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Hydrostatic-Pressure Tuning of Magnetic, Nonmagnetic and Superconducting States in Annealed $Ca(Fe_{1-x}Co_x)_2As_2$

Elena Gati[1], Sebastian Köhler[1], Daniel Guterding[1], Bernd Wolf[1], Stephan Knöner[1], Sheng Ran[2], Sergey L. Bud'ko[2], Paul C. Canfield[2], Michael Lang[1]

[1] Physikalisches Institut, Goethe-Universität, 60438 Frankfurt (Main), Germany

[2] Ames Laboratory, Iowa State University, Ames, Iowa 50011, USA

DFG Schwerpunktprogramm 1458

Iron-pnictide family

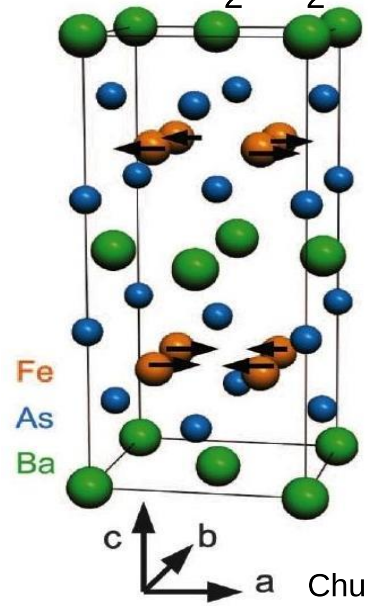
11 **e.g. FeSe** $\mathbf{T_{c,max}}$ **= 15 K** K.-W. Yeh *et al*., Europhys. Lett. **84**, 37002 (2008).	**111** **e.g. LiFeAs** $\mathbf{T_{c,max}}$ **= 18 K** X. C. Wang *et al*., Solid State Commun. **148**, 53[illegible] (2008).	**122** **e.g.** $\mathbf{BaFe_2As_2}$ $\mathbf{T_{c,max}}$ **= 38 K** M. Rotter *et al*., Phys. Rev. Lett. **101**, 107006 (2008).	**1111** **e.g. LaFeAsO** $\mathbf{T_{c,max}}$ **= 56 K** C. Wang *et al*., Europhys. Lett. **83**, 67006 (2008).

most extensively studied

$A\mathrm{Fe_2As_2}$ → A = Ba, Sr, Ca, Eu

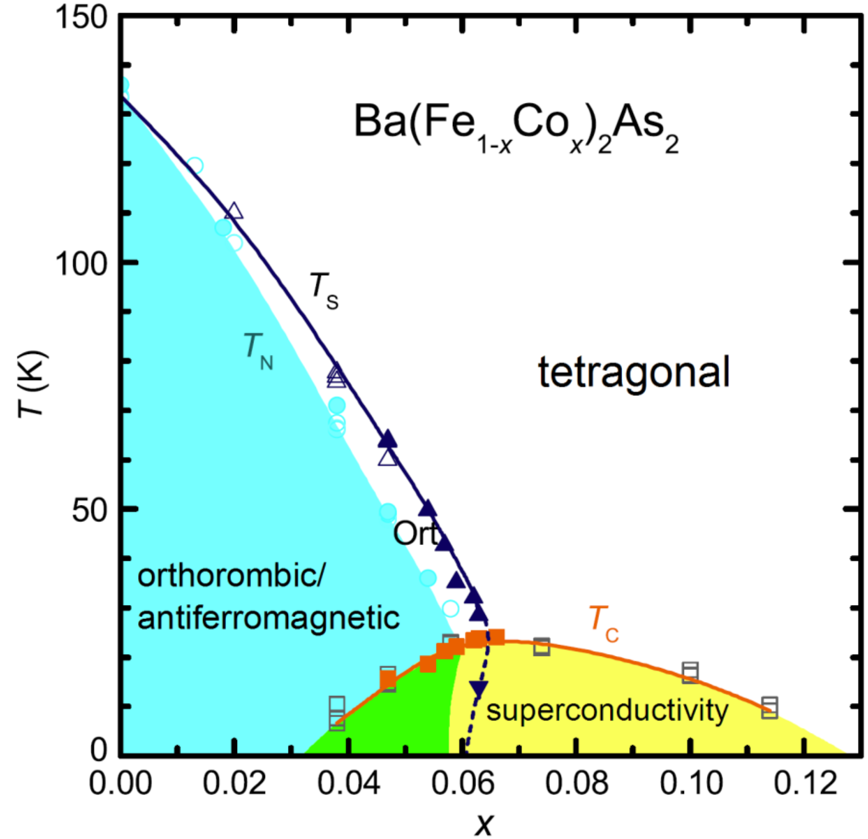
- large, high-quality single crystals available
- control substitutions: model systems
- *A* = Ca: high sensitivity to pressure
  → pressure tuning

$BaFe_2As_2$



Chu *et al.*, Science **329**, 824 (2010).

Phase diagrams

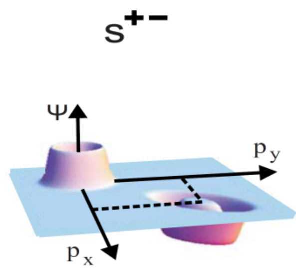


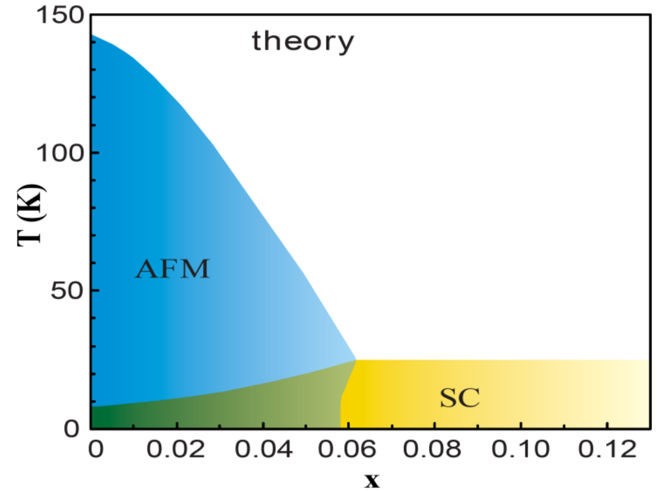
S. Nandi *et al.*, Phys. Rev. Lett. **104**, 057006 (2010)

homogeneous coexistence of SC and AFM: competing for the same electrons

Phase diagrams & pairing symmetry

afm fluctuations

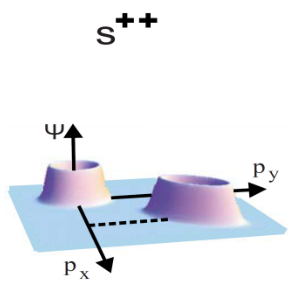


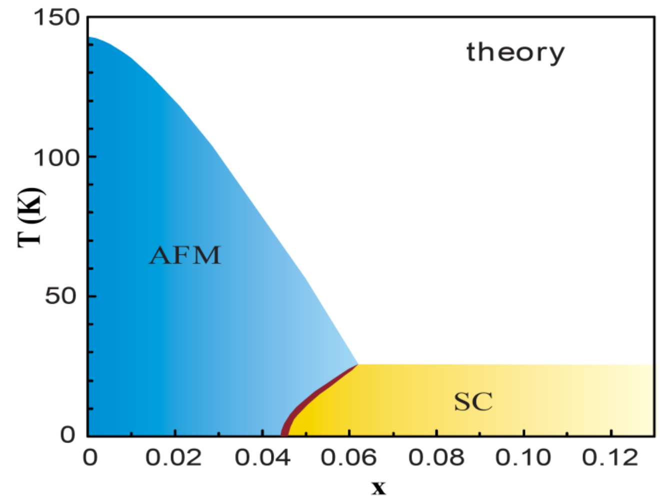


Mazin *et al.*, Phys. Rev. Lett. **101**, 057003 (2008).

Kuroki *et al.*, Phys. Rev. Lett. **101**, 087004 (2008).

orbital fluctuations





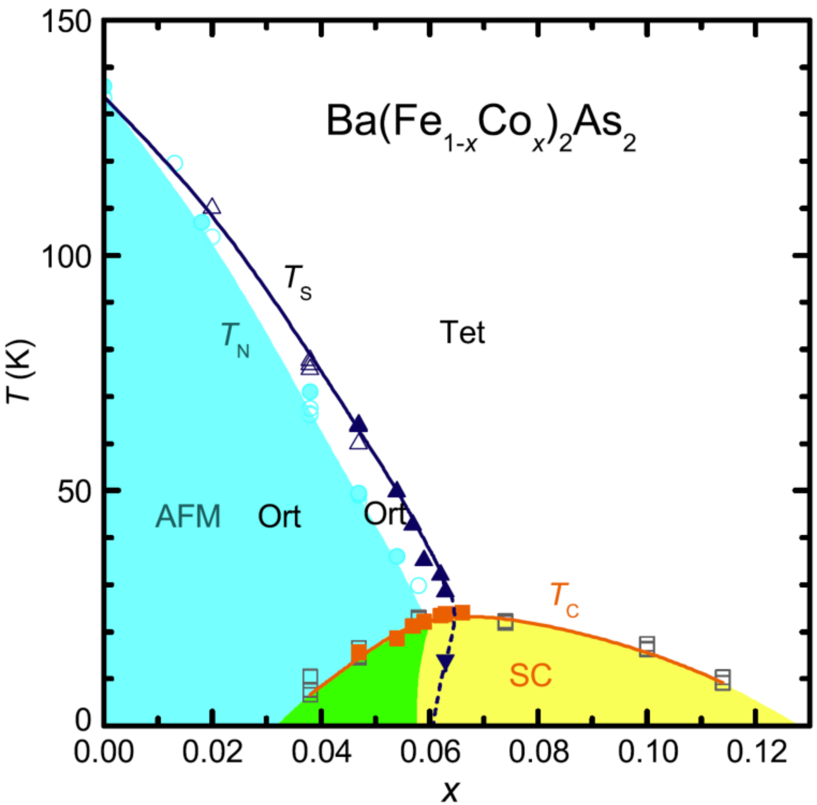
Kontani and Onari, Phys. Rev. Lett. **104**, 157001 (2010).

Yanagi *et al.*, Phys. Rev. B **81**, 054518 (2010).

Fernandes *et al.*, Phys. Rev. B **81**, 140501 (2010).

So far: phase diagrams *T* vs. *x*

implying effects of disorder, inhomogenities etc.



