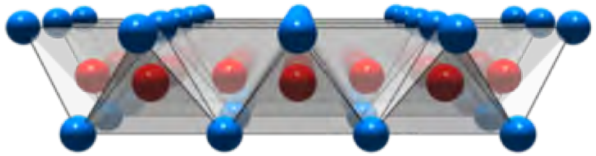
Strain dependent transport and nematicity in Fe based superconductors

Bernd Büchner

IFW Dresden

TU Dresden

GRK 1621



Deutsche Forschungsgemeinschaft DFG

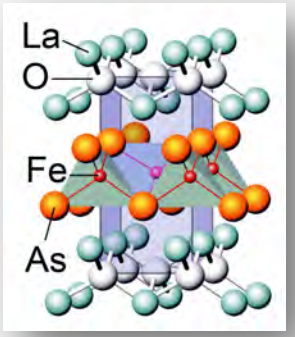
IFW Leibniz Institute for Solid State and Materials Research Dresden

TECHNISCHE UNIVERSITÄT DRESDEN

OUTLINE

Nematic fluctuatons in doped La1111 crystals

- Doped LaOFeAs: an „extraordinary“ Fe based SC
- Magnetic & nematic transitions in LaOFeAs
- Phase diagram of Co-doped LaOFeAs
- Nematic fluctuations in (doped) LaOFeAs



(Development of) methods for strain dependent …

- Strain dependent NMR on $BaFe_2As_2$, strain up to (-0.86%;0.42%)
- Elasto-Seebeck effect on Fe based superconductors
- Elasto-Nernst effect on Fe based superconductors
- ARPES@1^3 beamline under strain (ongoing)

Thanks to

Synthesis

S. Aswartham

S. Wurmehl, **R. Kappenberger,** S. Khim — IFW Dresden
J. M. Ok, J. S.Kim — U Pohang
S. Ran, L. Bud'ko, P. C. Canfield — Ames Lab.

NMR/NQR

H. Grafe

S.H. Baek

G. Lang, P. Lepucki — IFW Dresden
F. Hammerath, A. Dioguardi
P. Carretta, S. Sanna, G. Prando — U. Pavia

Nematic susceptibility

C. Hess

C. Hess, C. Wuttke, **F. Caglieris, X. Hong** — IFW Dresden
F. Wissmann, F. Steckel, s. Sykora

Thermodynamics Magnetization

A. Wolter

F. Scaravaggi — IFW Dresden
L. Wang, S. Sauerland, R.Klingeler — U Heidelberg

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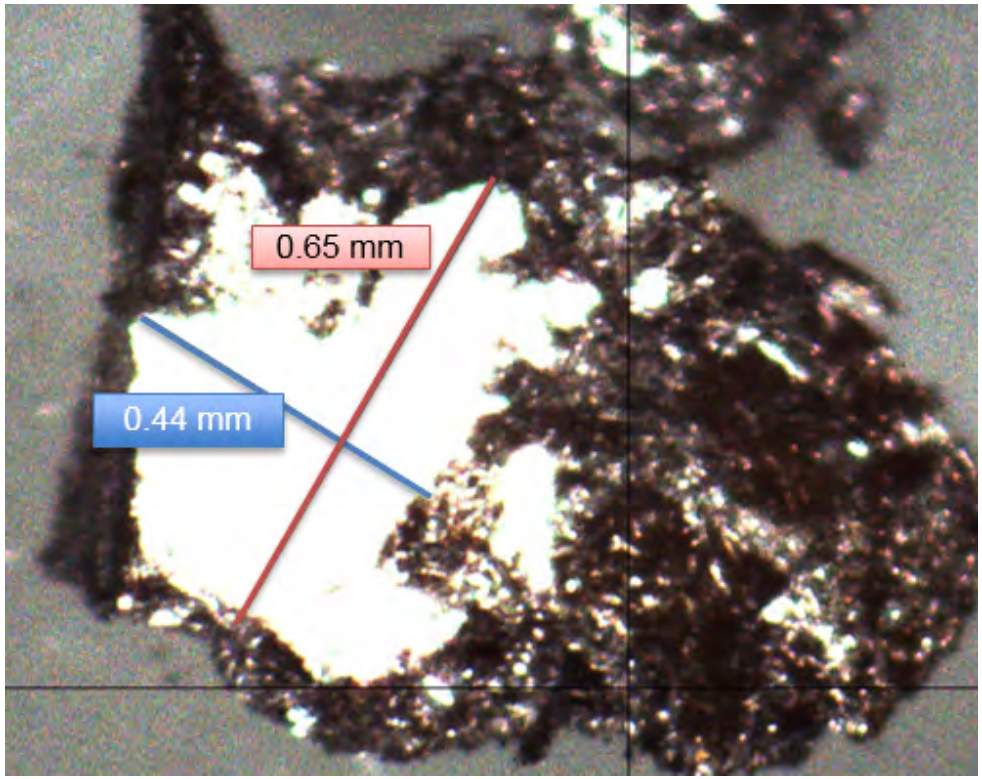
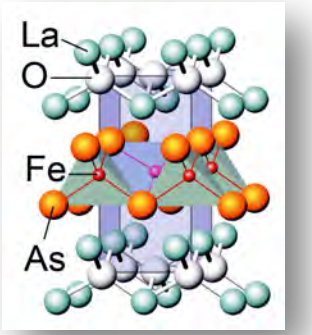
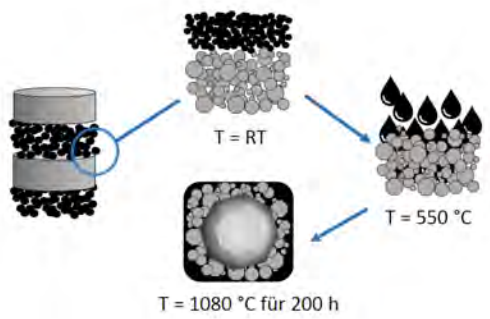
Solid state single crystal growth of LaOFeAs





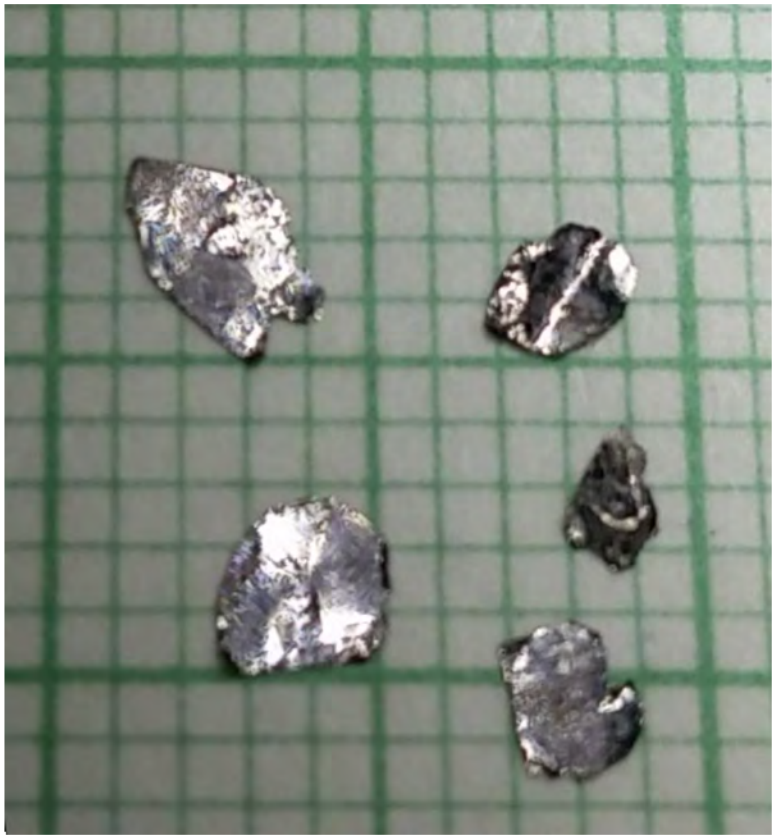
- Subsequent sintering of LaFeAsO polycrystals leads to the formation of crystals
- Optimization of process → large faceted crystals (Solid State Crystal Growth (SSCG))



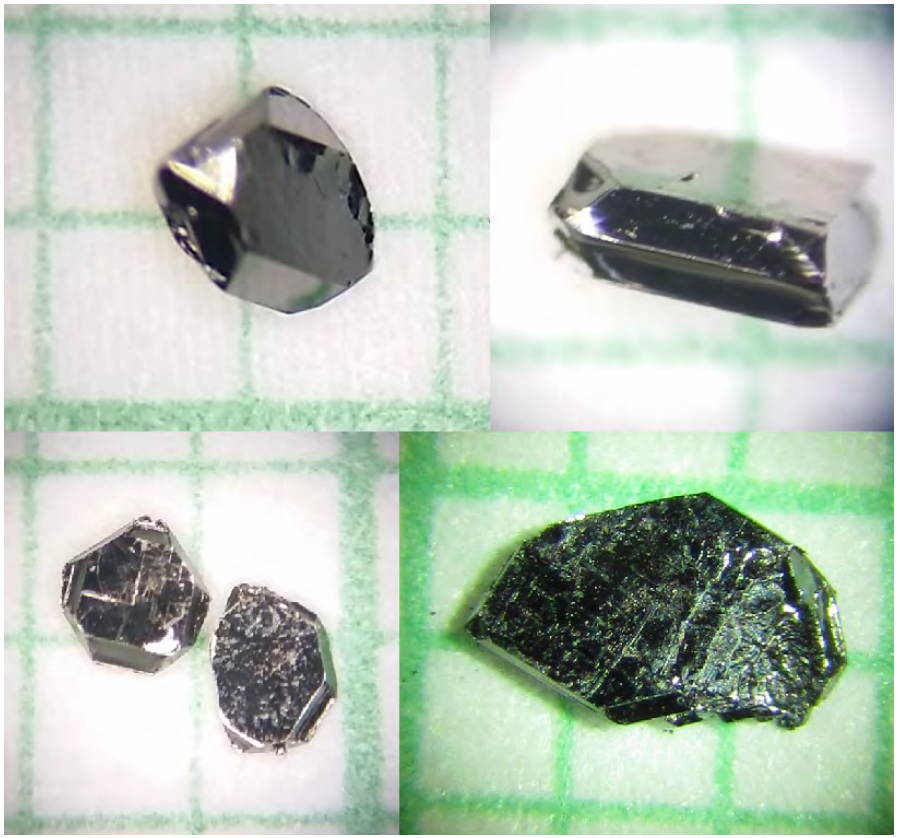
R. Kappenberger, BB. et al., J. Cryst. Growth 2017

LaOFeAs crystals

24 h @ 1080° C:



200 h @ 1080° C:



R. Kappenberger, BB. et al., J. Cryst. Growth 2017

LaOFeAs crystals

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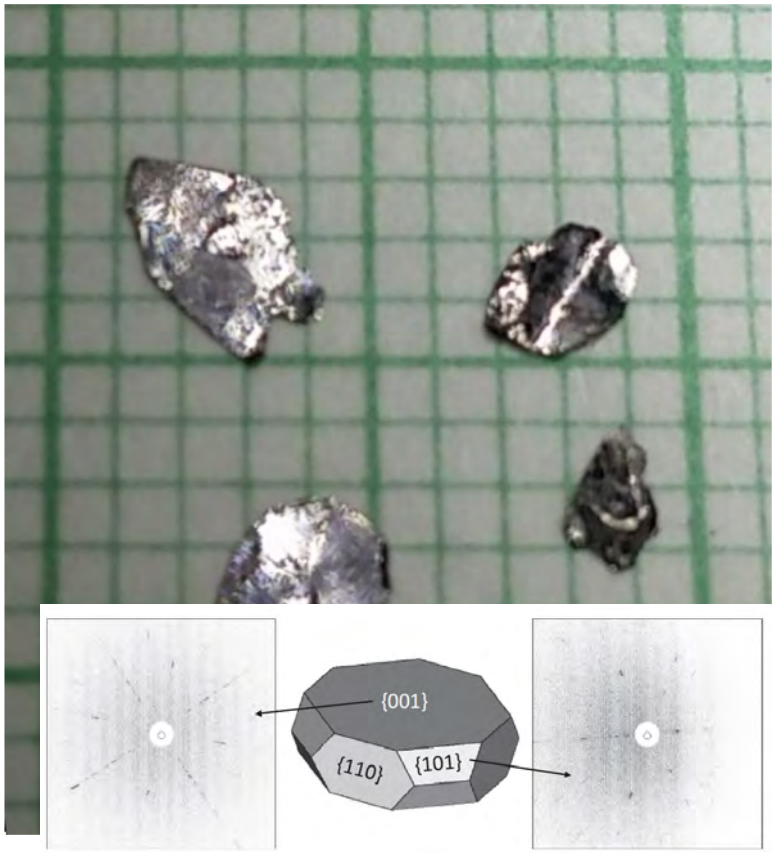

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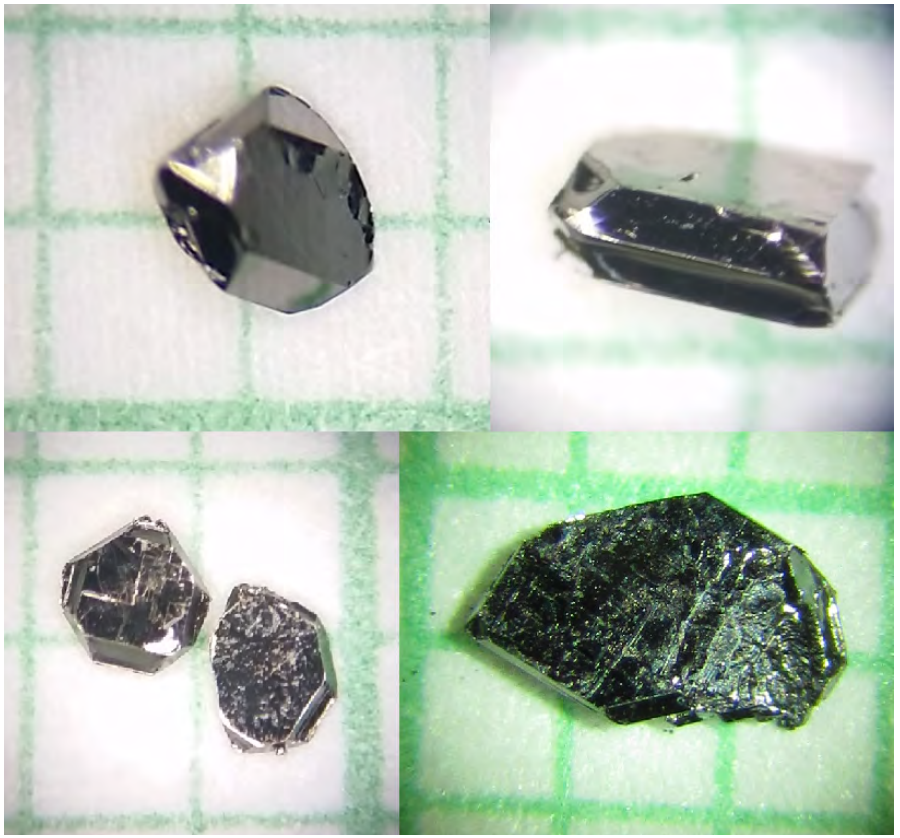
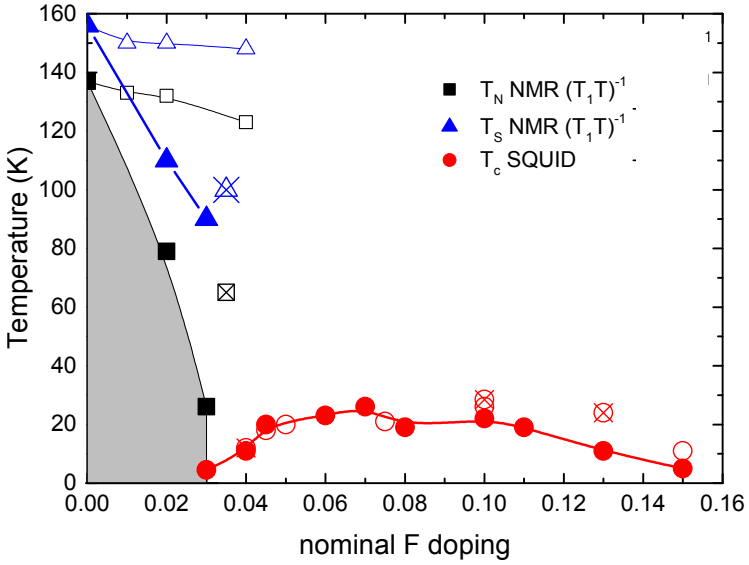
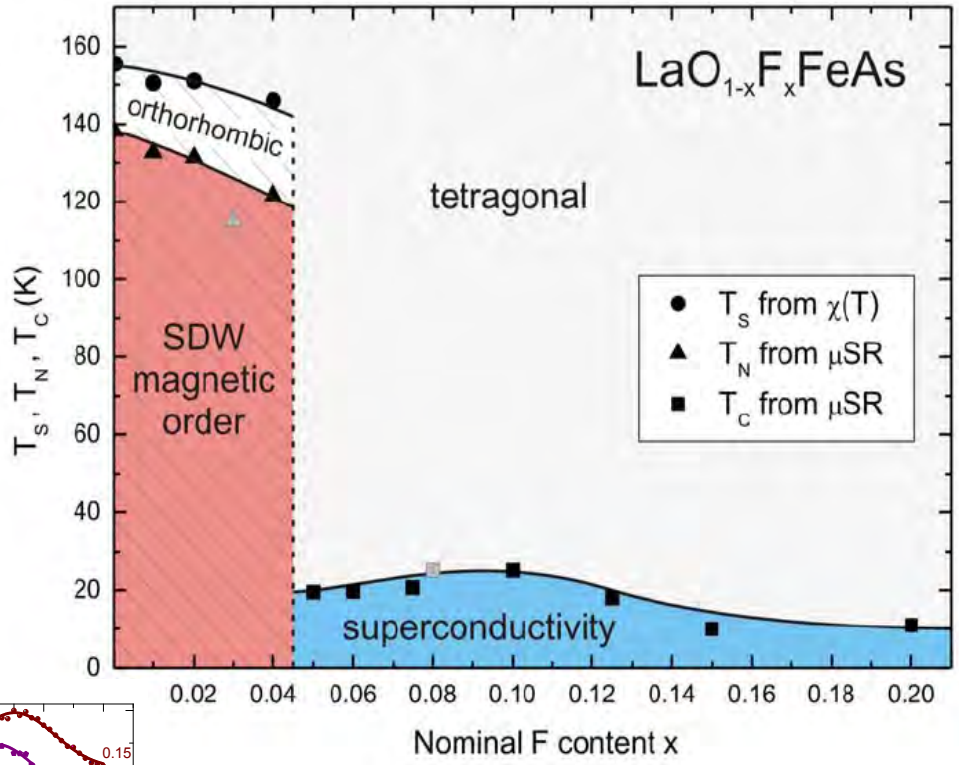


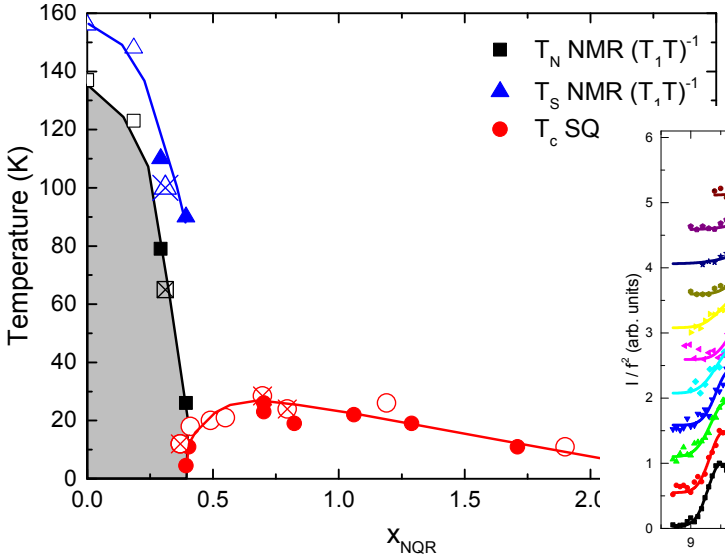
R. Kappenberger, BB. et al., J. Cryst. Growth 2017

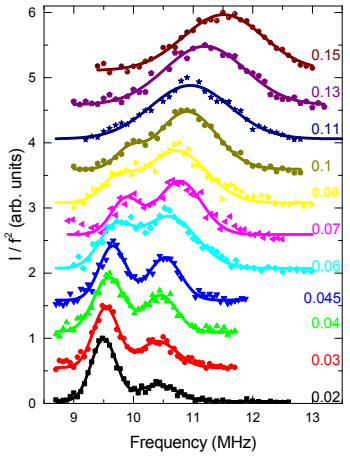
Phase diagram of F doped La 1111: Revisited





H. Luetkens, BB et al., Nat. Mat. (2009)

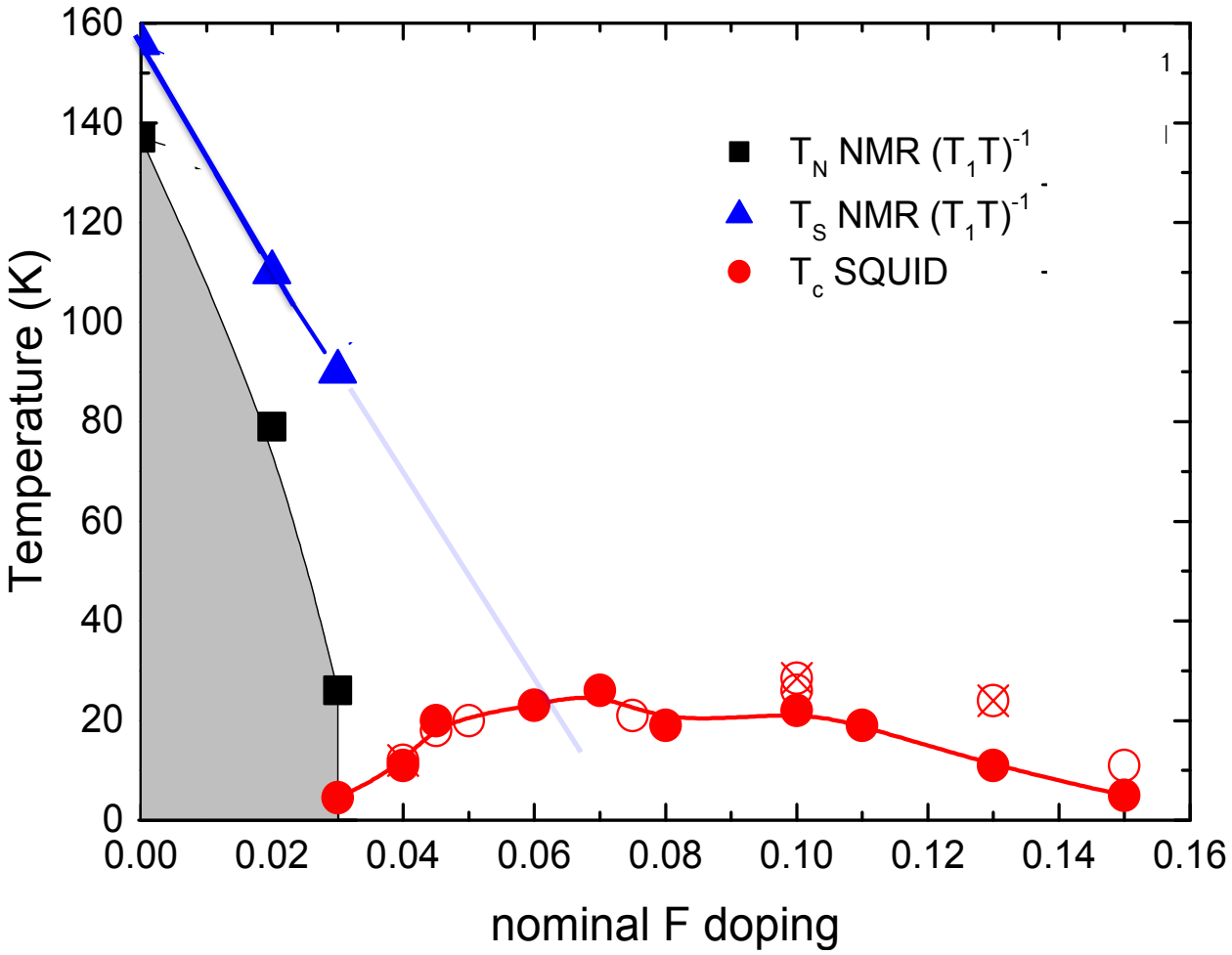




- **Rapid suppression of T_N**
- **Clear separation between T_s and T_N**
- **No coexistence of SC and AFM for La1111**

→ **non-magnetic underdoped phase**

Revised phase diagram of F doped La 1111



- **Rapid suppression of T_N**
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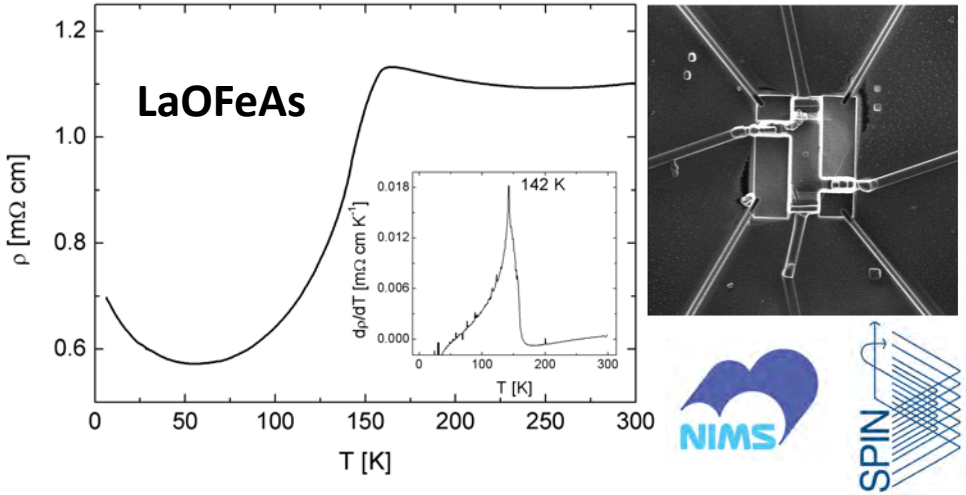
- **No coexistence of SC and AFM for La1111**

→ **non-magnetic underdoped phase**

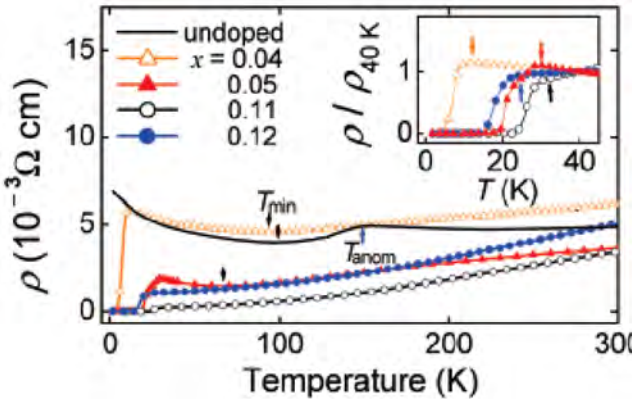
Fe based SC: good and/or bad metals?

