Phase Diagram of Pnictide Superconductors

Interplay between magnetism, structure, and superconductivity

Leibniz-Institut
für Festkörper- und
Werkstoffforschung
Dresden

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High Temperature Superconductivity in FeAs Compounds

OUTLINE

- **Introduction**
- **Phase Diagram of $LaFeAsO_{1-x}F_x$ (and other pnictides)**
  Structural, magnetic, and superconducting transitions
- **Superconducting State**
  Gap, penetration depth, relaxation rate
- **Normal State Properties**
  Electronic Structure (XAS, PES, ARPES)
  „Pseudogap“ (NMR, χ)
  Electronic transport and spin fluctuations
  Charge inhomogeneity (NQR)

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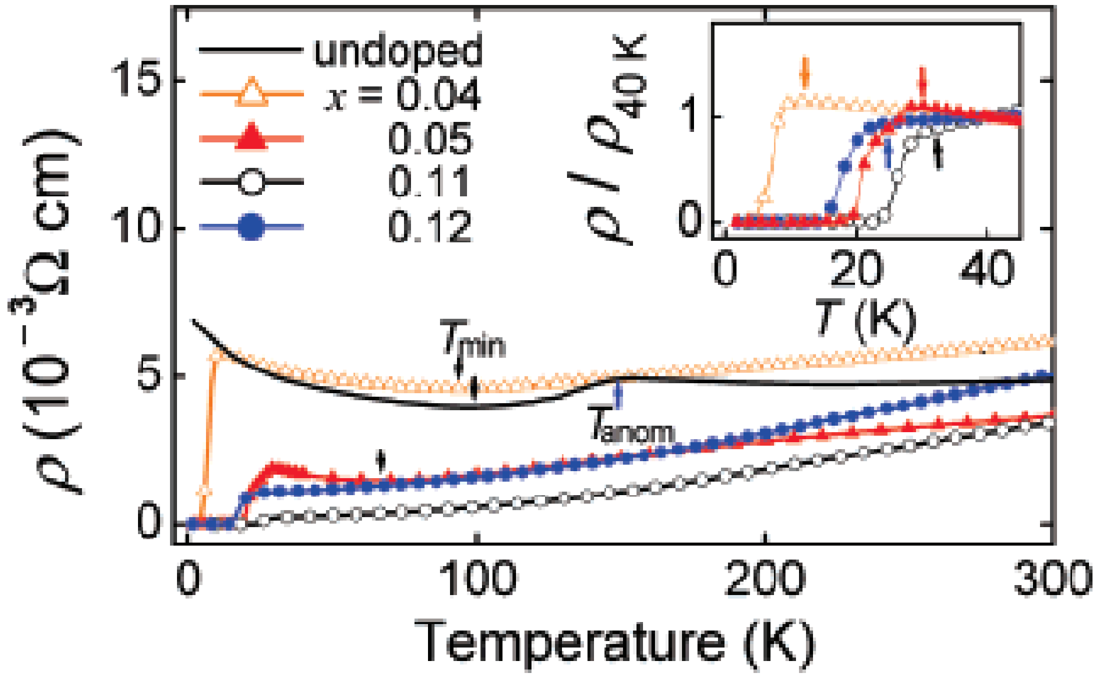
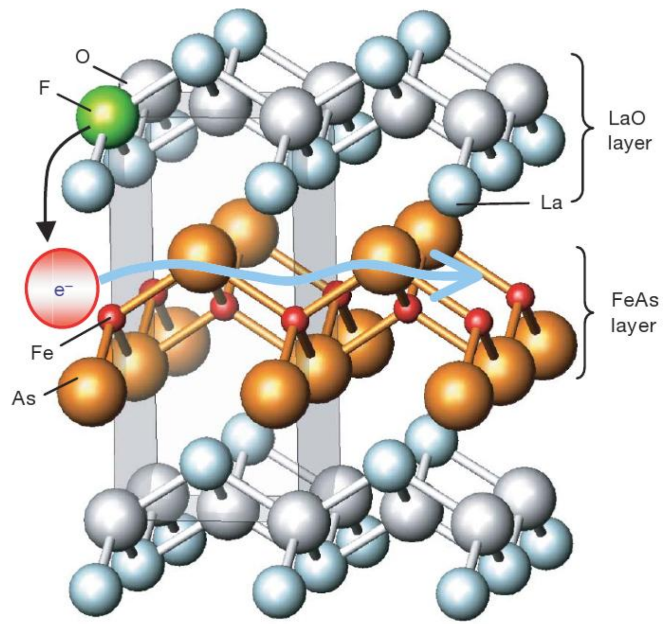
Superconductivity in $La(O_{1-x}F_x)FeAs$: The initiation



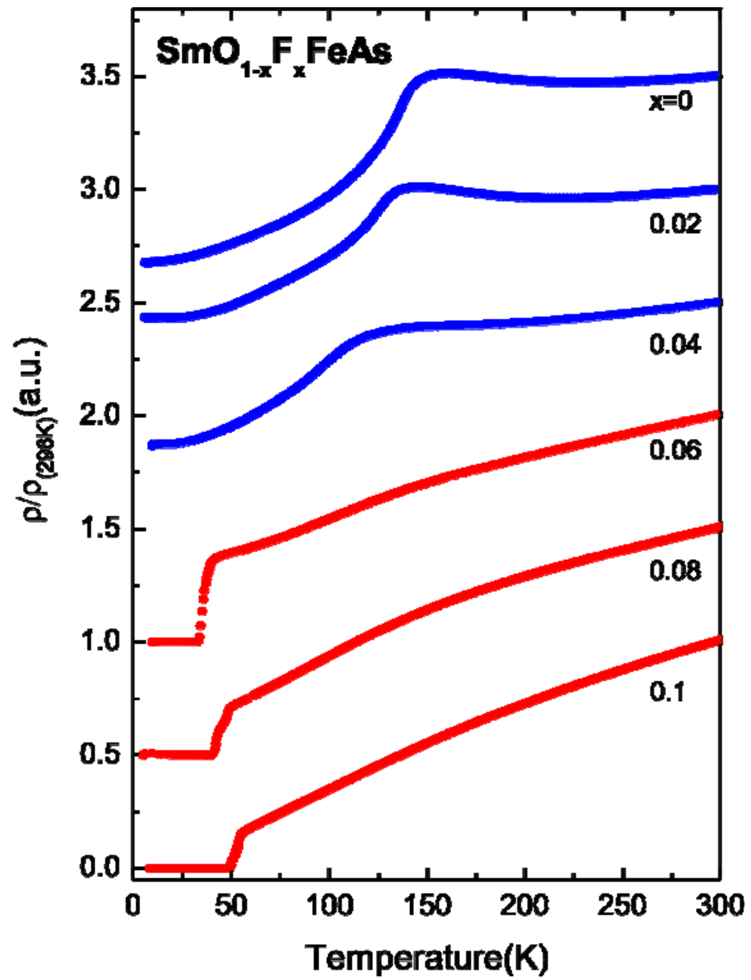
Y. Kamihara et al.,
J. Am. Chem. Soc. 130, 3296 (2008)
Februrary 2008

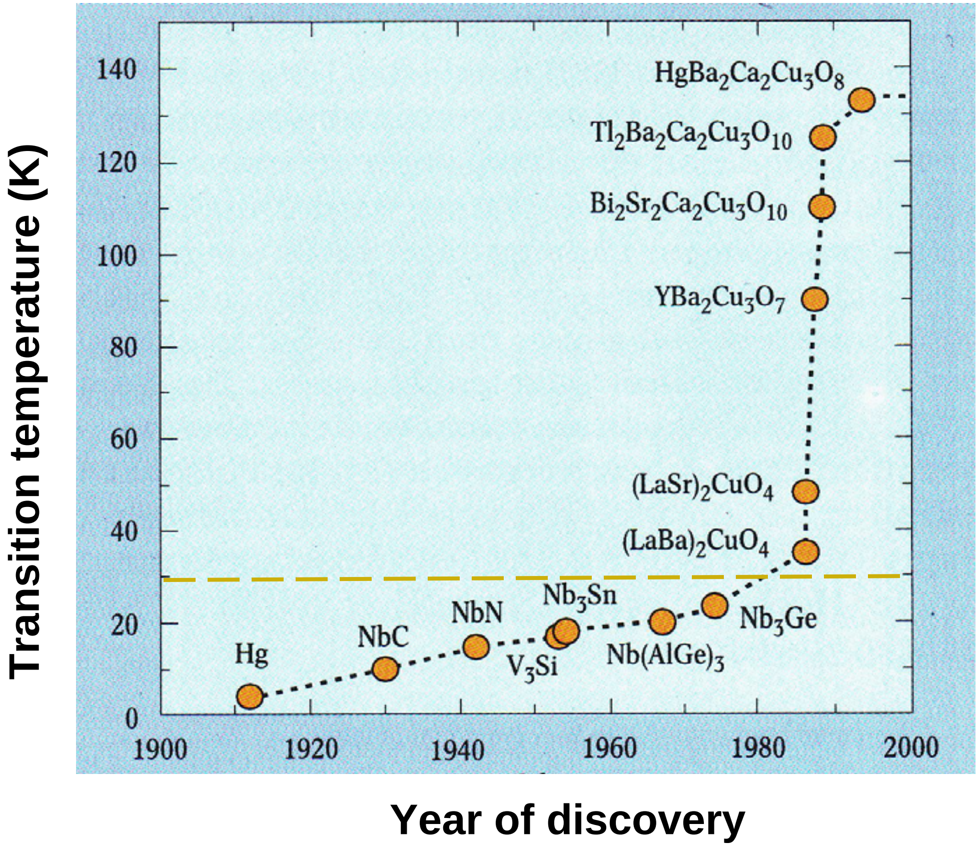


Picture: H. Takahashi et al.,
Nature 453, 376 (2008)

Dec. 2008: More than 600 papers on pnictide superconductors

Superconductivity above 50 K



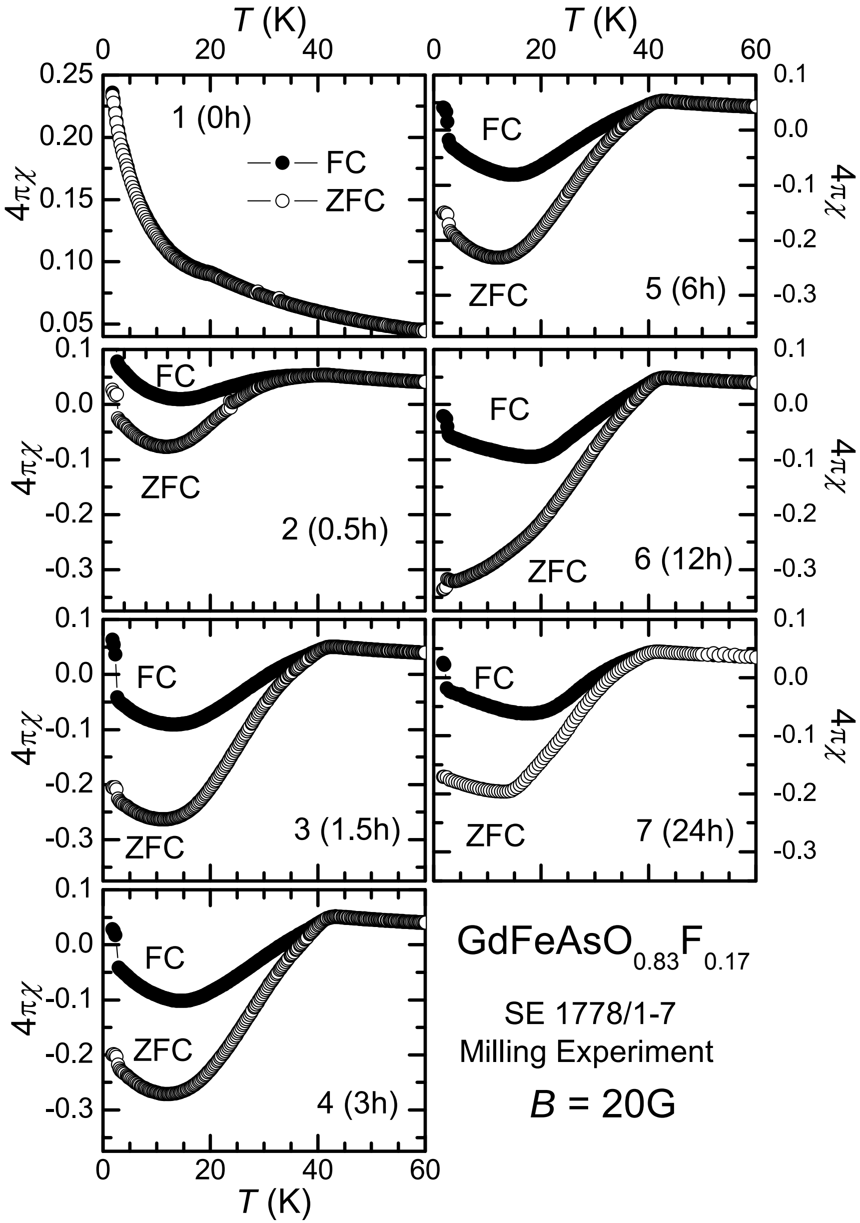


C. Hess et al., EPL (2009)

similar data: e.g. Ren et al. Chin Phys. Lett. 2008

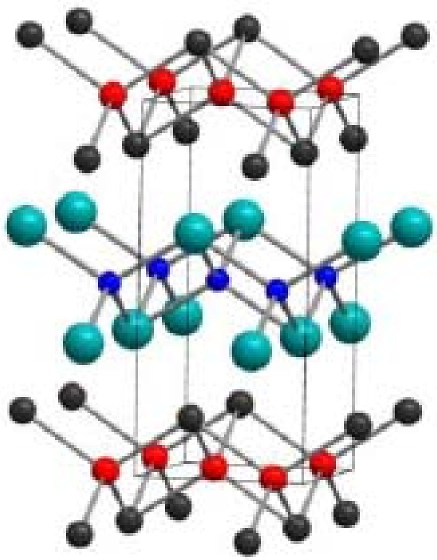
Superconductivity above 50 K

La → …. Sm … → Gd



S. Wurmehl et al, work in progress

Fe pnictides: A class of high T_c superconductors



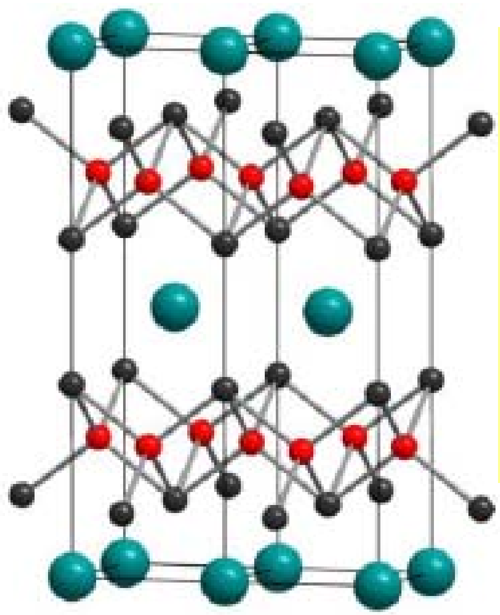
LaFeAsO

1111 systems

La, Ce … Gd-based
F, O doped

F doped REOFeAs
O defici. REOFeAs

Sm doped SrFFeAs



$Ba(FeAs)_2$

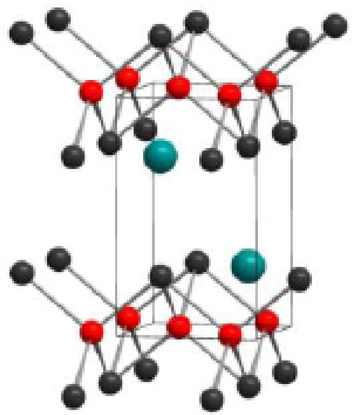
122 systems

Ba, Sr, Eu, Ca- based
K, Na, **Co** doped

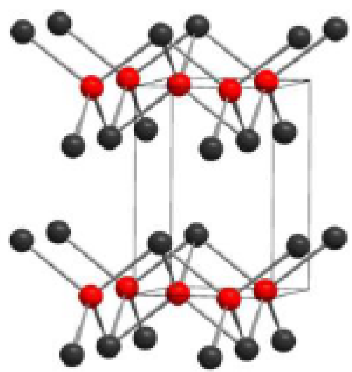
T_c up to 39 K

Intermetallic comp.
Single crystals

M. Rotter, M. Tegel, and D. Johrendt PRL 2008

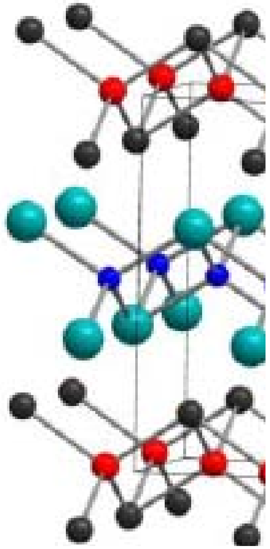


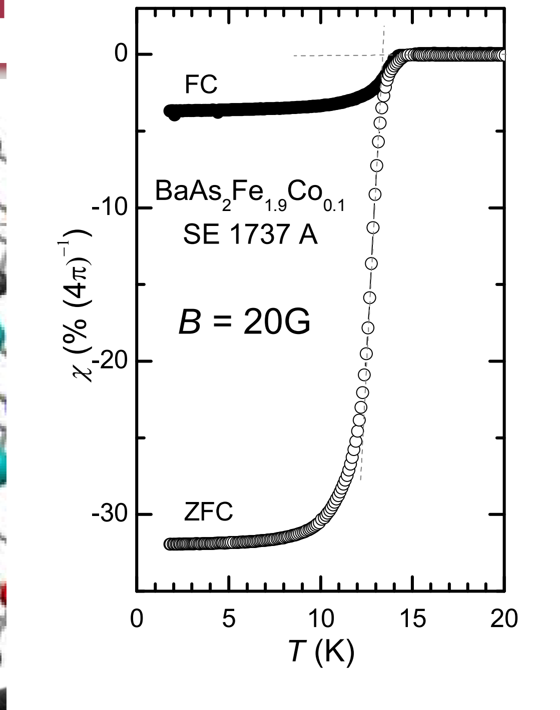
LiFeAs



FeSe

Fe pr… of high T_c superconductors





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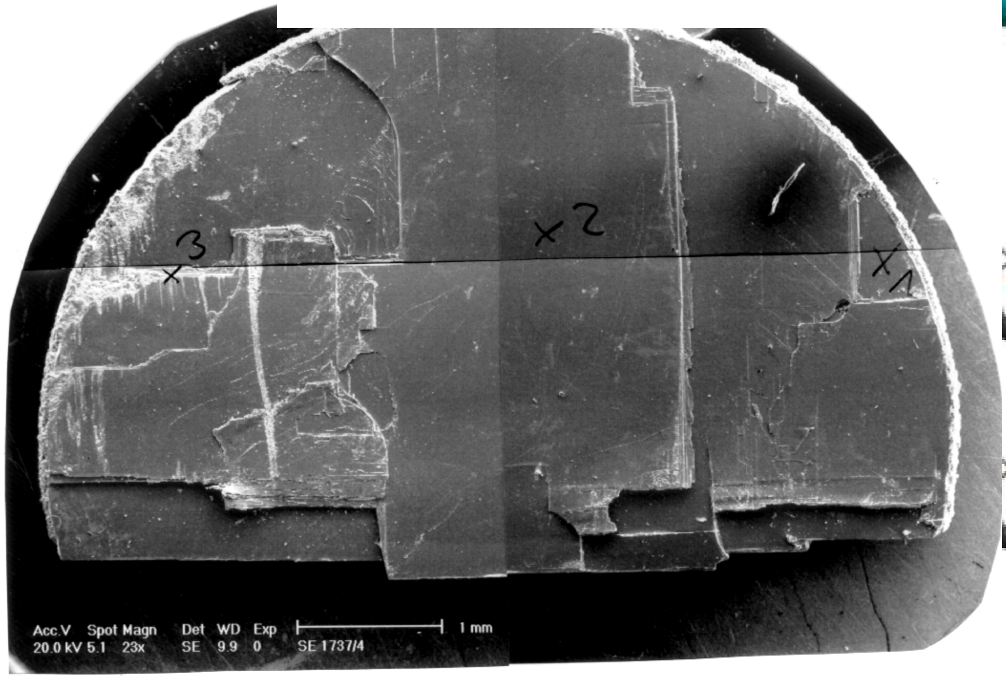

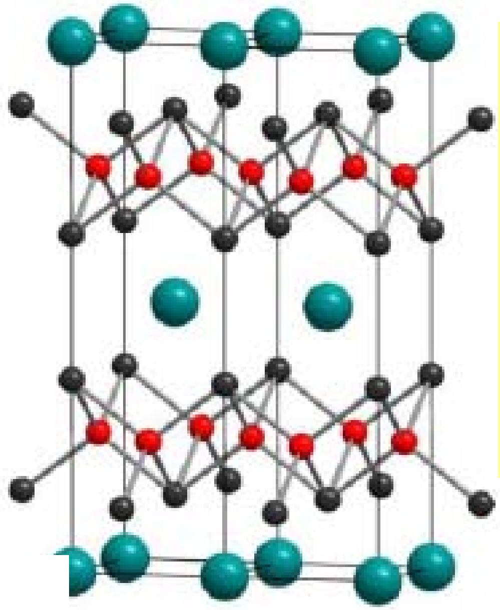

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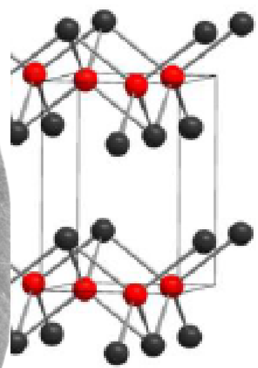
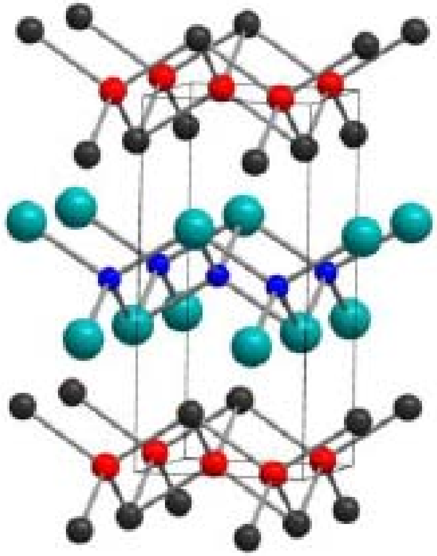


FeSe

Fe pnictides: A class of high T_c superconductors



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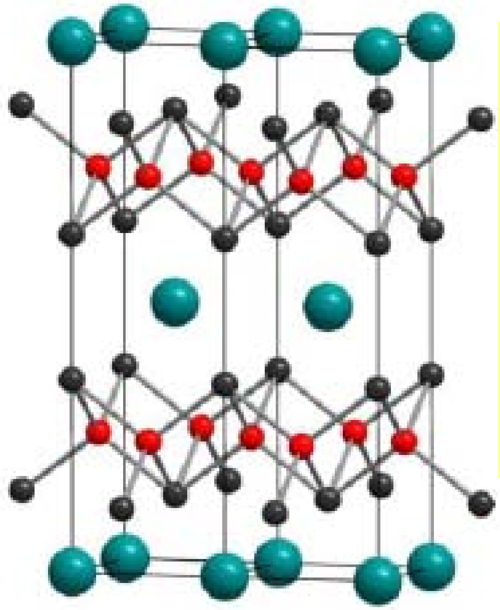

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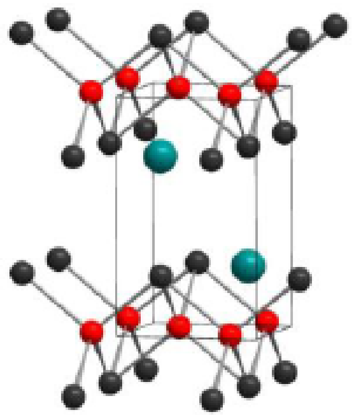
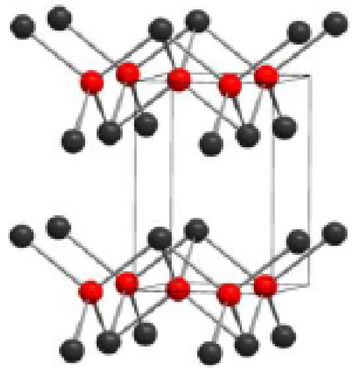


LiFeAs



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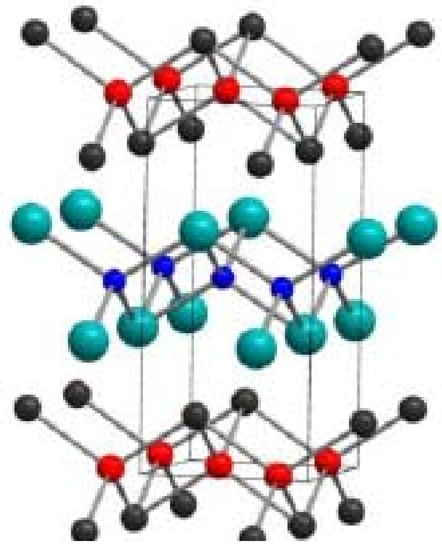

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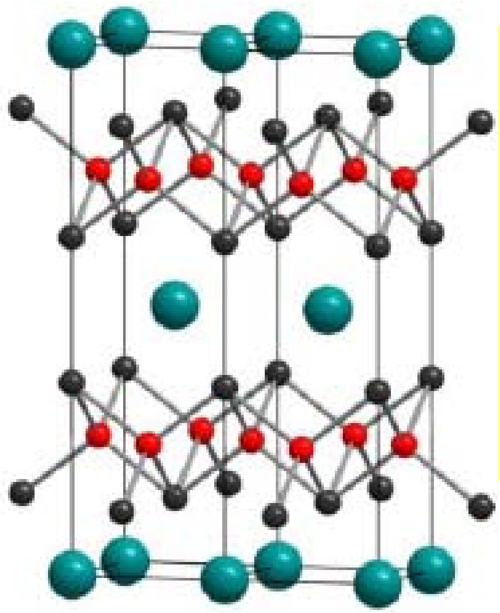

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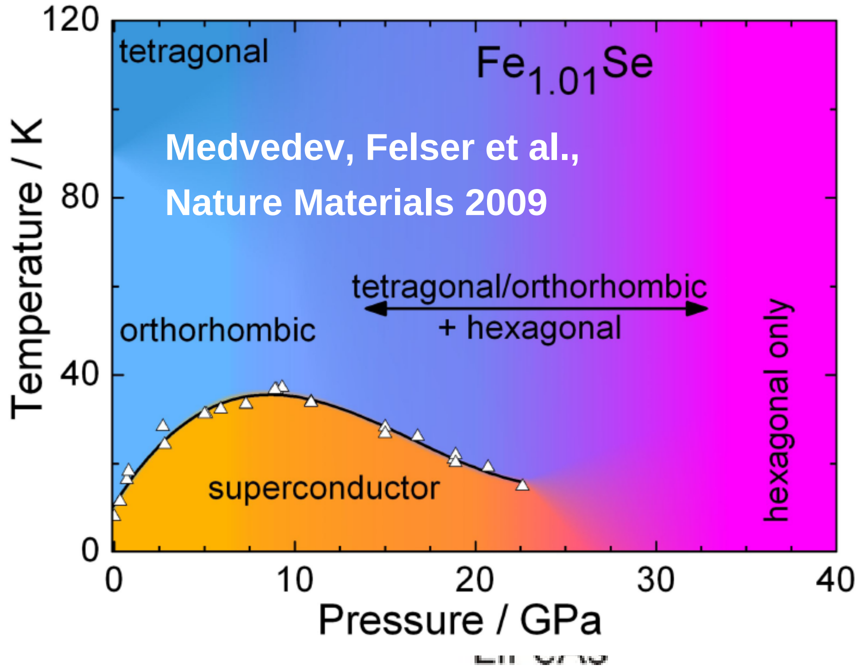
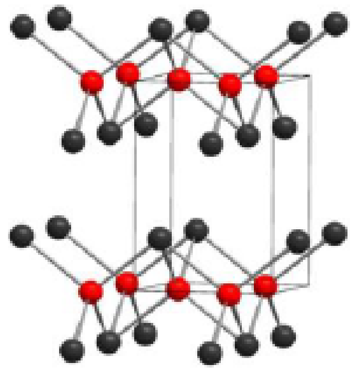
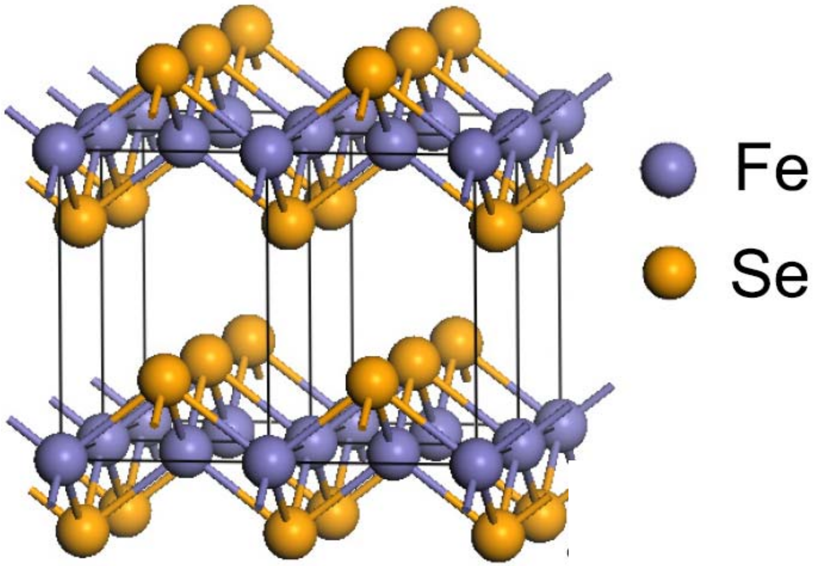


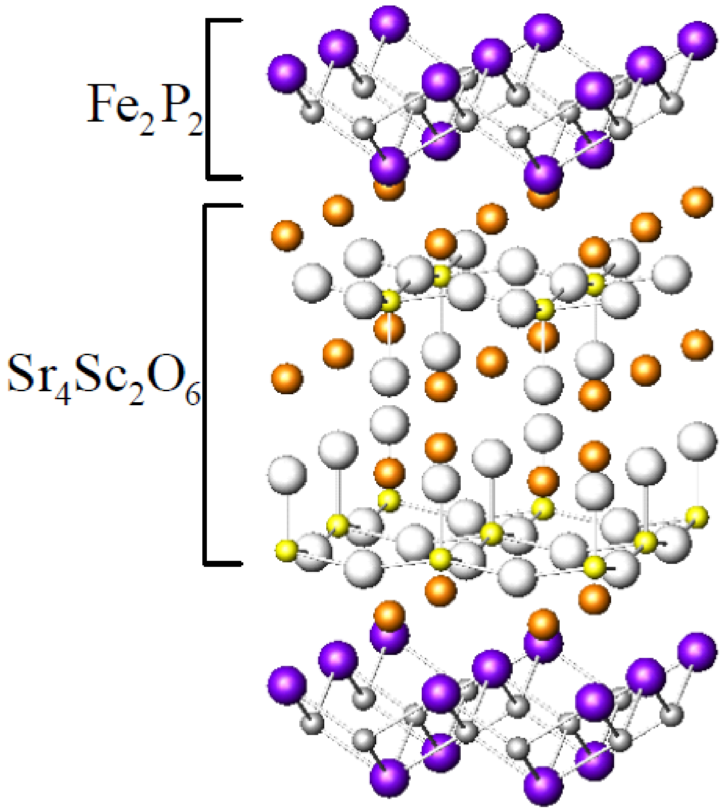


FeSe

Interplanar distance may differ very much!



$FeSe_{1-x}Te_x$

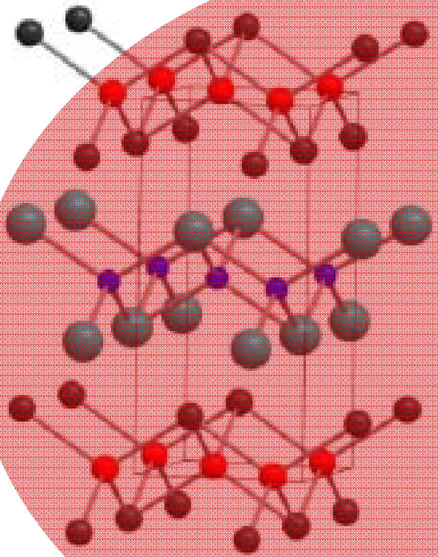


$(Fe_2P_2)(Sr_4Sc_2O_6)$

$T_{C,\ max}$ = 17 K

H. Ogino *et al.*, arXiv:0903.3314

Fe pnictides: A class of high T_c superconductors



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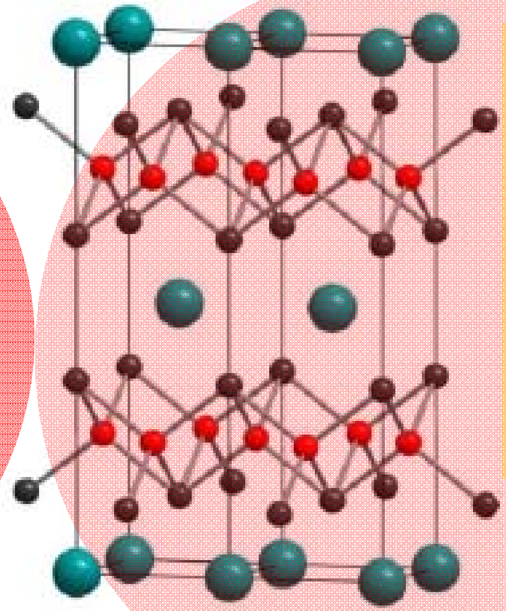

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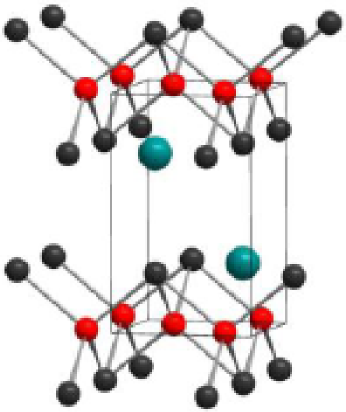

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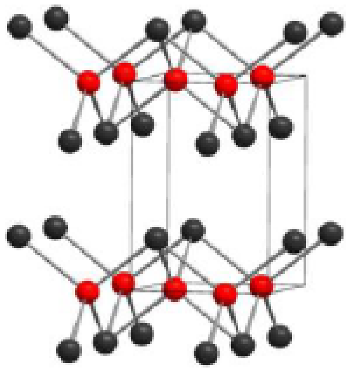
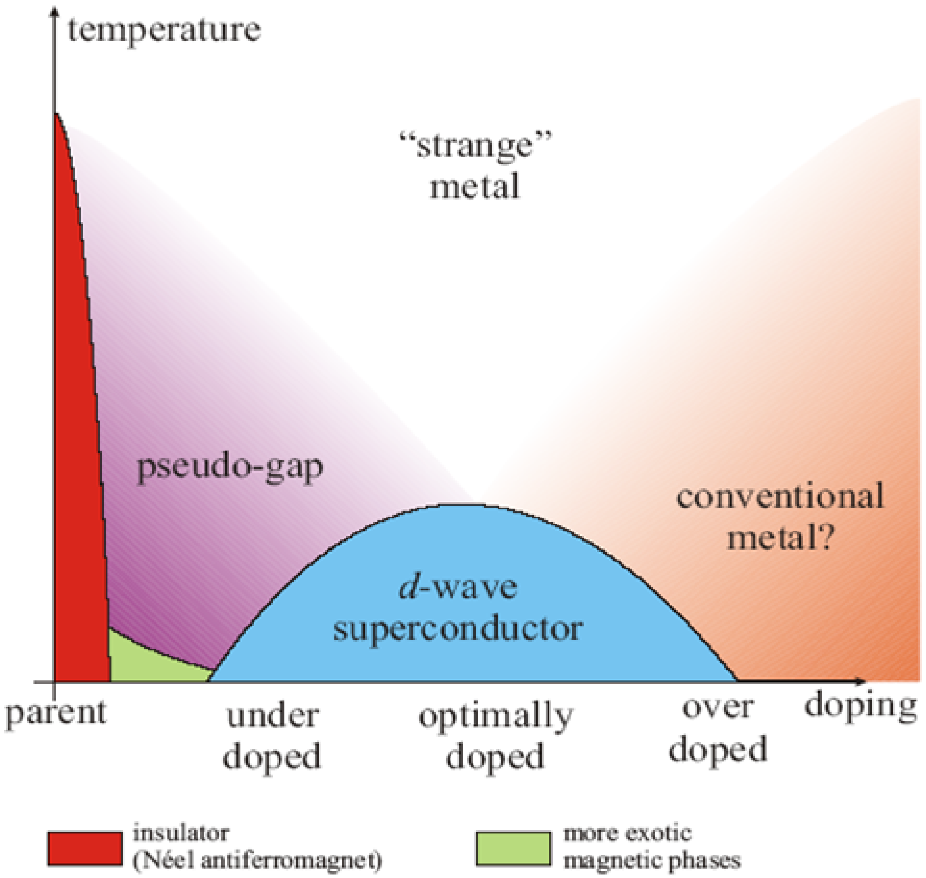


FeSe

Magnetism and Superconductivity

Cuprates



Magnetism and Superconductivity

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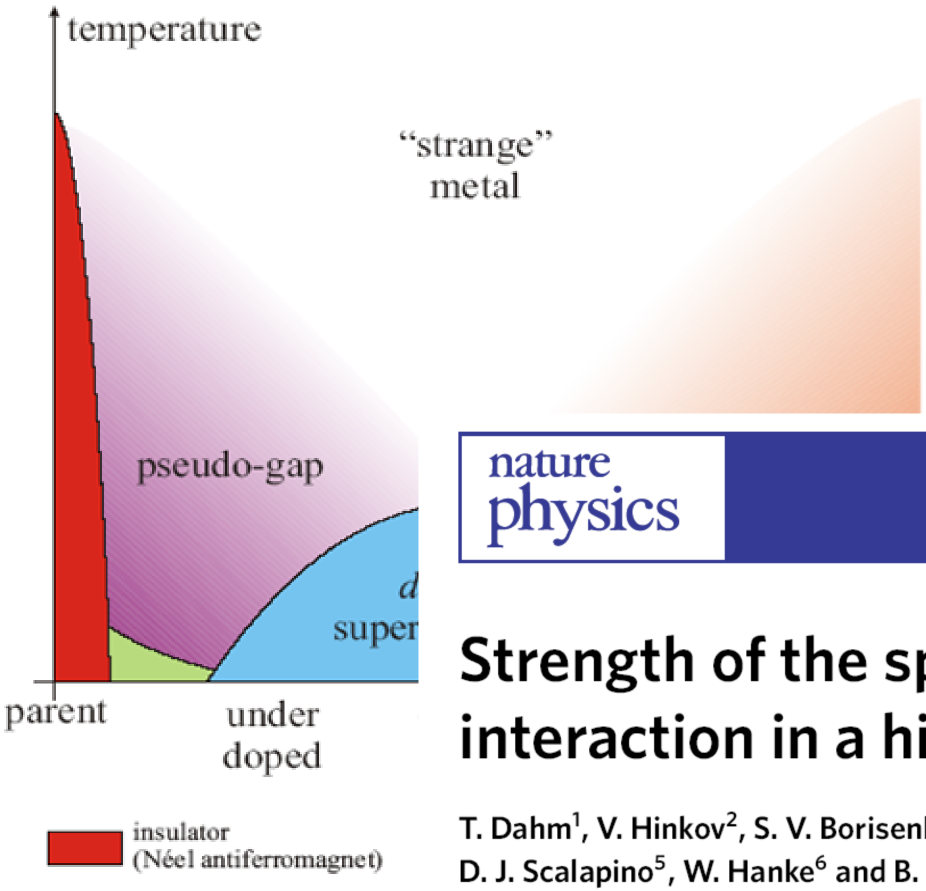


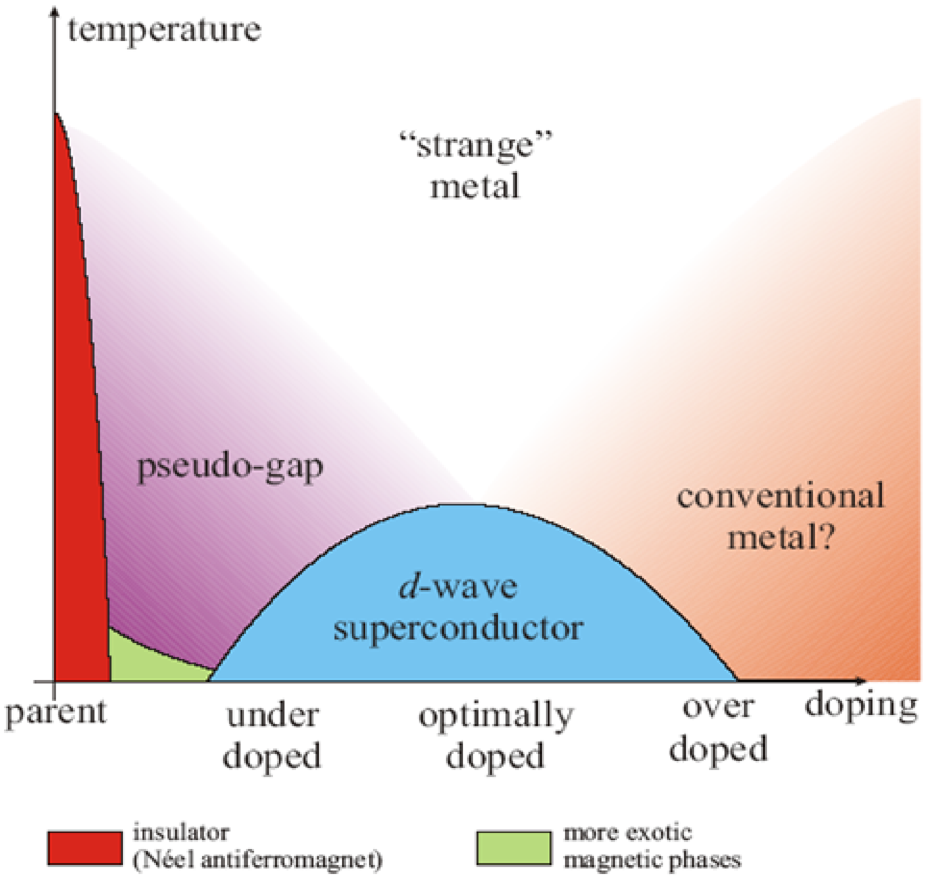
nature physics
LETTERS
PUBLISHED ONLINE: 18 JANUARY 2009 | DOI: 10.1038/NPHYS1180

Strength of the spin-fluctuation-mediated pairing interaction in a high-temperature superconductor

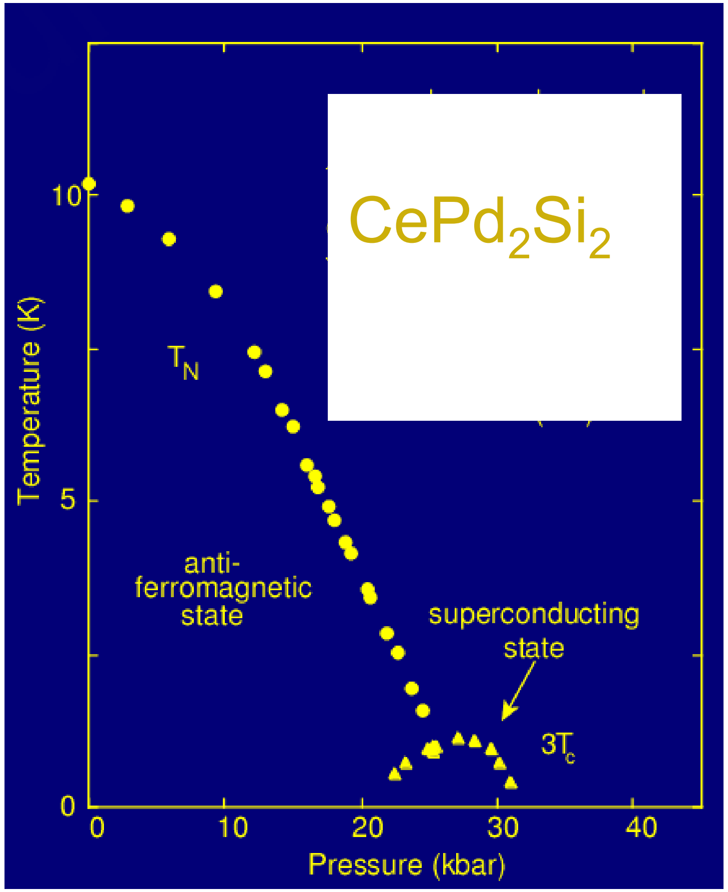
T. Dahm[1], V. Hinkov[2], S. V. Borisenko[3], A. A. Kordyuk[3], V. B. Zabolotnyy[3], J. Fink[3,4], B. Büchner[3], D. J. Scalapino[5], W. Hanke[6] and B. Keimer[2]*

Magnetism and Superconductivity

Cuprates



Heavy fermions



Mathur, Julian, Lonzarich et al. 1998

Magnetism and Superconductivity

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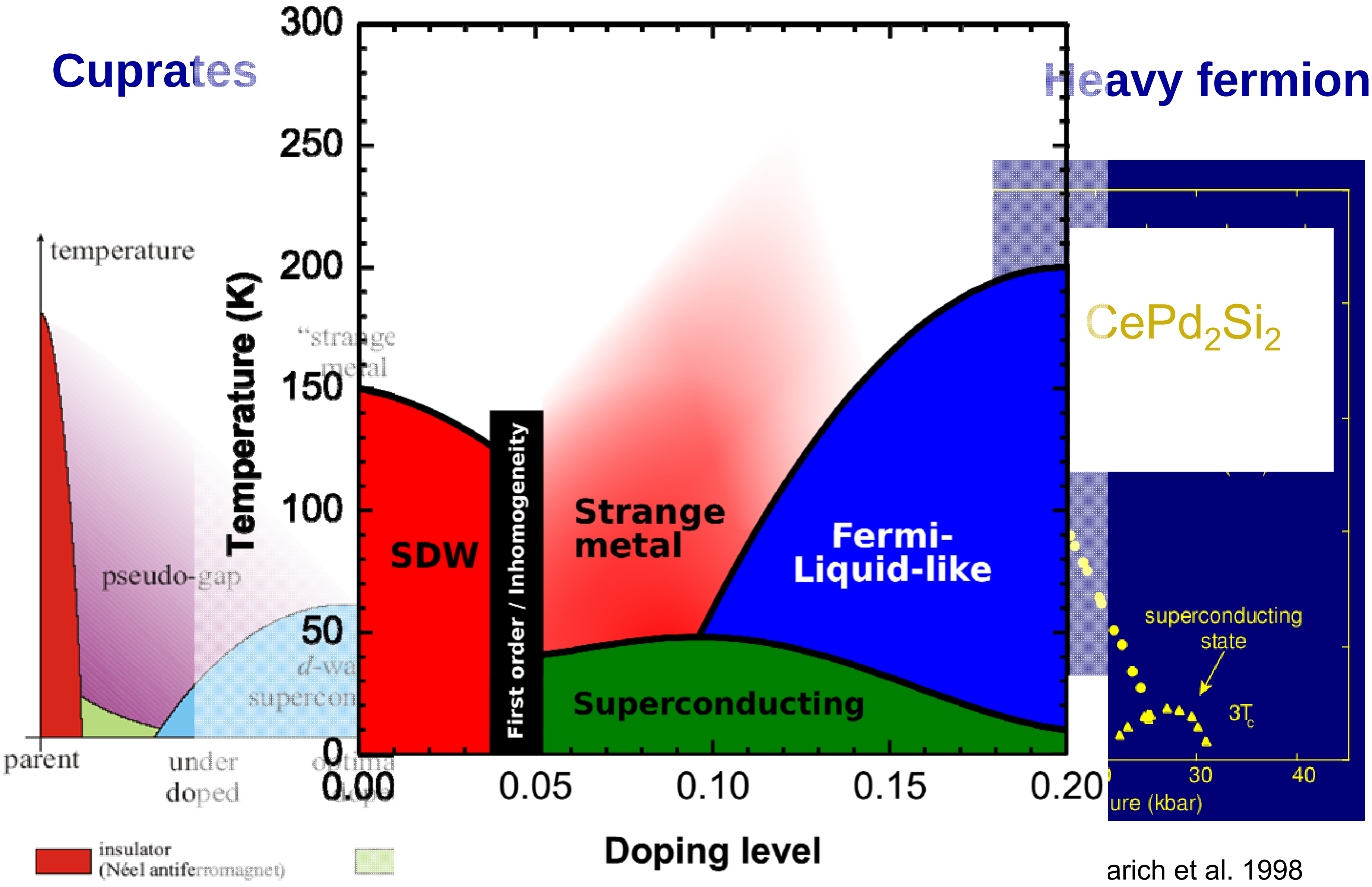

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  Electronic Structure (XAS, PES, ARPES)
  „Pseudogap“ (NMR, χ)
  Electronic transport and spin fluctuations
  Charge inhomogeneity (NQR)

Some of the people @ IFW involved in the research on FeAs …

Synthesis:	G. Behr, J. Werner, S. Singh, C. Nacke, S.Wurmehl et al.
M, Thermodynamics:	N. Leps, L. Wang, R. Klingeler et al.
NMR, ESR:	H. Grafe, G. Lang. F. Hammerath, V. Kataev et al.
Transport :	A. Kondrat, G. Friemel, C. Hess et al.
X-ray diffraction:	J. Hamann-Borrero
Spectroscopy:	S. Borysenko, D.V. Evtushinsky, A. Koitzsch, J. Geck A. Kordyuk, V.B. Zabolotnyy, T. Kroll, M. Knupfer et al.