S. Nandi *et al.*, Phys. Rev. Lett. **104**, 057006 (2010).

→ *P* – studies provide more direct information

$CaFe_2As_2$

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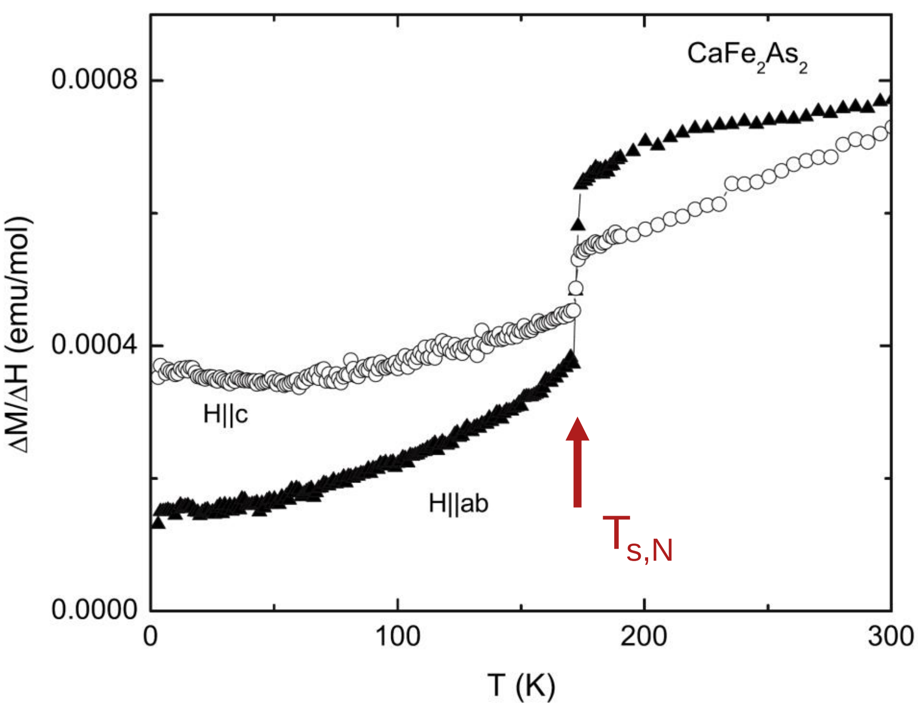
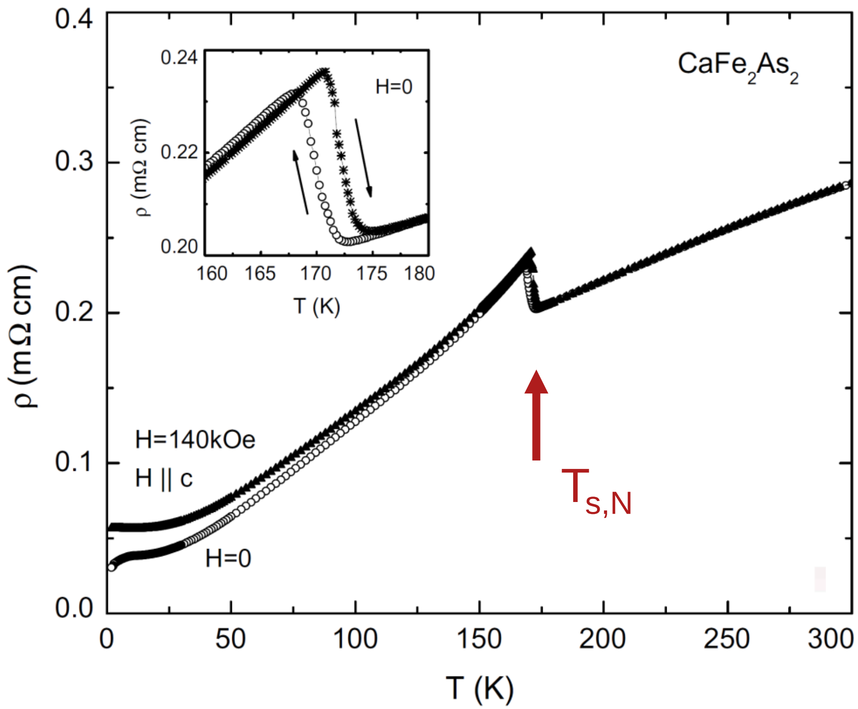




N. Ni *et al.*, Phys. Rev. B **78**, 014523 (2008).

- **strongly coupled transitions at $T_s = T_N = 170$ K**
- **hysteresis of several K**

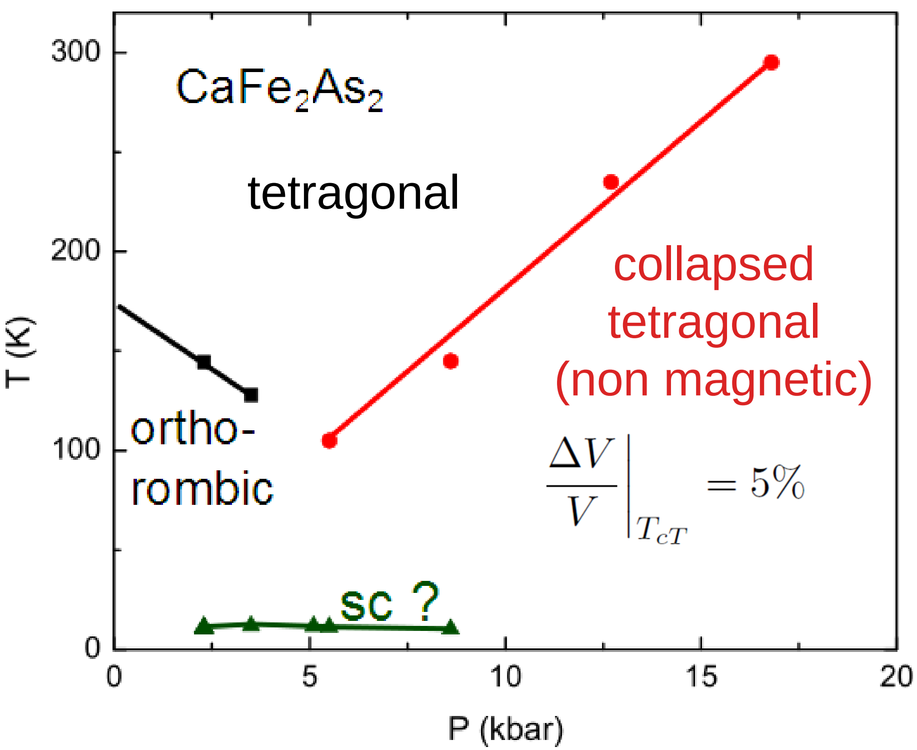
  ⇒ first-order phase transition,

  cf. 2^{nd} order phase transition in Co-doped $BaFe_2As_2$

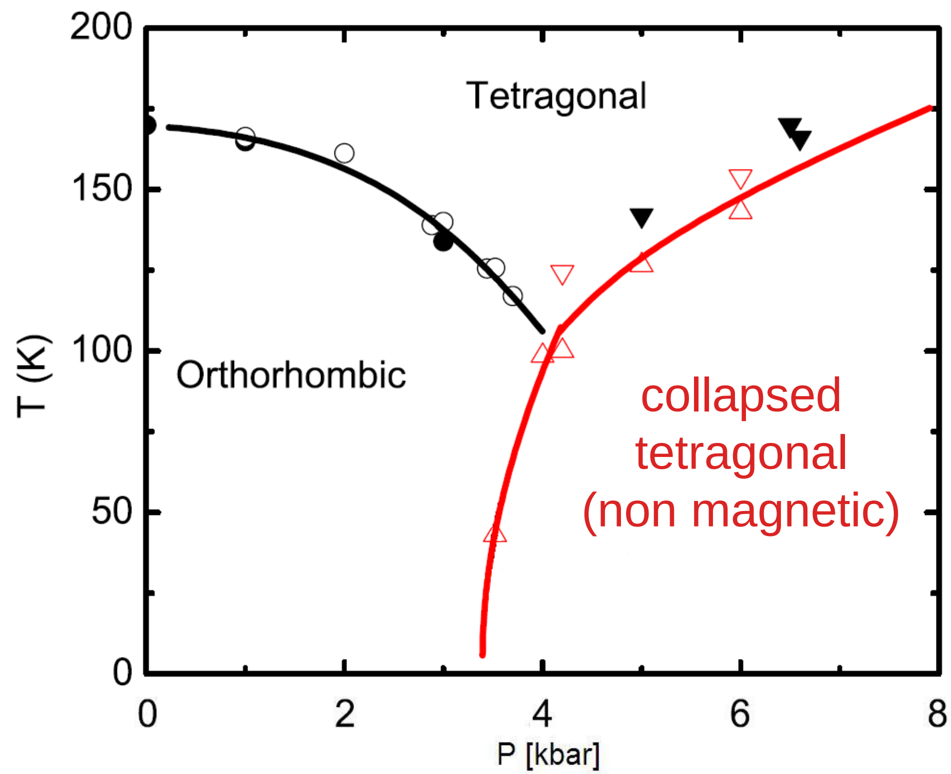
Sensitivity to pressure & non-hydrostatic conditions

oil pressure cell
sc

helium pressure cell
no sc



M. Torikachvili *et al.*,
Phys. Rev. Lett. **101**, 057006 (2008).

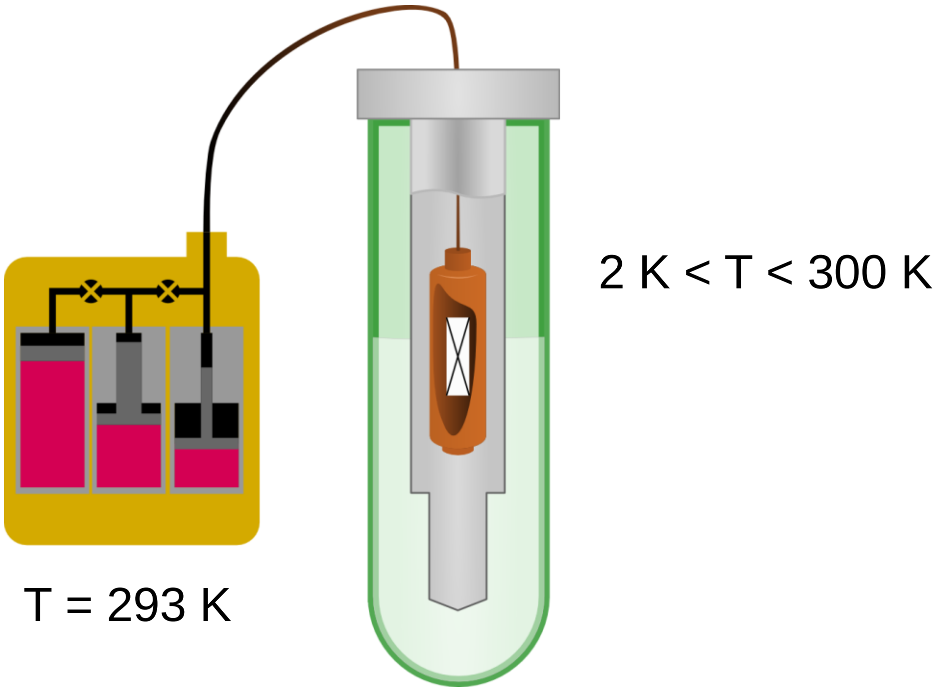


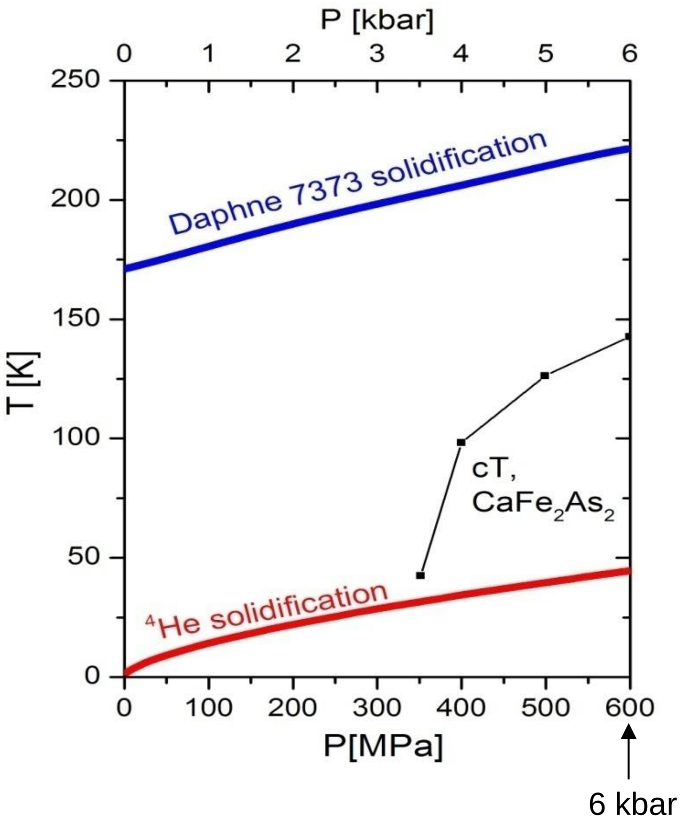
W. Yu *et al.*, Phys. Rev. B **79**, 020511 (R) (2009).

