Electronic phase diagrams of 1111 oxy-pnictides investigated by means of μ^+ spin spectroscopy

Giacomo Prando
Leibniz-Institut für Festkörper- und Werkstoffforschung (IFW) Dresden, Germany
and
Alexander von Humboldt Stiftung
Fellowship for Postdoctoral Researchers

30 September 2013

HTS 2013
Звенигород, Россия
(Zvenigorod, Russia)

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Sample preparation

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A. Palenzona's group University of Genova, Italy
J. Karpinski's group ETH Zurich, Switzerland
V. P. S. Awana's group NPL, New Delhi, India

Review and summarizing discussion of results

Carretta, De Renzi, Prando, Sanna, *arXiv*:1307.8283
(2013, to appear soon on Physica Scripta)

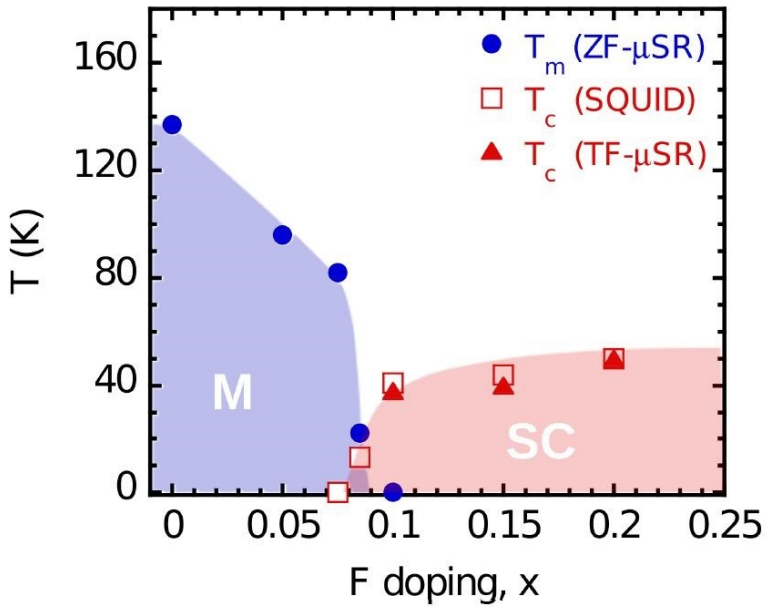
e⁻-doped ReFeAsO: Electronic Phase Diagram

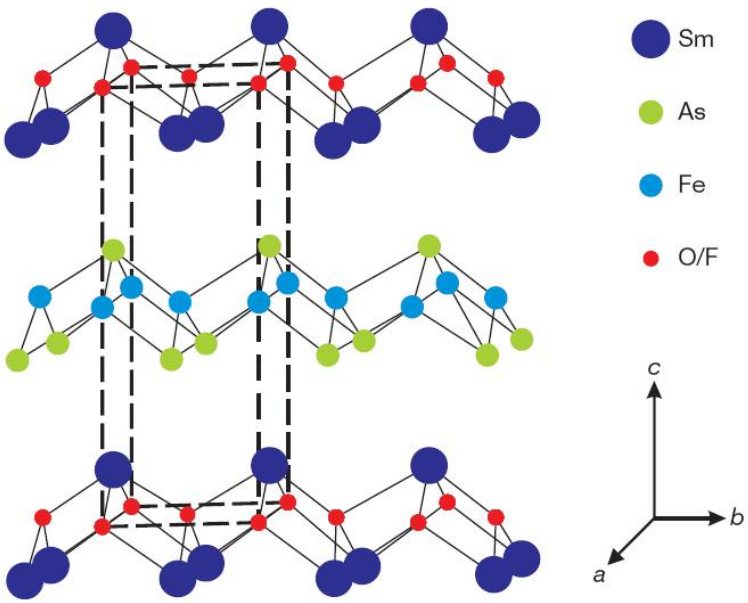
$x \lesssim 0.07$. **Magnetism (SDW)**

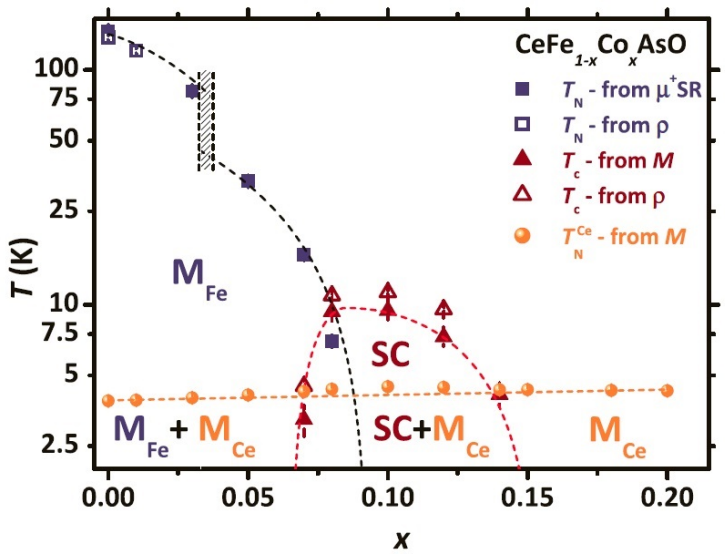
$x \gtrsim 0.1$. **Superconductivity**

What between M and SC?

(Chen et al., *Nature* **453**, 761)

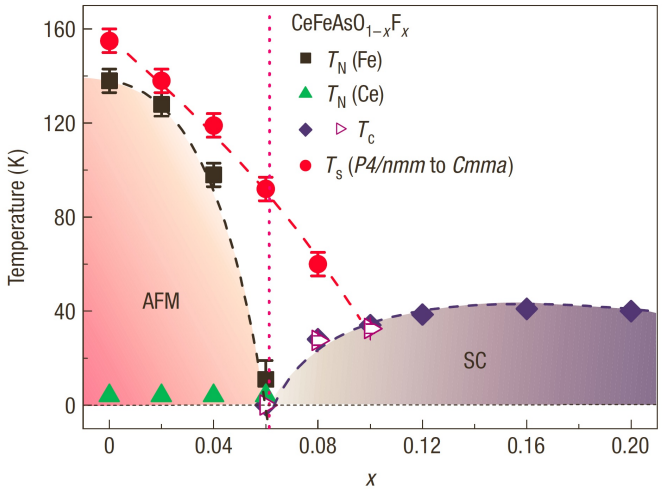


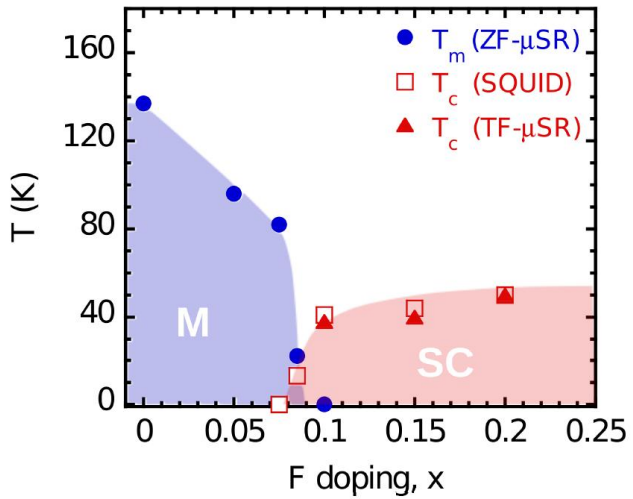




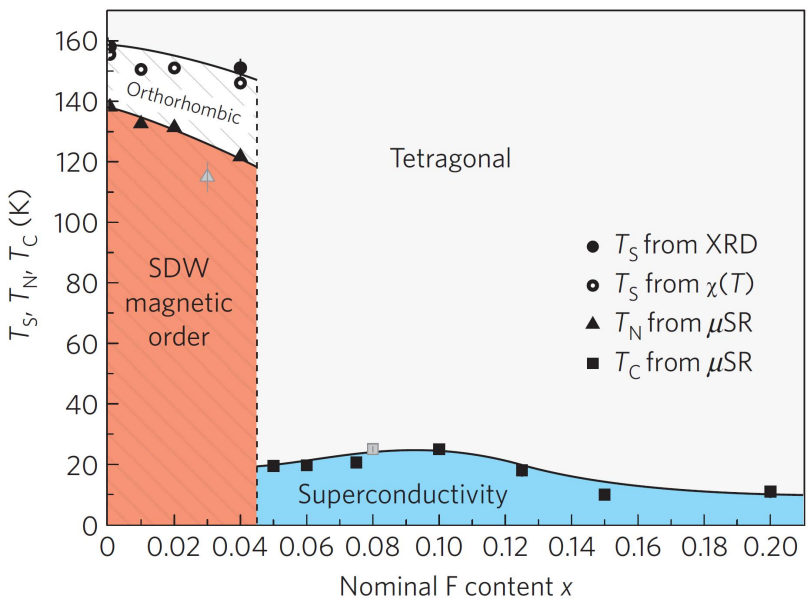
(Sanna et al., *PRB* **80**, 052503; Prando et al., *PRB* **87**, 174519)

Electron doping: the O/F substitution





(Zhao et al., *Nat. Mater.* **7**, 953 – Ce; Sanna et al., *PRB* **80**, 052503 – Sm)



(Luetkens et al., *Nat. Mater.* **8**, 305 – La)

Crucial importance of the intermediate region

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **81**, 140501(R) (2010)

Unconventional pairing in the iron arsenide superconductors

Rafael M. Fernandes,* Daniel K. Pratt, Wei Tian, Jerel Zarestky, Andreas Kreyssig, Shibabrata Nandi, Min Gyu Kim, Alex Thaler, Ni Ni, Paul C. Canfield, Robert J. McQueeney, Jörg Schmalian, and Alan I. Goldman

Ames Laboratory, U.S. DOE, and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA

(Received 15 February 2010; revised manuscript received 13 March 2010; published 2 April 2010)

We use magnetic long-range order as a tool to probe the Cooper-pair wave function in the iron arsenide superconductors. We show theoretically that antiferromagnetism and superconductivity can coexist in these materials only if Cooper pairs form an unconventional, sign-changing state. The observation of coexistence in $Ba(Fe_{1-x}Co_x)_2As_2$ then demonstrates unconventional pairing in this material. The detailed agreement between theory and neutron-diffraction experiments, in particular, for the unusual behavior of the magnetic order below T_c, demonstrates the robustness of our conclusions. Our findings strongly suggest that superconductivity is unconventional in all members of the iron arsenide family.

A careful investigation of magnetism at the border between **M** and **SC** regions in the electronic phase diagram is required

Beyond macroscopic techniques of investigation

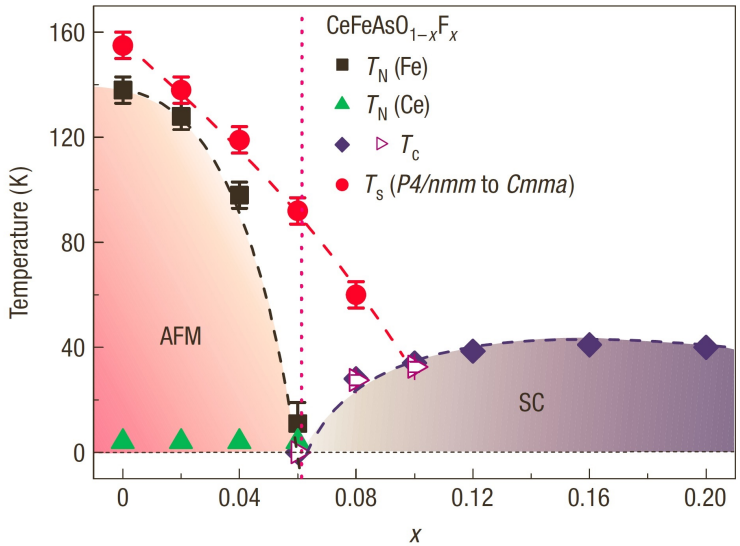
Resistivity: broadening of anomalies

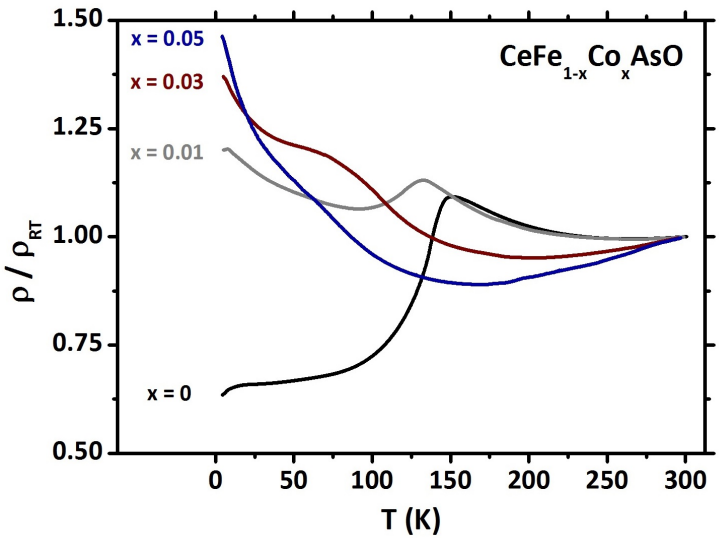
(Prando et al., *PRB* **87**, 174519)

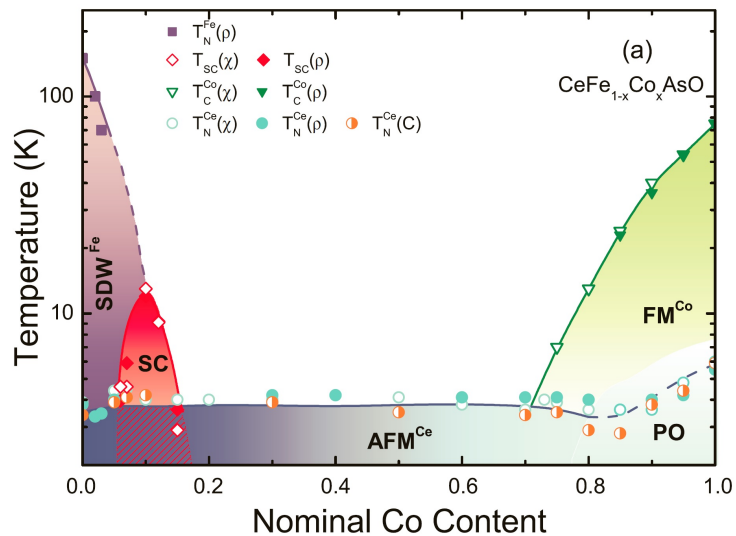
Magnetization: magnetic impurities

Neutrons: blind to SRO

(Zhao et al., *Nat. Mater.* **7**, 953)

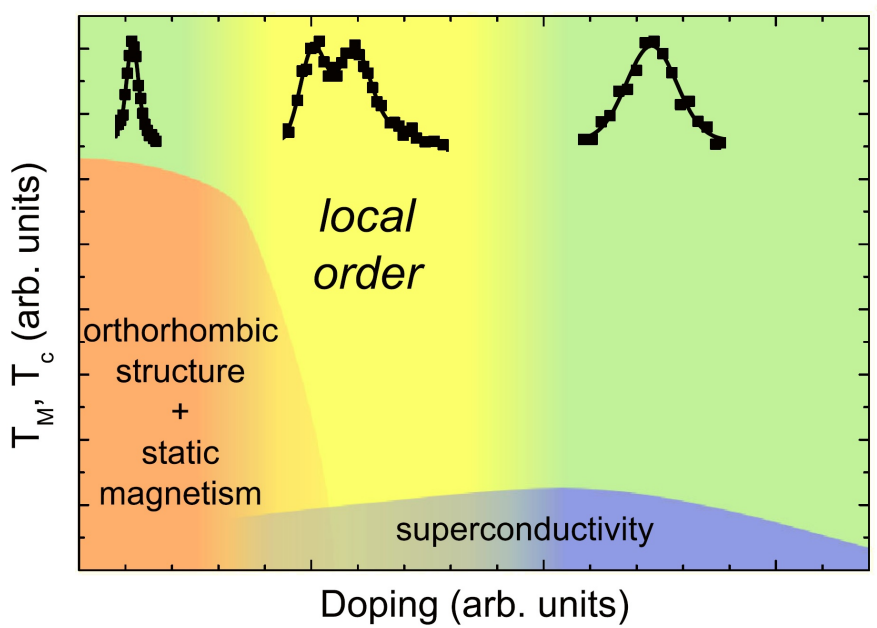


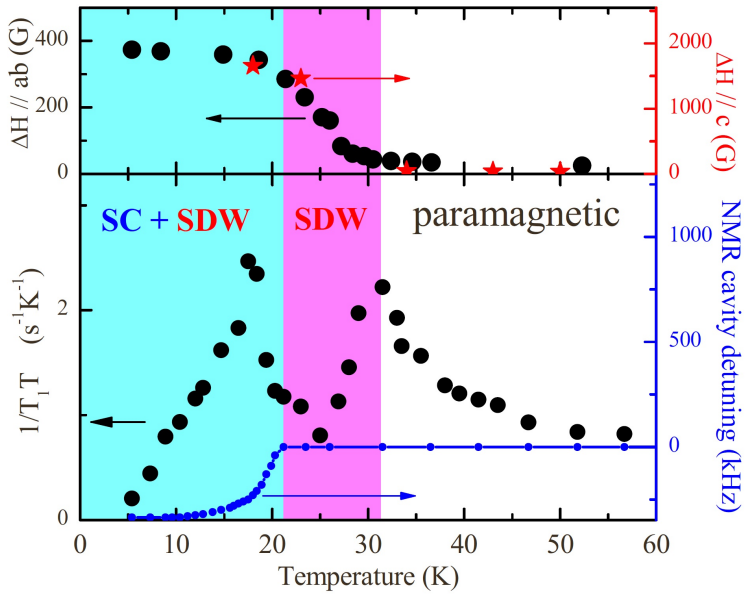




(Prando et al., *PRB* **87**, 174519; Shang et al., *PRB* **87**, 075148)

Microscopic local-probe techniques – NMR





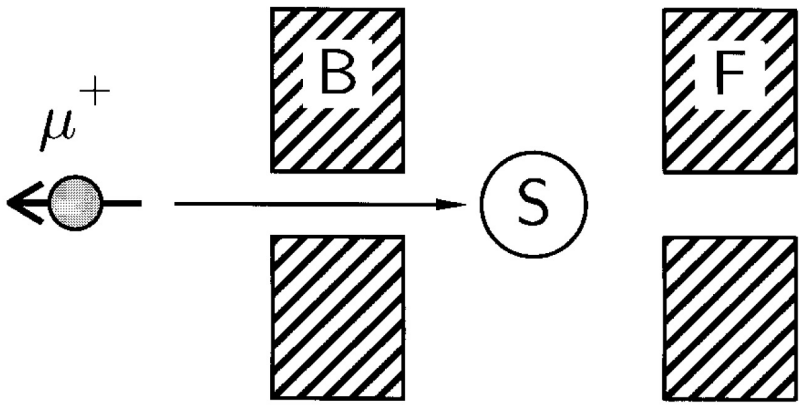
(Lang et al., *PRL* **104**, 097001; Laplace et al., *PRB* **80**, 140501)

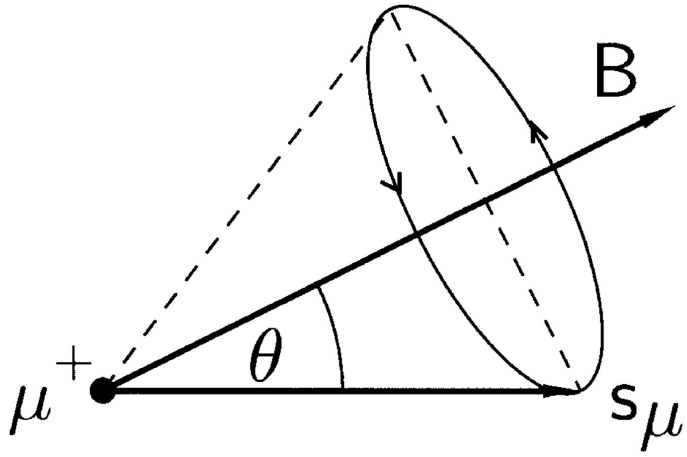
NMR: nuclei detect coexistence on nanoscopic or even atomic scale for the different ground states (both static and dynamic features)

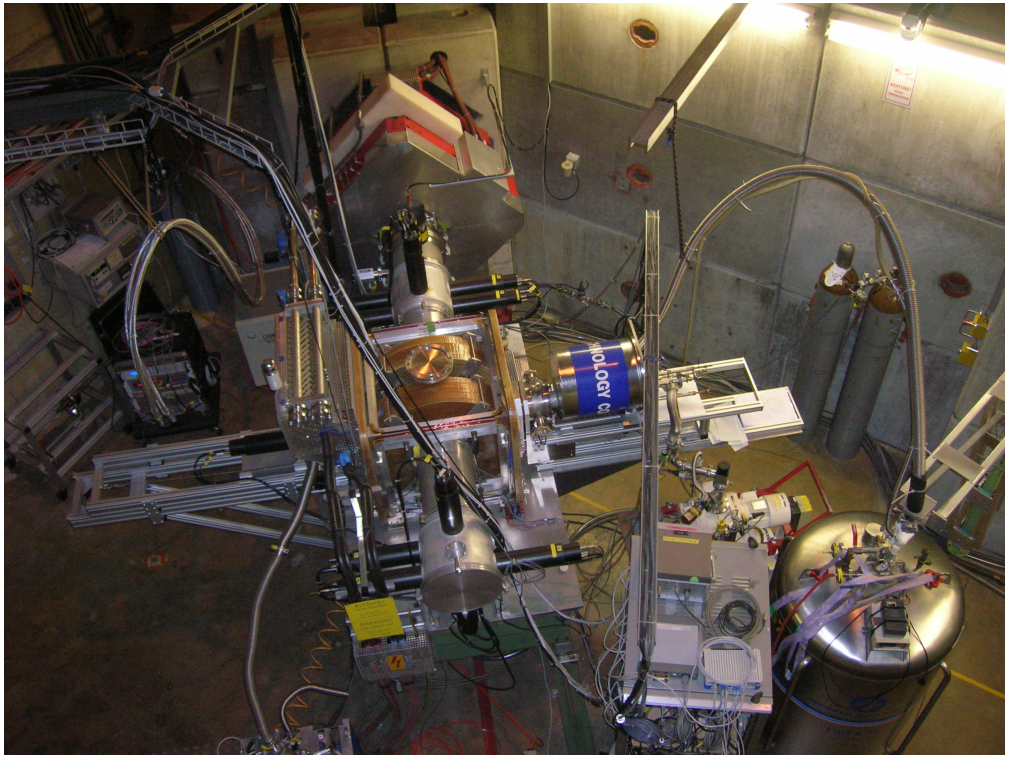
<u>Drawbacks</u>

- Strong local fields from magnetic Re ions
  (Prando et al., *PRB* **81**, 100508(R))
- No information on absolute values of V_m

μ^+ Spin Rotation, Relaxation, Resonance (μ^+SR)





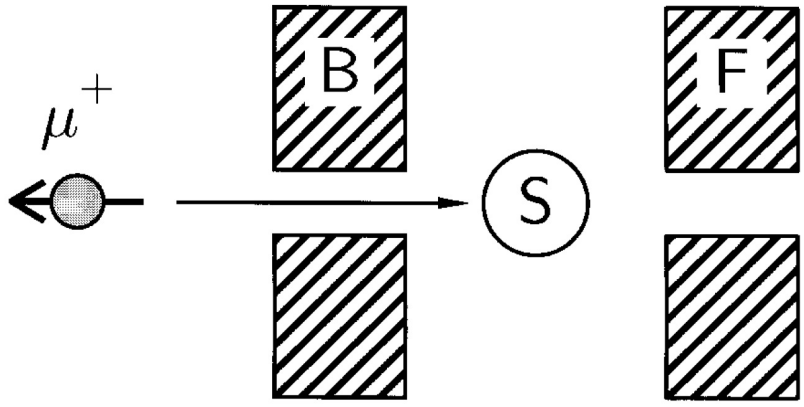


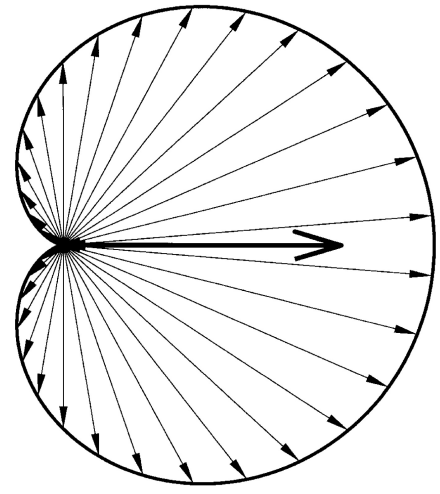
Spin-polarized beam of μ^+ implanted in sample **S**

Once thermalized, Larmor precession around local field $\mathbf{B}_\mu$

Left: experimental setup for GPS spectrometer at Paul Scherrer Institute

μ^+ Spin Rotation, Relaxation, Resonance (μ^+SR)





After $\langle \tau_\mu \rangle \simeq 2.19\ \mu$s: muon decays as $\mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu_\mu}$