Most Fe based superconductors are “good metals“

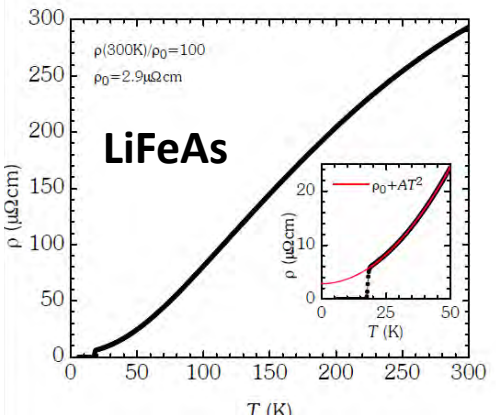
Exception: 1111 (in particular doped LaOFeAs)



F. Caglieris, M. Fujioka et al.

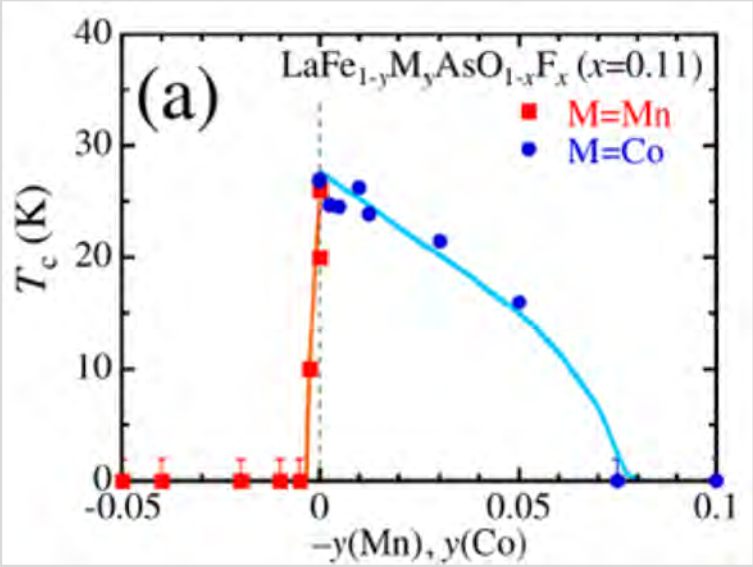


Y. Kamihara et al., J. Am. Chem. Soc. 2008



O. Heyer, C. Hess, BB et al., PRB 2011

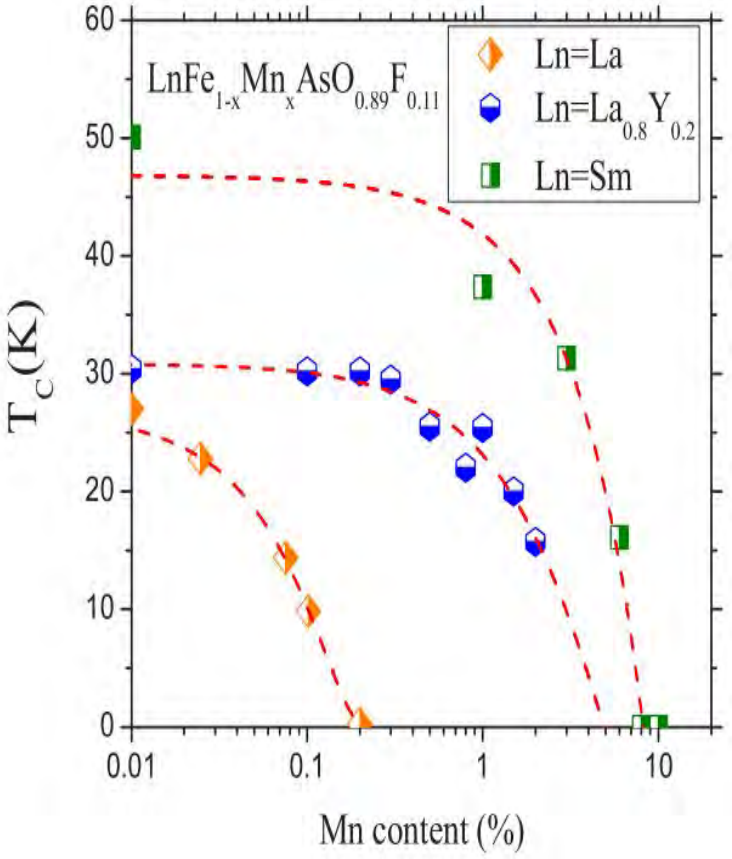
Poisoning effect of Mn doping in La 1111



$Mn_{0.002}Fe_{0.998}$

Substitution of Fe by tiny amounts of Mn
→ Drastic suppression of superconductivity

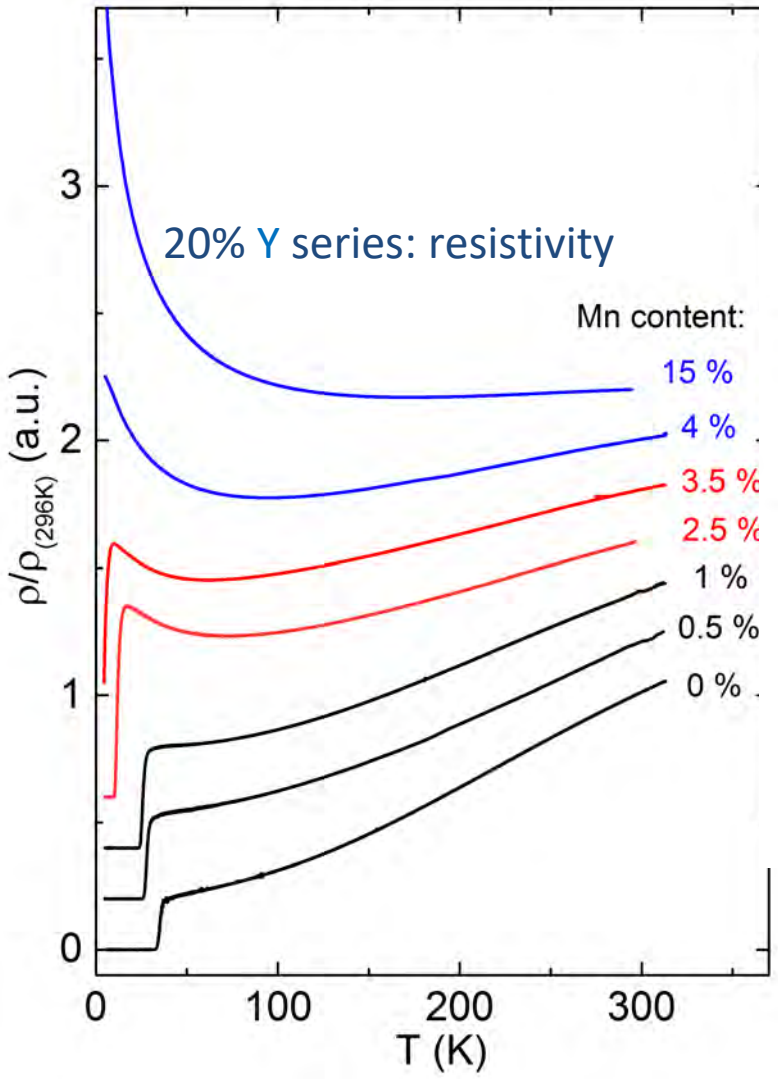
M. Sato et al. , J. Phys. Soc. Jpn. 2010

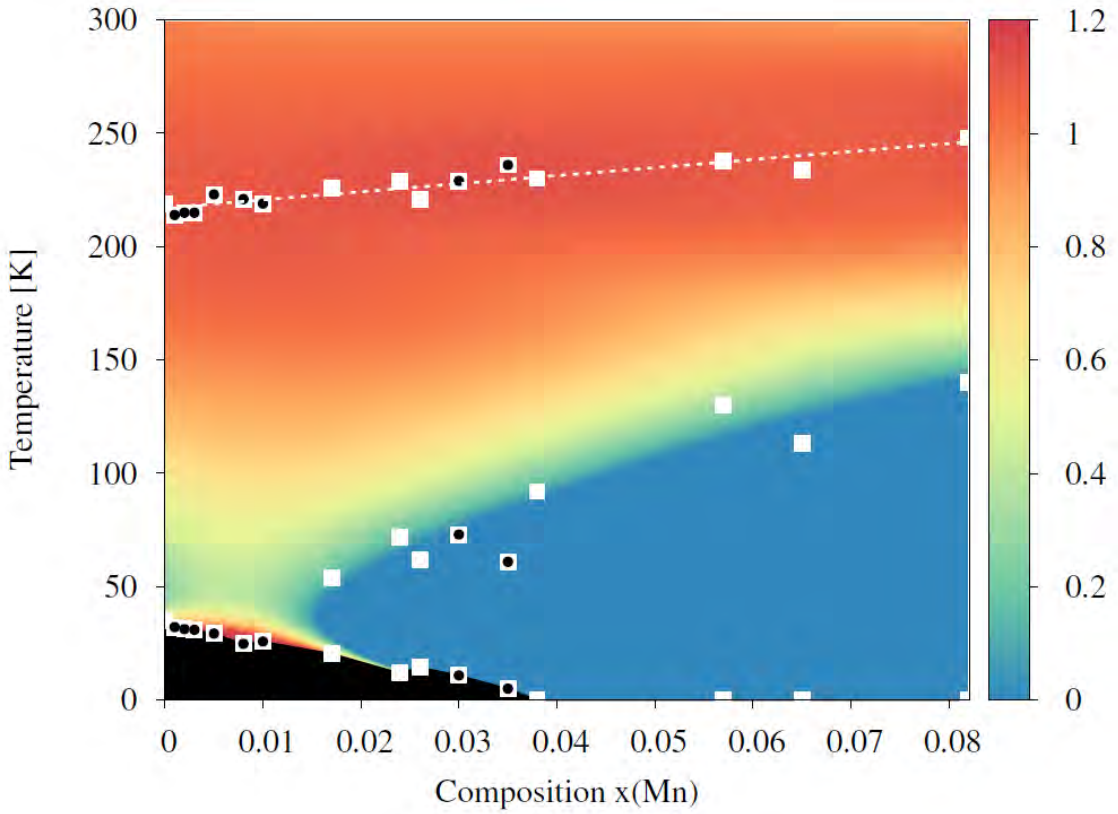


Suppression is stronger for La>(La,Y)>Sm

F. Hammerath P. Carretta, BB et al. Phys. Rev. B(R) 2015

Poisoning effect of Mn doping in La 1111





Substitution of Fe by tiny amounts of Mn

→ drastic suppression of superconductivity

→ localisation of electrons

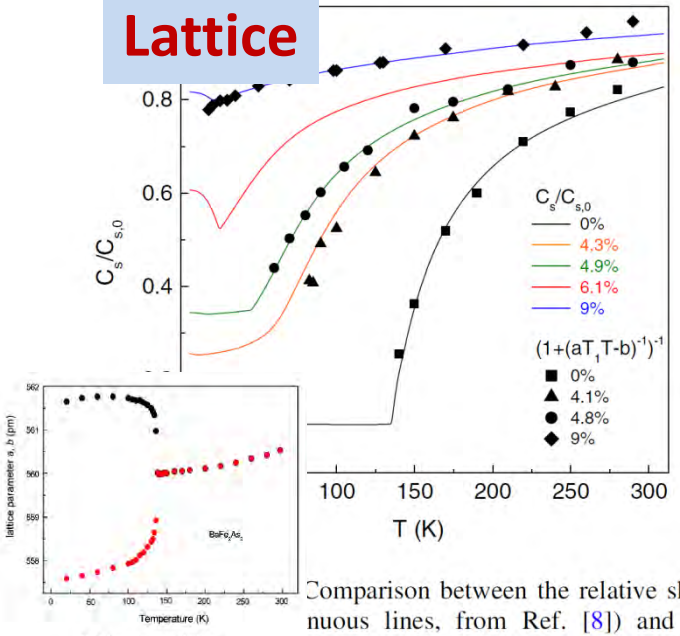
R. Kappenberger, P. Carretta, BB et al.
Phys. Rev. B 2018

OUTLINE

- Doped LaOFeAs: an „extraordinary“ Fe based SC
- Magnetic & nematic transitions in LaOFeAs
- Phase diagram of Co-doped LaOFeAs
- Nematic fluctuations in (doped) LaOFeAs

Nematic order in Fe based SC

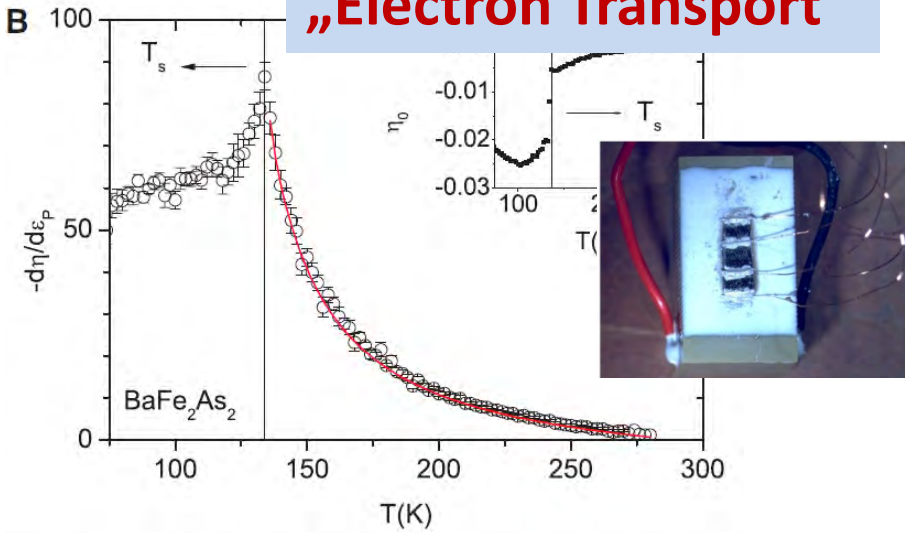
Lattice



Comparison between the relative shear
nuous lines, from Ref. [8]) and the
rescaled NMR $1/T_1T$ (closed symbols, from Ref. [3]) for different "effective" Co concentrations in $Ba(Fe_{1-x}Co_x)_2As_2$. The

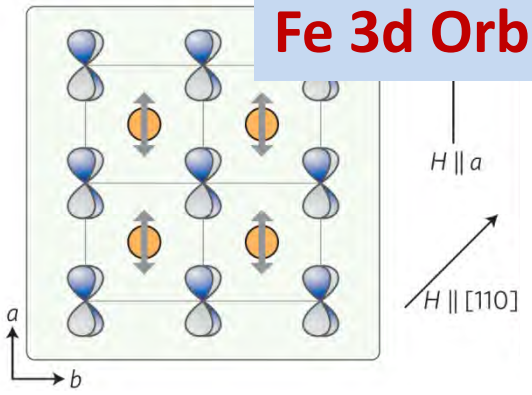
R.M. Fernandes, A.E. Böhmer, C. Meingast, and J. Schmalian, PRL 2013

„Electron Transport“

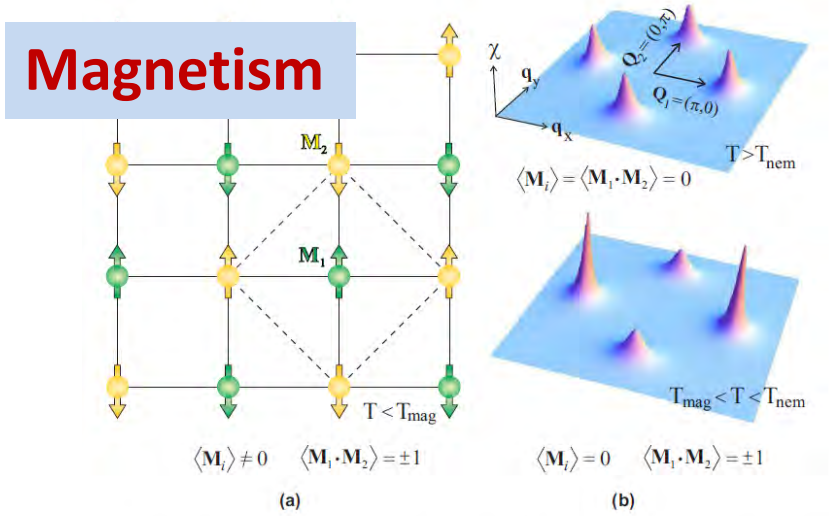


Chu et al. Science 2012

Fe 3d Orbitals

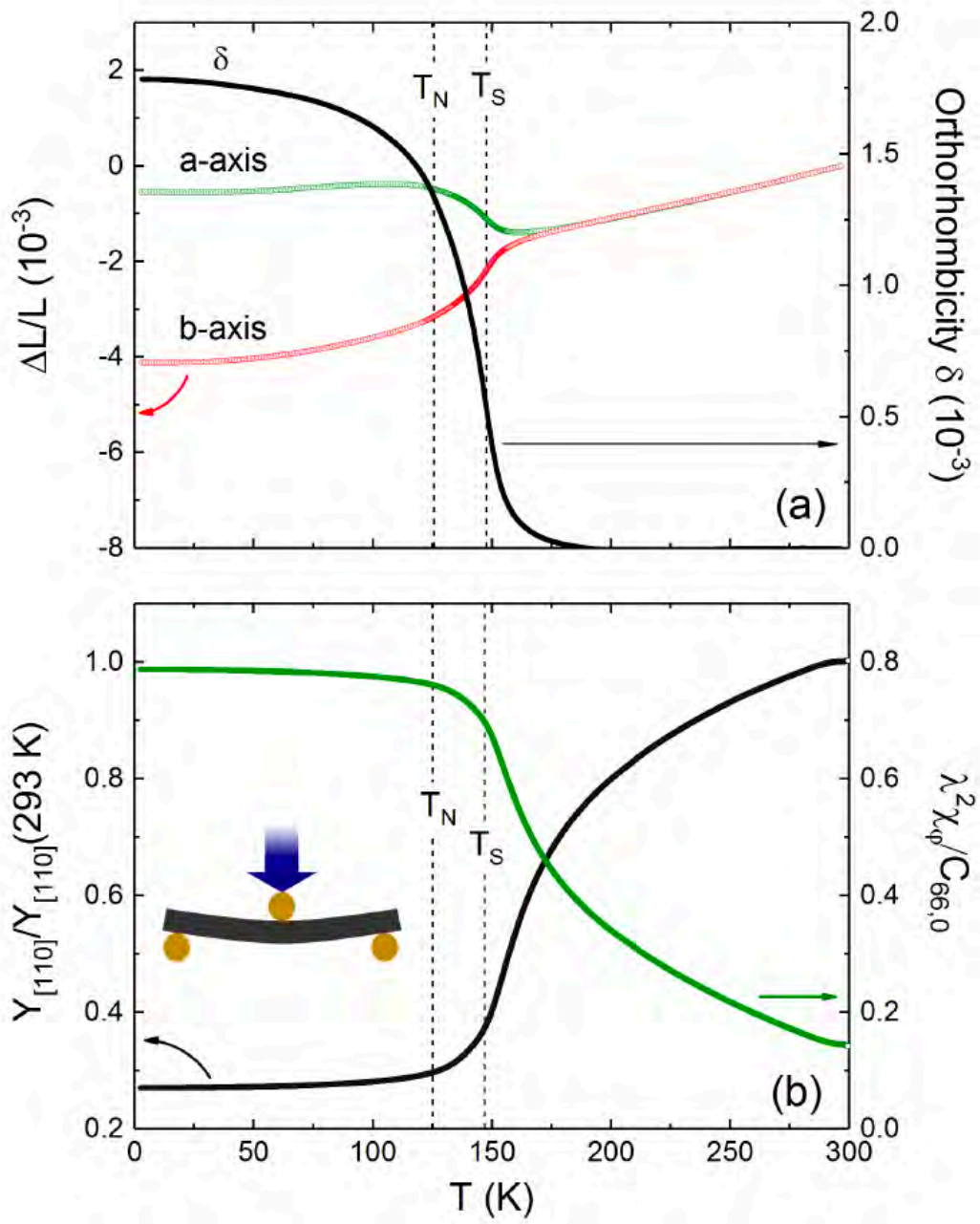


Magnetism

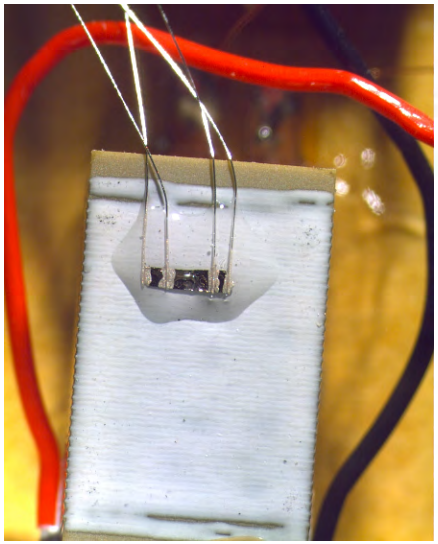


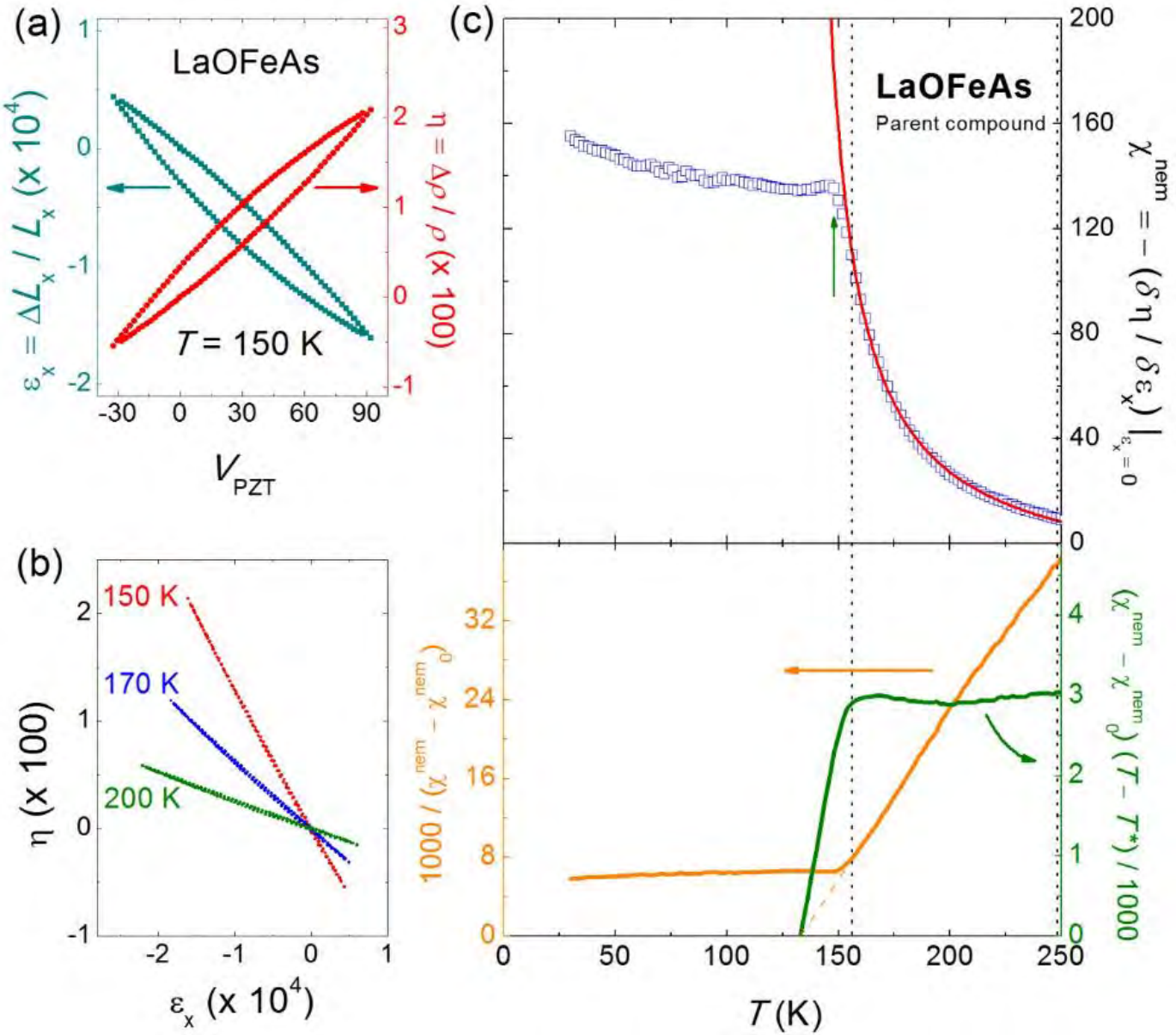
R. Fernandes, A. Chubukov, J. Schmalian Nat. Phys. 2014