⇒ Solidification of oil: Strain-stabilized SC due to non-hydrostatic conditions

Helium as pressure-transmitting medium

- **low solidification temperature**
- **soft solid**
  van-der-Waals-bondings
- **constant pressure conditions**



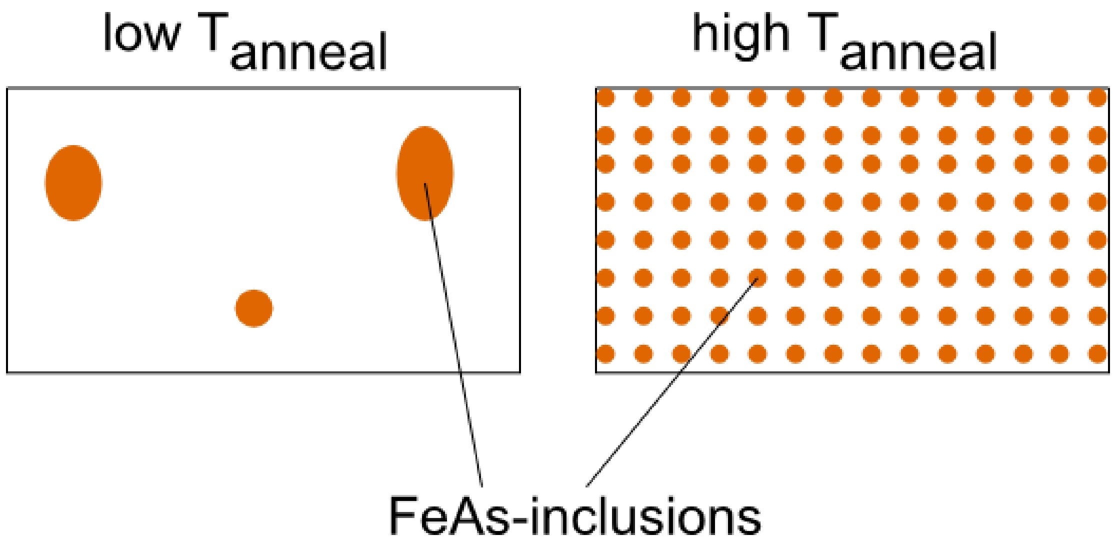


$CaFe_2As_2$: Role of annealing and Co-substitution

New approach: growth of crystals out of FeAs-flux

S. Ran *et al.*, Phys. Rev. B **83**, 144517 (2011).

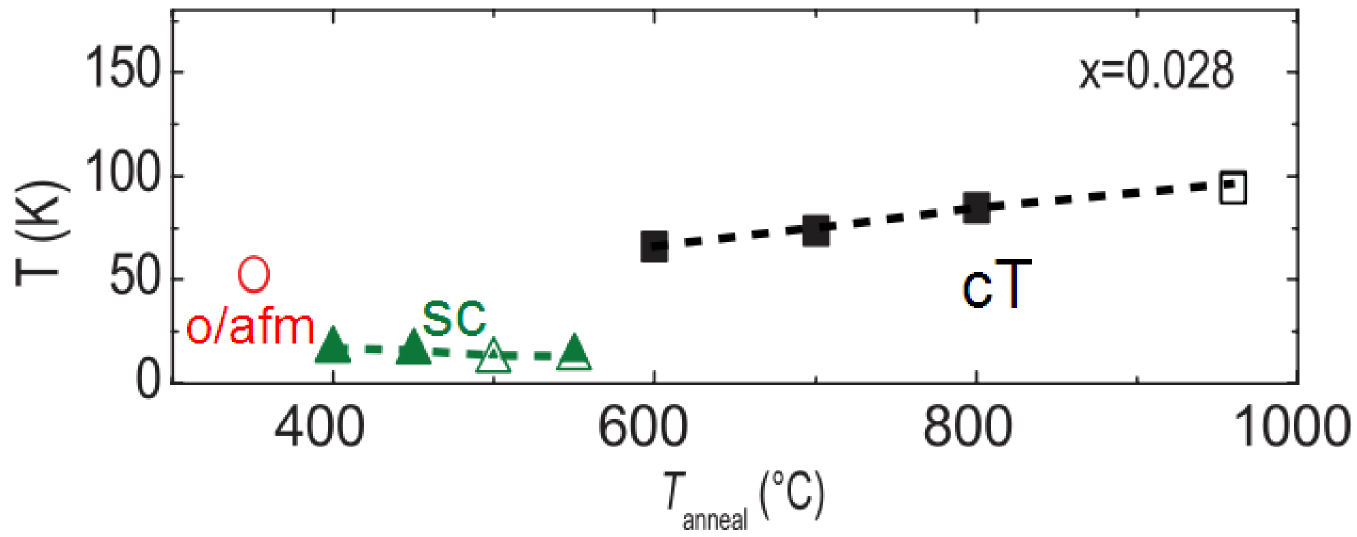
→thermal treatment: annealing (quenching) at T_{anneal} (⇔ solubility of FeAs)



→ T_{anneal} = 350°C: strain-free crystals

→ speculation: T_{anneal} ≡ hydrostatic pressure in $CaFe_2As_2$

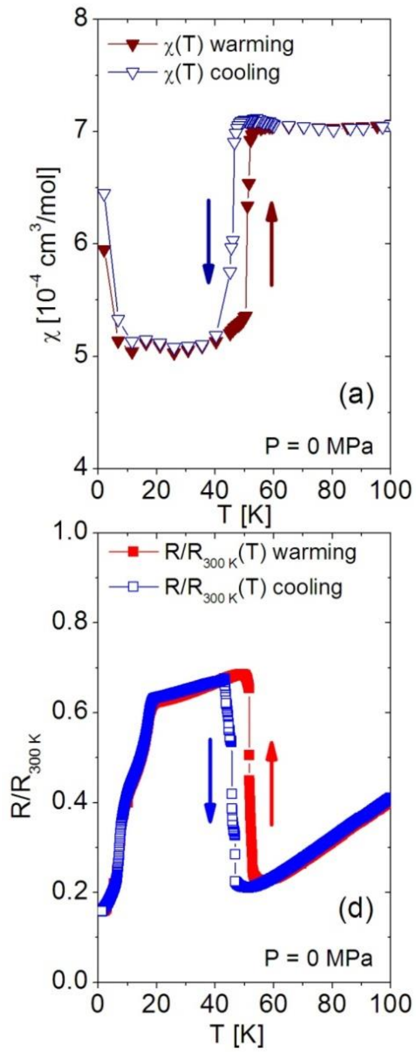
SC achieved by Co-substitution & annealing



S. Ran *et al.*, Phys. Rev. B **85**, 224528 (2012).

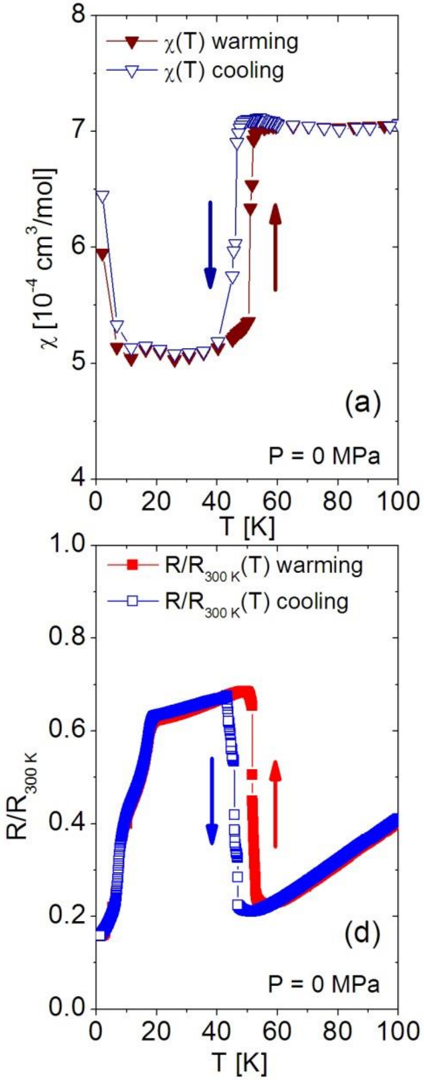
Is there a $T_{anneal} \Leftrightarrow P$ analogy ?

$Ca(Fe_{1-x}Co_x)_2As_2$, x = 0.028, T_{anneal} = 350°C

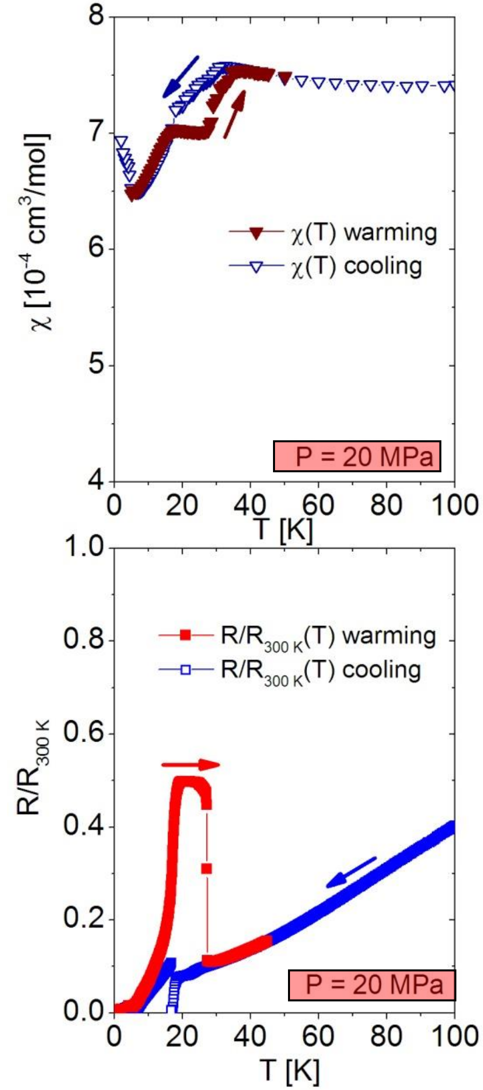


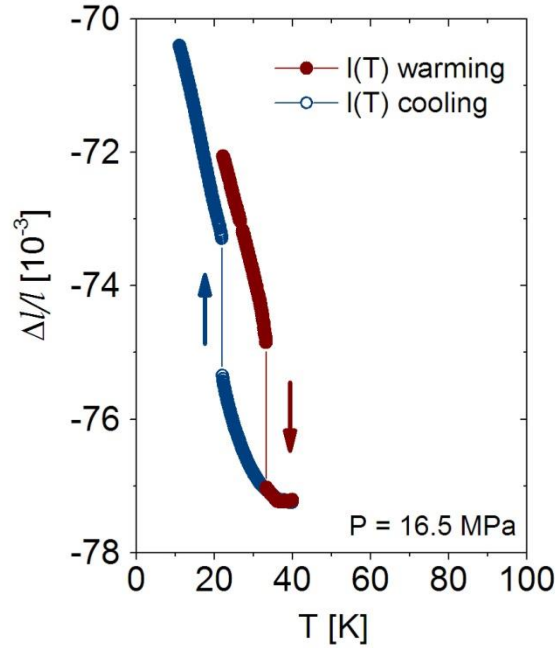
E. Gati *et al.*, Phys. Rev. B **86**, 220511(R) (2012).