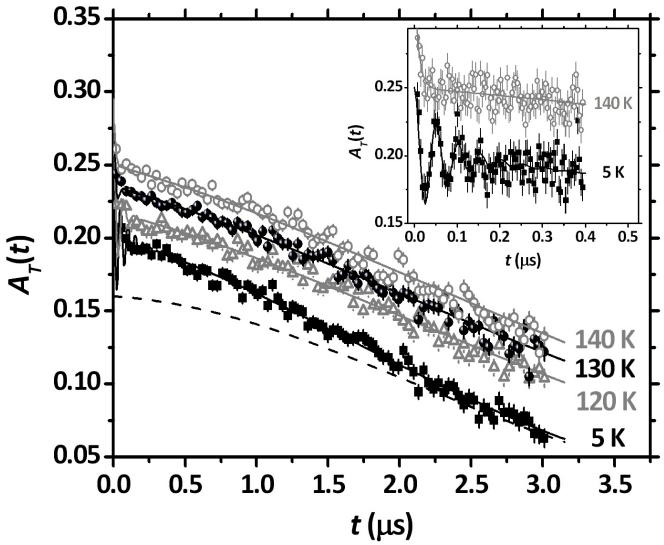
Weak decay $\Rightarrow$ **Parity conservation is violated**

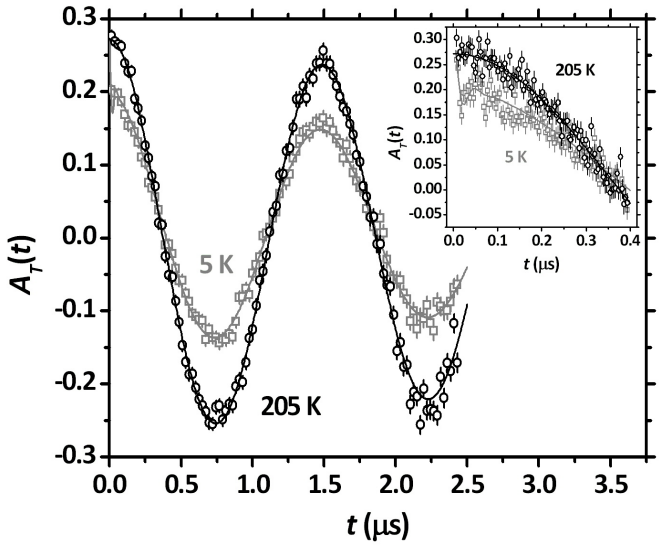
Positrons from μ^+ decay $\Rightarrow$ Experimental access to the time-dependent autocorrelation function $G(t)$ for the μ^+ spin

$$G(t) = \frac{\langle \mathbf{s}(t) \cdot \mathbf{s}(0) \rangle}{s^2(0)} \equiv \frac{A(t)}{A_0} \qquad \text{where} \qquad A(t) = \frac{N_\mathrm{B}(t) - N_\mathrm{F}(t)}{N_\mathrm{B}(t) + N_\mathrm{F}(t)}$$

Single crystals: information about possible anisotropies of $G(t)$

μ^+SR: simultaneous presence of different phases





(Prando, *Ph. D. Thesis*)

μ^+ randomly and uniformly implanted into the sample

% of μ^+ probing features of some electronic environment

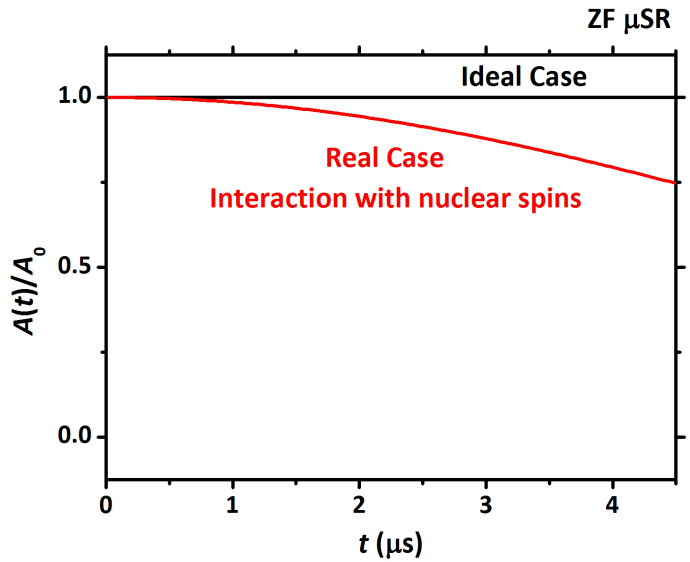
$\Updownarrow$

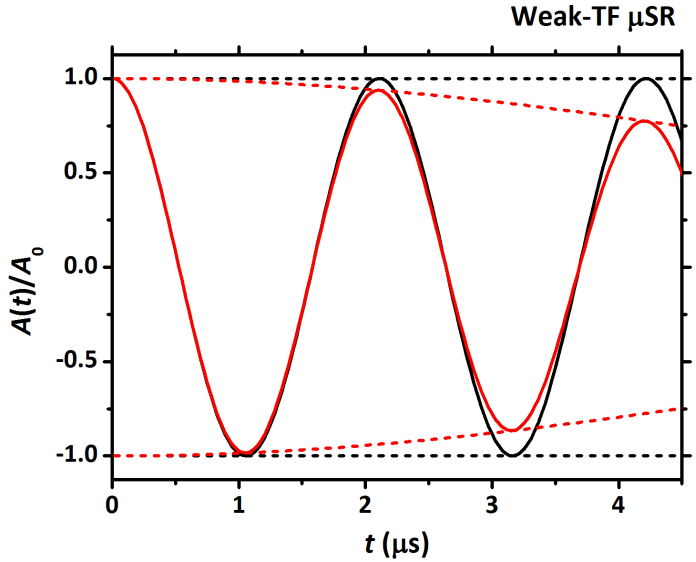
$V_\mathbf{m}$ of the sample associated to that environment

Disentangle signals: combination of ZF and TF

Intrinsic features: low-background spectrometers

μ^+SR: the paramagnetic phase (SC in ZF!)



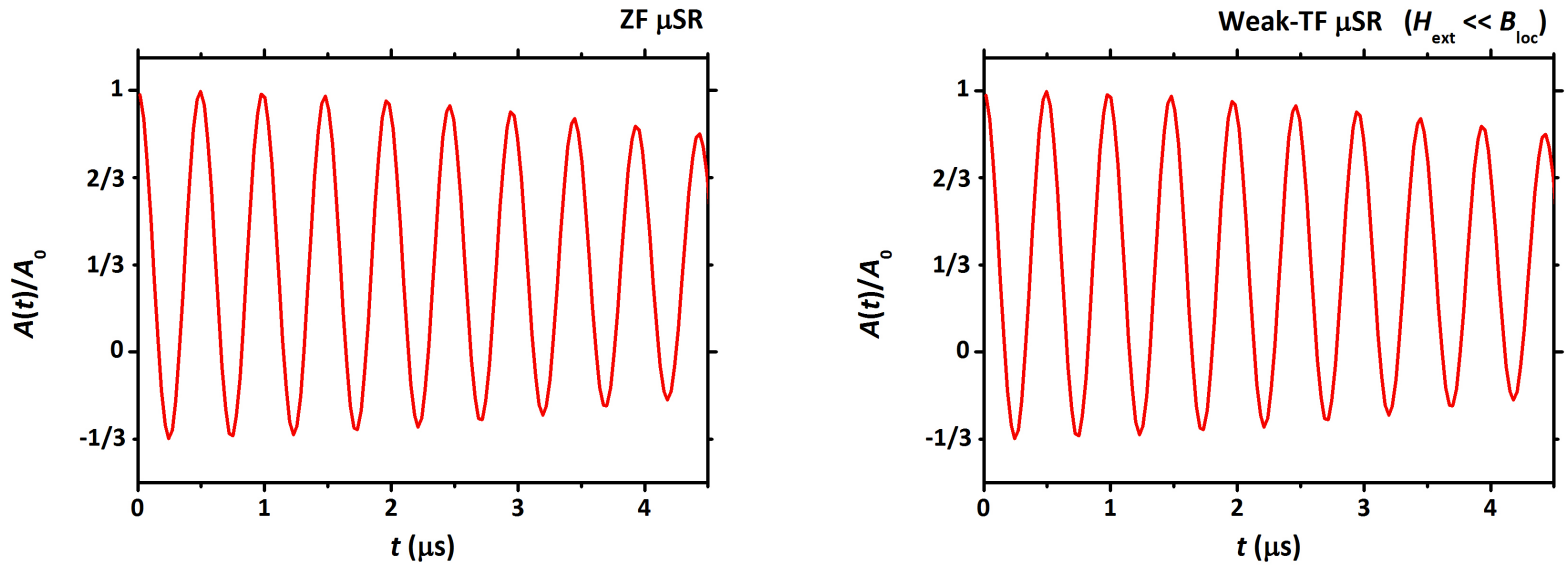


No $\mathbf{B}_\mu$ of electronic origin: spin polarization ideally preserved in conditions of zero external field (ZF)

Real case: weak nuclear magnetism leads to a slow depolarization

Weak $\mathbf{H_{ext}}$ transverse to initial direction of spins (weak-TF): coherent precession damped by nuclei

μ^+SR: the magnetic phase (powders)

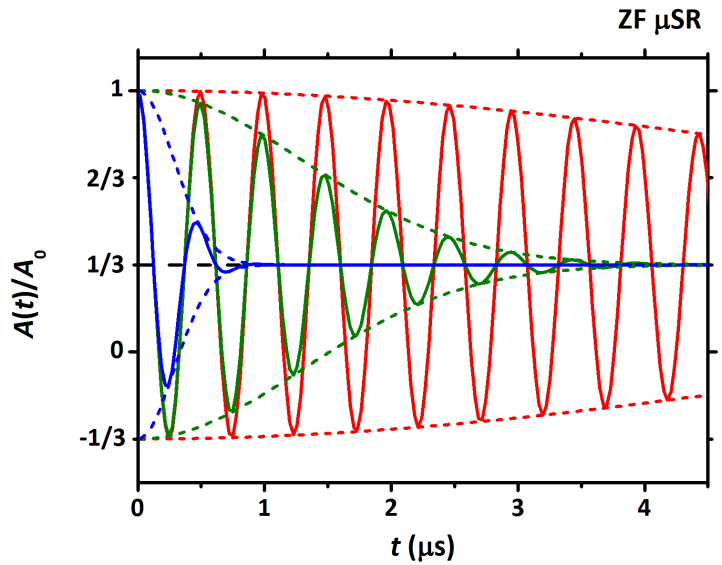


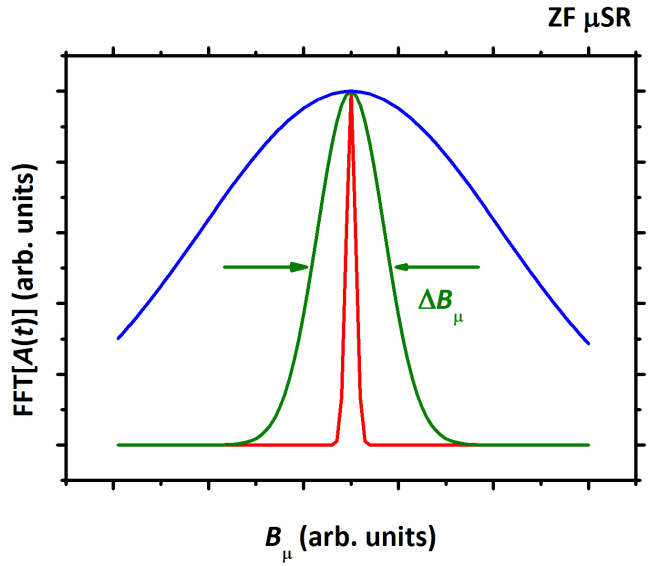
Long-range ordered phase leads to well-defined $\mathbf{B}_\mu$ of electronic origin: 2/3 of spins precess ($\omega = \gamma_\mu B_\mu,\ \gamma_\mu = 2\pi \times 135.54$ MHz/T)

Weak nuclear magnetism leads to a slow depolarization

Weak-TF: no effect as long as $\mathbf{H_{ext}} \ll \mathbf{B}_\mu$.
ZF and weak-TF are equivalent in strongly-magnetic phases

μ^+SR: the magnetic phase. Disorder





Distribution of local magnetic fields: damping of oscillations

- $\Delta \mathbf{B}_\mu \ll \mathbf{B}_\mu$: (almost) long-ranged order
- $\Delta \mathbf{B}_\mu \sim \mathbf{B}_\mu$: disorder, short-ranged order

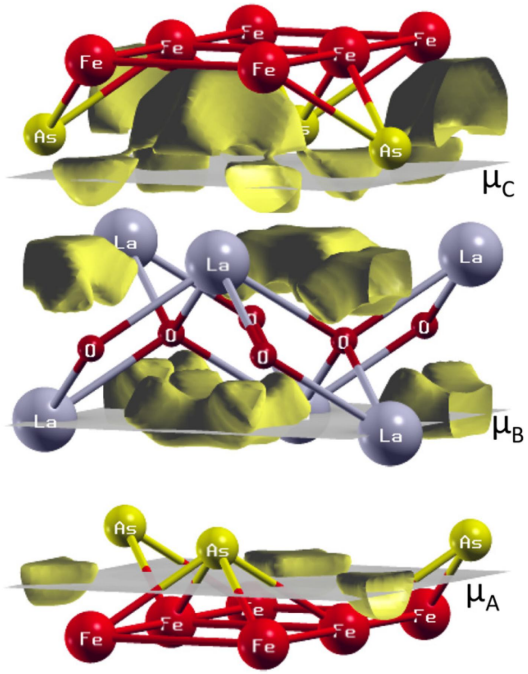
μ^+SR highly sensitive to V_m **in both the cases**

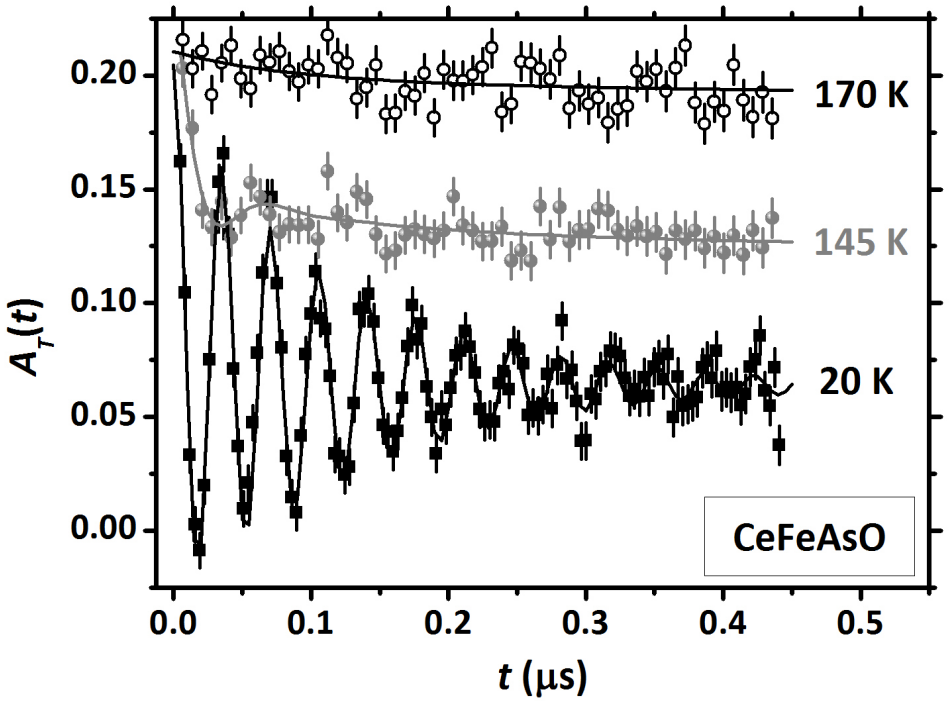
Analysis of μ^+SR signal

Two sites for muons (DFT - electrostatic potential and zero-point energy):

- Inside FeAs layers (dominant signal)
- Close to Re (clear only for La)

(De Renzi et al., SUST **25**, 084009)



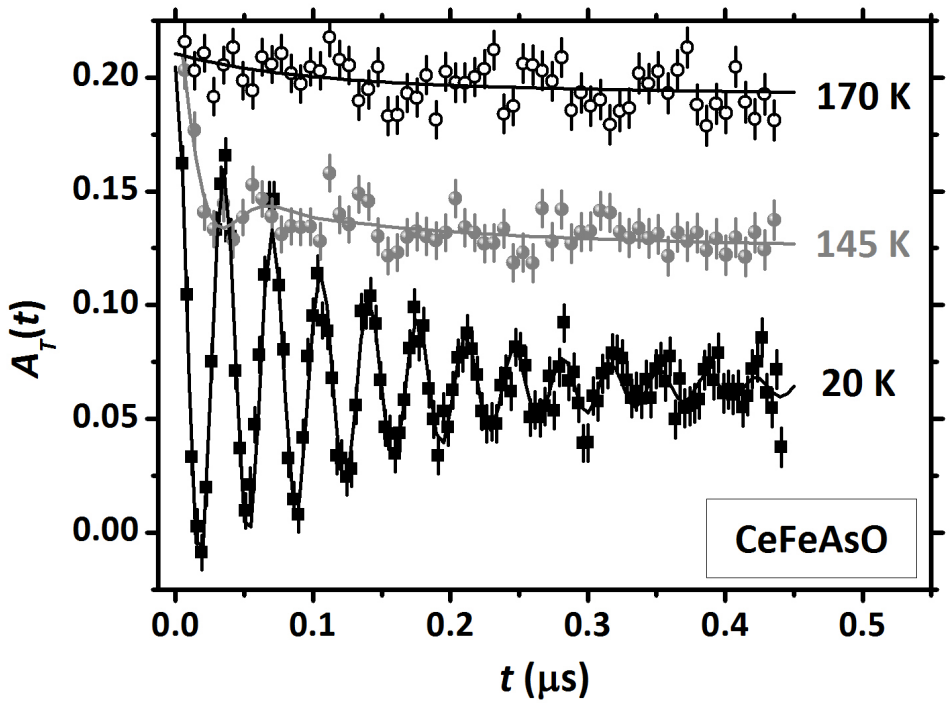


Long-range order: coherent precession, $\omega = \gamma_\mu B_\mu$ ($\gamma_\mu = 135.54$ MHz/T)

Analysis of μ^+SR signal

$$\frac{A_T(t)}{A_0} = \left\{ [1 - V_m(T)]\, e^{-\frac{\sigma^2 t^2}{2}} + \left[a^{Tr}(T) F(t) D^{Tr}(t) + a^{L}(T) D^{L}(t) \right] \right\}$$

$$V_m(T) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{T - T_N}{\sqrt{2}\Delta}\right) \qquad \left[\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{+\infty} e^{-t^2} dt\right]$$



Long-range order: coherent precession, $\omega = \gamma_\mu B_\mu$ ($\gamma_\mu = 135.54$ MHz/T)

$$B_\mu(T) =$$

$$= \left| \underbrace{\mathbf{B}_{\mathrm{dip}}(\mathbf{r}_\mu)}_{\text{dipolar}} + \underbrace{\mathbf{B}_{\mathrm{c}}(\mathbf{r}_\mu)}_{\text{contact}} + \underbrace{\mathbf{B}_{\mathrm{L}}}_{\text{Lorentz}} \right|$$

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$$\frac{A_T(t)}{A_0} = \left\{ [1 - V_m(T)]\, e^{-\frac{\sigma^2 t^2}{2}} + \left[a^{Tr}(T) F(t) D^{Tr}(t) + a^{L}(T) D^{L}(t) \right] \right\}$$

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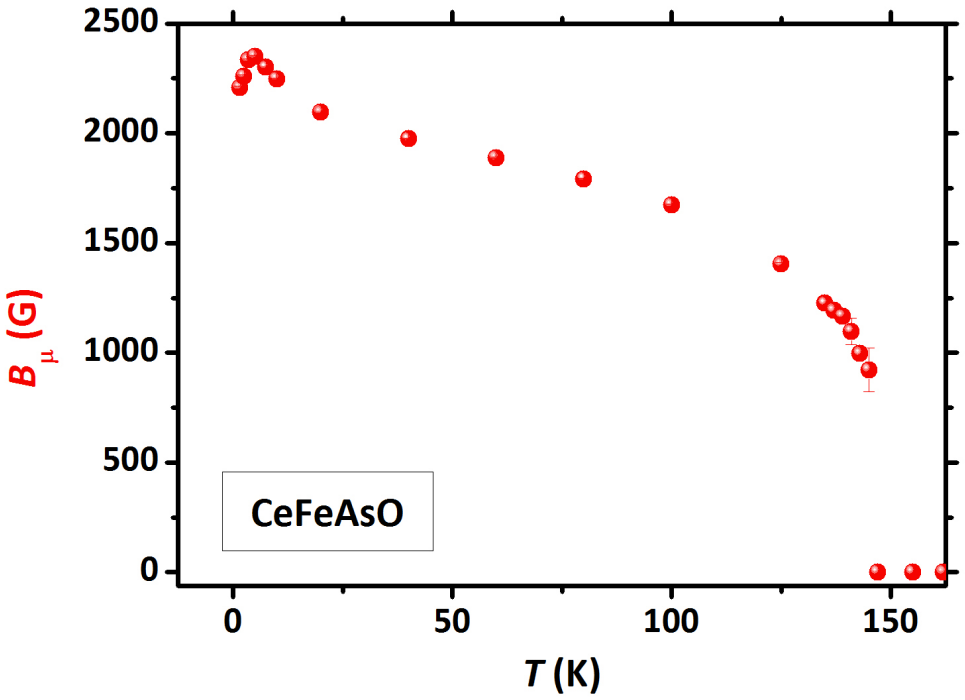

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$$\frac{A_T(t)}{A_0} = \left\{ [1 - V_m(T)]\, e^{-\frac{\sigma^2 t^2}{2}} + \left[a^{Tr}(T) F(t) D^{Tr}(t) + a^{L}(T) D^{L}(t) \right] \right\}$$

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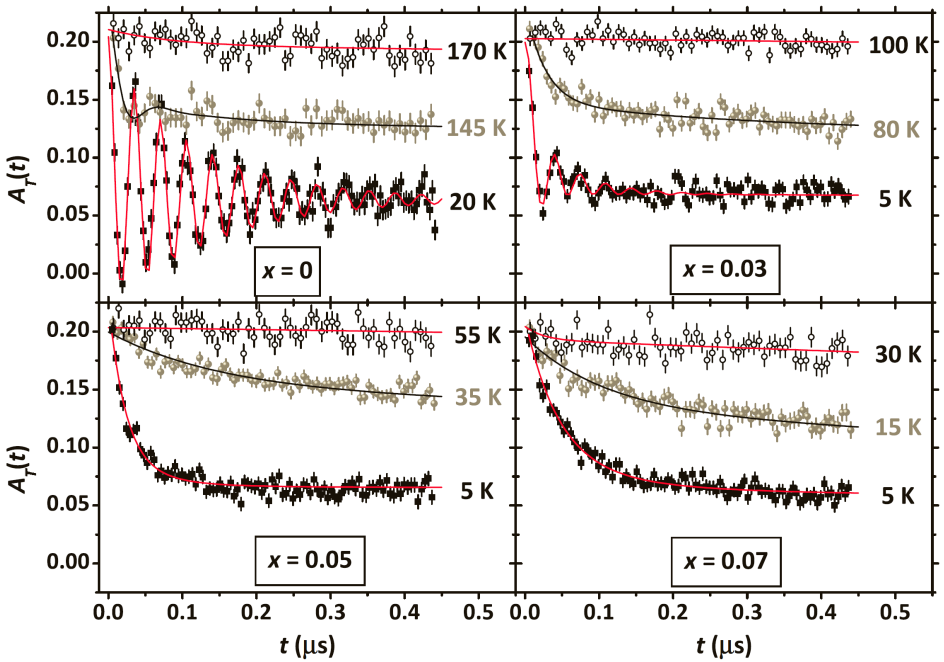

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Analysis of μ^+SR signal

$$\frac{A_T(t)}{A_0} = \left\{ [1 - V_m(T)]\, e^{-\frac{\sigma^2 t^2}{2}} + \left[a^{Tr}(T) F(t) D^{Tr}(t) + a^{L}(T) D^{L}(t) \right] \right\}$$

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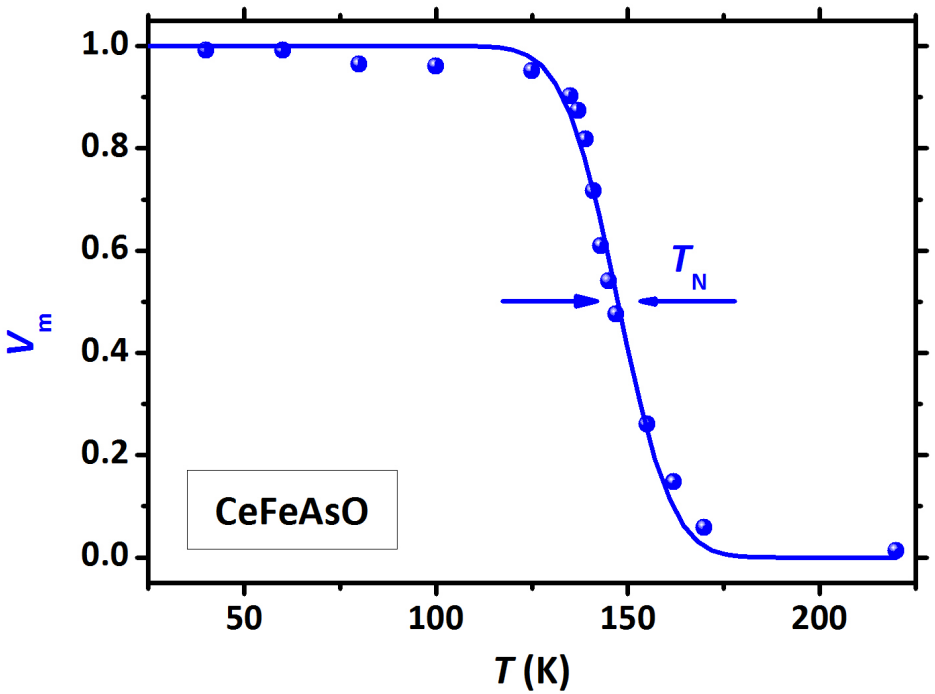

