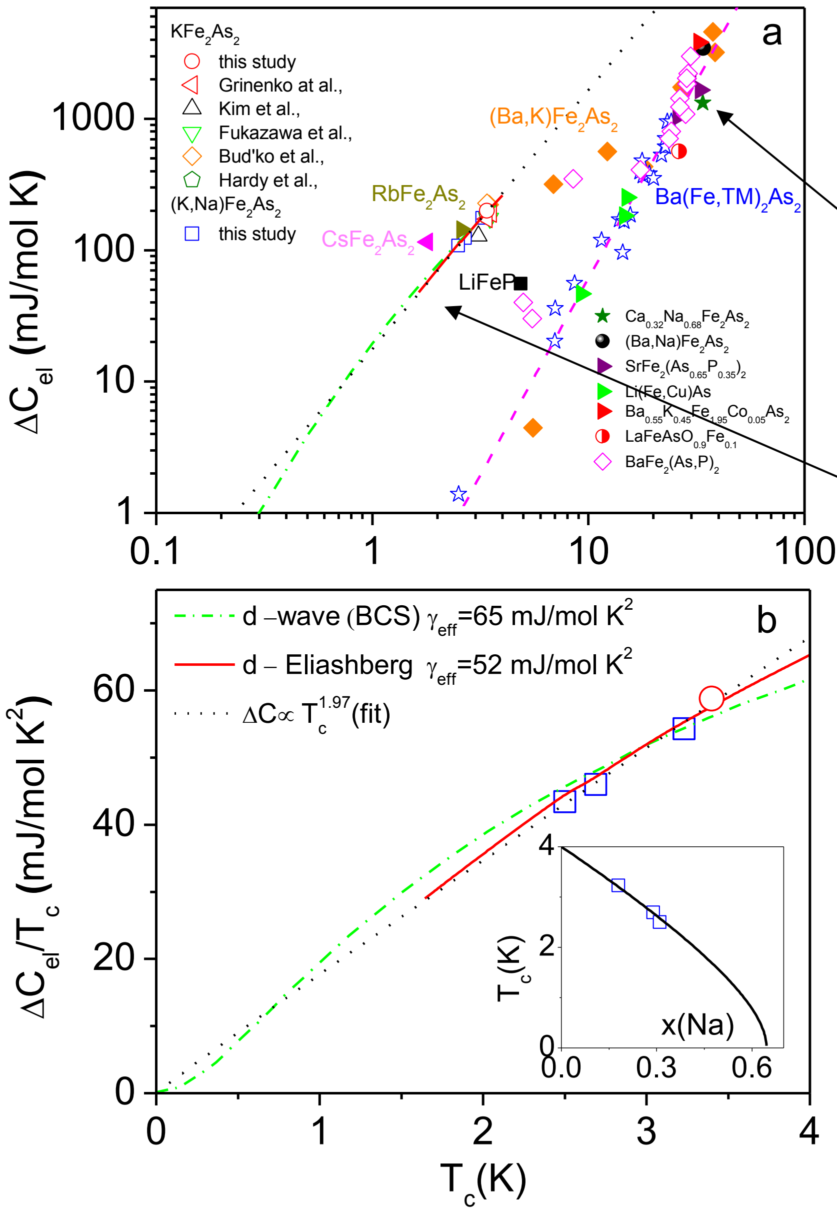


- independent on Na doping;
- does not change the correlation effect
- good agreement between experiment and Eliashberg theory for single-band *d*-wave with nonmagnetic disorder;
- unusual T^2 dependence cannot be explain by nodless s-wave gap

- Monotonic reduction of SH jump height -> pair breaking effect

V.Grinenko et al., arXiv:1308.2201

Specific heat jump at T_c



- two regions can be indentified:

i) BNC scaling $\Delta C \propto T_c^{\,3}$ for the most of iron-pnictides

ii) new scaling for $K_{1-x}Na_xFe_2As_2$

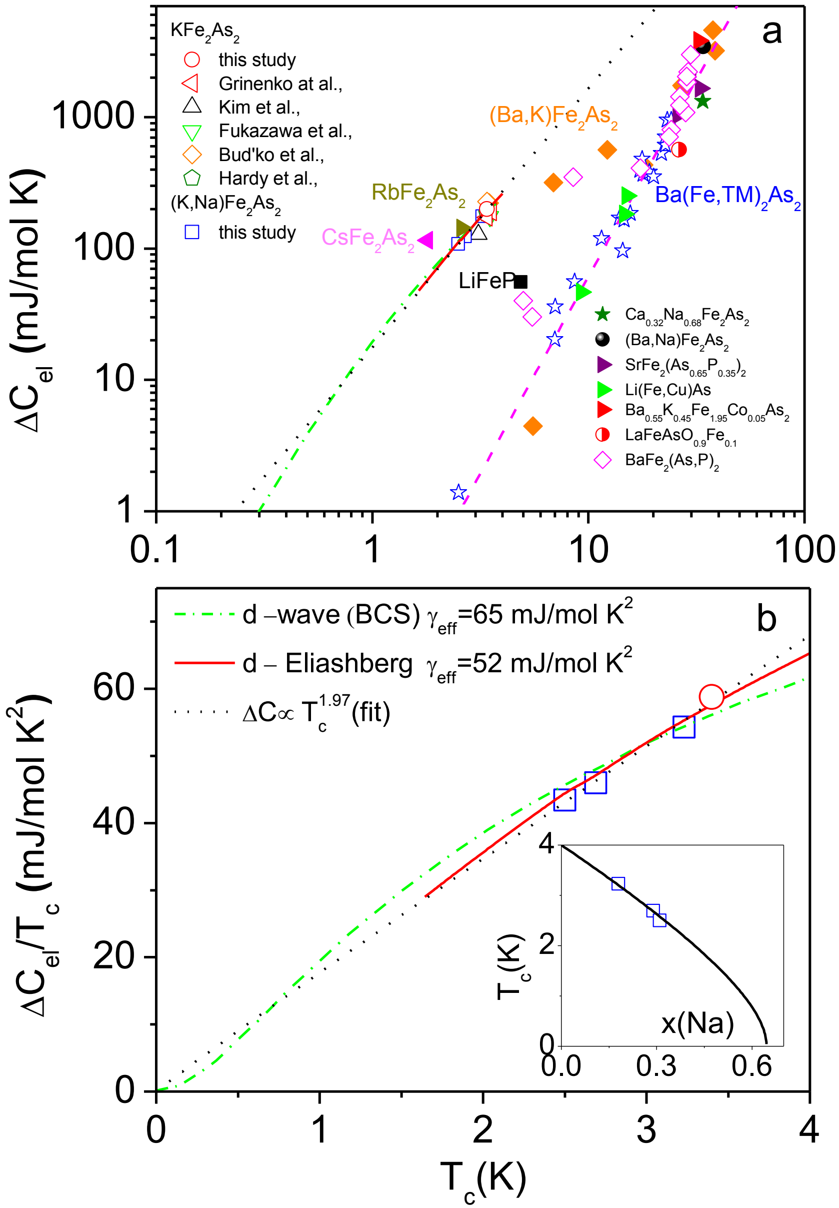
$$\Delta C \propto T_c^{\,2}$$

Consistent with d-wave SC gap but with reduced γ_{el};