$Ca(Fe_{1-x}Co_x)_2As_2$, x = 0.028, T_{anneal} = 350°C



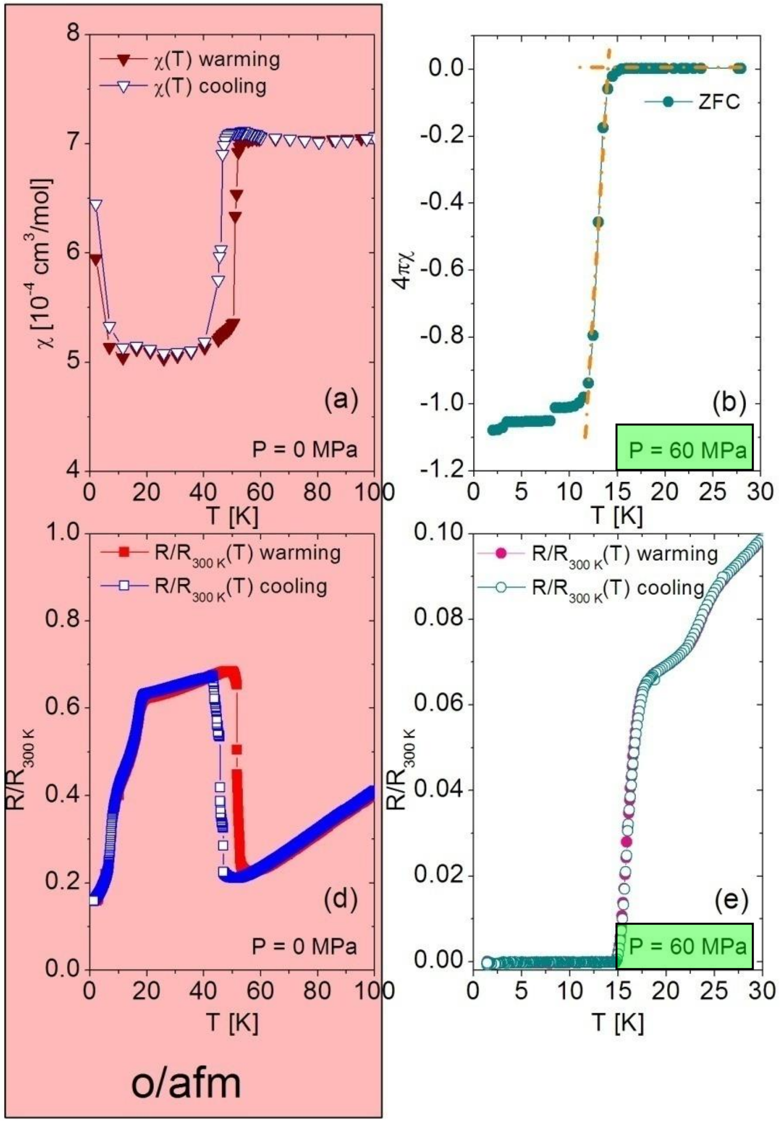
increasing *P*





R. S. Manna and F. Schnelle

$Ca(Fe_{1-x}Co_x)_2As_2$, x = 0.028, T_{anneal} = 350°C



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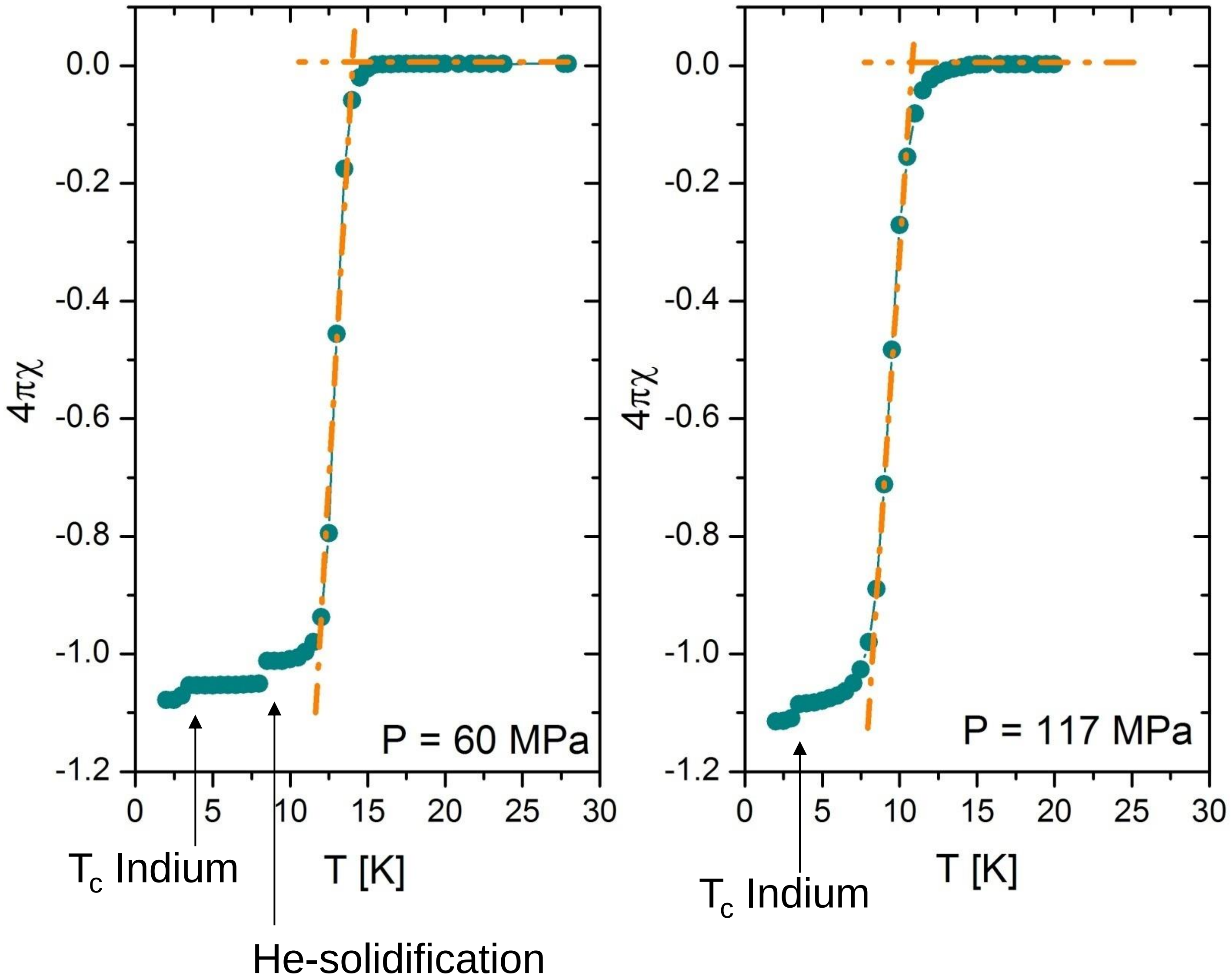

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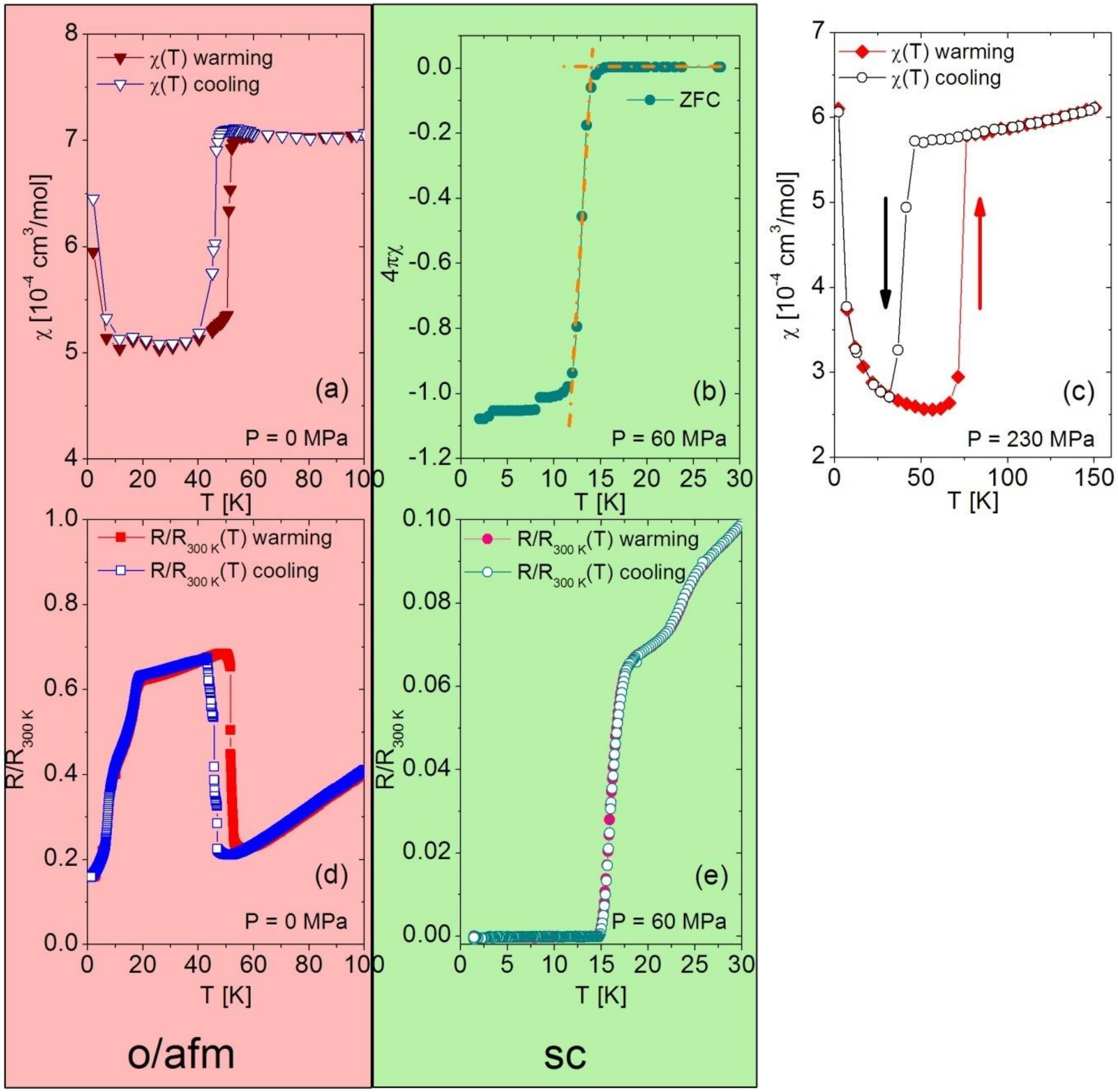