Nematic order in LaOFeAs: Structure, elastic constant

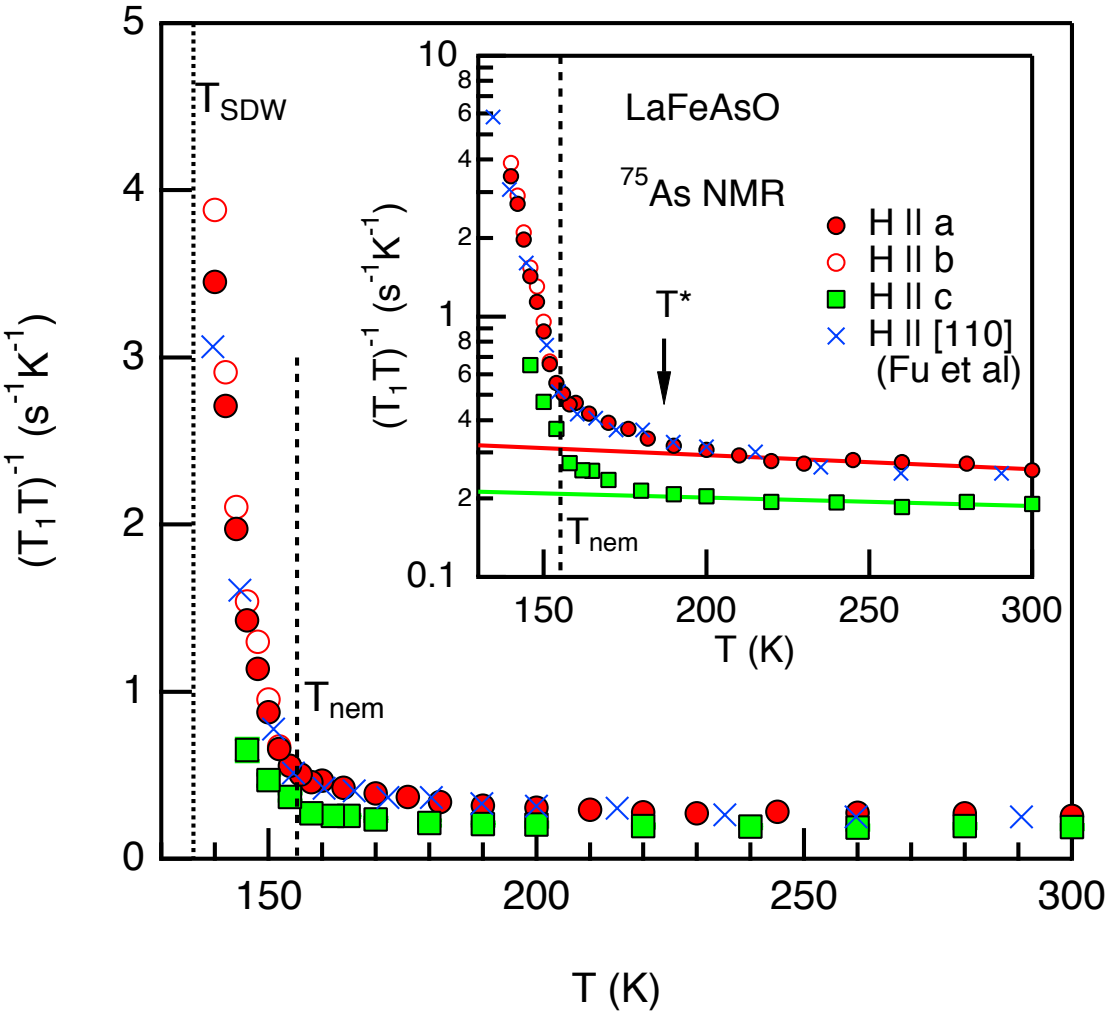


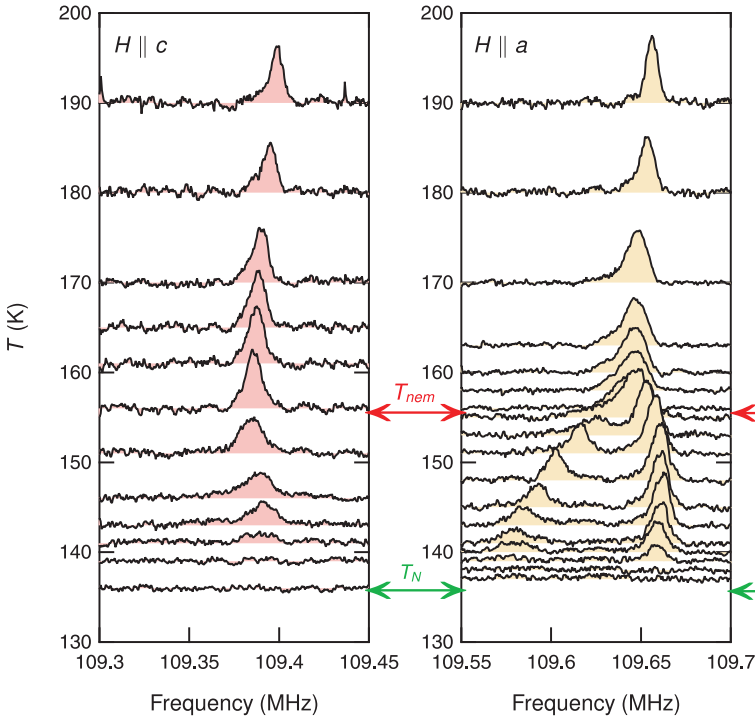
Nematic susceptibility of Co doped LaOFeAs





Nematic order in LaOFeAs: NMR





S. Baek, BB et al., Phys. Rev. B 2018

No clear evidence for magnetic instability above T_S

Strong (>> FeSe) enhancement of slow spin fluctuations at T_S

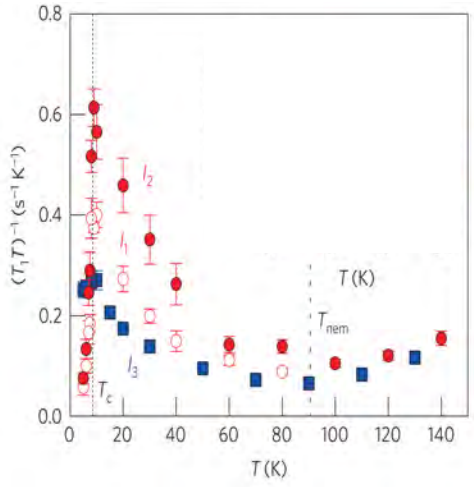
Nematic transitions of Fe based SC

Coupling between orbitals/lattice and (slow) spin fluctuations (NMR)

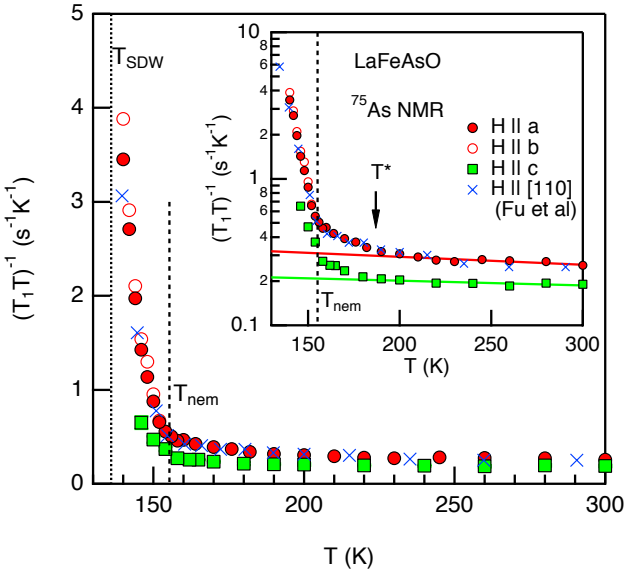
FeSe
$T_N = 0$

LaOFeAs
$T_N < T_S$

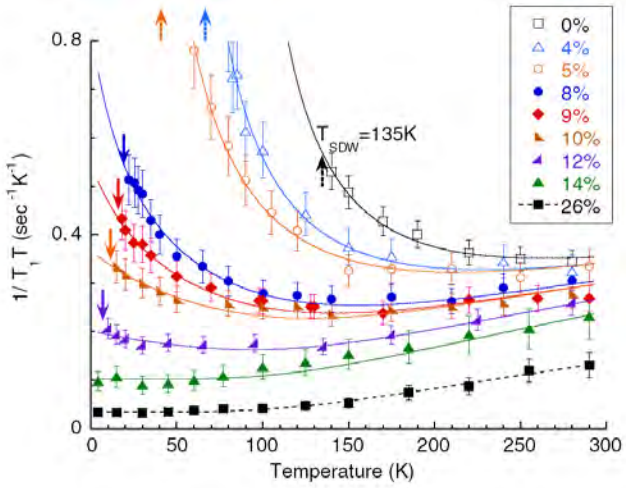
$BaFe_2As_2$
$T_N = T_S$



S. Baek, BB et al., Nat. Mat. 2015

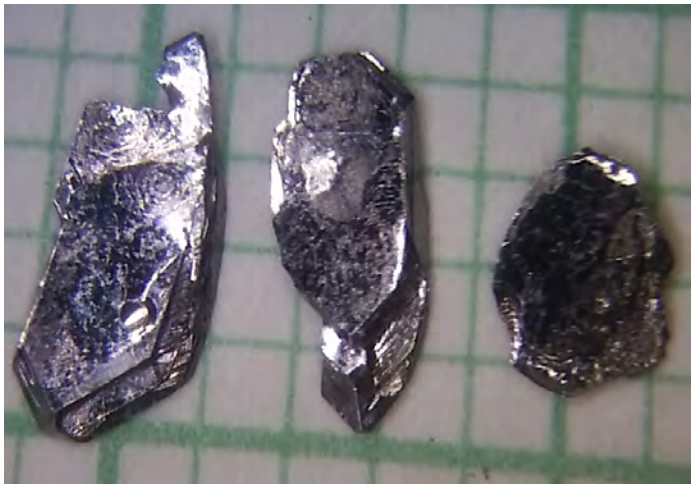


S. Baek, BB et al., Phys. Rev. B 2018



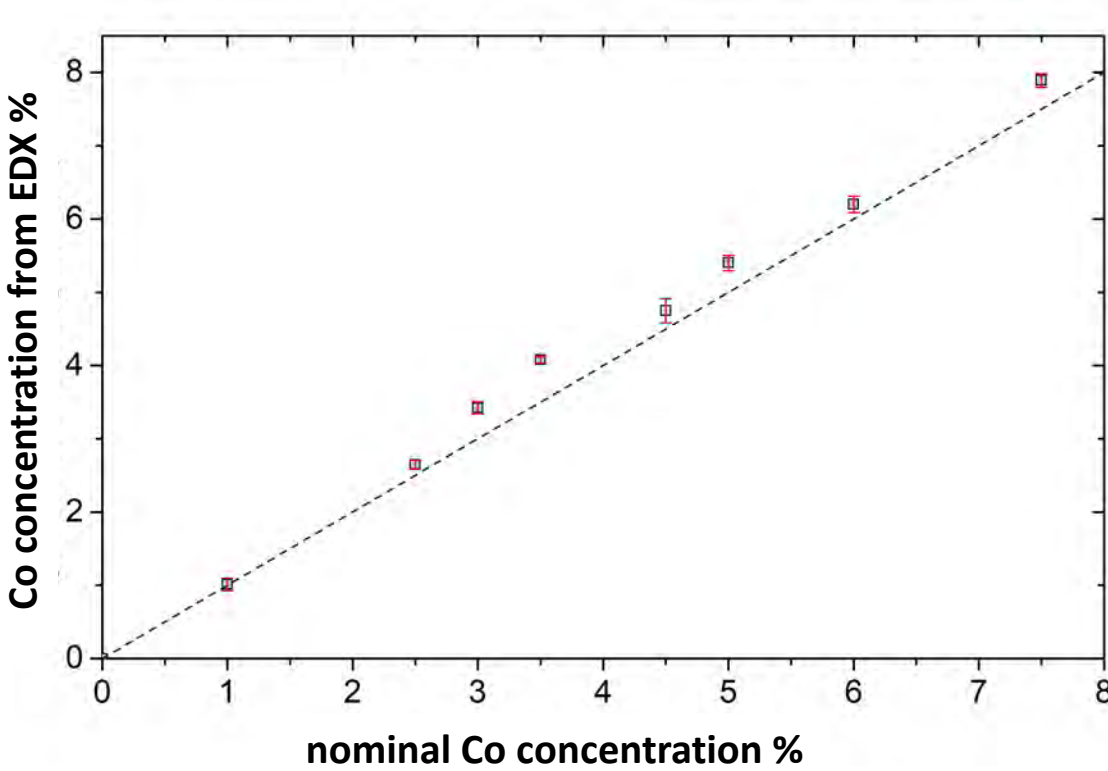
Ning *et al*. PRL 104, 037001 (2010)

Crystals of Co doped LaO(Fe,Co)As



Co doping:

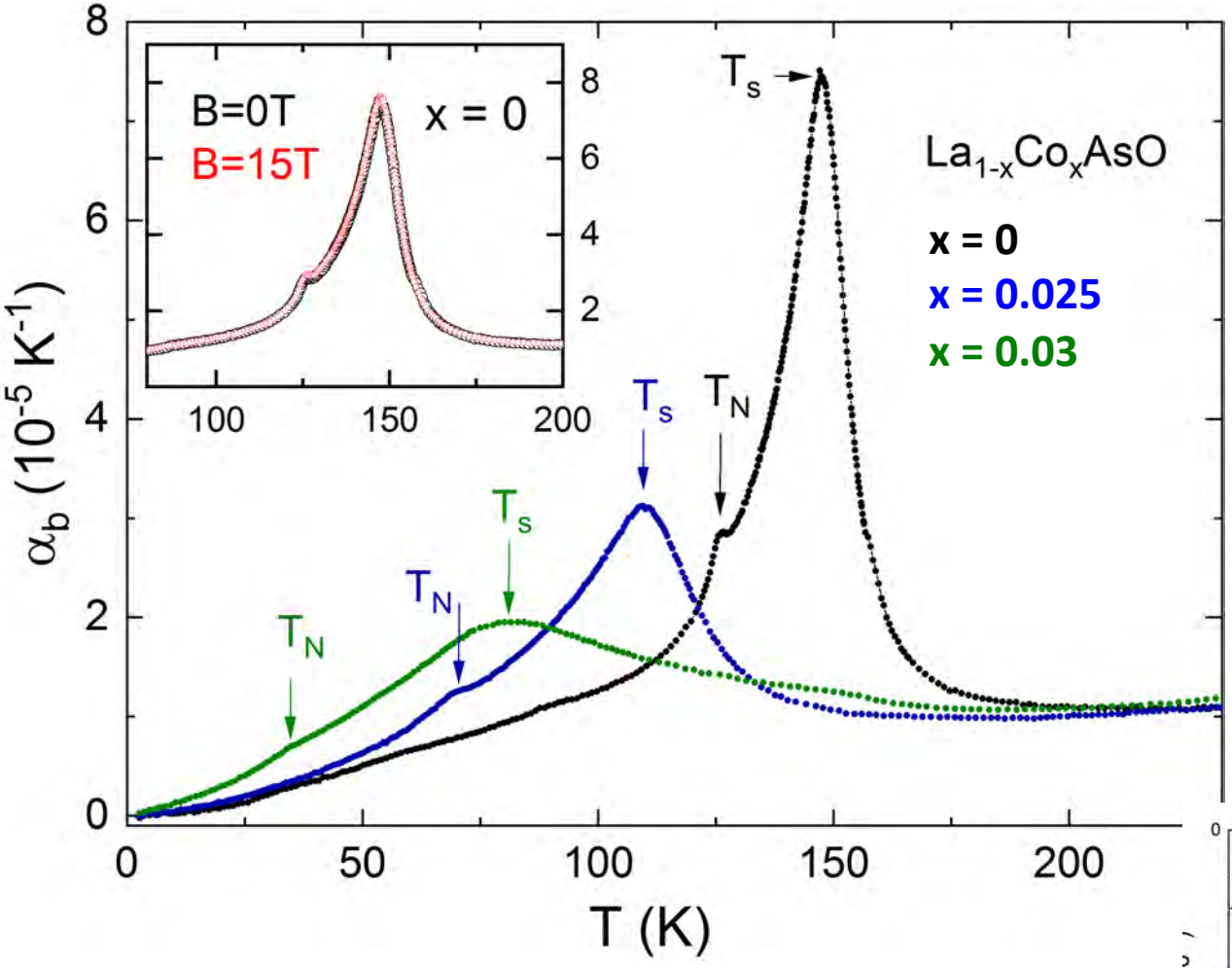
- **electron doping**
- **impurities**

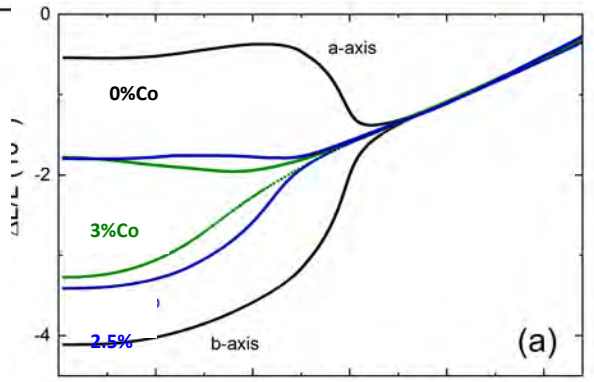


work in progress

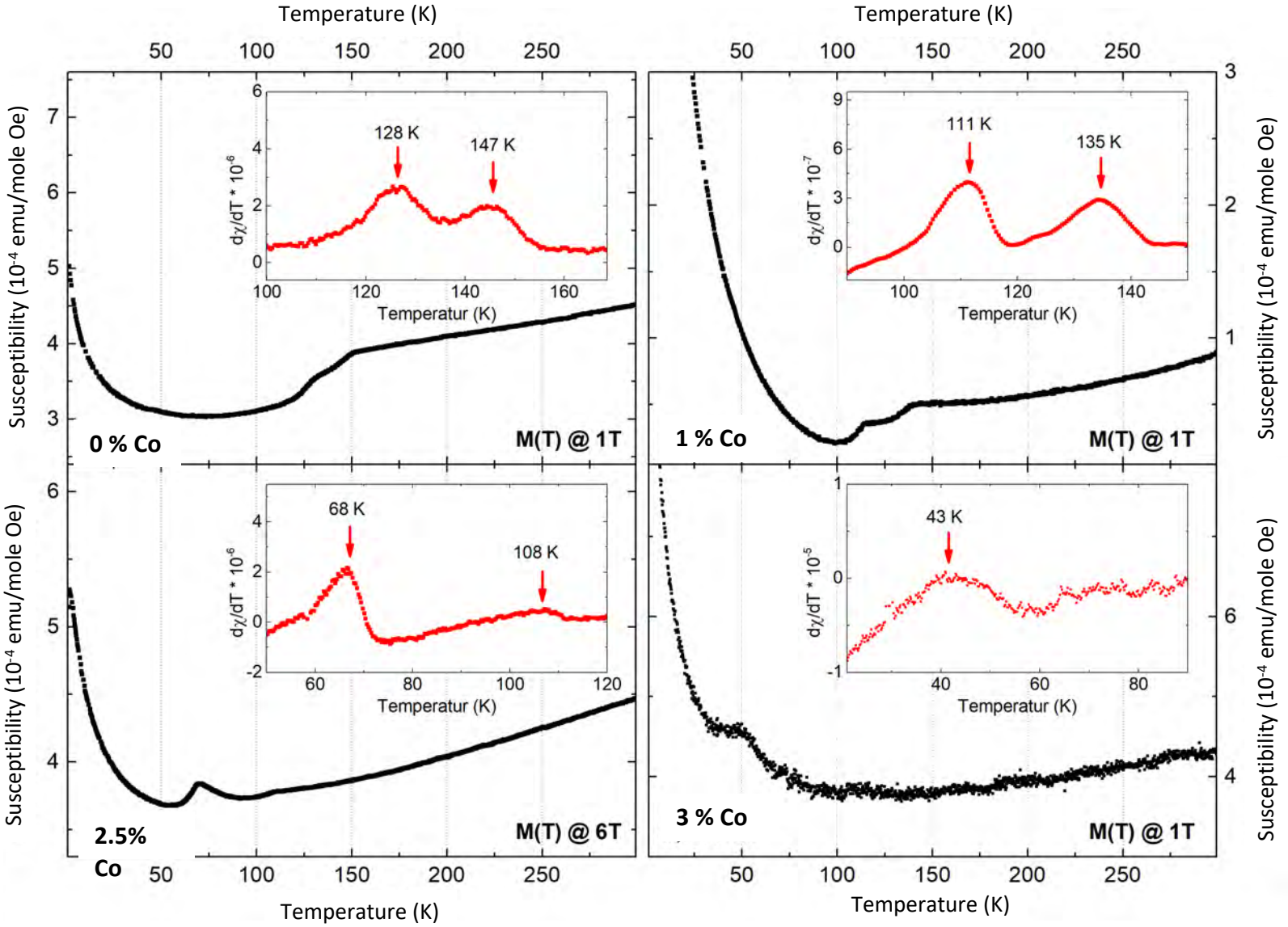
- fluorine doping
- Sm 1111
- Ce 1111
- …