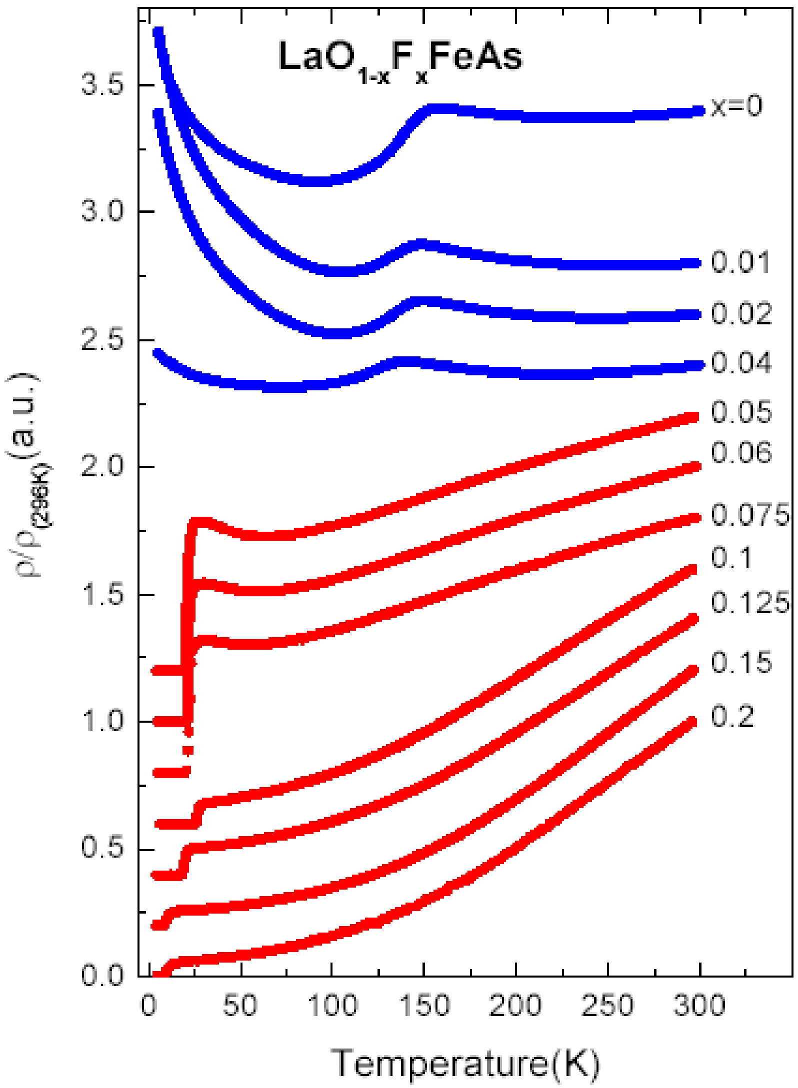
Cooperations

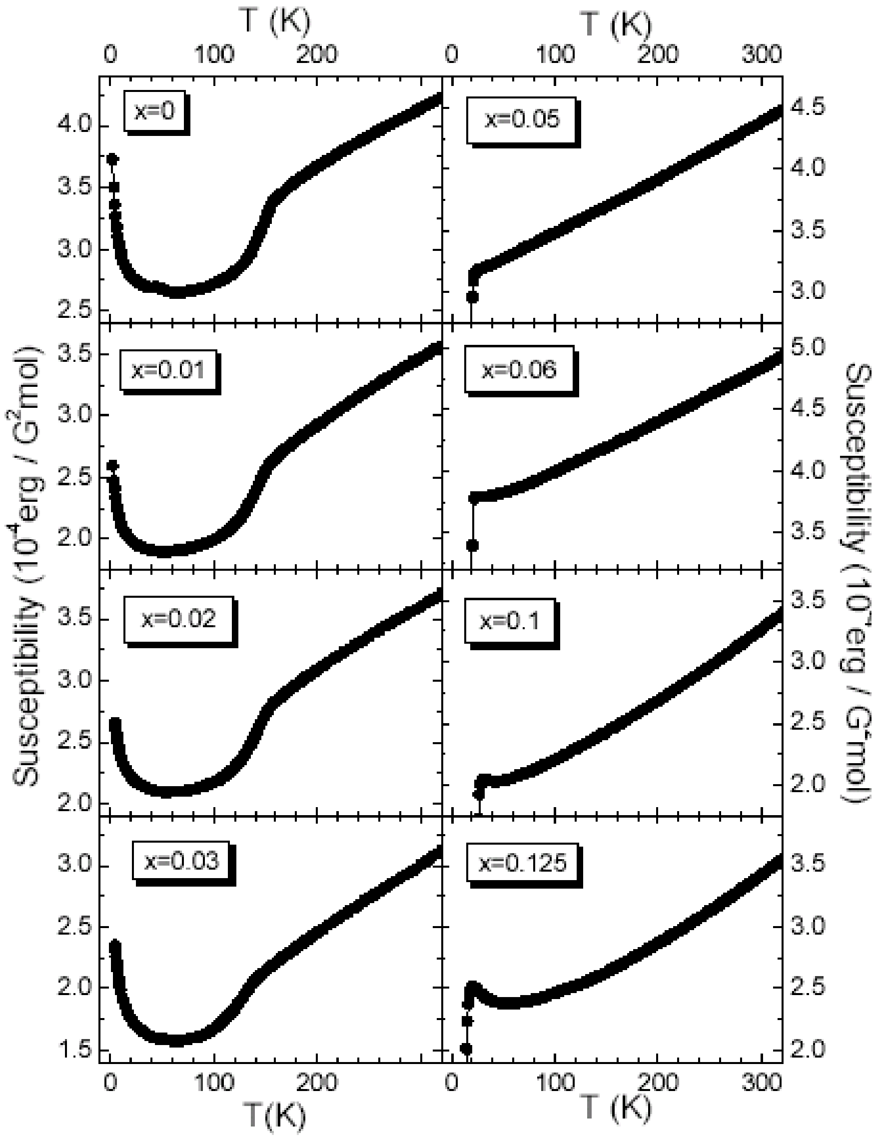
μSR, Mößbauer	**H.H.Klauss, H. Maeter et al.**	**TU Dresden**
μSR	H. Luetkens, R. Khasanov et al.	PSI Villingen
Crystals	C.T. Lin, D. Inosov, V. Hinkov, B. Keimer et al.	MPI FKF Stuttgart
NMR	N. Curro	UC Davis
X-ray/neutron diffraction	M. Braden et al.	U Köln
X-ray/neutron diffraction	R. Feyerherm, D. Argyriou et al.	HZ Berlin

DFG-Research Unit FOR538

Doping Dependence of Phase Transitions and Ordering Phenomena in Copper-Oxygen Superconductors

Resistivity and Susceptibility of $La(O_{1-x}F_x)FeAs$

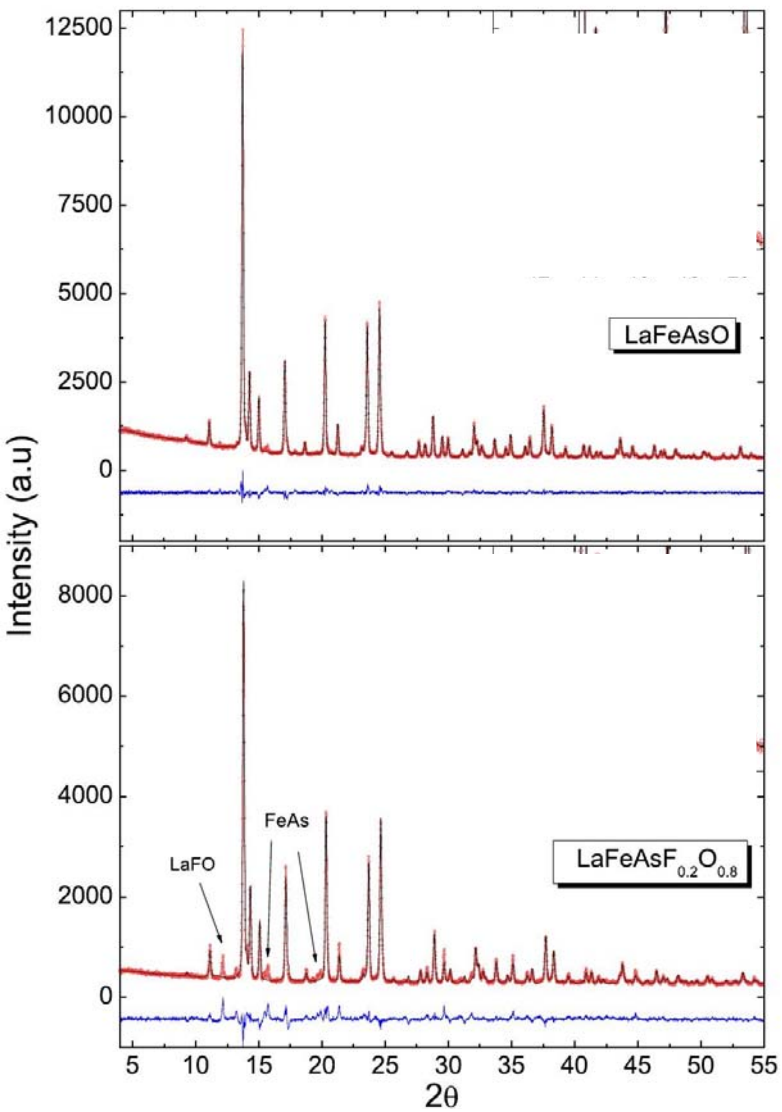




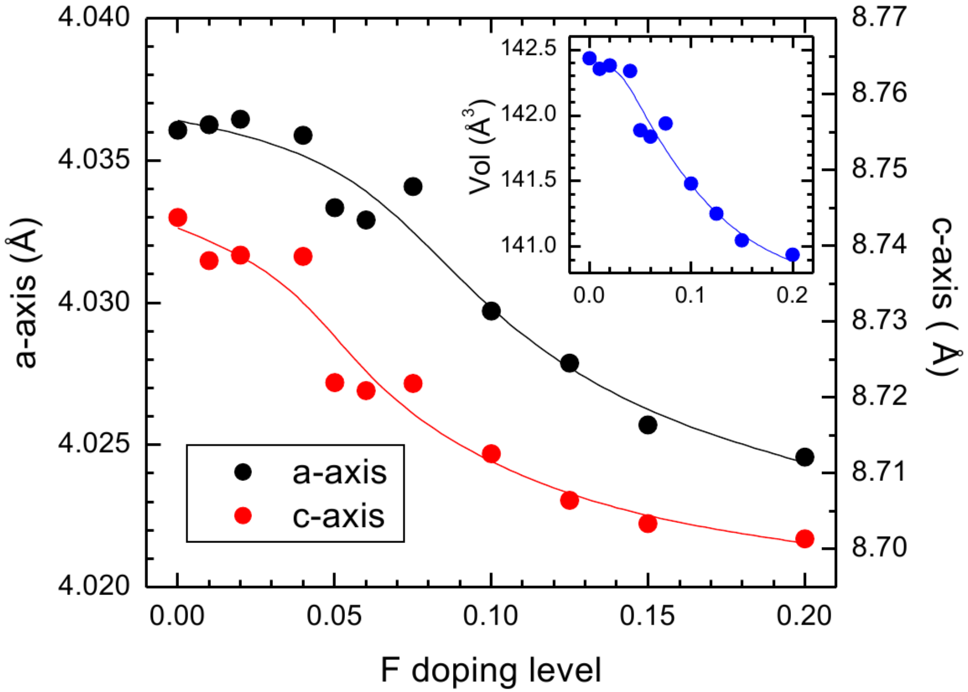
Preparation & Characterization

$LaO_{1-x}F_xFeAs$, x=0 ... 0.2

Phase purity…



Lattice constants…



Preparation & Characterization

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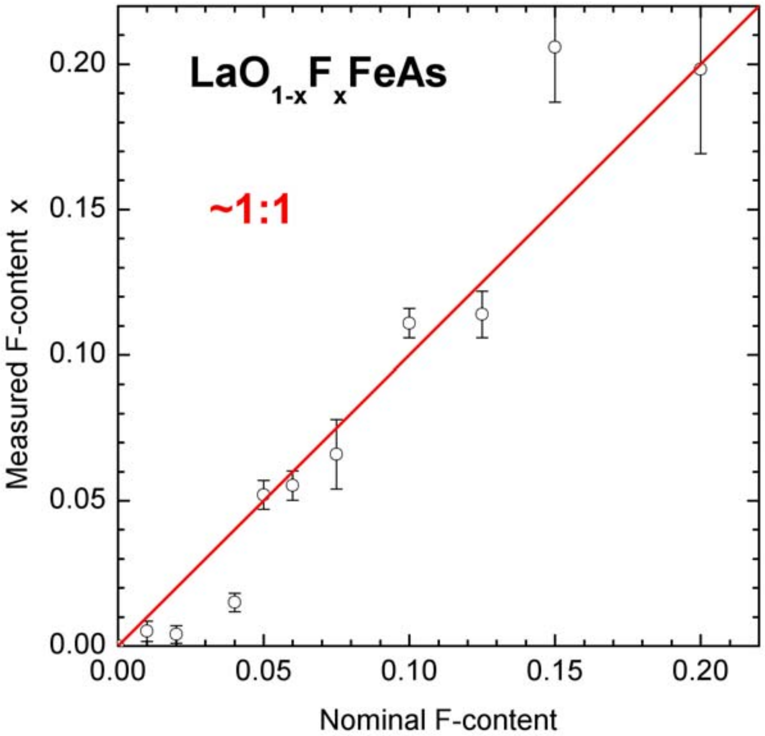
Fluorine content…



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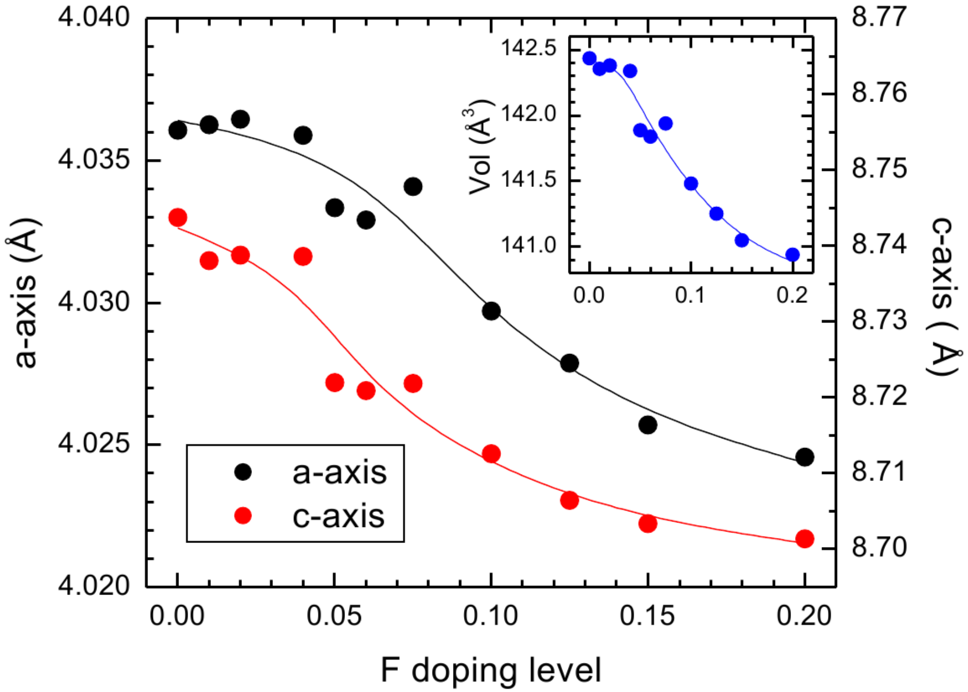
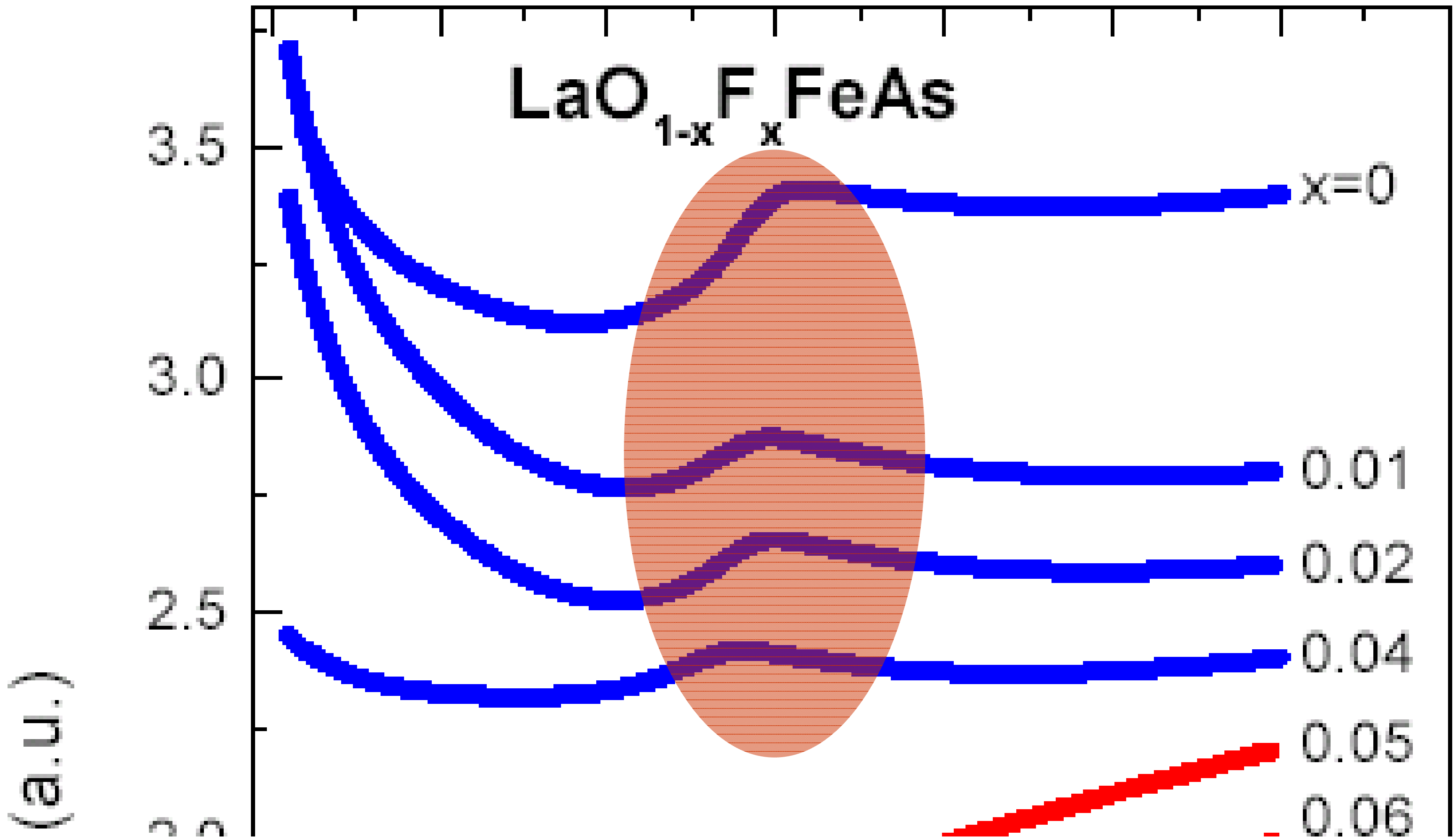
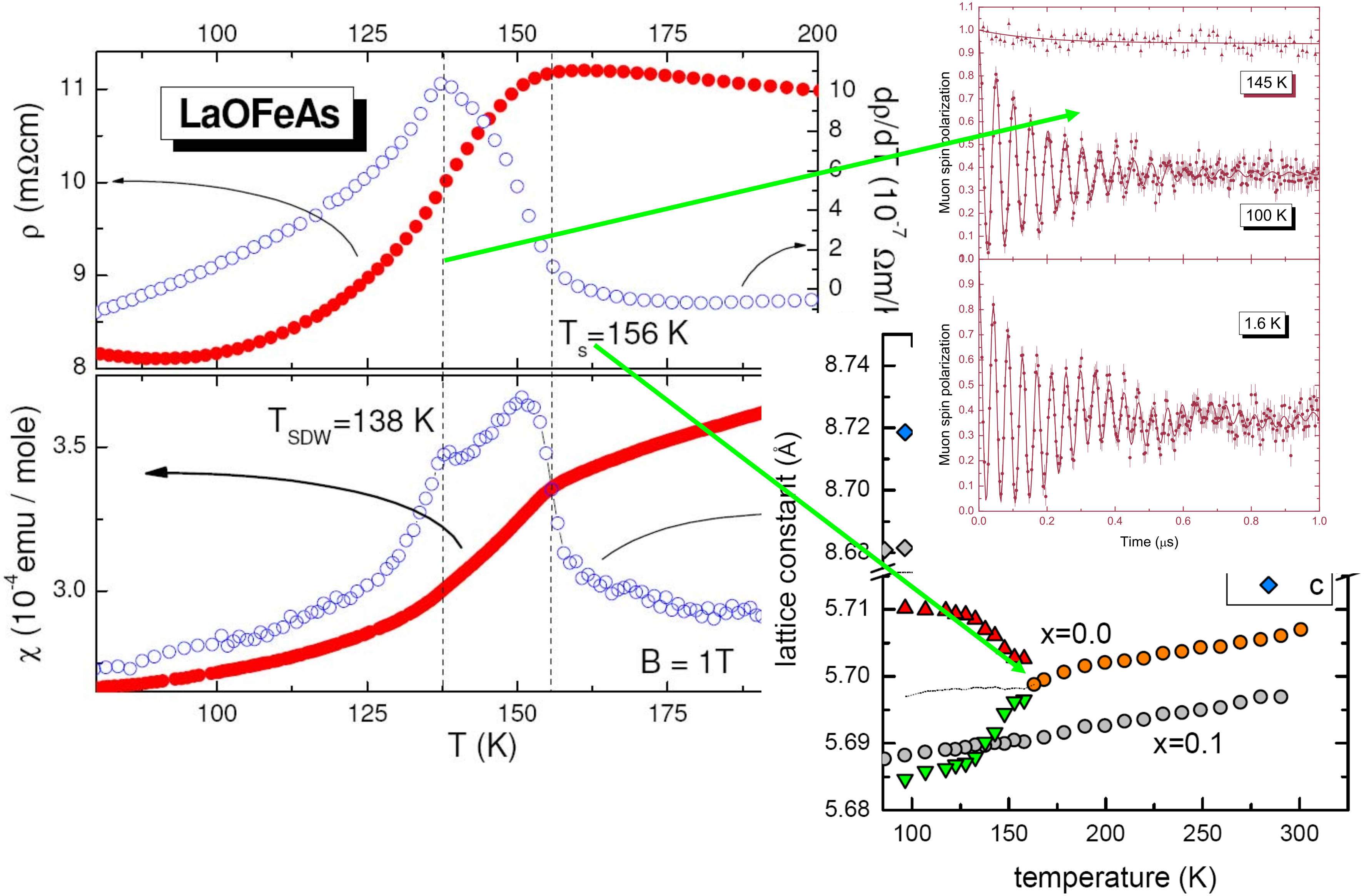


Resistivity of $La(O_{1-x}F_x)FeAs$

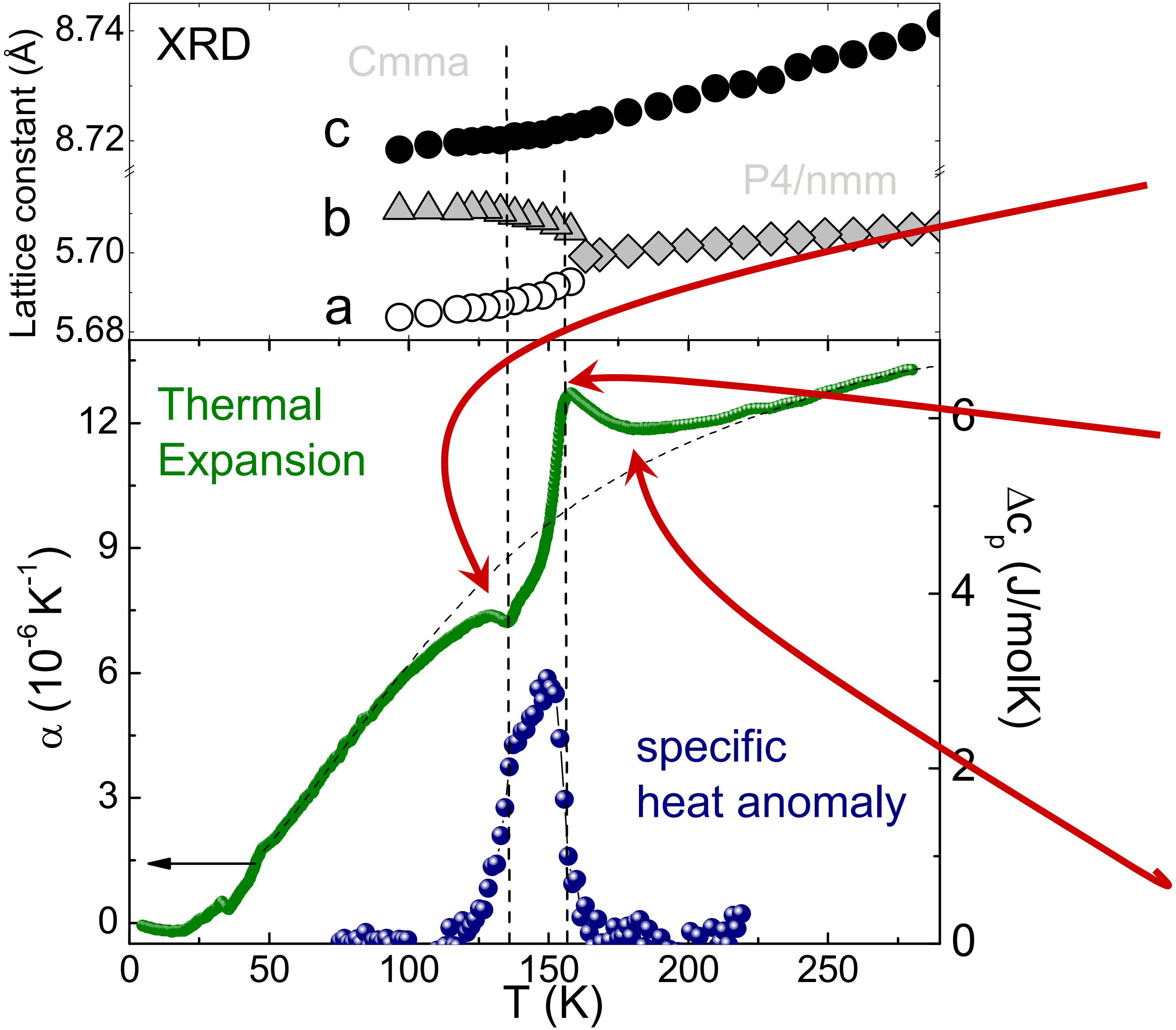


Two phase transitions in LaOFeAs



H.-H. Klauss et al., PRL 101, 077005 (2008)

LaOFeAs: Competing OP above T_S?



$$\frac{dT_N}{dp} = TV \frac{\Delta\alpha}{\Delta c_p}$$

negative!

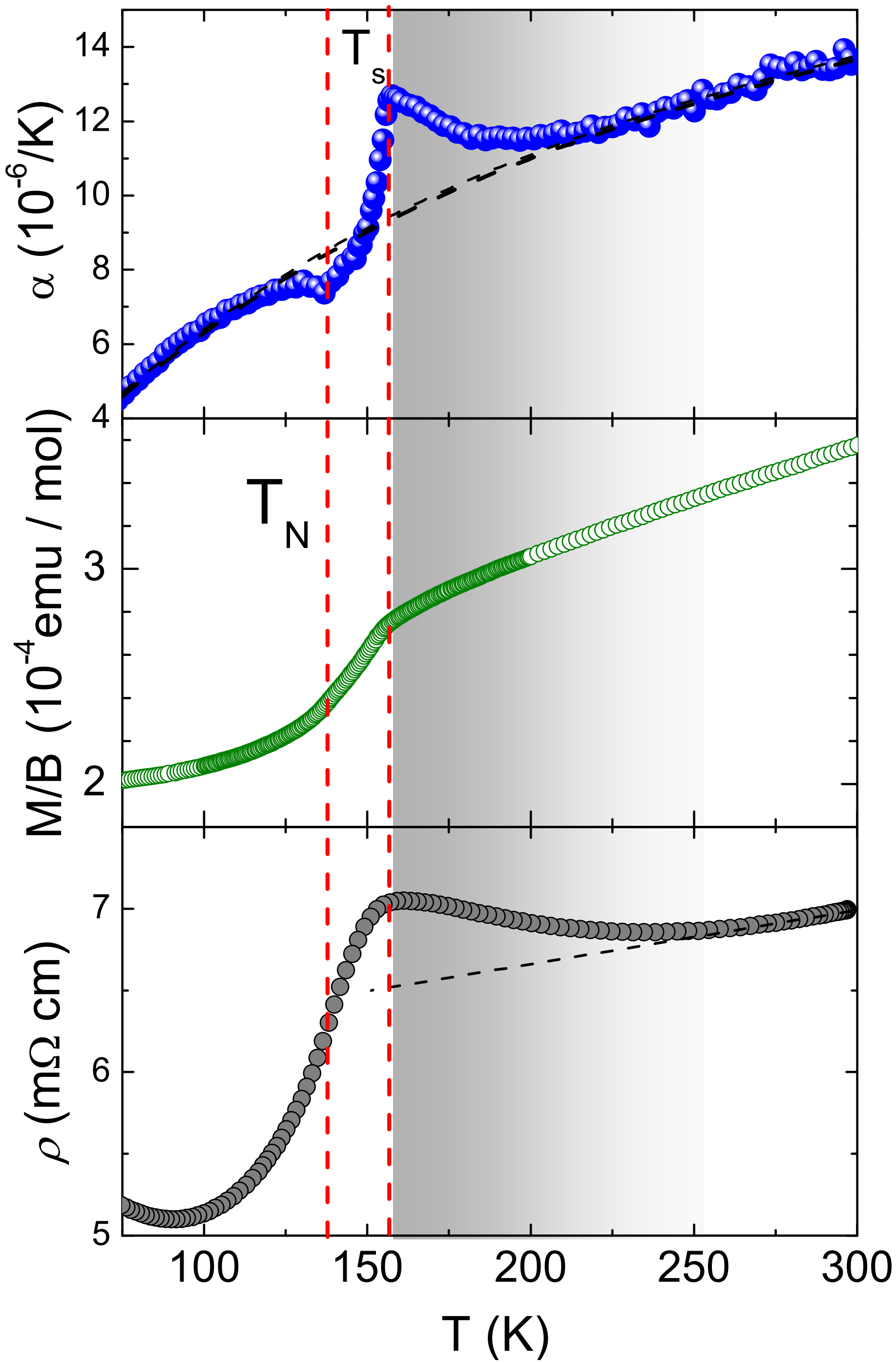
at T_S:

upturn truncated

$$\left(\frac{\partial V}{\partial T}\right)_p \propto -\left(\frac{\partial S}{\partial p}\right)_T$$

positive pressure dependence!

L. Wang et al., arXiv:0903.1235



LaOFeAs

Thermal Expansion

- large fluctuation region at $T>T_S$

Magnetisation:

- linear T-dependence at high T, only weak changes due to fluctuations

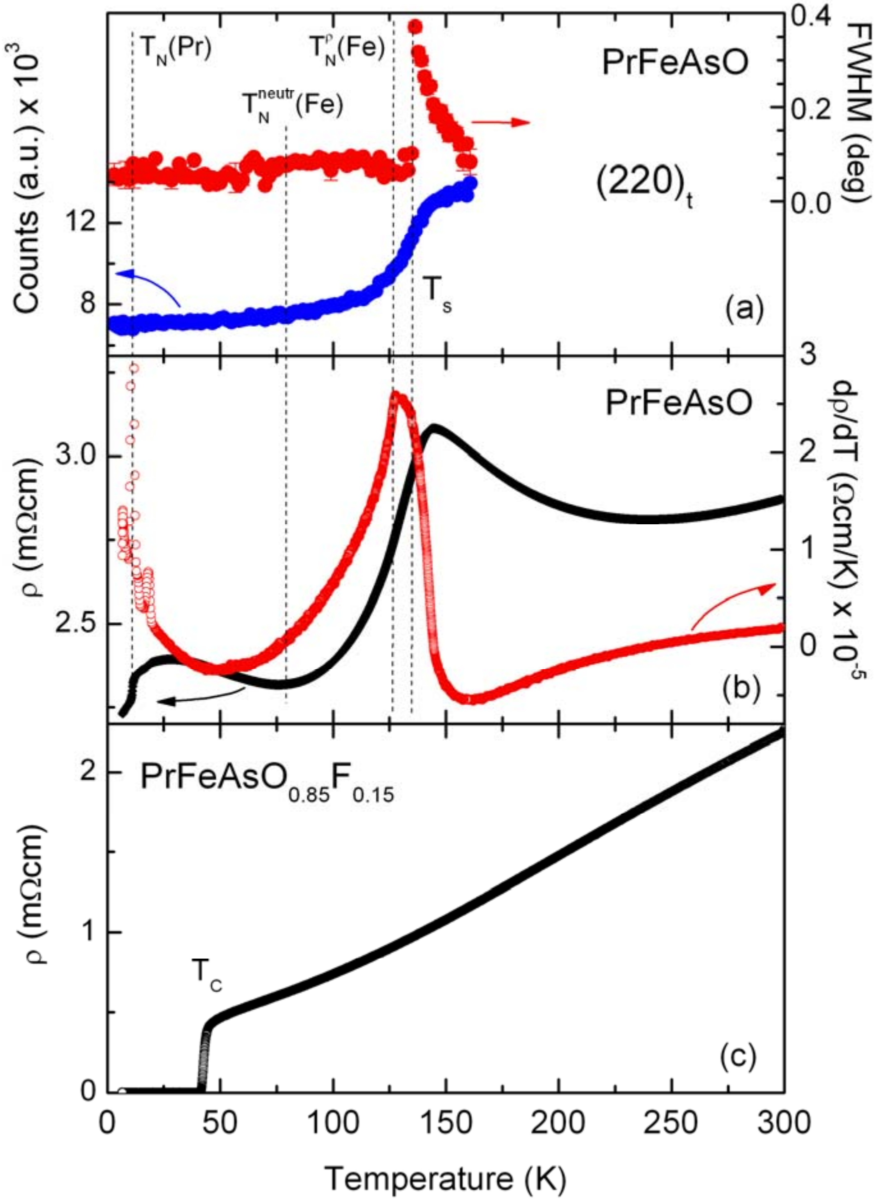
Resistivity

- Peak at T_S
  enhanced scattering in the fluctuation regime

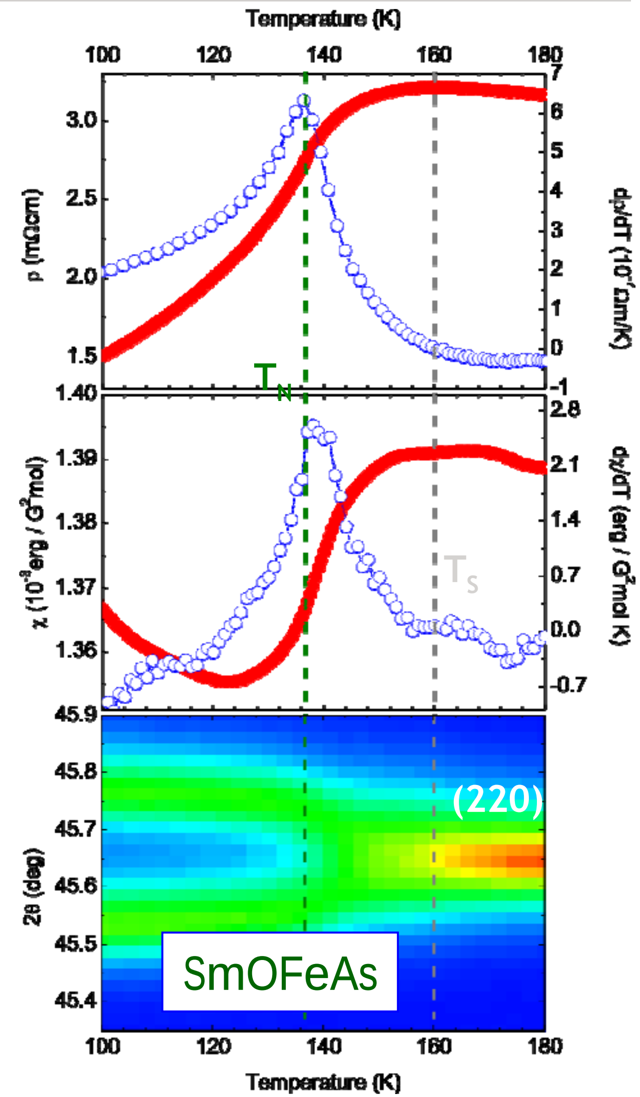
Strong link between electronic and structural degrees of freedom

Wang et al., subm. to PRB

Two phase transitions in (Pr,Sm)OFeAs

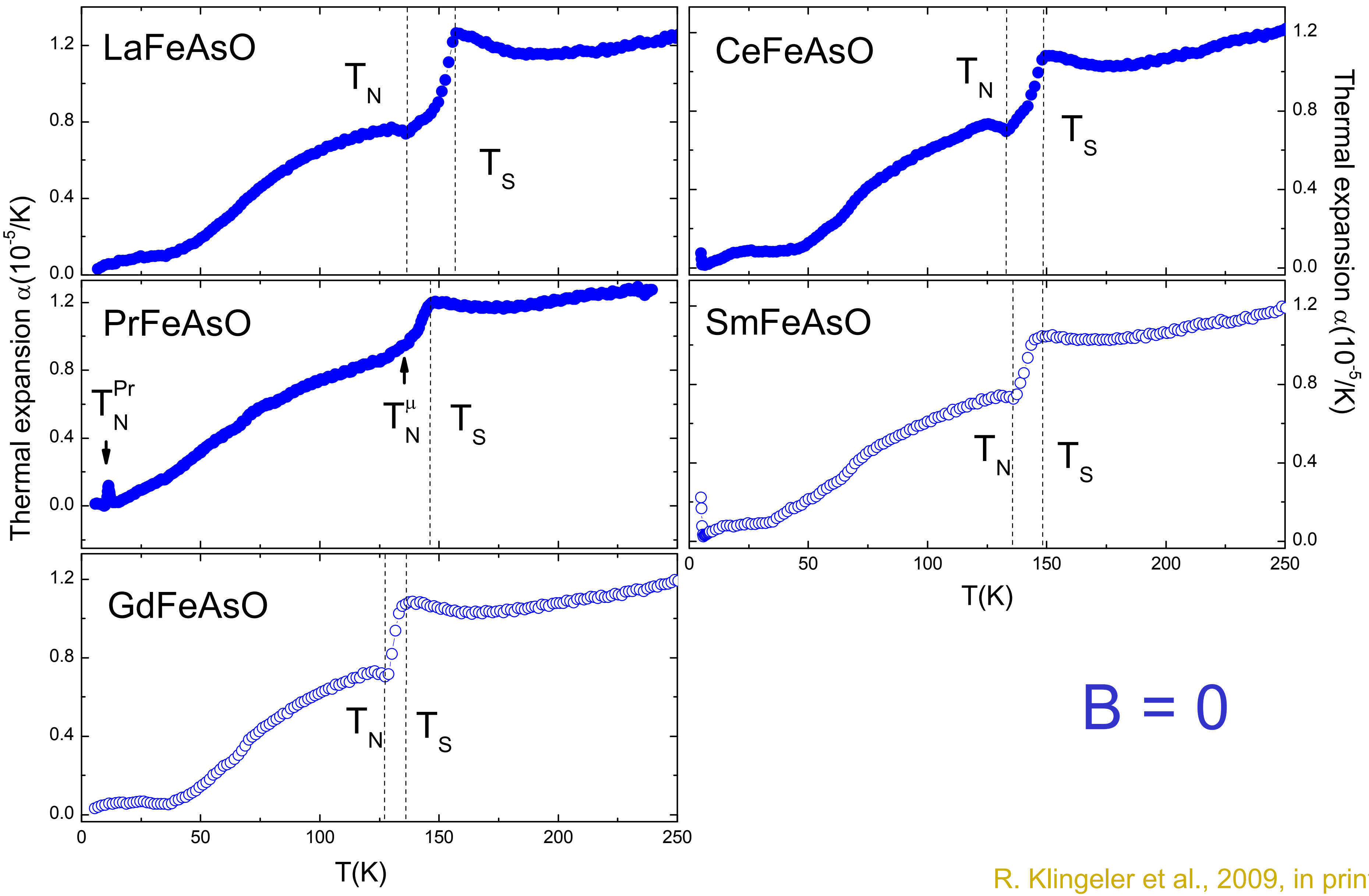


Kimber et al., PRB (2008)



- Structural Transition similar for all RE
- No transition in doped systems (x ~0.1)

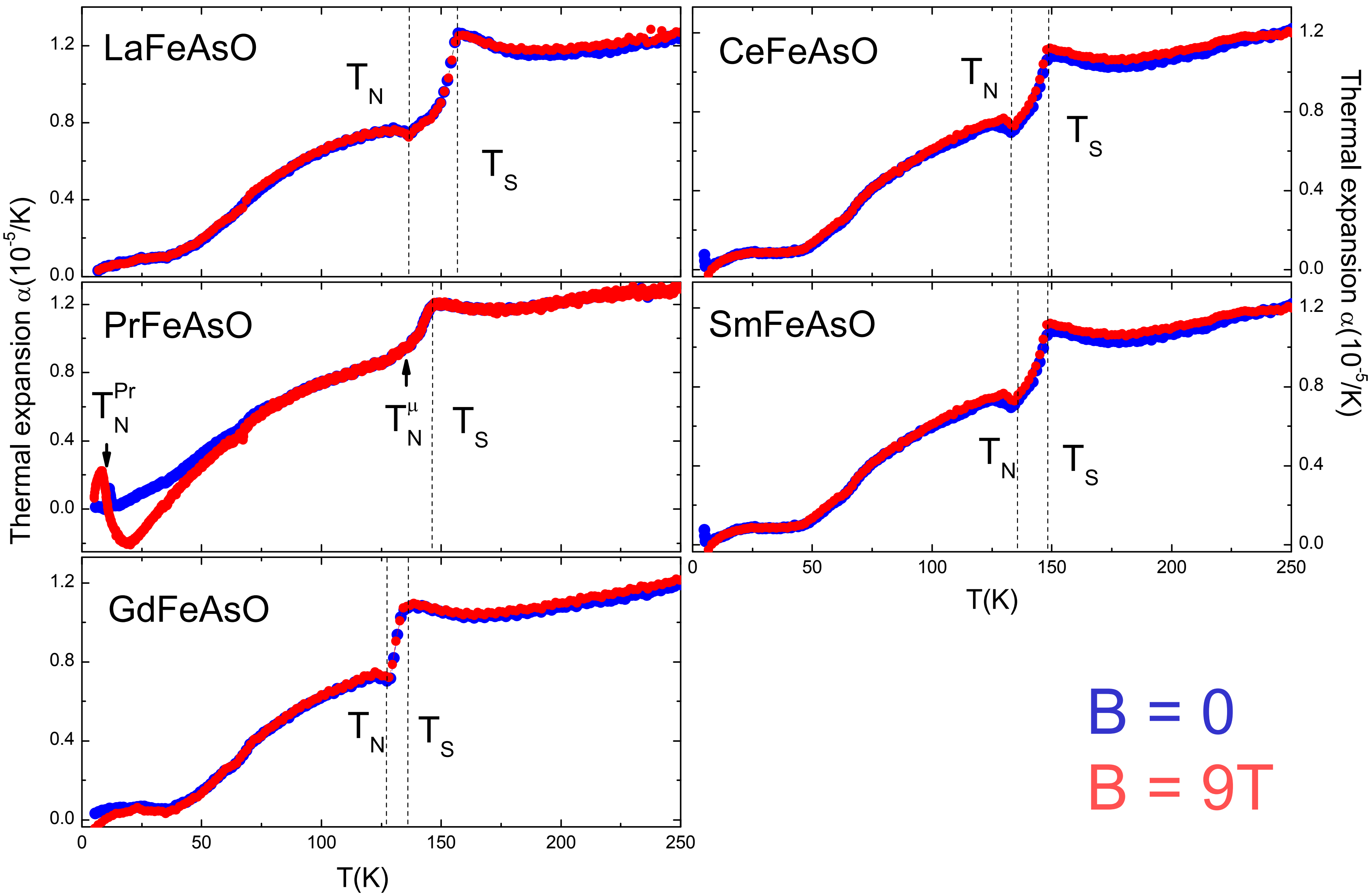
REOFeAs: Structural changes



B = 0

R. Klingeler et al., 2009, in print

REOFeAs: Structural changes



Phase transitions in undoped 122 compounds

$BaFe_2As_2$

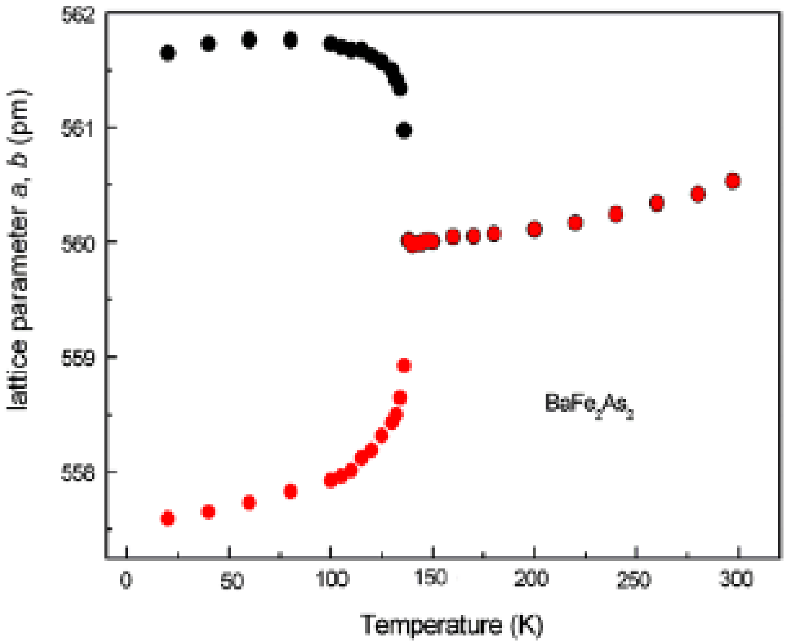
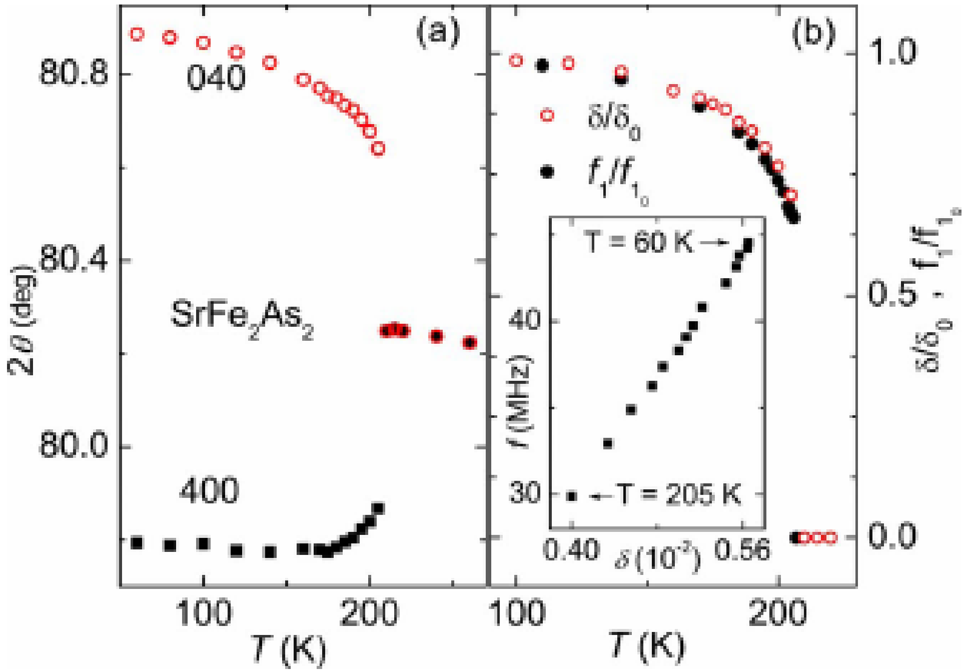


Fig. 2. Lattice parameters of $BaFe_2As_2$.