$Ca(Fe_{1-x}Co_x)_2As_2$, x = 0.028, T_{anneal} = 350°C

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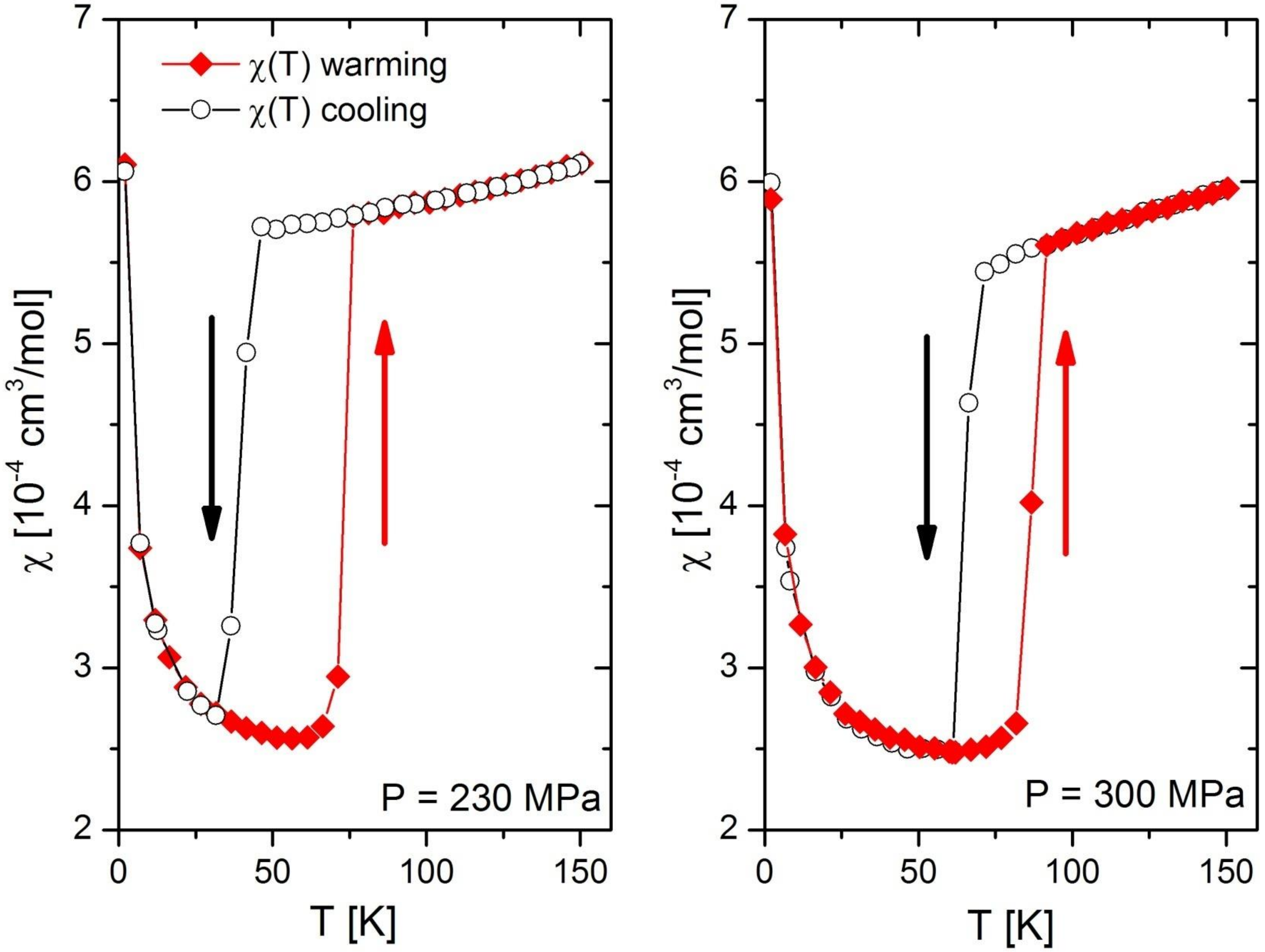
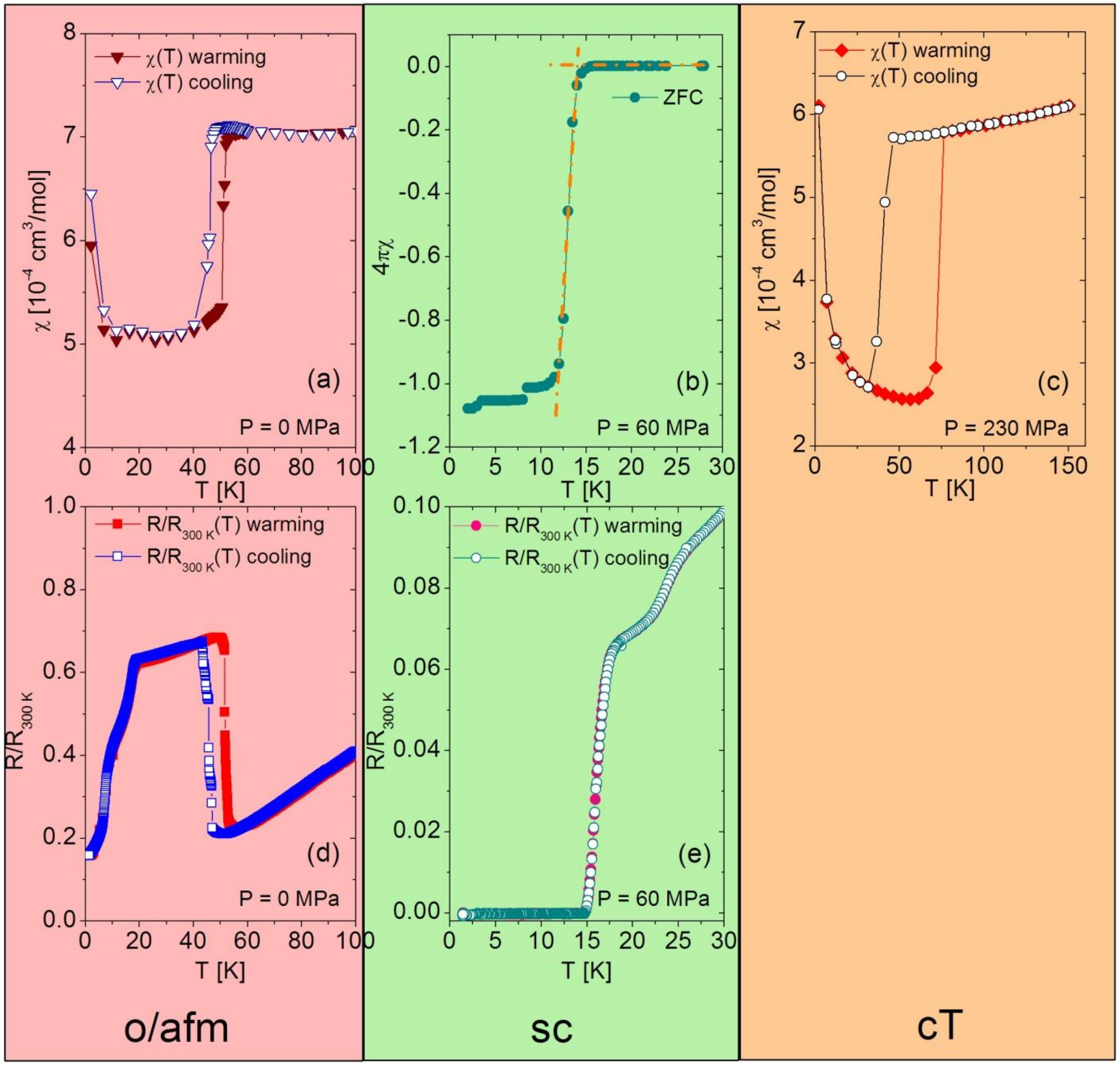
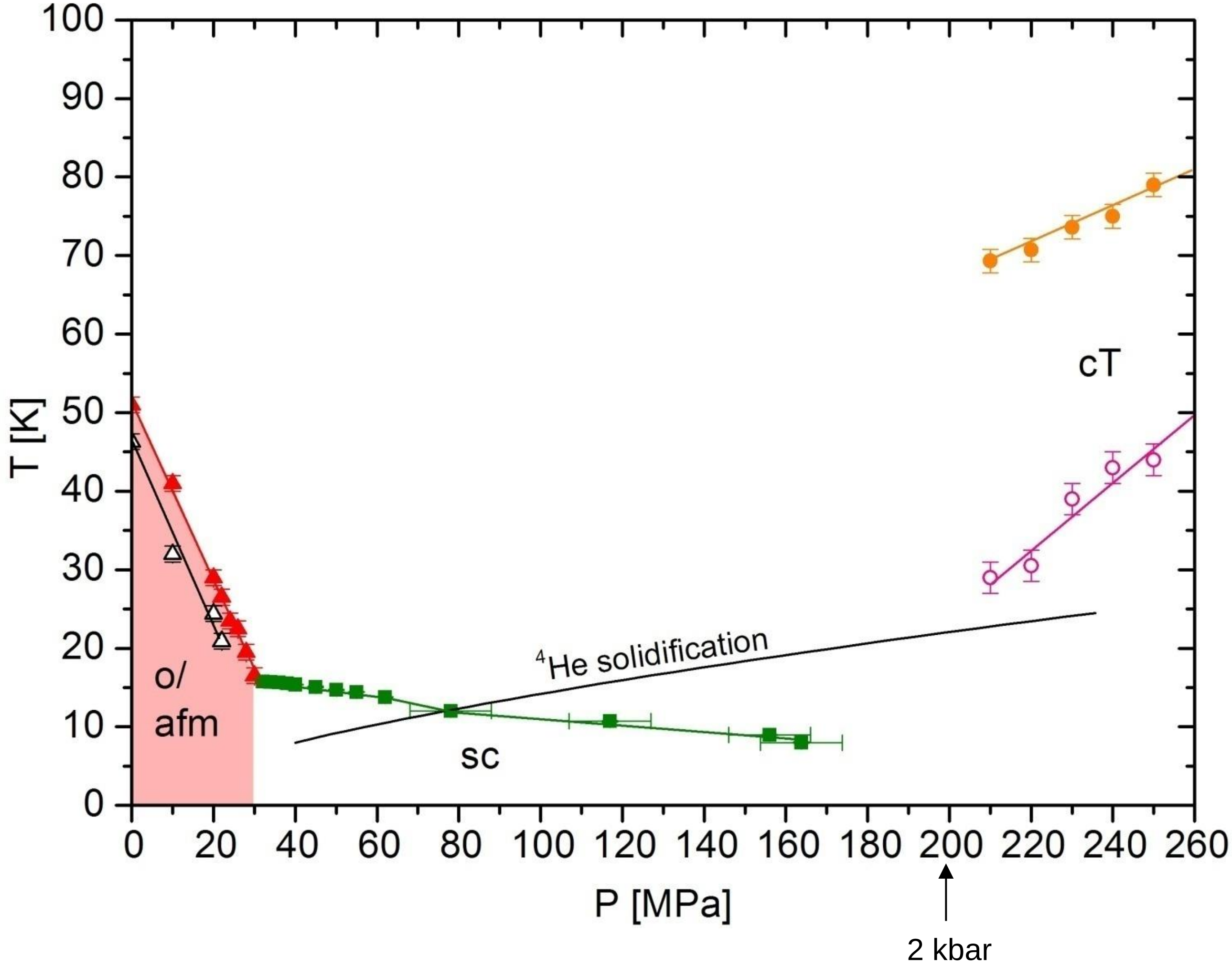


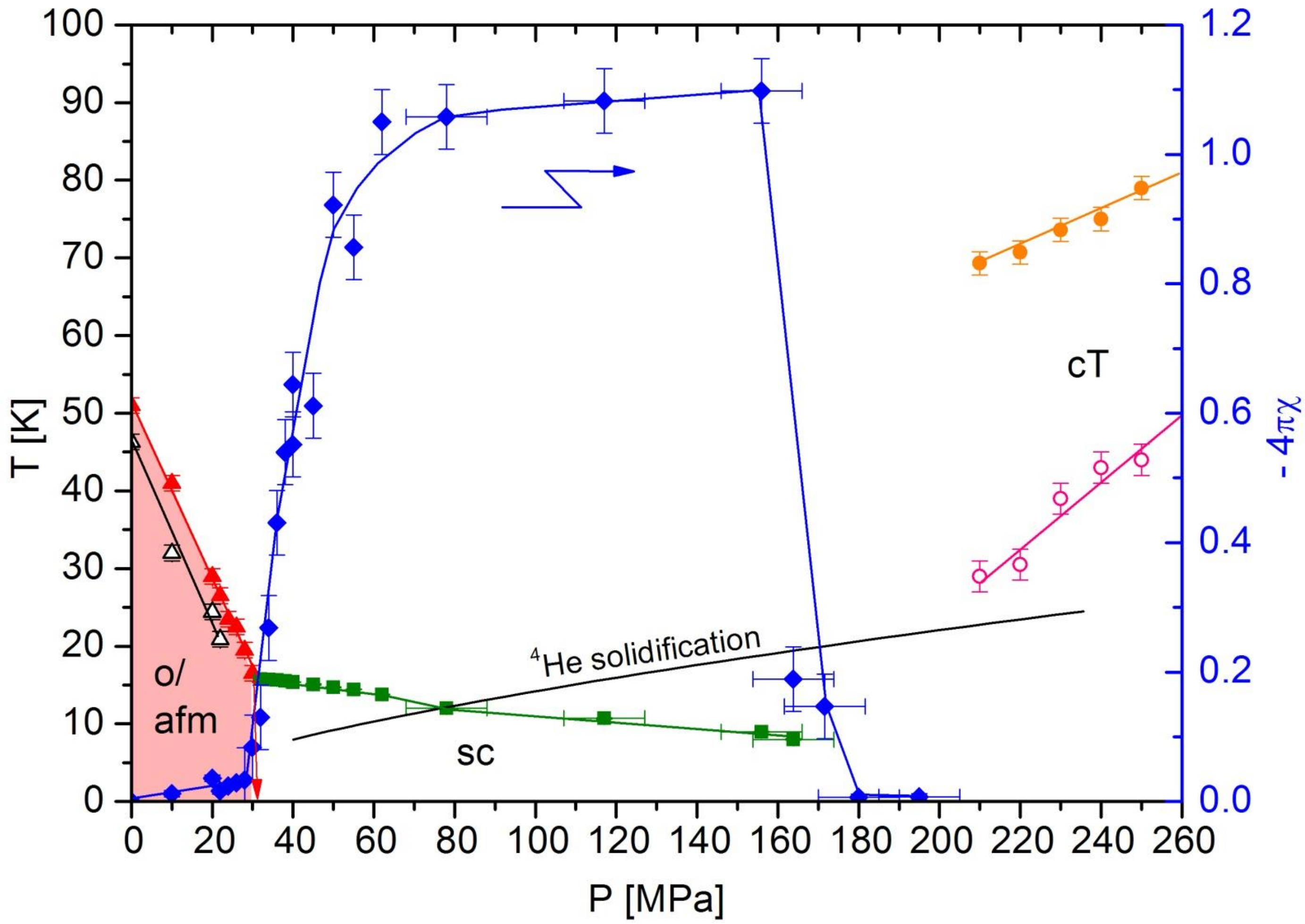
$Ca(Fe_{1-x}Co_x)_2As_2$, x = 0.028, T_{anneal} = 350°C