Phase diagram of Co-doped La 1111 revisited …

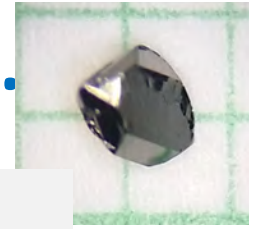


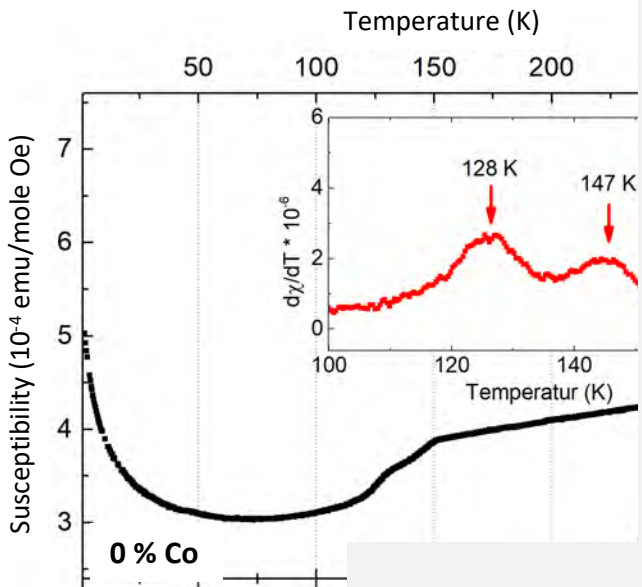


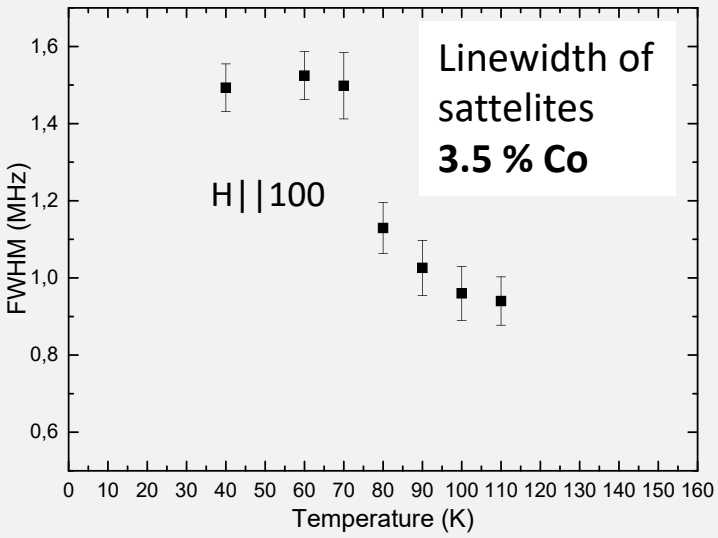
Phase diagram of Co-doped La 1111 revisited …

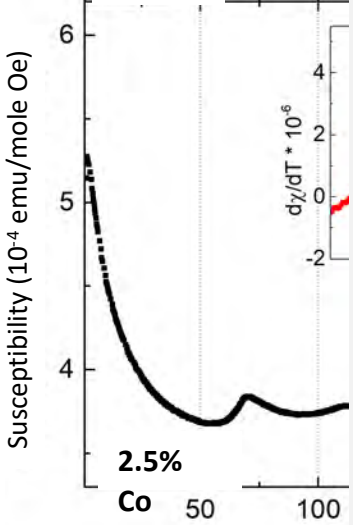


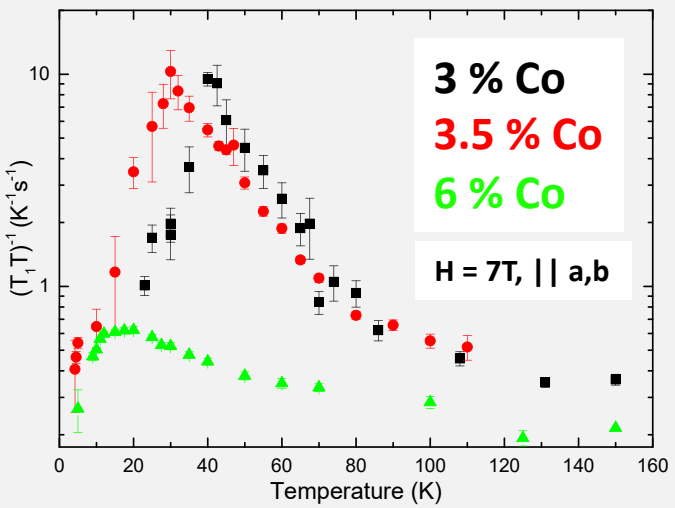
Phase diagram of Co-doped La 1111 revisited …

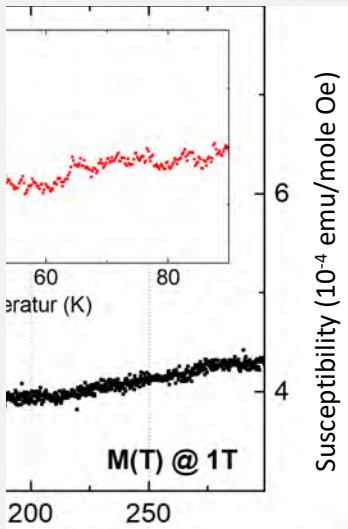




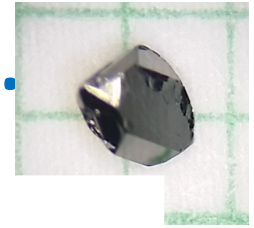


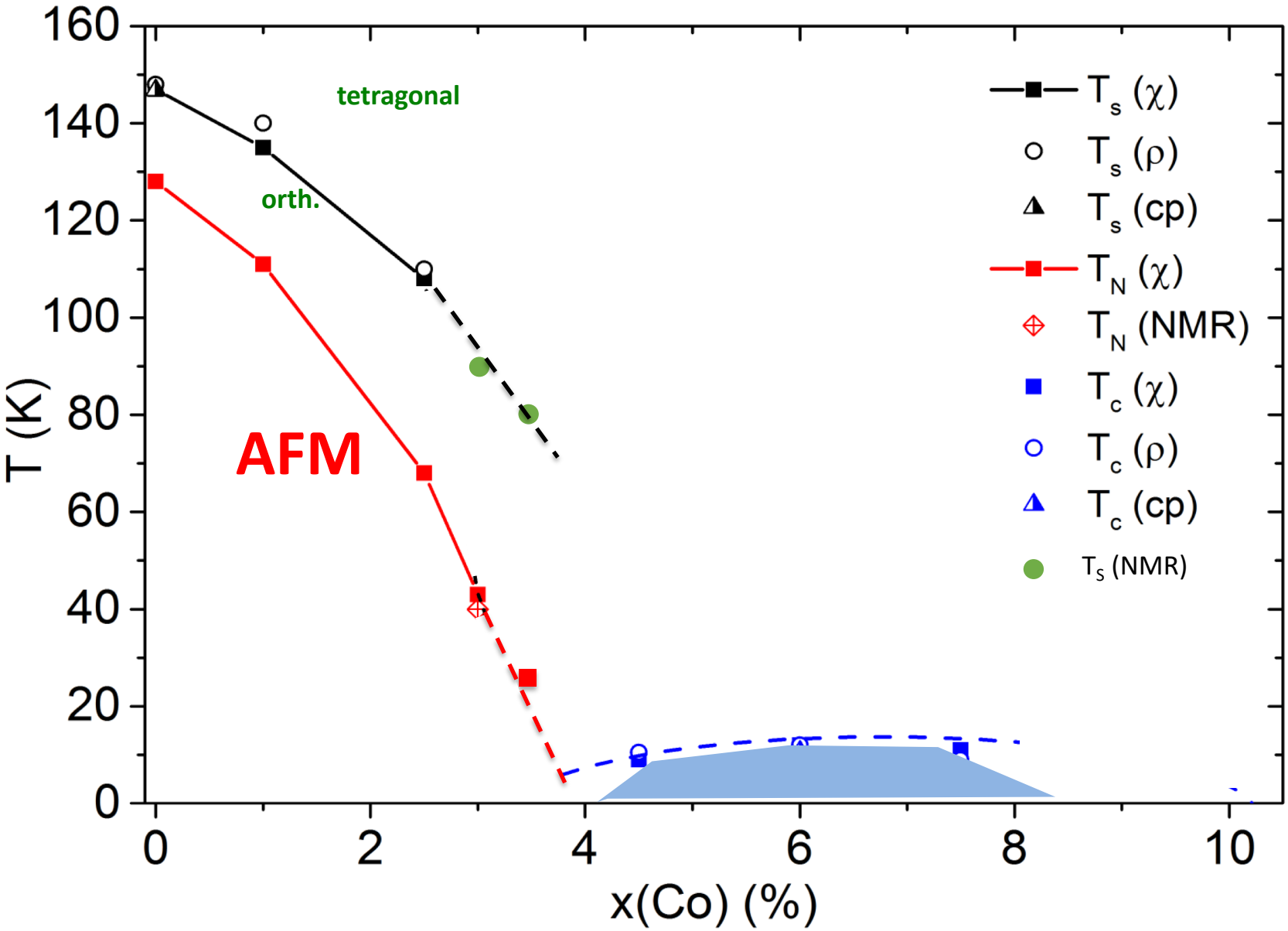




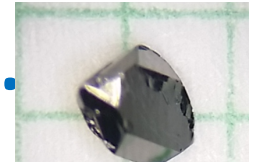


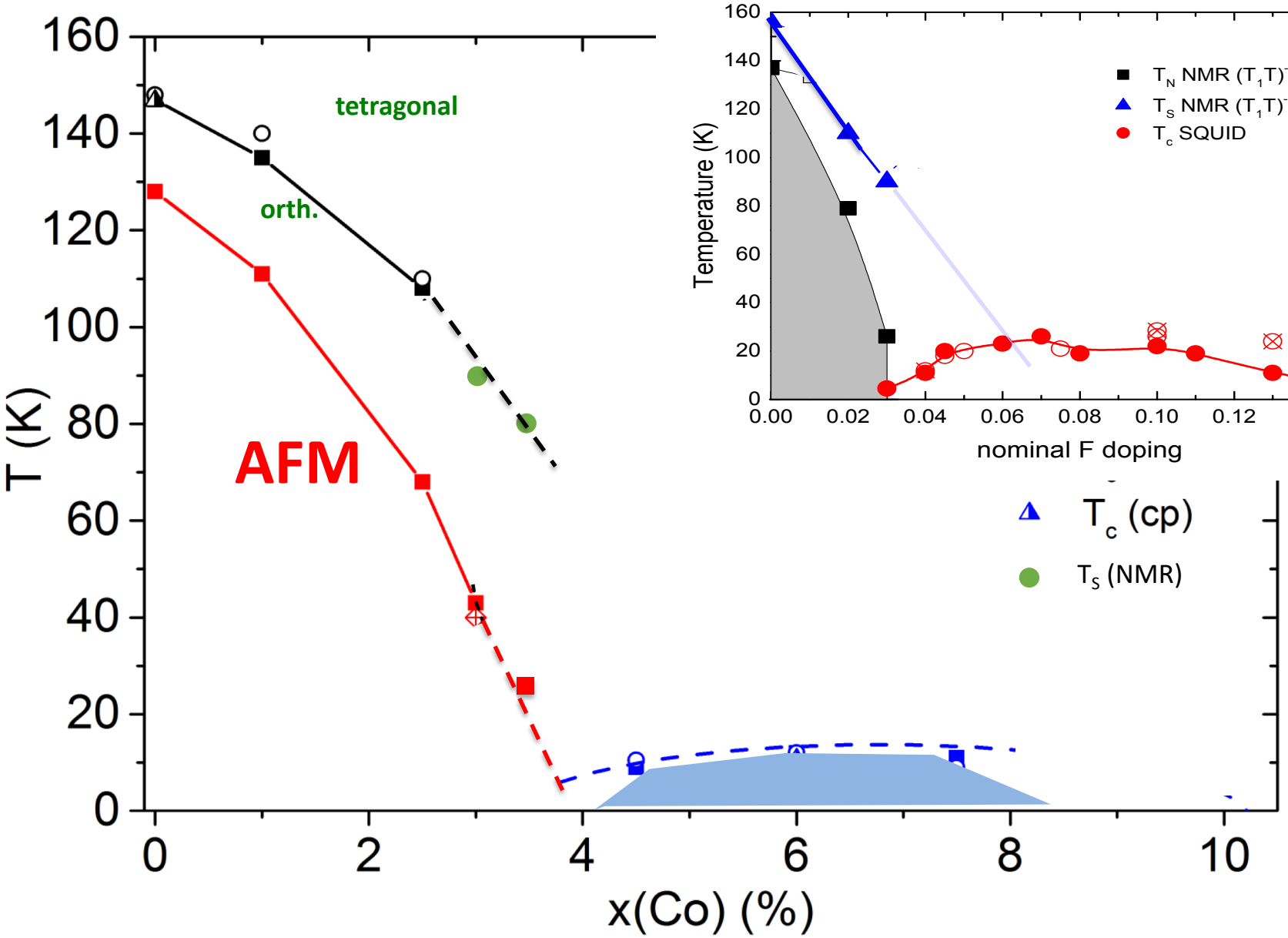
Phase diagram of Co-doped La 1111 revisited …



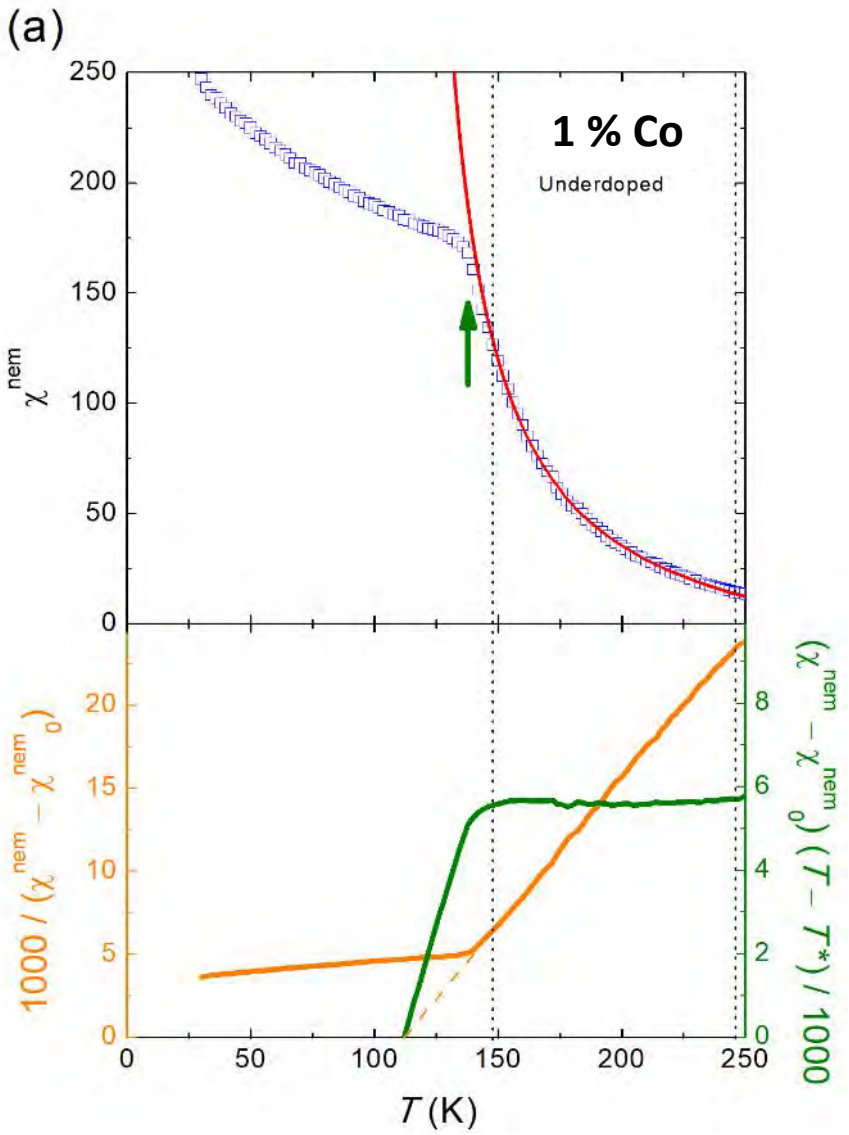


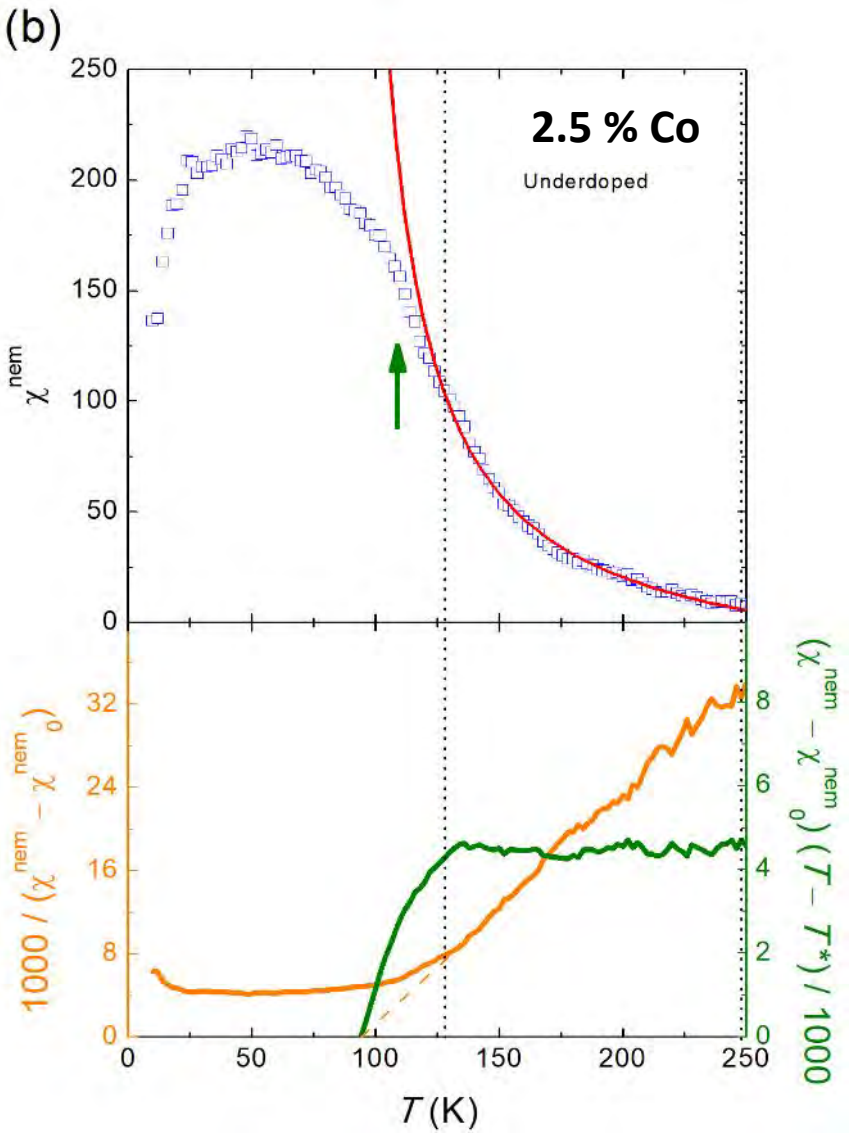
Phase diagram of Co-doped La 1111 revisited …



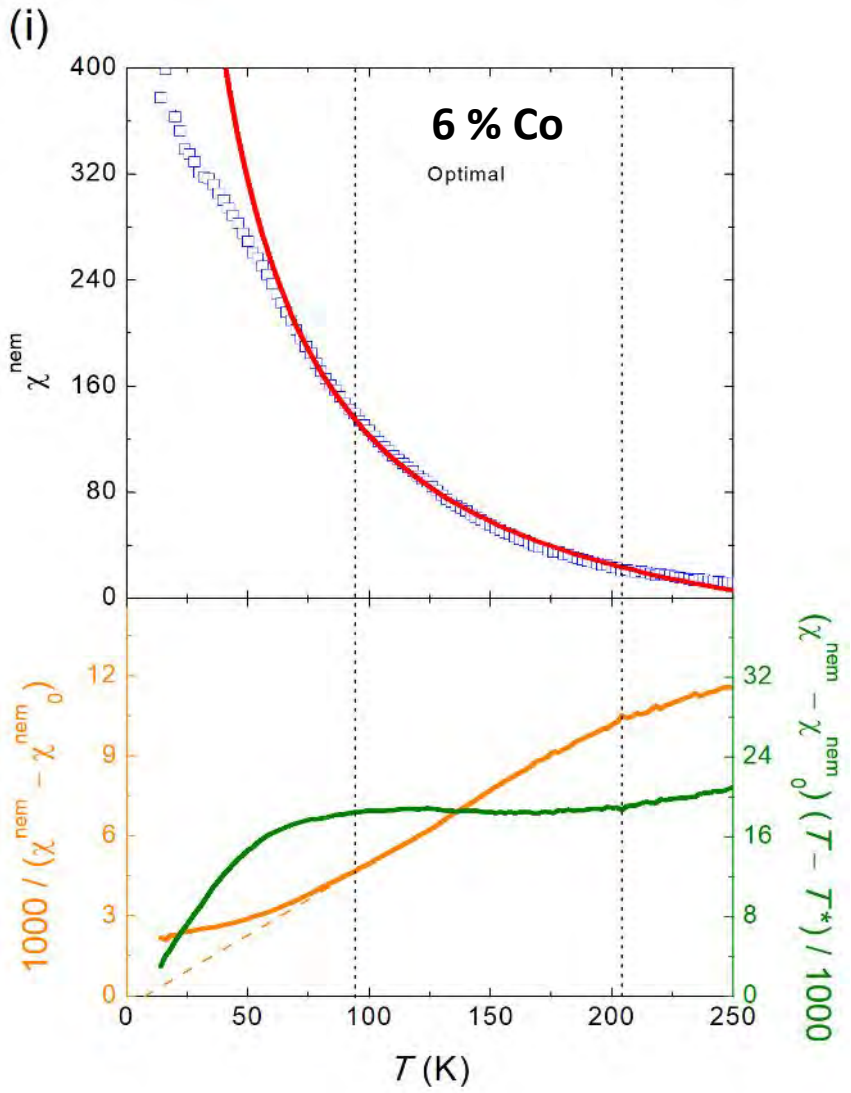


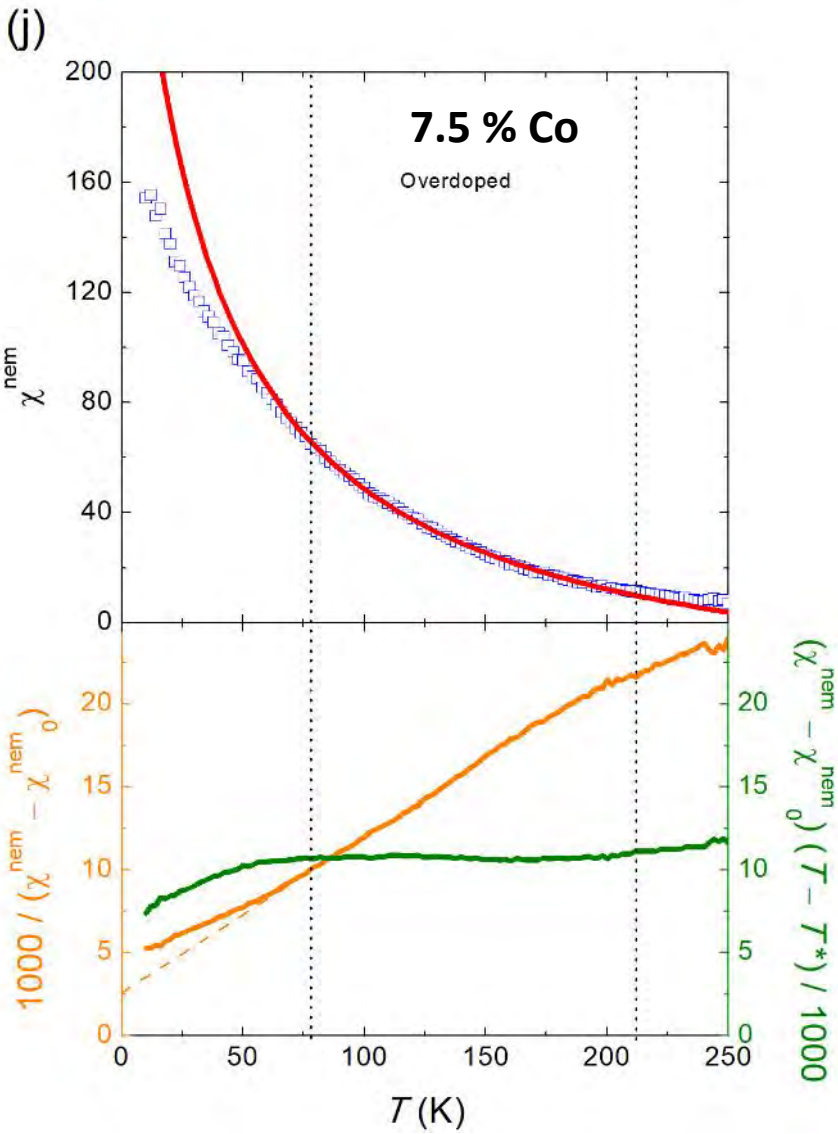
Nematic susceptibility of Co doped LaOFeAs