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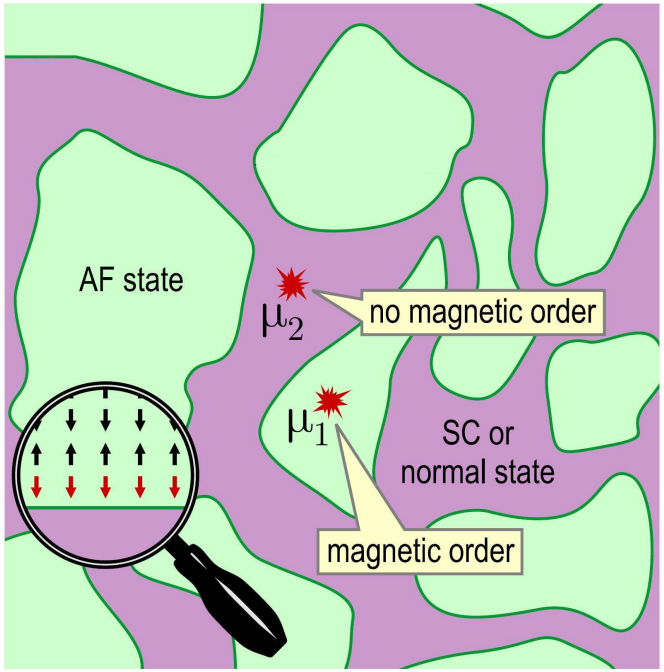
μ^+SR: simultaneous presence of different phases

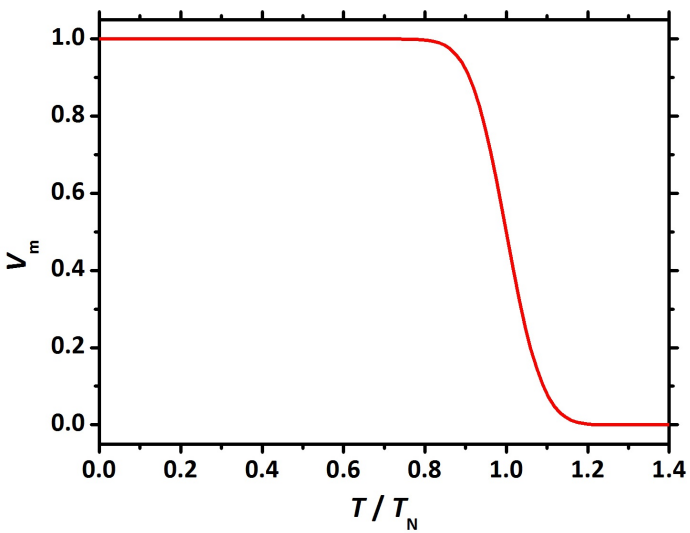


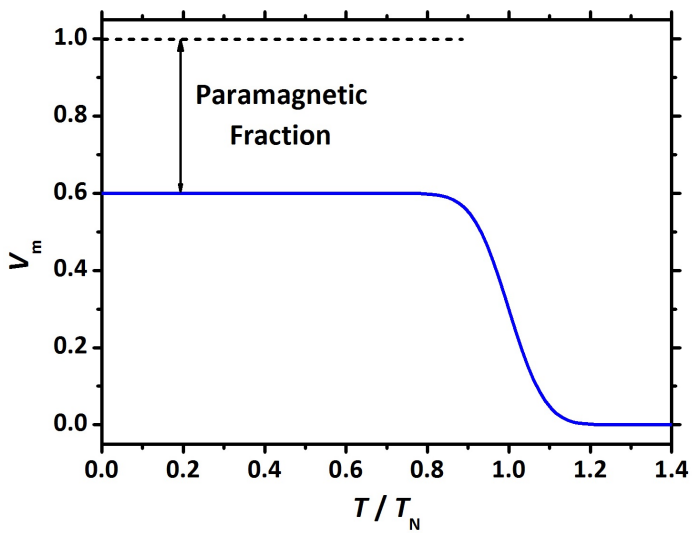
- μ^+ inside domains probe magnetism
- μ^+ outside domains probe magnetism (dipolar range $d \sim 1$ nm)

(Park et al., PRL **102**, 117006)

Closely-packed domains $\Rightarrow$ $V_\mathrm{m} = 100$ %
Nanoscopic coexistence

Widely-separated domains $\Rightarrow$ $V_\mathrm{m} < 100$ %
Maroscopic segregation





Advantages of μ^+SR

- Extremely high sensitivity to absolute values of V_m
- Extremely high sensitivity to SRO magnetism
- Direct access to the magnetic order parameter for LRO phases
- Spin polarization: typically $\sim 100\%$ (never the case in NMR)
- Possibility of performing zero-field measurements
- No need for "suited" materials (e. g., good nuclei for NMR)
- Relatively quick measurements

- Phase diagram upon chemical substitutions
  (both charge dopings and isovalent substitutions)

- Phase diagram upon external/chemical pressures

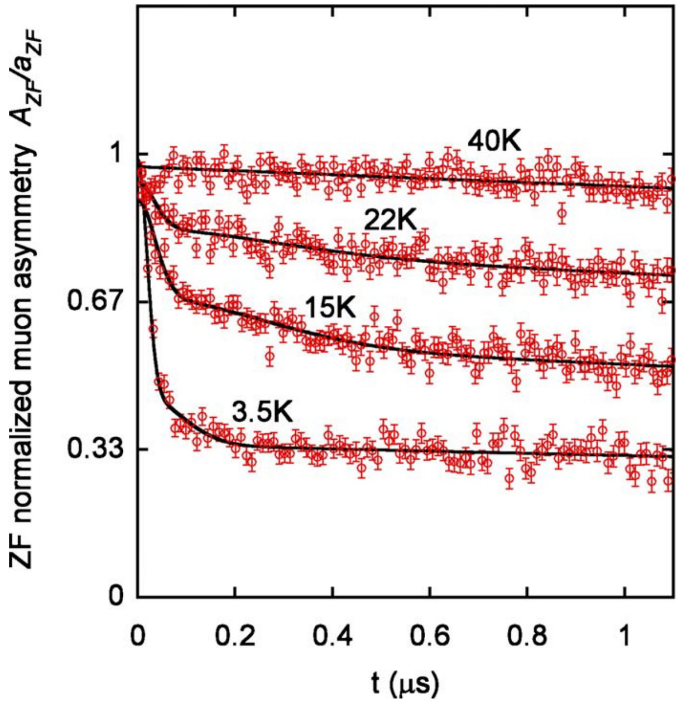
- Phase diagram upon chemical substitutions
  (both charge dopings and isovalent substitutions)

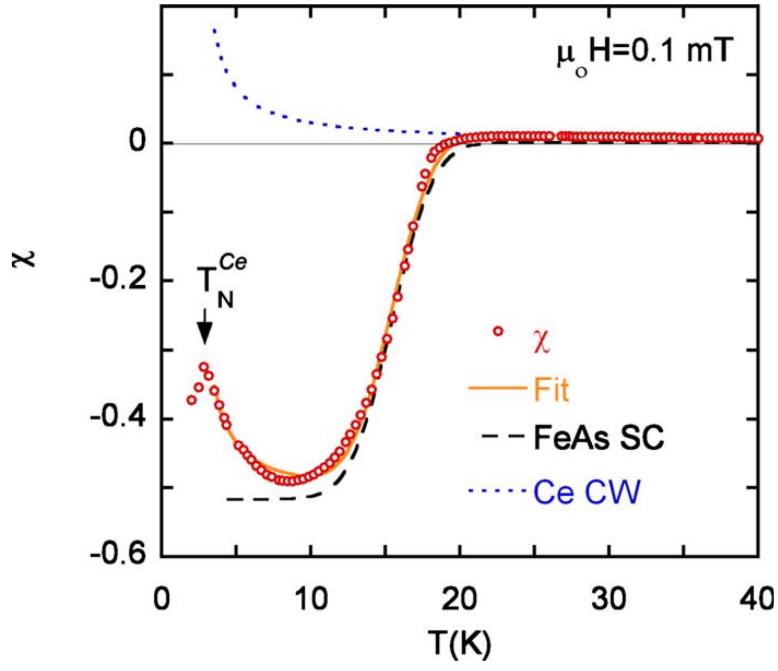
- Phase diagram upon external/chemical pressures

Nanoscopic coexistence in $CeFeAsO_{0.94}F_{0.06}$

μ^+SR signal: no oscillations! Still, clear signature of SRO magnetism ($V_m = 100\%$)

Diamagnetic contribution to $\chi \Rightarrow$ Bulk **SC** coexists with **M**





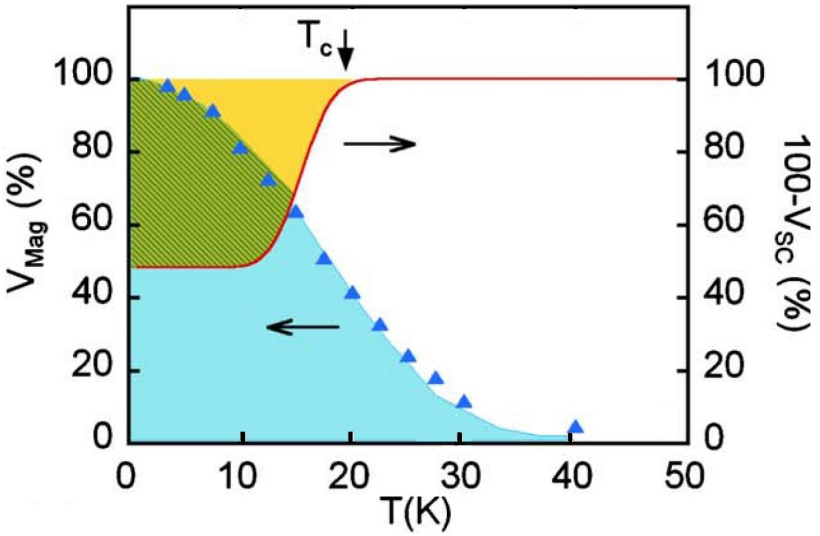
(Sanna et al., *PRB* **82**, 060508(R))

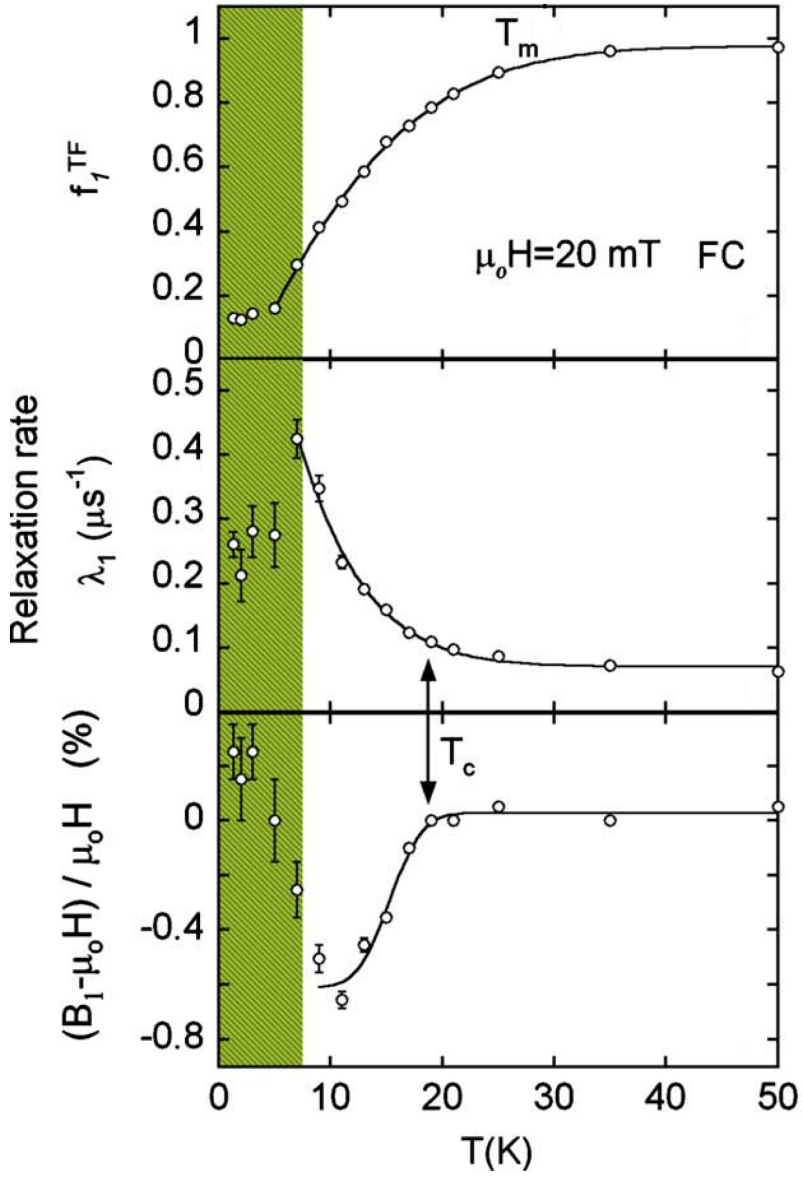
Nanoscopic coexistence in $CeFeAsO_{0.94}F_{0.06}$

- $V_m = 100\%$
- $V_{SC} < 100\%$ but still bulk (SQUID magnetometry)

Coexistence of M and SC on the scale of nanometer

QCP ruled out by μ^+SR



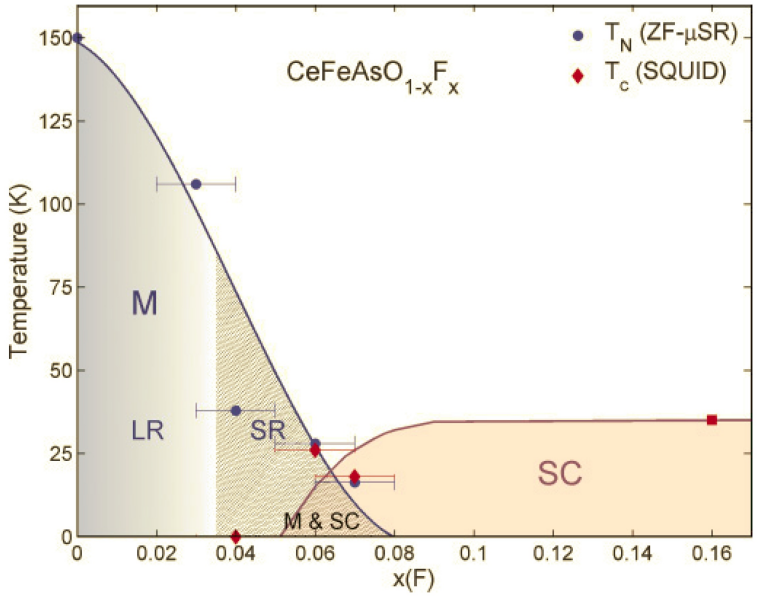


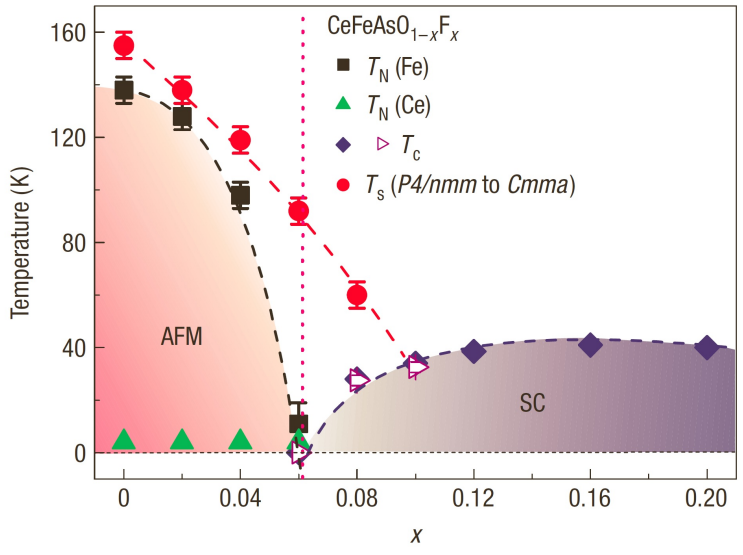
(Sanna et al., *PRB* **82**, 060508(R))

Nanoscopic coexistence in $CeFeAsO_{1-x}F_x$

μ^+SR measurements performed across the whole phase diagram

Qualitative difference with respect to results of neutrons





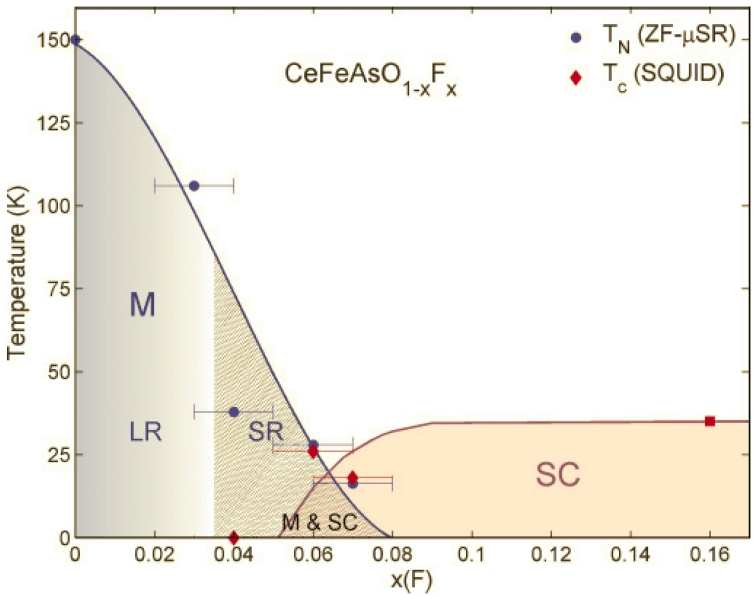
(Shiroka et al., *PRB* **84**, 195123; Zhao et al., *Nat. Mater.* **7**, 953)

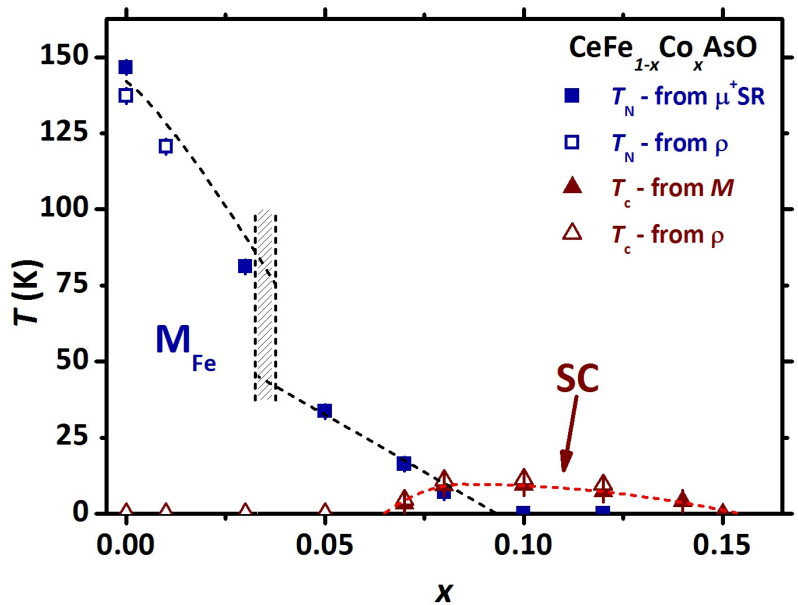
A posteriori estimate of F^- content via quantitative ^{19}F-NMR

Out-of-plane vs. in-plane doping/disorder. $CeFeAsO_{1-x}F_x$ vs. $CeFe_{1-x}Co_xAsO$

Electron doping via Fe/Co: still matter of debate

(Wadati et al., *PRL* **105**, 157004; Wadati et al., *PRL* **108**, 207003)





(Shiroka et al., *PRB* **84**, 195123; Prando et al., *PRB* **87**, 174519)

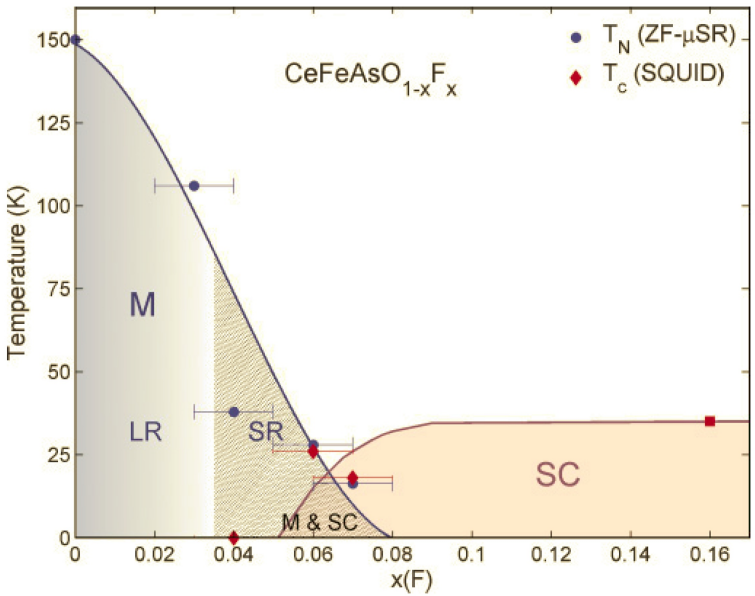
Qualitative identical phase diagram (nanoscopic coexistence)

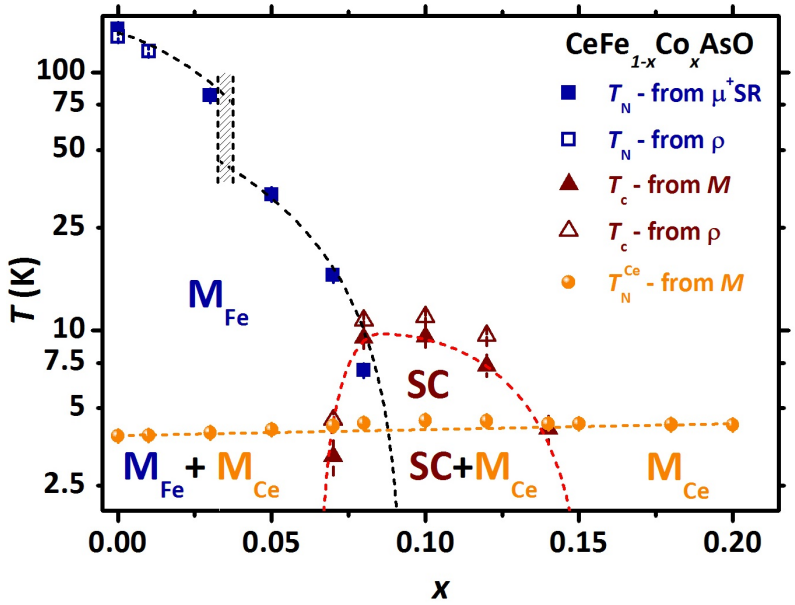
In-plane disorder strongly suppresses T_c values

Out-of-plane vs. in-plane doping/disorder. $CeFeAsO_{1-x}F_x$ vs. $CeFe_{1-x}Co_xAsO$

Electron doping via Fe/Co: still matter of debate

(Wadati et al., *PRL* **105**, 157004; Wadati et al., *PRL* **108**, 207003)





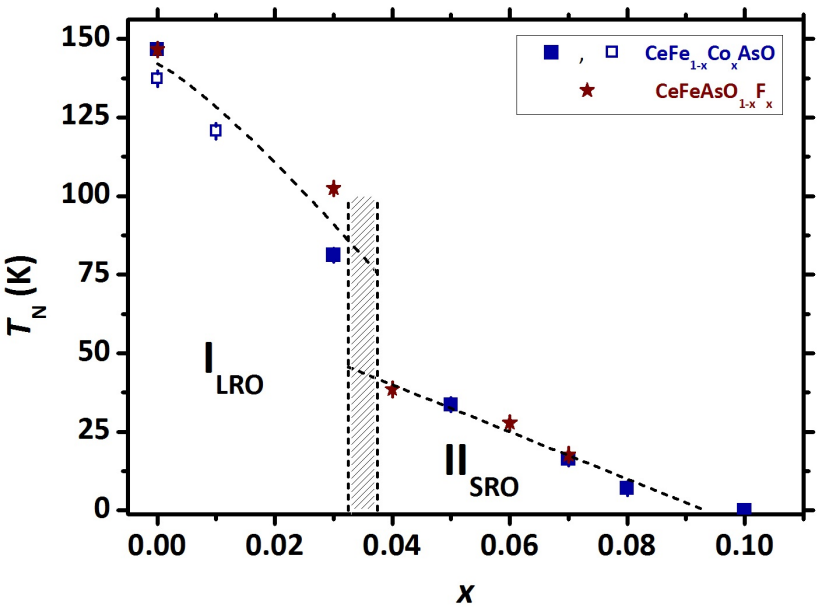
(Shiroka et al., *PRB* **84**, 195123; Prando et al., *PRB* **87**, 174519)