Residual specific heat cannot be explained by pair-breaking due to disorder

V.Grinenko et al., arXiv:1308.2201

Open questions



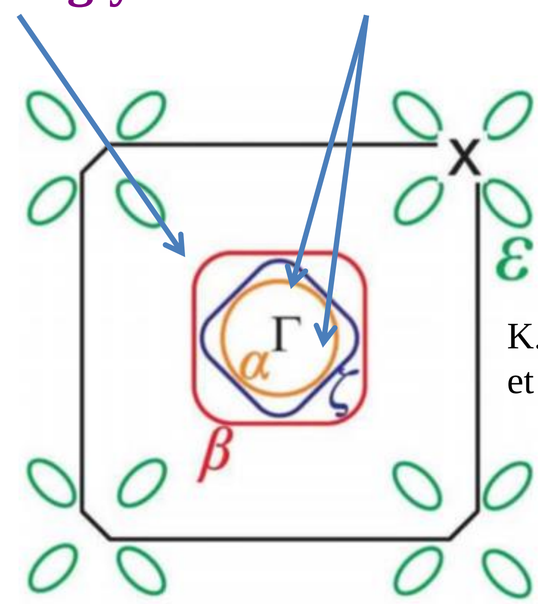
V.Grinenko et al., arXiv:1308.2201

- Part of quasiparticles does not contribute to SH jump at T_c

  $\gamma_n \sim$ 100mJ/mol K^2

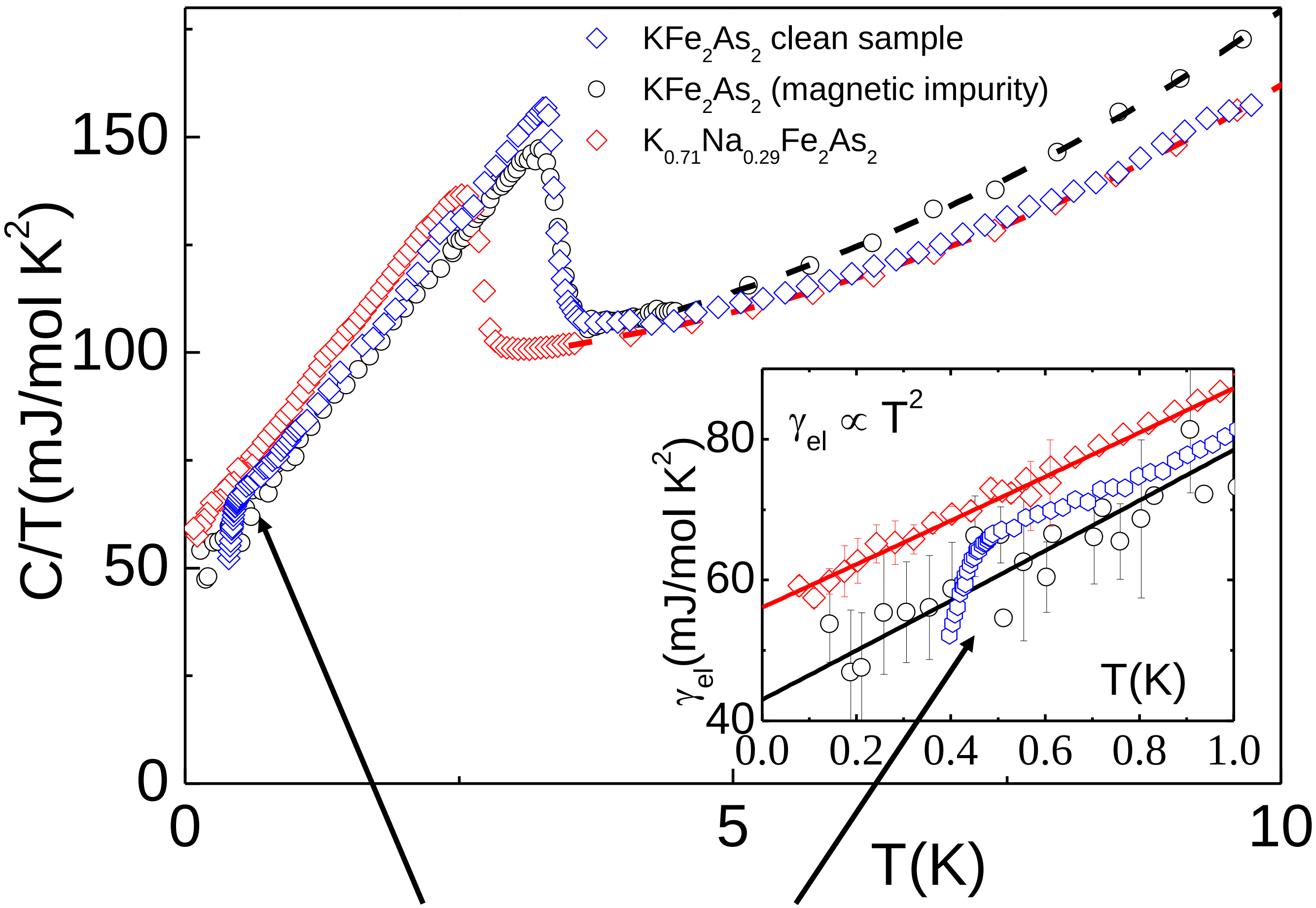
  $\gamma_{eff} \sim$ 60mJ/mol K^2

- What bands are superconducting strongly or less correlated?