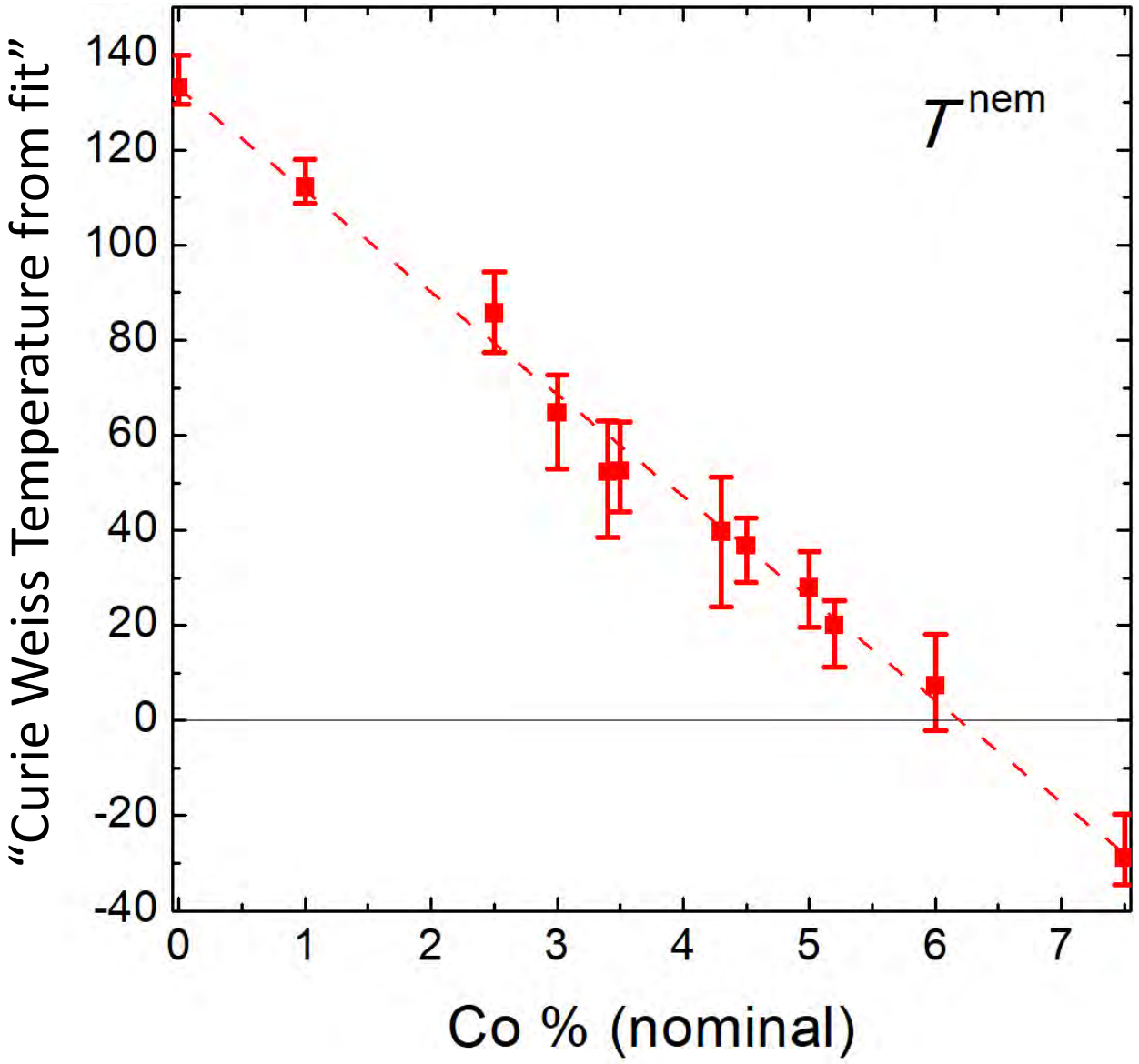


Nematic susceptibility of Co doped LaOFeAs

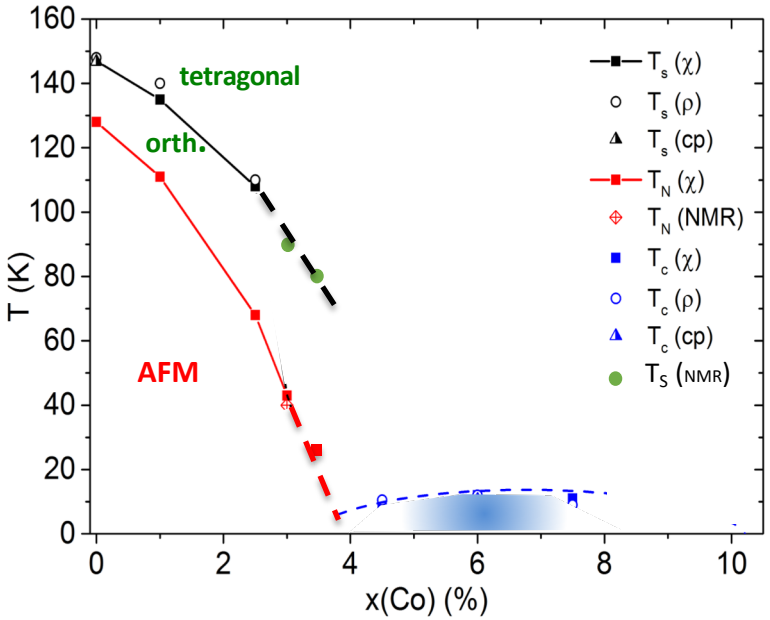




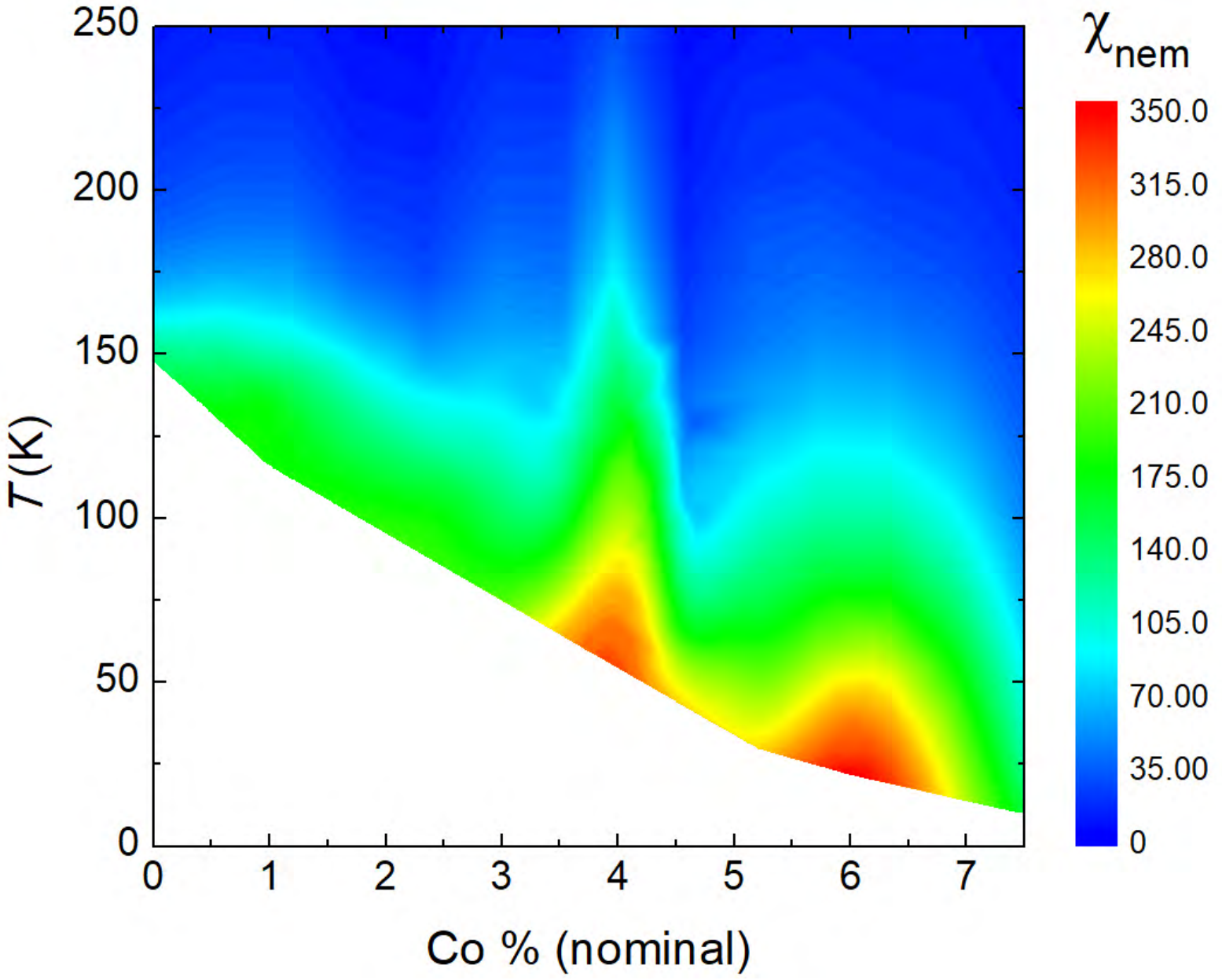
Nematic susceptibility of Co doped LaOFeAs



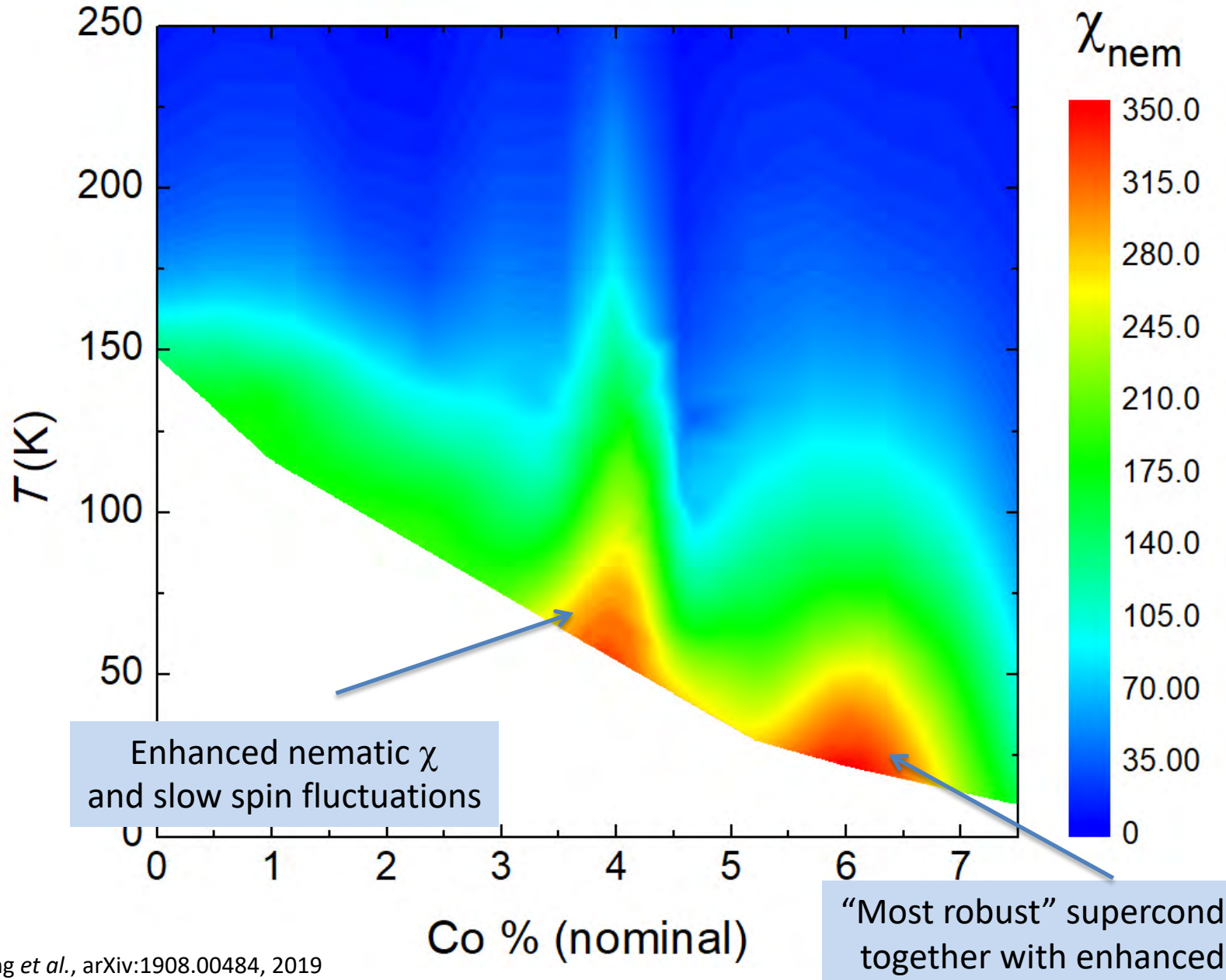
Nematic susceptibility of Co doped LaOFeAs



Nematic susceptibility of Co doped LaOFeAs

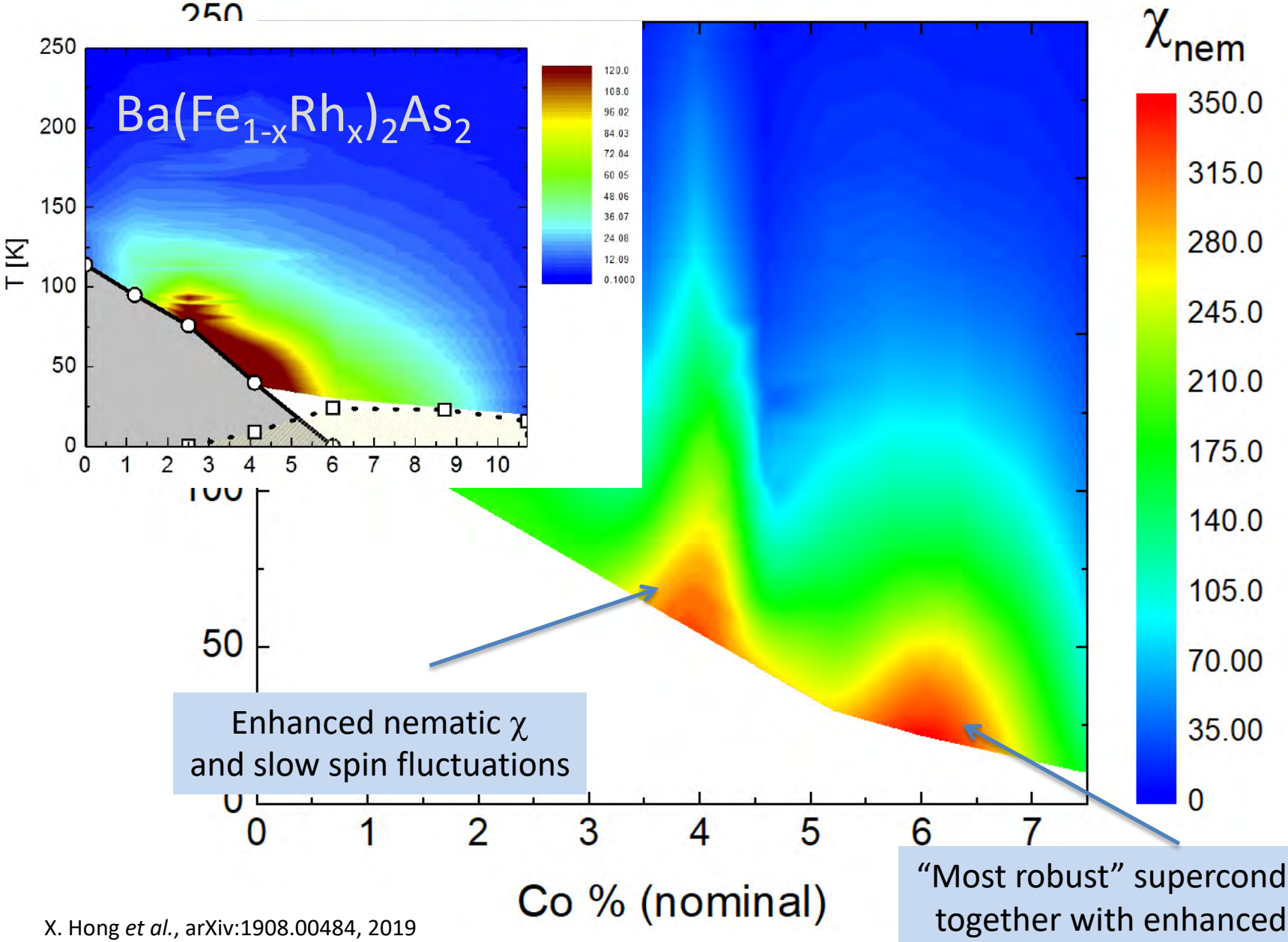


Nematic susceptibility of Co doped LaOFeAs



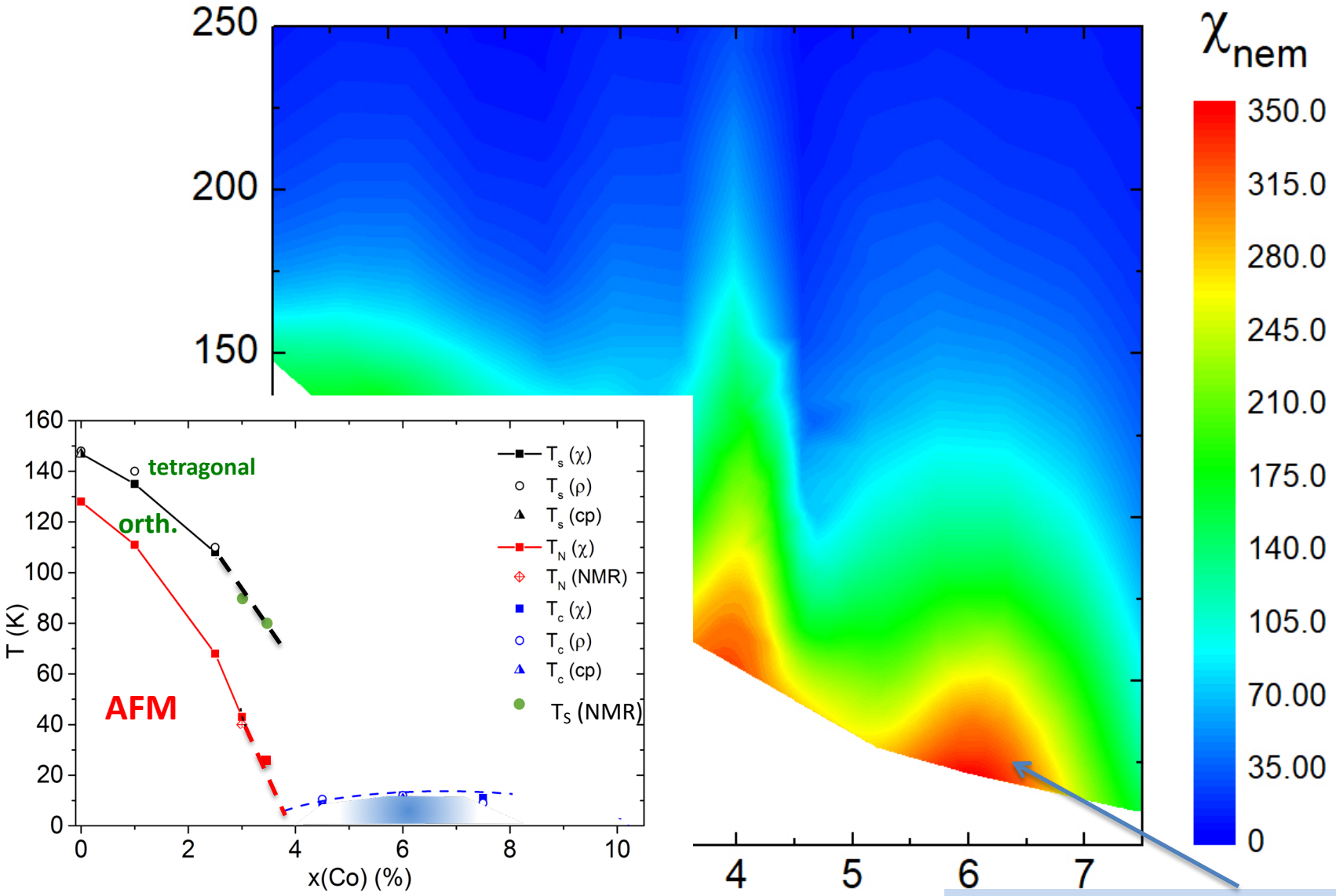
X. Hong *et al.*, arXiv:1908.00484, 2019

Nematic susceptibility of Co doped LaOFeAs



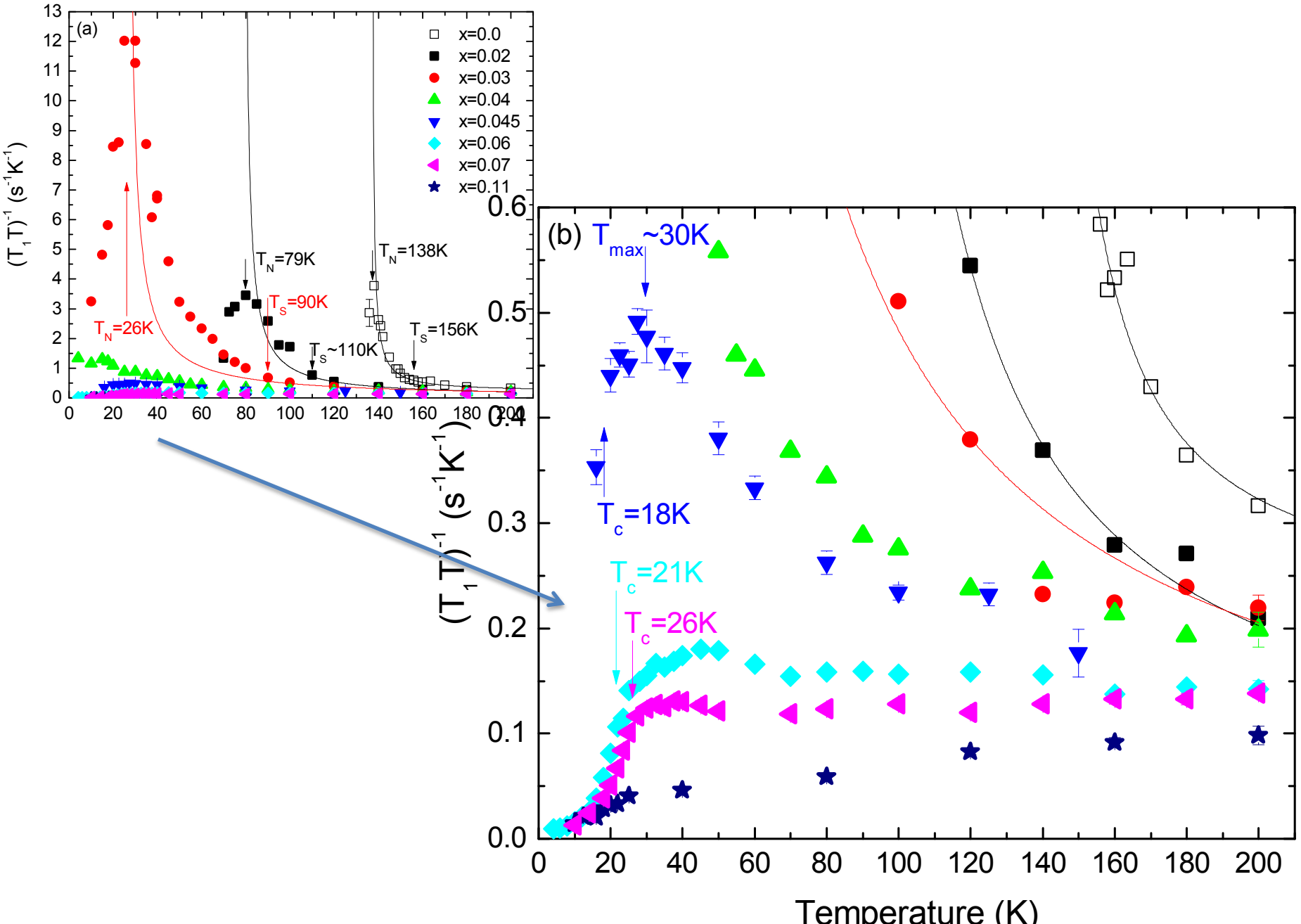
X. Hong *et al.*, arXiv:1908.00484, 2019