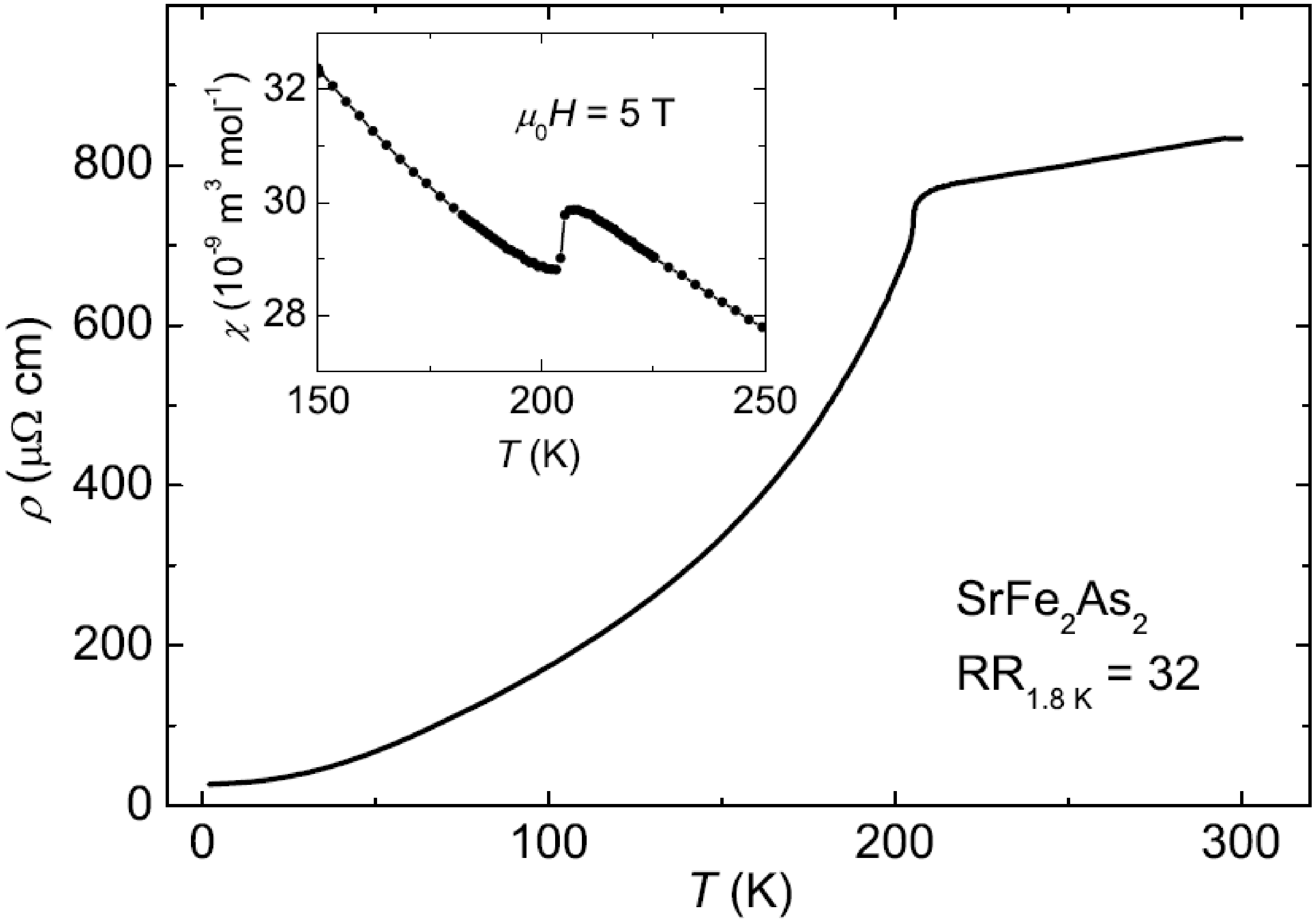
D. Johrendt and R. Pöttgen, Physica C 2009

$SrFe_2As_2$



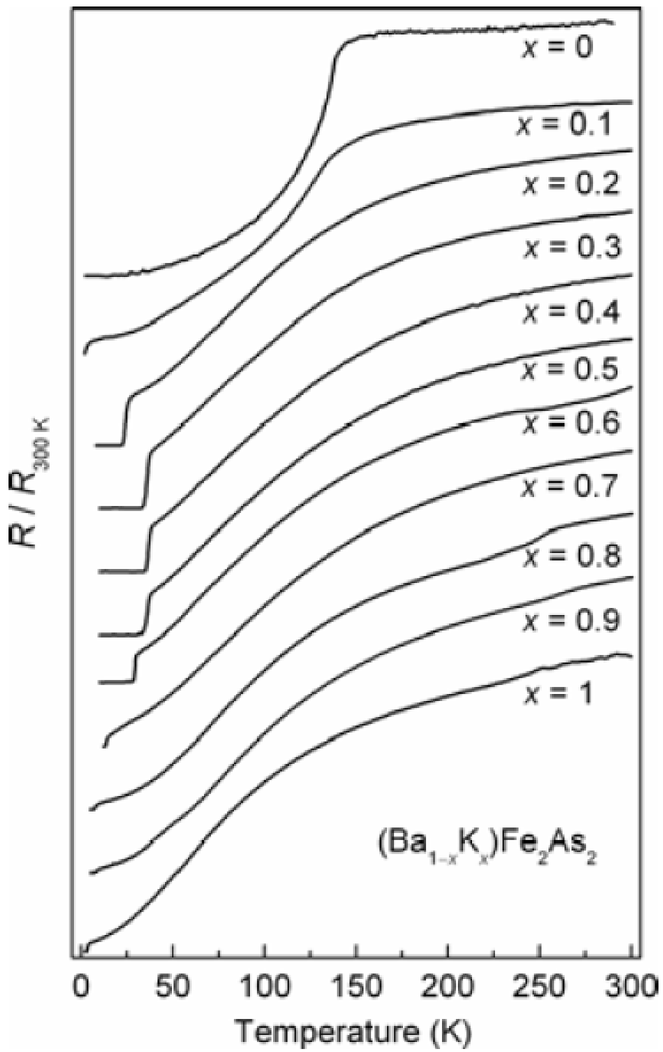
A. Jesche et al., PRB 2008

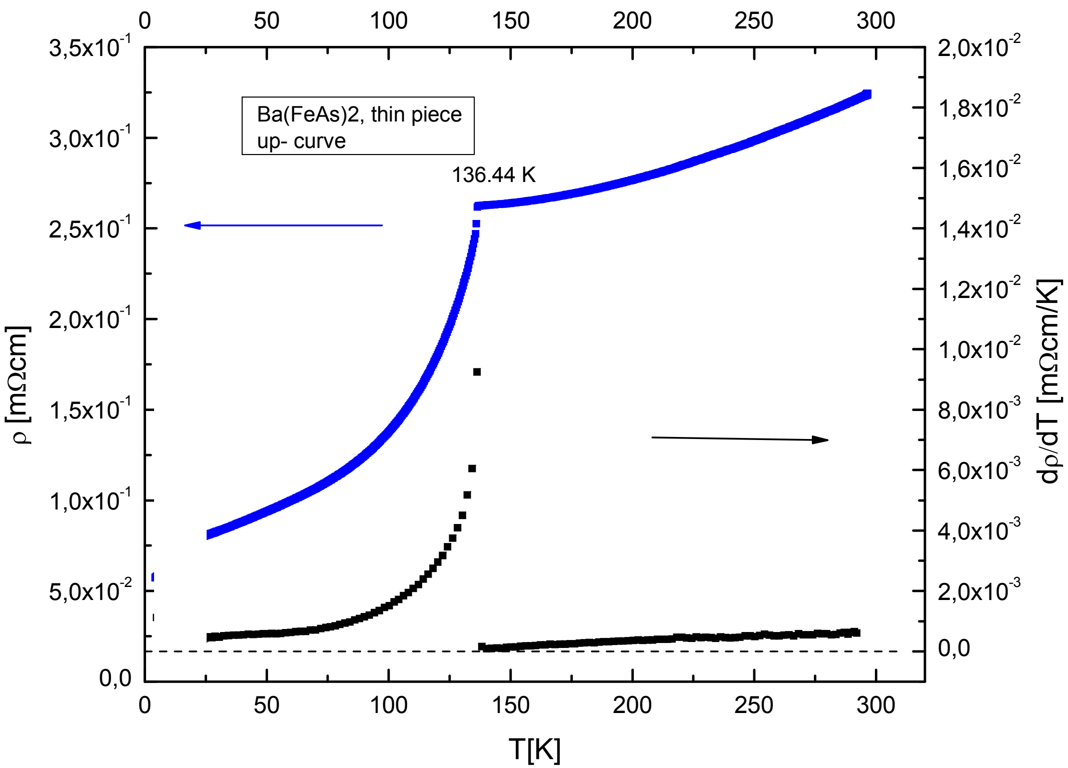
SDW magnetism in $SrFe_2As_2$



Krellner et al., PRL `08, arXiv:0806.1043

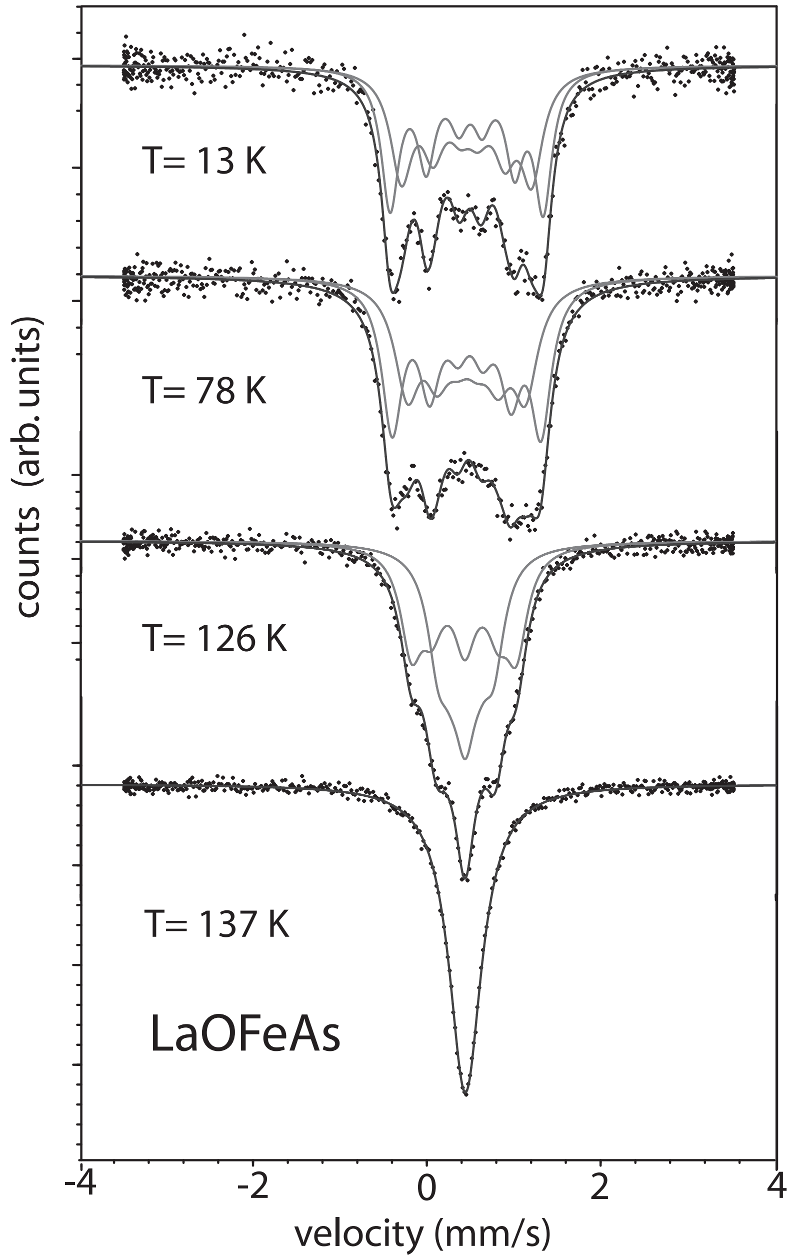
Resistivity of $Ba_{1-x}K_xFe_2As_2$





M. Rotter et al., Ang. Chem. 2008

Magnetic order of LaOFeAs



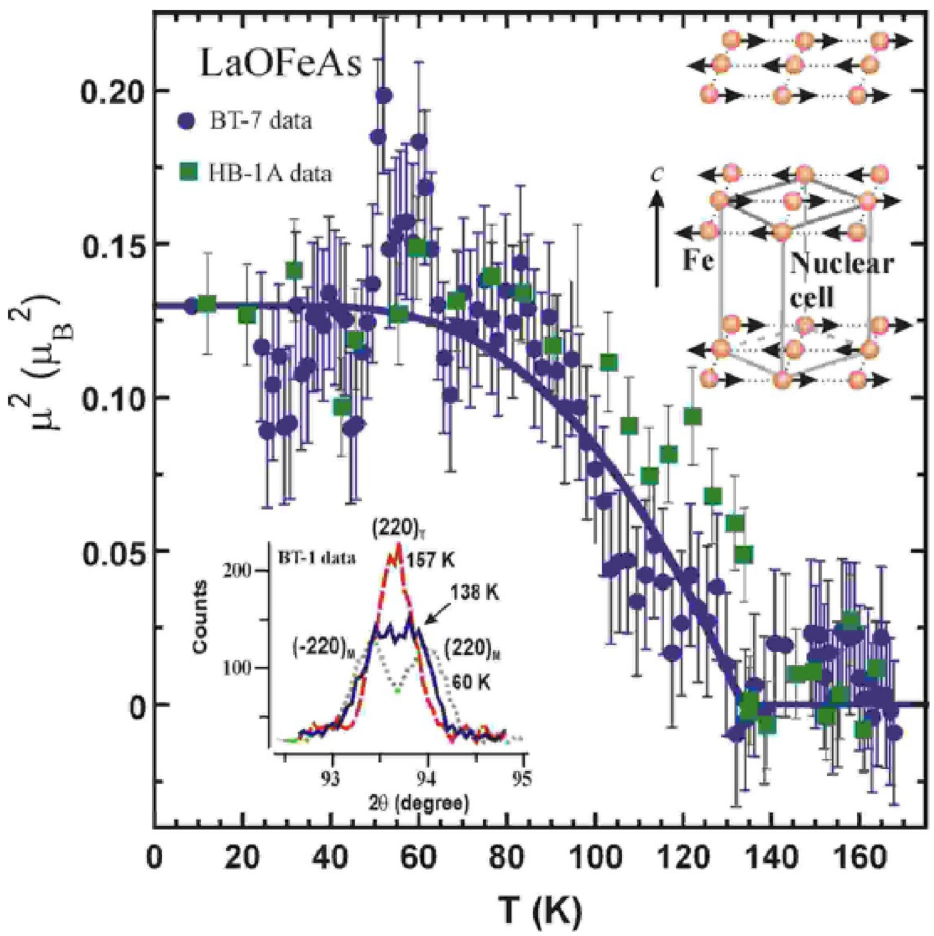
^{57}Fe Mössbauer spectroscopy

→ well defined magnetic hyperfine field
→ commensurate magnetic order below 138 K

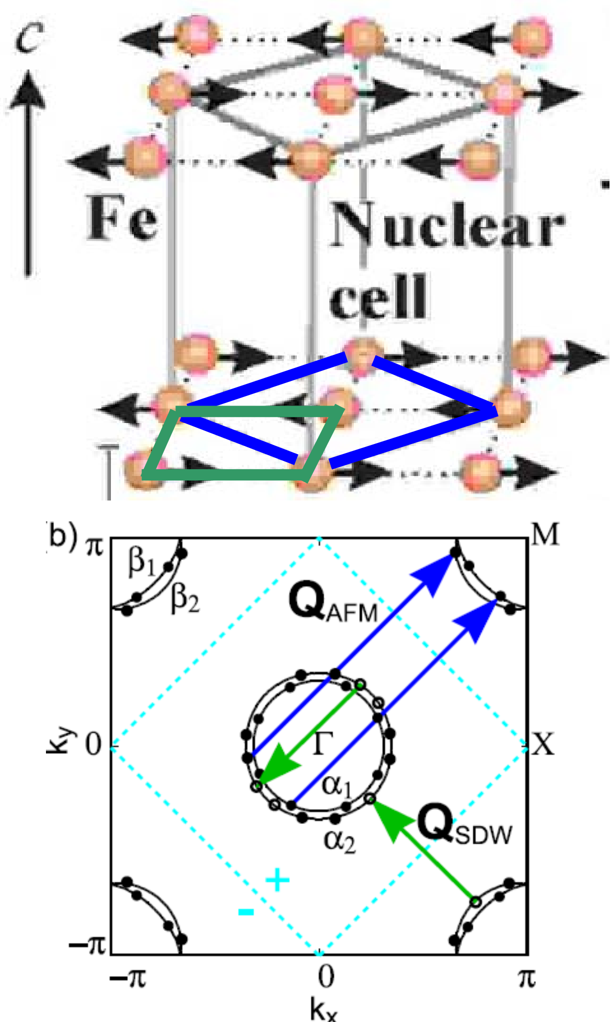
B_{hyp} (T→ 0) ~ 4.86 T
→ ordered moment ~ 0.3 μ_B
→ itinerant magnet

H.-H. Klauss et al., PRL 101, 077005 (2008)

Magnetic order of LaOFeAs



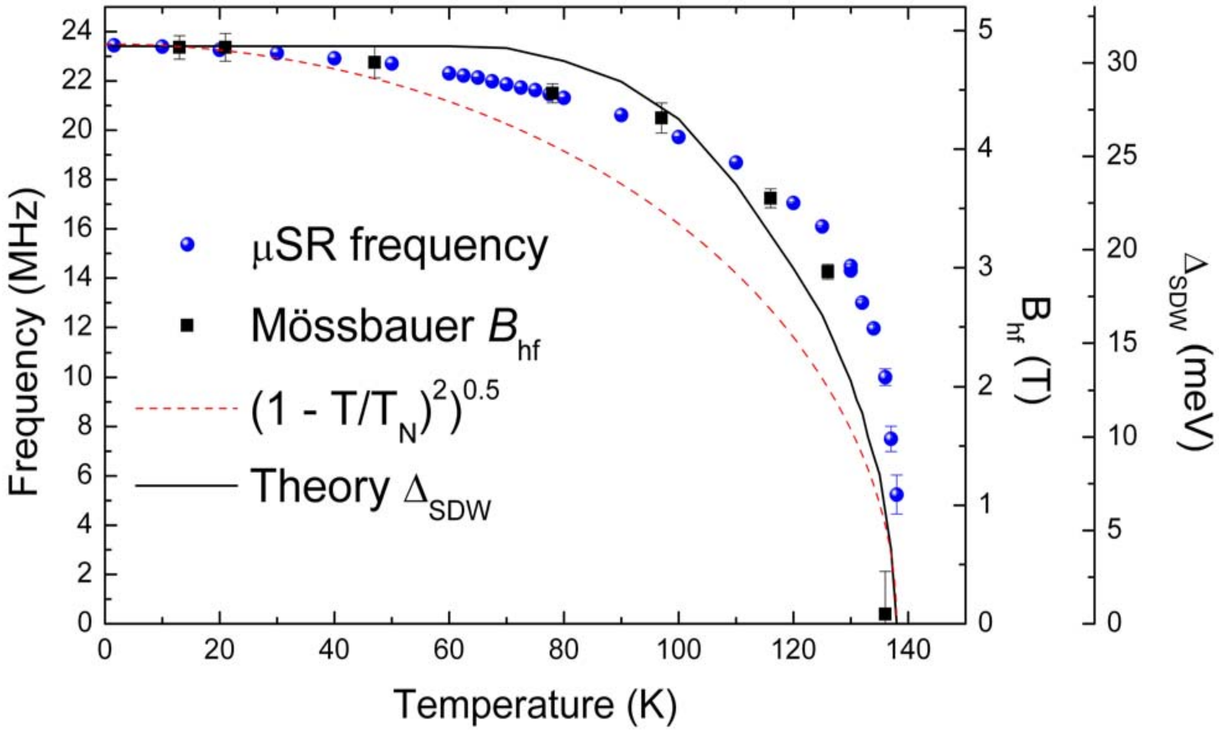
C. de la Cruz, et al., Nature 453, 899 (2008)



M. Korshunov, I. Eremin, PRB 78, 140509(R) (2008)

I. Mazin et al., PRL 101, 057003 (2008)
J. Dong et al., EPL 83, 27006 (2008)
K. Kuroki et al., PRL 101, 087004 (2008)
S. Raghu et al., PRB 77 220503 (2008)

Magnetic order parameter in undoped LaOFeAs



Four band SDW theory

U=0.26eV

J=U/5

$Q_{AFM} = (\pi,\pi)$

$\Delta_{SDW}(0)$ = 31 meV

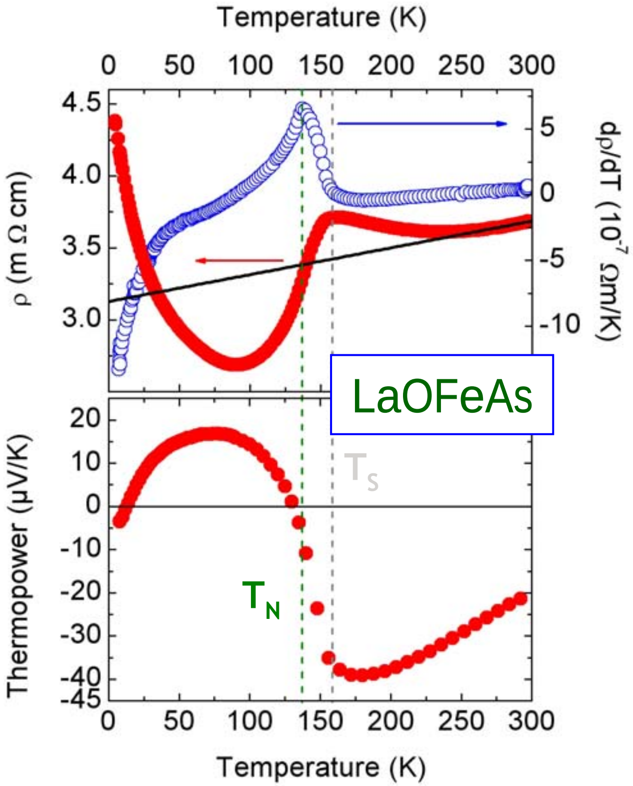
→ $\mu = 0.33\ \mu_B$

See:

M. Korshunov and I. Eremin

arXiv:0804.1793

H.-H. Klauss et al., PRL 101, 077005 (2008)



x=0: Stuctural and SDW Transistions

Resistivity

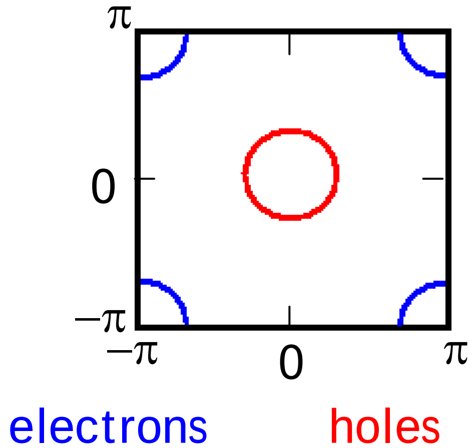
$$\rho \propto \frac{1}{n}, \frac{1}{\lambda}$$

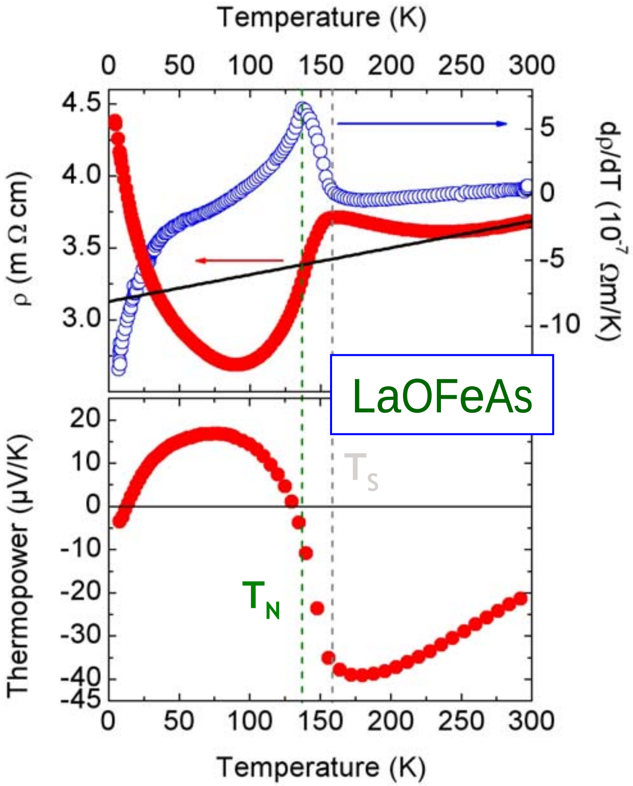
- Peak at T_S
  - enhanced scattering at higher T
- Inflection point at T_N
  - reduced scattering + localization at $T<T_N$

Thermopower S

- Sign change at T_N

$$S = \frac{\partial \ln(\sigma(\varepsilon))}{\partial \varepsilon} = \frac{\partial \ln \lambda}{\partial \varepsilon} + \partial \frac{\ln A}{\partial \varepsilon}$$





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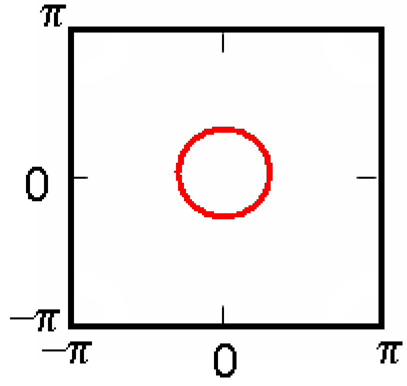
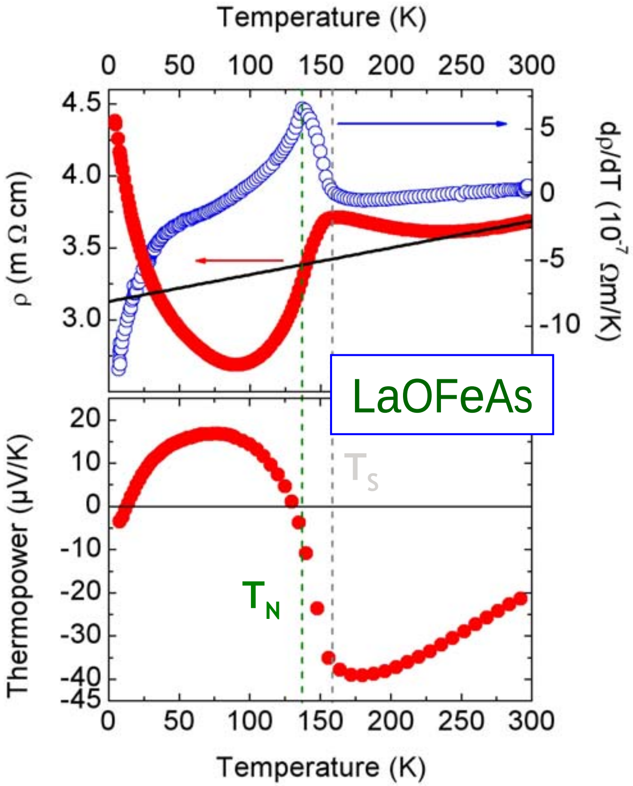


➡ Consistent with gapping of electron-like FS



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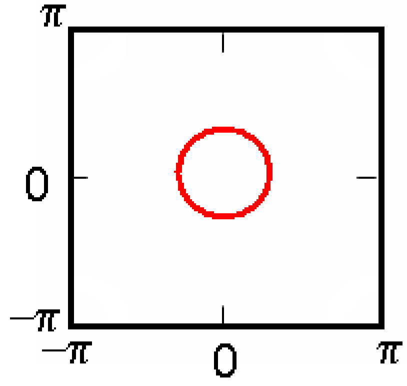
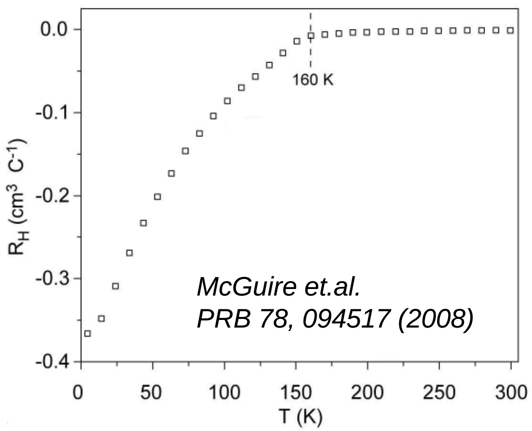


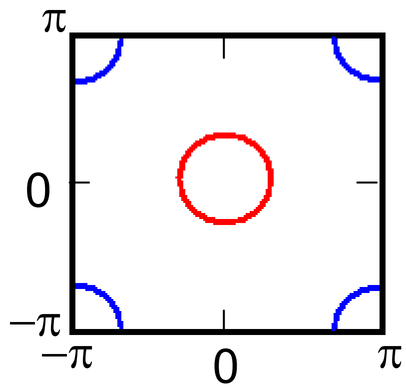
➡ Consistent with gapping of electron-like FS

electrons holes

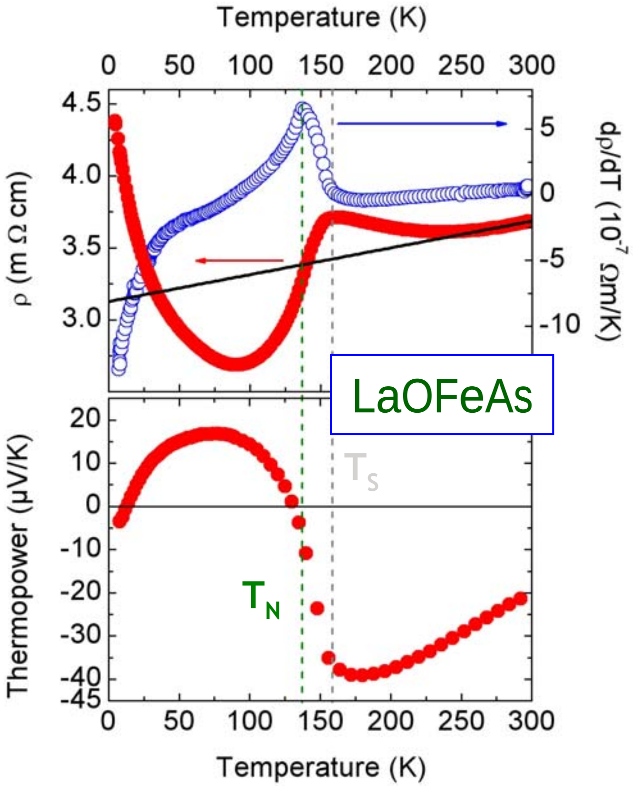


Hall-Effect: More negative at $T<T_N$

$$R_H = \frac{p\mu_e^2 - n\mu_h^2}{q(n\mu_e + p\mu_h)^2}$$



x=0: Stuctural and SDW Transistions



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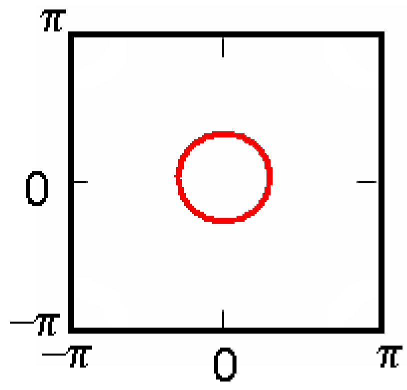
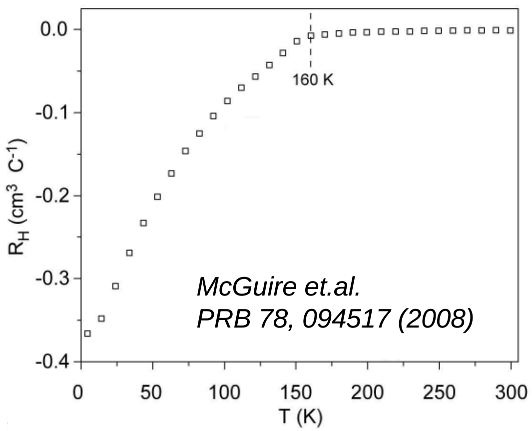


Consistent with gapping of electron-like FS

electrons holes



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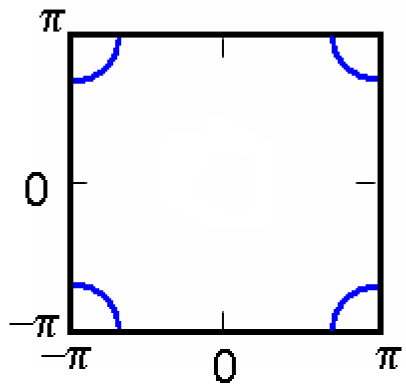
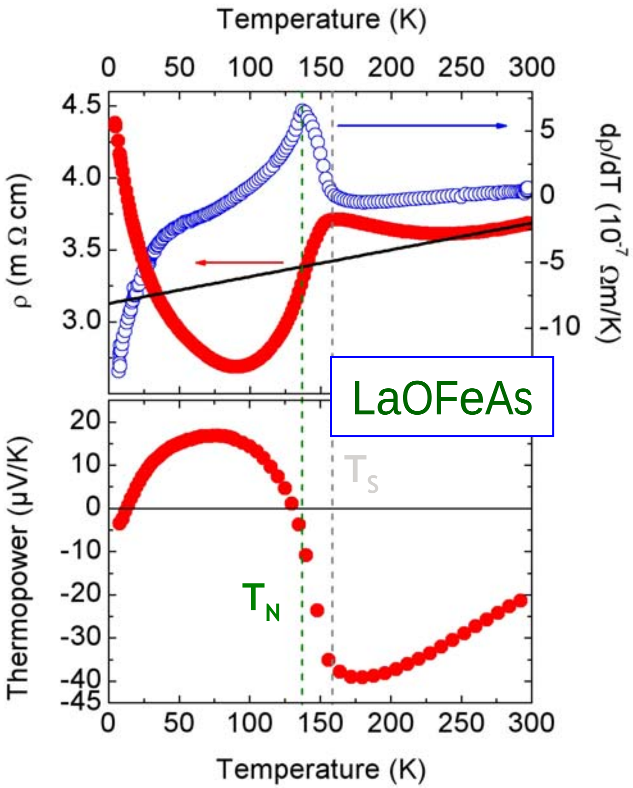


Consistent with gapping of hole-like FS

x=0: Stuctural and SDW Transistions



Resistivity

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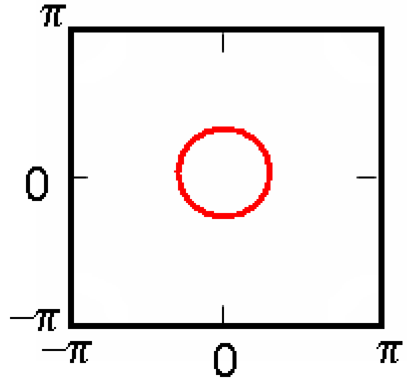
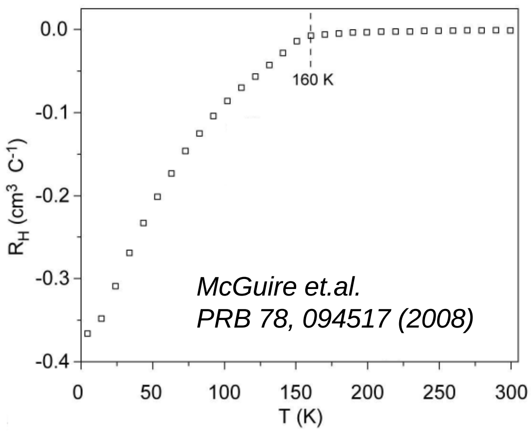


Consistent with gapping of electron-like FS

electrons holes



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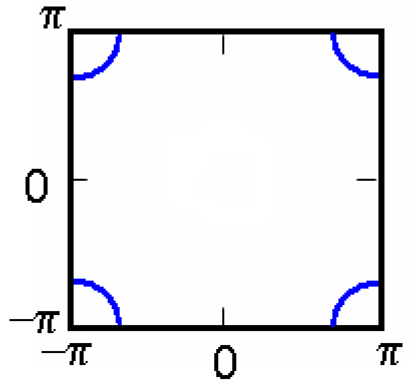
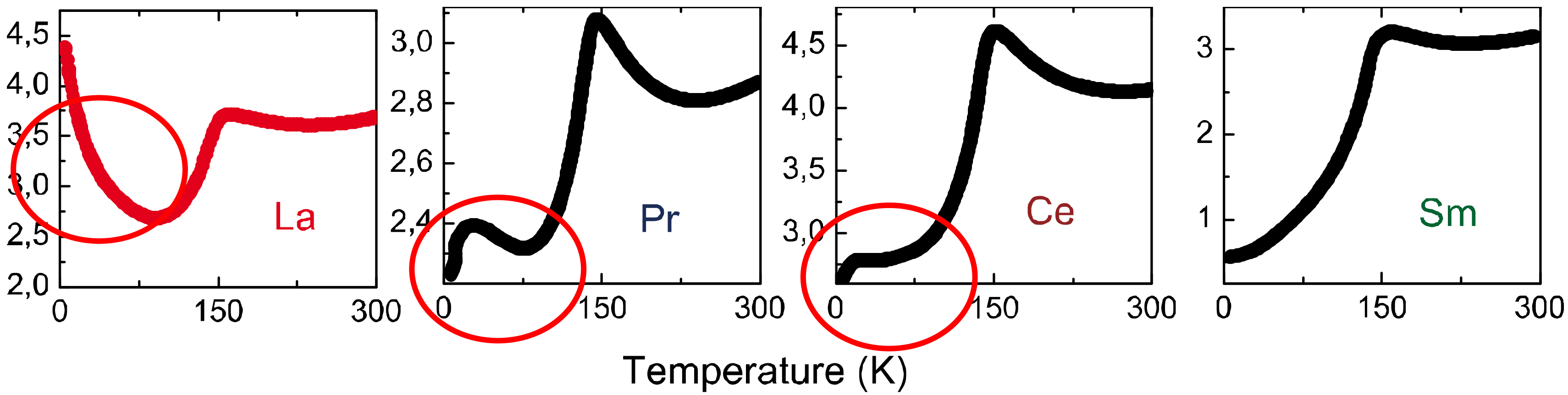


Consistent with gapping of hole-like FS

Work in progress…

Resistivity of ReOFeAs



Resistivity

- Peak at T_S
  enhanced critical scattering
- Inflection point at T_N
  reduced scattering + gap opening at $T<T_N$

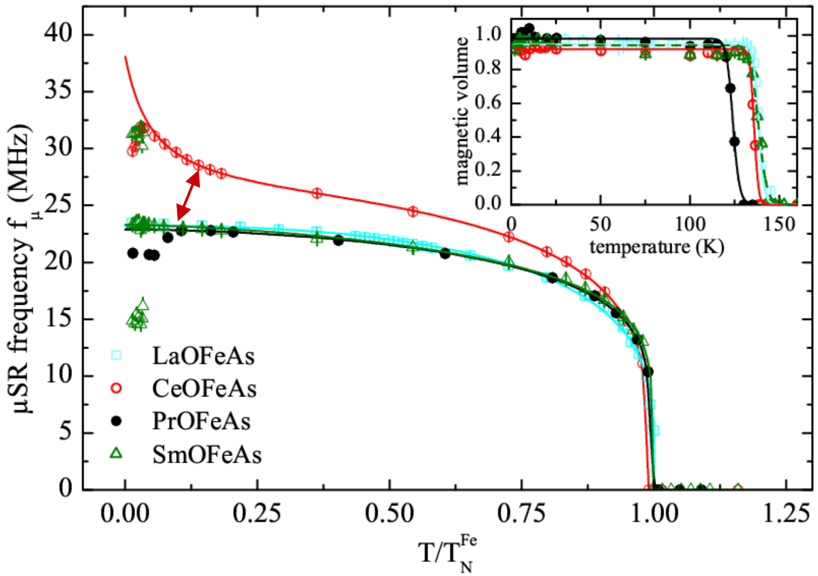
- Rare earth influence:
  induced in-gap states ?

$$\rho \propto \frac{1}{n}, \frac{1}{\lambda}$$

C.Hess et al., arXiv:0811.1601
Kimber et al., PRB 08

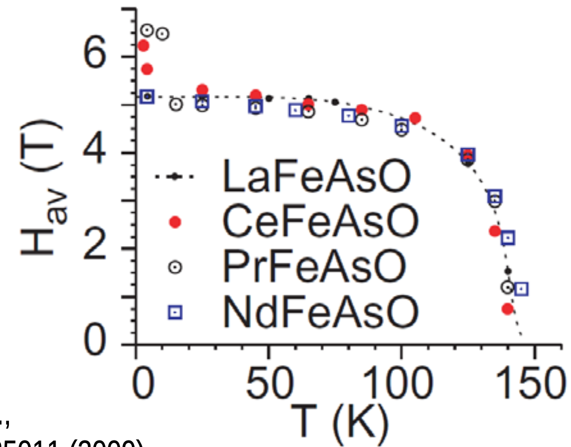
ROFeAs (R = La, Pr, Ce, Sm)

ZF-μSR:



H. Maeter, *et al.*, arXiv:0904.1563 (2009).

Moessbauer:

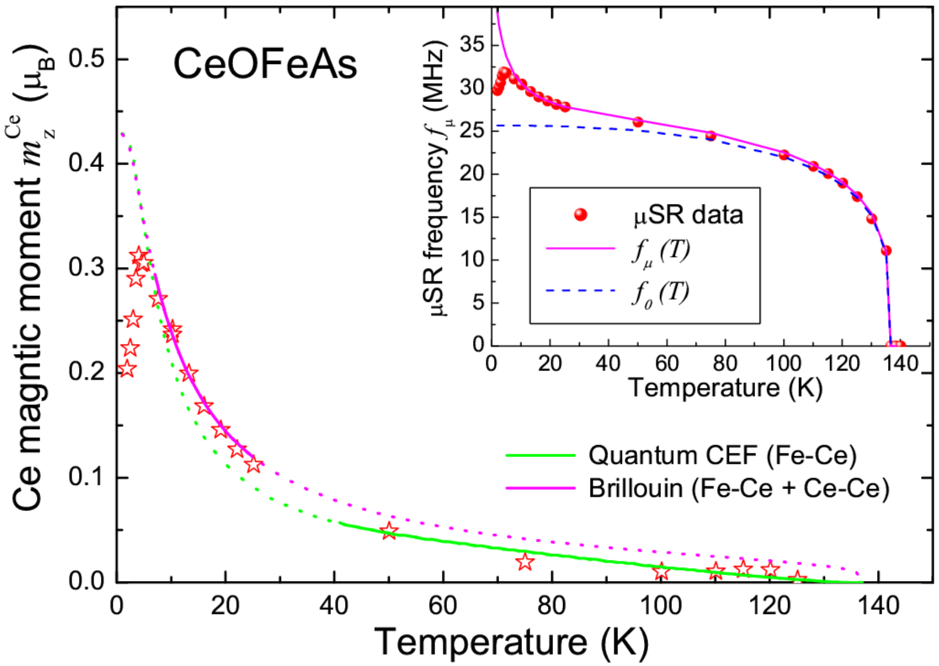


M. A .McGuire *et al.*,
New J. Phys. 11, 025011 (2009).

- Zero Field Muon Spin Rotation
  - Static magnetic order below T_N
  - 100% magnetic volume fraction
  - Commensurate magnetic structure
- T-dependence of μSR frequency
  - Second order transition at T_N(Fe)
  - $T_N(R)$
  - **Why is CeOFeAs different ?**
- Moessbauer spectroscopy
  - All compounds possess the same ordered Fe moment (~0.35 μ_B) !
- Neutron scattering: 0.25 – 0.8 μ_B ?