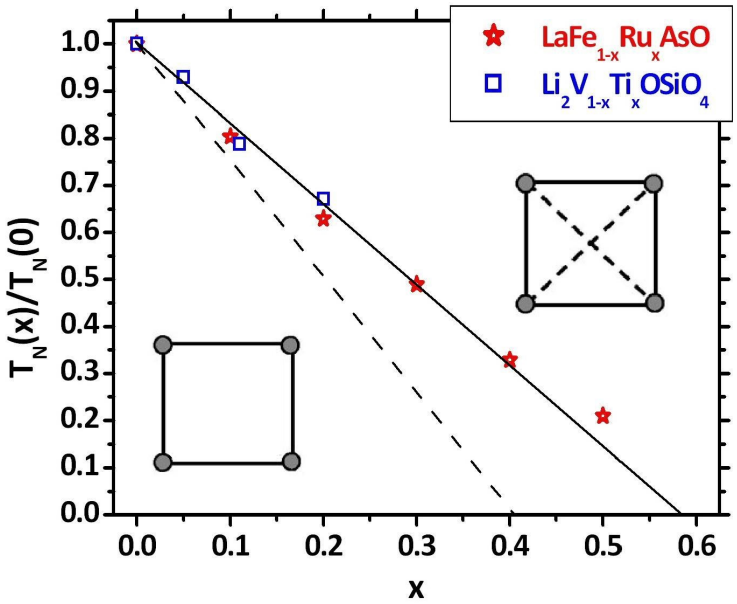
Qualitative identical phase diagram (nanoscopic coexistence)

In-plane disorder strongly suppresses T_c values

Charge doping vs. isovalent substitution

No apparent effect of disorder on magnetic phase





(Prando et al., *PRB* **87**, 174519; Bonfà et al., *PRB* **85**, 054518)

$LaFe_{1-x}Ru_xAsO$. DFT: no magnetic moment on Ru

(Tropeano et al., *PRB* **81**, 184504)

$\Rightarrow$ **Spin-dilution model** for Fe moments. $J_1 - J_2$ model

Percolative thresholds (Papinutto et al., *PRB* **71**, 174425)

- $x \simeq 0.41$, "standard" square lattice (dashed line)
- $x \simeq 0.59$, $J_1 - J_2$ square lattice (continuous line)

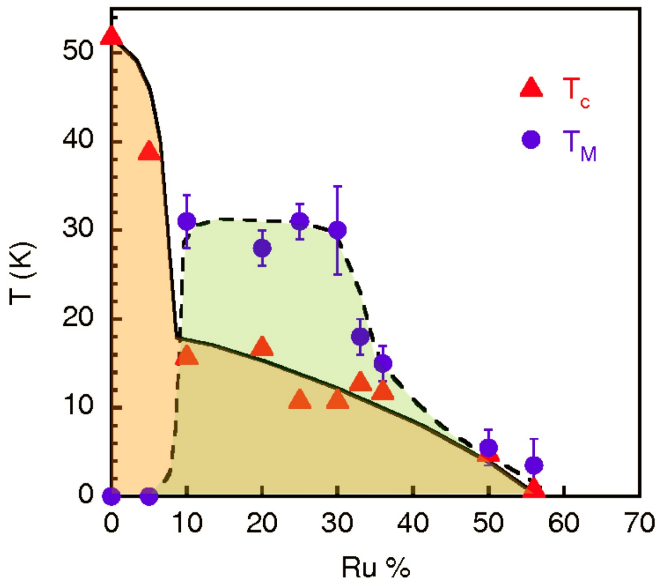
$Fe_{1-x}Ru_x$ substitution from optimal doping

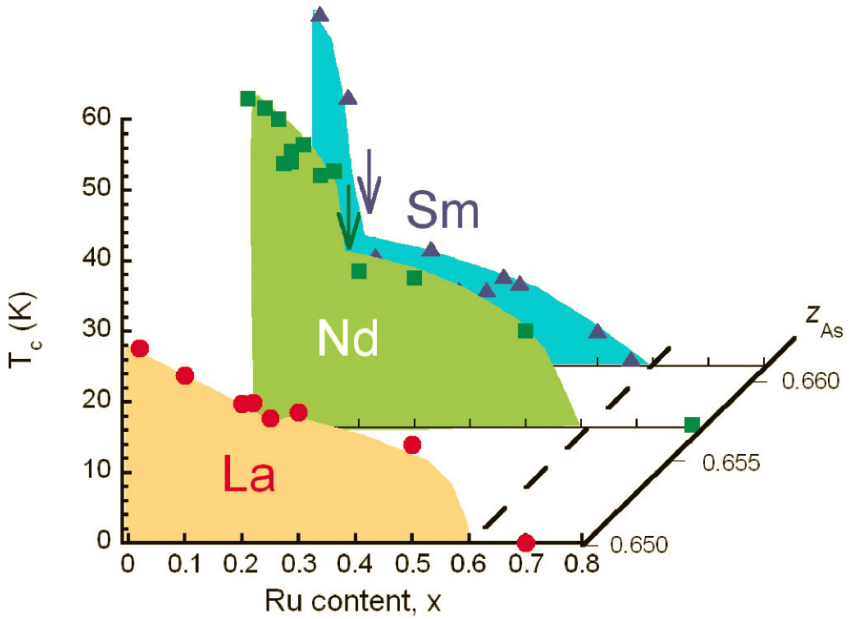
$ReFe_{1-x}Ru_xAsO_{0.89}F_{0.11}$:
chemical doping kept constant

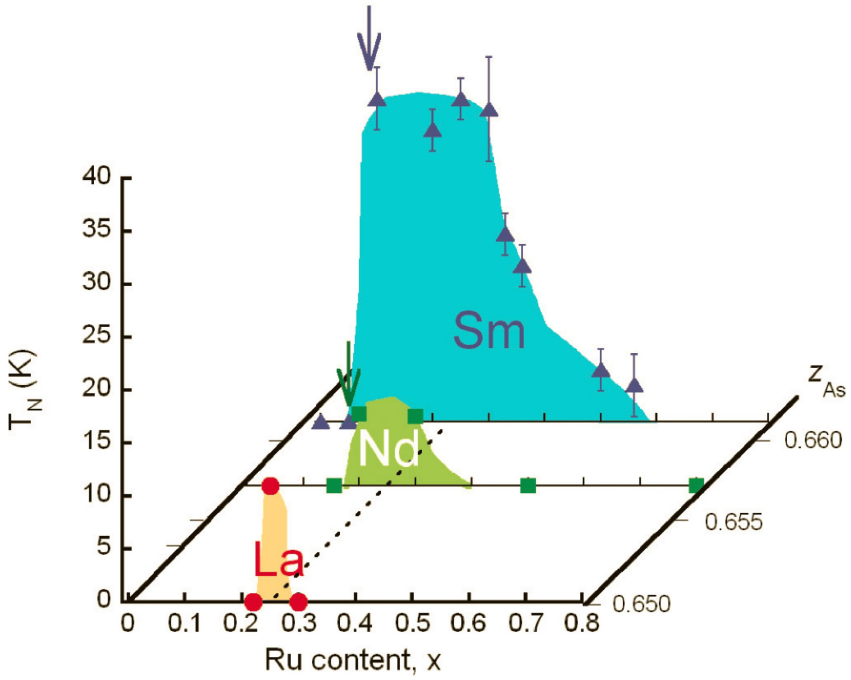
Increasing x: re-entrant static magnetism for all Re

Ru freezes fluctuations, kills superconductivity and triggers static magnetism

(Sanna et al., *PRL* **107**, 227003
+ *PRB* **87**, 134518)







Conclusions

- Charge doping leads to nanoscopic coexistence of **M** and **SC** both for O/F and Fe/Co
- No qualitative difference between magnetic Re ions
- In-plane disorder is detrimental for **SC** but not for **M**
- Correlation/localization/frustration are important in 1111 pnictides
- Fe/Ru possibly enlightens strong relation among magnetic fluctuations and **SC**

- Phase diagram upon chemical substitutions
  (both charge dopings and isovalent substitutions)

- Phase diagram upon external/chemical pressures

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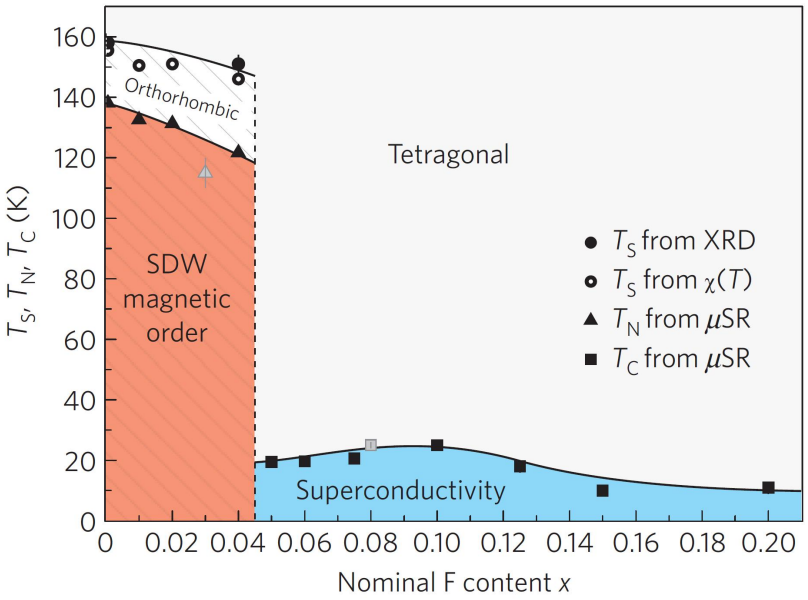
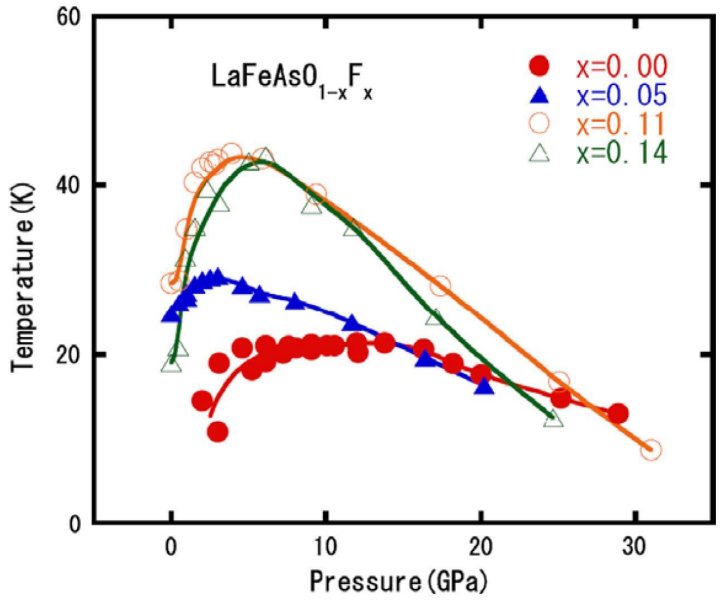
Chemical vs. external pressures

Phase diagram: also scanned with P as tuning parameter **avoiding direct modification of the chemical doping**

SC induced even in undoped LaFeAsO ($P \gtrsim 3 \div 4$ GPa)



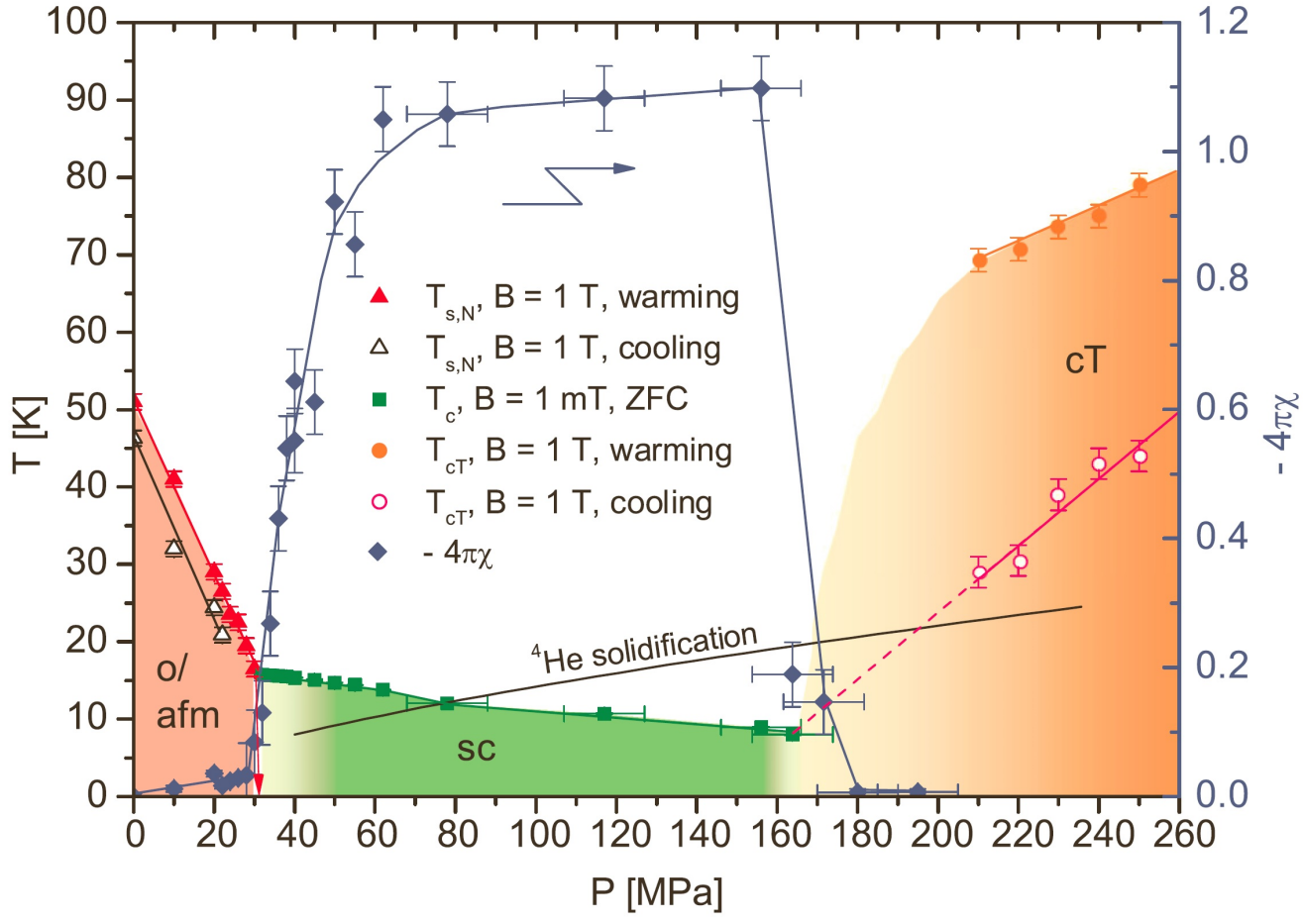


(Luetkens et al., *Nat. Mater.* **8**, 305 and Chu et al., *Physica C* **469**, 385)

$LaFeAs_{1-x}P_xO$: same phenomenology induced by chemical pressure resulting from As/P substitution (Wang et al., *EPL* **86**, 47002)

Charge doping vs. external pressures

Similarly to 1111: same effects in $Ca(Fe_{1-x}Co_x)_2As_2$

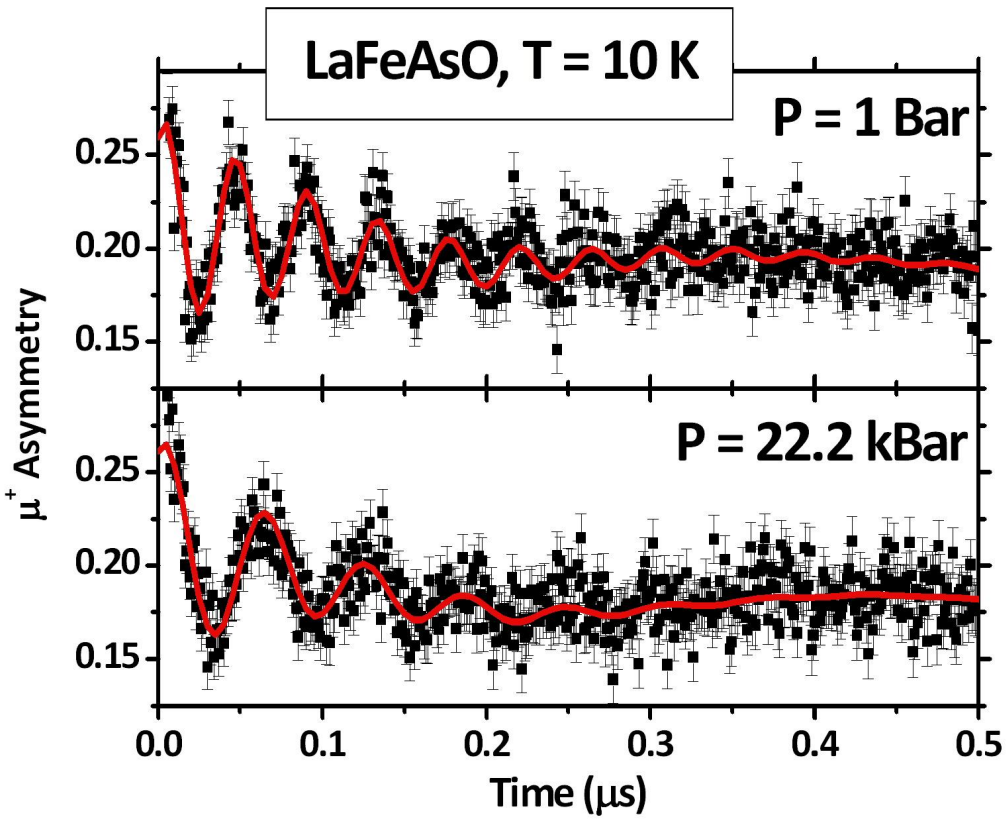


(Gati et al., *PRB* **86**, 220511(R))

μ^+SR under hydrostatic pressure ($P \leq 2.5$ GPa)

$$A_T(t) = A_0 \left[a_{PC} e^{-\frac{\sigma^{PC^2} t^2}{2}} \right] + A_0 (1 - a_{PC}) \cdot \qquad \underline{(a_{PC} \simeq 0.5!)}$$

$$\cdot \left\{ [1 - V_m(T)] e^{-\frac{\sigma^2 t^2}{2}} + \left[a^{Tr}(T) F(t) D^{Tr}(t) + a^L(T) D^L(t) \right] \right\}$$



Long-range order: coherent precession, $\omega = \gamma_\mu B_\mu$ ($\gamma_\mu = 135.54$ MHz/T)

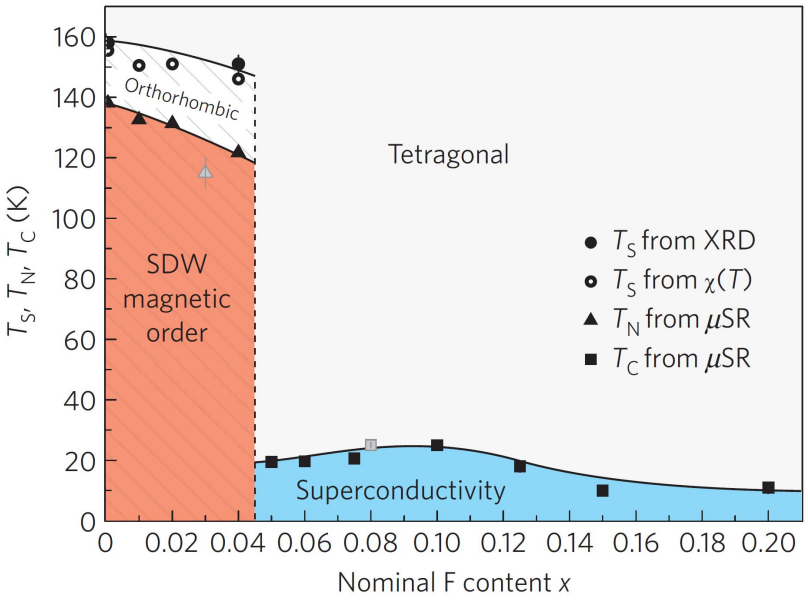
$$B_\mu(T) =$$

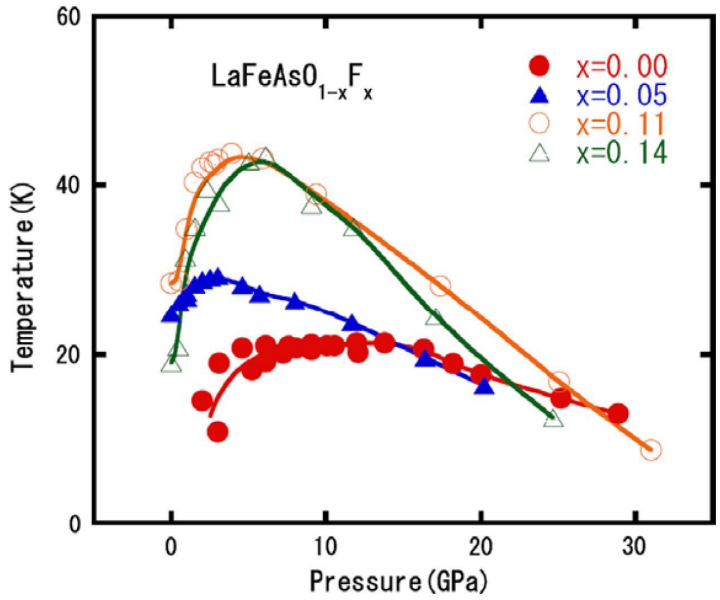
$$= | \underbrace{\mathbf{B}_{\mathrm{dip}}(\mathbf{r}_\mu)}_{\text{dipolar}} + \underbrace{\mathbf{B}_{\mathrm{c}}(\mathbf{r}_\mu)}_{\text{contact}} + \underbrace{\mathbf{B}_{\mathrm{L}}}_{\text{Lorentz}} |$$

Lightly-doped $LaFeAsO_{1-x}F_x$ ($x = 0.055$)

Phase diagram: also scanned with P as tuning parameter **avoiding direct modification of the chemical doping**

SC induced even in undoped LaFeAsO ($P \gtrsim 3 \div 4$ GPa)





(Luetkens et al., *Nat. Mater.* **8**, 305 and Chu et al., *Physica C* **469**, 385)

$LaFeAs_{1-x}P_xO$: same phenomenology induced by chemical pressure resulting from As/P substitution (Wang et al., *EPL* **86**, 47002)

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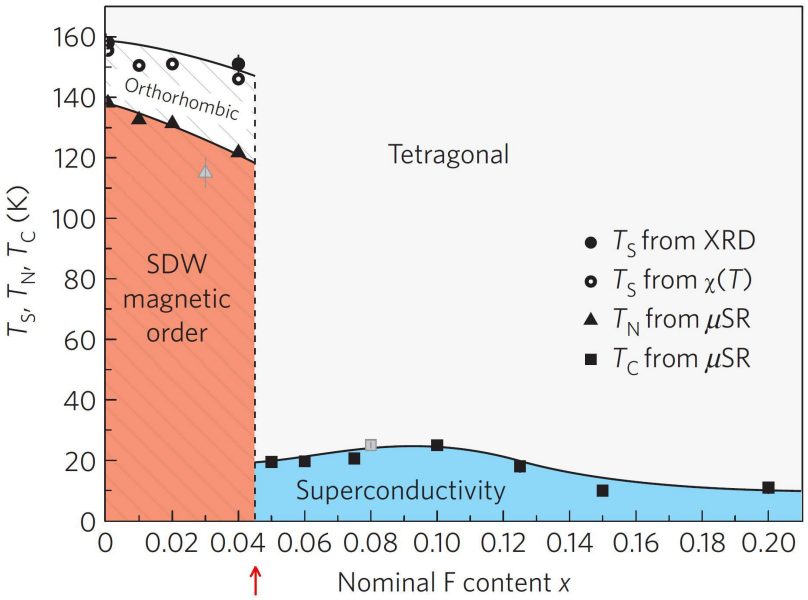