K. Hashimoto, et al, PRB 2010

Possible nodal *multi-band* superconductivity of KFe_2As_2

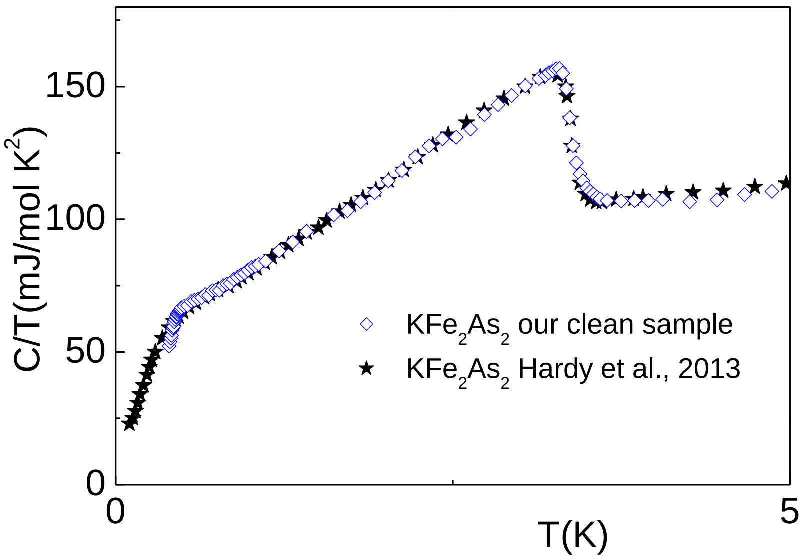


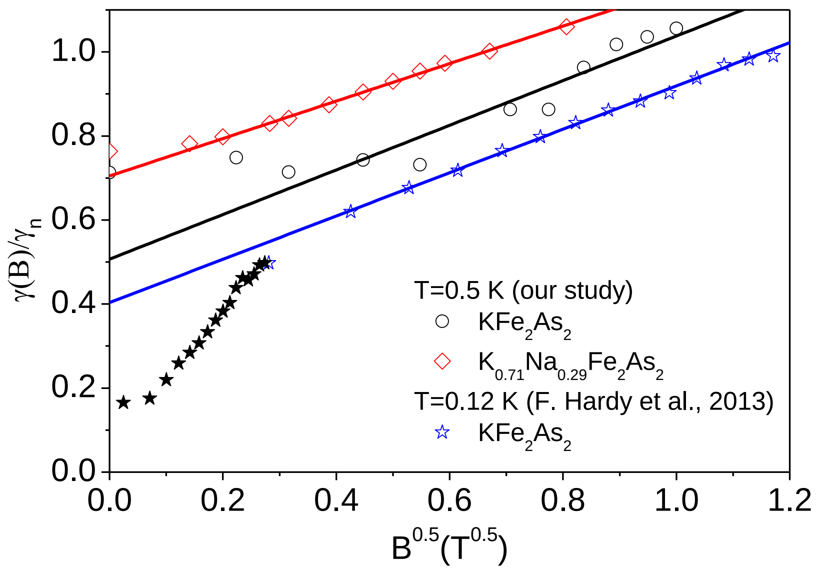
anomaly at T ~ 0.5 K in clean sample

small gaps suppressed by weak disorder;

T_c is nearly unaffected by magnetic impurity

Possible nodal *multi-band* superconductivity of KFe_2As_2

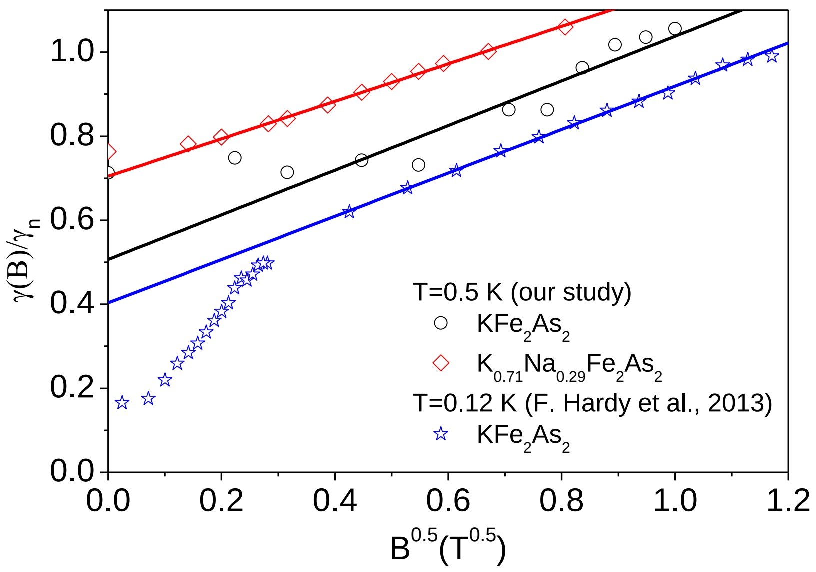




Consistent with data from F. Hardy et al., arXiv:1309.5654v1;