Ce magnetization above T_N^{Ce}

CeOFeAs



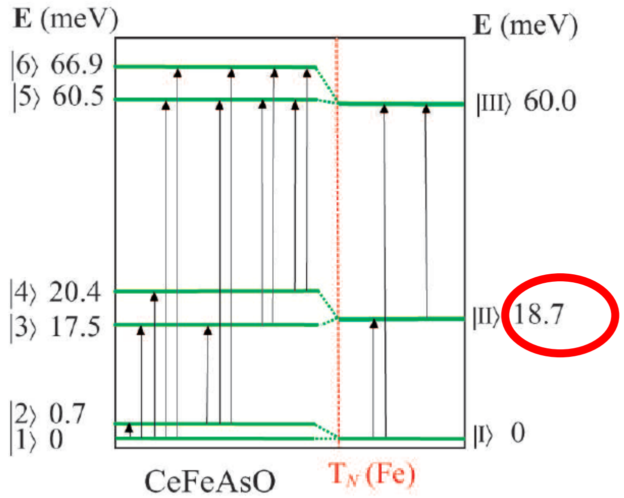
$$f(T) = f_0\left[1-\left(\frac{T}{T_N}\right)^{\alpha}\right]^{\gamma}\cdot\left[1+\frac{\tilde{C}}{T-\Theta}\right]$$

Fe sublattice magnetization

Curie-like Ce magnetization

H. Maeter, *et al.*, arXiv:0904.1563 (2009).

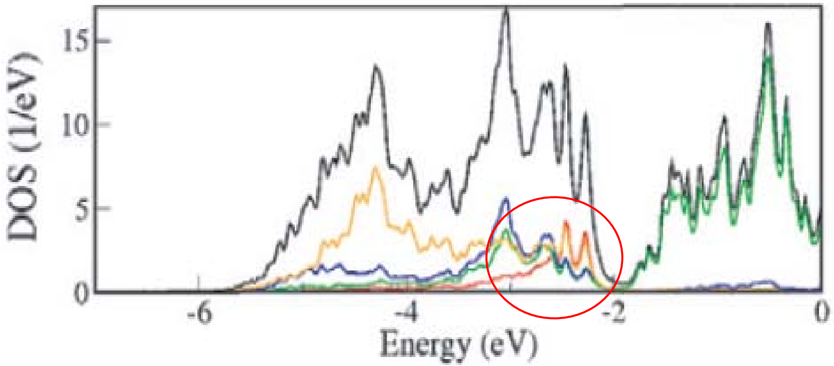
- Magnetization in molecular field of the Fe sublattice
  - Contributes to the same magnetic Bragg peak as the Fe order
  - Creates a field at the muon site which is proportional to the Ce magnetization
- This can be modeled by:
  - a Curie-like term to the μSR frequency
  - a calculation of thermal population of crystal electric field (CEF) levels

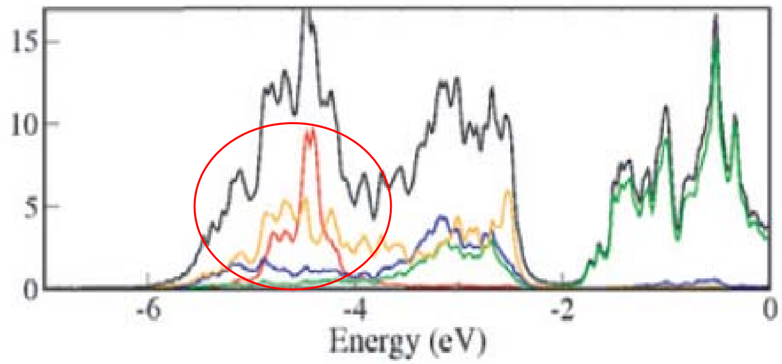


S. Chi *et al.*, arXiv:0807.4986 (2008).

Interplay of Rare Earth and FeAs electronic systems

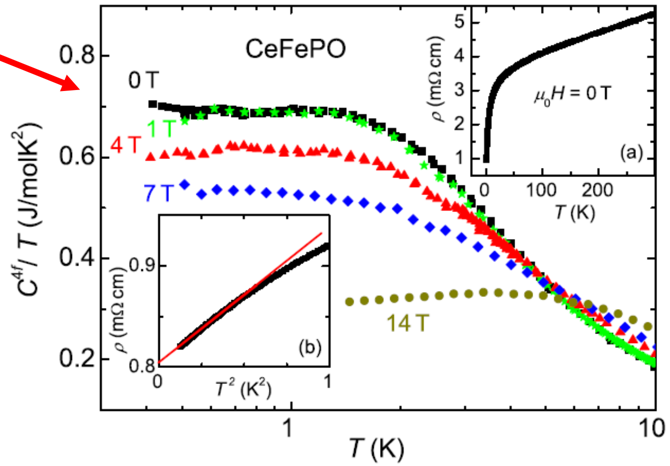
- **LDA band structure CeOFeAs PrOCeAs**





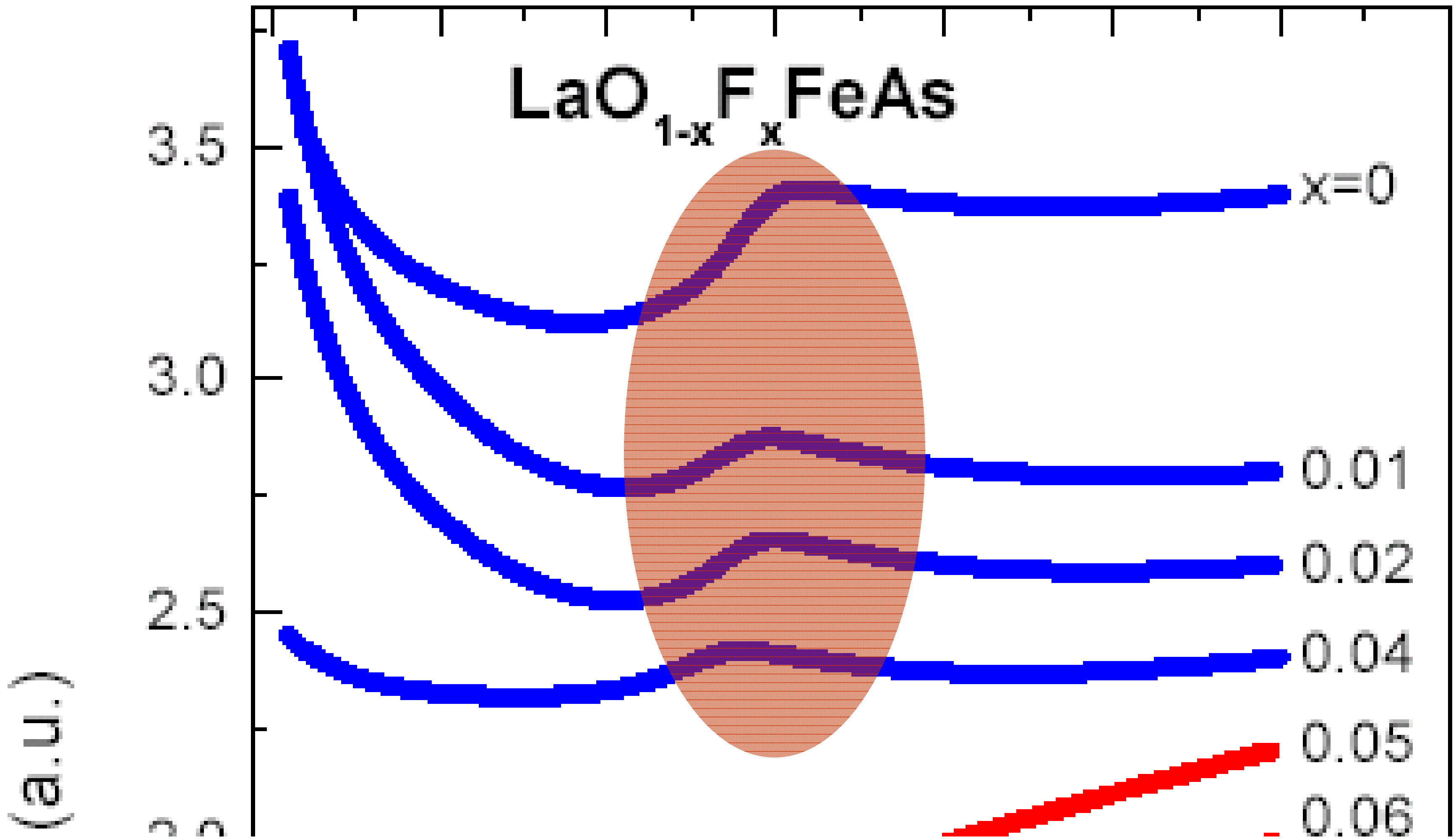
L. Pourovskii et al., EPL 84 37006 (2008)

- **Strong hybridization between Fe and Ce states**
- **CeOFeP is a moderate heavy fermion system**
- **Pr states shifted 2 eV downwards**

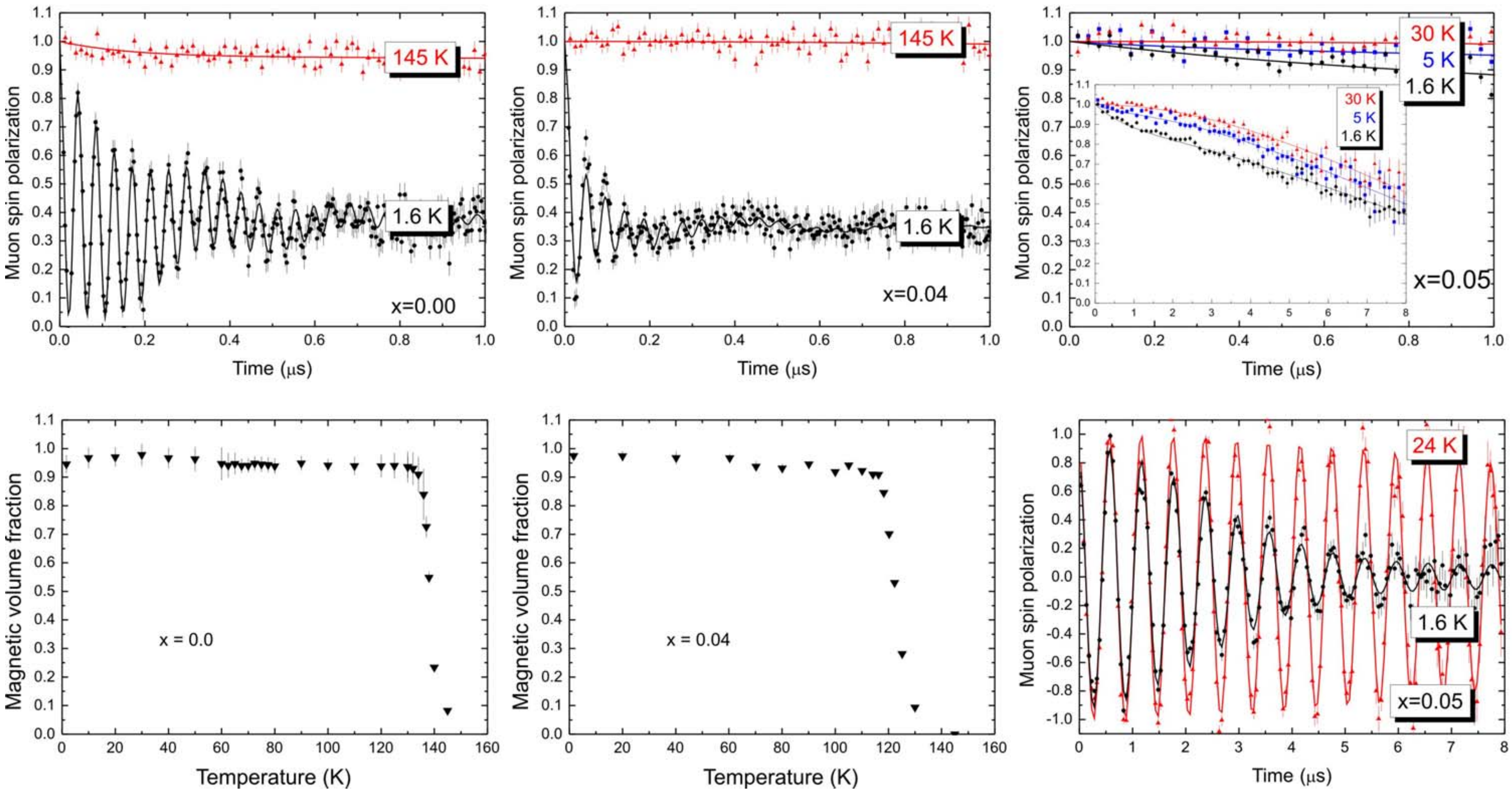


E. M. Brüning et al., Phys. Rev. Lett. 101, 117206 (2008)

Resistivity of $La(O_{1-x}F_x)FeAs$



Magnetism of lightly doped $La(O_{1-x}F_x)FeAs$



H. Luetkens et al., Nature Materials 2009

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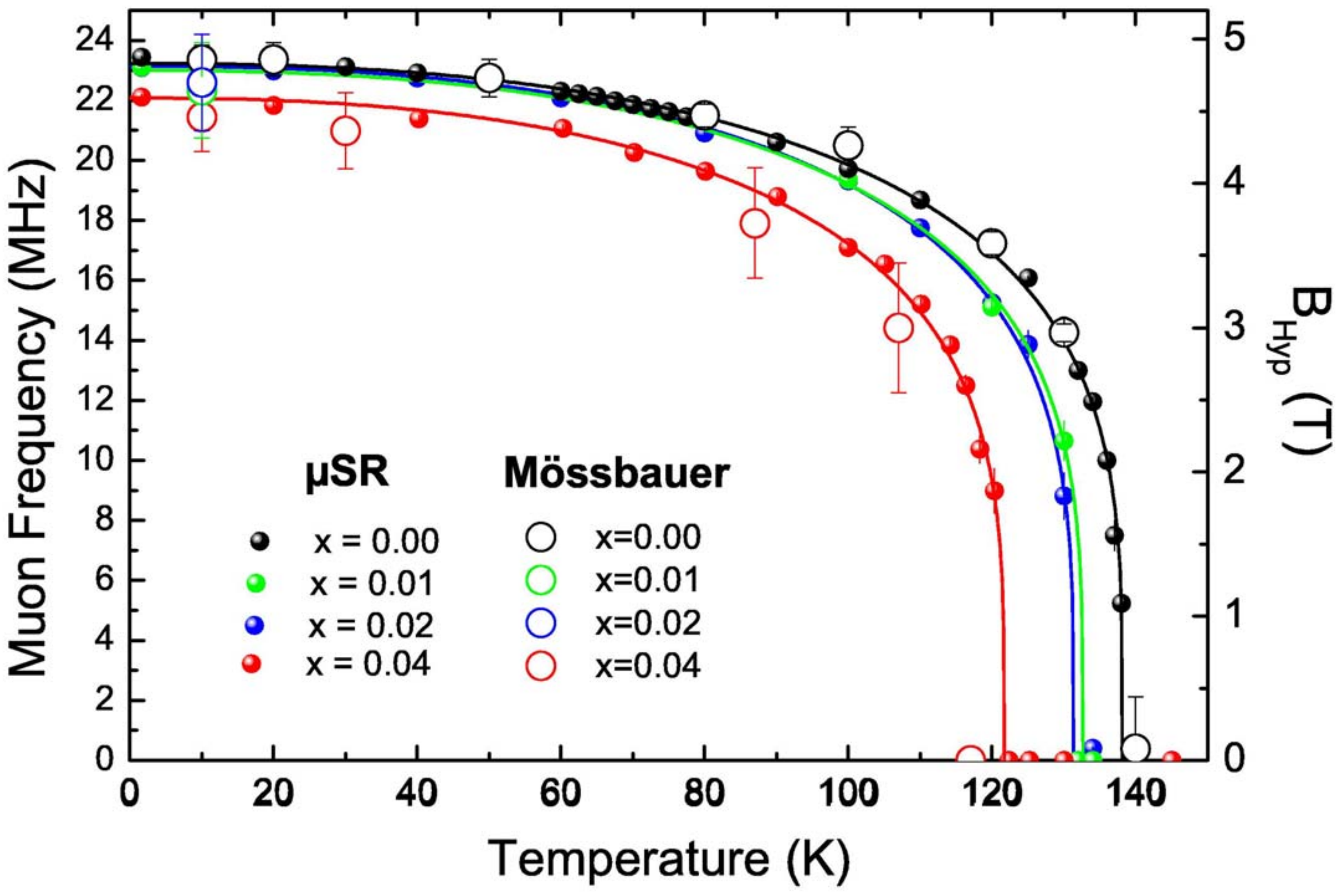
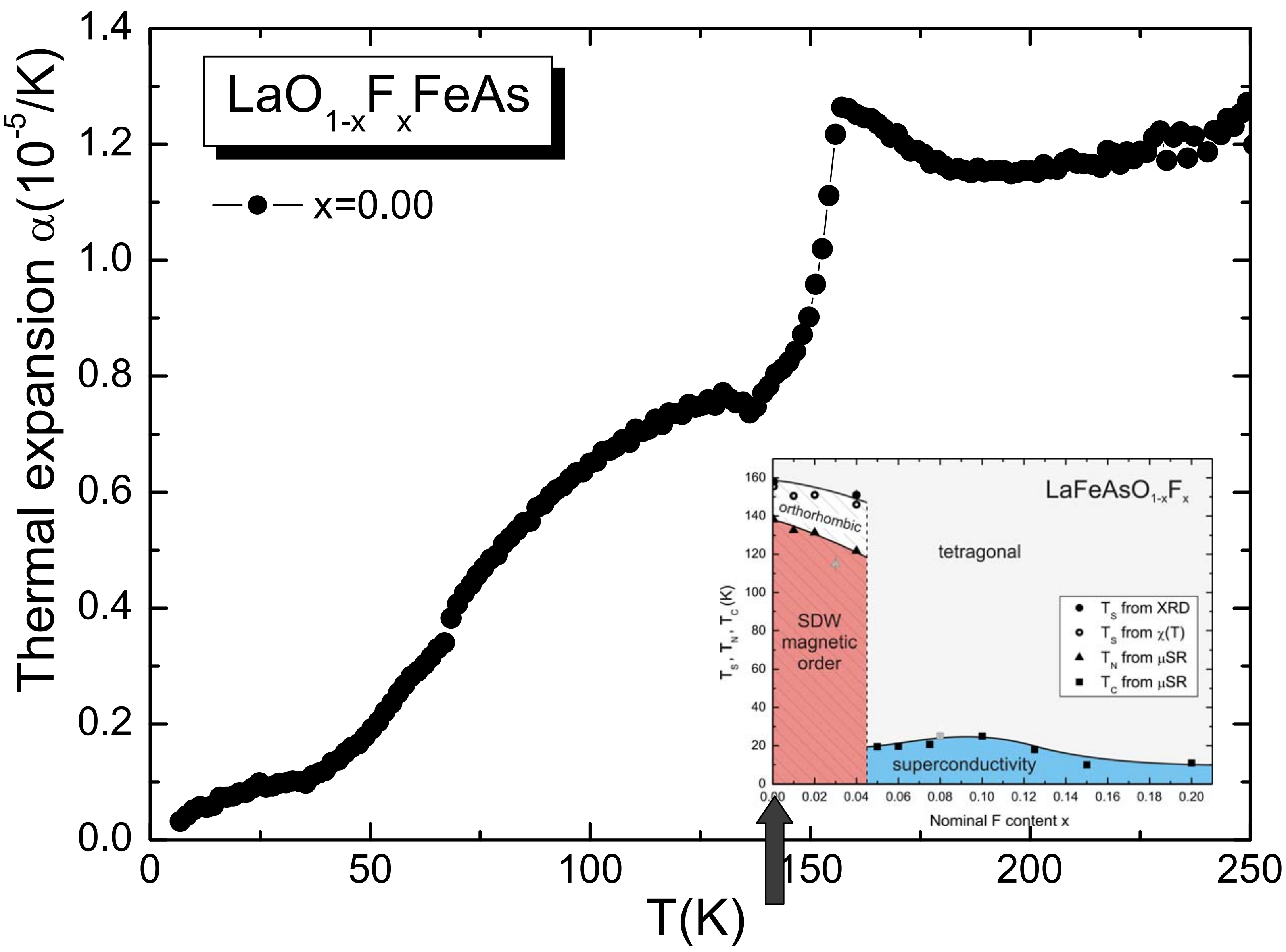


H. Luetkens et al., Nature Materials 2009

Doping effect: $LaFeAsO_{1-x}F_x$



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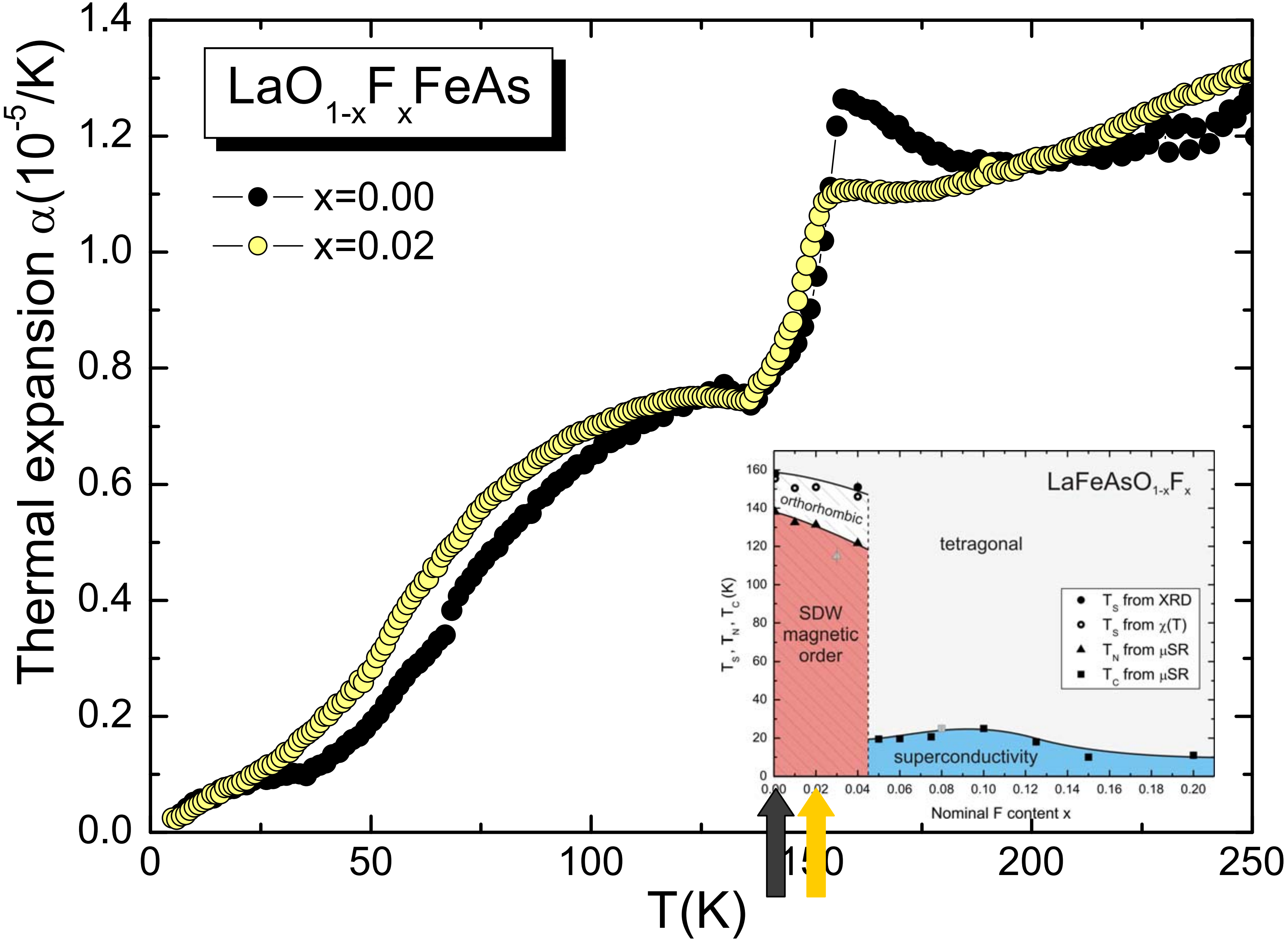

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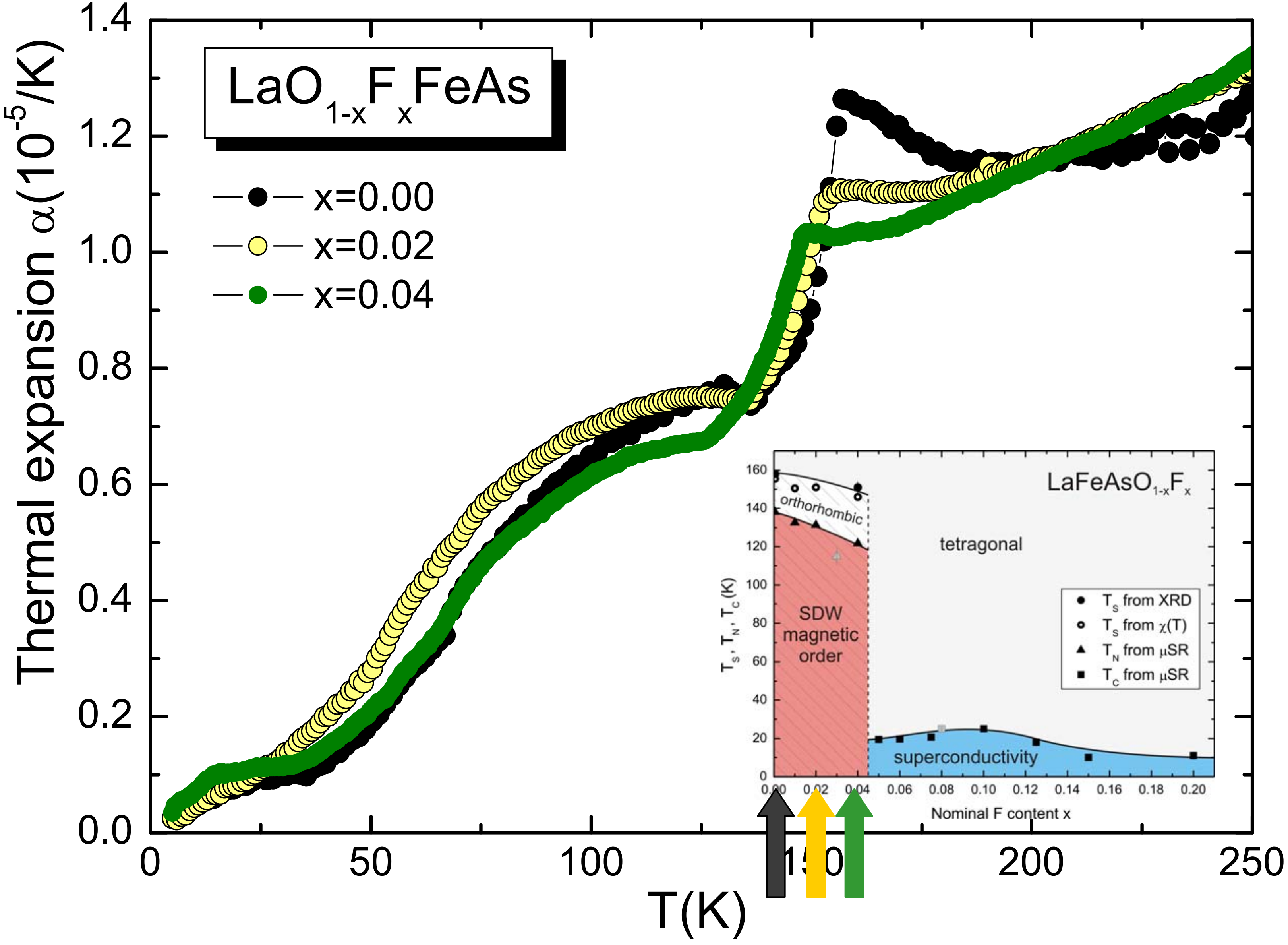

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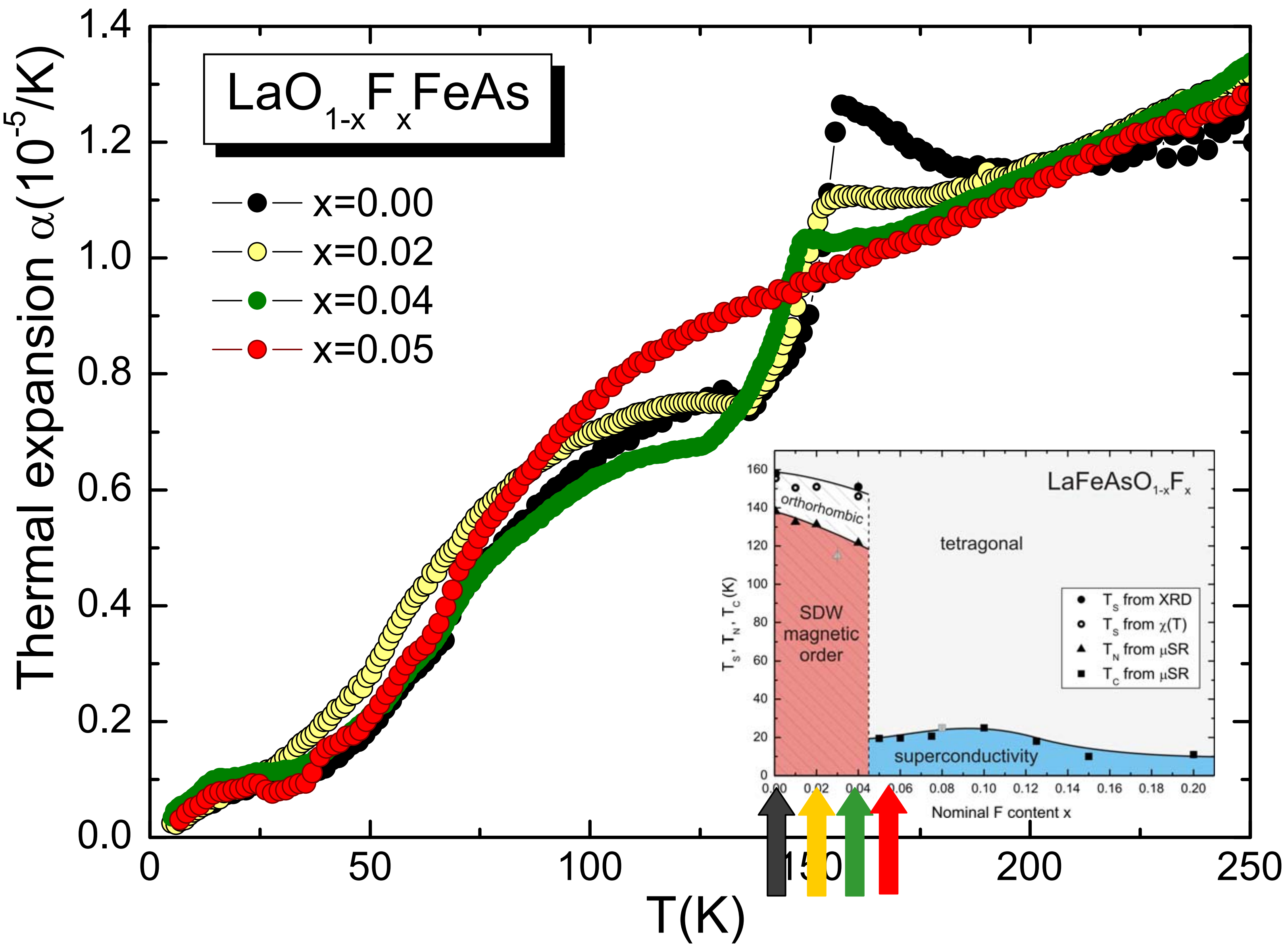

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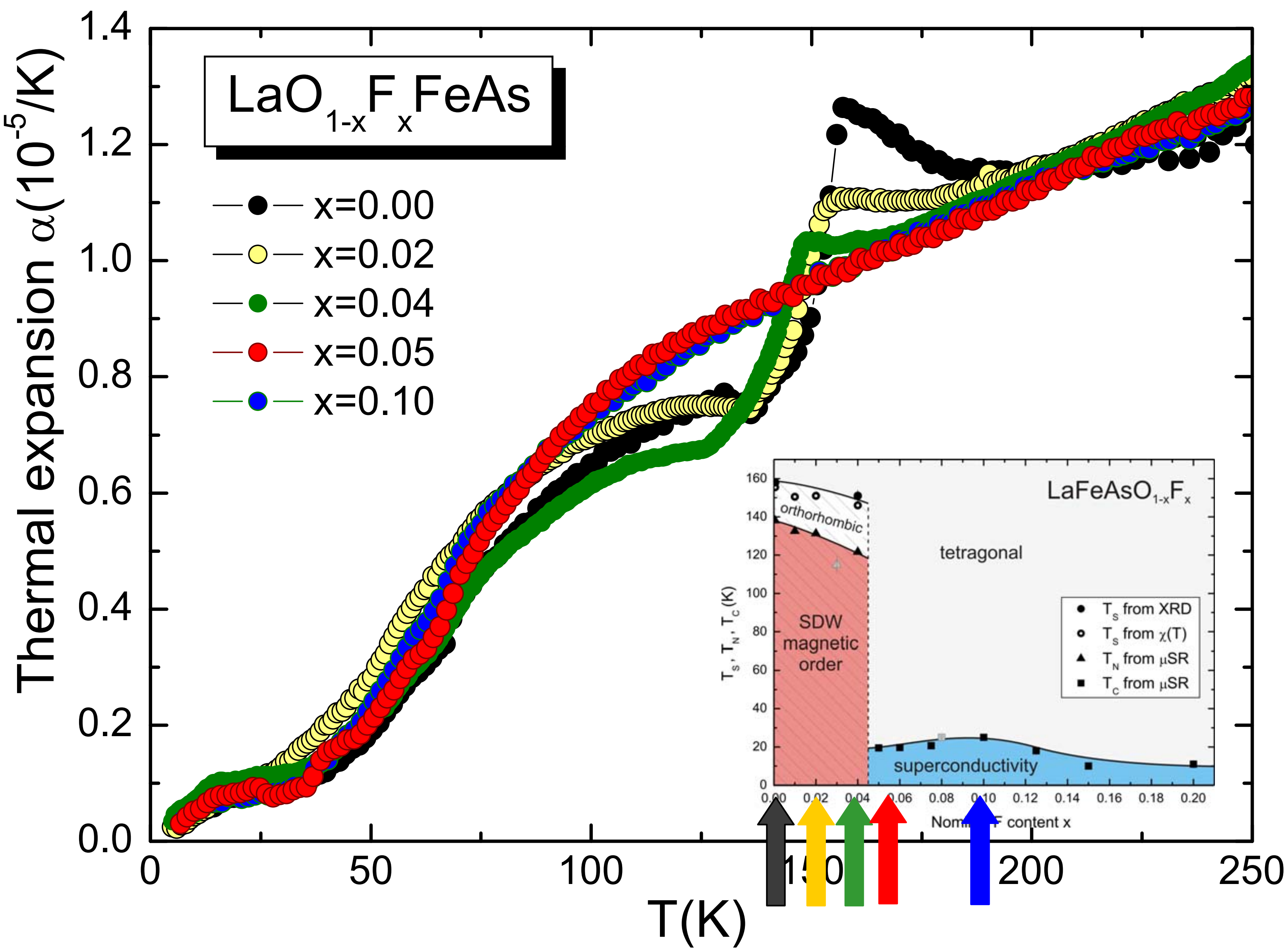
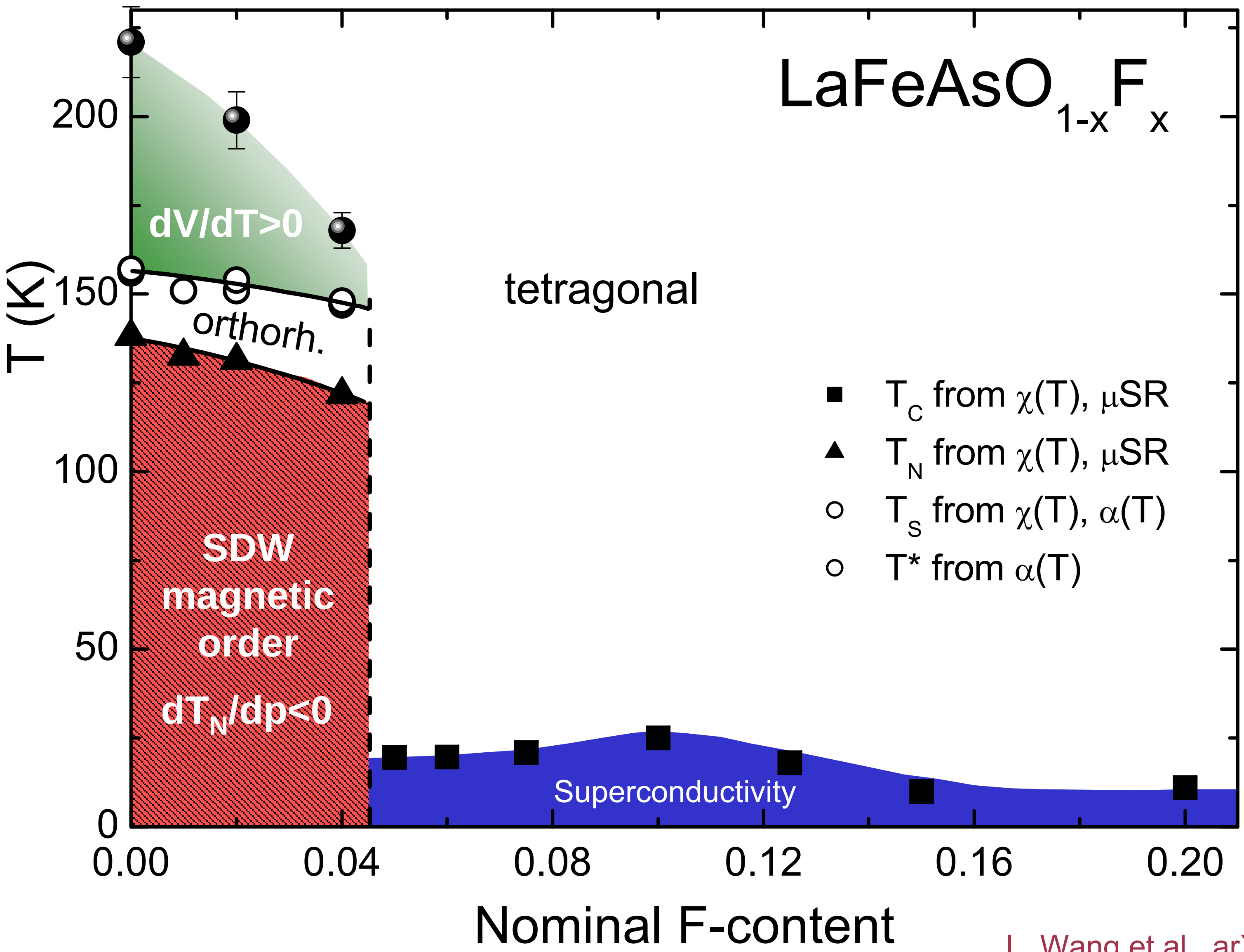
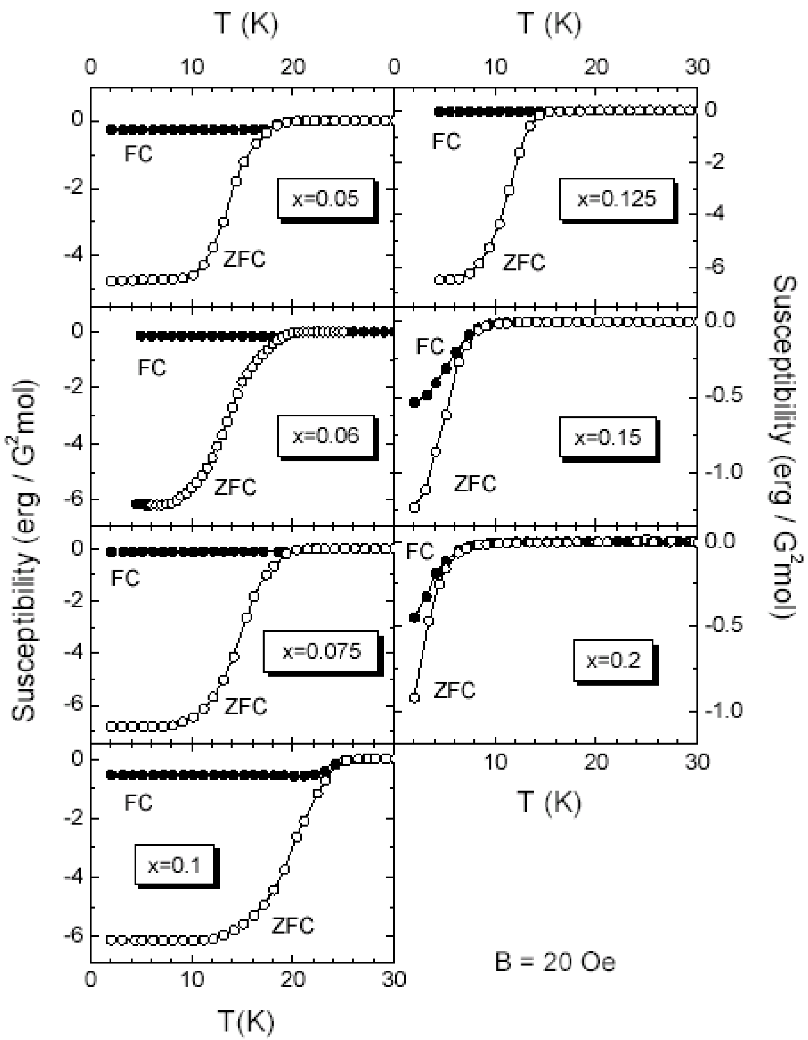