$Ca(Fe_{1-x}Co_x)_2As_2$, x = 0.028, T_{anneal} = 350°C



$Ca(Fe_{1-x}Co_x)_2As_2$, x = 0.028, T_{anneal} = 350°C



$Ca(Fe_{1-x}Co_x)_2As_2$, x = 0.028, T_{anneal} = 350°C

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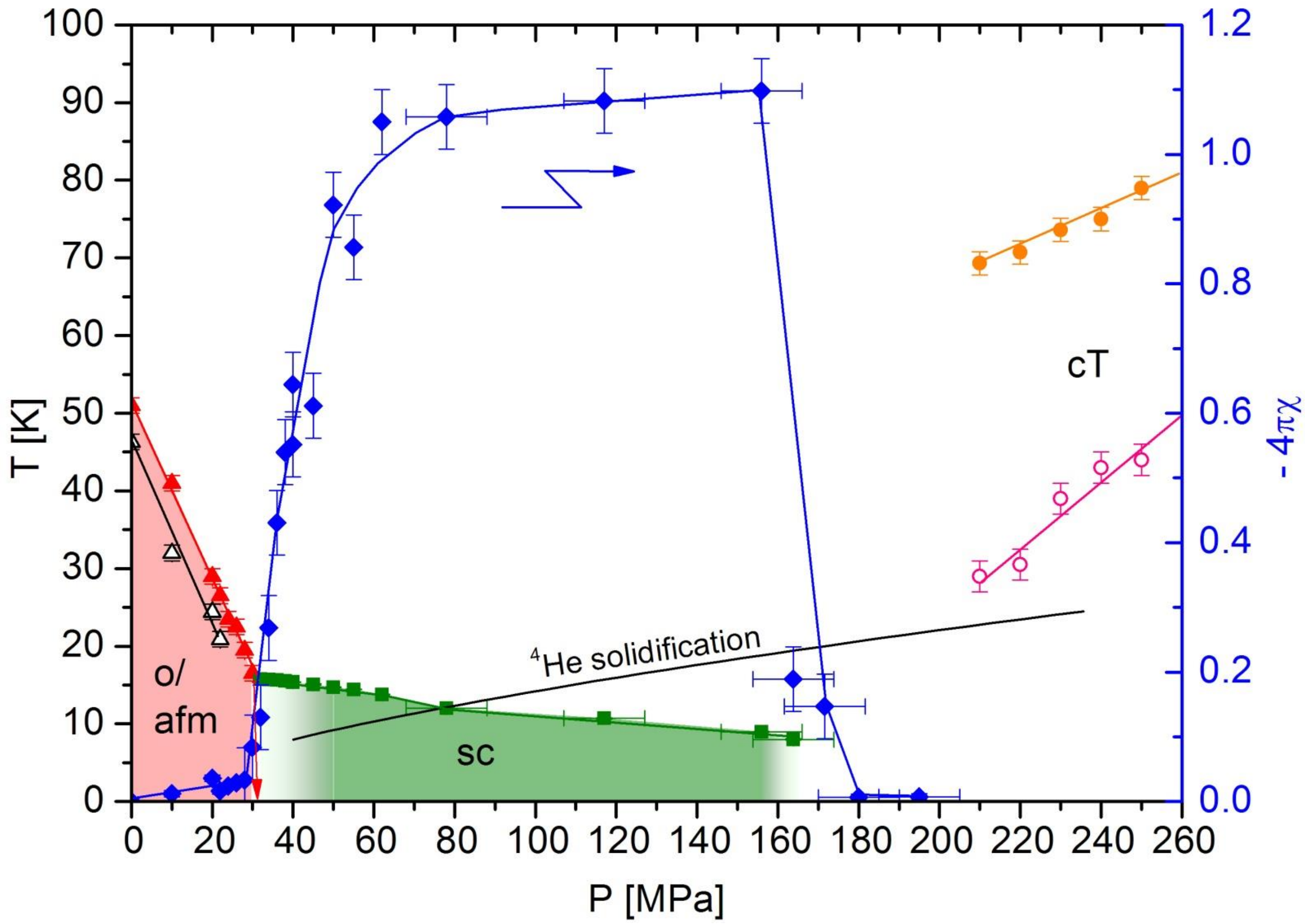
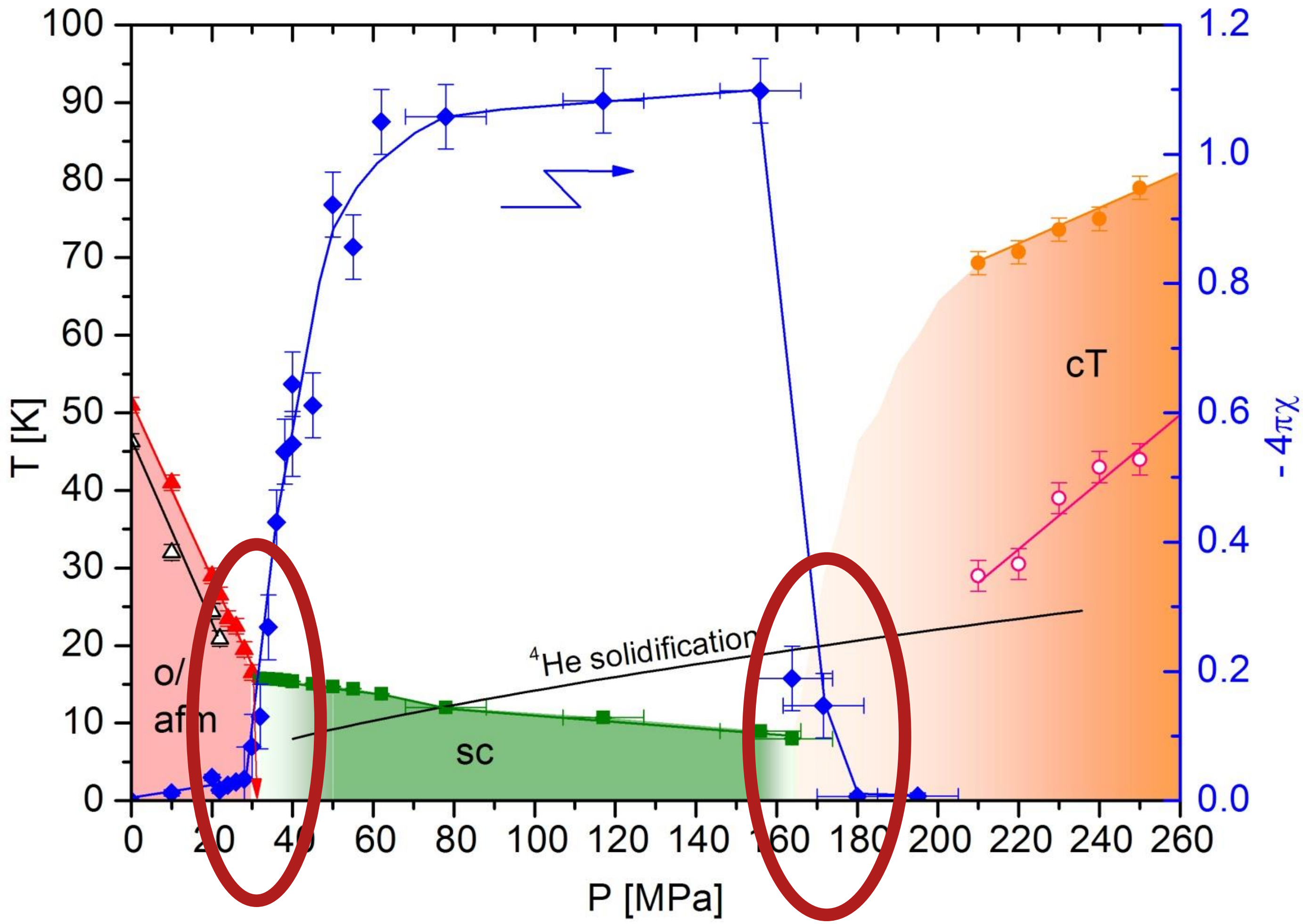
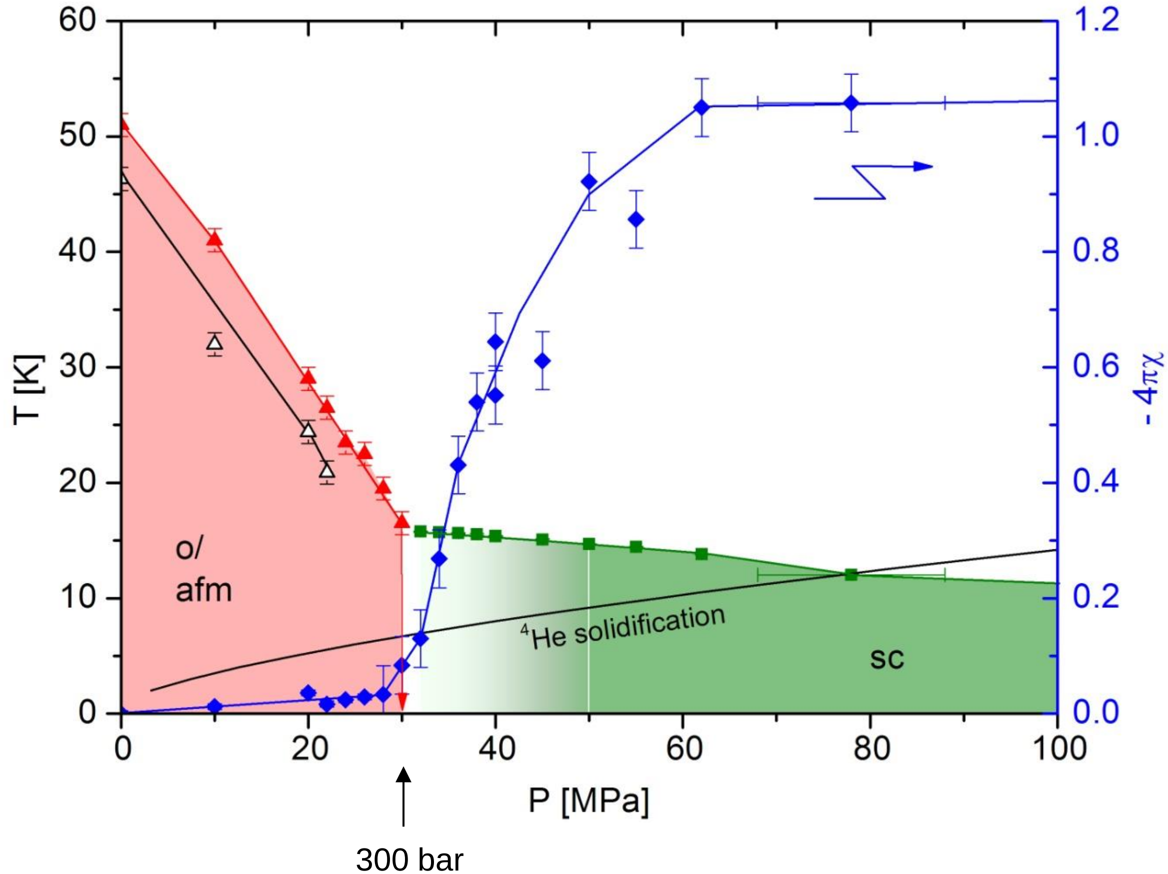