Low-T anomaly interpreted as small gaps

Possible nodal *multi-band* superconductivity of KFe_2As_2



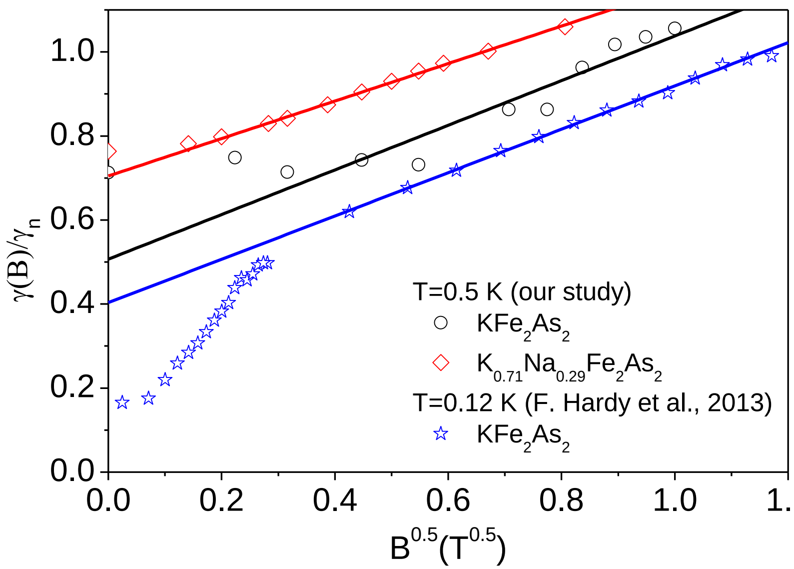
$B^{0.5}$ dependence of specific heat due to Doppler shift of electrons in magnetic field

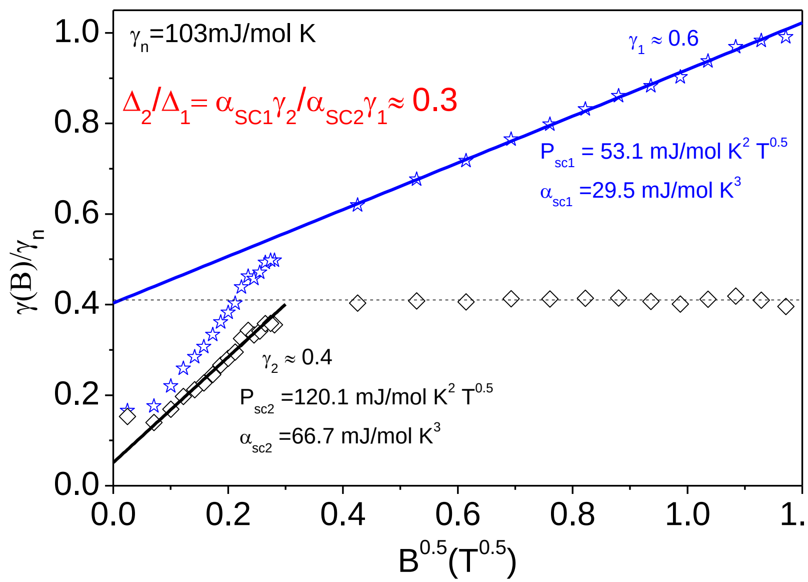
$$C(T,H) \approx \frac{2TE_H}{\pi v_f v_\Delta}\left(\frac{\pi^2}{3}M_1 + \frac{7\pi^4}{15}P(0)\frac{T^2}{E_H^2}\right)$$

$$E_H = \hbar v_F (\pi B/\Phi_0)^{0.5}$$

Possible nodal *multi-band* superconductivity of KFe_2As_2

F. Hardy et al., arXiv:1309.5654v1





$B^{0.5}$ dependence of specific heat due to Doppler shift of electrons in magnetic field

$$\frac{\Delta_1}{\Delta_2} = \frac{\alpha_1 \gamma_2}{\alpha_2 \gamma_1} \approx 0.3$$

$$C(T,H) \approx \frac{2TE_H}{\pi v_f v_\Delta}\left(\frac{\pi^2}{3}M_1 + \frac{7\pi^4}{15}P(0)\frac{T^2}{E_H^2}\right)$$

$$E_H = \hbar v_{\mathrm{F}} (\pi B/\Phi_0)^{0.5}$$

$$\alpha_{\mathrm{sc}}(\mathrm{mJ/mol\ K^3}) \approx 0.283\frac{\varkappa \gamma_{\mathrm{el}}(\mathrm{mJ/mol\ K^2})}{\Delta_0(\mathrm{meV})}$$

consistent with multi-band nodal superconductivity (*d*-wave ?)