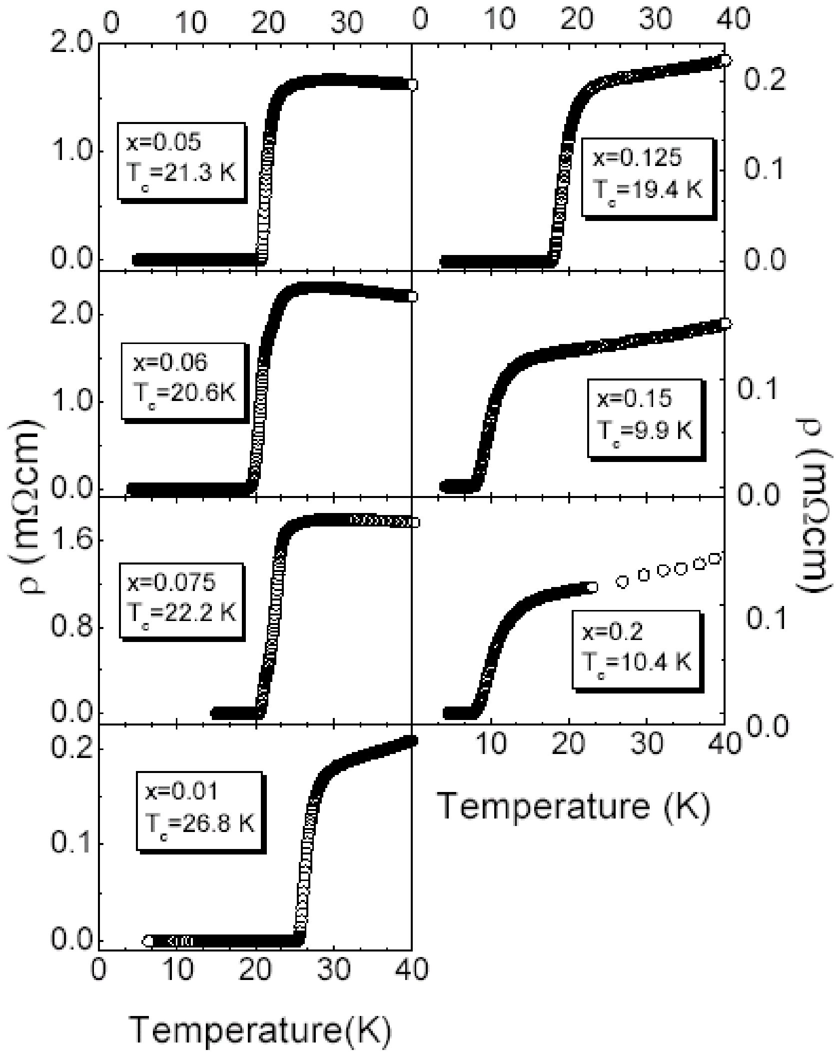
Phase diagram of $LaFeAsO_{1-x}F_x$



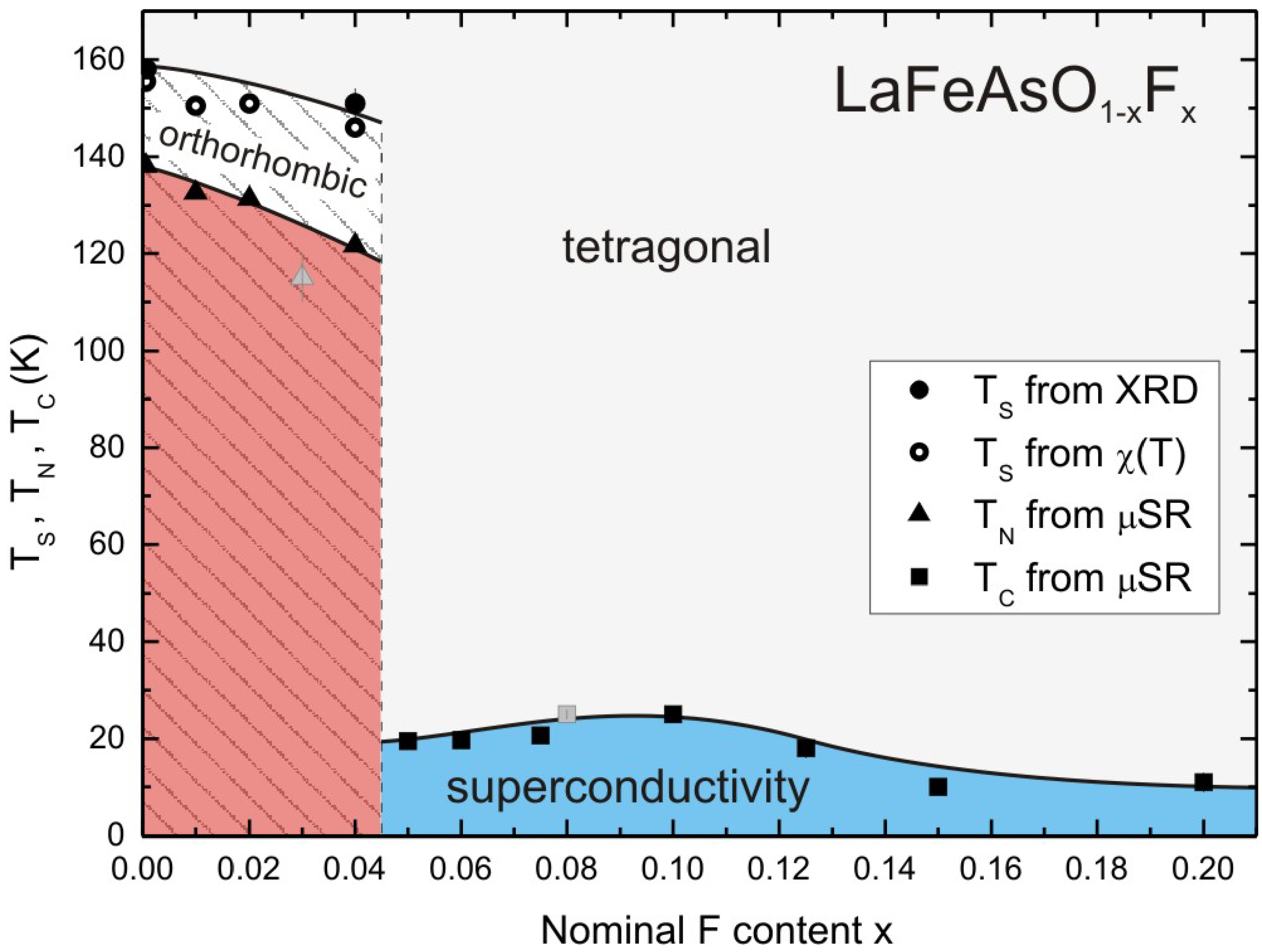
L. Wang et al., arXiv:0903.1235

Superconductivity of $La(O_{1-x}F_x)FeAs$



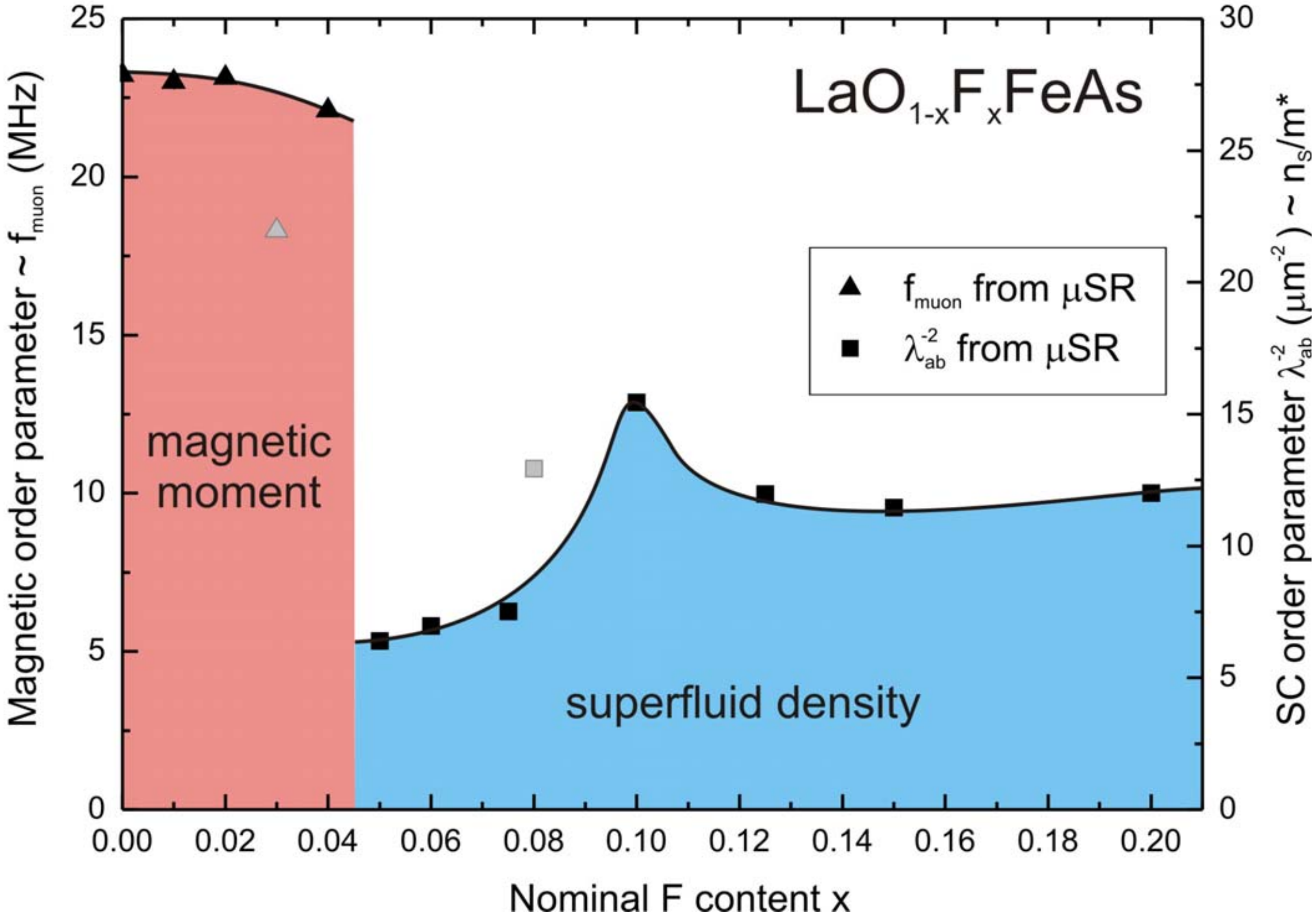


Phase Diagram of $La(O_{1-x}F_x)FeAs$



H. Luetkens et al., Nature Materials 2009

Phase Diagram of $La(O_{1-x}F_x)FeAs$

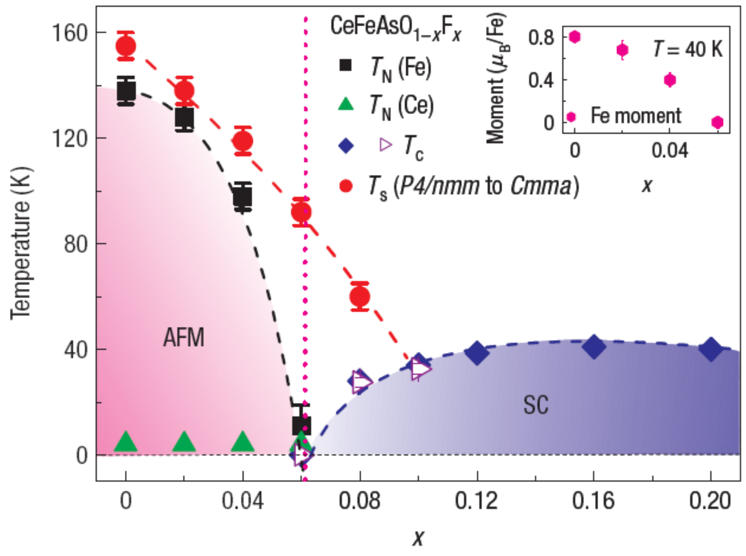


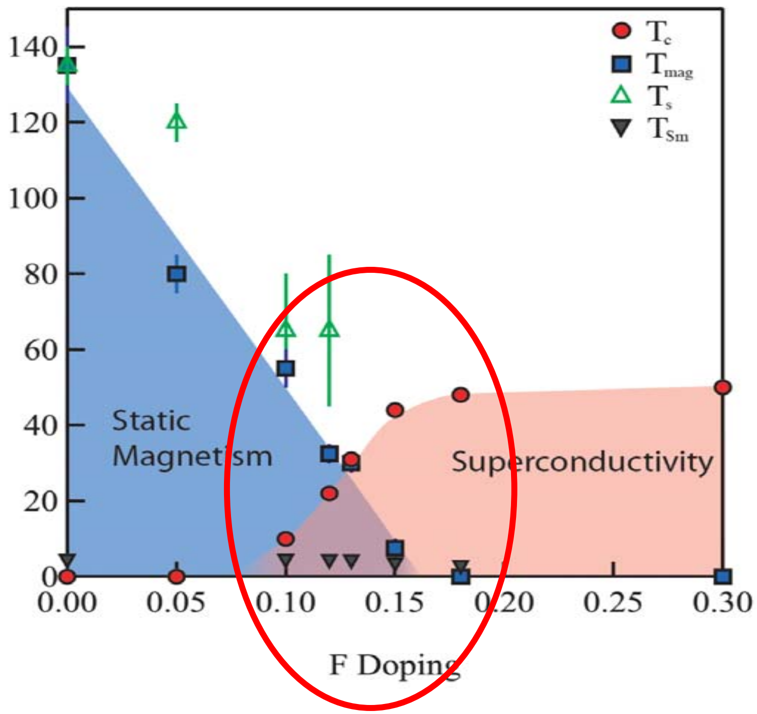
H. Luetkens et al., Nature Materials 2009

Phase Diagrams of $CeFeAsO_{1-x}F_x$ and $SmFeAsO_{1-x}F_x$

$CeO_{1-x}F_xFeAs$

Zhao et al., Nature Materials (2008), neutrons

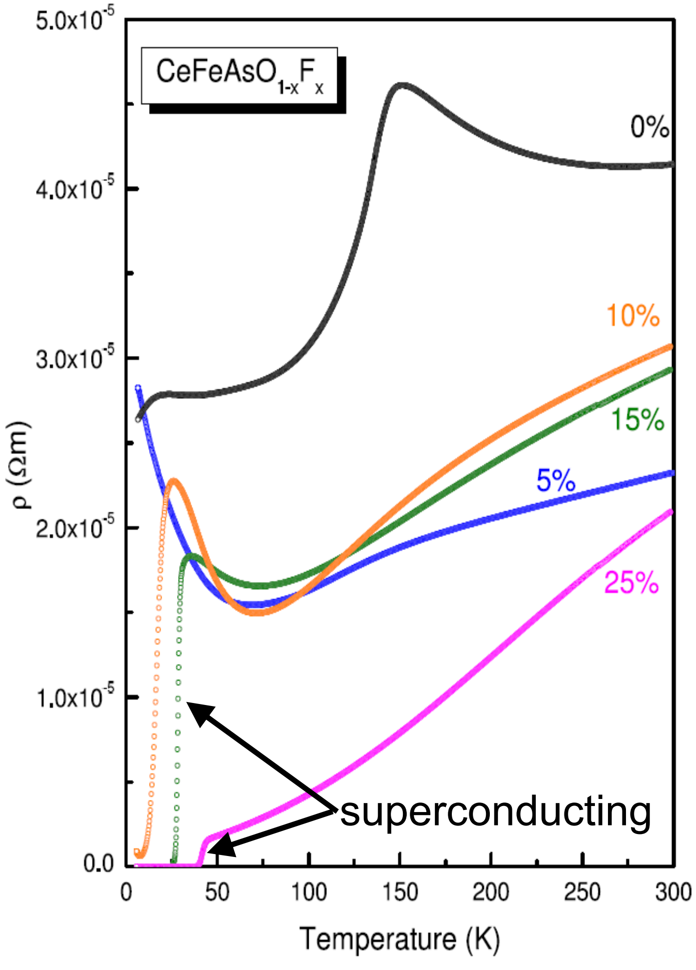




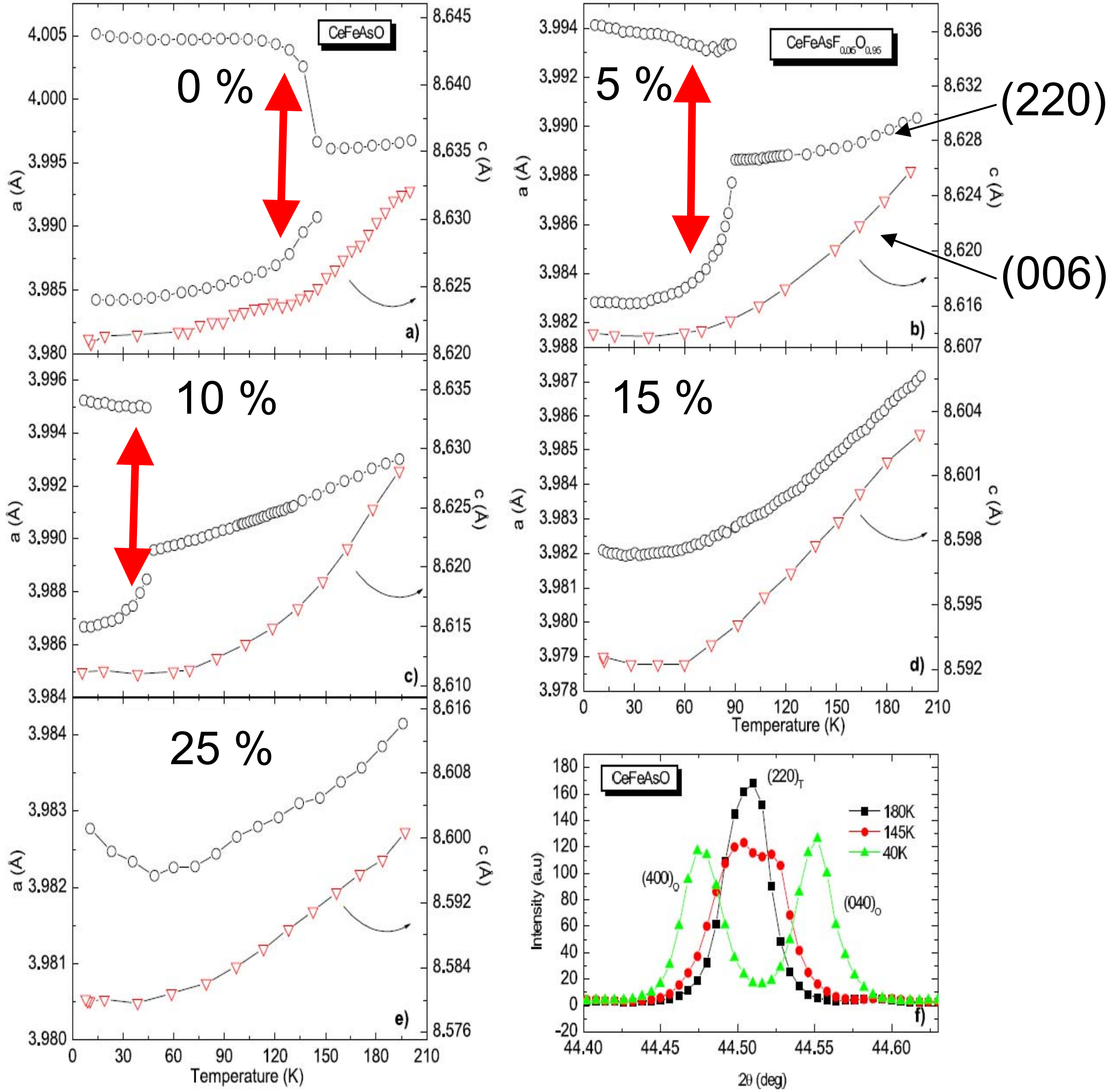
Drew et al., Nature Materials 2009

- 100 % rare earth doping (5% lattice constant change!) does not change the structural distortion, but a few percent Flourine (electron doping) completely suppresses T_s !
- gradual decrease of FeAs Neel temperature to zero ?
- coexistence of magnetism and superconductivity? Yes

Resistivity



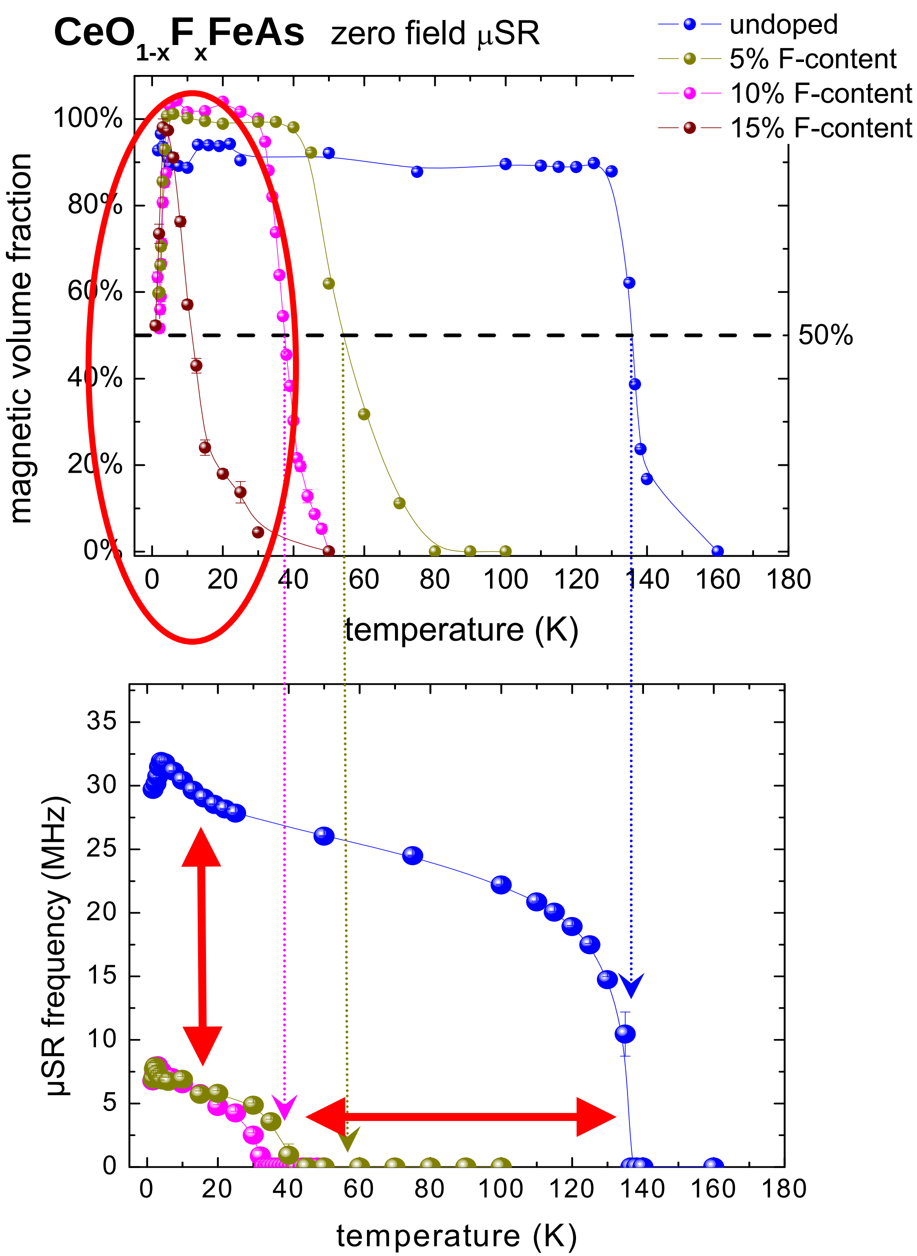
Tetragonal → Orthorombic structural transition via synchrotron XRD



J. E. Hamann-Borrero, A. Kondrat et al., in preparation

0 30 60 90 120 150 180 210
Temperature (K)

Zero field μSR: $CeO_{1-x}Fe_xAs$



Determine T_N(Fe) **from magnetic volume**:

- e.g.50% of signal shows static relaxation
- Strong reduction of T_N for x>0!

Appearance of **μSR frequency**
→ Long range coherent sublattice magnetization

- Strong reduction of sublattice magnetization for x>0

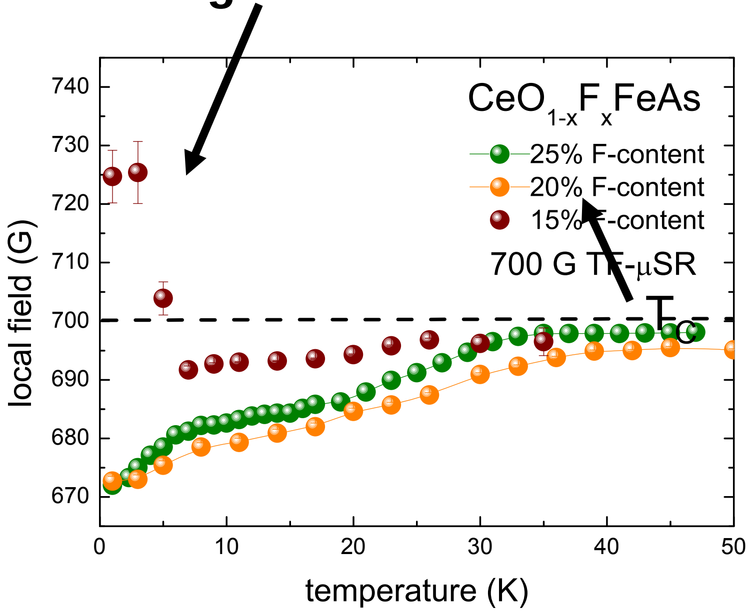
- **No long range order for x=0.15**

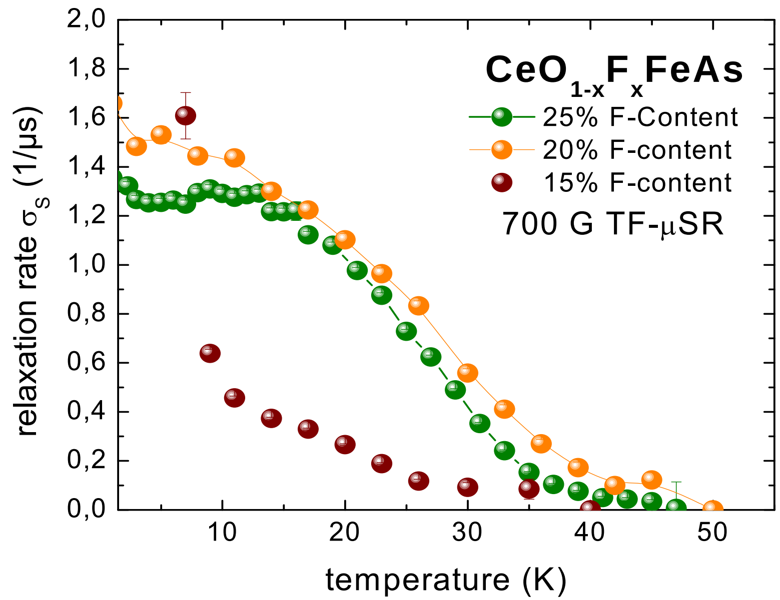
- but short range magnetic order present with $f_\mu(T)=0$!
  → *Mean* sublattice magnetization = 0
  → **not visible in neutron scattering**

H. Maeter, *et al.*, in preparation.

Transverse field μSR: $CeO_{1-x}Fe_xAs$

Static magnetic order





Frequency shift

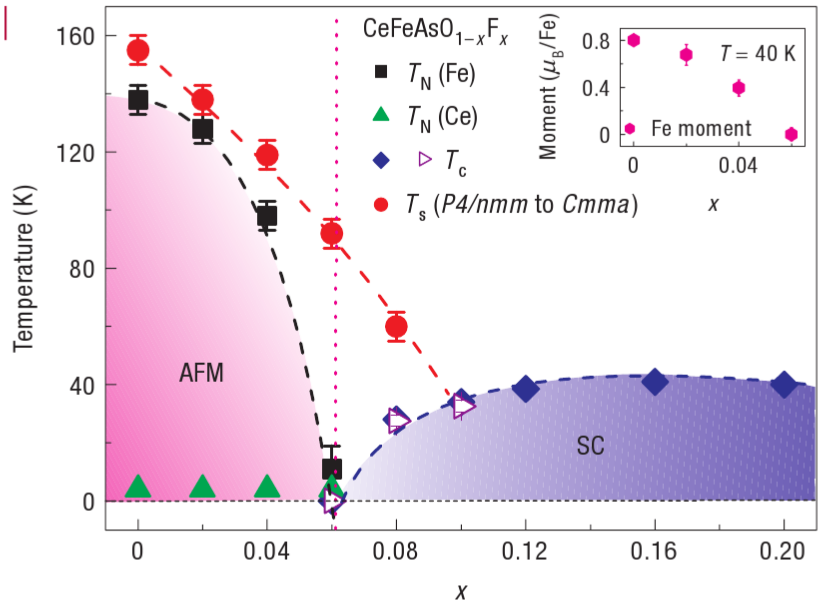
- Additional diamagnetic frequency shift
- *Bulk* superconductivity → T_C
- *Bulk* static magnetism for 15%!

Static line width

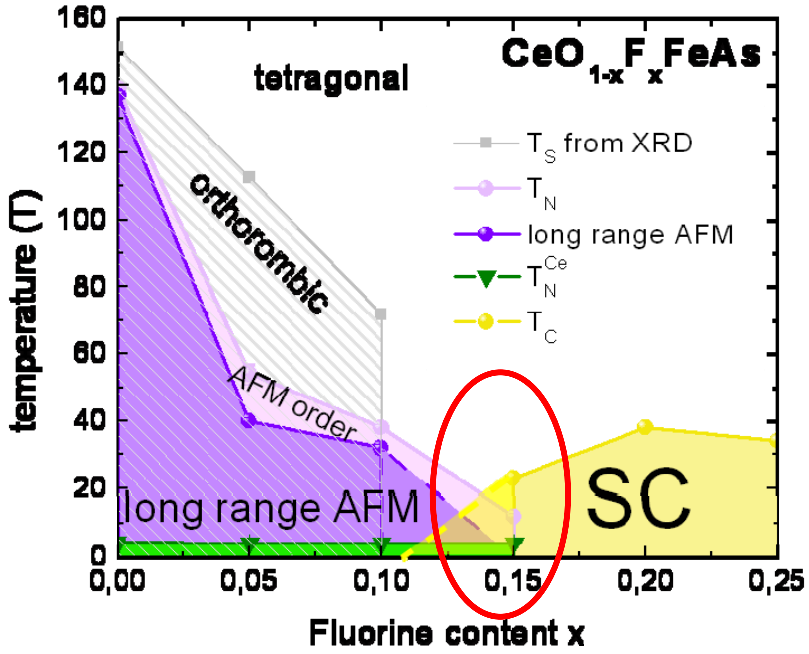
- *Bulk* superconductivity → T_C
- *Bulk* static magnetism for 15%!

H. Maeter, *et al.*, in preparation.

$CeO_{1-x}F_xFeAs$: coexistence of magnetism and SC?



Zhao et al., Nature Materials (2008), neutrons



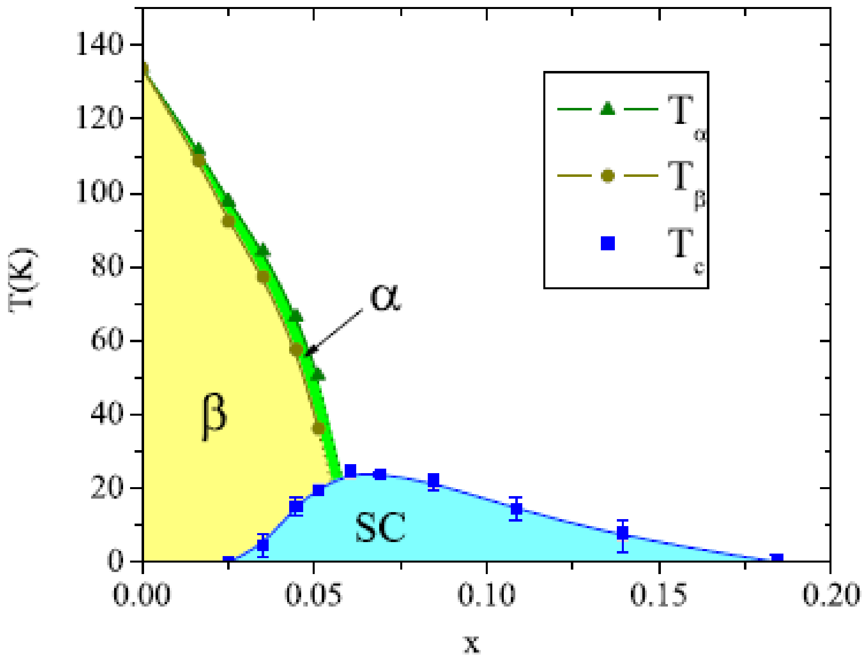
Evidence for coexistence!

XRD, ρ, μSR,…

H. Maeter, *et al.*, in preparation.

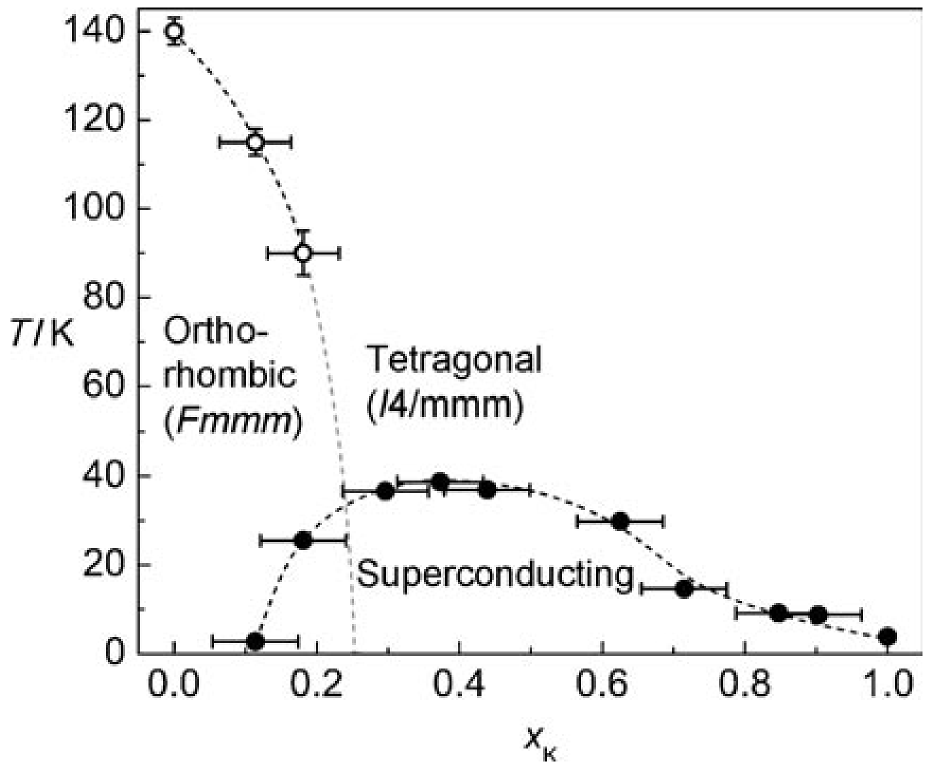
Phase Diagrams of doped $BaFe_2As_2$

$BaFe_{2-x}Co_xAs_2$



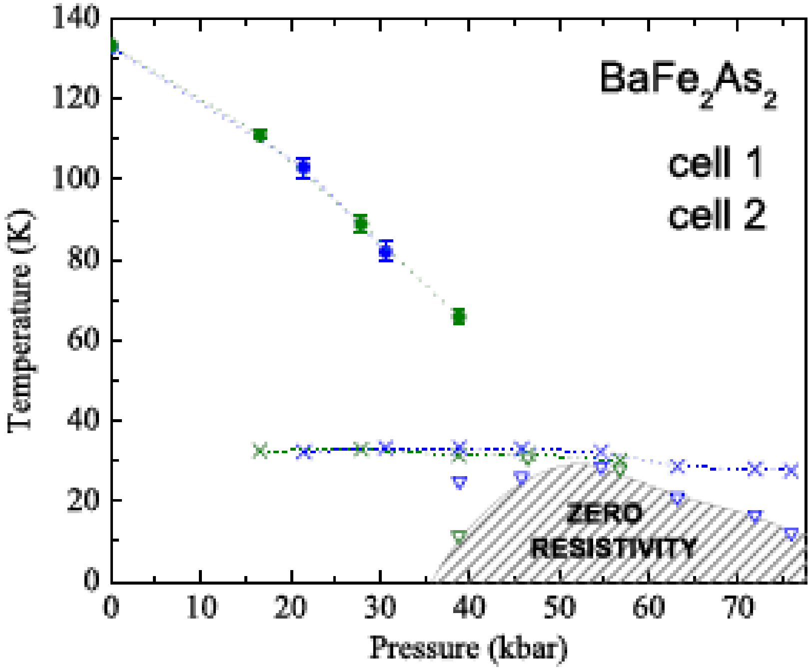
Chu et al., PRB 2009

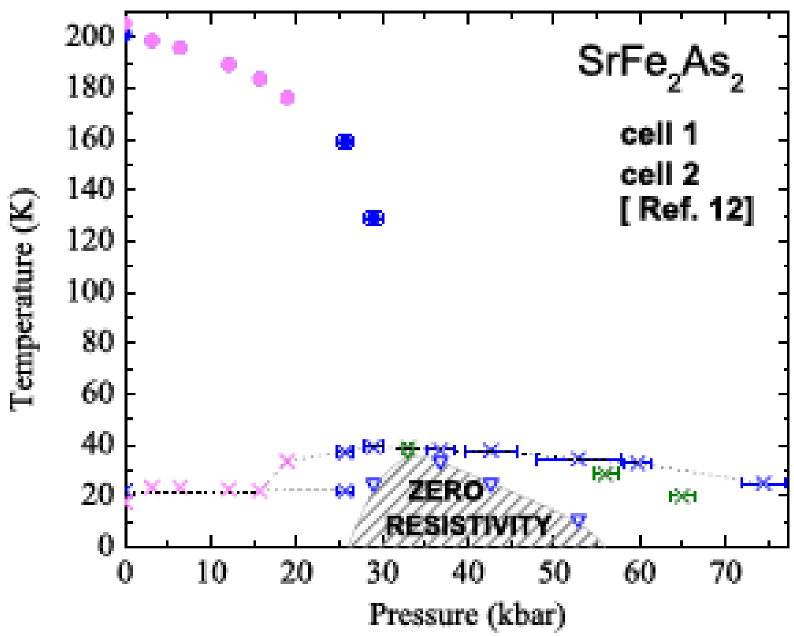
$Ba_{1-x}K_xFe_2As_2$



Rotter et al., Ang. Chem. 2008

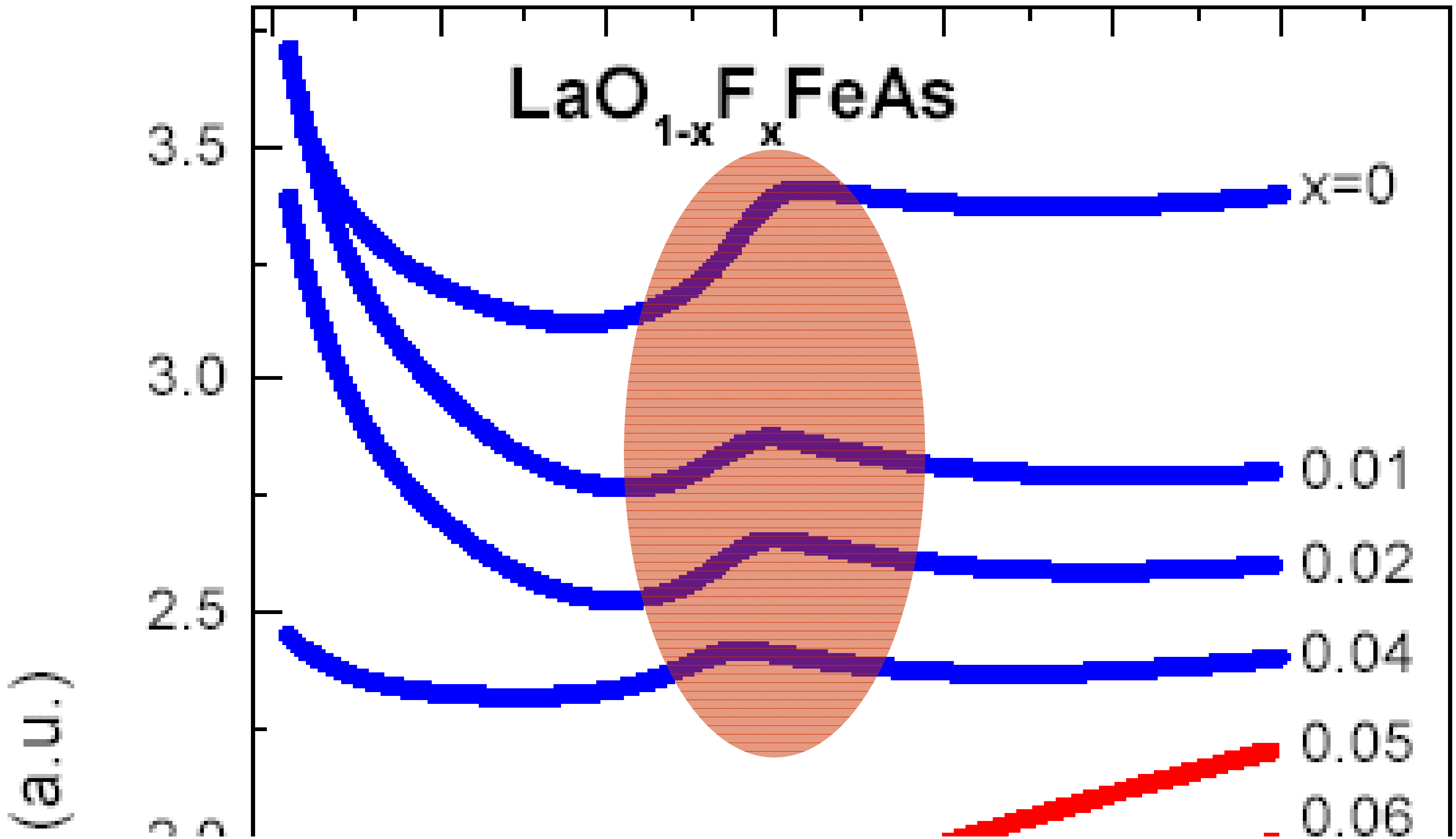
Pressure induced Superconductivity in (Ba,Sr)Fe_2As_2



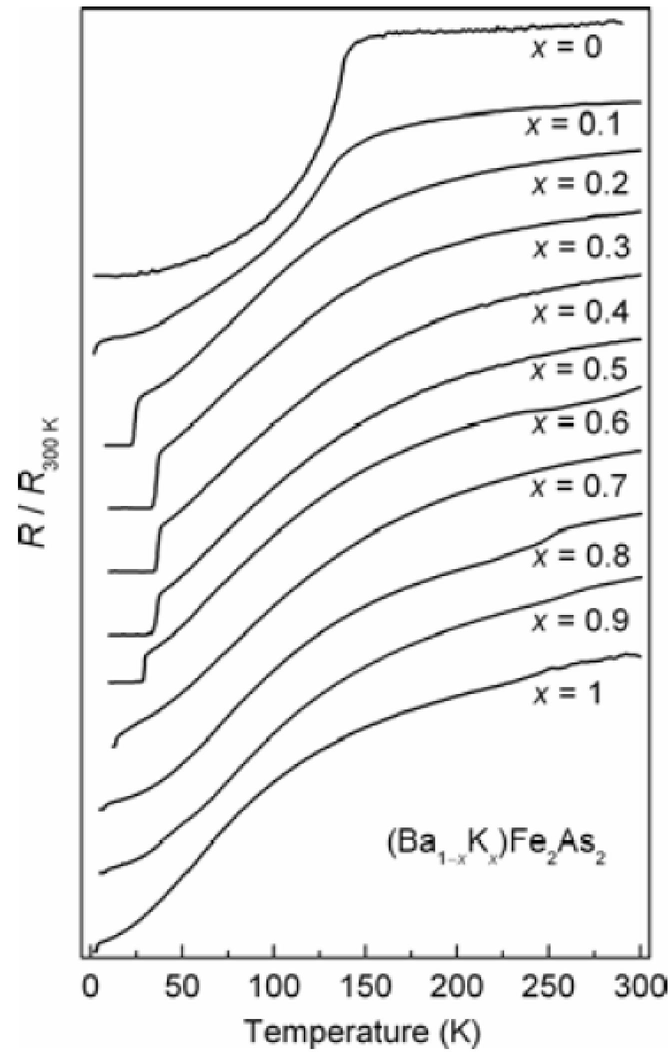


Colombier et al., arxiv.org/abs/0904.4488v1

Resistivity of La($O_{1-x}F_x$)FeAs



Phase Diagram of $Ba_{1-x}K_xFe_2As_2$

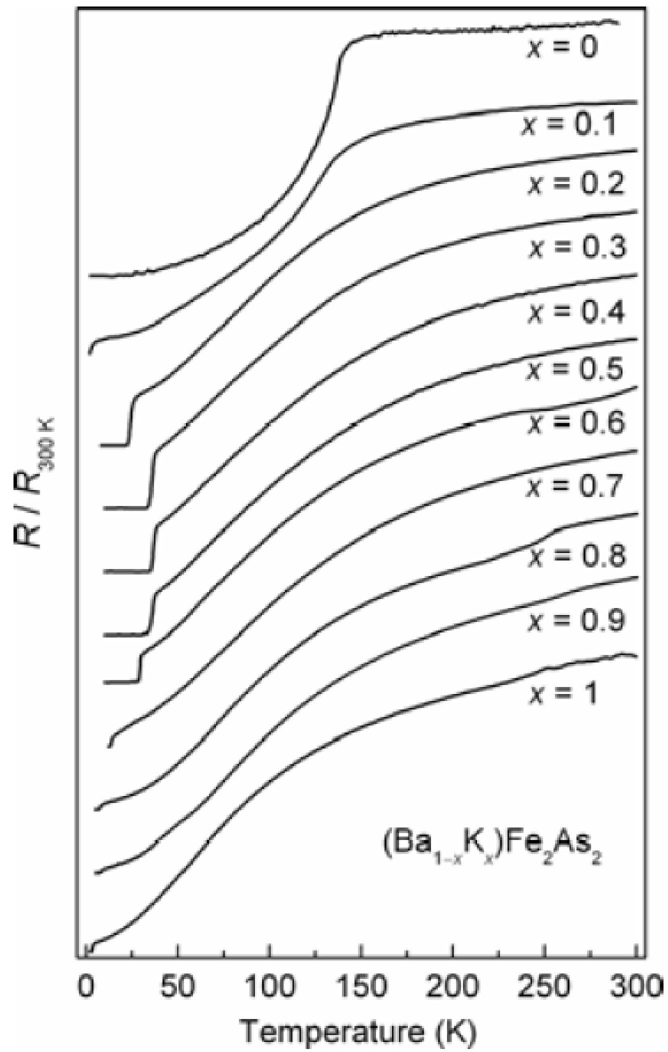


Superconductivity and Crystal Structures of $(Ba_{1-x}K_x)Fe_2As_2$ (x = 0 - 1)

*Marianne Rotter, Michael Pangerl, Marcus Tegel and Dirk Johrendt**

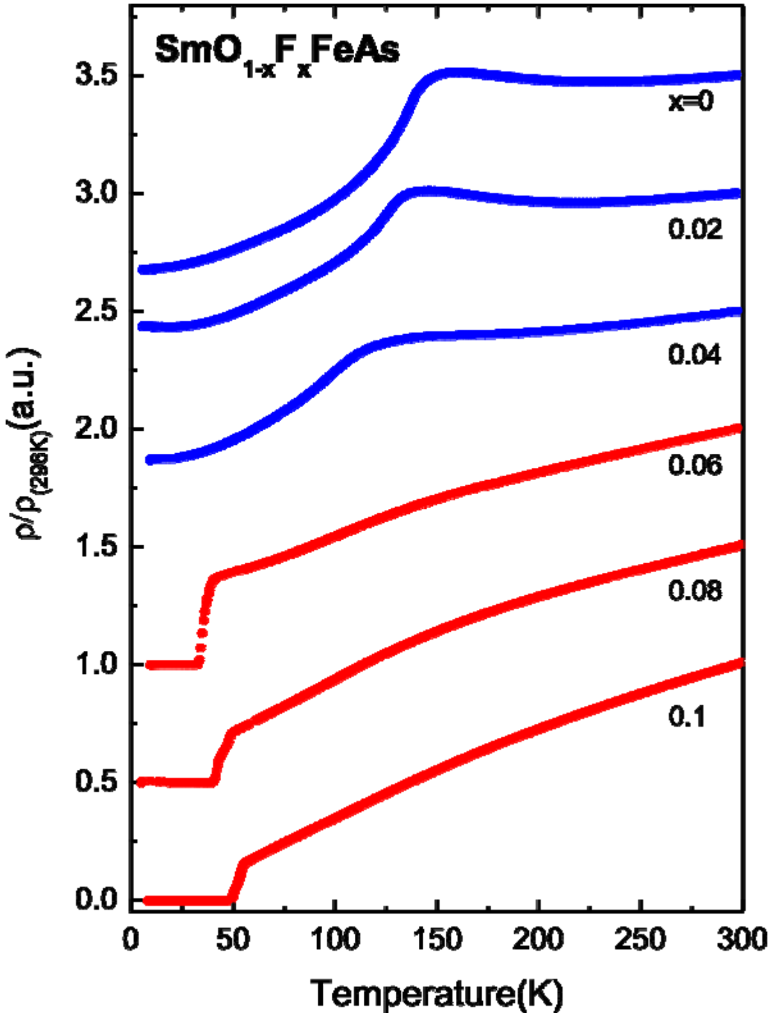
Ang. Chem. 2008

Resistivity of doped pnictides



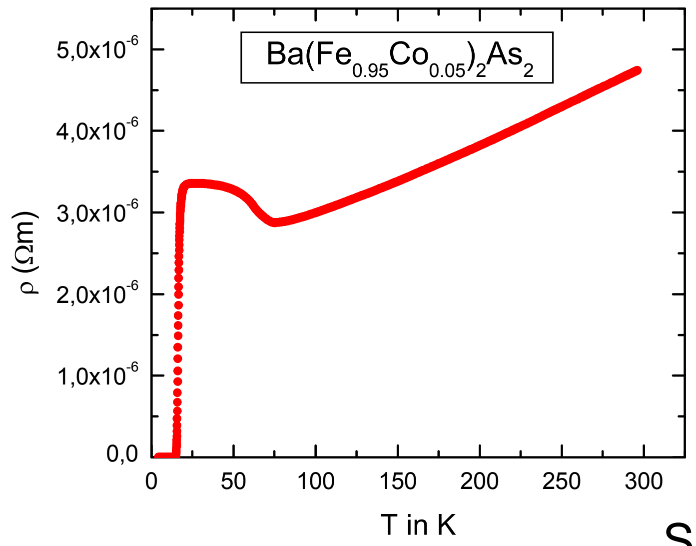
Rotter et al.,
Ang. Chem. 2008

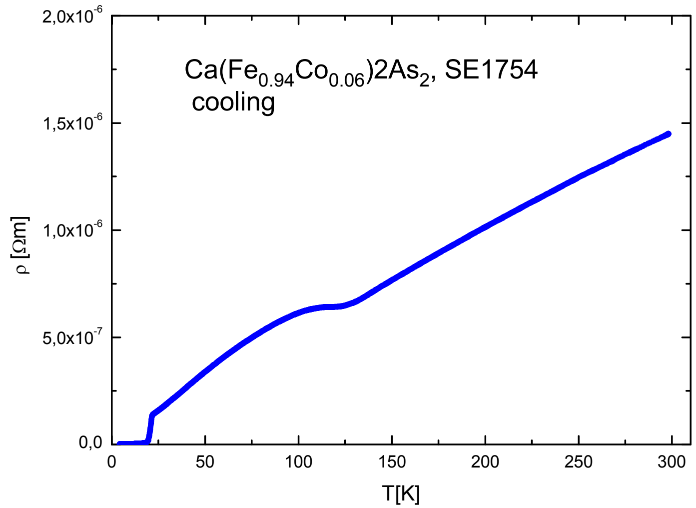
$SmO_{1-x}F_xFeAs$ – highest T_c



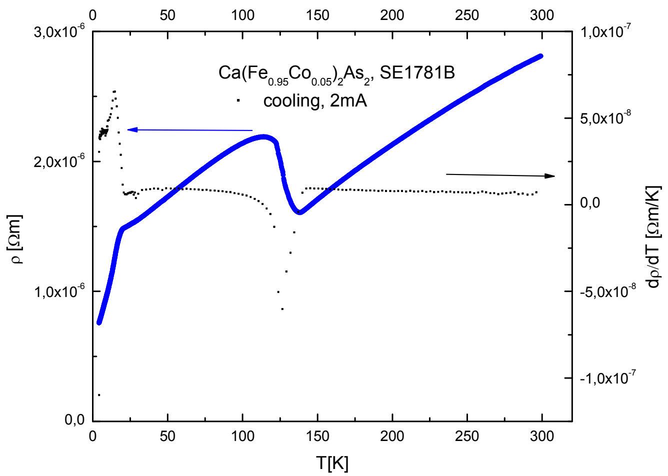
C. Hess et al., EPL (2009)

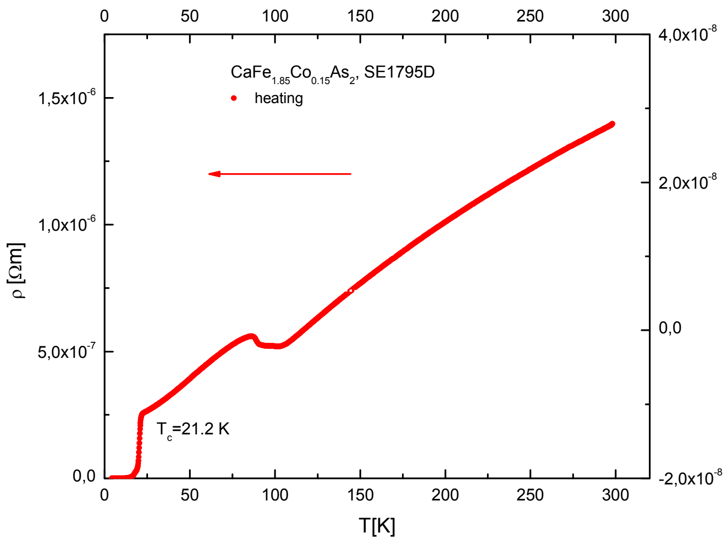
Resistivity of Co doped pnictides



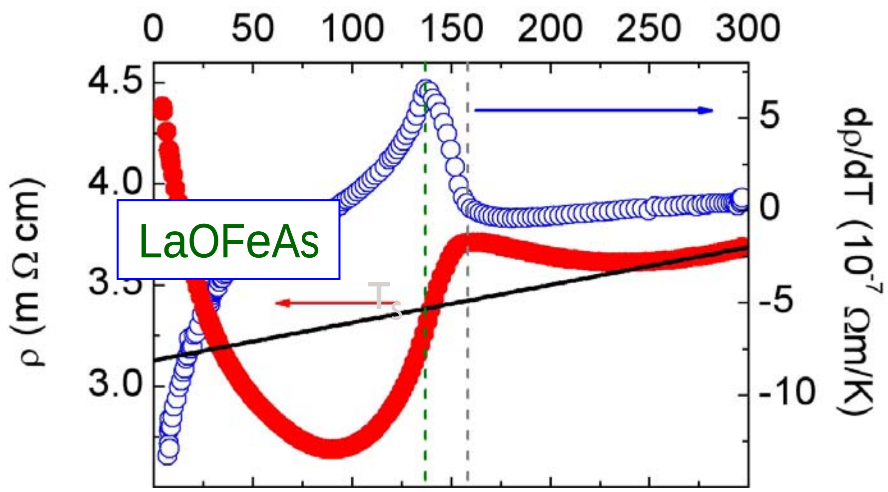


Single crystals





Resistivity at the stuctural and SDW transistions



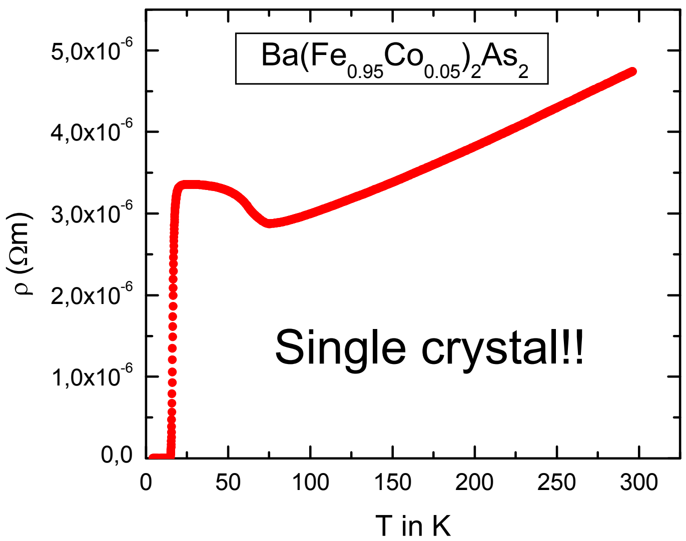
$$\rho \propto \frac{1}{n}, \frac{1}{\lambda}$$

Resistivity

- Peak at T_S

  enhanced scattering at higher T
- Inflection point at T_N

  reduced scattering



Resistivity in Co doped systems

- Reduction of scattering at T_N smaller
- Mean free path limited by disorder due to Co atoms!!