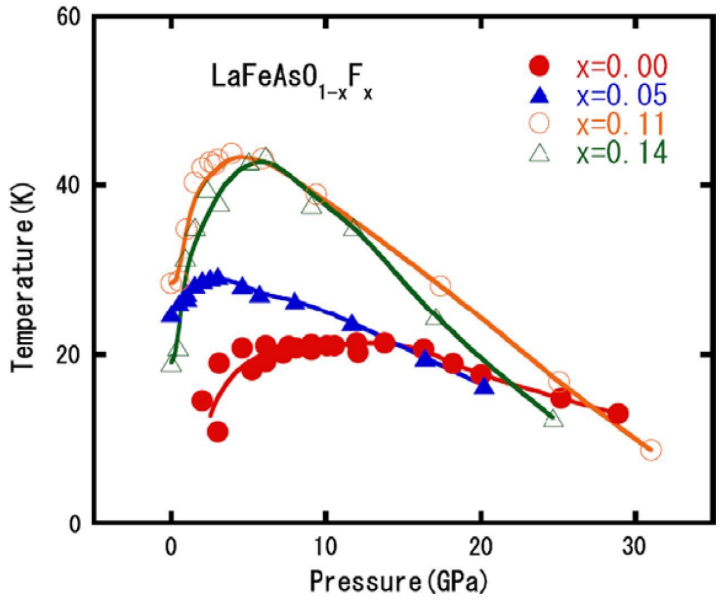

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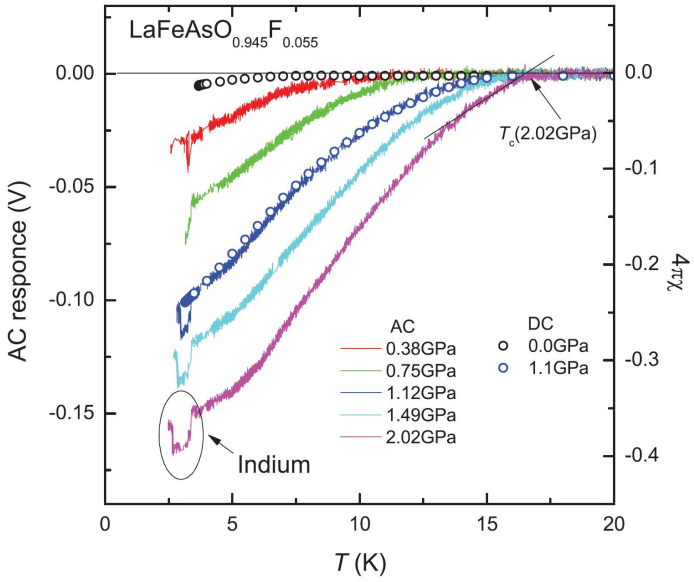
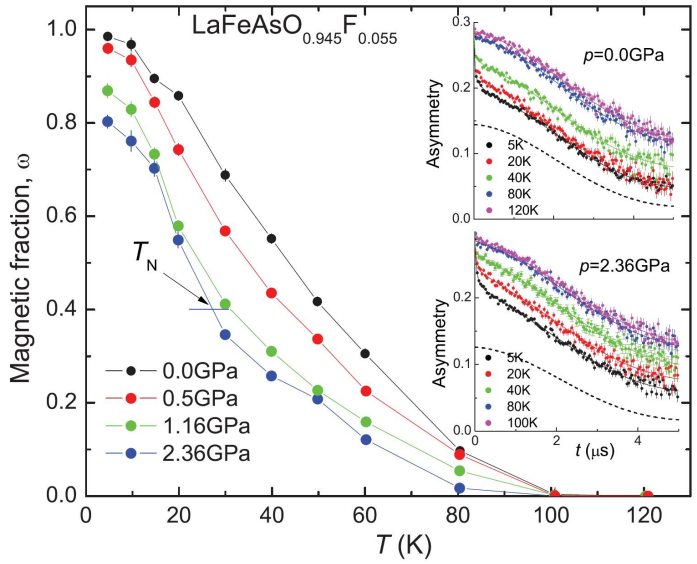
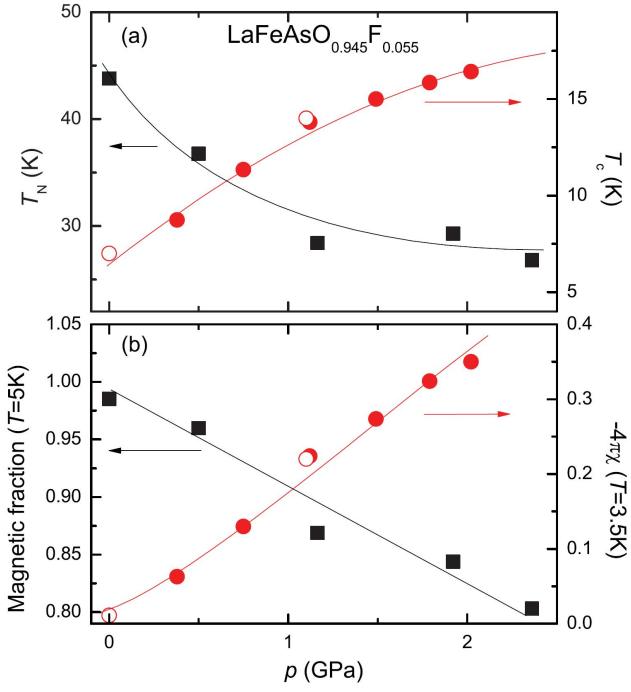




Pressure is highly effective in inducing **SC** and in suppressing **M**

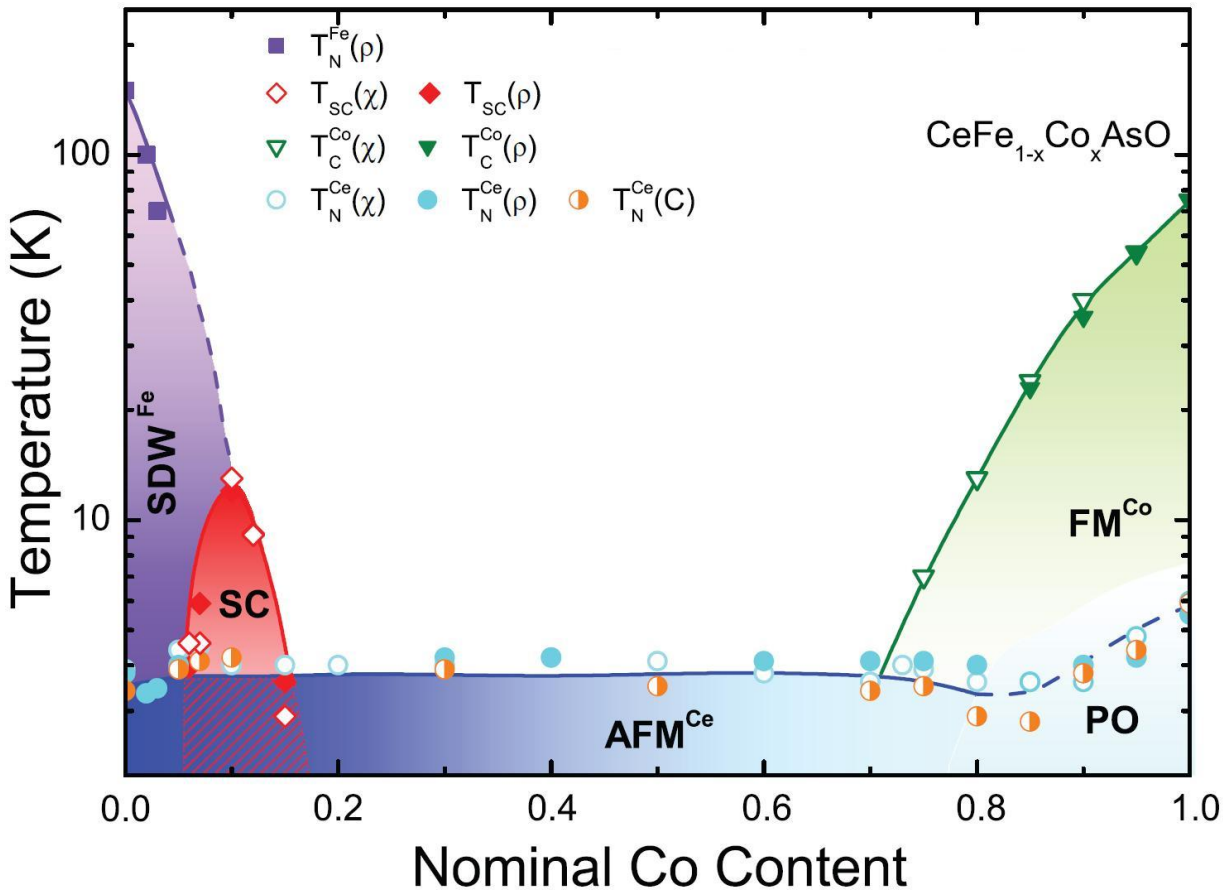
The two different phases strongly compete for volume

(Khasanov et al., PRB **84**, 100501(R))



Investigated systems - $Fe_{1-x}Co_x$ dilution

- Undoped ReFeAsO (Re = La, Ce, Pr, Sm)
- Undoped ReCoAsO and ReCoPO



(Shang et al., PRB **87**, 075148)

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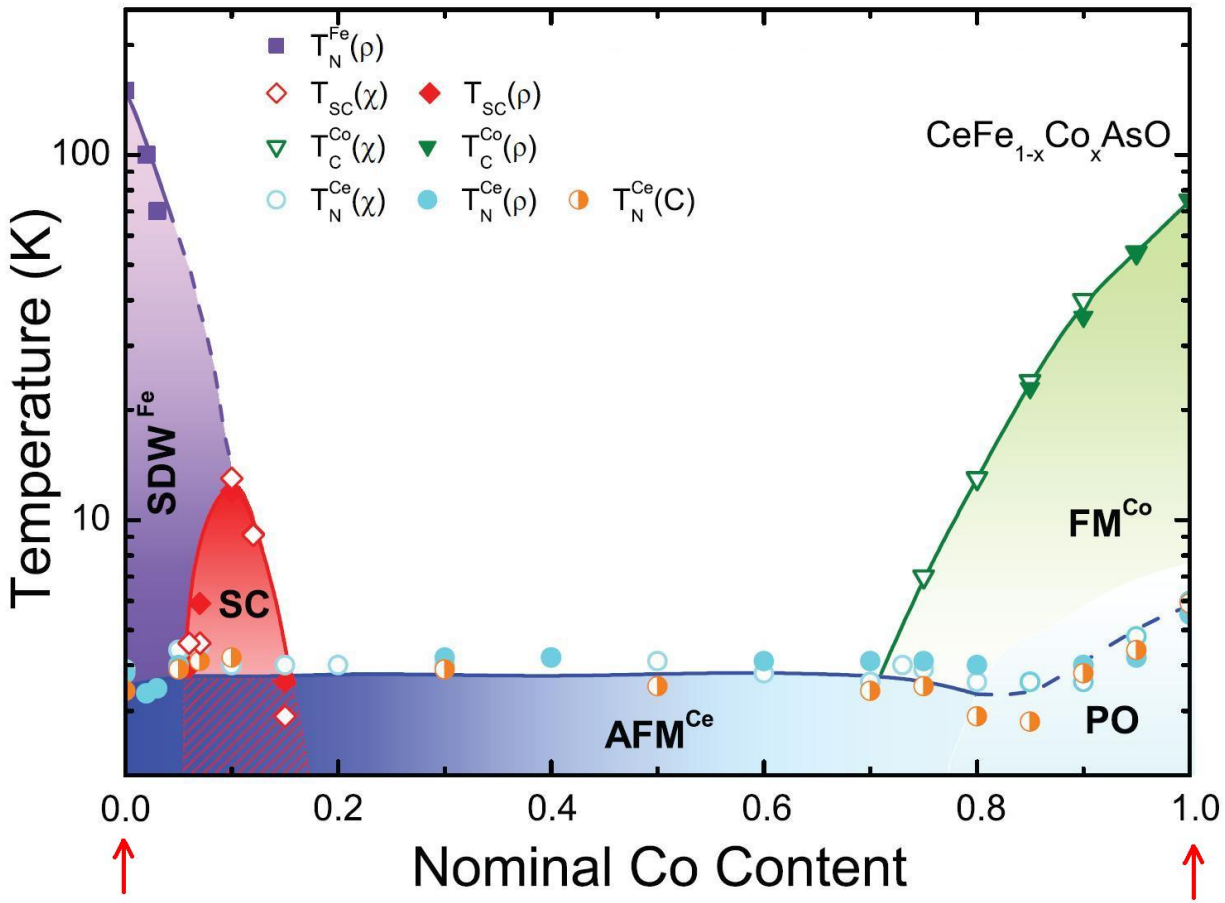

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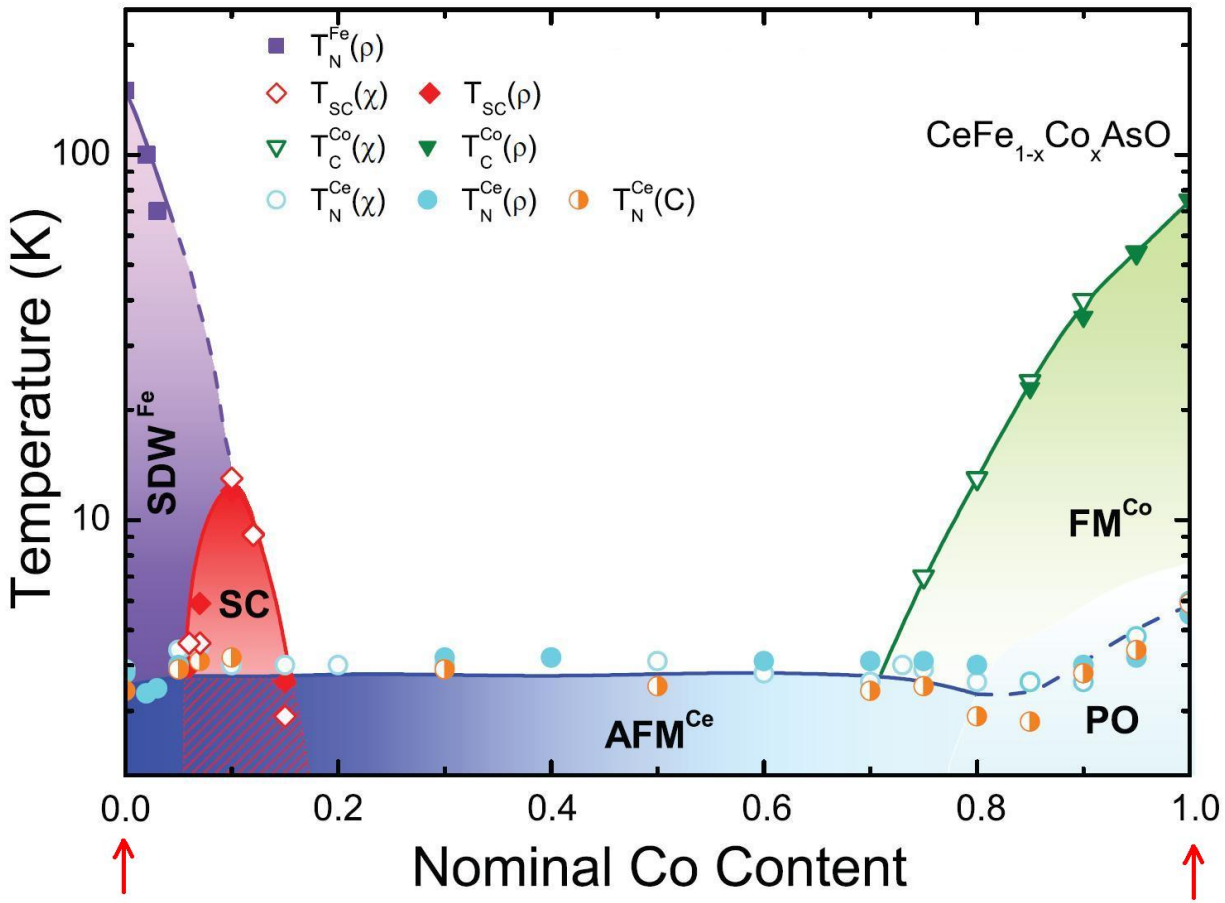

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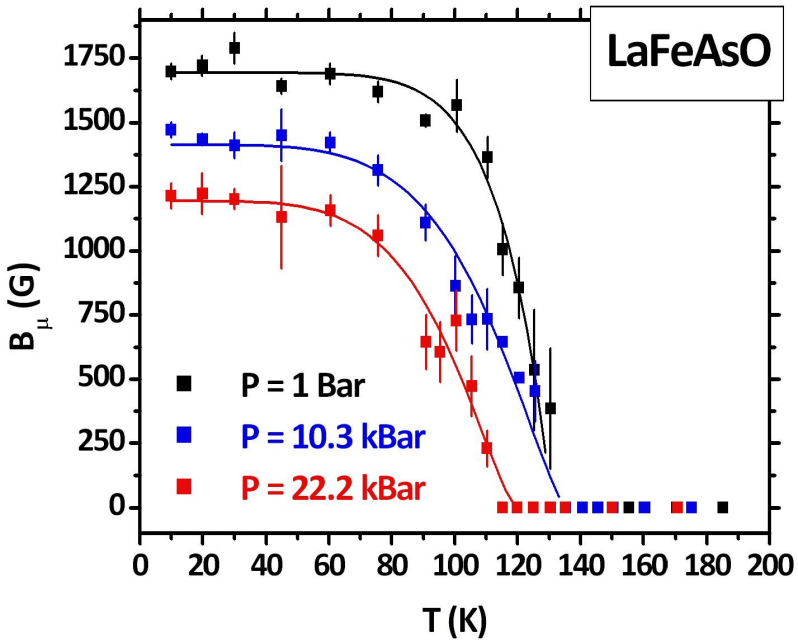

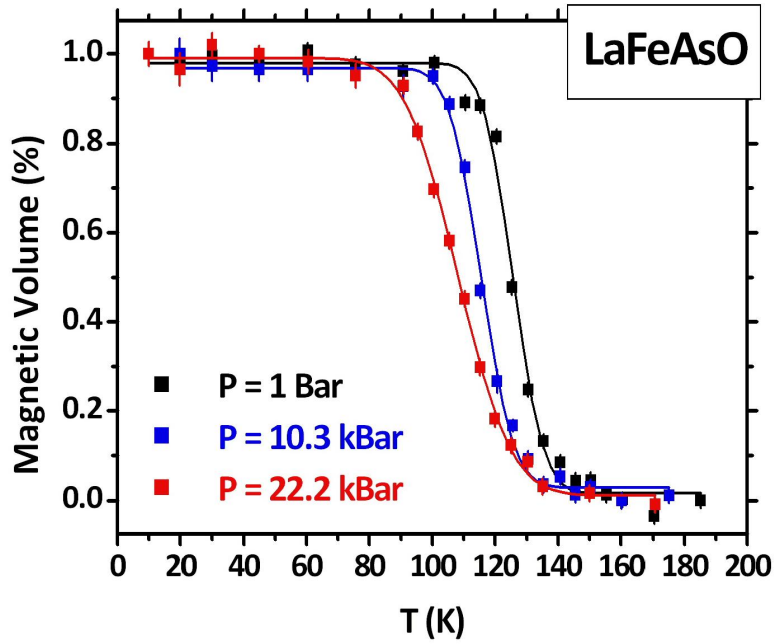

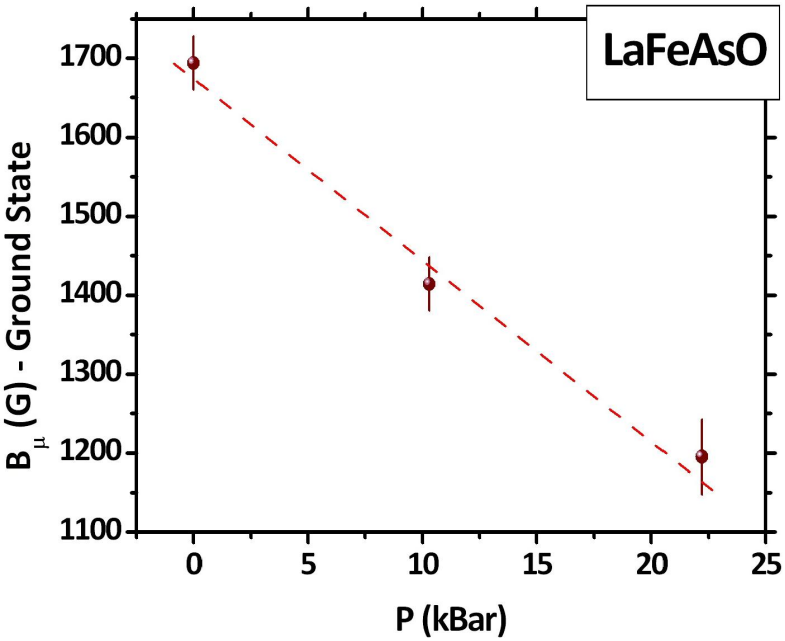

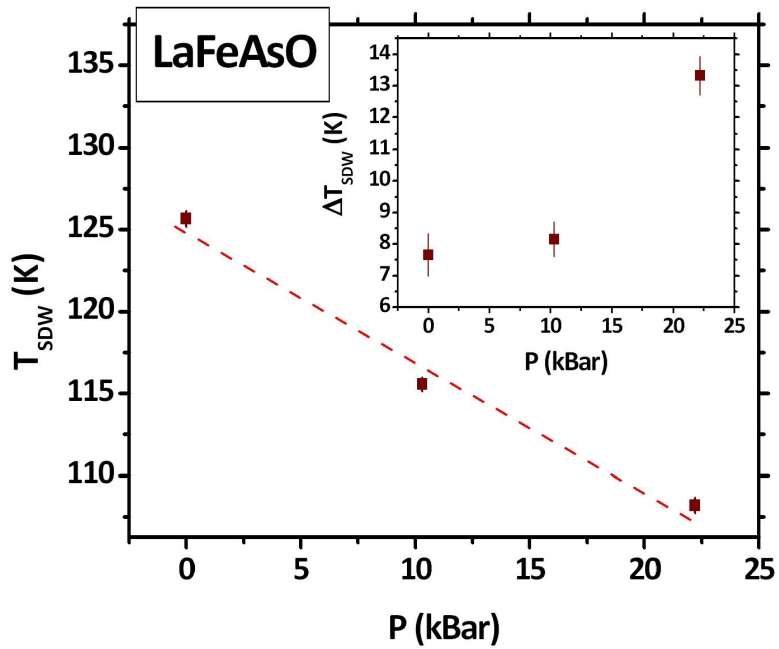

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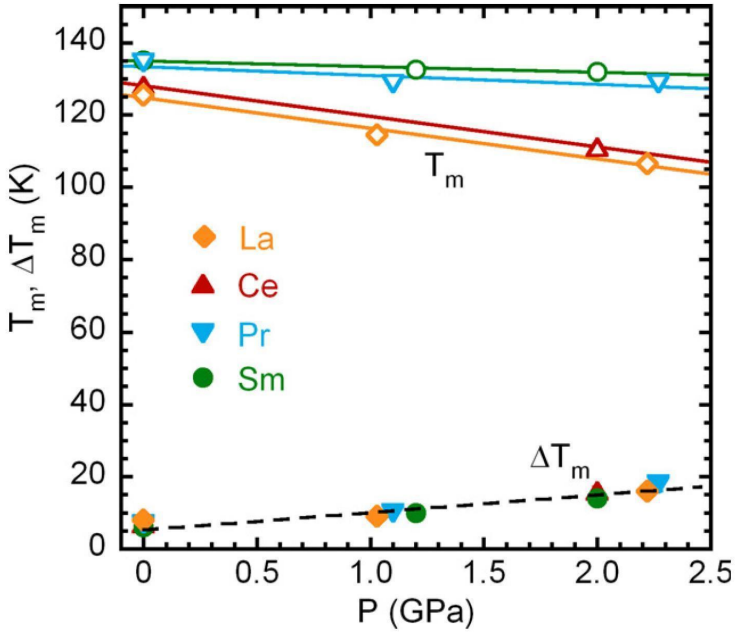
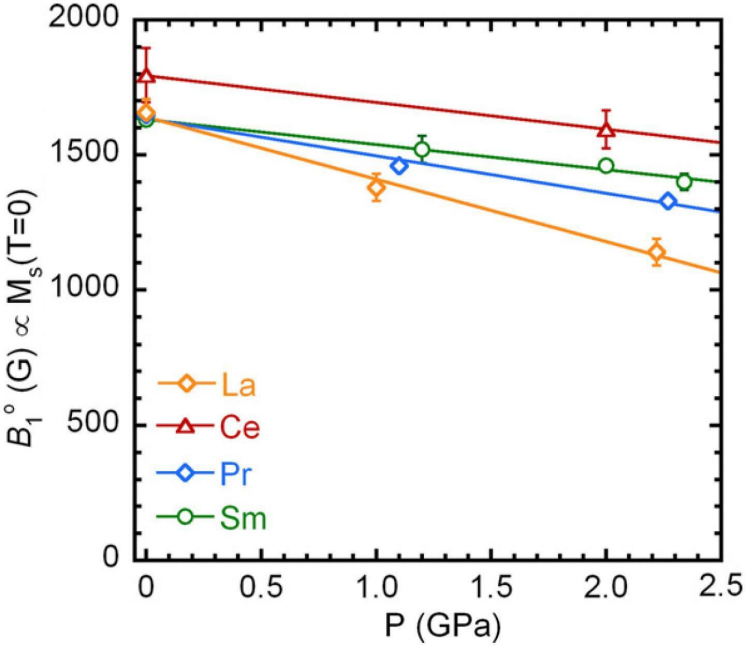
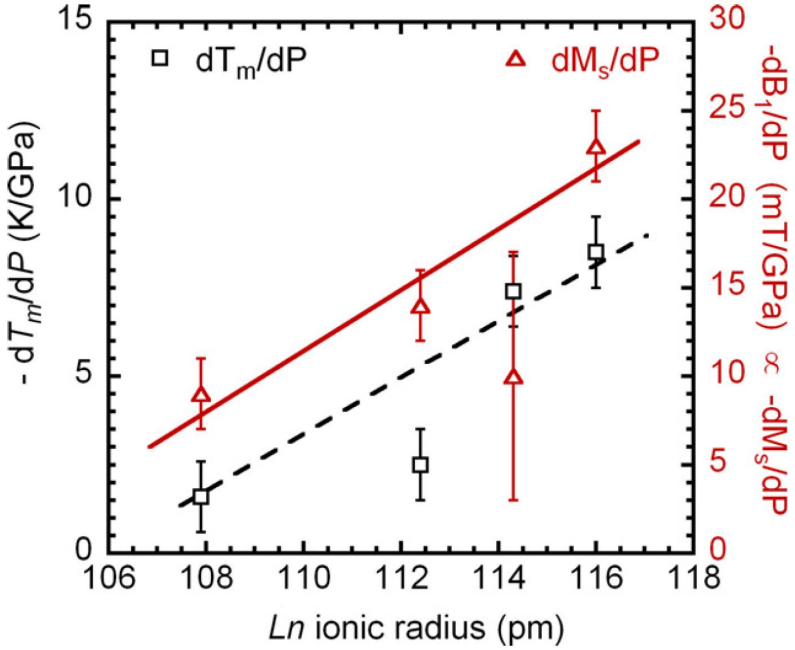




Strong dependence on Re ion

(De Renzi et al., SUST **25**, 084009)