Conclusion

Disorder under control:
the powerful tool to investigate physical properties of iron-pnictides

•Disorder suppresses small gaps and results in the large residual electronic specific heat;

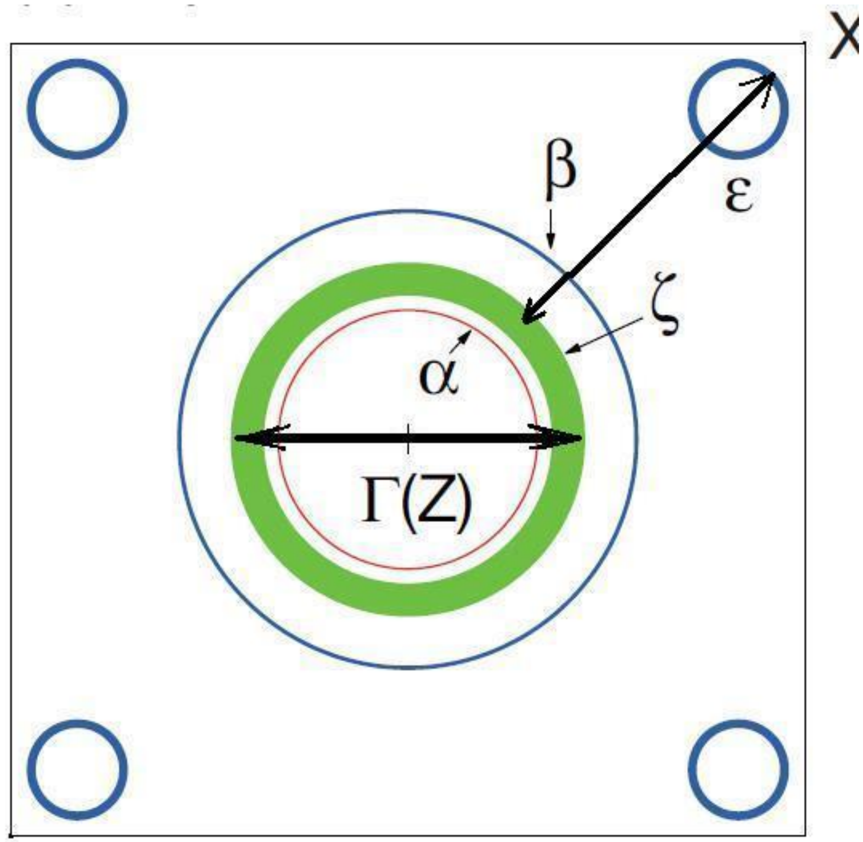
•Nodes in the large superconducting gap stable against disorder: evidence for *d*-wave;

•Conventional behavior of $\Delta C_{el} \propto T_c^2$ for unconventional Fe-pnictides, also consistent with *d*-wave superconductivity;

•Nodal multi-band superconductivity, in clean samples;

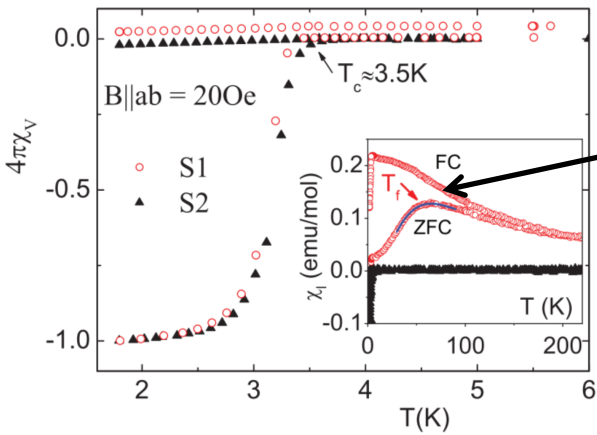
Thank you for attention!

T. Terashima et al., 1304.6469v2



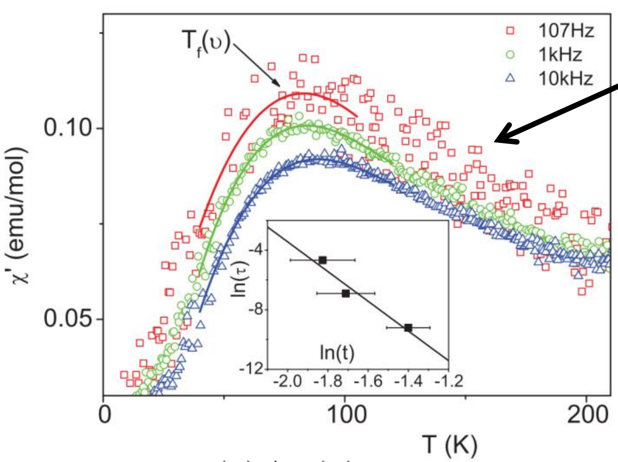
Critical behavior I: susceptibility

DC susceptibility



Hysteresis in the normal state
between zero field cooled
and field cooled curves
***T_f* - freezing temperature**