Intrinsic sources of scattering masked by disorder in Co doped single crystals!!!

Leibniz-Institut
für Festkörper- und
Werkstoffforschung
Dresden

High Temperature Superconductivity in FeAs Compounds

OUTLINE

- Introduction

- Phase Diagram of $LaFeAsO_{1-x}F_x$ (and other pnictides)

  Structural, magnetic, and superconducting transitions

- **Superconducting State**

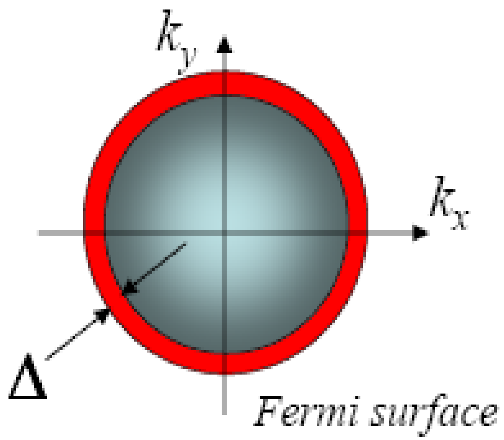
  Gap, penetration depth, relaxation rate

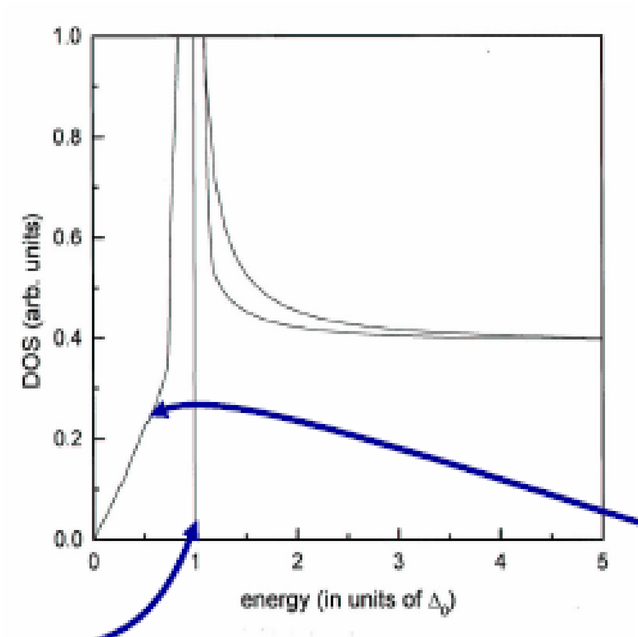
- Normal State Properties

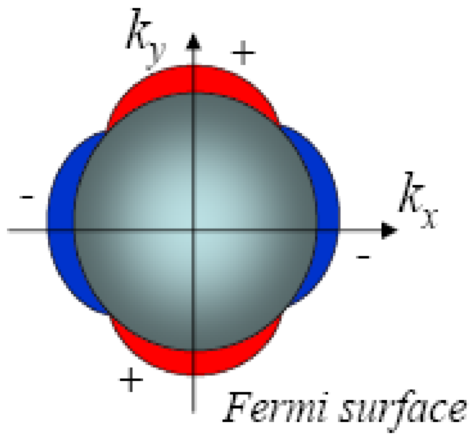
  Electronic Structure (XAS, PES, ARPES)
  „Pseudogap“ (NMR, χ)
  Electronic transport and spin fluctuations
  Charge inhomogeneity (NQR)

Superconducting Order Parameter (Gap)

The fundamental parameter of a superconductor is the gap $\Delta(\mathbf{k})$







s-wave: isotropic gap

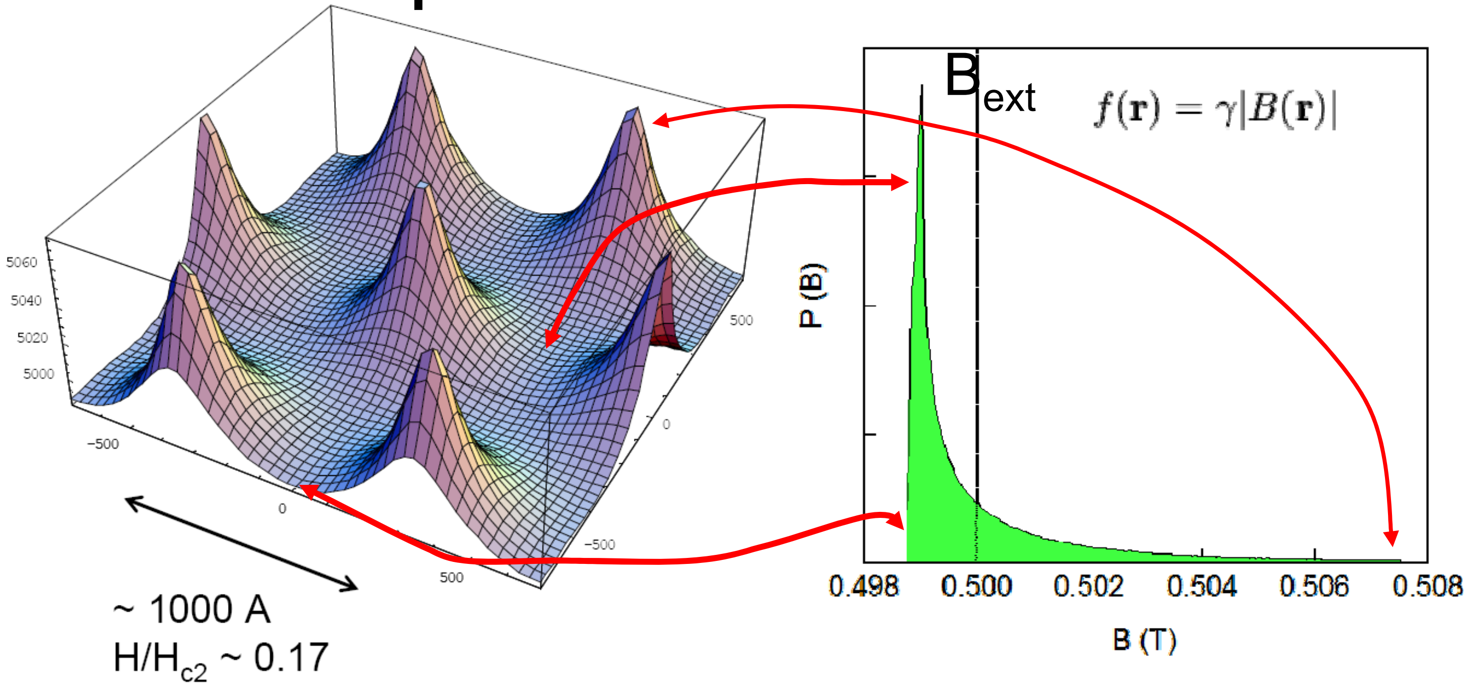
d-wave: nodes in k-space where gap vanishes

How can we measure the superfluid density?

via the magnetic penetration depth λ
n_s / m* is proportional to 1/ λ^2

- **measure λ in vortex state of type II superconductor via field profile p(B)**

→ transverse field μSR



In anisotropic powder superconductors P*(B)* shows Gaussian shape

$$\langle \Delta B^2 \rangle \propto \lambda_{ab}^{-4}$$

Superconductivity in $La(O_{1-x}F_x)FeAs$

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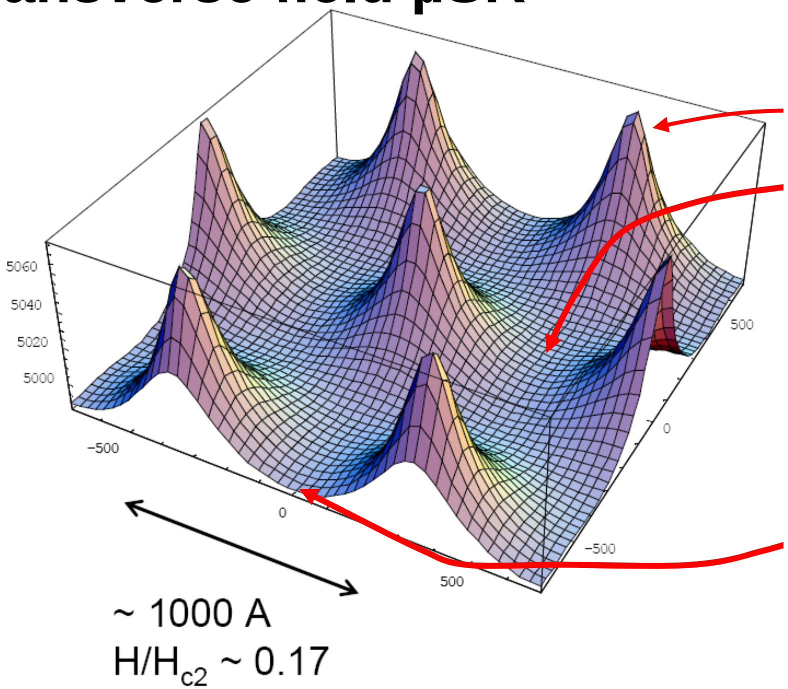

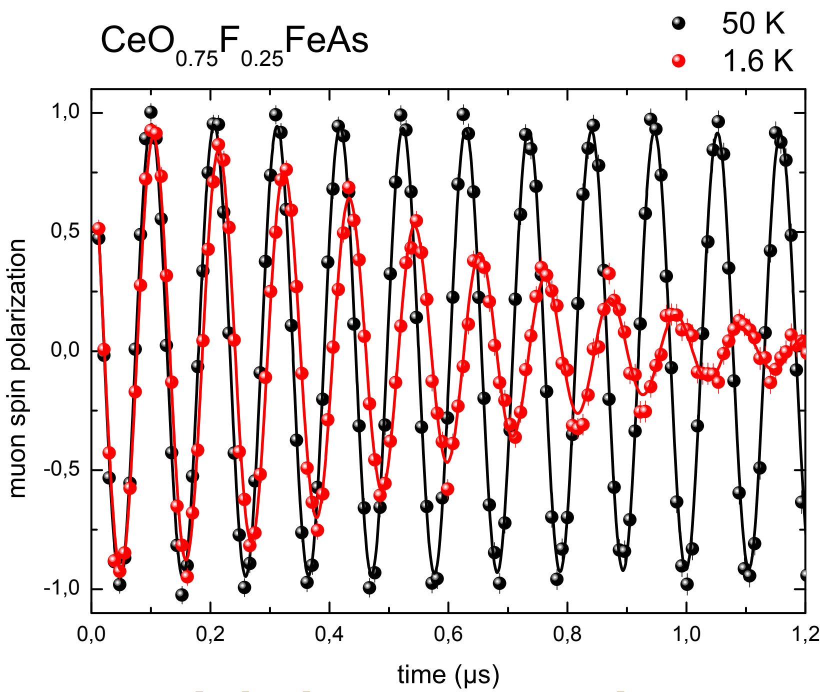

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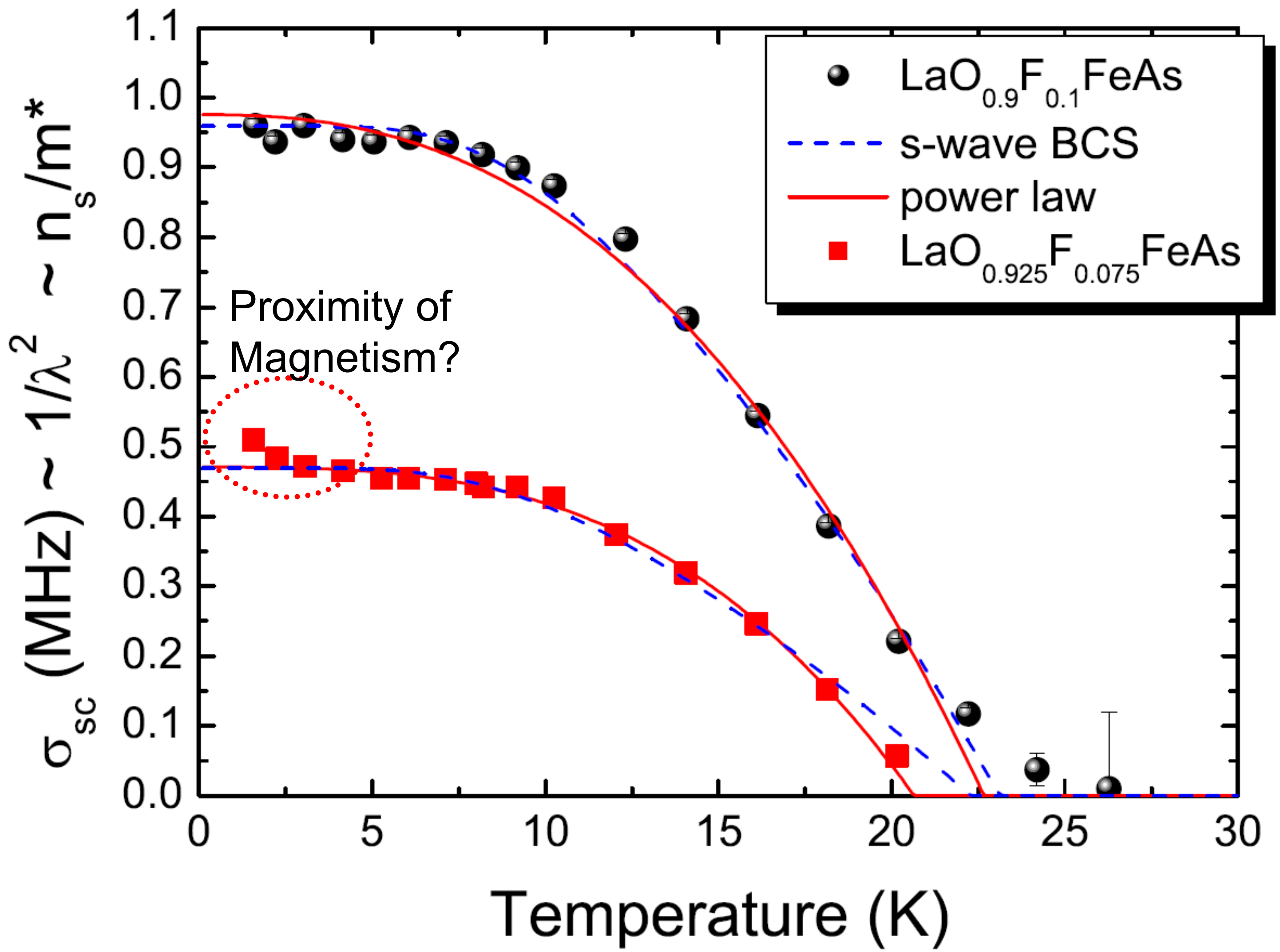
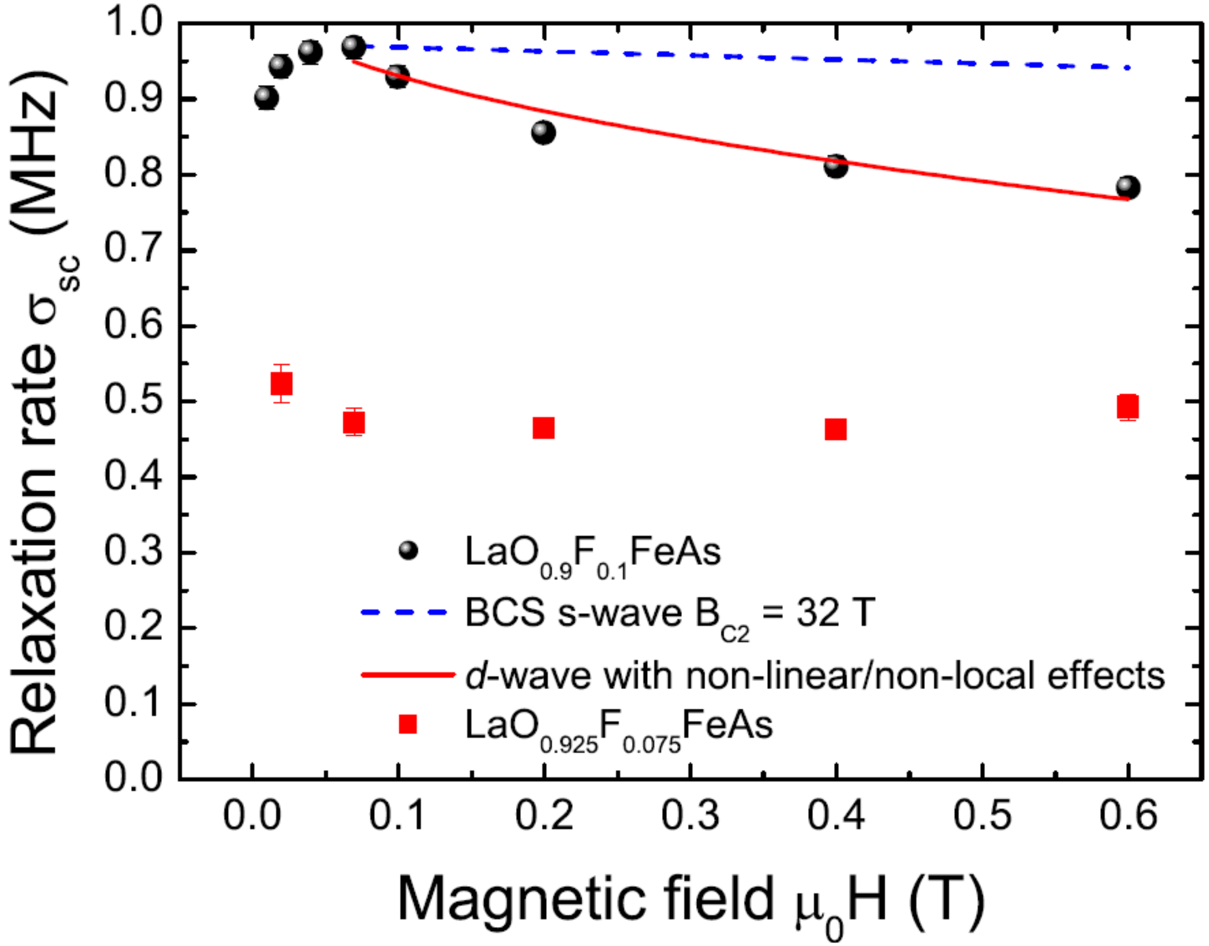
Penetration Depth of La($O_{1-x}F_x$)FeAs



H. Luetkens et al., PRL 101, 097009 (2008)

Penetration Depth of $La(O_{1-x}F_x)FeAs$

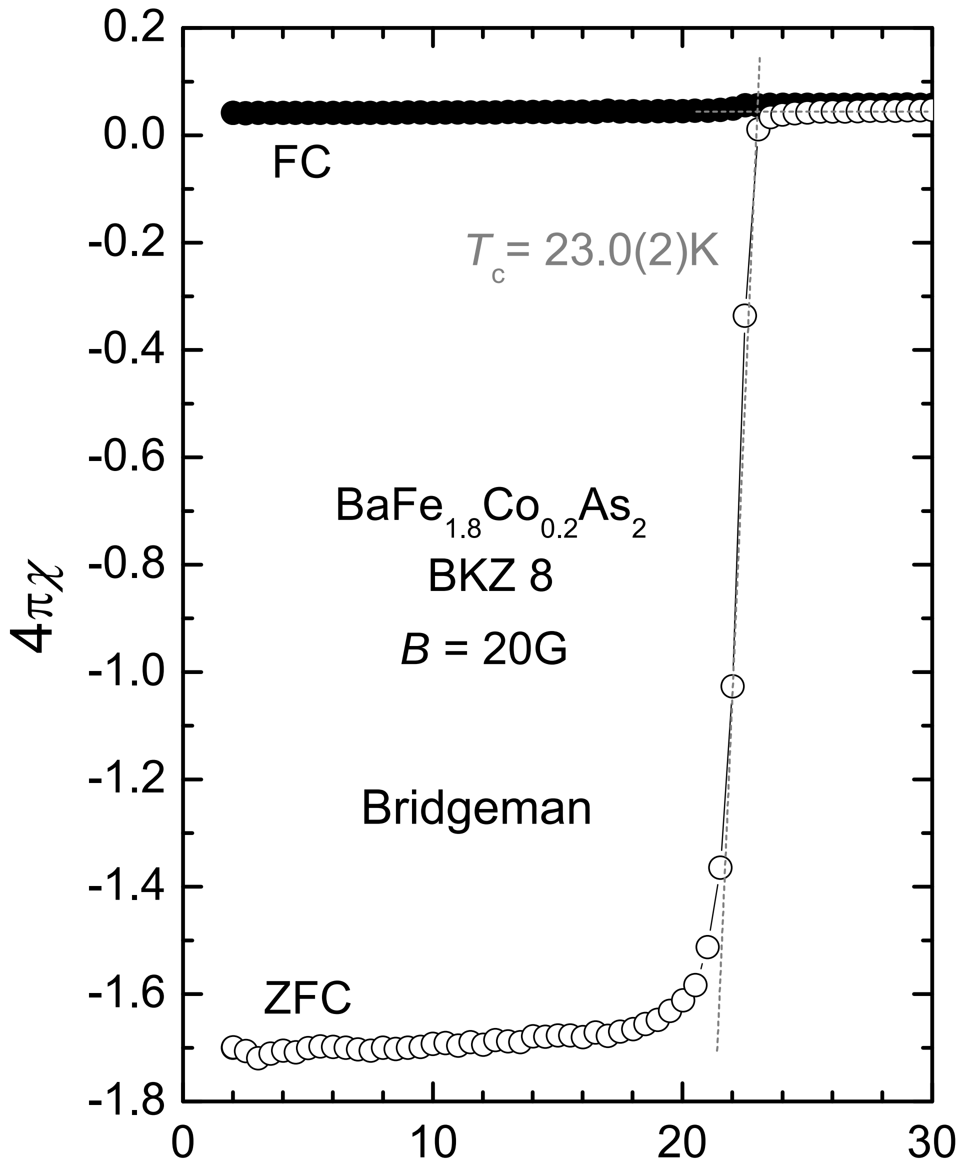


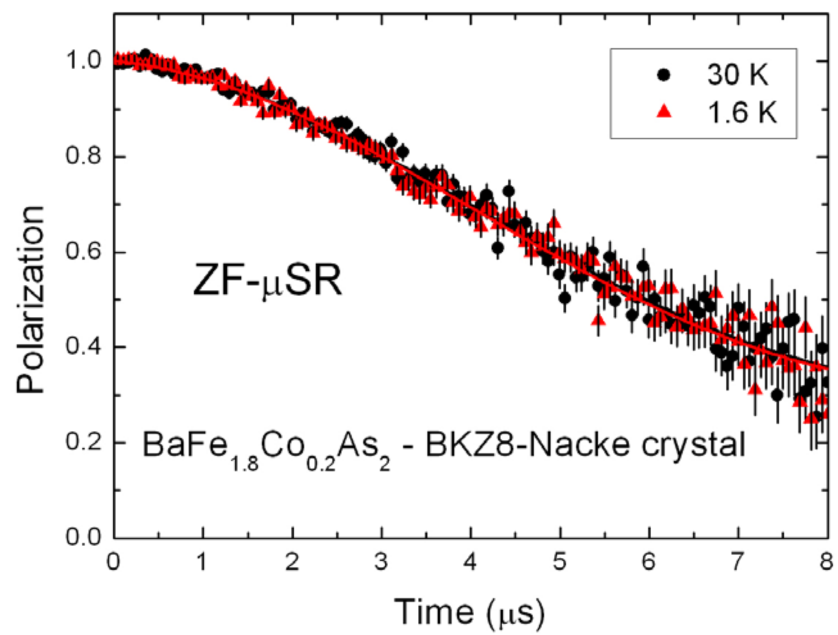
T dependence of λ: consistent with BCS s-wave

B dependence of λ: not simple s-wave: d, ext. s, multiband

H. Luetkens et al., PRL 101, 097009 (2008)

Superconducting Properties of Co doped Ba122

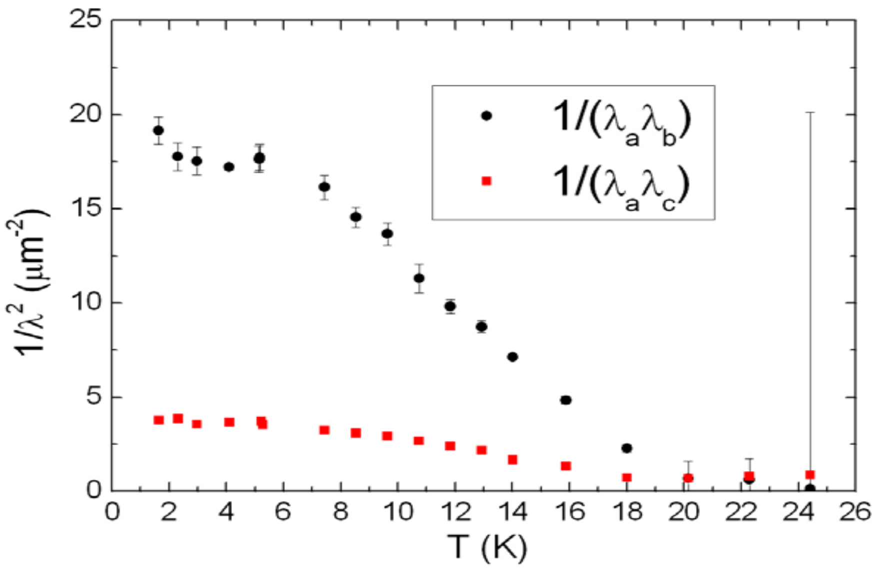


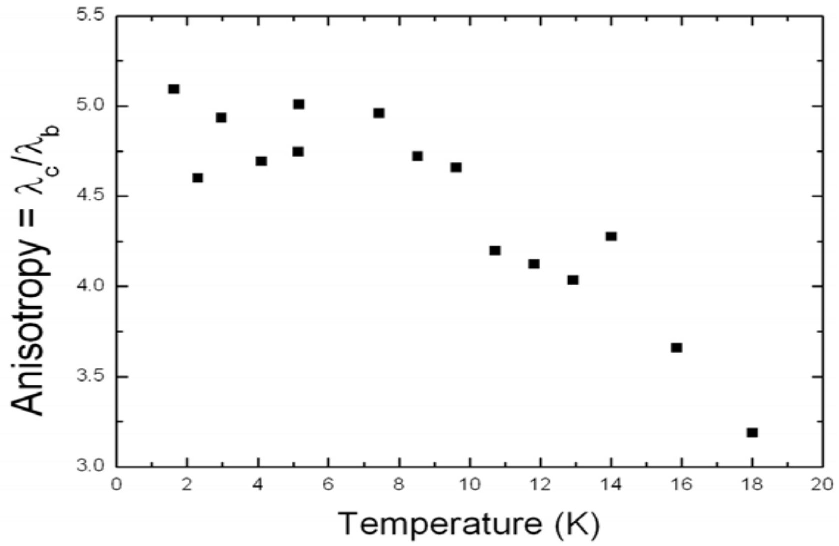


μSR: no trace of magnetism

H. Luetkens, C. Nacke et al., in preparation

Superconductivity of Co doped Ba122– TF-μSR

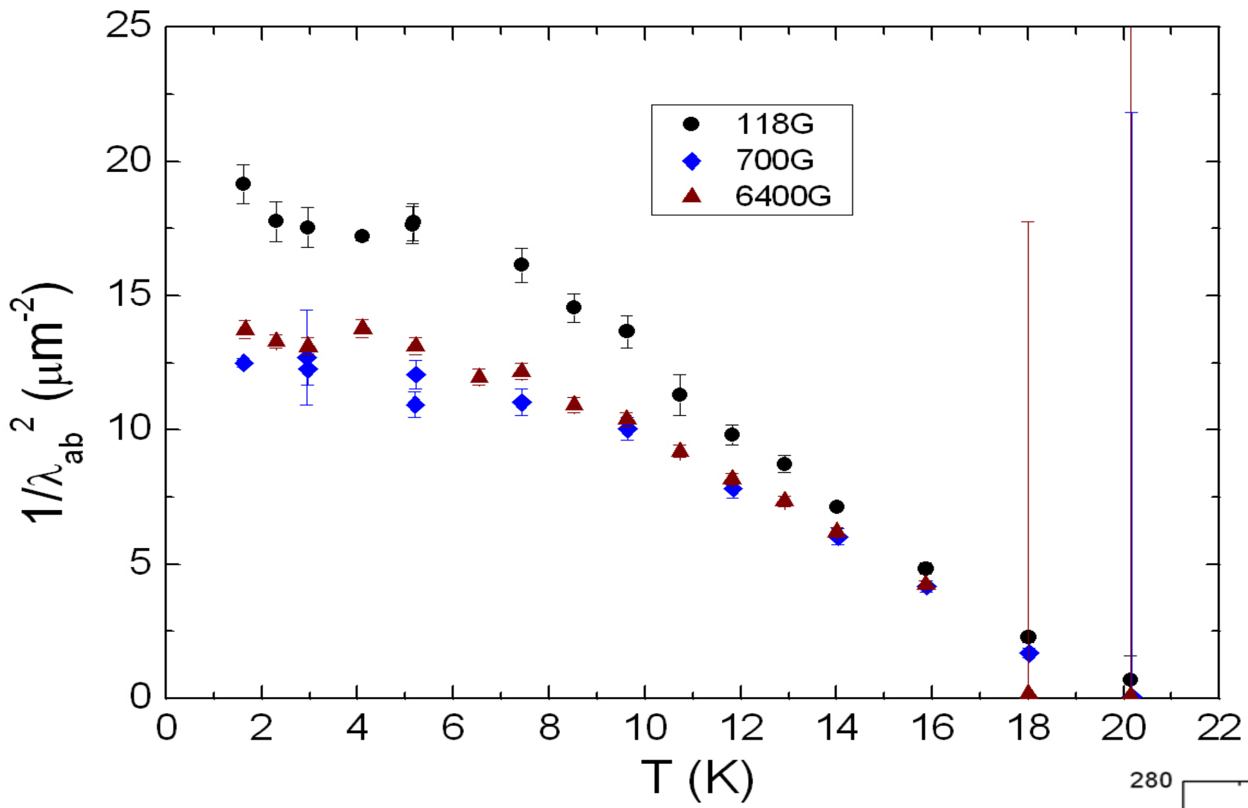


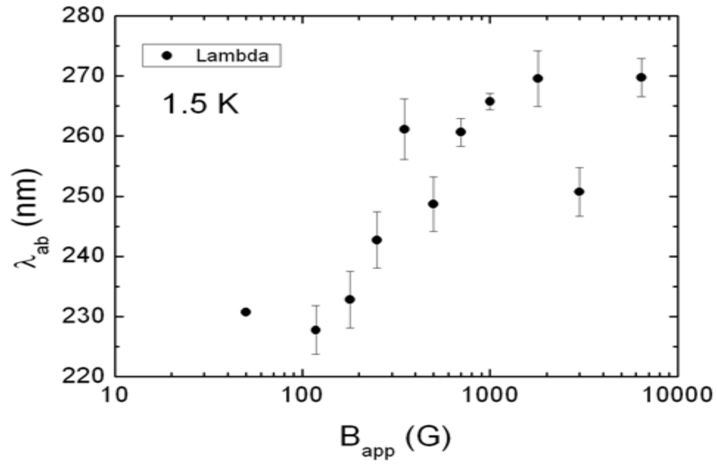


- Superfluid density (full line shape analysis) for field applied in different direction.
- Pronounced anisotropy of the penetration depth λ.
- Assuming $\lambda_a = \lambda_b$ one can calculate the low temperature values:
- $\lambda_a(T=0) = 220$ nm
- $\lambda_c(T=0) = 1100$ nm

H. Luetkens, C. Nacke et al., in preparation

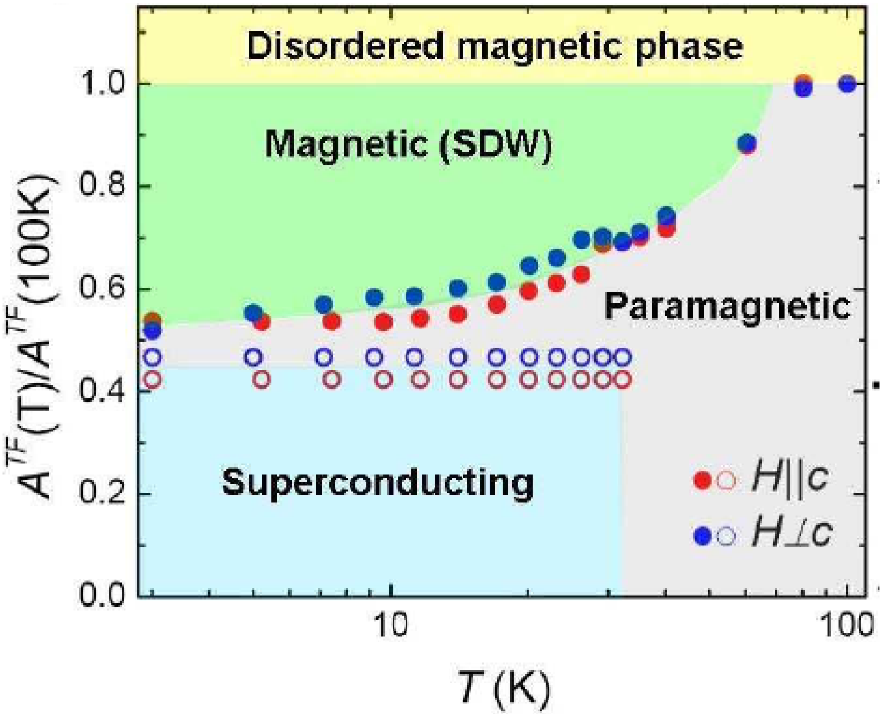
Superconductivity of Co doped Ba122– TF-μSR



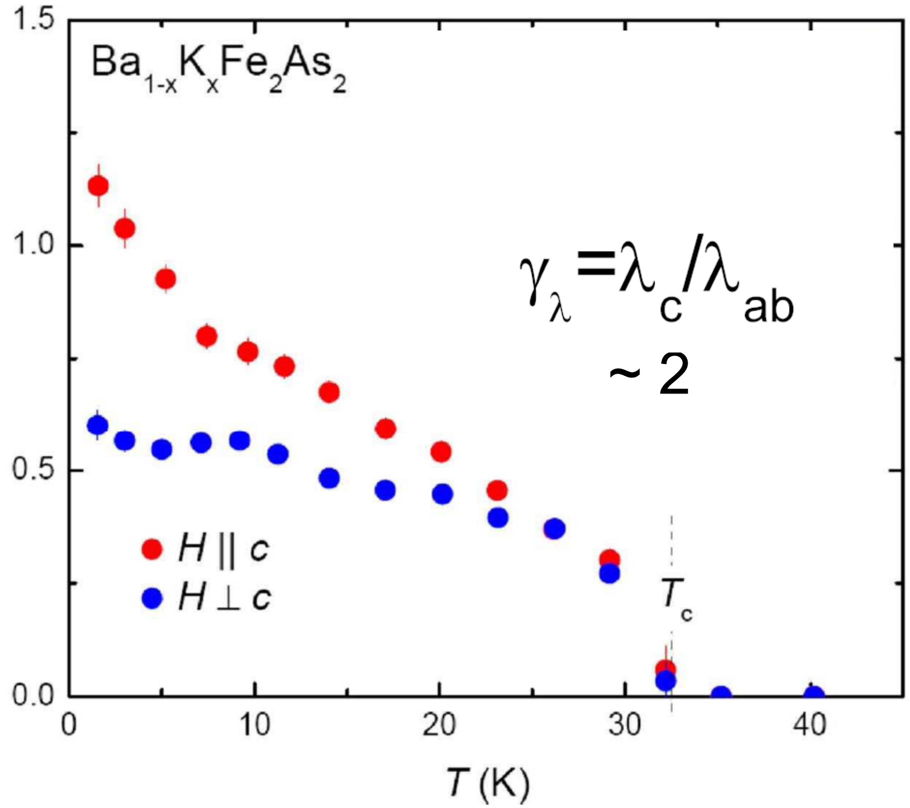


Superconductivity in $Ba_{1-x}K_xFe_2As_2$

μSR: Phase separation into commensurate SDW and superconducting volumes



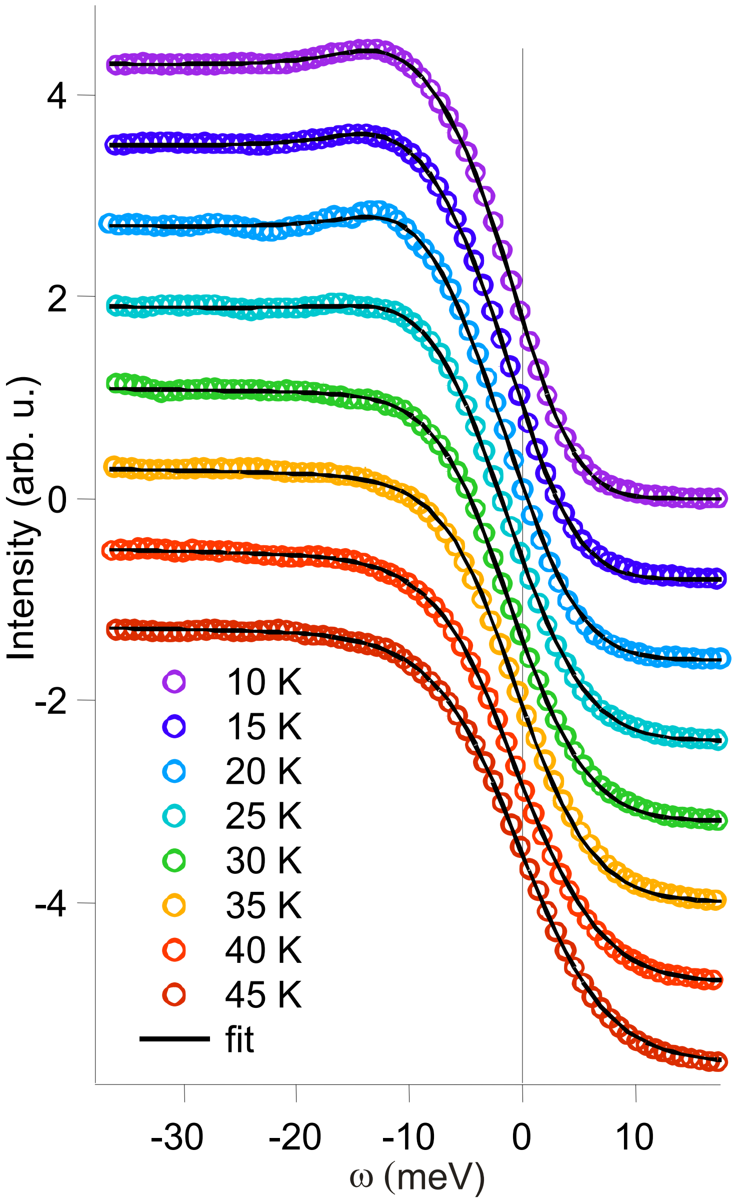
μSR: 50 % non-magnetic

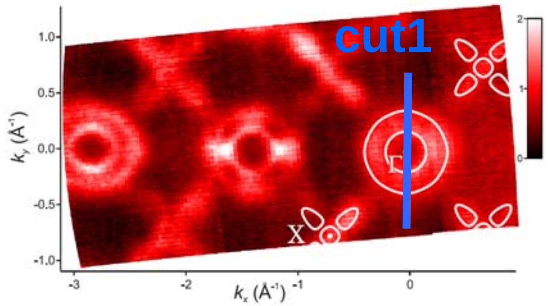


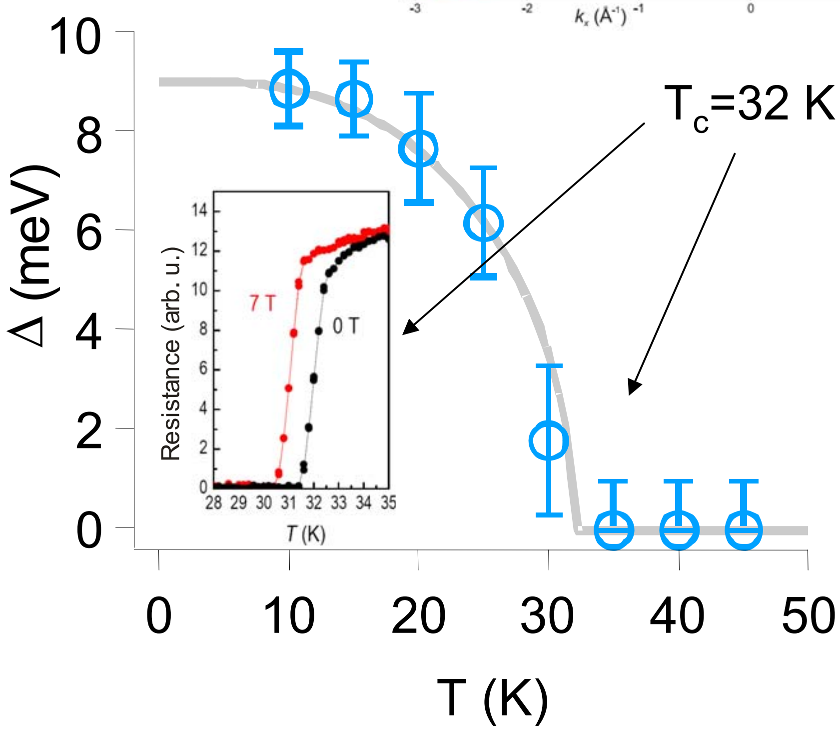
- stronger temperature dependence of λ^{-2}
  → large and small gap ?