$Ca(Fe_{1-x}Co_x)_2As_2$, x = 0.028, T_{anneal} = 350°C

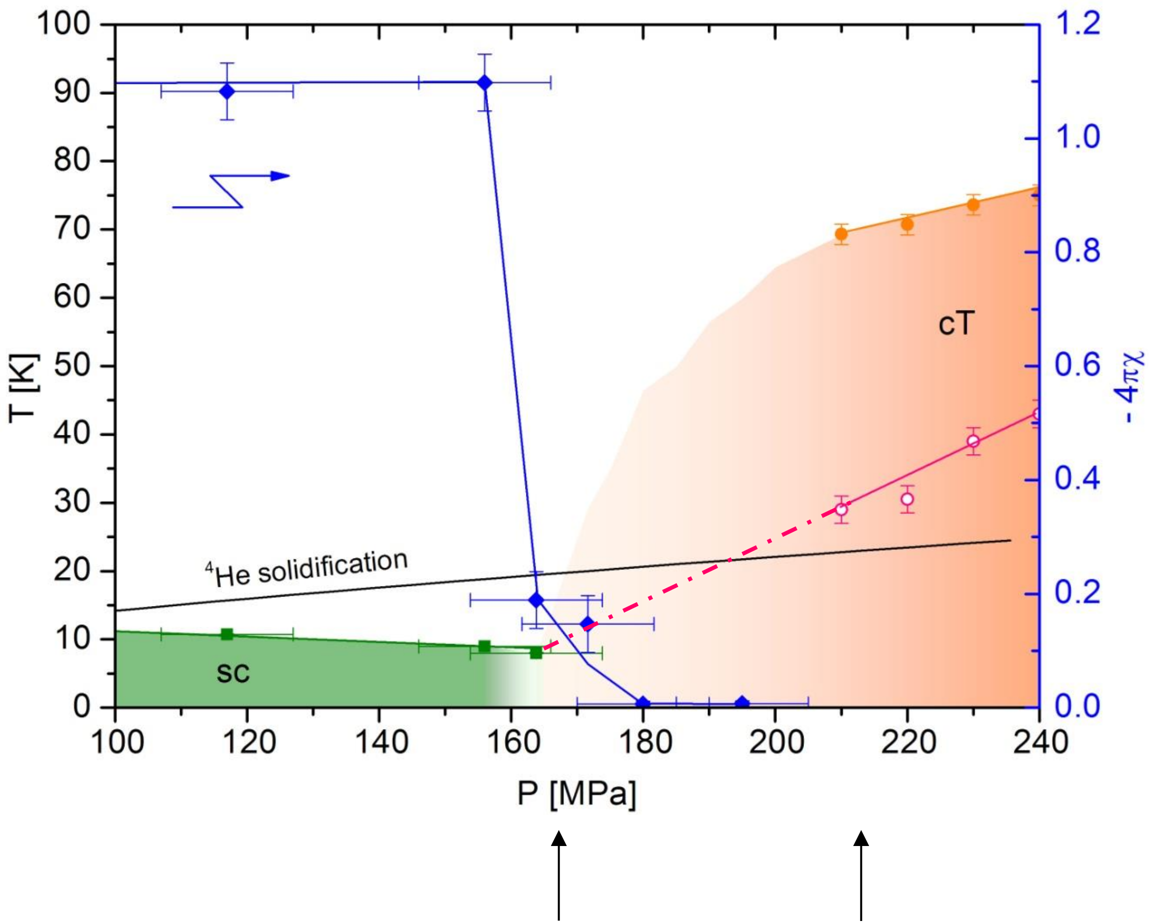


Interplay between o/afm and sc (*P* ~ 32 MPa)

- no coexistence of o/afm and sc
- $T_{s,N}$ remains 1st order!
- huge pressure coefficient $dT_{s,N}/dP$ = -(110 ± 5) K/kbar !



Interplay between sc and cT (*P* ~ 165 MPa)



- T_{cT}^{cool} line truncates T_c line at critical pressure 165 MPa
- no coexistence of sc and cT
- experiment limited by
  (i) He-solidification
  (ii) vanishingly small signal in χ_{cT}

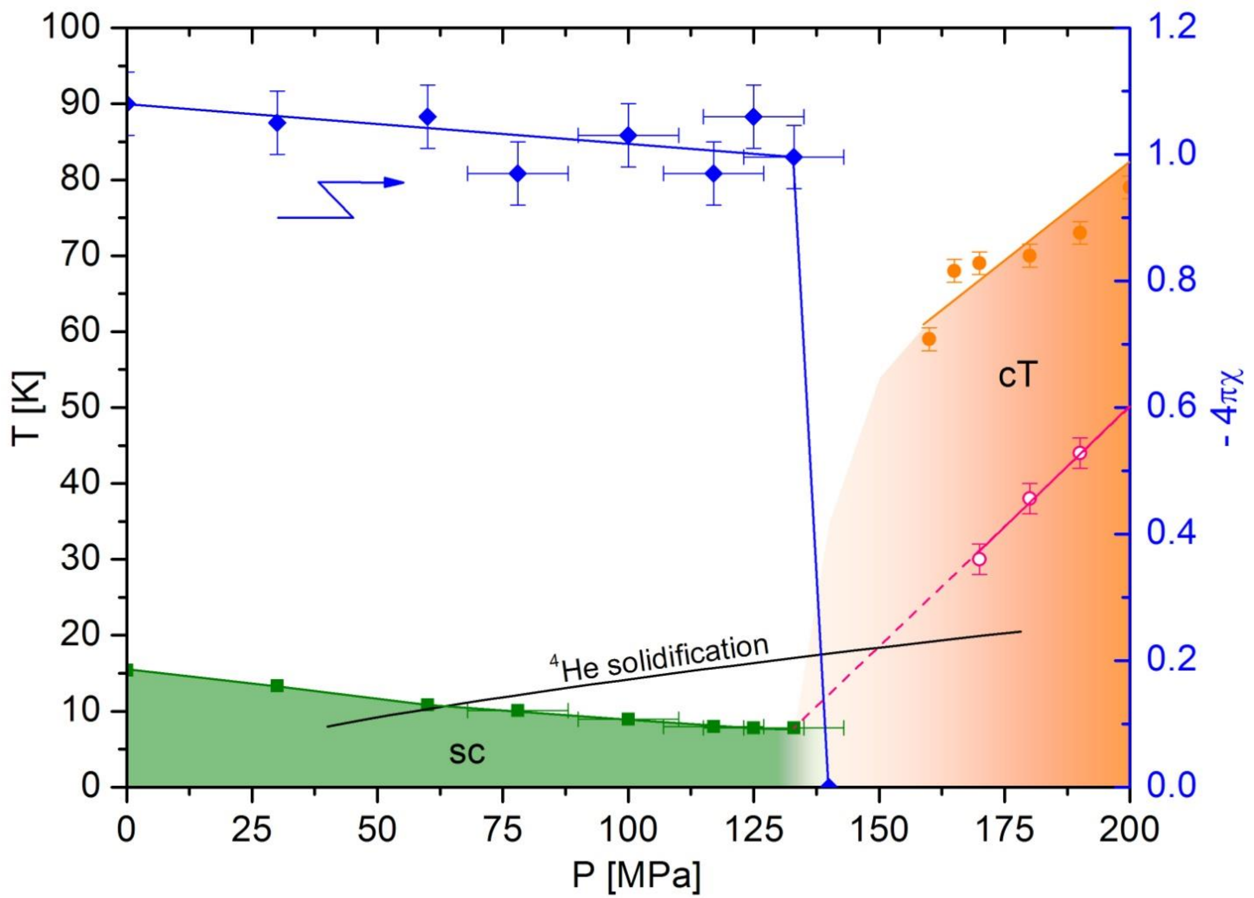
→ Use sample with higher T_{anneal} (pre-stressed)

shielding signal drops

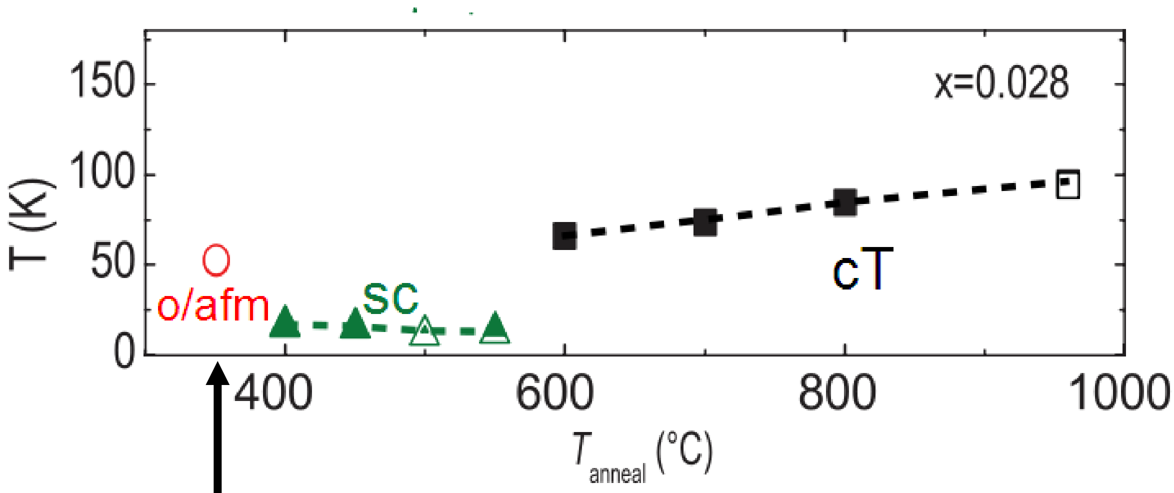
first indications for cT-phase

Annealing-pressure-analogy

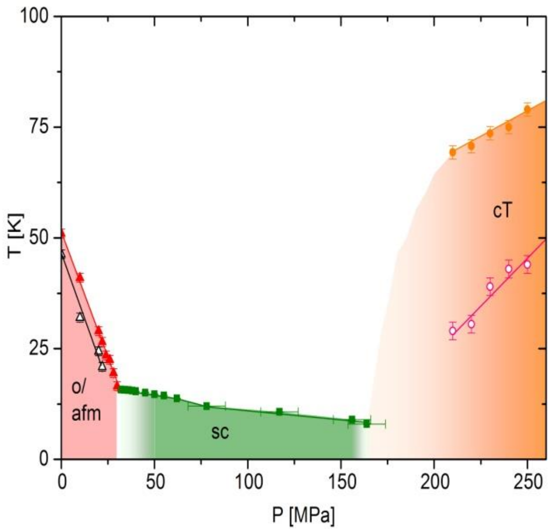
$x = 0.029 \pm 0.0016$ $T_{anneal} = 400°C$ → bulk sc at ambient pressure
(Ran *et al*., Phys. Rev. B **85**, 224528 (2012))



Annealing-pressure-analogy



T_{anneal} = 350 °C



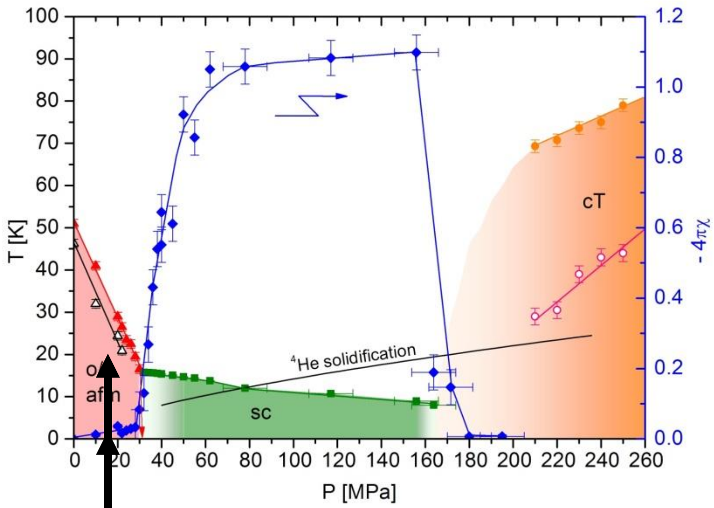
S. Ran *et al.*,
Phys. Rev. B **85**, 224528 (2012).