Nematic susceptibility of Co doped LaOFeAs

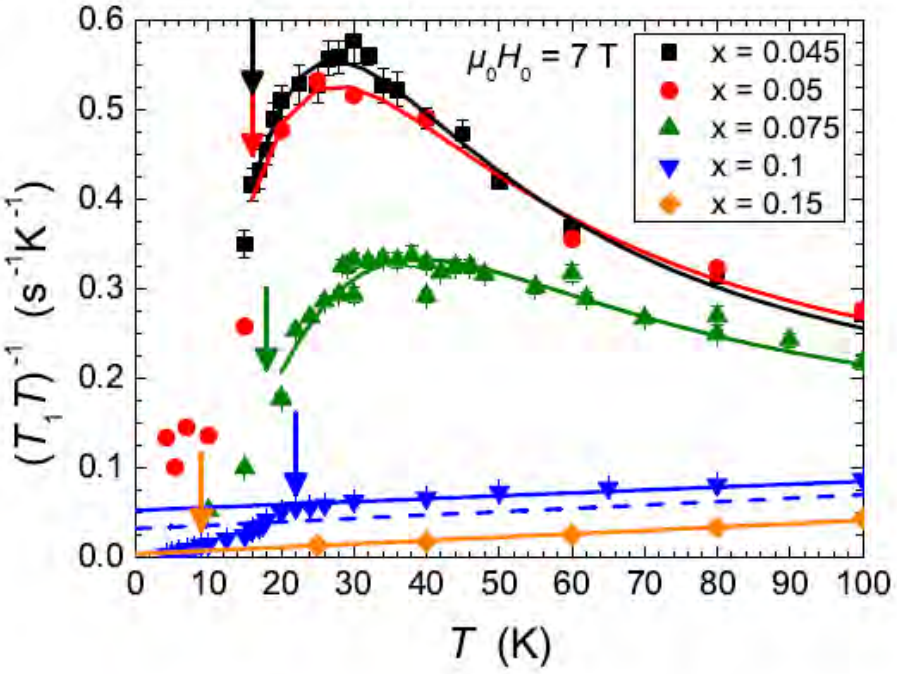


"Most robust" superconductivity together with enhanced χ_{nem}

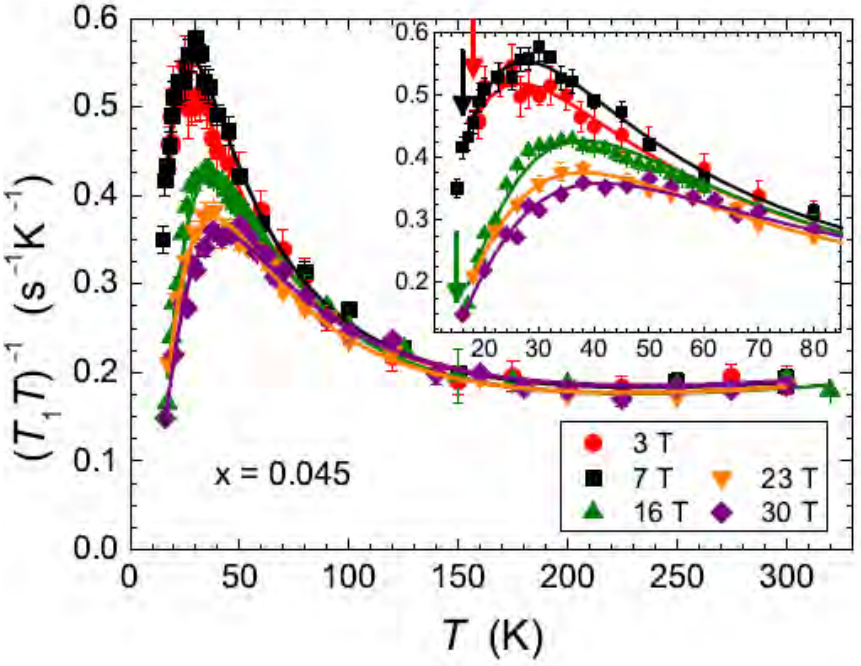
Anomalous slow spin fluctuations in underdoped $LaO_{1-x}F_xFeAs$



Anomalous slow spin fluctuations in underdoped LaOFeAs



NMR on underdoped 1111:
No long range magnetic order



Bloembergen-Purcell-Pound (BPP) model

$$T_{1,BPP}^{-1}(T) = \gamma^2 h_\perp^2 \frac{\tau_c(T)}{1+\tau_c^2(T)\omega_L^2}$$

Peak in 1/T1 if correlation time of spin fluctuation τ_c equals the inverse (H dep.) Larmor frequency, i.e. for

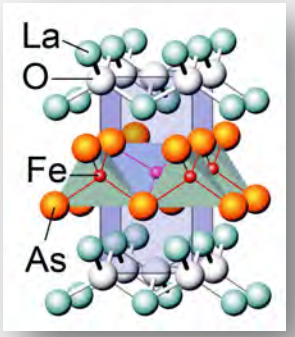
$$\tau_c \sim 1/\omega_L$$

F. Hammerath, P. Caretta, BB et al., PRB 2013

OUTLINE

Nematic fluctuatons in doped La1111 crystals

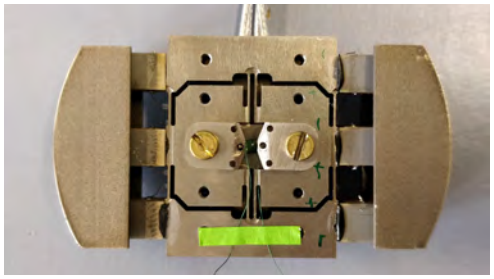
- Doped LaOFeAs: an „extraordinary“ Fe based SC
- Magnetic & nematic transitions in LaOFeAs
- Phase diagram of Co-doped LaOFeAs
- Nematic fluctuations in (doped) LaOFeAs



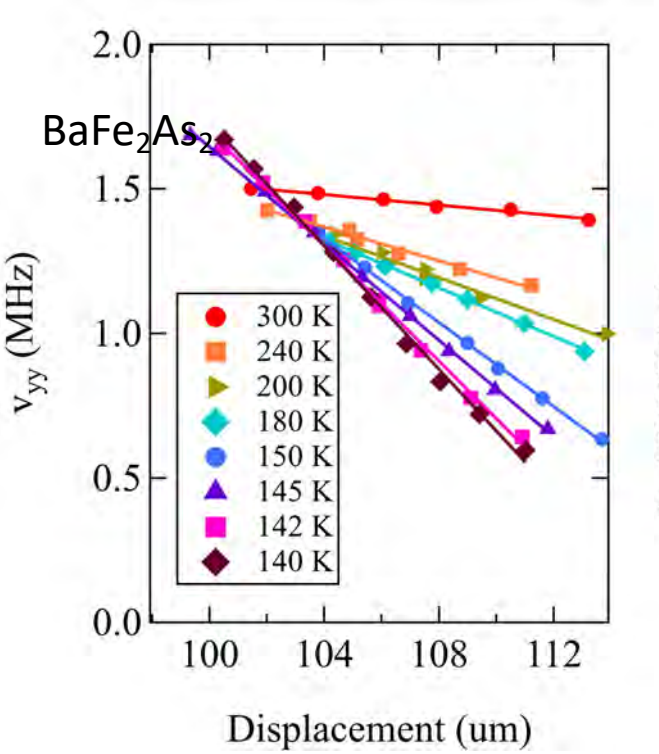
(Development of) methods for strain dependent …

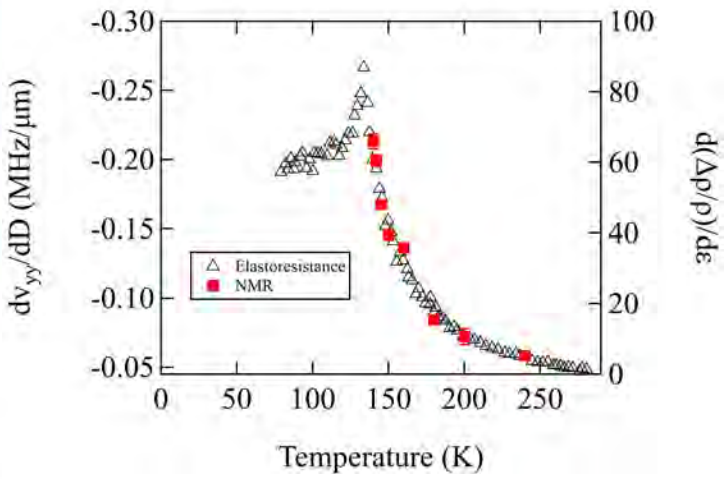
- Strain dependent NMR on $BaFe_2As_2$, strain up to (-0.86%;0.42%)
- Elasto-Seebeck effect on Fe based superconductors
- Elasto-Nernst effect on Fe based superconductors
- ARPES@1^3 beamline under strain (ongoing)

Electric Field Gradient (EFG) vs strain



In-situ strain control
Measure same sample
for H || a,b & H || c
Min = -0.86 % strain
Max = 0.42 % strain





Chu et al., Science, 337(6095), 710 (2012)

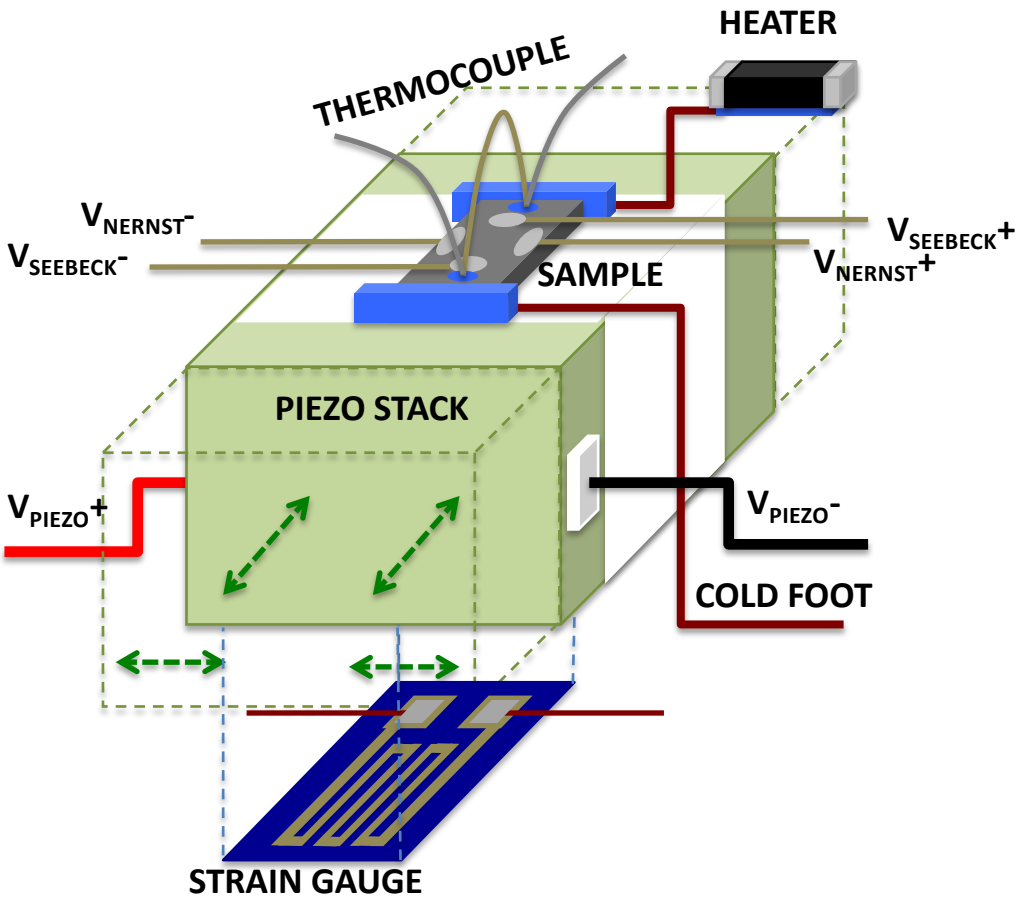
- Extract EFG from NMR spectral measurements vs strain
- EFG, $d\eta/d\varepsilon \sim \chi_{nem}$; As *p*- and Fe *d*-orbitals hybridize

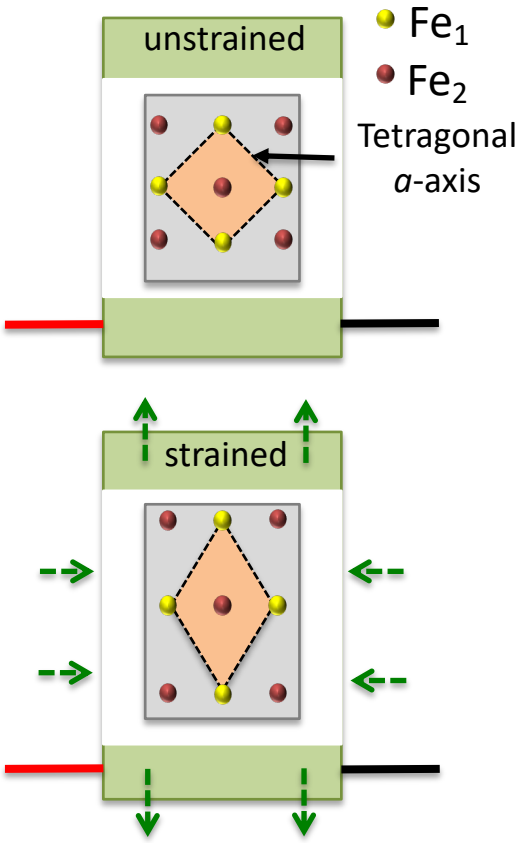
→ **Quadrupolar NMR = Local probe of nematic susceptibility**

See also N. Curro et al.

Strain-derivative of thermoelectric coefficients

The experimental setup





max strain 0.08% at T = 300K

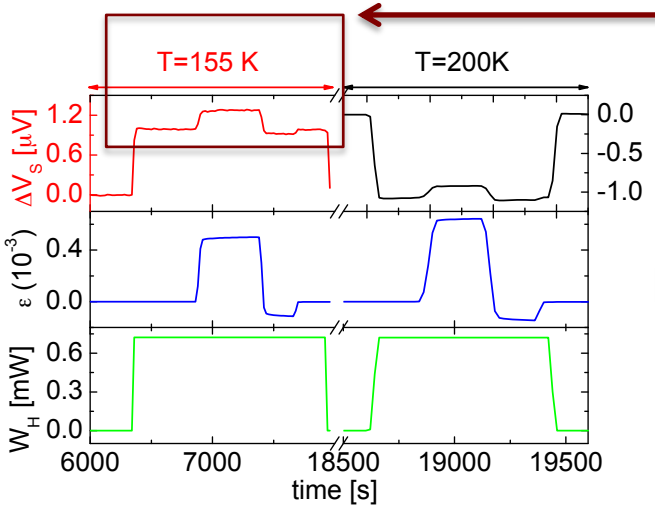
The strain-derivative of S and N

Large effect with tiny strain

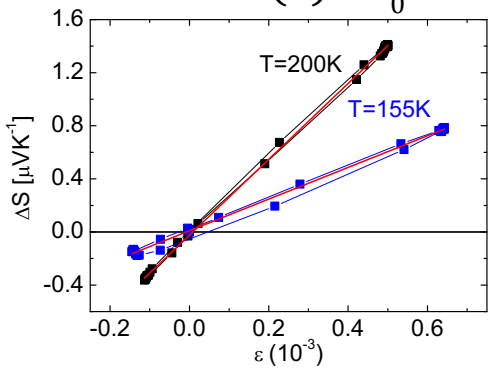
S signal

Piezo

Heater



$$\Delta S = S(\varepsilon) - S_0$$

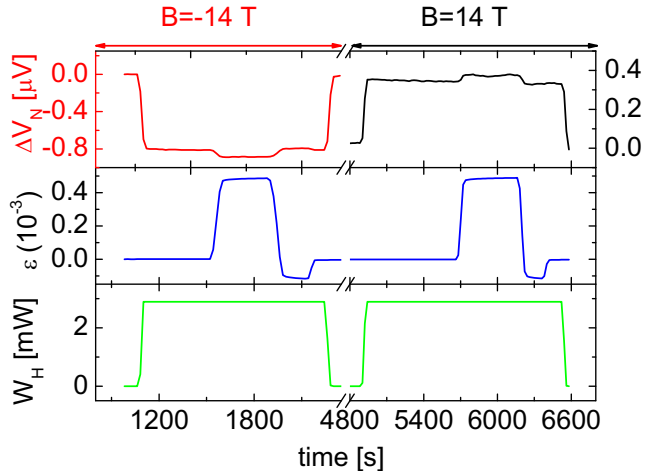


$$\frac{\delta(\Delta S)}{\delta\varepsilon}$$

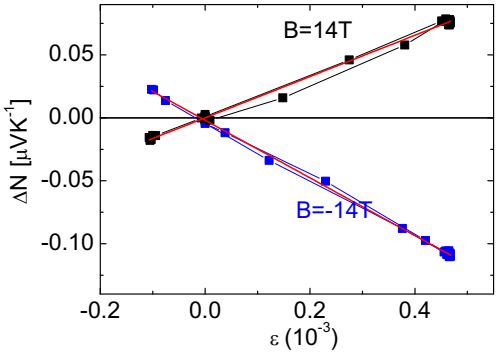
N signal

Piezo

Heater

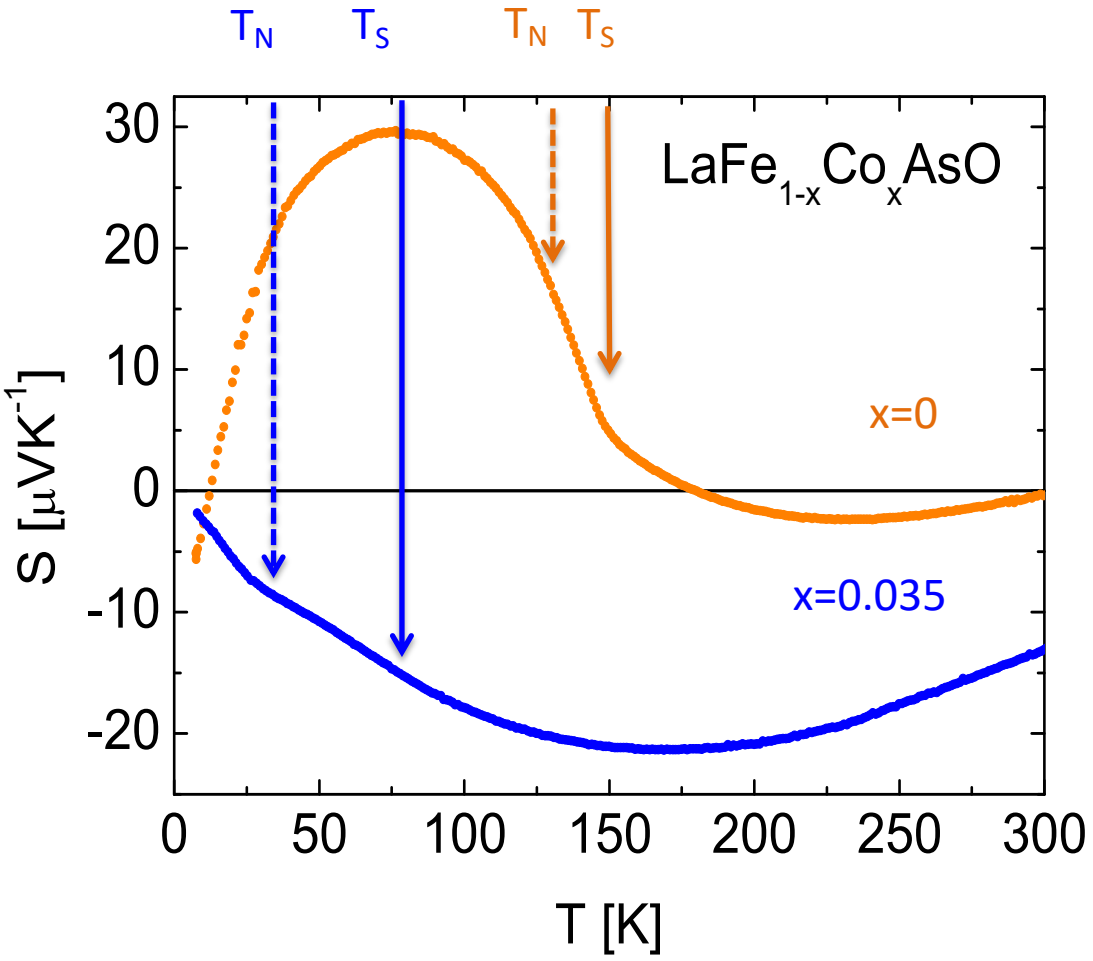


$$\Delta N = N(\varepsilon) - N_0$$



$$\frac{\delta(\Delta N)}{\delta\varepsilon}$$

Seebeck effect S(T) in $LaFe_{1-x}Co_xAsO$



$$S = \frac{E_x}{\nabla_x T}$$

Mott formula

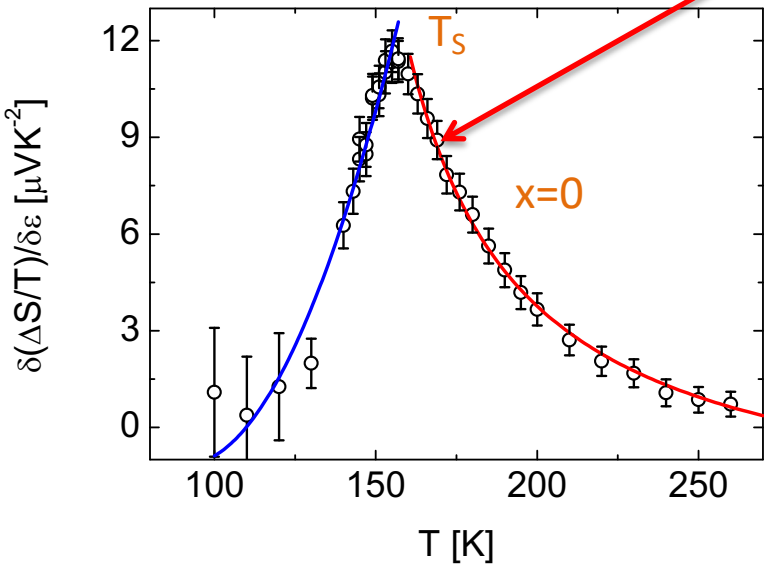
$$S = -\frac{\pi^2}{3}\frac{k_B^2 T}{e}\left(\frac{\partial \ln \sigma(\epsilon)}{\partial \epsilon}\right)_{\epsilon_F}$$

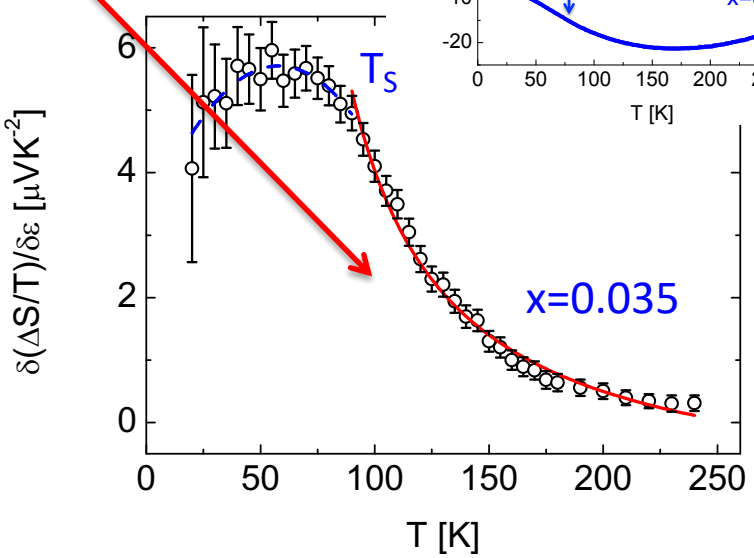
Energy derivatives of density and mobility