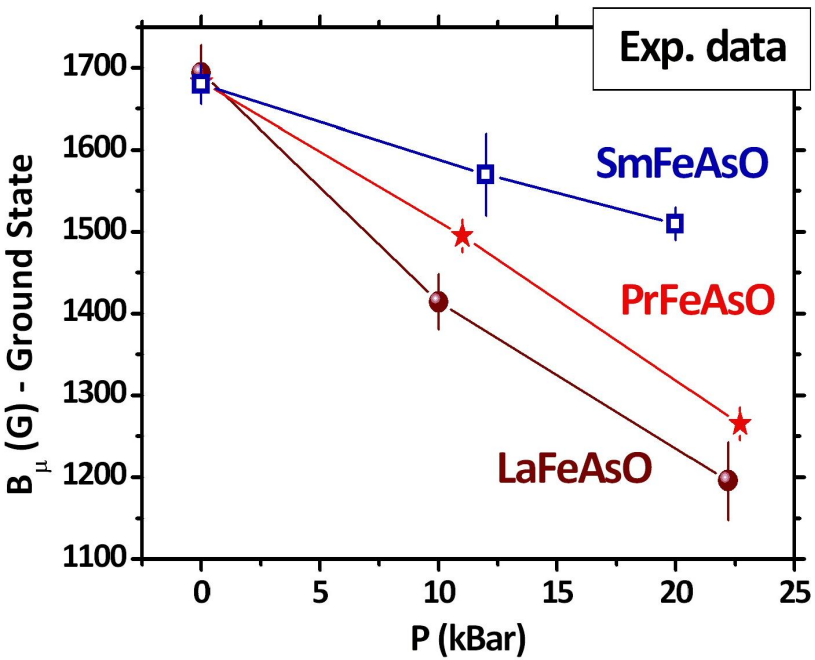
Almost linear correlation of pressure effects and ionic radii

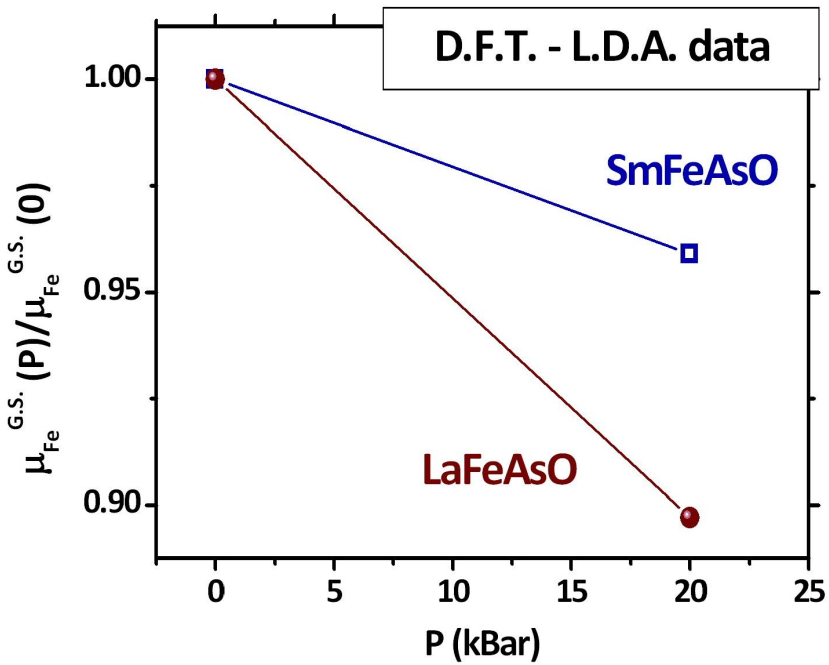
LaFeAsO is "softer" than SmFeAsO

Undoped ReFeAsO (Re = La, Ce, Pr, Sm)

- T_N and ground state B_μ: almost linear decrease with P
  Sizeable dependence on Re ion
- DFT calculations. Inputs: structural parameters (c/a), Re ionic radii, stripelike magnetic ground state of Fe

(see also Opahle et al., PRB **79**, 024509 and Yang et al., JAP **106**, 073910)





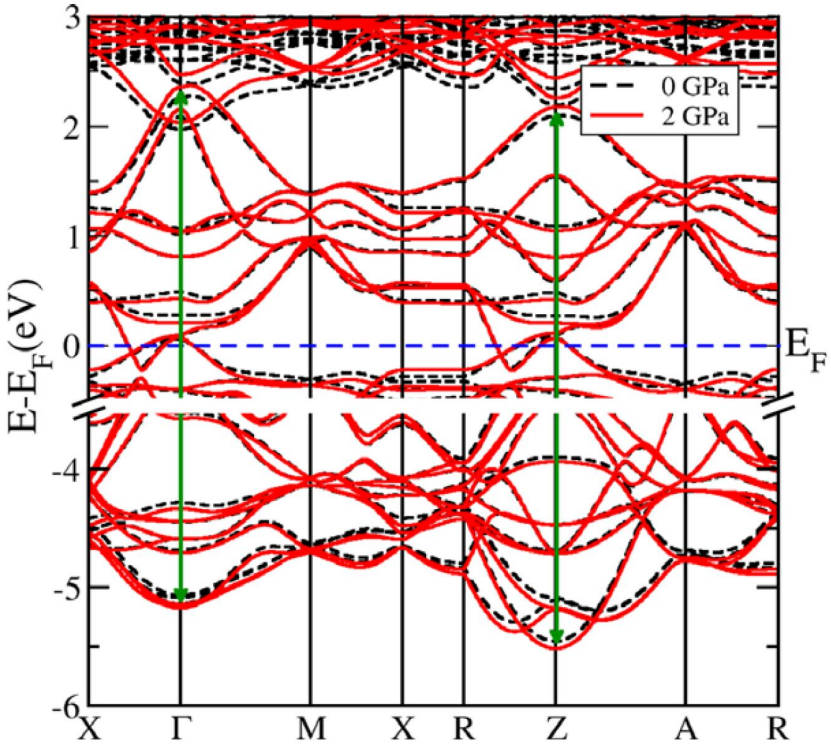
No quantitative agreement on :

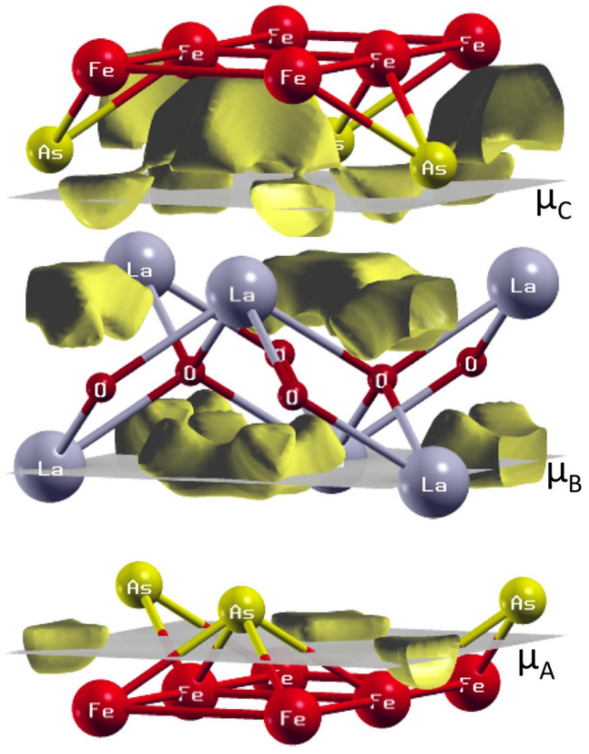
- Abs. value of μ_{Fe} (neutrons): DFT strongly overestimates
- % amount of reduction: DFT strongly underestimates

Undoped ReFeAsO (Re = La, Ce, Pr, Sm)

DFT: band-width increased by P

(De Renzi et al., SUST **25**, 084009)



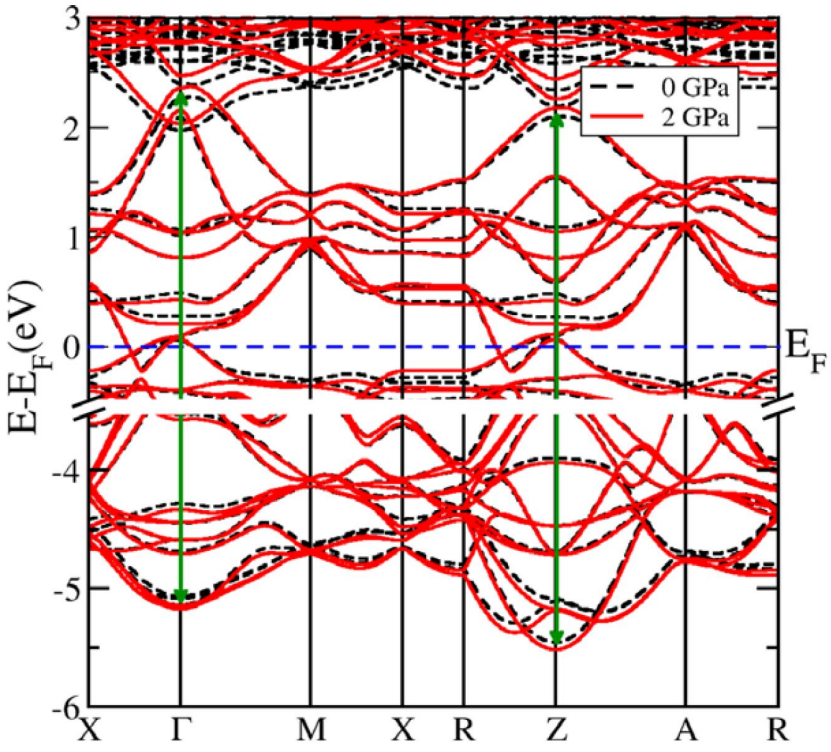


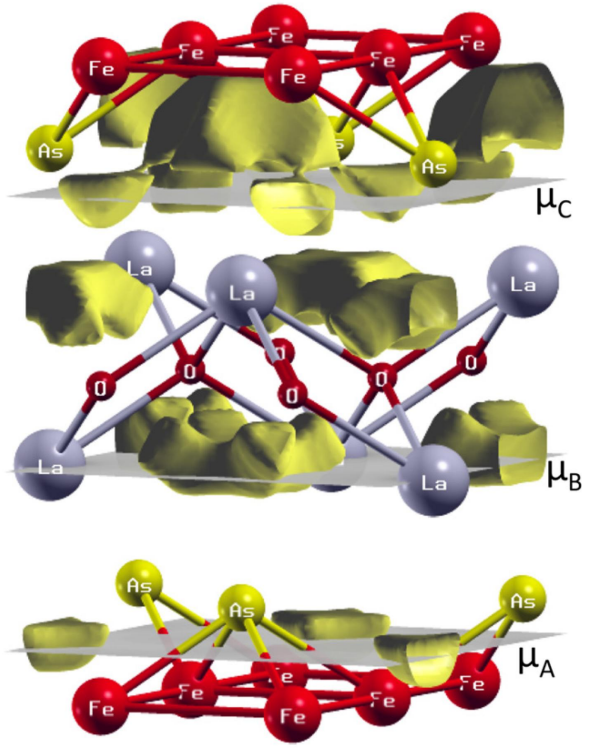
Site A: $B_\mu(T) = |\mathbf{B}_{\mathrm{dip}}(\mathbf{r}_\mu) + \mathbf{B}_{\mathrm{c}}(\mathbf{r}_\mu) + \mathbf{B}_{\mathrm{L}}|$

Undoped ReFeAsO (Re = La, Ce, Pr, Sm)

DFT: band-width increased by P

(De Renzi et al., SUST **25**, 084009)



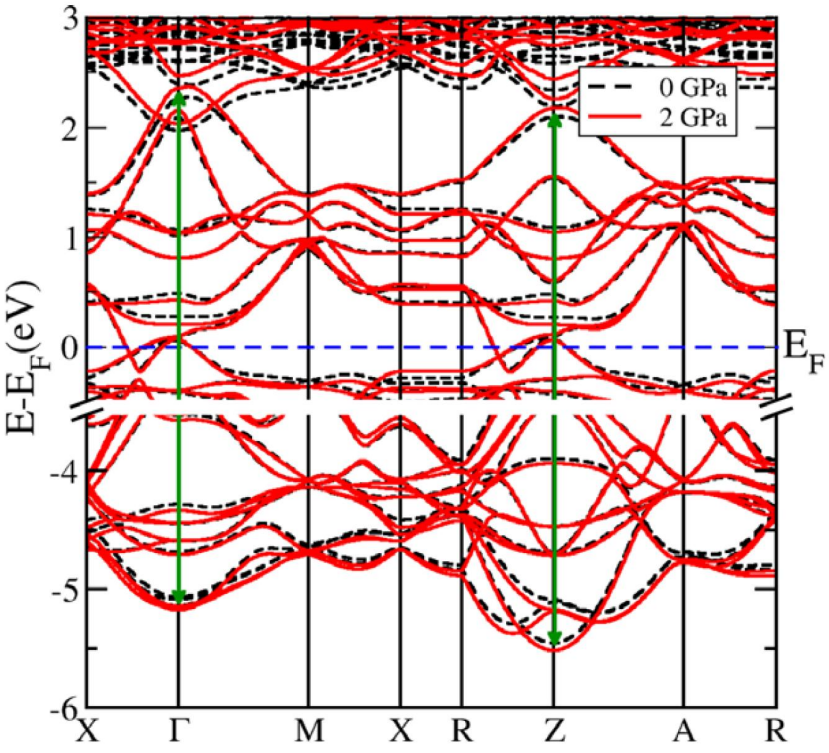


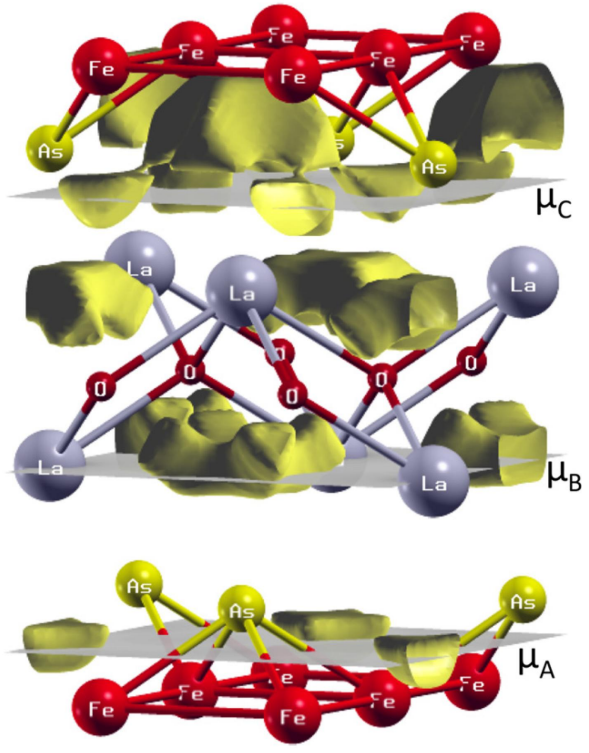
Site A: $B_\mu(T) = |\mathbf{B}_{\mathrm{dip}}(\mathbf{r}_\mu) + \underbrace{\mathbf{B}_{\mathrm{c}}(\mathbf{r}_\mu)}_{\text{NO!}} + \underbrace{\mathbf{B}_{\mathrm{L}}}_{\text{NO!}}|$ **(AFM ordering)**

Undoped ReFeAsO (Re = La, Ce, Pr, Sm)

DFT: band-width increased by P

(De Renzi et al., SUST **25**, 084009)

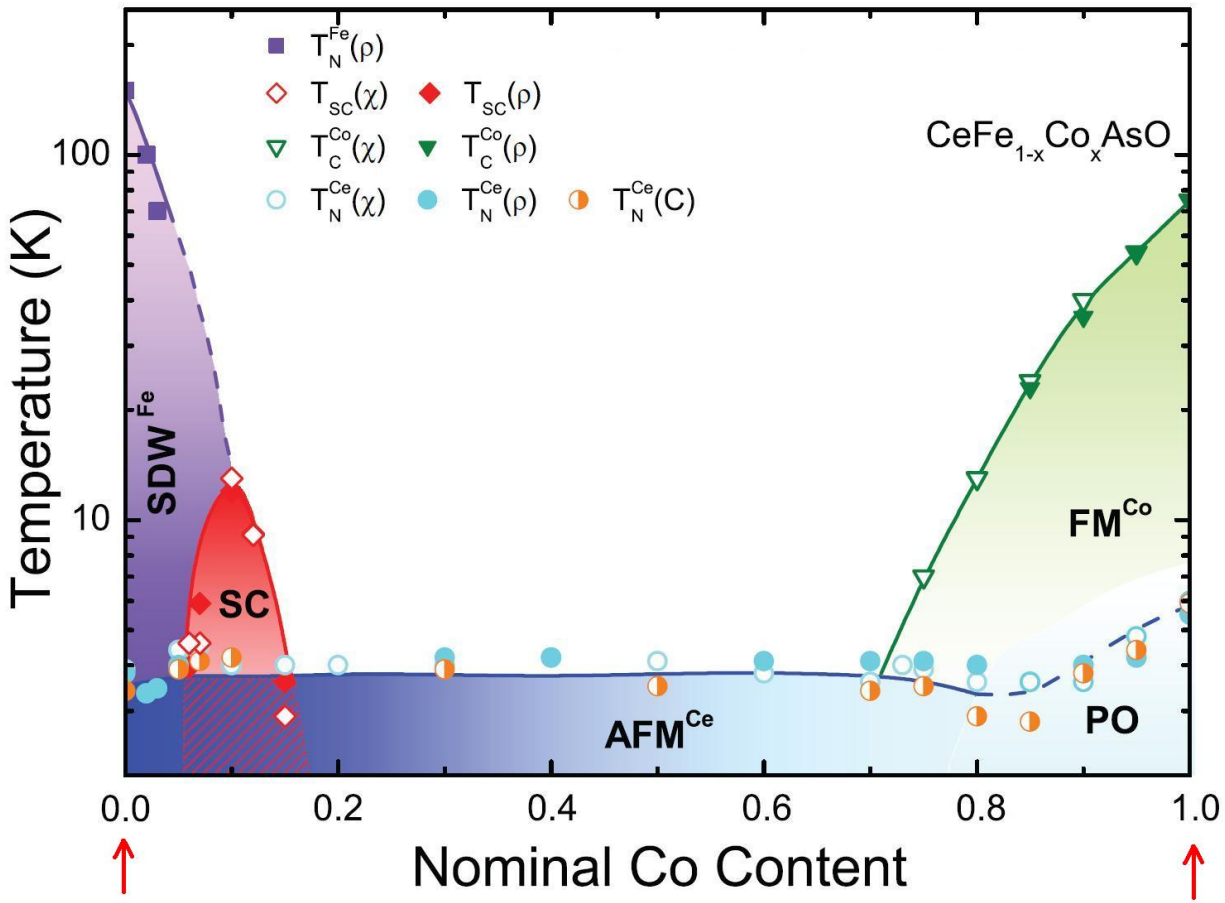




$\mu_{Fe} = 0.68 \pm 0.02\ \mu_B$ - agreement with NMR and neutron diffraction (Grafe et al., NJP **11**, 035002 and Qureshi et al., PRB **82**, 184521)

Investigated systems - $Fe_{1-x}Co_x$ dilution

- Undoped ReFeAsO (Re = La, Ce, Pr, Sm)
- Undoped ReCoAsO and ReCoPO



(Shang et al., PRB **87**, 075148)

Investigated systems - $Fe_{1-x}Co_x$ dilution

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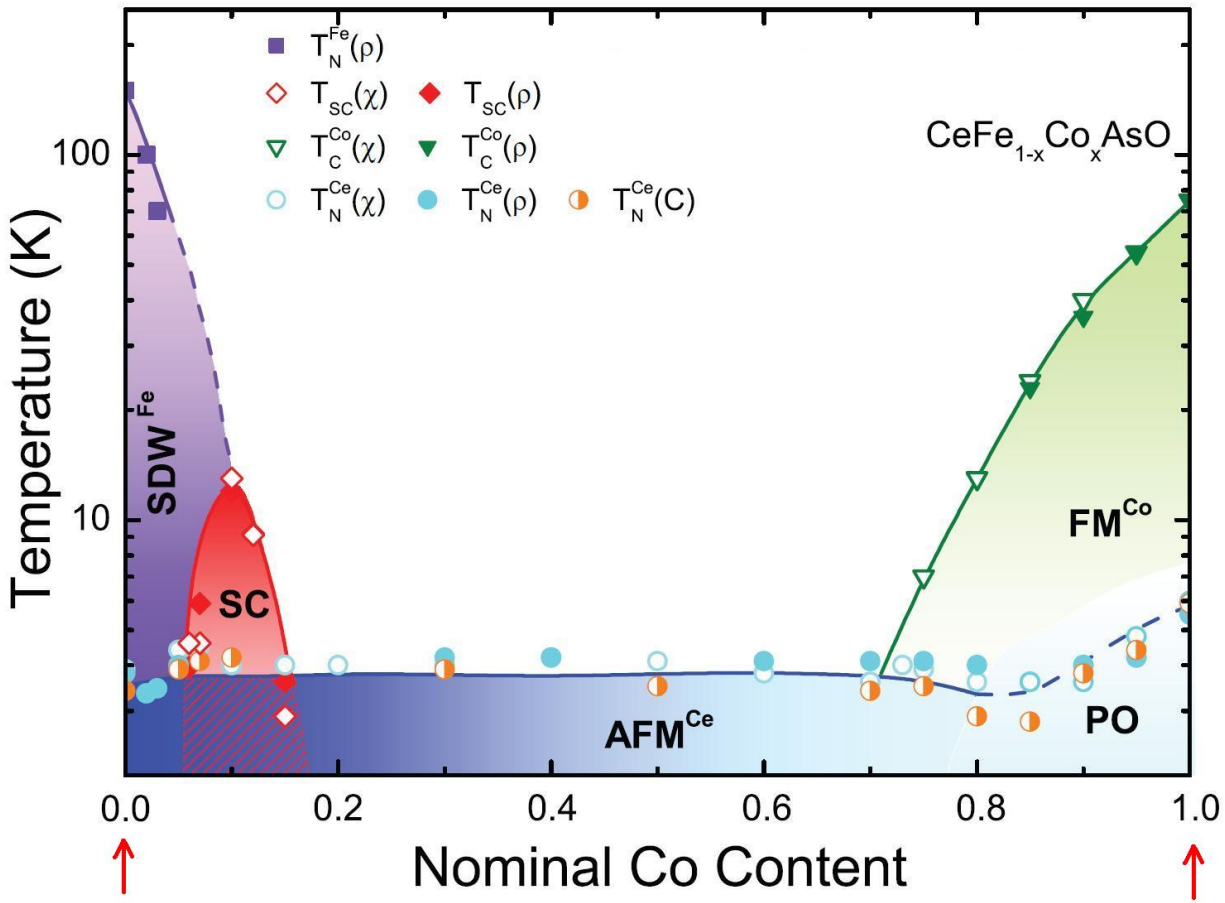

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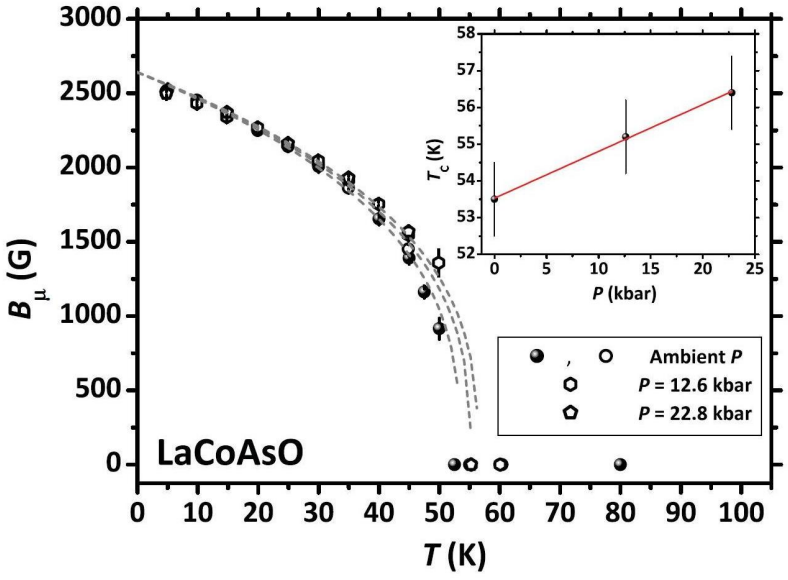
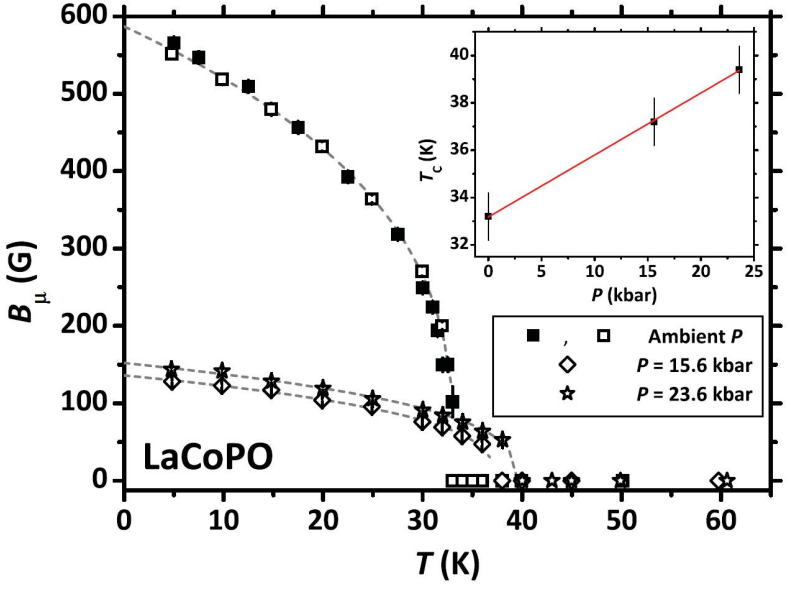