annealing mimics the effect of hydrostatic pressure:

$$\Delta T_{anneal} = 100°C \equiv 84.6 \text{ MPa}$$

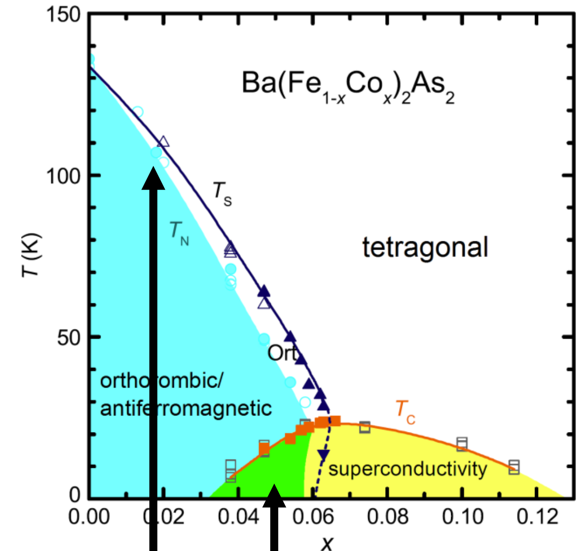
Summary & implications

Co-doped $CaFe_2As_2$



1st order
coexistence

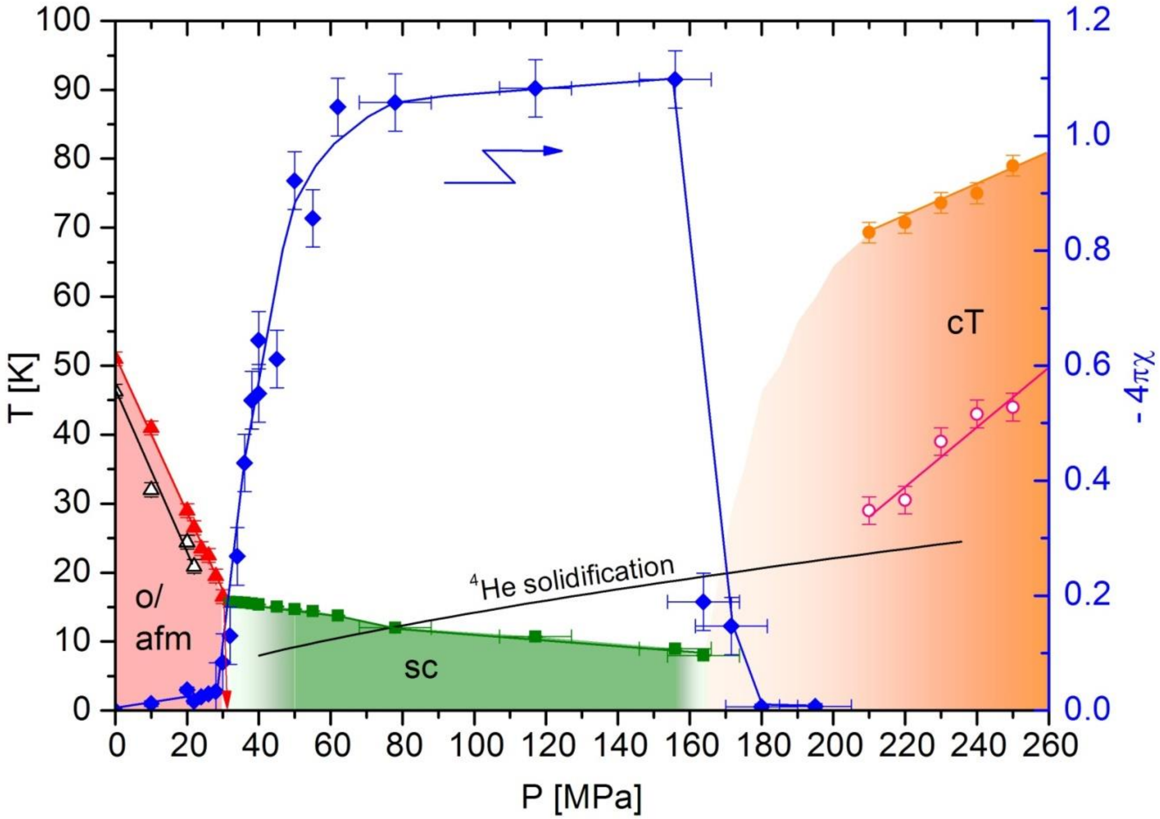
Co-doped $BaFe_2As_2$



2nd order
coexistence

- non-coexistence ⟷ 1st order character of phase transition
  → fluctuations important for sc
- no coexistence of sc and cT
- large pressure dependencies → Ca 122 is close to an instability

Outlook

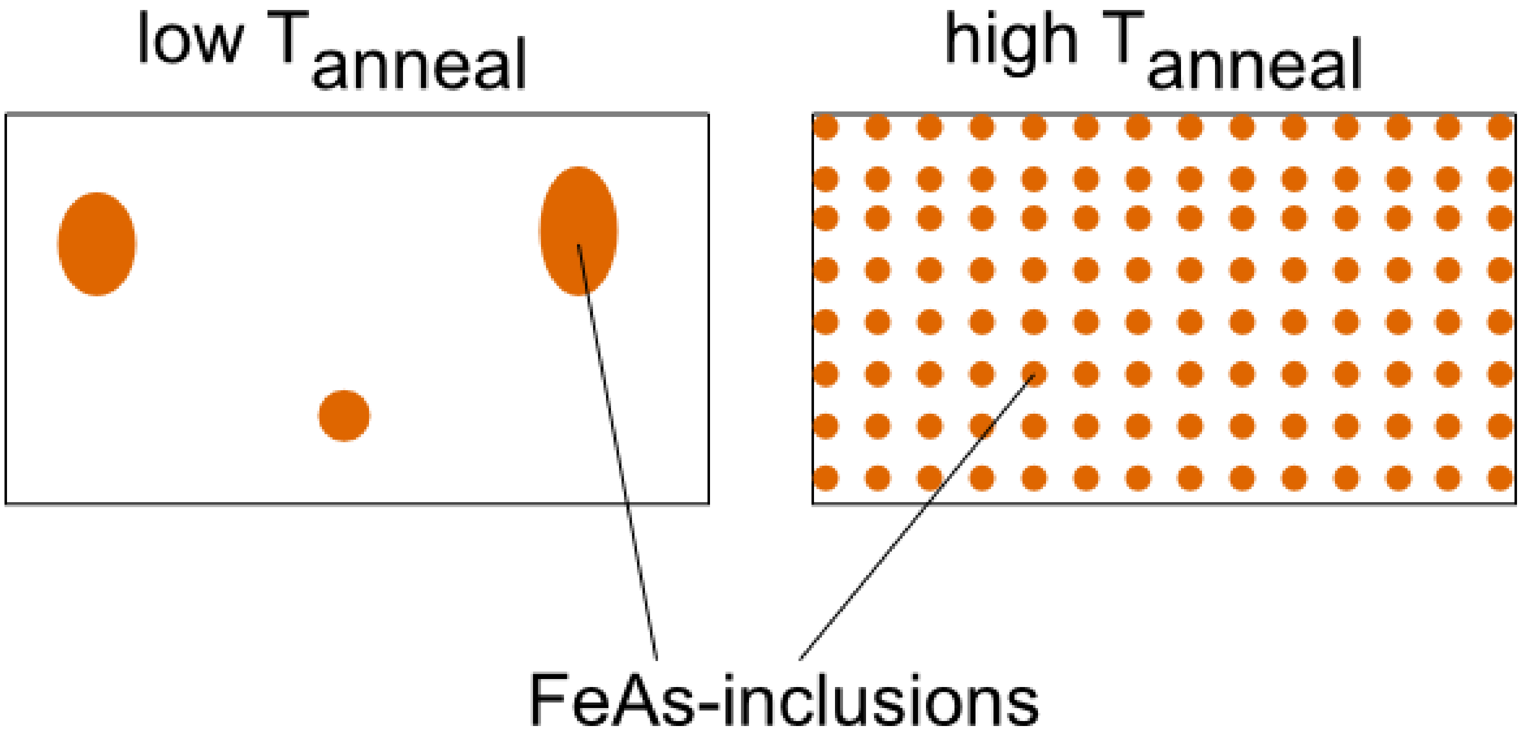


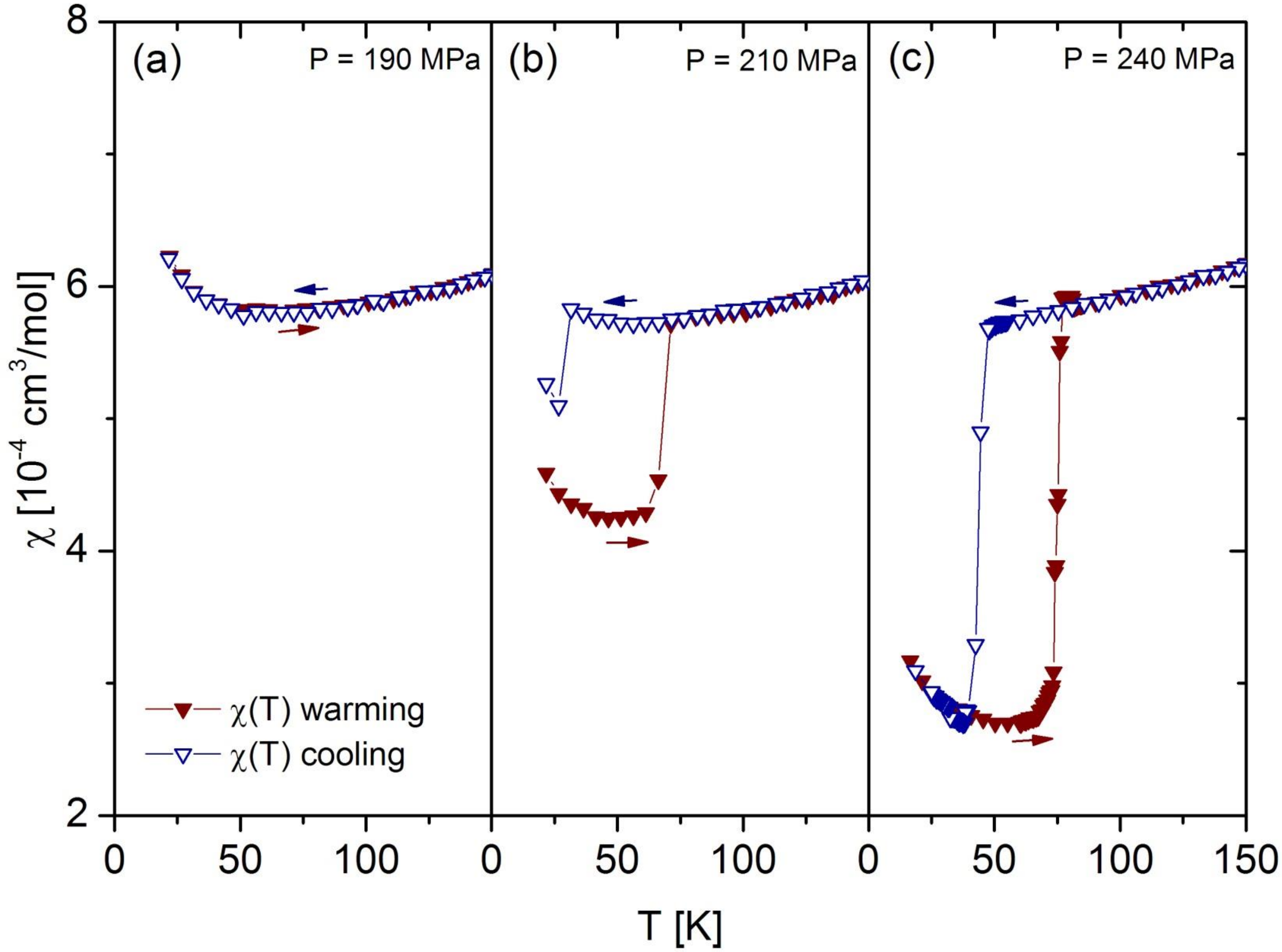
- neutron scattering
- thermal expansion

...

under hydrostatic ^{4}He pressure

Thank you for your attention!


low T_{anneal}
high T_{anneal}
FeAs-inclusions



(a)
P = 190 MPa
(b)
P = 210 MPa
(c)
P = 240 MPa
χ [10^-4 cm^3/mol]
T [K]
χ(T) warming
χ(T) cooling
8
6
4
2
0
50
100
0
50
100
0
50
100
150