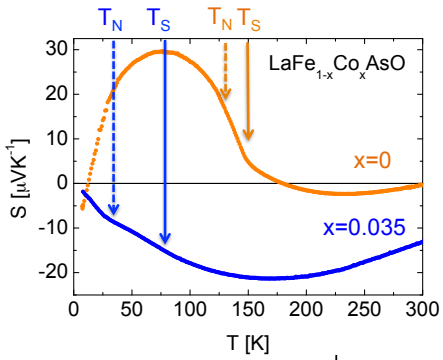
- **S changes sign: multi-band, electron & holes**
- **e-doping: increase of S with negative sign**

Strain dependent Seebeck

$$\frac{\delta(\Delta S/T)}{\delta\varepsilon} = k + \frac{C}{T - T^*}$$





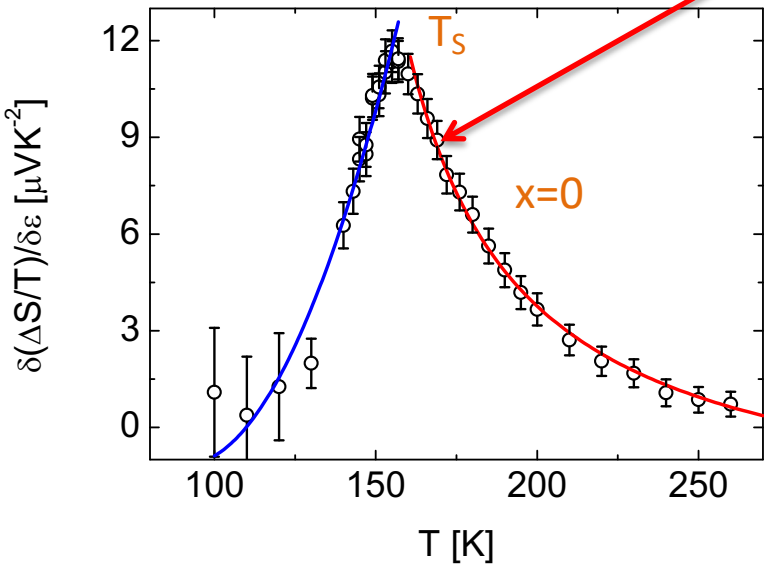


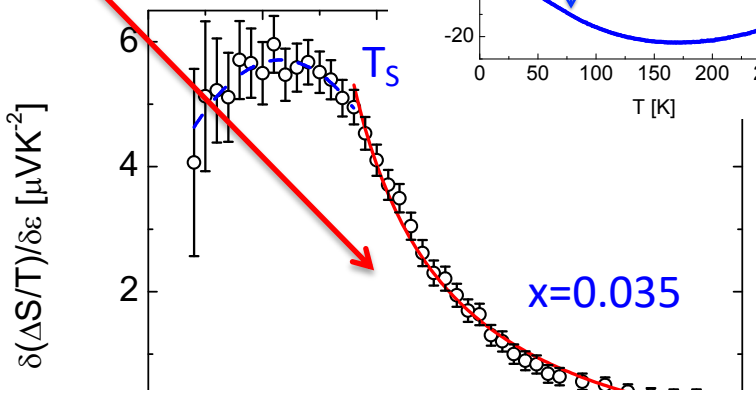
$BaFe_2As_2$

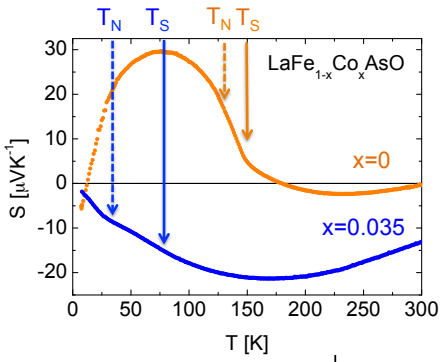
- Anomaly of $\delta S/\delta\varepsilon$ at T_S and not at T_N
- $\delta S/\delta\varepsilon$ Independent on the sign of S → Band selectivity of nematic fluctuations?
- Curie-Weiss like behaviour in the tetragonal phase, $T^* \approx T^*(\rho)$

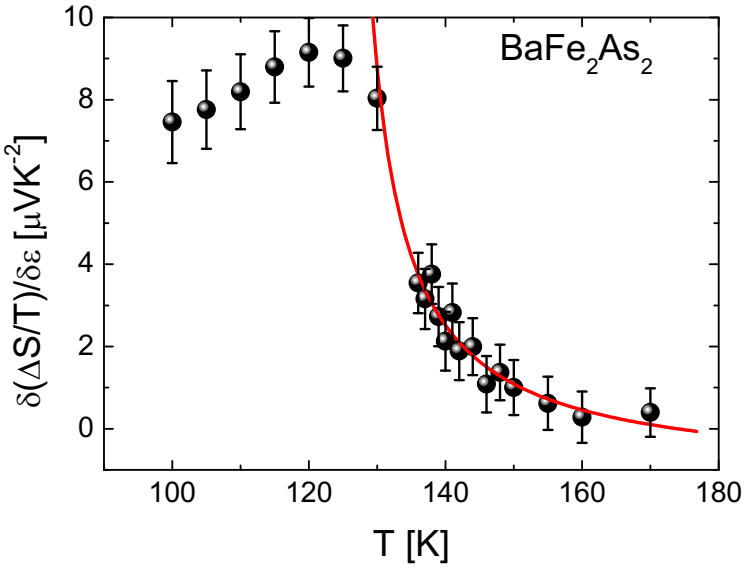
Strain dependent Seebeck

$$\frac{\delta(\Delta S/T)}{\delta\varepsilon} = k + \frac{C}{T - T^*}$$





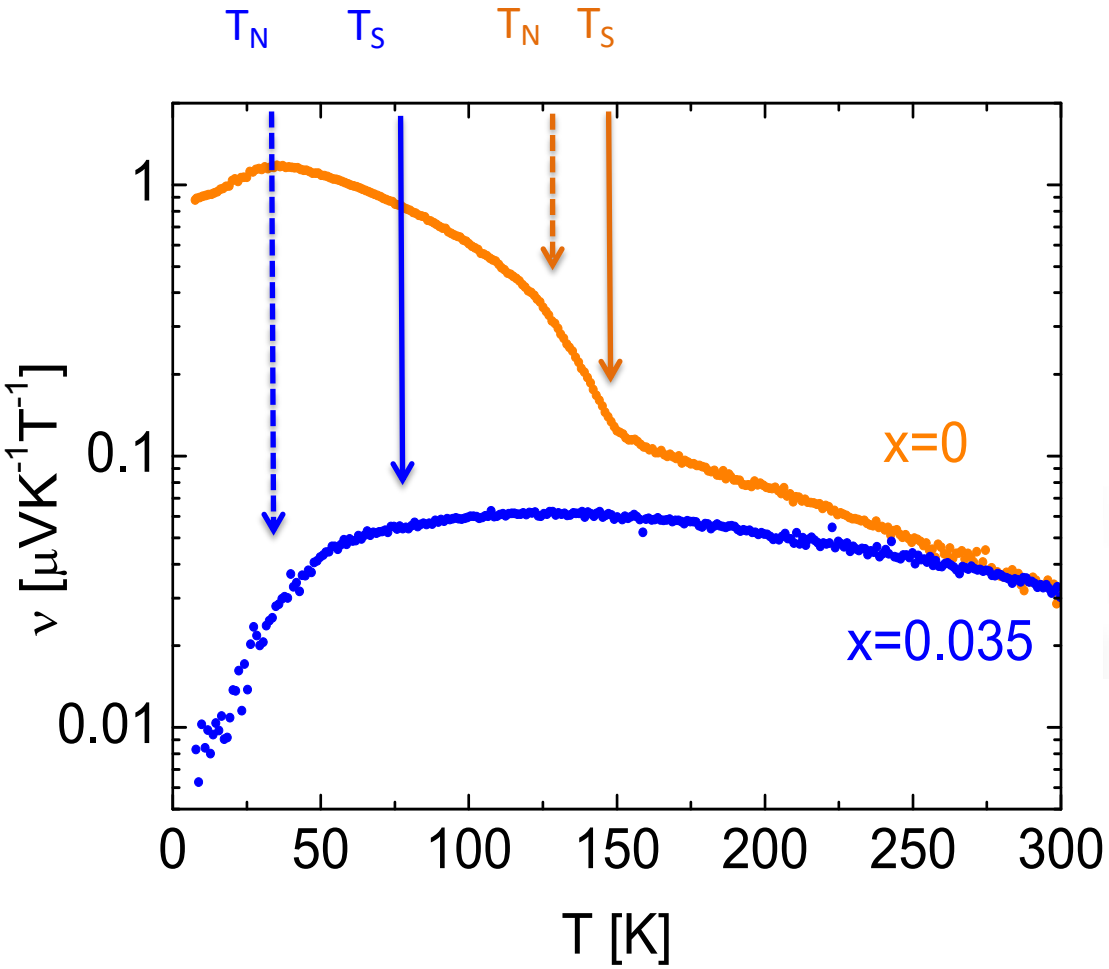




- Anomaly of $\delta S/\delta\varepsilon$ at T_S and not at T_N
- $\delta S/\delta\varepsilon$ Independent on the sign of S
- Curie-Weiss like relaxation in the tetragonal phase, $T^* \approx T^*(\rho)$

ns?

Nernst effect in $LaFe_{1-x}Co_xAsO$



$$N = -\frac{E_y}{\nabla_x T}$$

Sonheimer formula

$$N = \frac{\pi^2}{3}\frac{k_B^2 T}{e}\frac{\partial \Theta_H}{\partial \epsilon}\Big|_{\varepsilon_F}$$

N: energy derivative of the Hall angle $\Theta_H = \frac{\sigma_{xy}}{\sigma_{xx}}$

Simple metals (large ε_F): $N \approx 0$

If $N \neq 0$ "often": $N \sim \mu_H/\varepsilon_F$

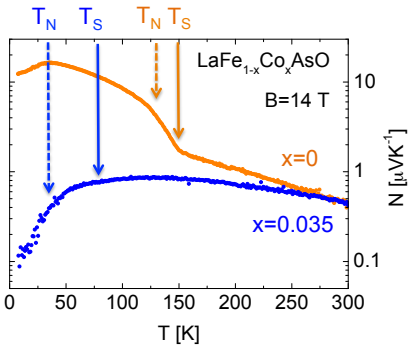
- **x=0: Strong increase below T_s**
- **X= 3.5 % : Decrease at low T (below T_N?)**
- **T > T_s: similar behaviour of N for x = 0 and 3.5%**

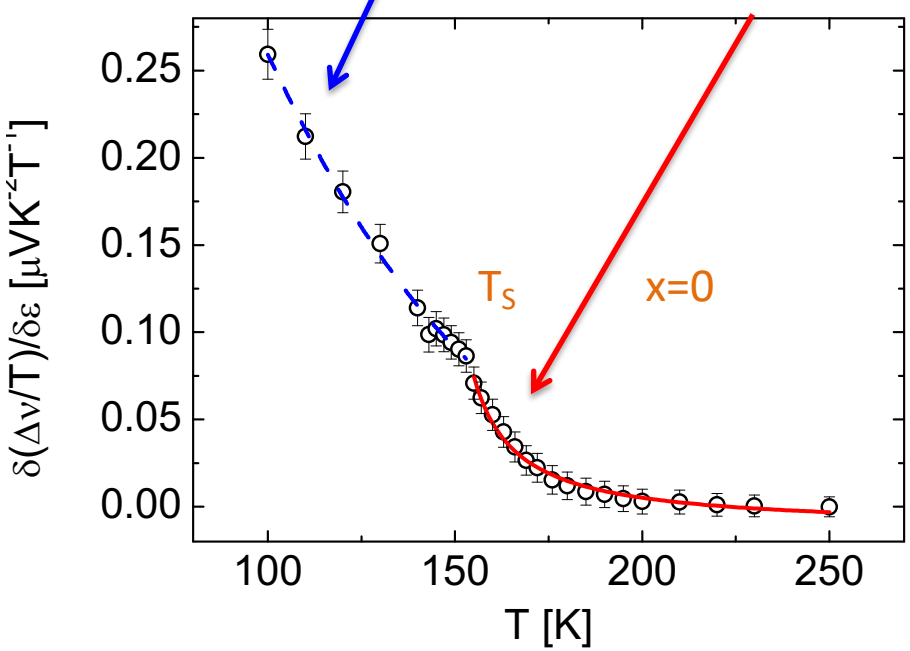
Strain dependent Nernst effect

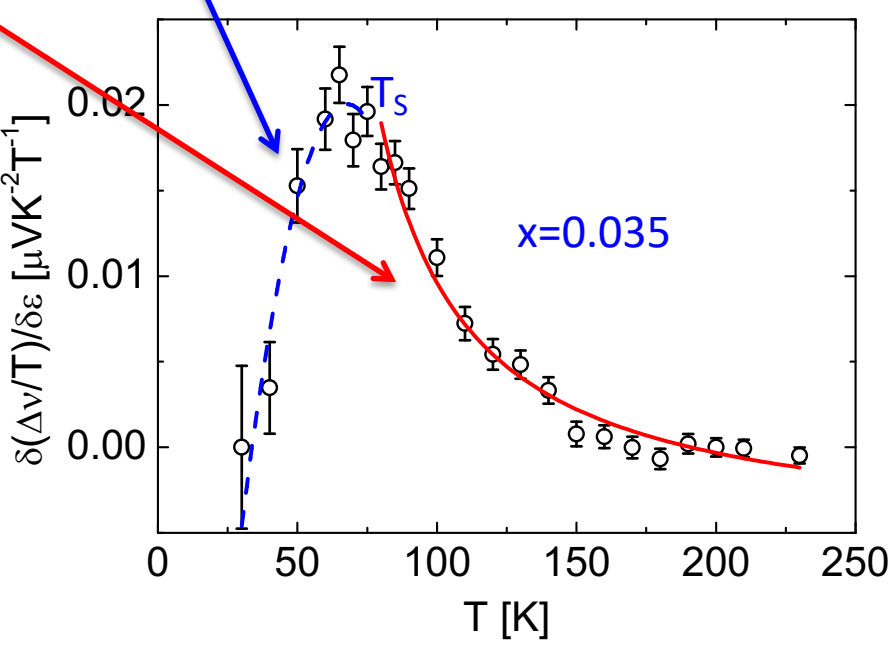
Strong increase below T_S

Decrease below T_S

$$\frac{\delta(\Delta\nu/T)}{\delta\varepsilon} = k_\nu + \frac{C}{T - T^*}$$



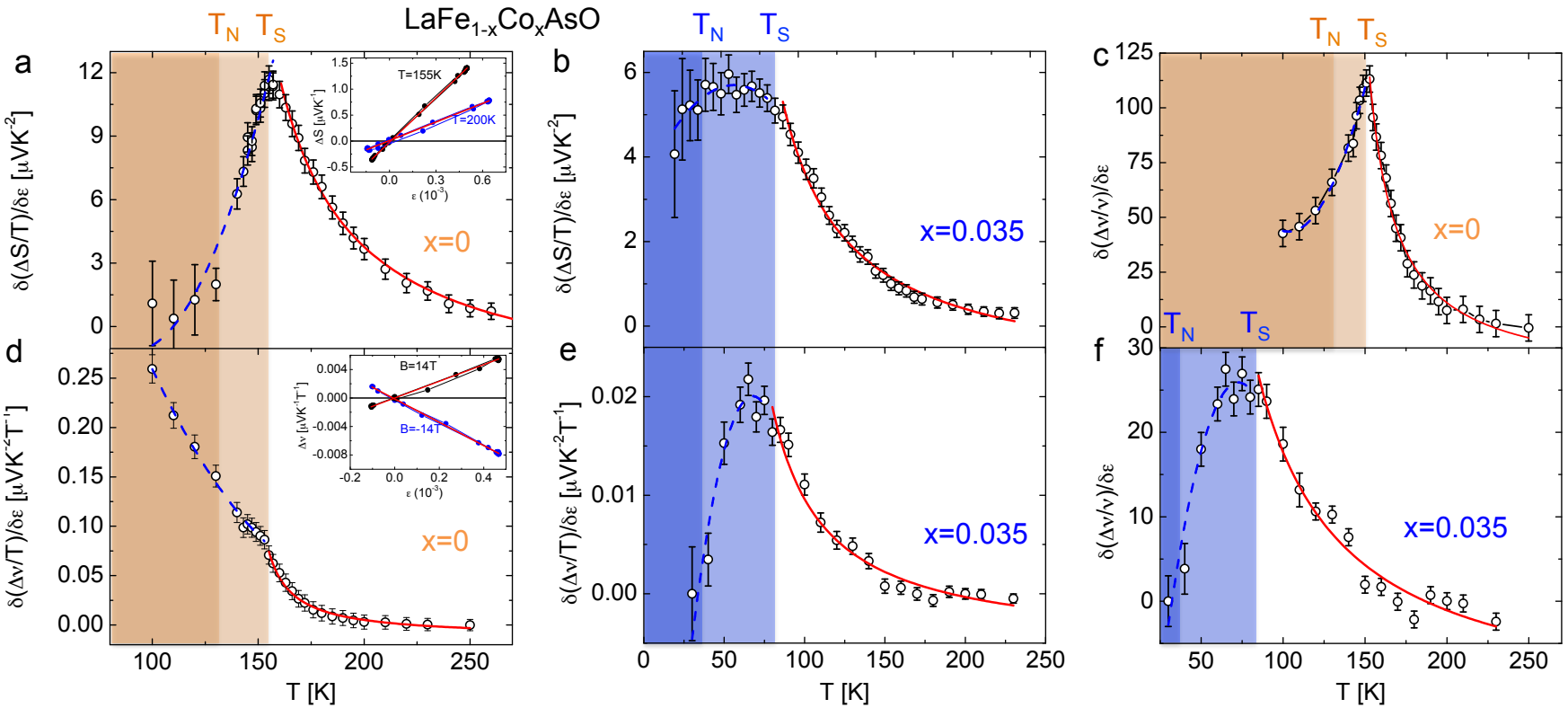




Curie-Weis behaviour for $T > T_s$

absolute value much larger for x = 0 (in contrast to $\delta\rho/\delta\varepsilon$)

Nernst and Seebeck effect under strain in LaOFeAs

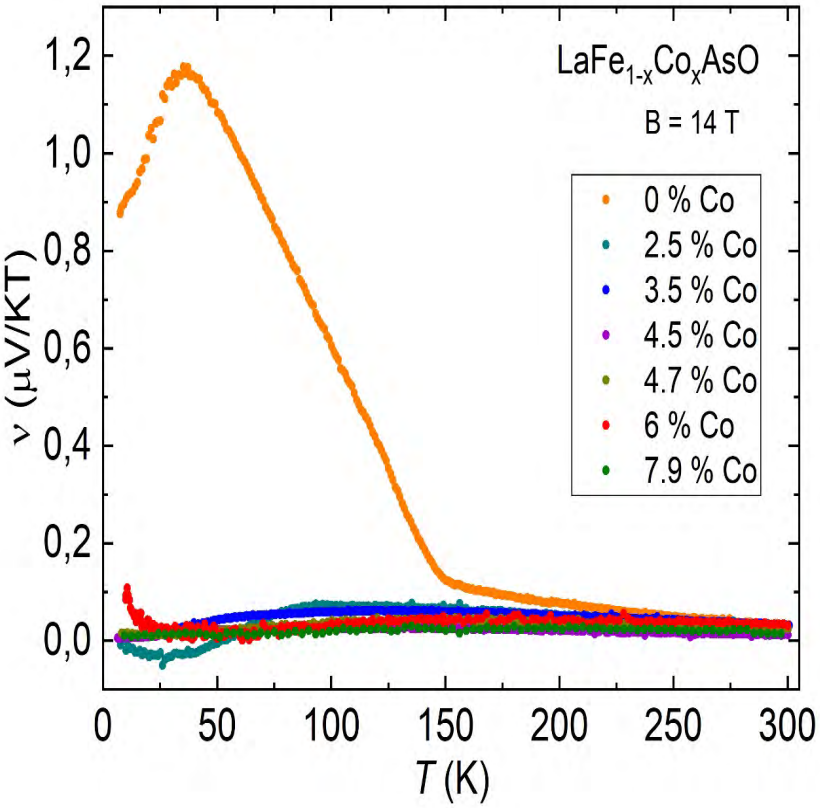


- **Nematic fluctuations/strain derivative of transport related to T_S and not to T_N**
- **Strain dependence of transport band selective (different signs of S)**
- **Universal Curie-Weiss behaviour of strain derivative for all transport properties**
- **Elasto-thermoelctric transport and elasto-resistivity not equivalently representative for nematic susceptibility!!**

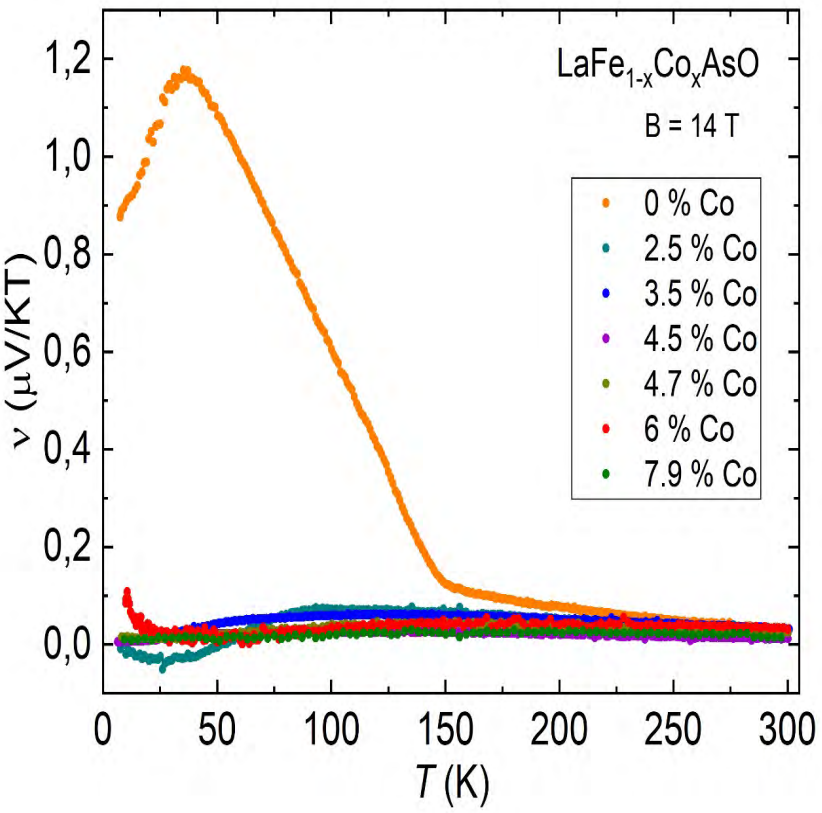
  (scattering, Fermi surface, different pockets ...)