R. Khasanov, PRL 09

Gap on the inner Γ-barrel, ΓM



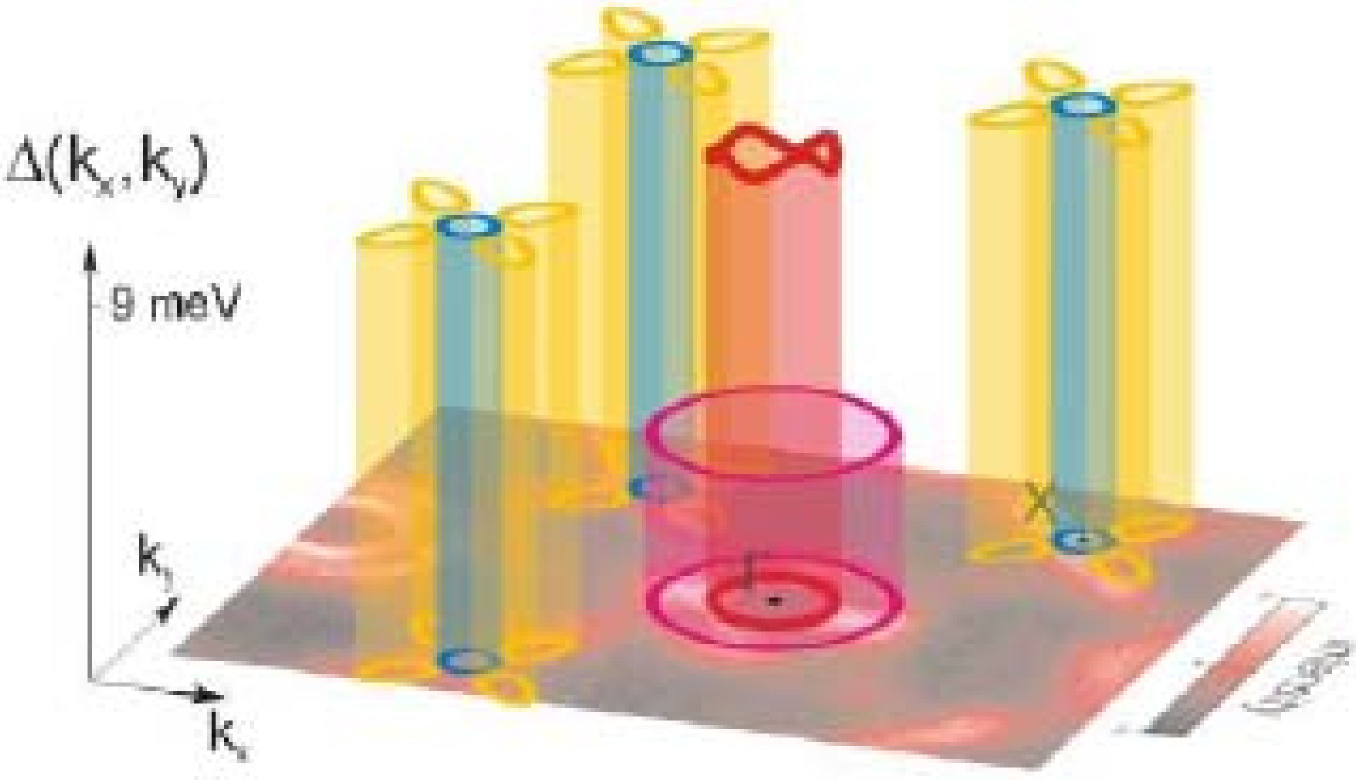




$$9.1 \pm 0.7\,\mathrm{meV}$$

D.V. Evtushinsky et al., PRB 2009

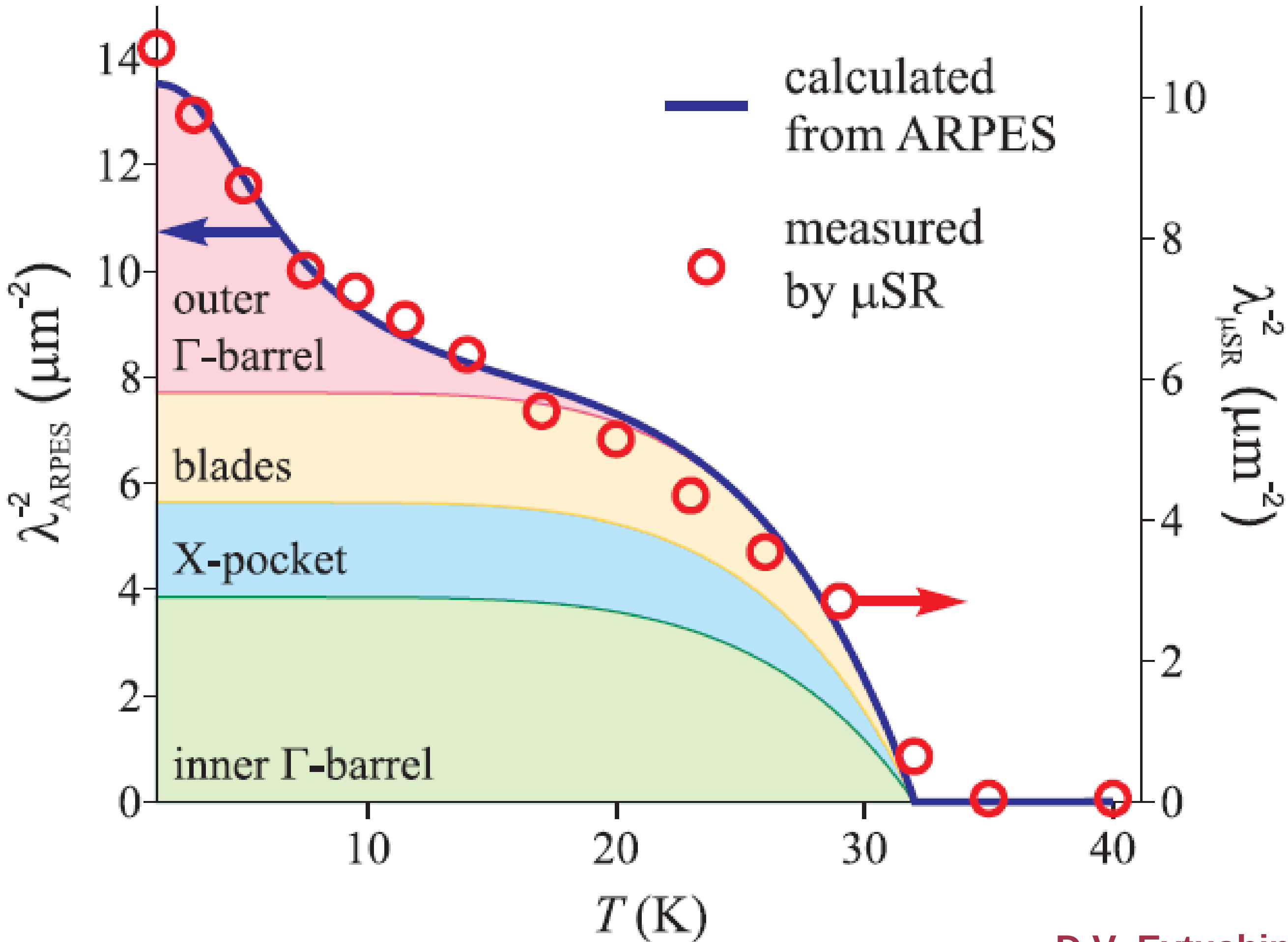
Anisotropy of Gap according to ARPES



D.V. Evtushinsky et al., PRB 2009

Similar results see eg. Ding et al EPL 2008

Penetration Depth of $Ba_{1-x}K_xFe_2As_2$, T_c = 32 K



Δ large: 9 meV (ARPES)

Δ small 1.1 mev (ARPES: < 4 meV)

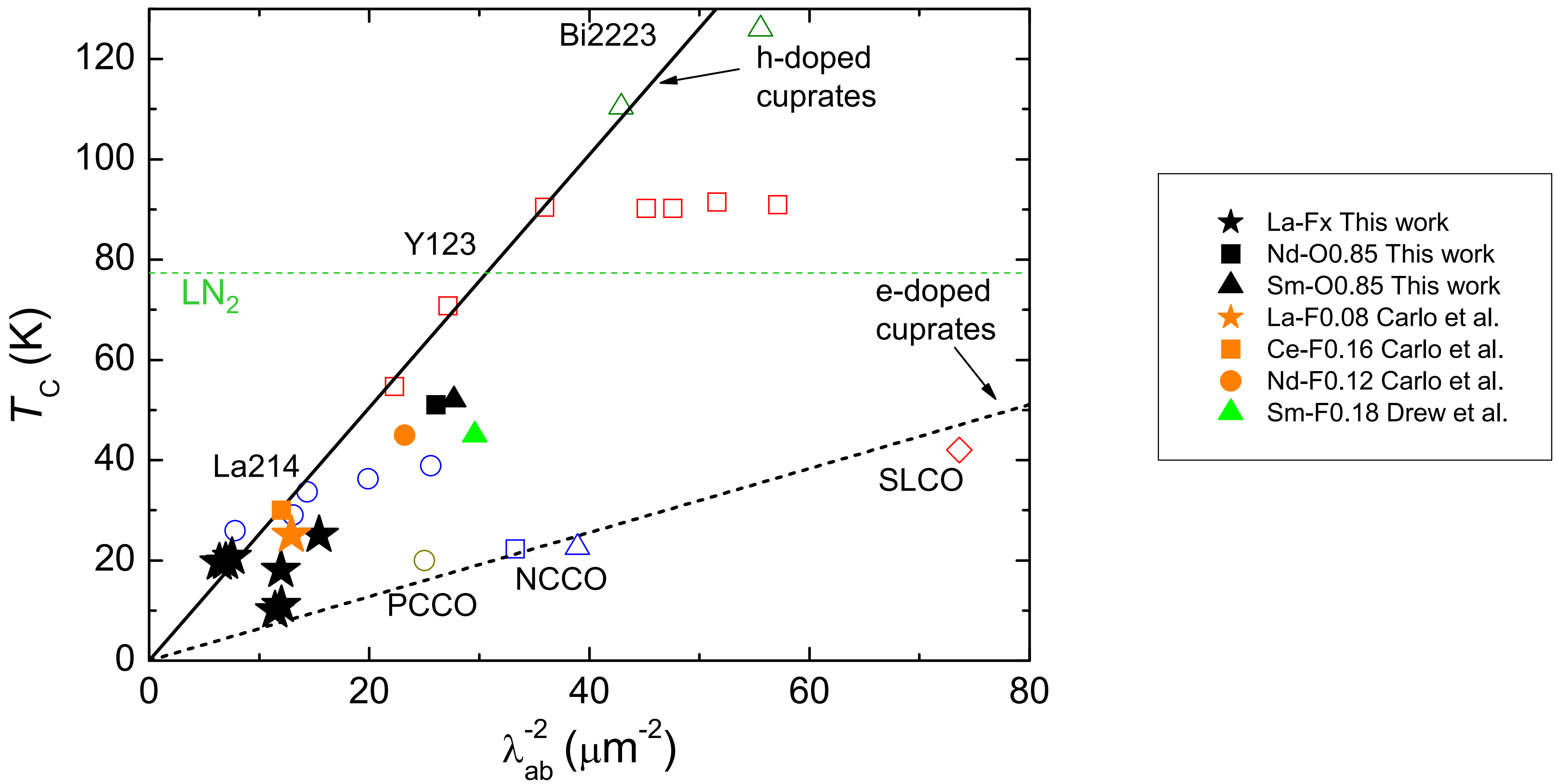
D.V. Evtushinsky et al., New J. Phys. 2009

$$\frac{1}{\lambda^2(0)} = I_1 + I_2 = \frac{e^2}{2\pi\varepsilon_0 c^2 h L_c}\left[\int_{\text{inner }\Gamma} v_F(\mathbf{k})\mathrm{d}k + \int_{\text{outer }\Gamma} v_F(\mathbf{k})\mathrm{d}k + \int_{\text{X-pocket}} v_F(\mathbf{k})\mathrm{d}k + \int_{\text{blades}} v_F(\mathbf{k})\mathrm{d}k\right]$$

Penetration Depth and Uemura Plot

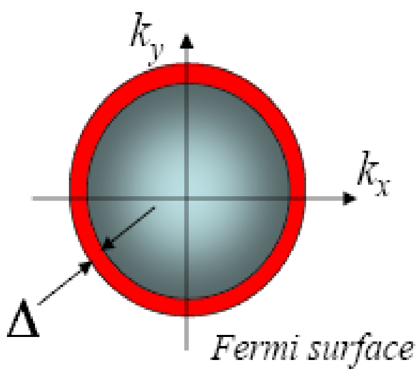
Uemura plot:

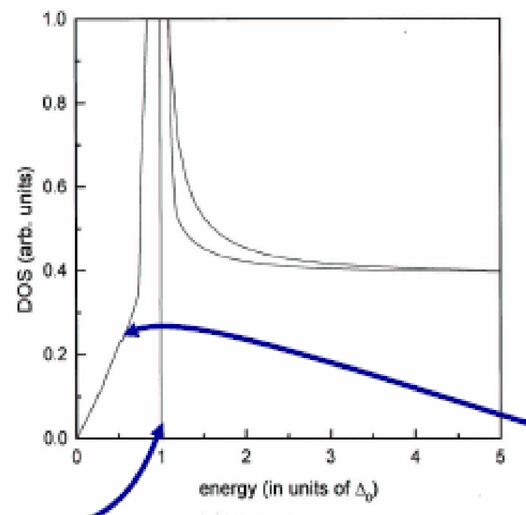
T_C scales linearly with the superfluid density, i.e. $T_C \propto 1/\lambda^2 \propto n_s/m^*$

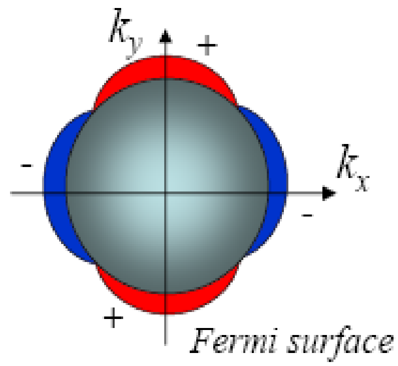


The Fe-based superconductors are close to the Uemura line for hole doped cuprates → hope for higher T_c in the future

Gap and Spin Lattice Relaxation Rate (NMR)





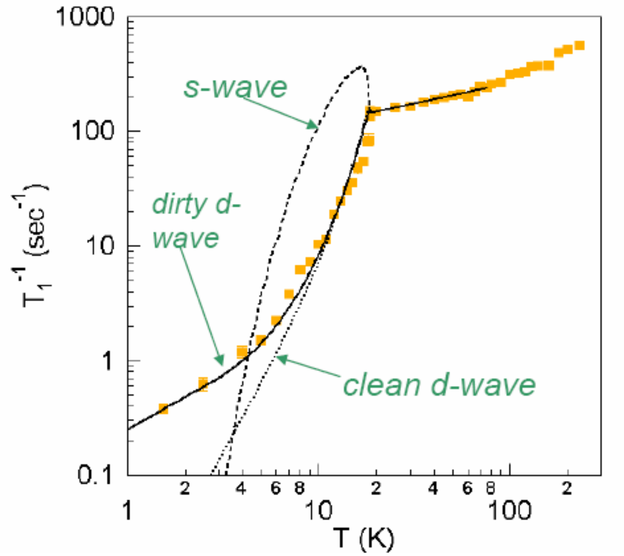


s-wave: isotropic gap

$T_1^{-1} \sim e^{-\Delta/k_B T}$

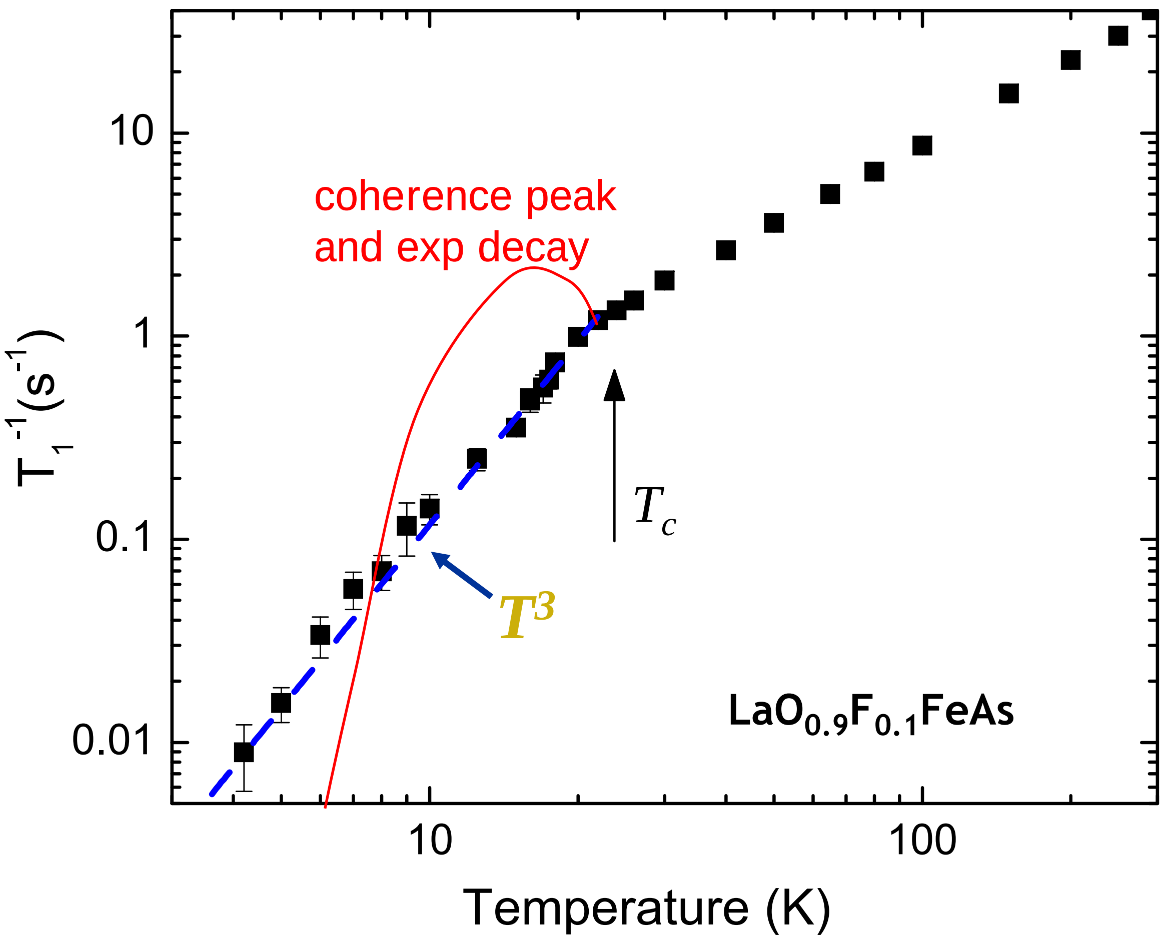
d-wave: nodes in k-space where gap vanishes

$T_1^{-1} \sim T^3$



^{75}As NMR on $La(O_{1-x}F_x)FeAs$: T_1

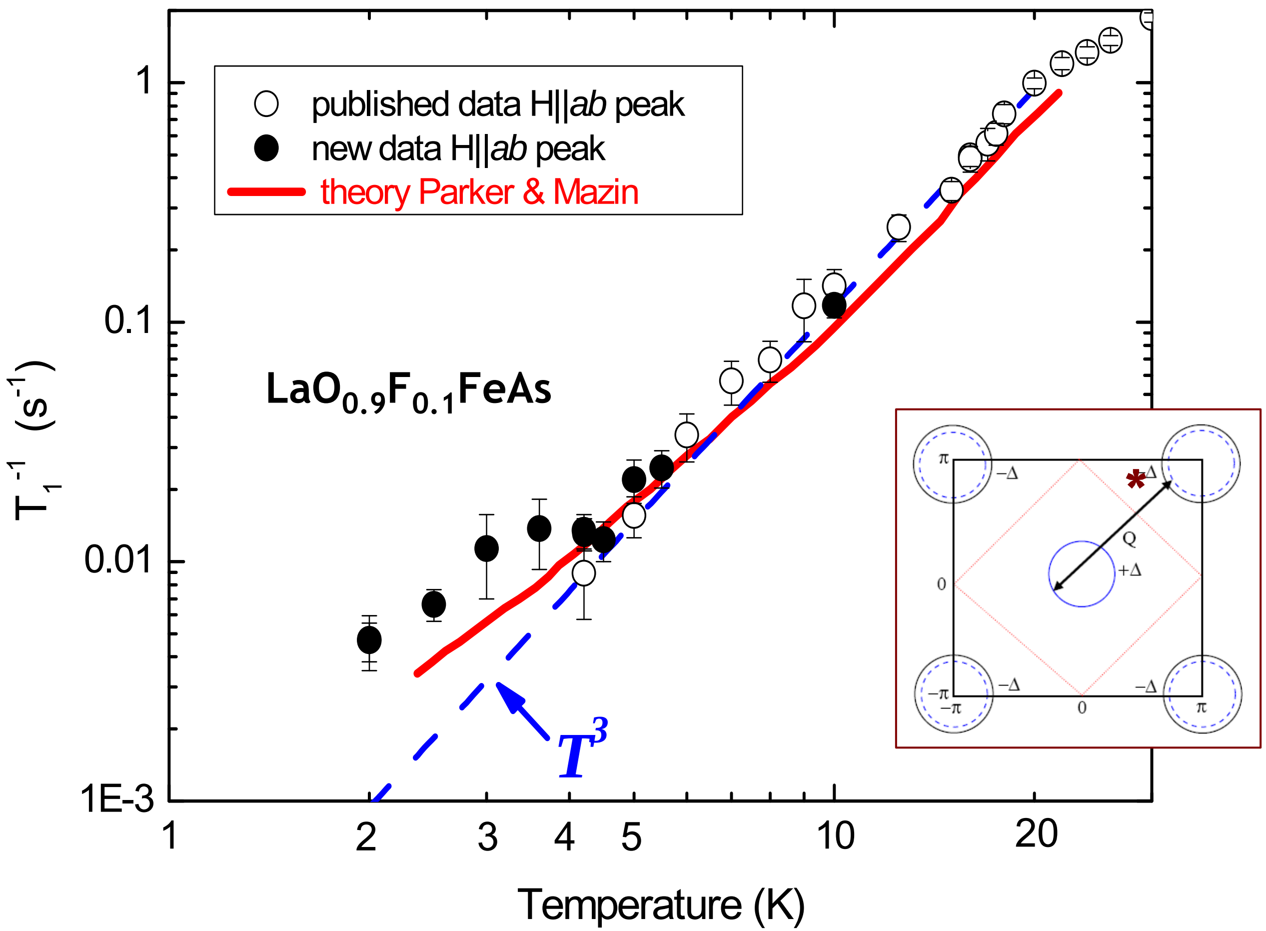
- No Hebel Slichter coherence peak, no expon. decay
- T^3 dependence below T_c is indicative for line nodes



⇒ suggestive of d-wave superconductivity

H.-J. Grafe et al., PRL 101, 047003 (2008)

^{75}As NMR on La($O_{1-x}F_x$)FeAs: T_1



At low temperatures deviation from T^3

extended $s_{+/-}$ wave - scenario

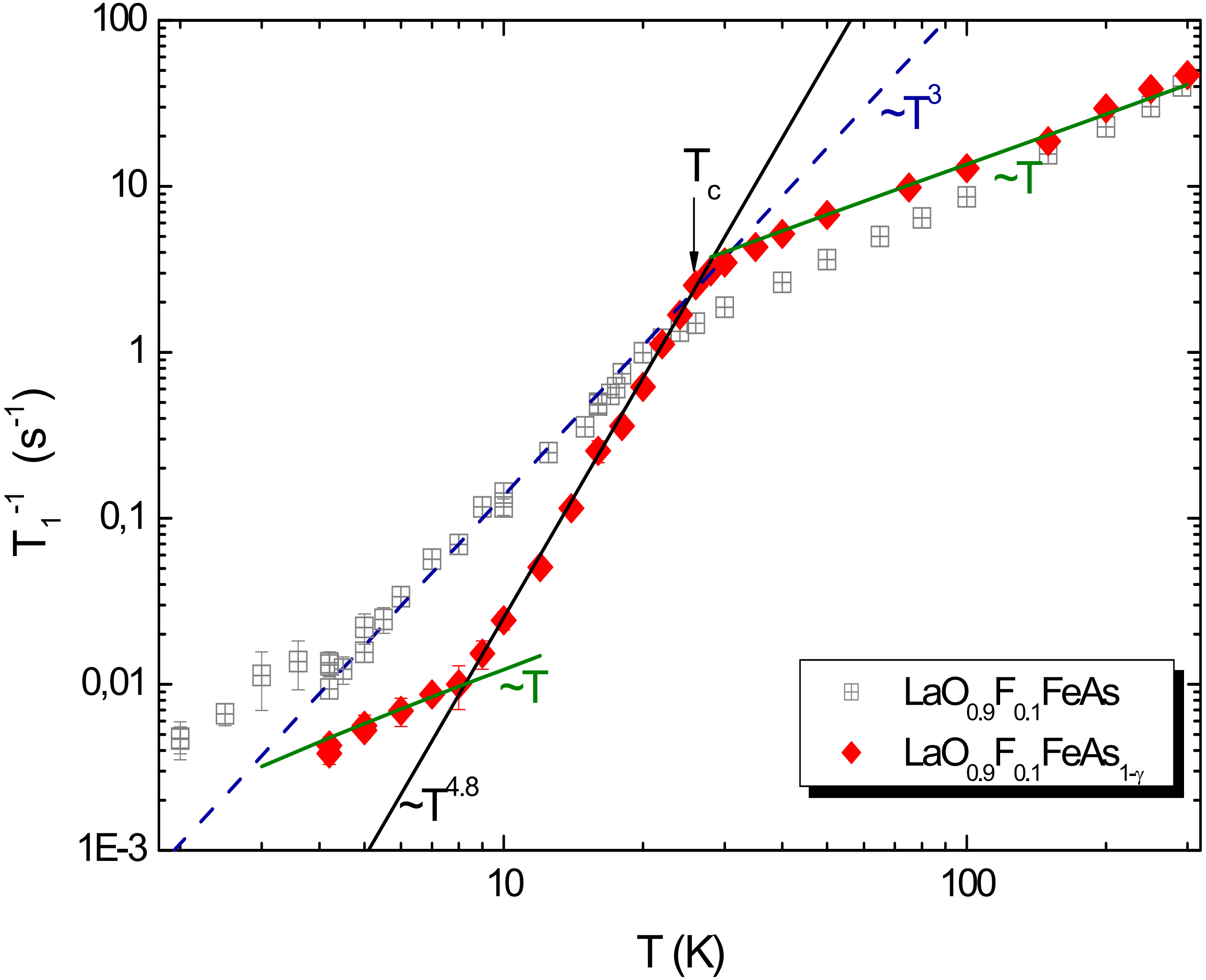
Mazin et al., PRL 101, 057003 (2008).

Parker et al. PRB 2008

Chubukov et al. PRB 2008

or dirty d-wave…

^{75}As NMR on La($O_{1-x}F_x$)FeAs: T_1



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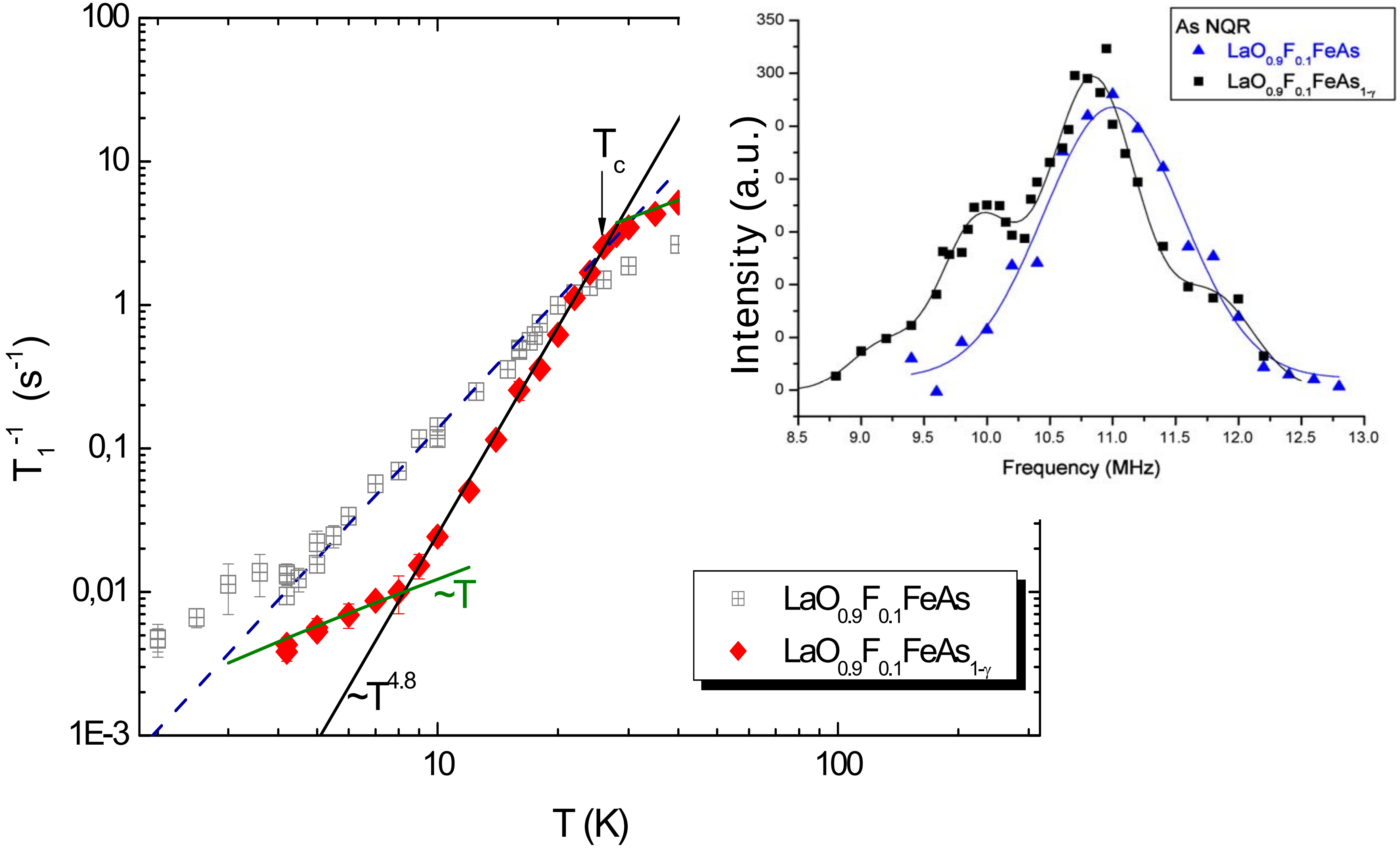

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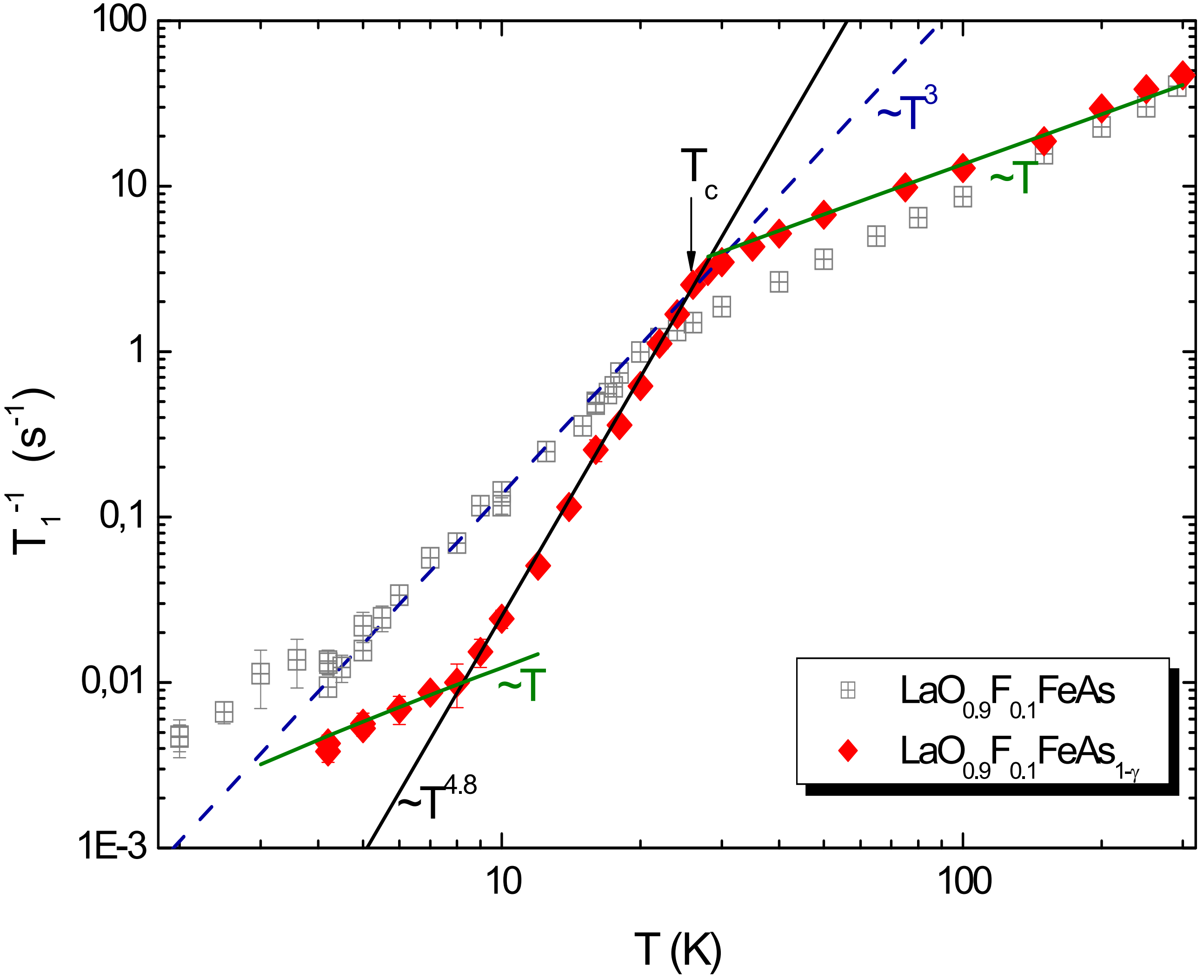


As-deficiency

⇒

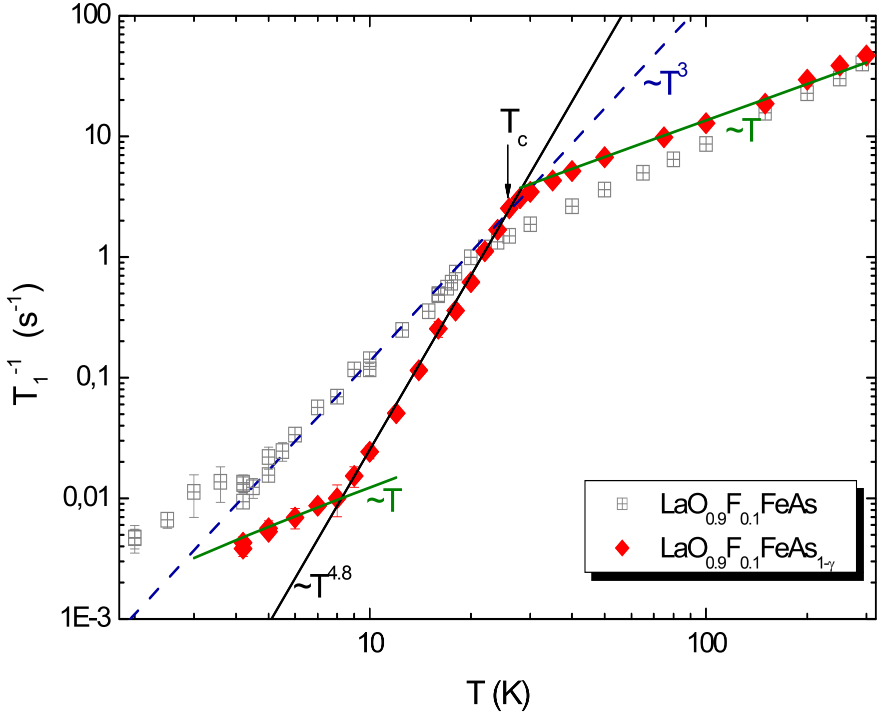
disorder

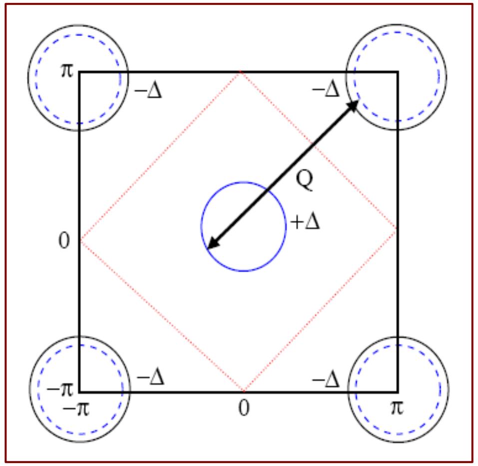
but:
higher T_c
higher $B_{c2}(0)$

$T < T_c$: $T_1^{-1} \sim T^{4.8}$

$T << T_c$: $T_1^{-1} \sim T$

^{75}As NMR on $La(O_{1-x}F_x)FeAs$: T_1





Scenarios:

Transition from $s_{+/-}$ to conventional $s_{+/+}$ state due to impurities

As deficiencies cause mainly intraband scattering and further protect the unconventional $s_{+/-}$ state (higher T_c, higher H_{c2}) („**smart impurities**“)

F. Hammerath, H.-J. Grafe, … S.L. Drechsler, I. Eremin et al.

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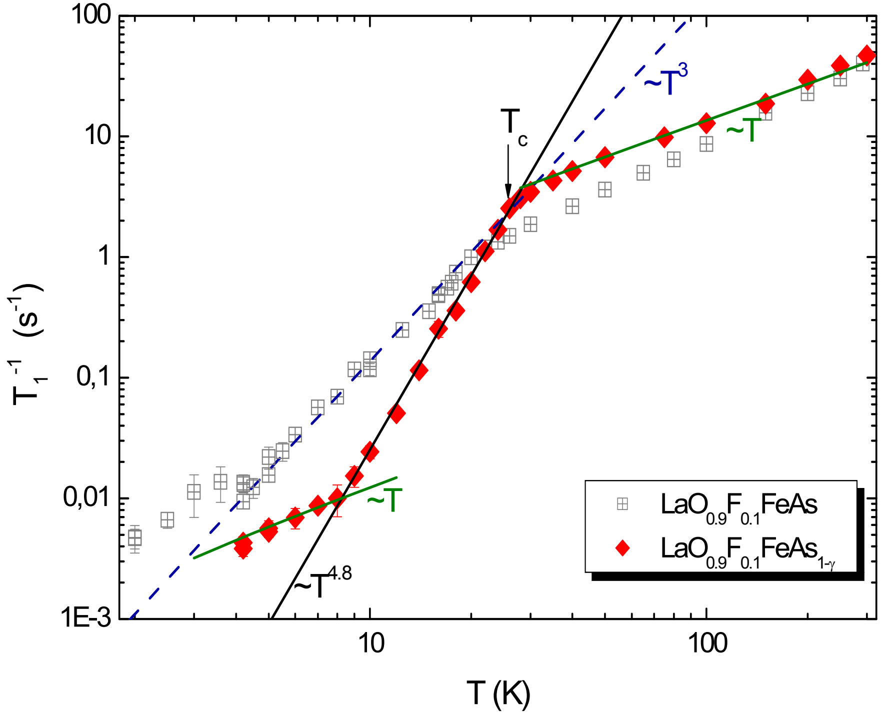

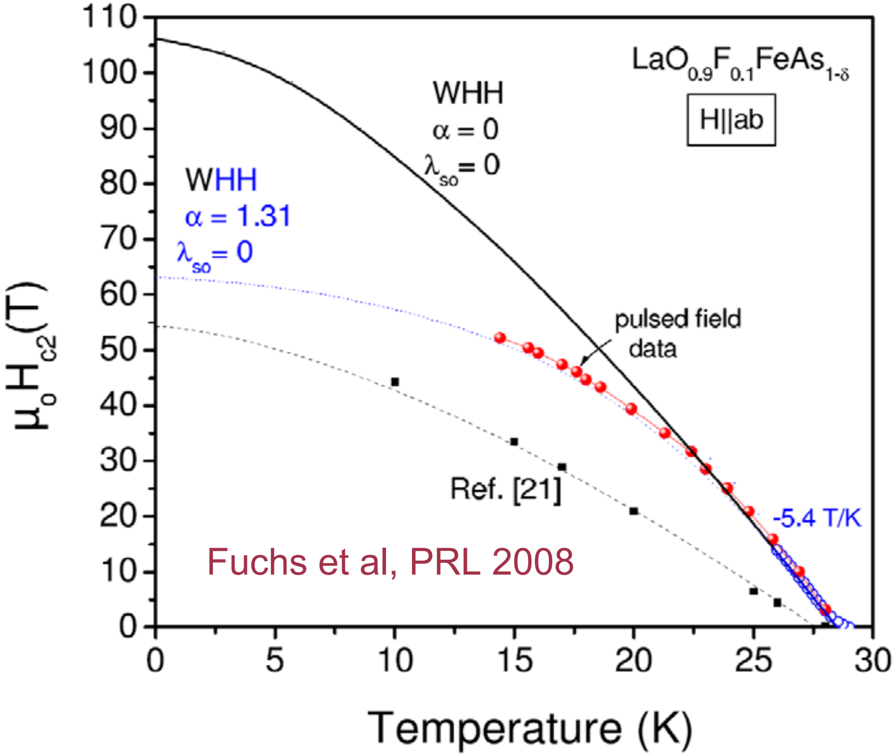

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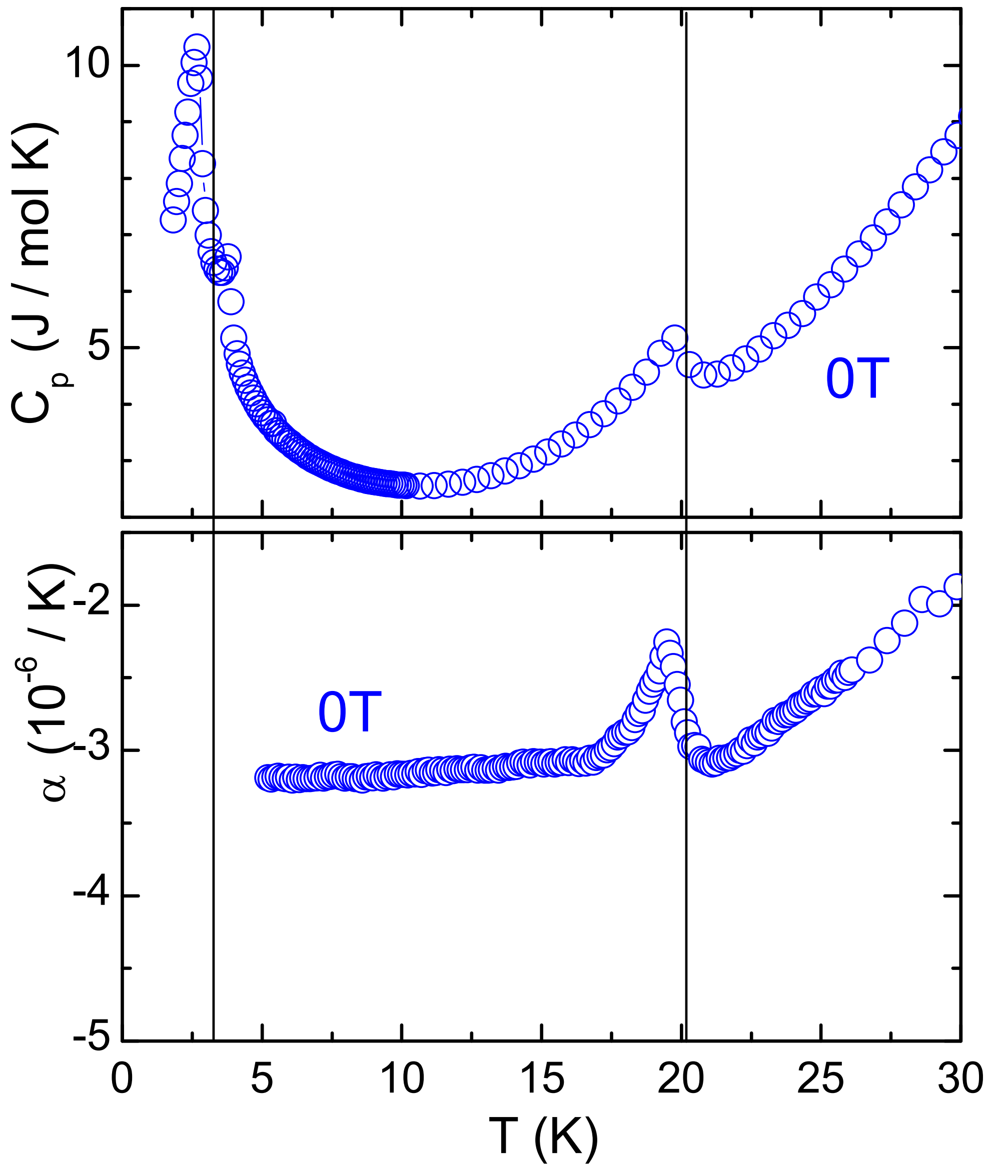
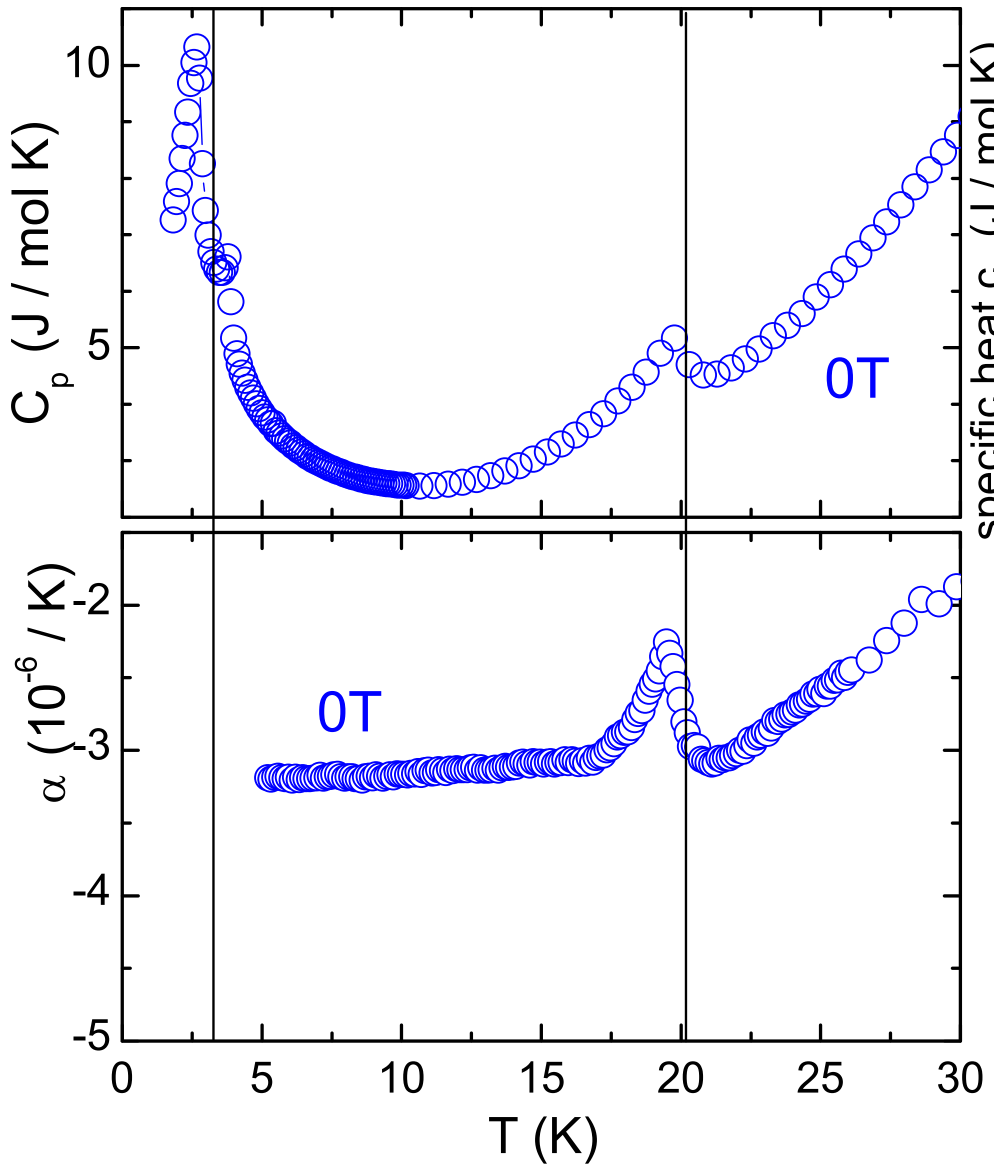
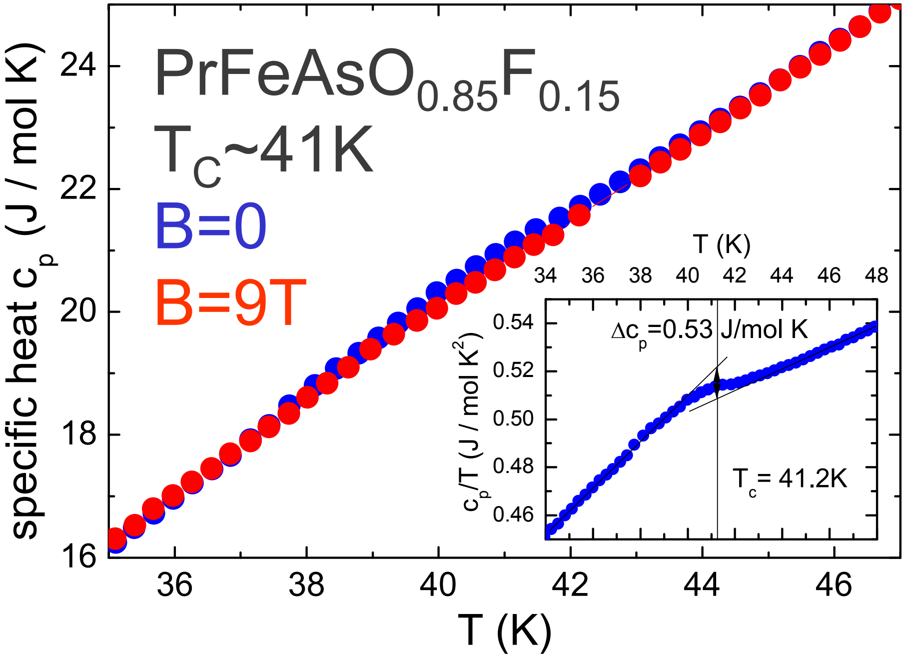
SC transition in $GdFeAsO_{0.85}F_{0.15}$:
Strange and Puzzling behavior