AC susceptibility



$$t = T_f(\nu)/T_f(0) - 1$$

Frequency shift of the maximum in AC susceptibility
shows conventional power-law divergence
of critical slowing down

$$\tau = \tau_0 \left[\frac{T_f(\nu)}{T_f(0)} - 1\right]^{-z\nu'}$$

$z\nu' = 10$ the dynamic critical exponent

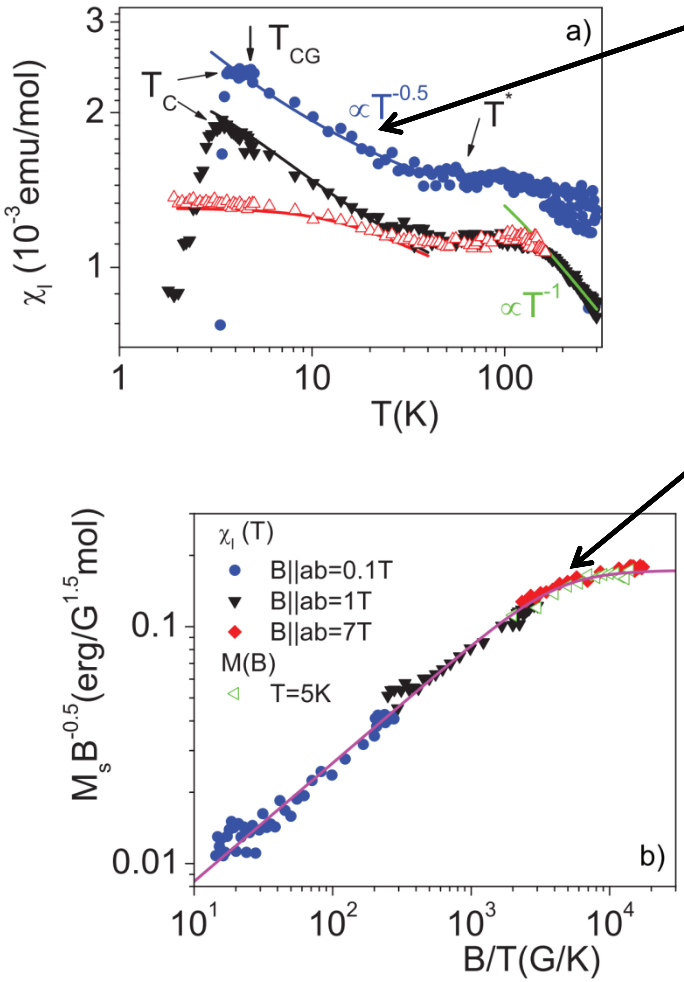
$\tau_0 = 6.9 \times 10^{-11}$ s relaxation time of a single spin flip

Cluster Glass phase

V. Grinenko et al., Phys. Status Solidi B (2013)

Non – universal critical behavior

DC susceptibility



Power low behavior at low temperatures

Scaling with a non-universal exponent λ_G = 0.5
and effective magnetic moment μ~3.5 μ_B