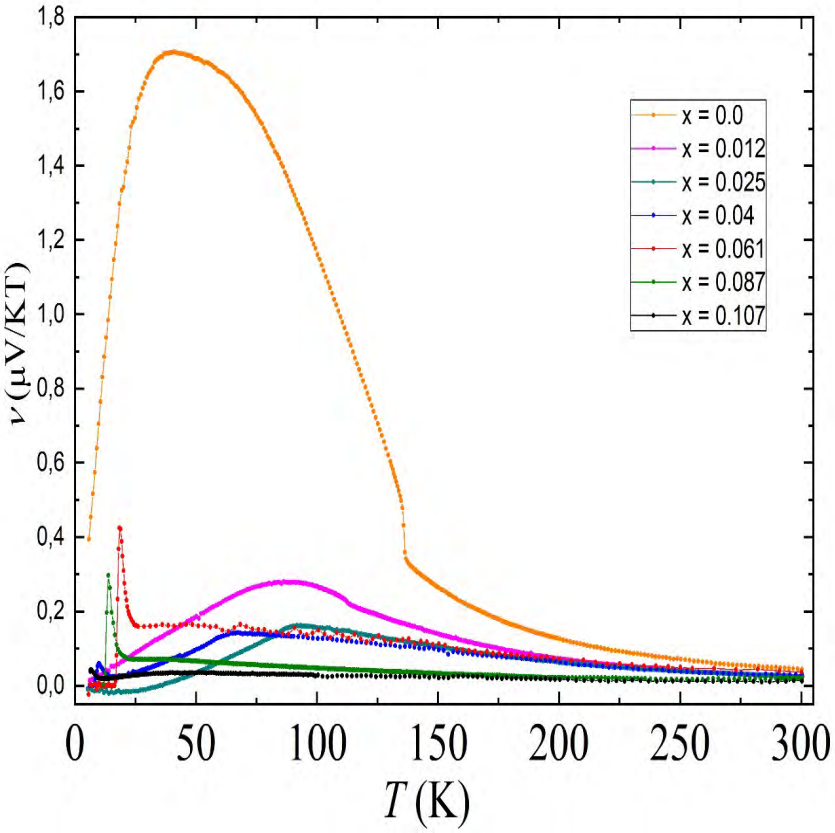
F. Caglieris et al., arxiv

Nernst effect of $LaFe_{1-x}Co_xAsO$



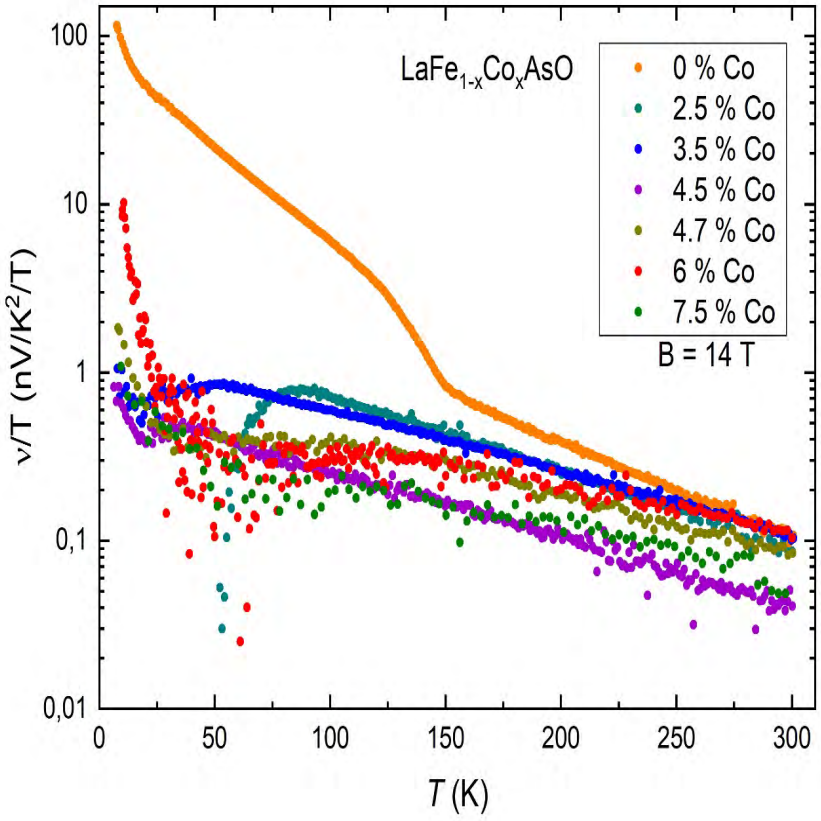
Nernst effect of $LaFe_{1-x}Co_xAsO$ and $Ba(Fe_{1-x}Rh_x)_2As_2$

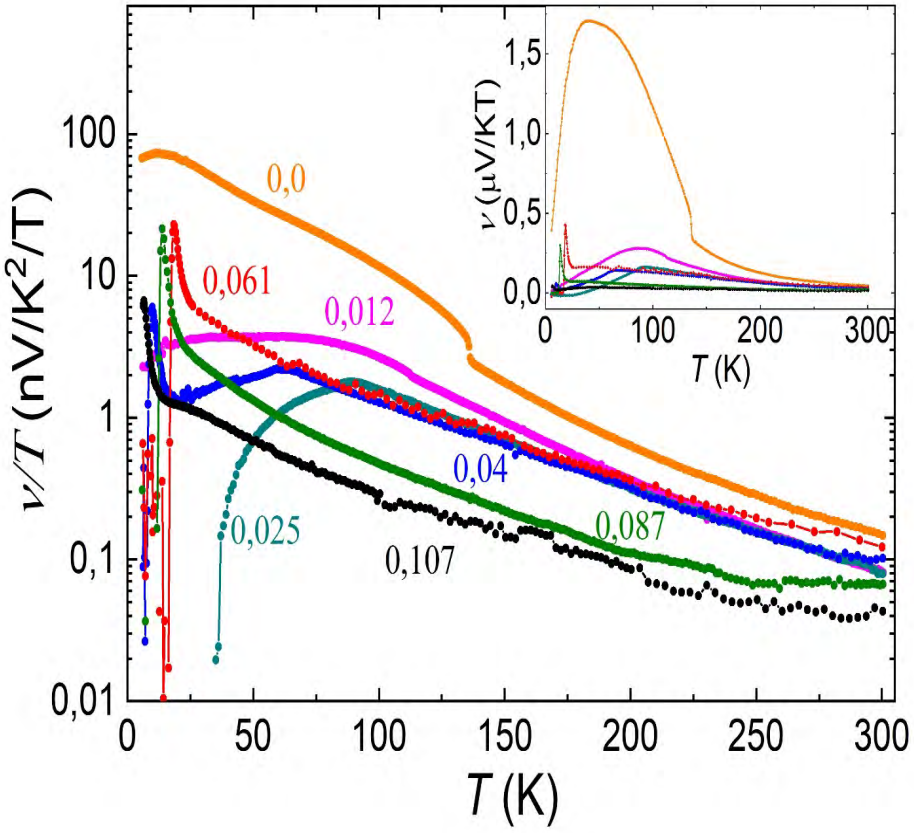




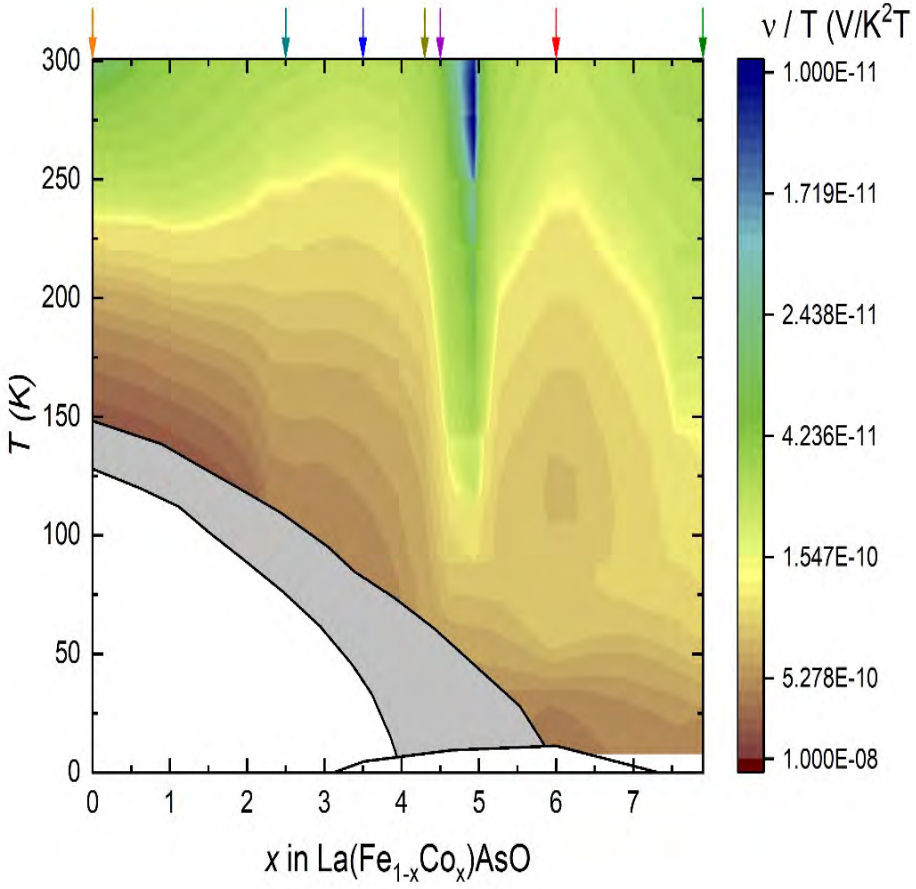
- Huge Nernst effect in nematic/magnetic phase of parent compounds
- Strinkingly similar behaviour in LaOFeAs and $BaFe_2As_2$
- **Peculiar "electronic state" independent on defects, dimensionality, …**
  but drastic suppression as a function of doping

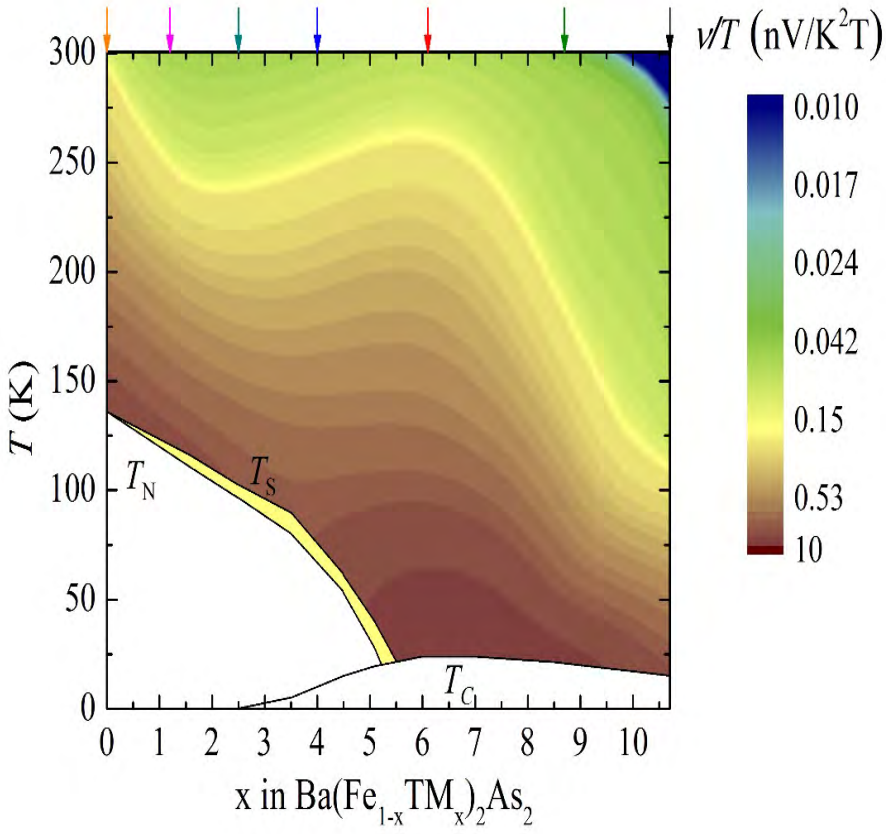
Nernst effect of $LaFe_{1-x}Co_xAsO$ and $Ba(Fe_{1-x}Rh_x)_2As_2$



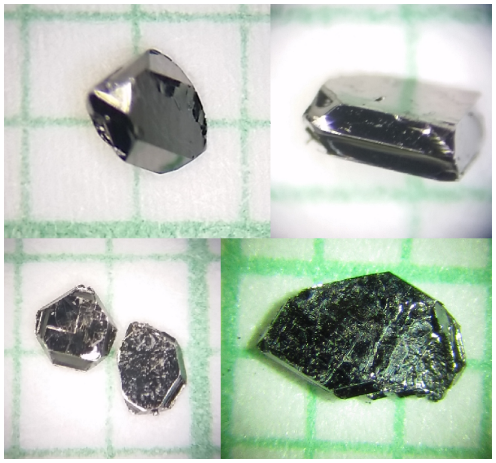


Nernst effect of $LaFe_{1-x}Co_xAsO$ and $Ba(Fe_{1-x}Rh_x)_2As_2$



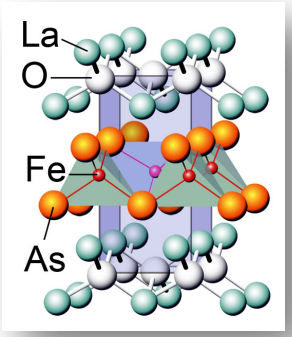


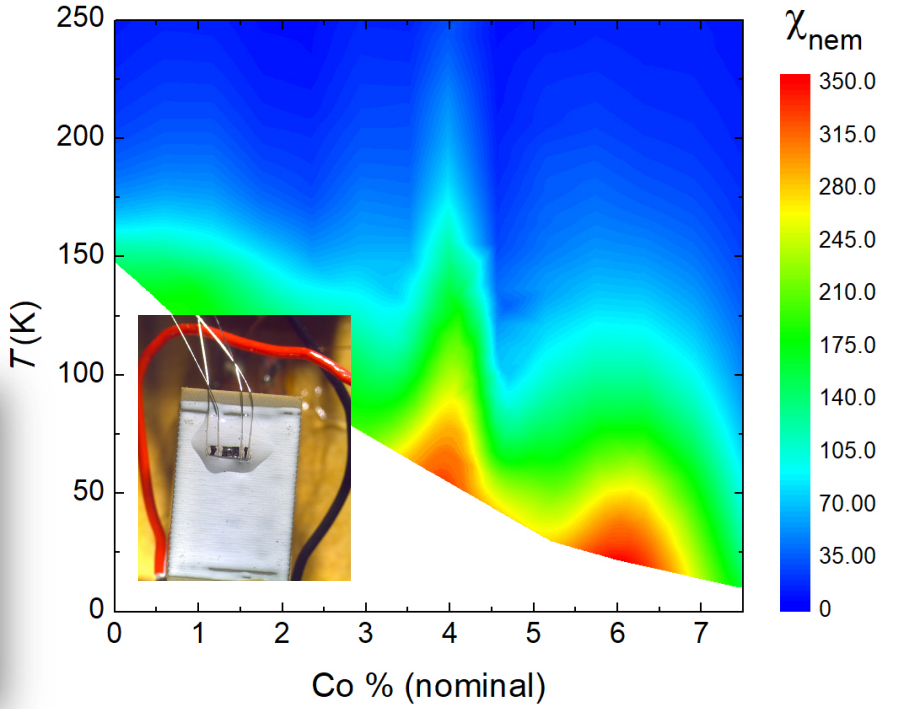
- **Does the Nernst effect for $T>T_s$ measure nematic flucfuations?**

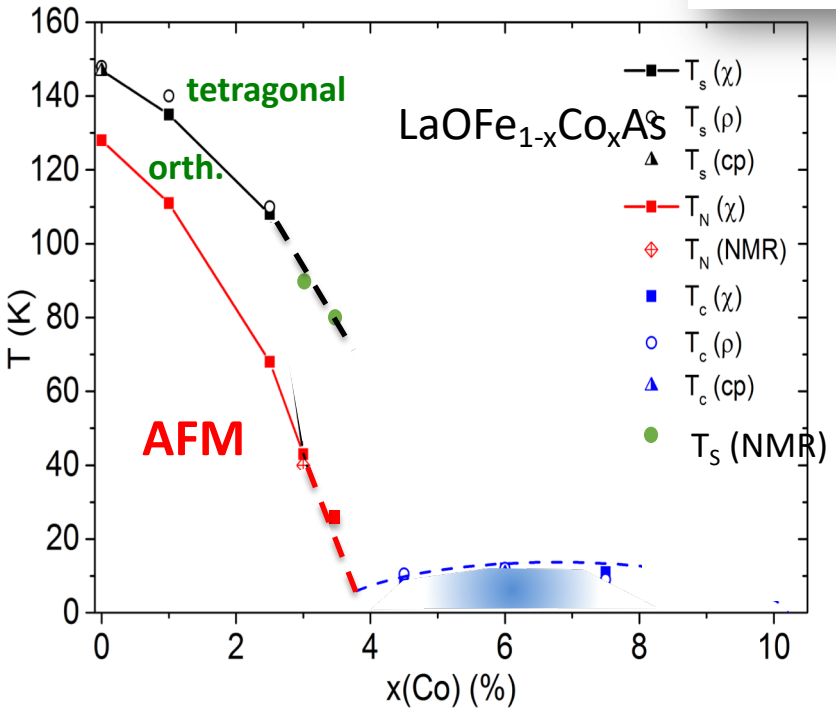


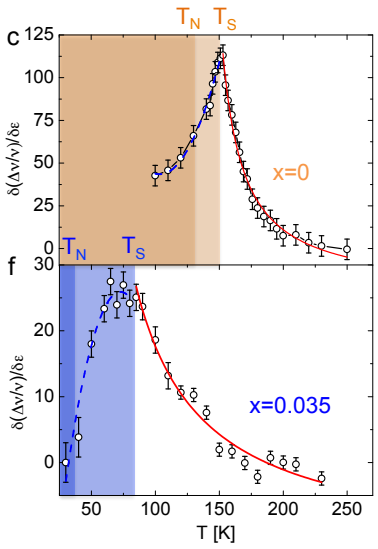
work in progress

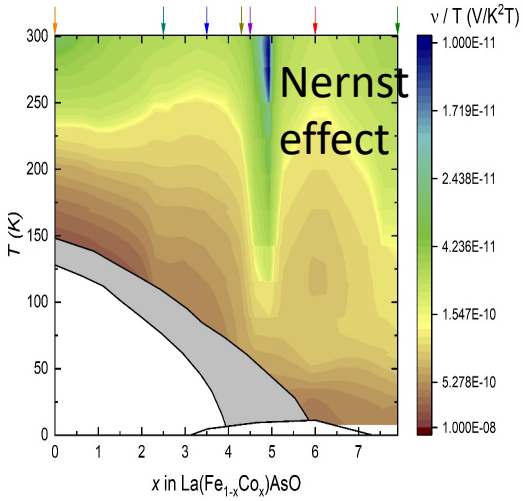
- fluorine doping
- Sm 1111
- Ce 1111
- …

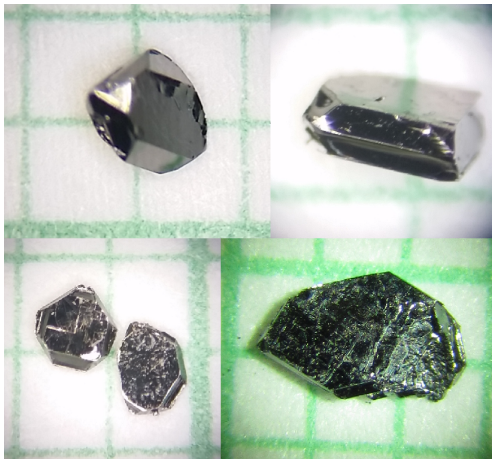






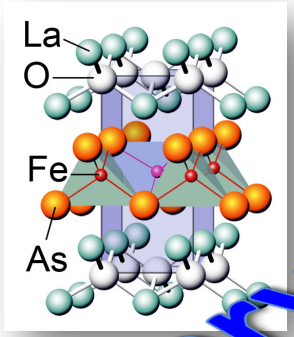


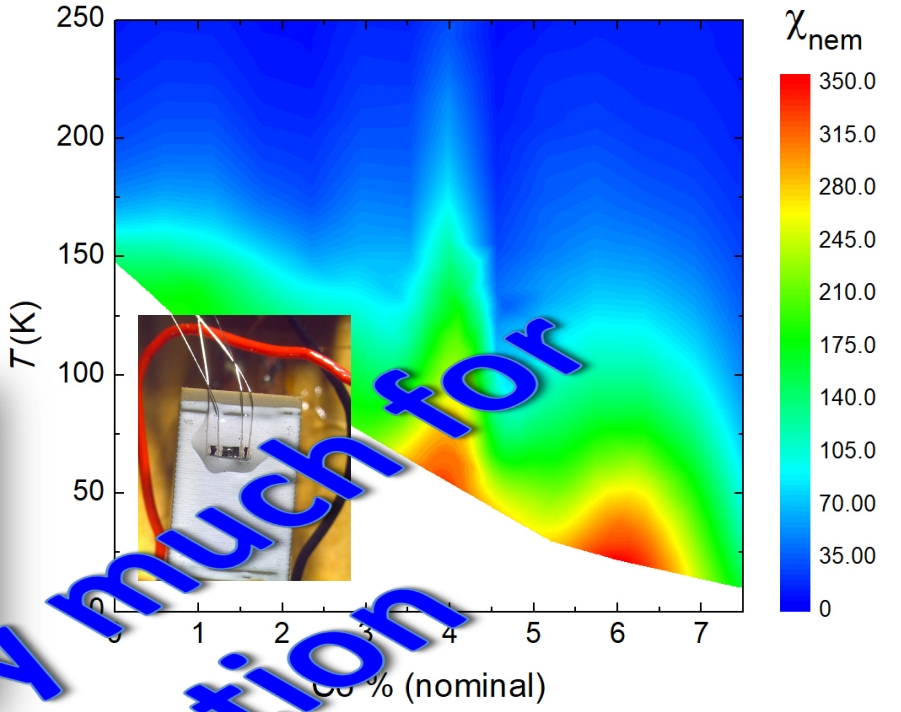


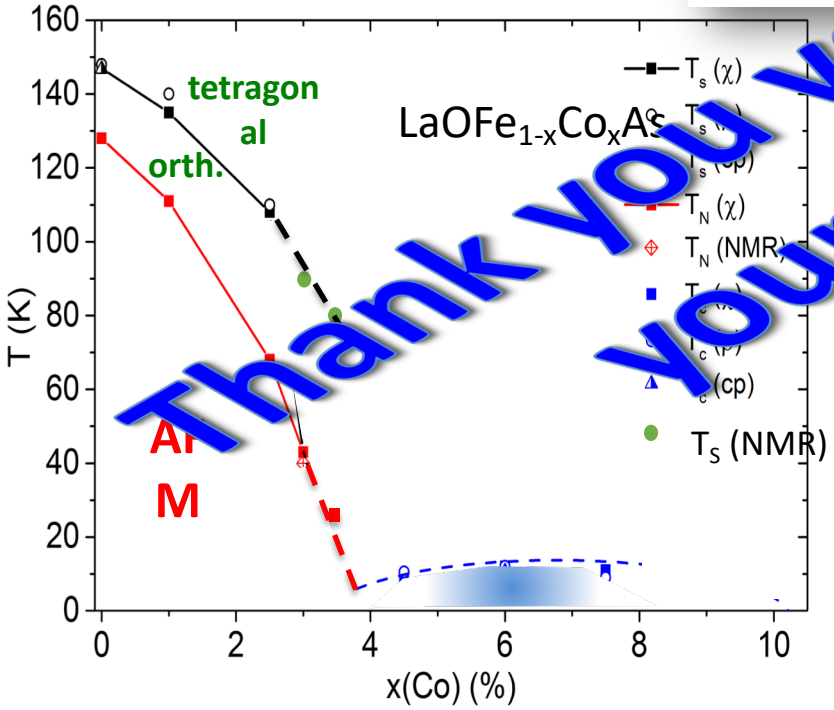


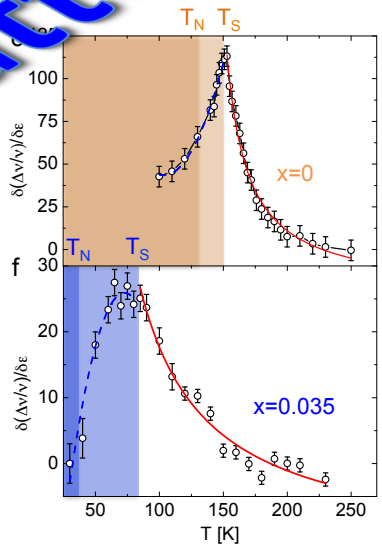
work in progress

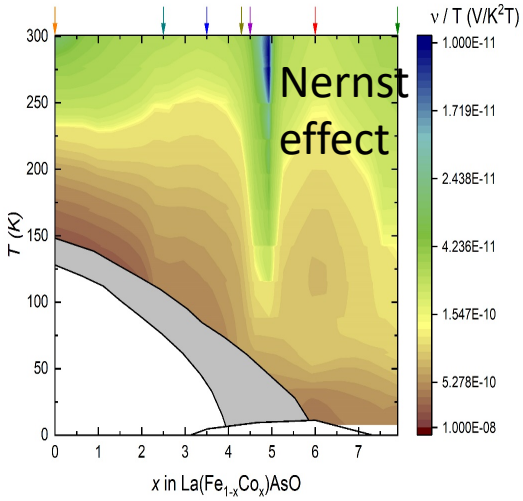
- fluorine doping
- Sm 1111
- Ce 1111
- …











Thank you very much for your attention