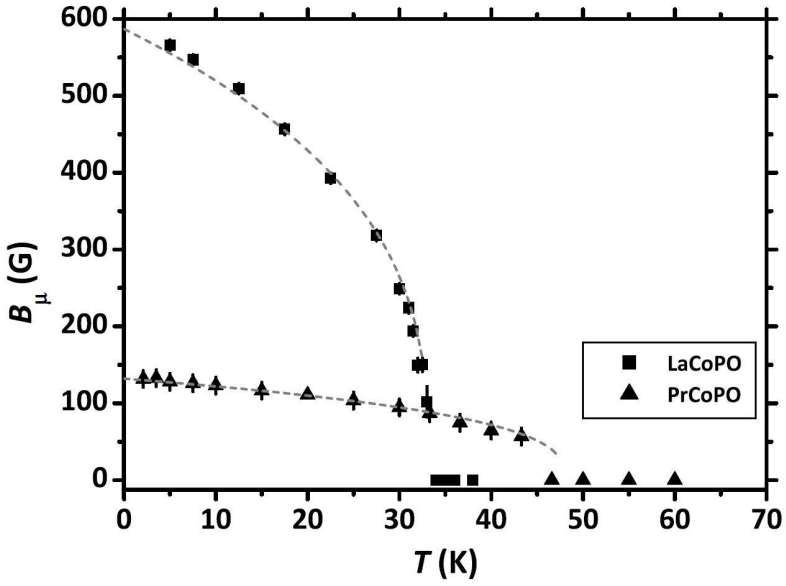


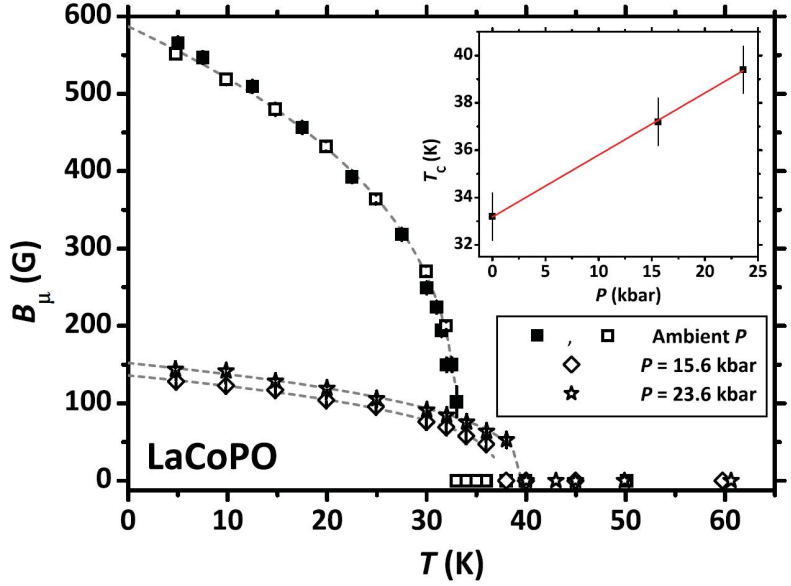
(Prando et al., PRB **87**, 064401)

Sizeable differences with respect to ReFeAsO

- Magnetic critical temperatures enhanced by P
- LaCoPO much more sensible than LaCoAsO in spite of stronger chemical pressure
- Clearly discontinuous behaviour is displayed in LaCoPO

Undoped ReCoAsO and ReCoPO





(Prando et al., PRB **87**, 064401)

Comparison among external and chemical (La/Pr) pressures

- **External and chemical pressure play the same role**
- Magnetic critical temperatures enhanced by P
- Internal field strongly suppressed
- **Pr does not magnetically contribute - only shrinkage**

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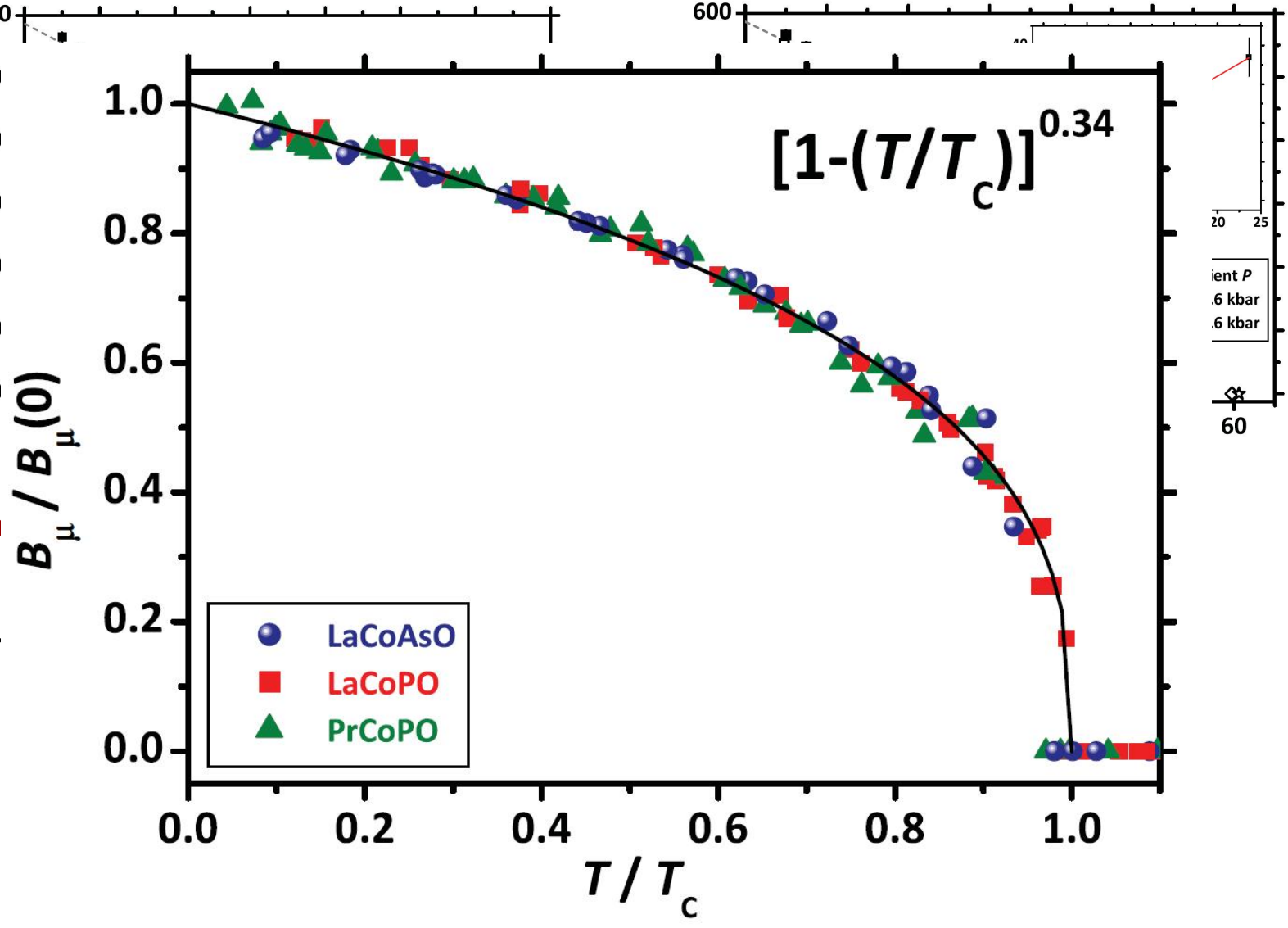

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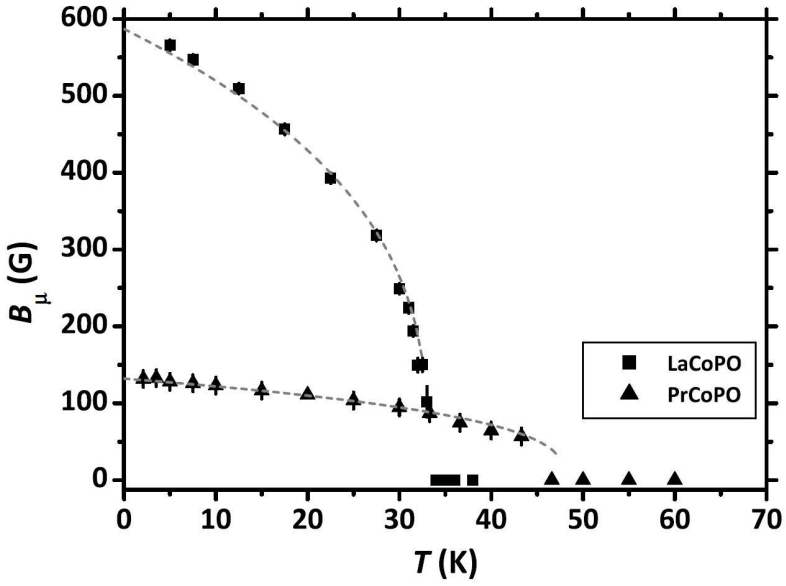

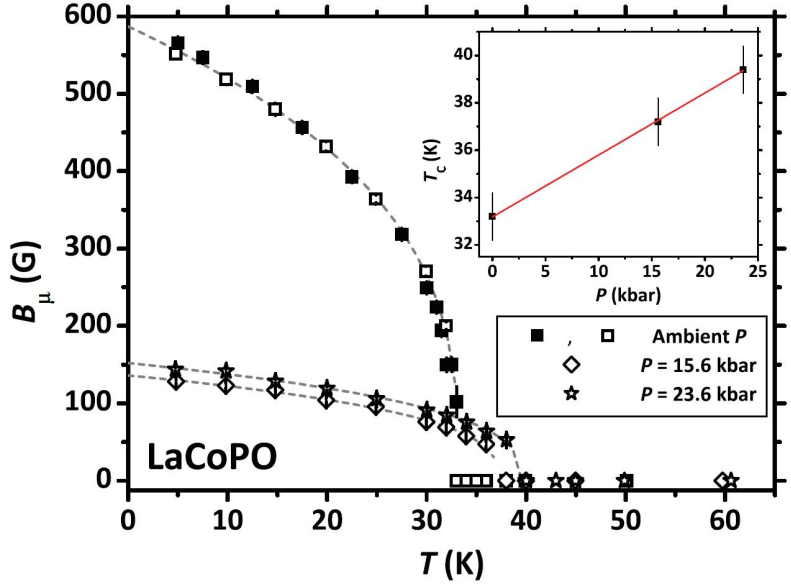

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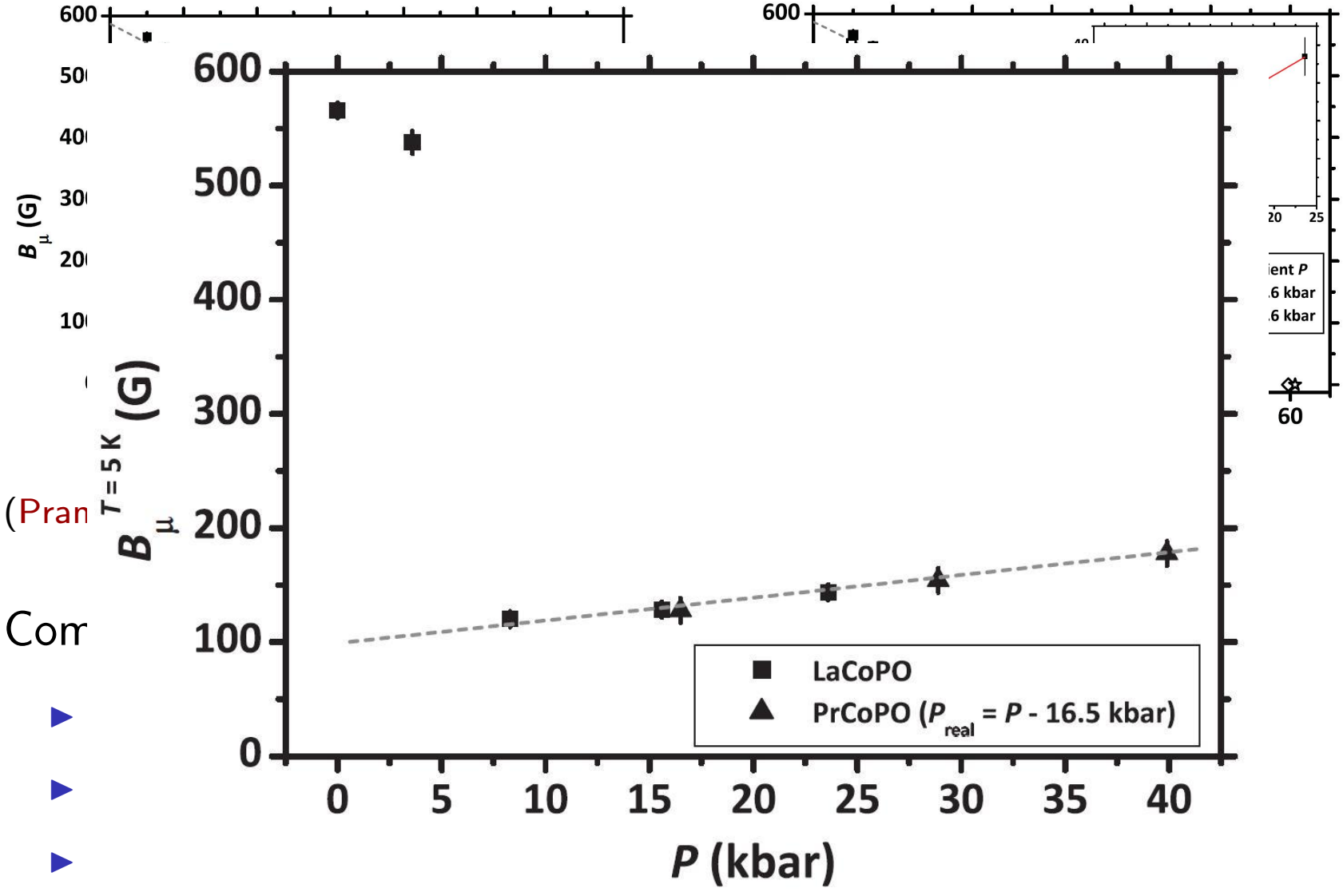

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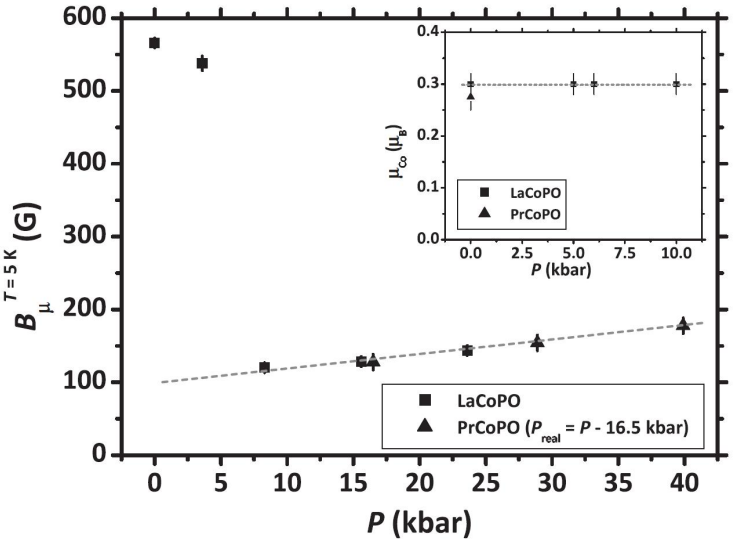

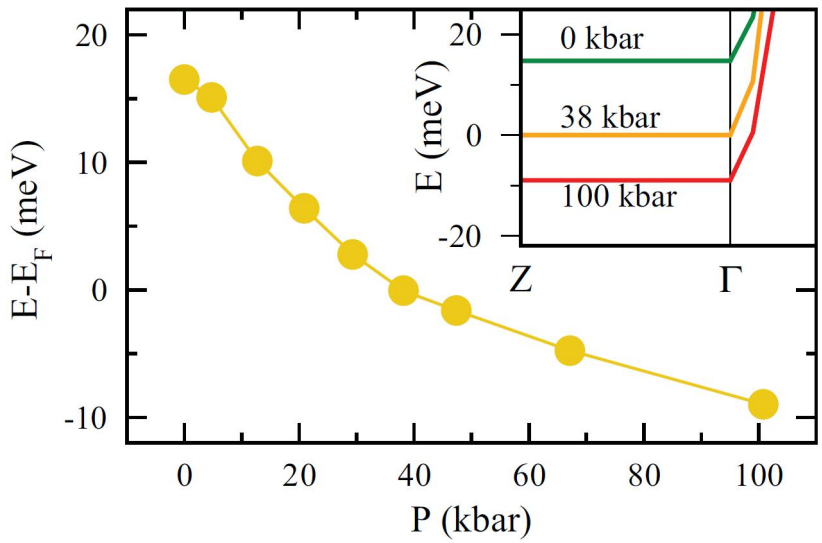

(Prando et al., PRB **87**, 064401)

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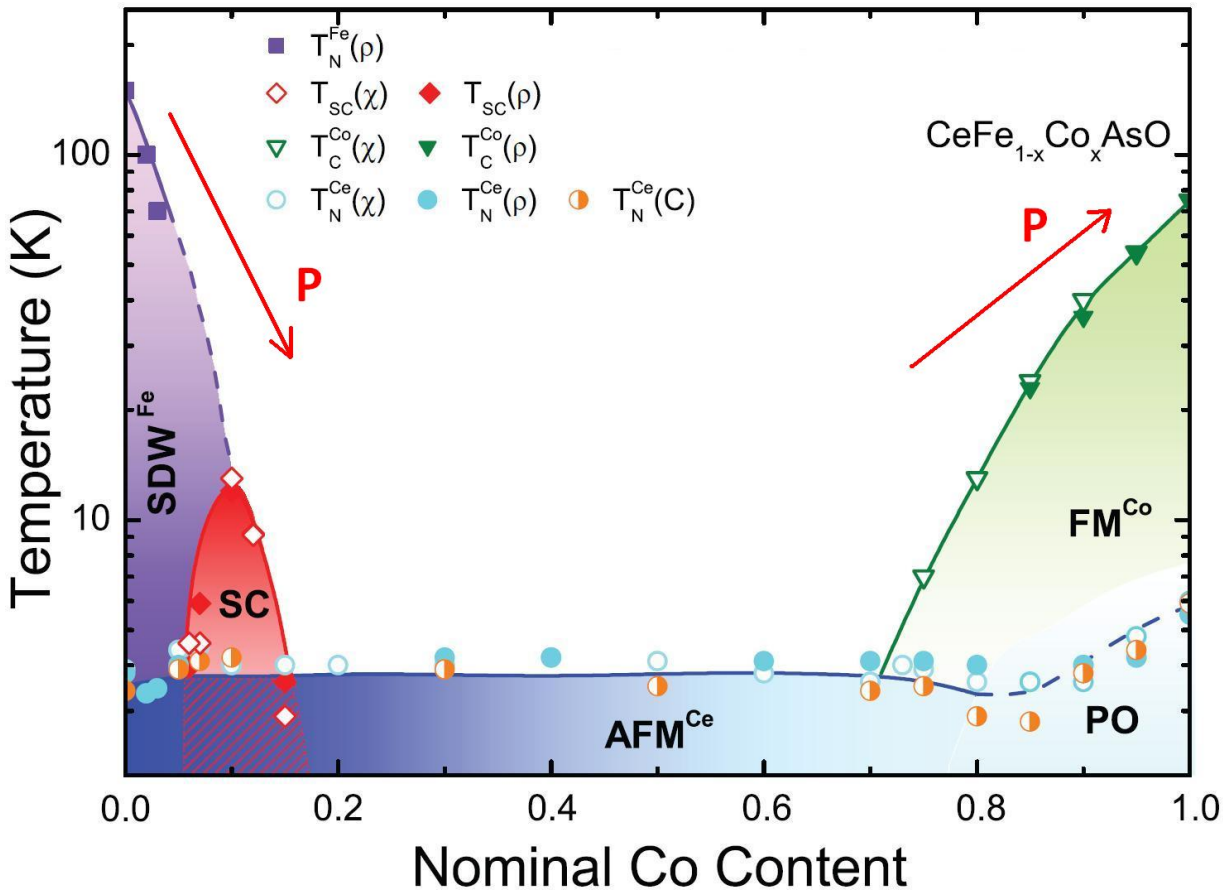
FM ordering: $B_\mu(T) = |\mathbf{B}_{dip}(\mathbf{r}_\mu) + \mathbf{B}_c(\mathbf{r}_\mu) + \mathbf{B}_L|$

Change in the electron density: $\mathbf{B}_c(\mathbf{r}_\mu)$ modified accordingly

- DFT calculations: electronic band crossing E_F at $P \simeq 40$ kbar
- **Likely modification of the hyperfine contact term**

Conclusions

- Undoped ReFeAsO (Re = La, Ce, Pr, Sm)
- Undoped ReCoAsO and ReCoPO



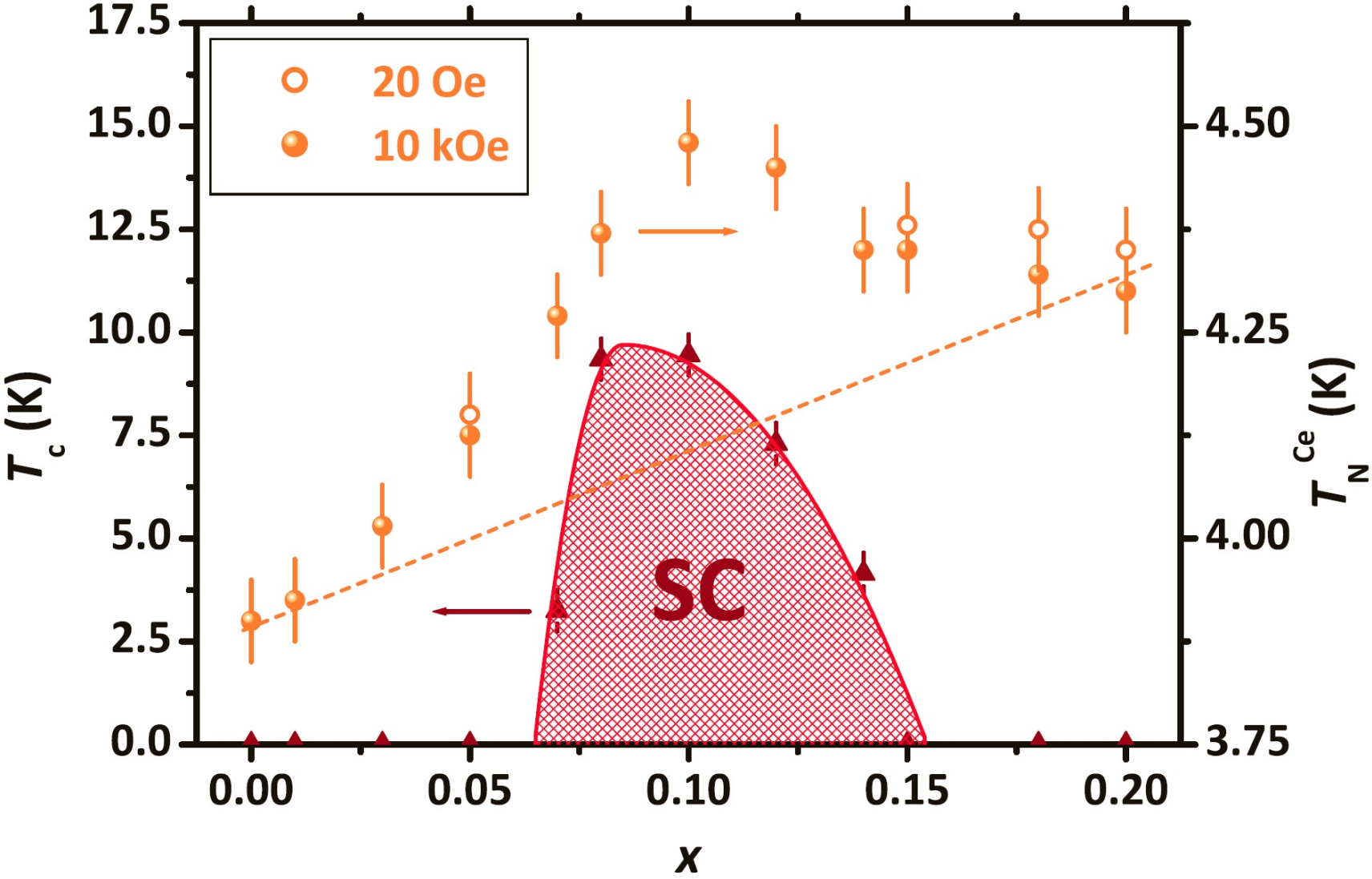
(Shang et al., PRB **87**, 075148)

Conclusions

μ^+SR + Pressure: useful to access phase diagram of 1111 pnictides

- **Lightly-doped $LaFeAsO_{1-x}F_x$**
  - Macroscopic segregation of **M** and **SC**
  - Possible change of pairing symmetry between La1111 and Ce1111, Sm1111 **?**
- **Undoped ReFeAsO (Re = La, Ce, Pr, Sm)**
  - Negative effect of pressure on both μ_{Fe} and T_N
  - Sizeable Re dependence: linear scaling with ionic radii (qualitative agreement from DFT)
- **Undoped ReCoAsO and ReCoPO**
  - Positive effect of pressure on T_C and negligible effect on μ_{Co}
  - Clear equivalence of external and chemical pressures
  - DFT suggests non-trivial sudden modifications of the electronic band structure modifying hyperfine coupling to μ^+ in turn
  - Planned: x-rays and ^{31}P-NMR under P (investigate structure and hyperfine term at the nuclei)