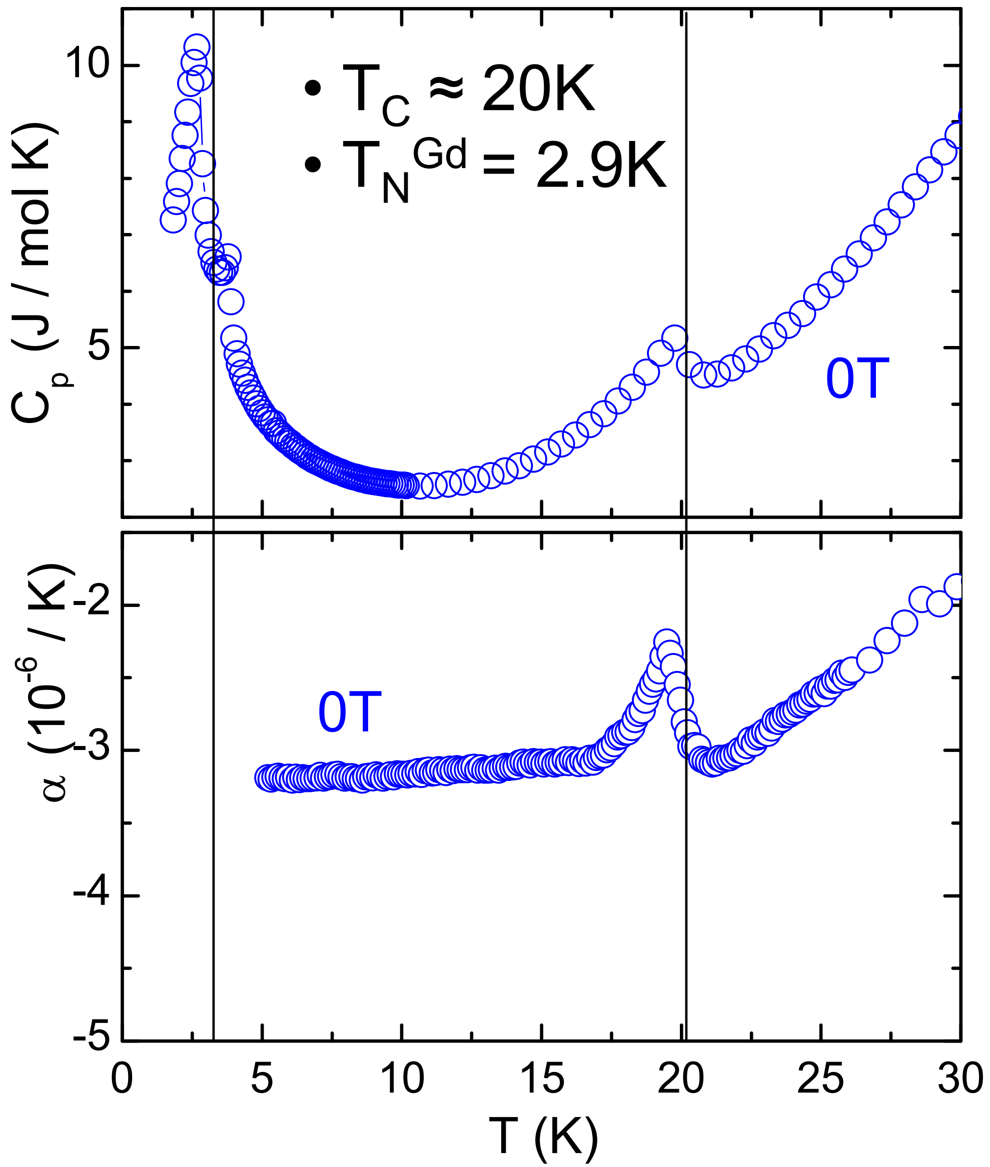


SC transition in $GdFeAsO_{0.85}F_{0.15}$





SC transition in $GdFeAsO_{0.85}F_{0.15}$



SC transition visible

$\Delta c_{p,\,SC}$ = 2.0 J / (mol K)

BCS theory:

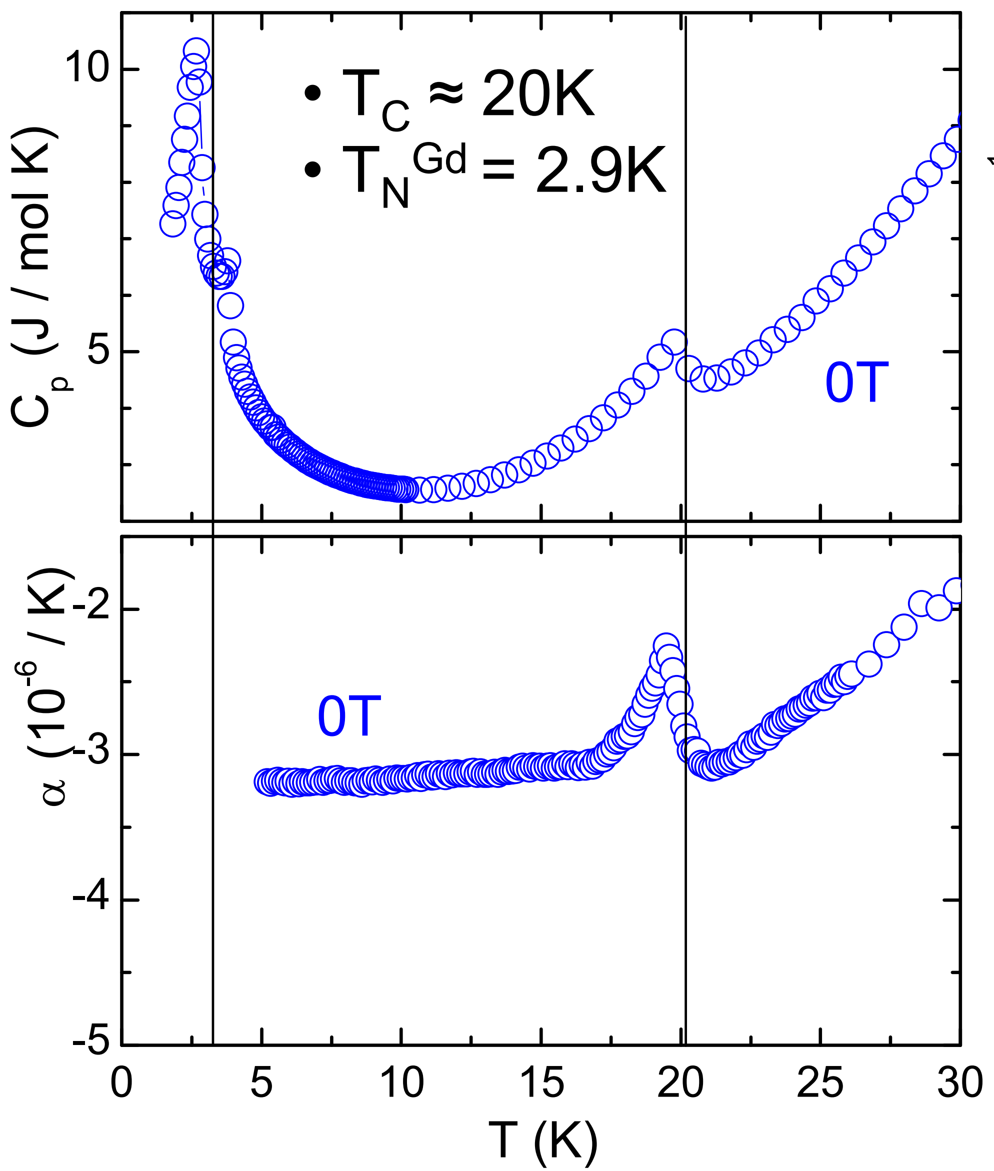
$\gamma = \Delta c/(1.43\ T_c)$

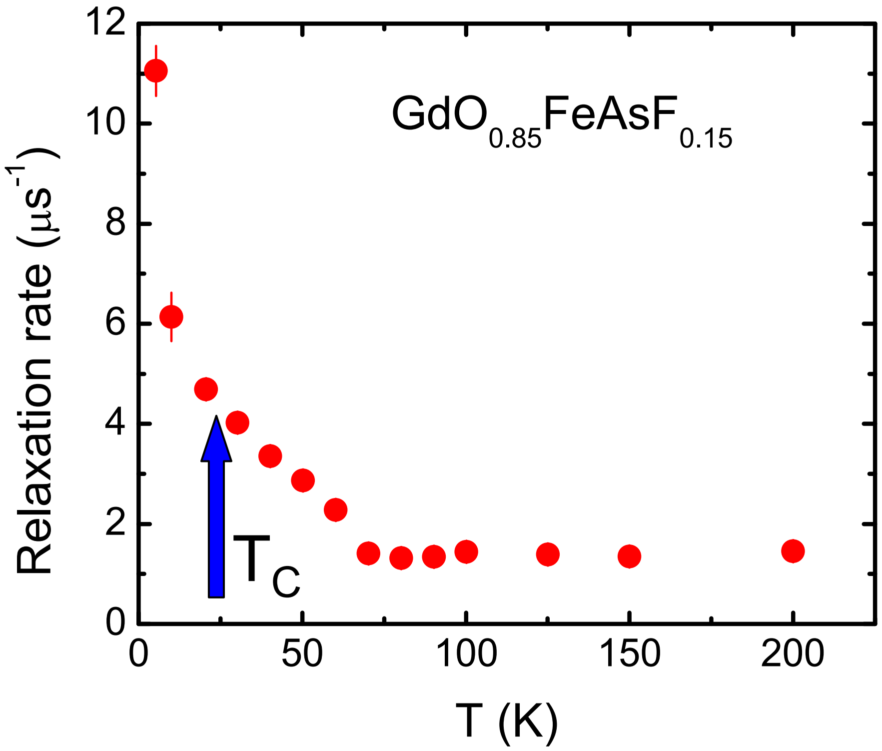
≈ 70 mJ/(molK)

$$\frac{dT_C}{dp} = -TV\,\frac{\Delta\alpha}{\Delta c_p}$$

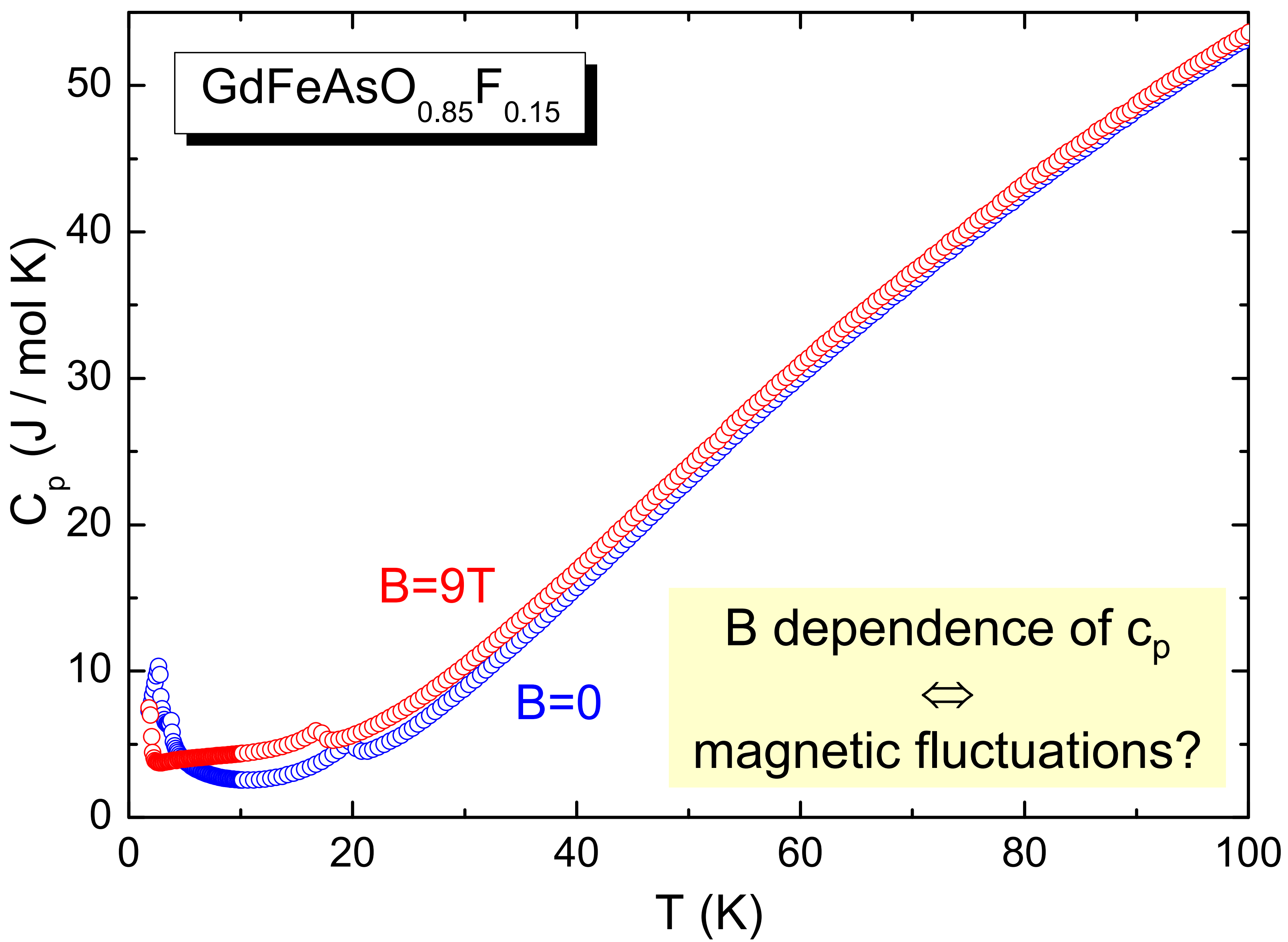
$$\approx 1.4\,\frac{K}{GPa}$$

SC transition in $GdFeAsO_{0.85}F_{0.15}$





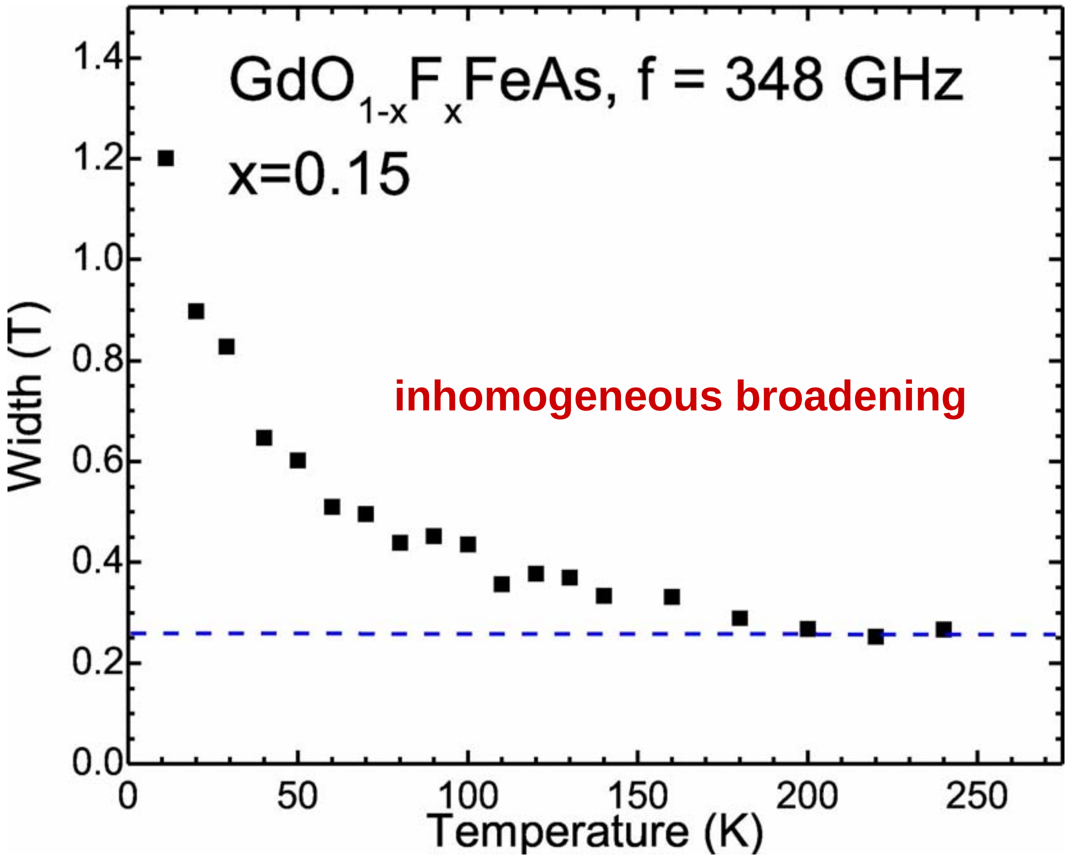
$GdFeAsO_{0.85}F_{0.15}$: Specific heat

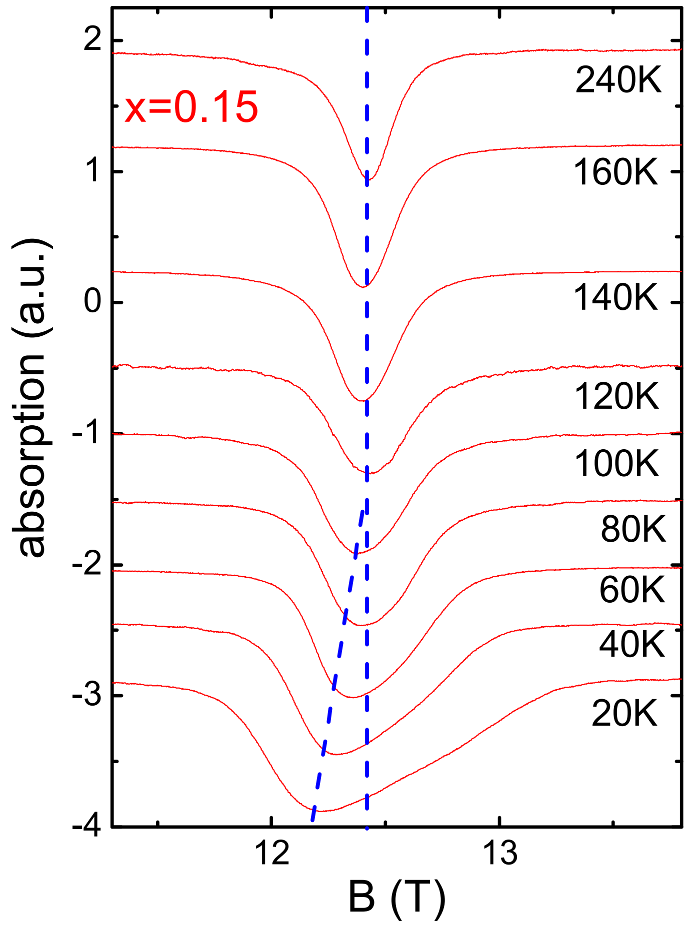


$GdO_{1-x}F_xFeAs$ - Gd HF-ESR: Width of the signal

Gd^{3+}: $4f^7$, L = 0; J = **S =7/2**

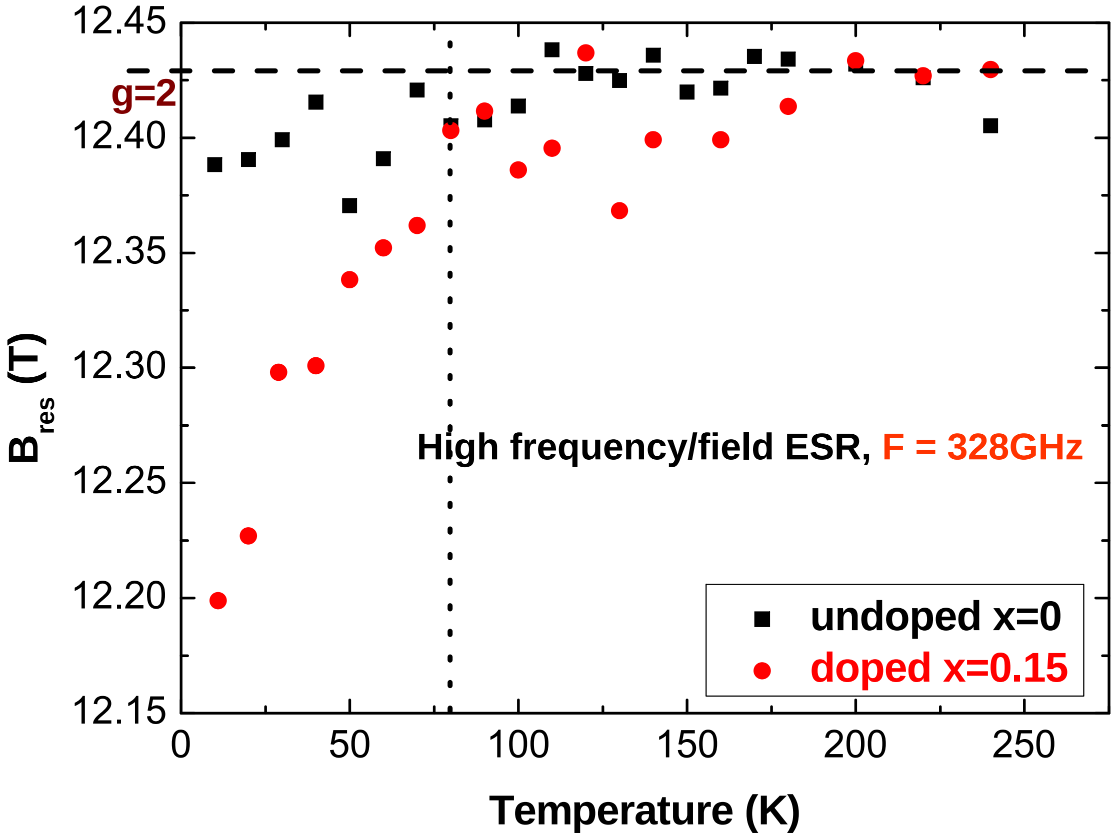
no coupling to lattice, **probes spin degrees of freedom**

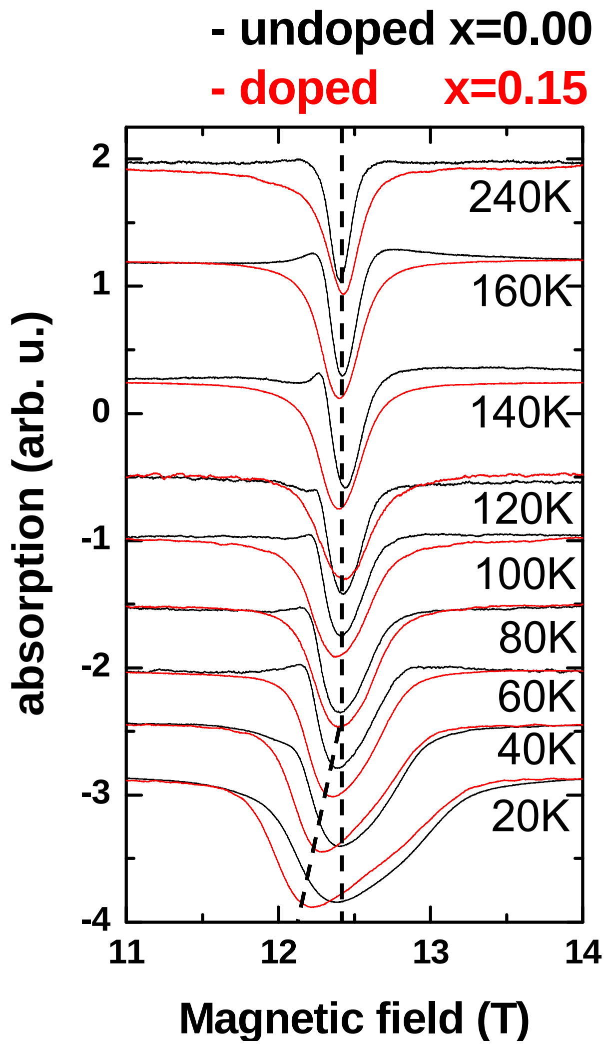




Gd sees enhanced magnetism

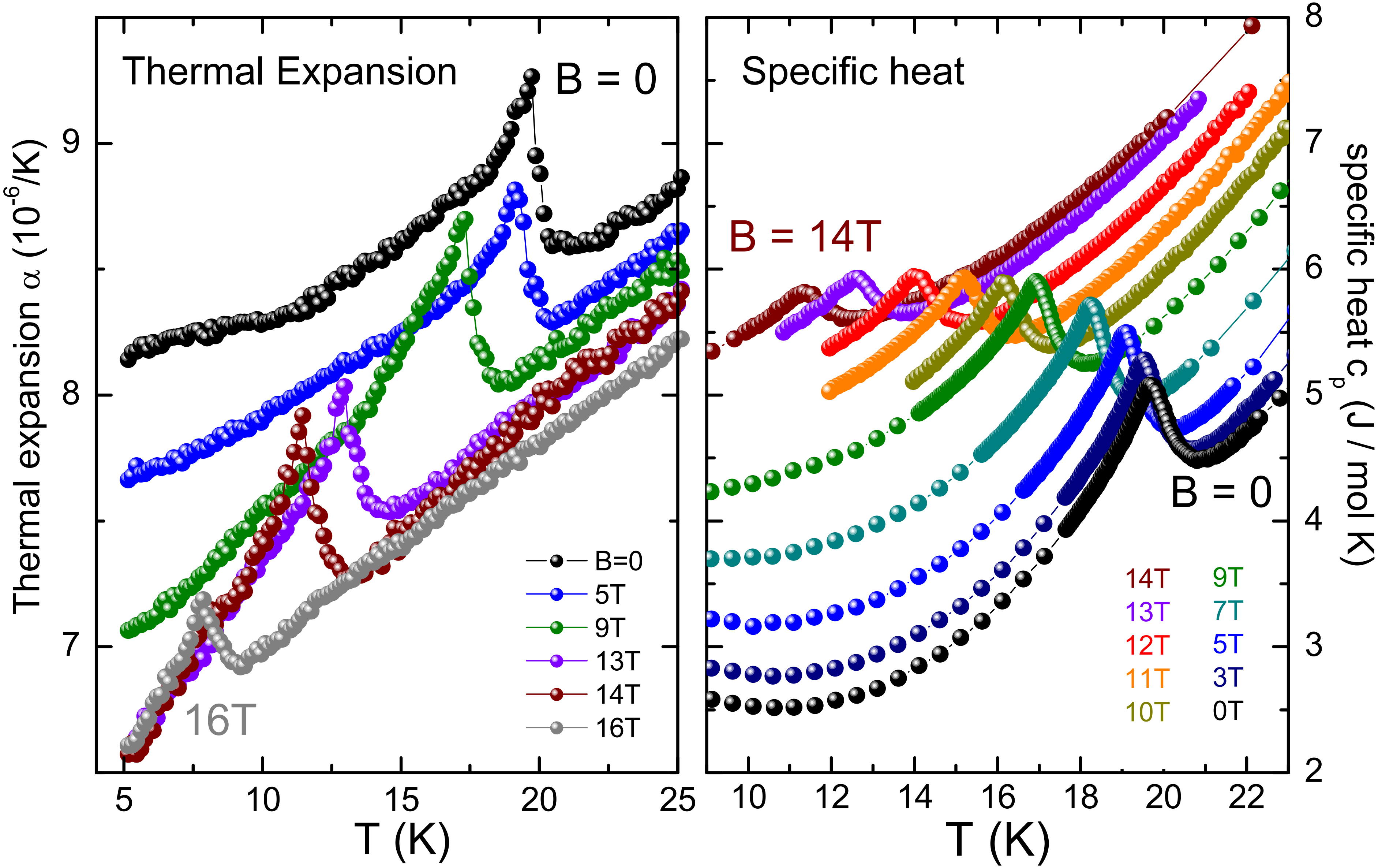
Electron Spin Resonance of *$GdO_{1-x}F_xFeAs$*



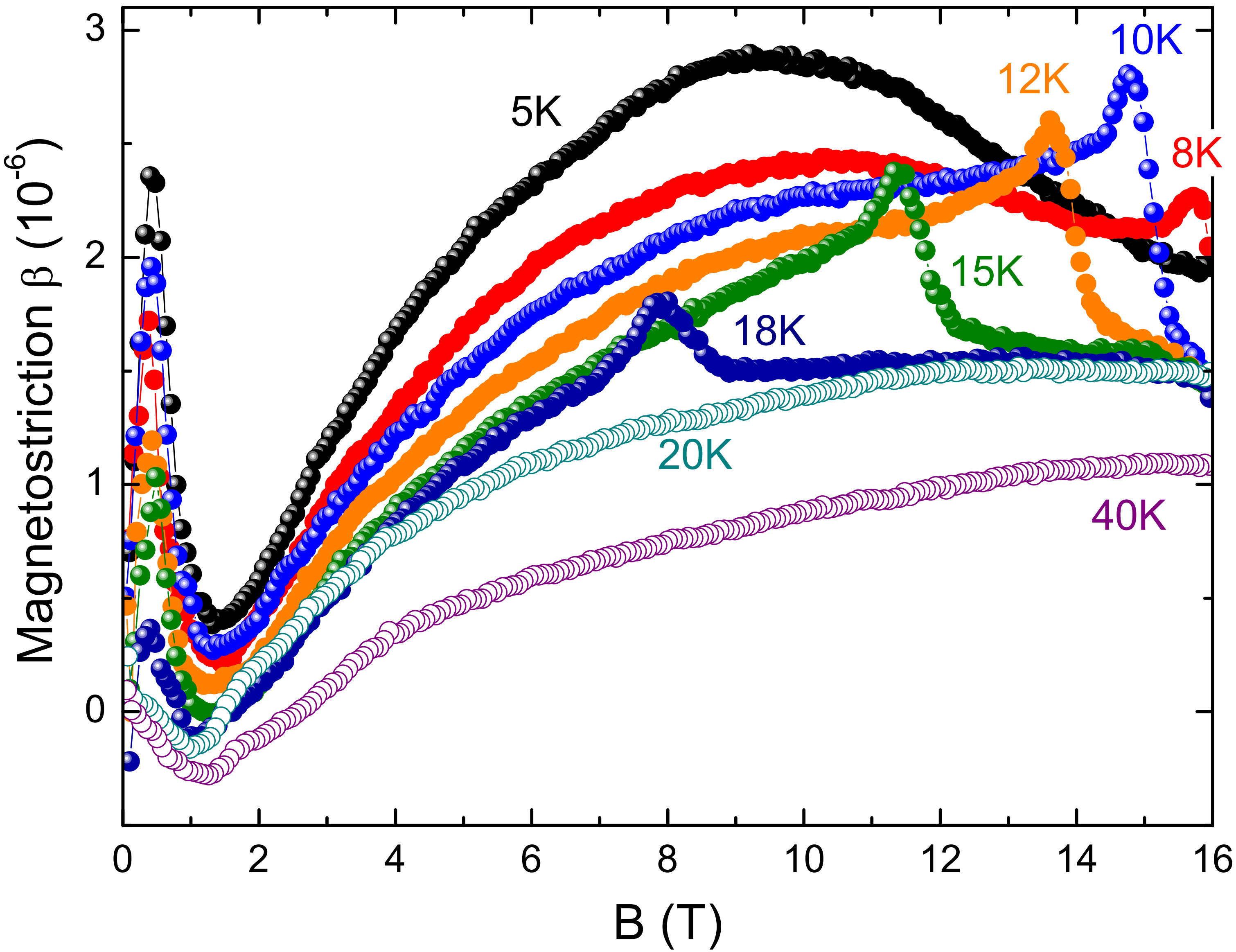


Superconductor (T_c = 21 K): strong broadening and shift of the Gd-ESR response
⇒ onset of inhomogeneous quasi-static spin correlations at T < 80 K

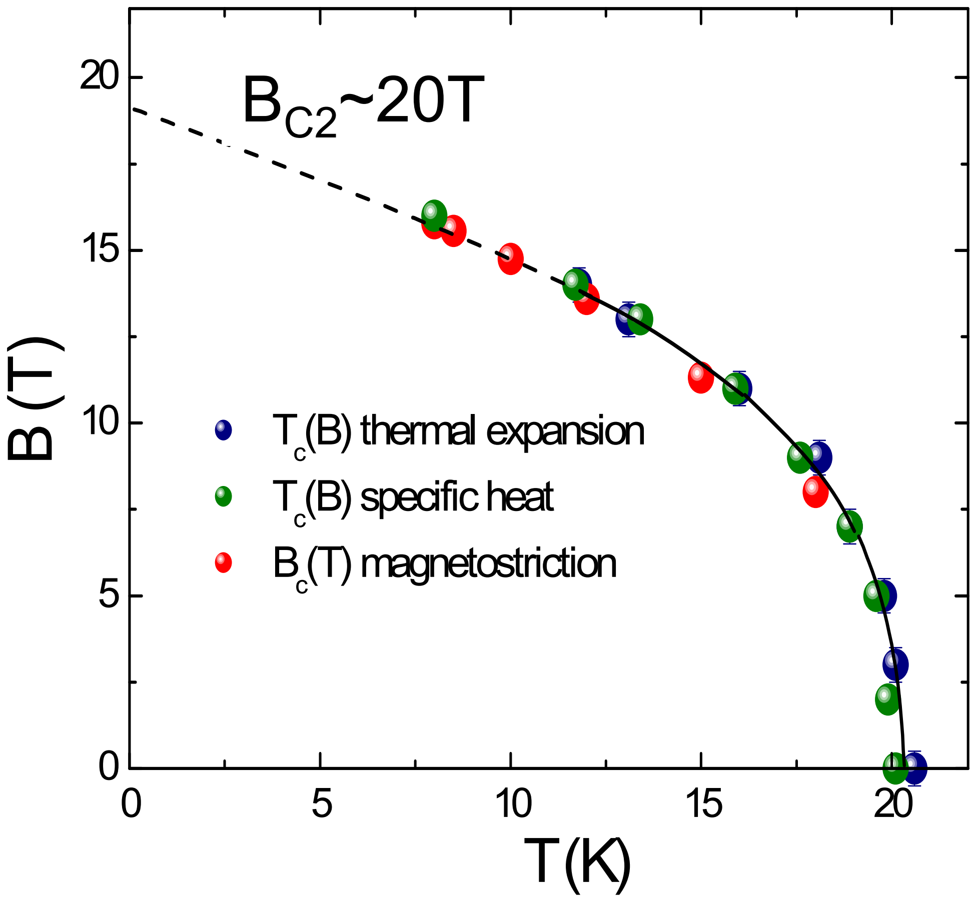
SC transition in $GdFeAsO_{0.85}F_{0.15}$



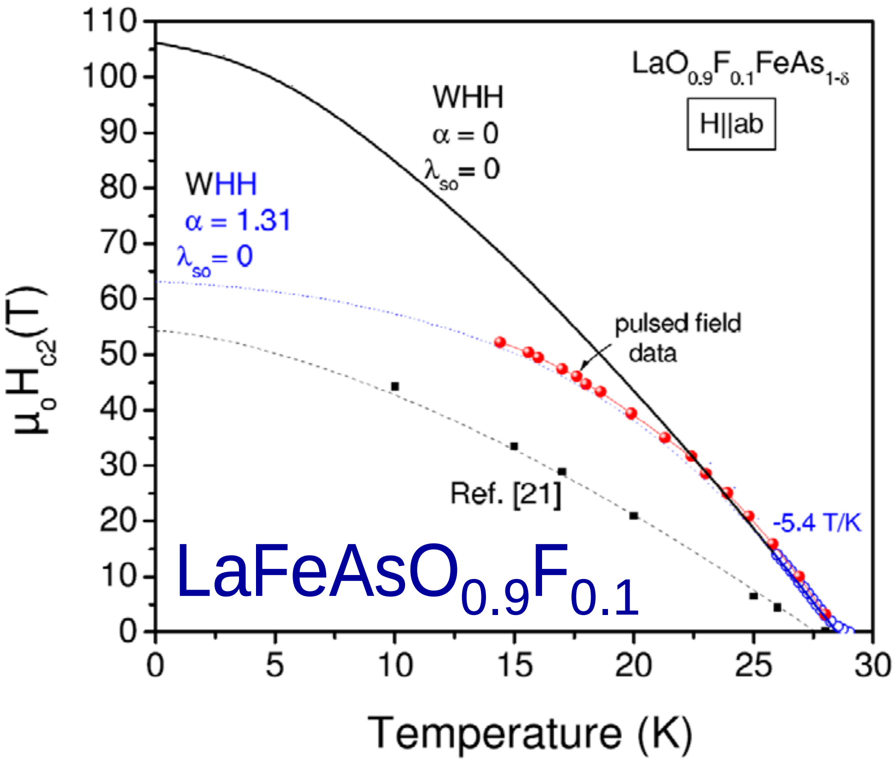
$GdFeAsO_{0.85}F_{0.15}$: Magnetostriction



$GdFeAsO_{0.85}F_{0.15}$

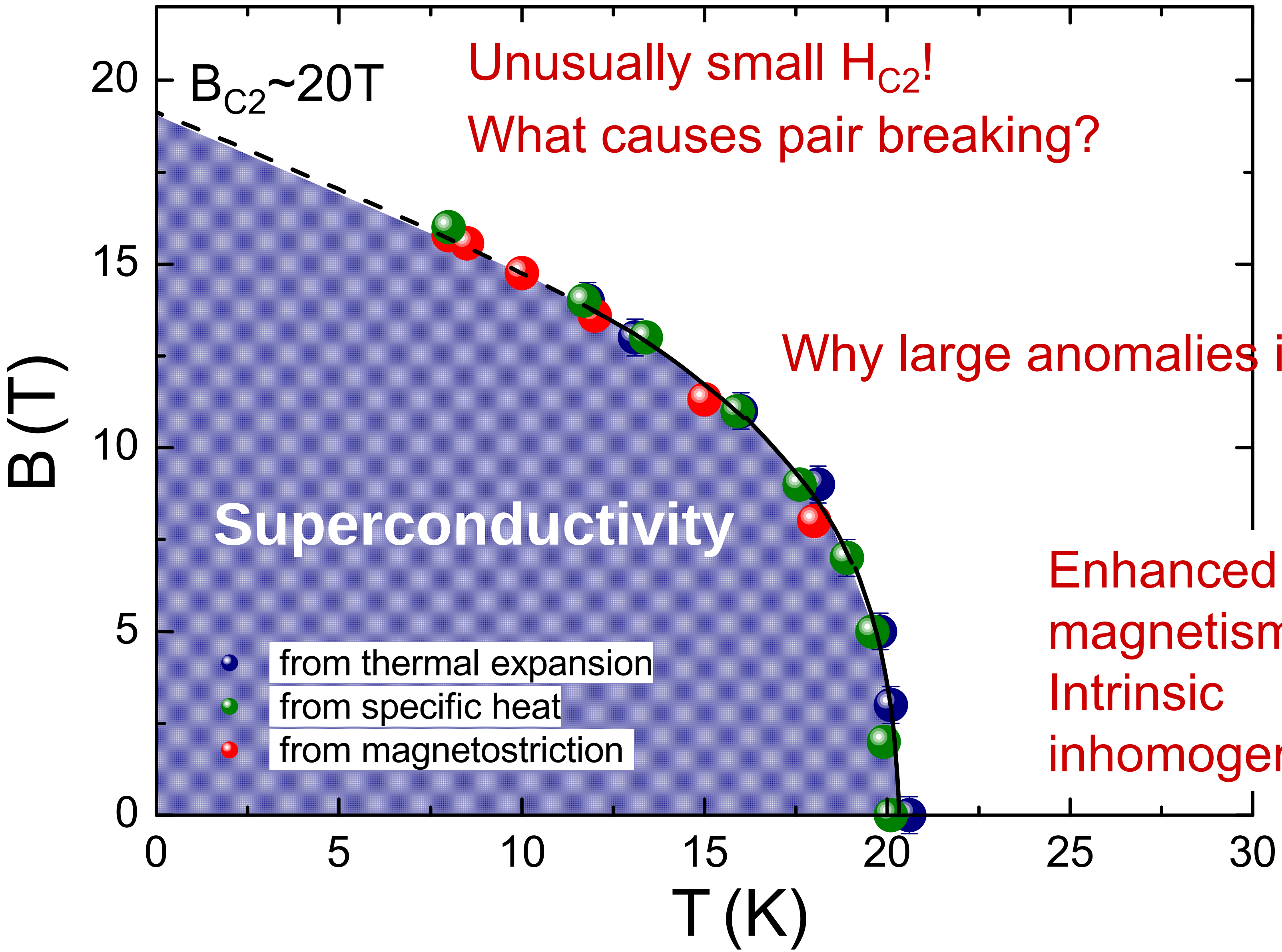


B_{C2}>60T



Fuchs et al, PRL 2008

SC transition in $GdFeAsO_{0.85}F_{0.15}$:
Strange and Puzzling behavior

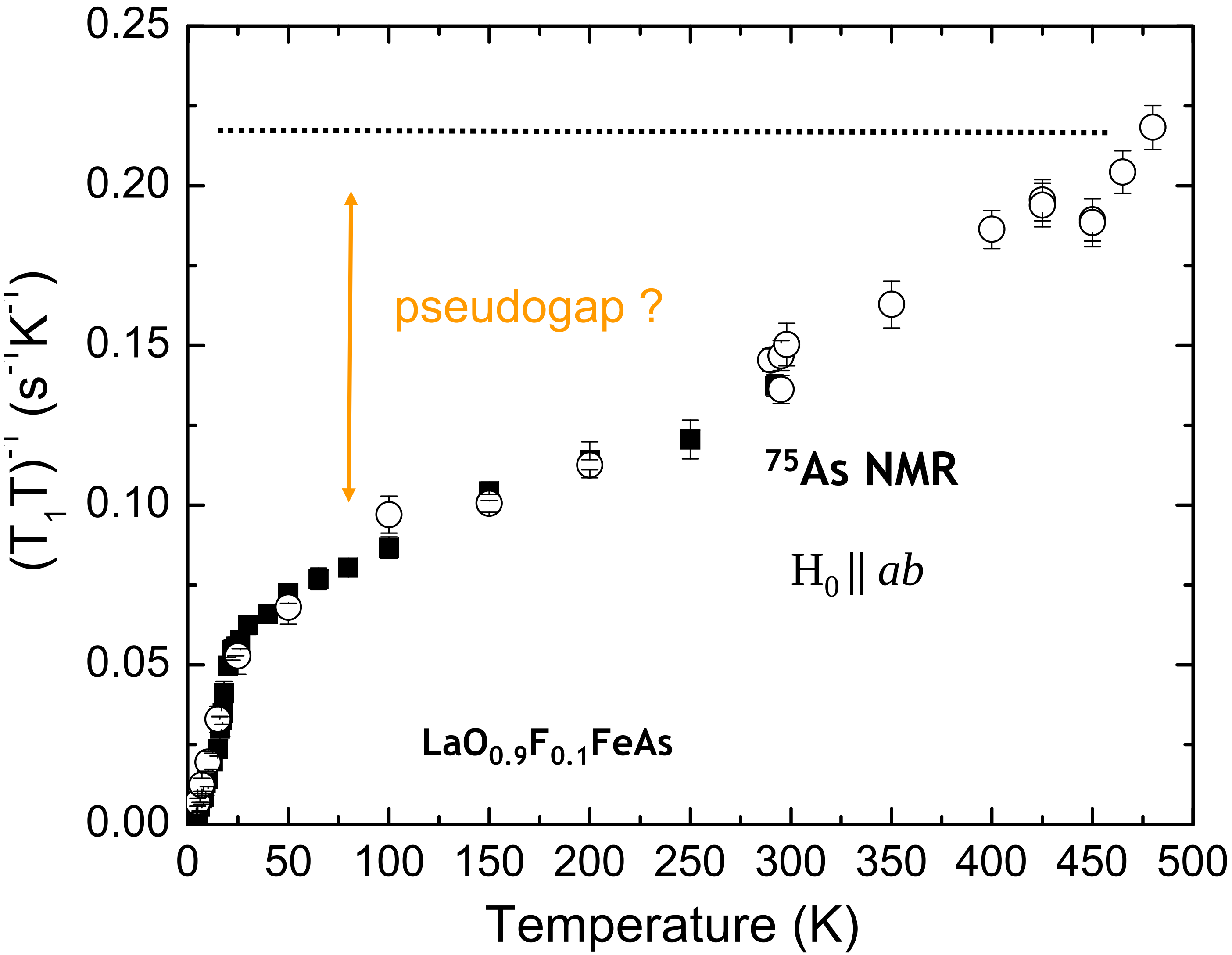


Unusually small H_{C2}!
What causes pair breaking?

Why large anomalies in c_p, α?

Enhanced magnetism ≤ 80K!
Intrinsic inhomogeneities?

Spin lattice relaxation rate, T_1^{-1}, normal state



H.-J. Grafe et al., PRL 101, 047003 (2008)
H.-J. Grafe et al., New J. Phys. 2009

Leibniz-Institut
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Werkstoffforschung
Dresden

High Temperature Superconductivity in FeAs Compounds

OUTLINE

- **Introduction**
- **Phase Diagram of $LaFeAsO_{1-x}F_x$ (and other pnictides)**
  Structural, magnetic, and superconducting transitions
- **Superconducting State**
  Gap, penetration depth, relaxation rate
- **Normal State Properties**
  Electronic Structure (XAS, PES, ARPES)
  „Pseudogap“ (NMR, χ)
  Electronic transport and spin fluctuations
  Charge inhomogeneity (NQR)

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