$$M_s(T,B) = B^{1-\lambda_G} Y\left(\frac{\mu B}{k_b T}\right)$$

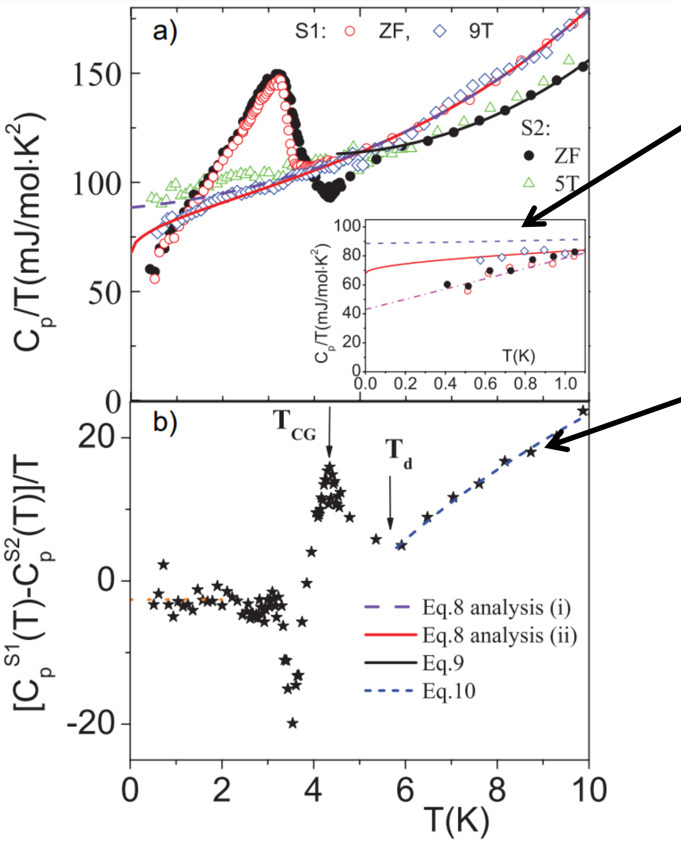
$$Y(z) = A'/(1+z^{-2})^{\lambda_G/2}$$

Griffiths phase - like behavior

V. Grinenko et al., Phys. Status Solidi B (2013)

Critical behavior II: specific heat

V. Grinenko et al., Phys. Status Solidi B (2013)

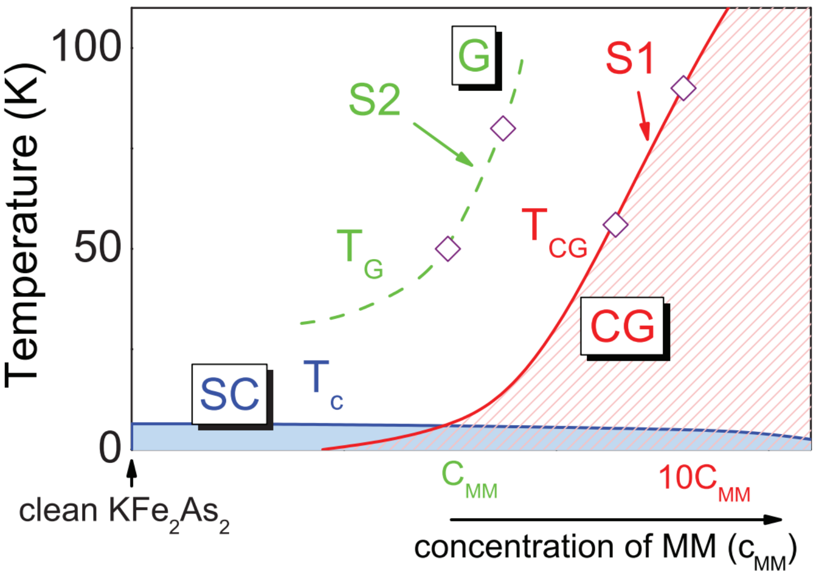


At low-T: $C_{CG} \approx \gamma_{CG} T + \varepsilon_{CG2} T^2$

The same the non-universal exponent λ_G = 0.5 in specific heat

$$[C_p^{S1}(T) - C_p^{S2}(T)]/T = C_{CG}^{S1}/T - \gamma_G T^{\lambda_G - 1}$$

Schematic phase diagram



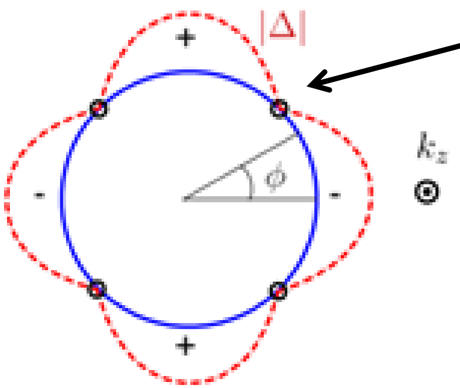
SC –superconductivity

G – Griffiths phase

CG – Cluster glass phase

Specific heat of d - wave SC

$\Delta_{\mathbf{k}} = \Delta_0 \cos 2\theta_{\mathbf{k}}$



The quasiparticle excitation spectrum at low-T

$$E_k = \hbar\sqrt{v_{\mathrm{F}}^2 k_\perp^2 + v_\Delta^2 k_\parallel^2}$$

contribution from the parts of the Fermi surface in the vicinity of the nods

$$v_\Delta \approx \partial\Delta/\hbar\partial k$$

$$\partial\Delta/\partial k = \partial\Delta/\partial\theta \frac{1}{k_f}$$

(DOS) linear in-energy

$$N_{SC}(E) = \sum_i \frac{E}{\pi\hbar v_f^i \partial\Delta^i/\partial k} \approx \frac{E}{\partial\Delta/\partial\theta} \sum_i \varkappa^i N^i(\varepsilon_f)$$

At T-> 0 electronic specific heat:

$$C_{SC} \propto \alpha_{sc} T^2$$