Out-of-plane vs. in-plane doping/disorder. $CeFeAsO_{1-x}F_x$ vs. $CeFe_{1-x}Co_xAsO$

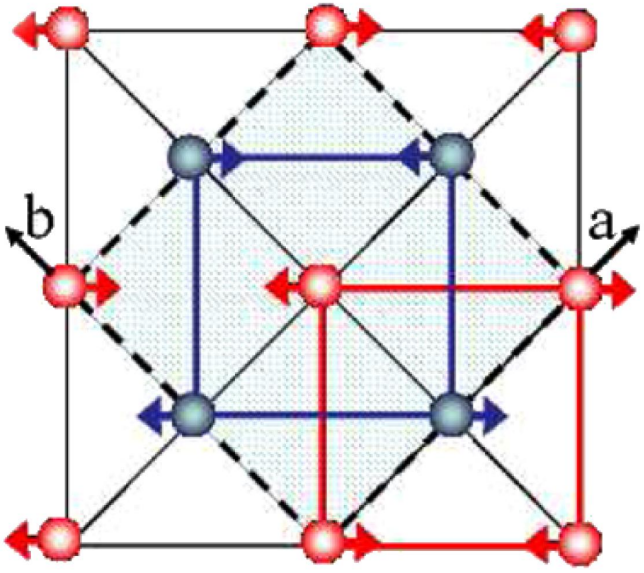


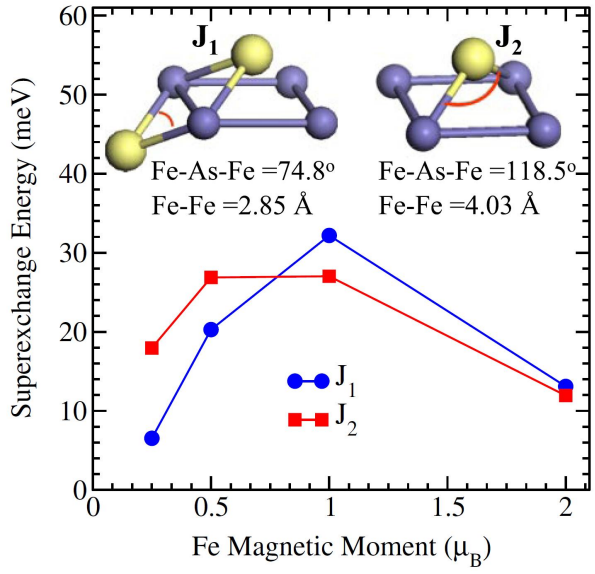
Enhancement of Ce^{3+} ordering on the top of SC dome

$LaFe_{1-x}Ru_xAsO$ – Hints for magnetic frustration

Superexchange paths on the Fe square lattice: $J_{nn} \sim J_{nnn}$.
Competition of interactions leading to a fully-frustrated g.s.
(Yildirim, *PRL* **101**, 057010)

$J_1 - J_2$ model: good agreement with experimental value of μ_{Fe}





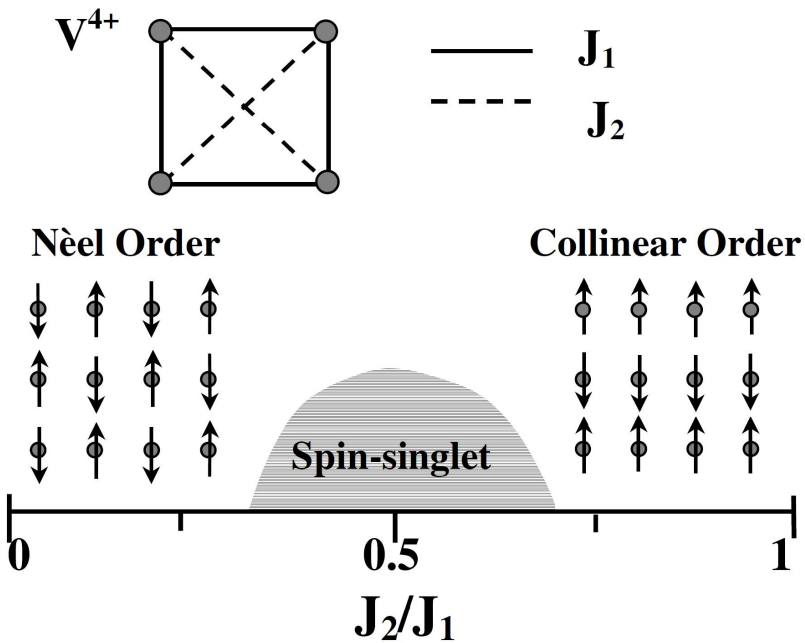
Selection of g.s. possibly associated with orthorombic-tetragonal structural phase transition ($T_{str} \gtrsim T_N$)

$LaFe_{1-x}Ru_xAsO$ – Hints for localization

- *Ab-initio* calculations: proximity to a Mott-like transition
  (Cao et al., *PRB* **77**, 220506; Si et al., *PRL* **101**, 076401)
- Experimental Wilson ratio $R = \frac{\pi^2 k_B^2}{3\mu_B^2}\frac{\chi_P}{\gamma} = 2.5 \div 6\ (> 1)$.
  (Brüning et al., *PRL* **101**, 117206; Baker et al., *NJP* **11**, 025010)

Electronic correlations: $U \sim t$ in one-band Hubbard Hamiltonian

$$\mathcal{H}_{Hubb} = -t \sum_{\langle i,j\rangle,\sigma} c^{\dagger}_{i,\sigma} c_{j,\sigma} + U \sum_i \prod_\sigma c^{\dagger}_{i,\sigma} c_{i,\sigma}$$



Pnictides: **multi-band** scenario

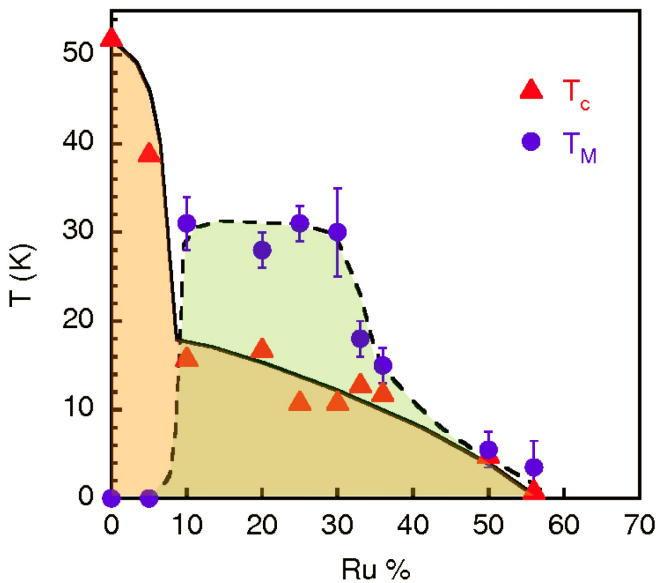
SDW band: possible localization effects. Analogies with $J_1 - J_2$ model in cuprates and vanadates
(Melzi et al., *PRL* **85**, 1318)

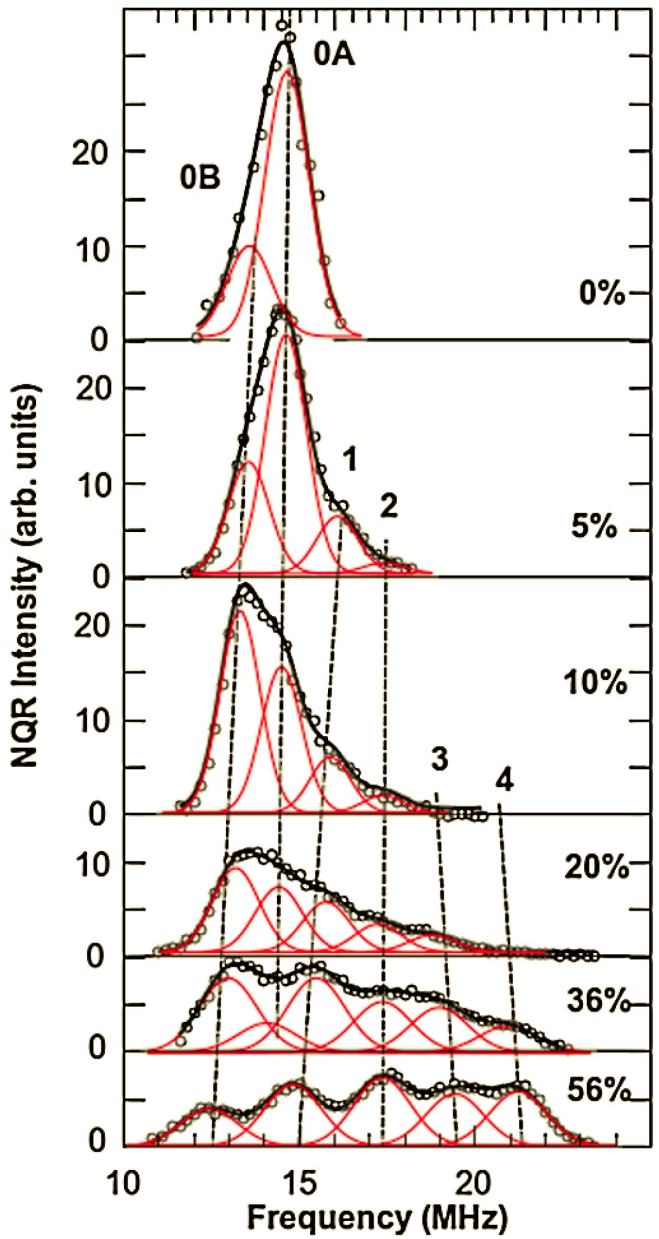
$Fe_{1-x}Ru_x$ substitution from optimal doping

Possibly in favour of **SC**
mediated by spin-fluctuations

^{75}As-NQR gives support to
nanoscopic coexistence of phases

(Sanna et al., *PRL* **107**, 227003
+ *PRB* **87**, 134518)





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Weight of the 2 peaks
as a function of x scale with
the two characteristic critical T

(Sanna et al., *PRL* **107**, 227003
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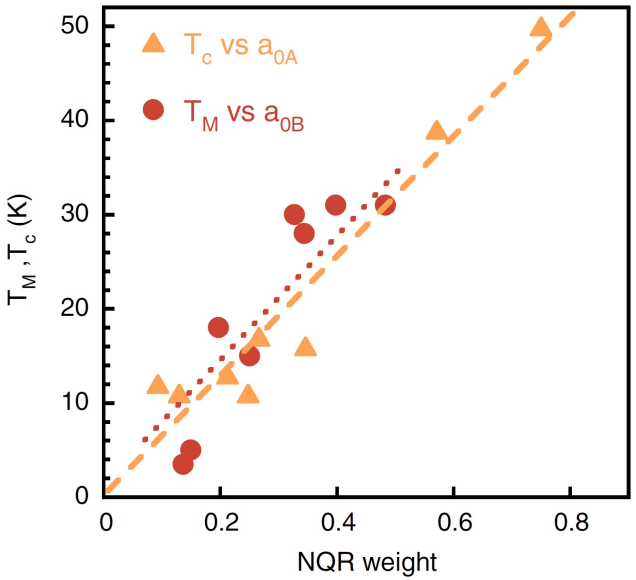
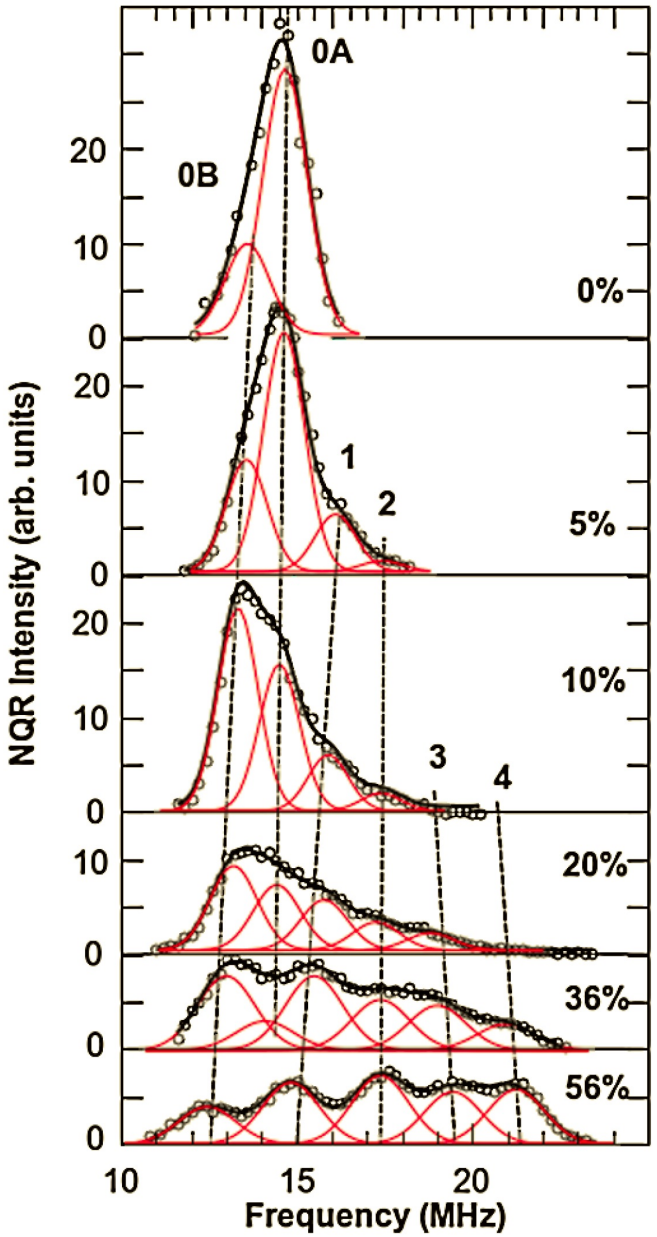
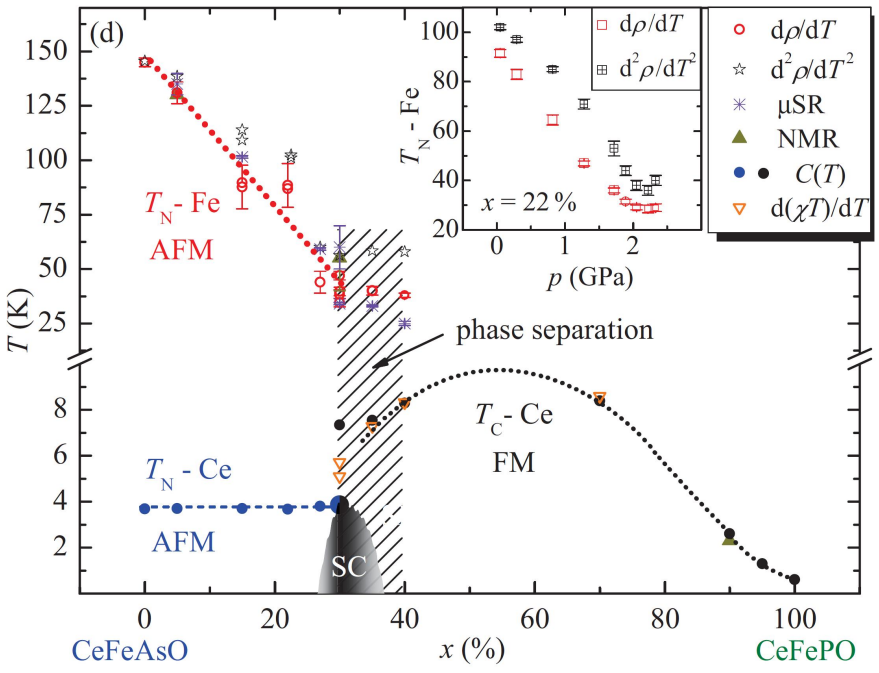


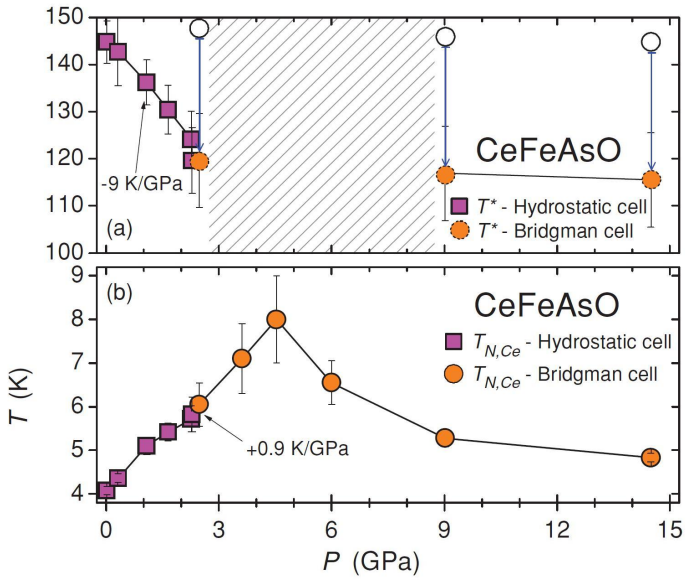


Chemical vs. external pressures

Sizeable $f - d$ hybridization is at work (Prando et al., PRB **81**, 100508(R))

Competition between superconductivity and Kondo effect
Exemplary case: $CeFeAs_{1-x}P_xO$ (Jesche et al., PRB **86**, 020501(R))





Magnetic features are qualitatively reproduced by application of pressure on CeFeAsO (Zocco et al., PRB **83**, 094528)

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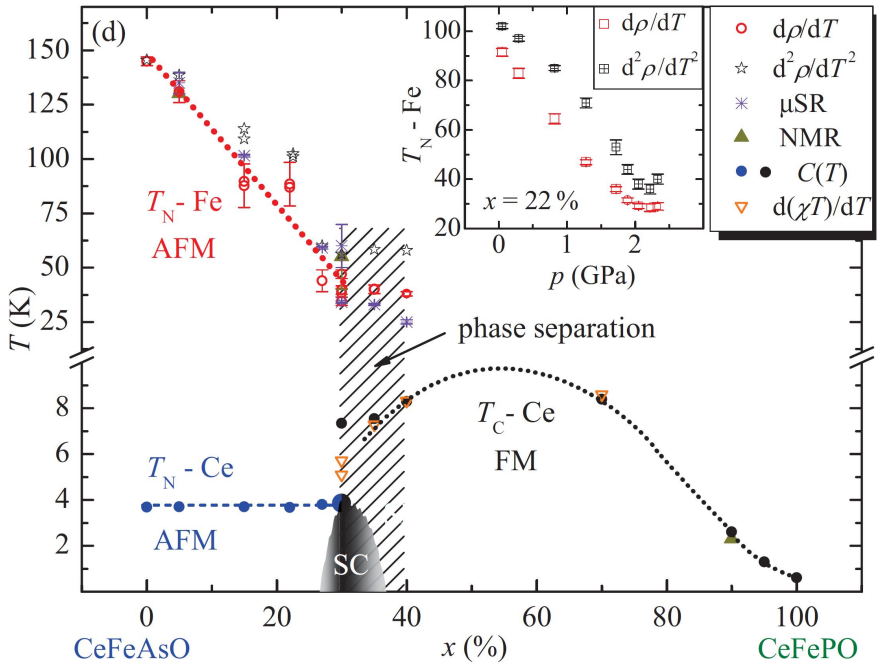


As/P substitution:
V and T_K enhancement

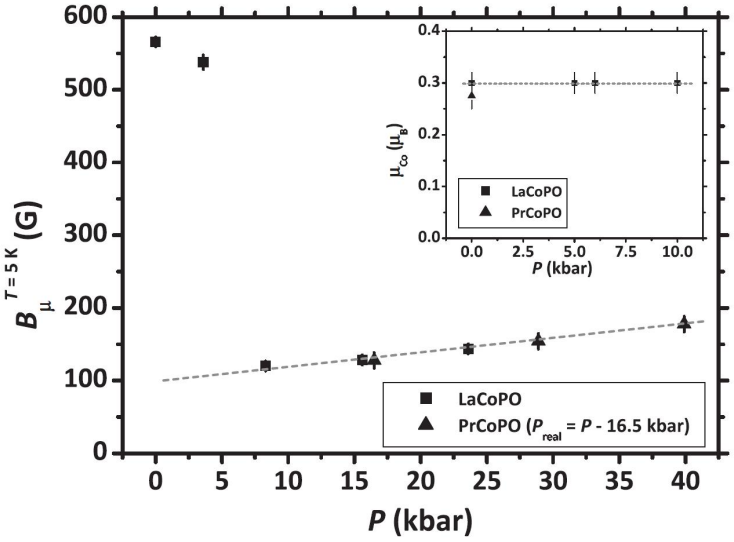
$$T_K \equiv \frac{W_F}{k_B} \exp\left(-\frac{|\varepsilon_f|}{2V^2 n(E_F)}\right)$$

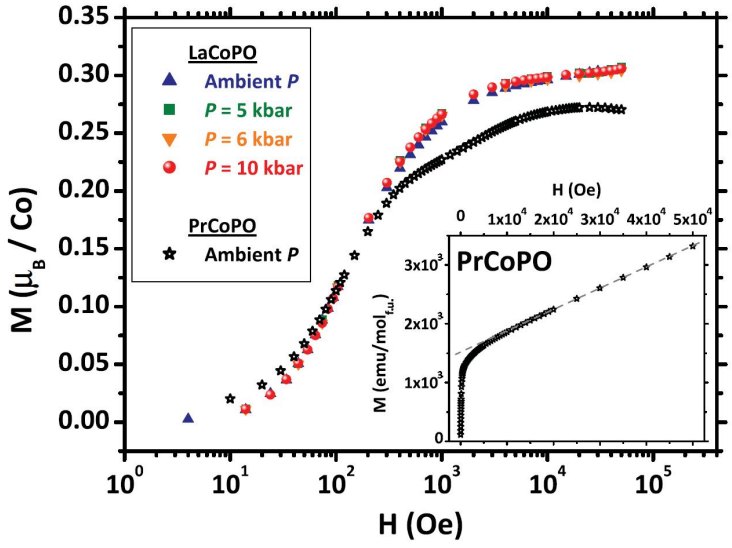
(Pourovskii et al., EPL **84**, 37006)

(Sun et al., EPL **91**, 57008)

Neither chemical nor external pressure induce bulk SC in CeFeAsO (Zocco et al., PRB **83**, 094528)

Undoped ReCoAsO and ReCoPO





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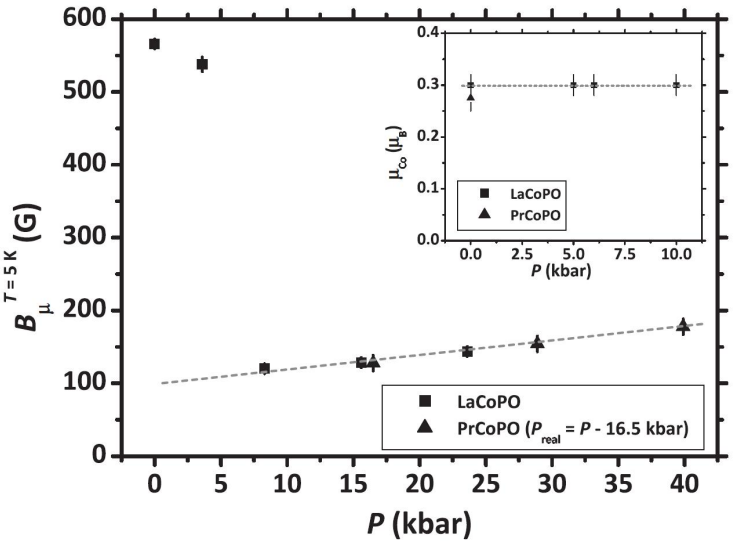
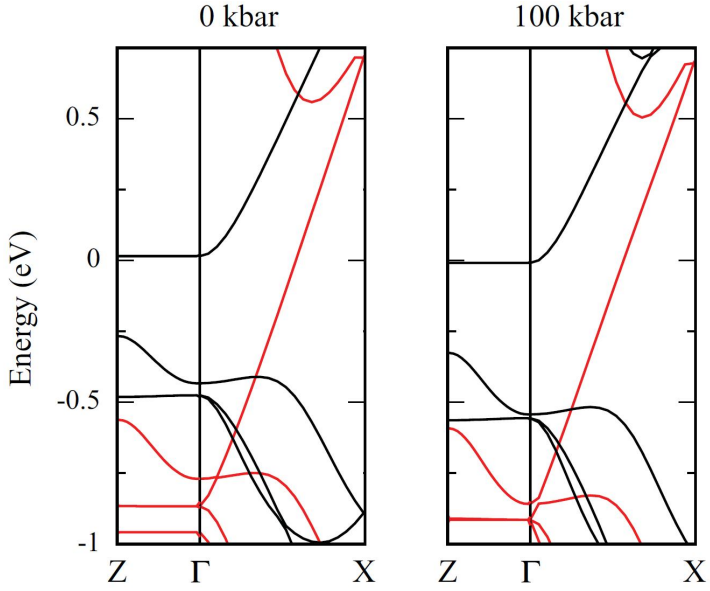
- Magnetic moment of Co is not affected by P
- DFT calculations: structure is negligibly modified by P

Still: experimental x-rays vs. P missing!

Undoped ReCoAsO and ReCoPO





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