Tuning magnetism in iron-based superconductors

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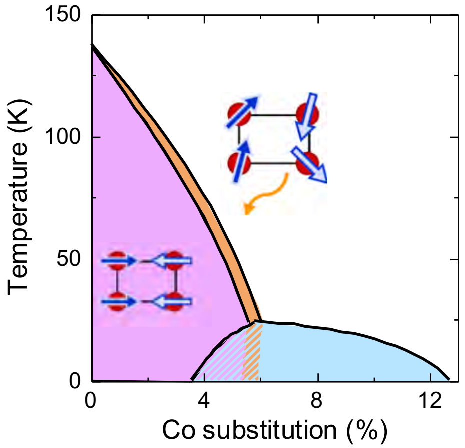

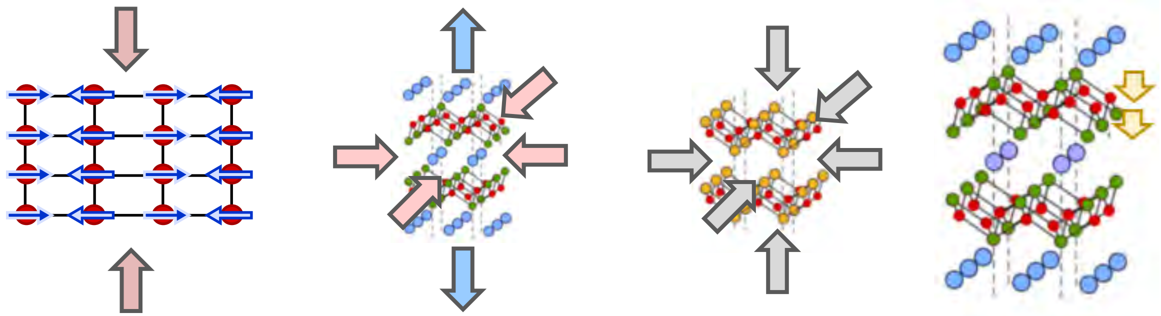

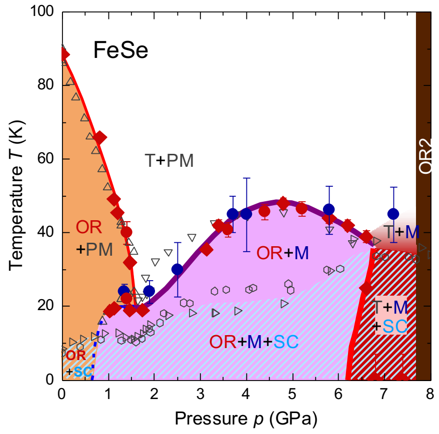

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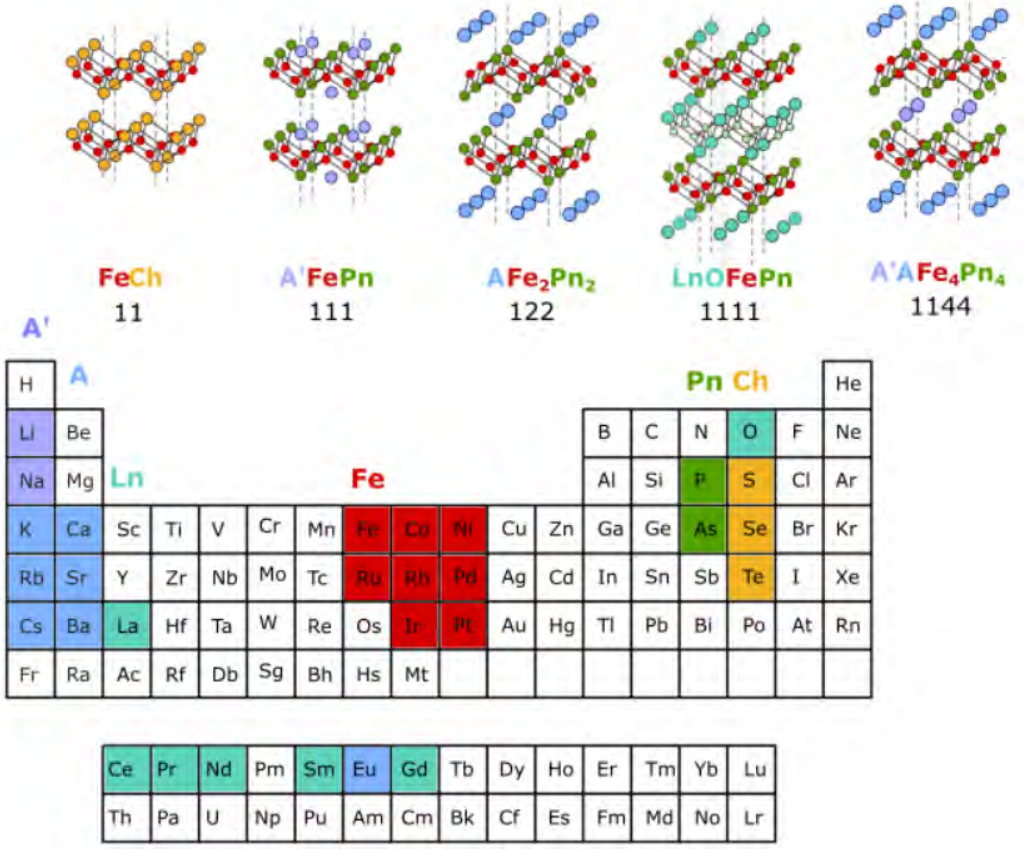
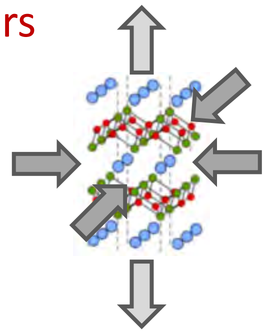
Materials, methods and phenomena

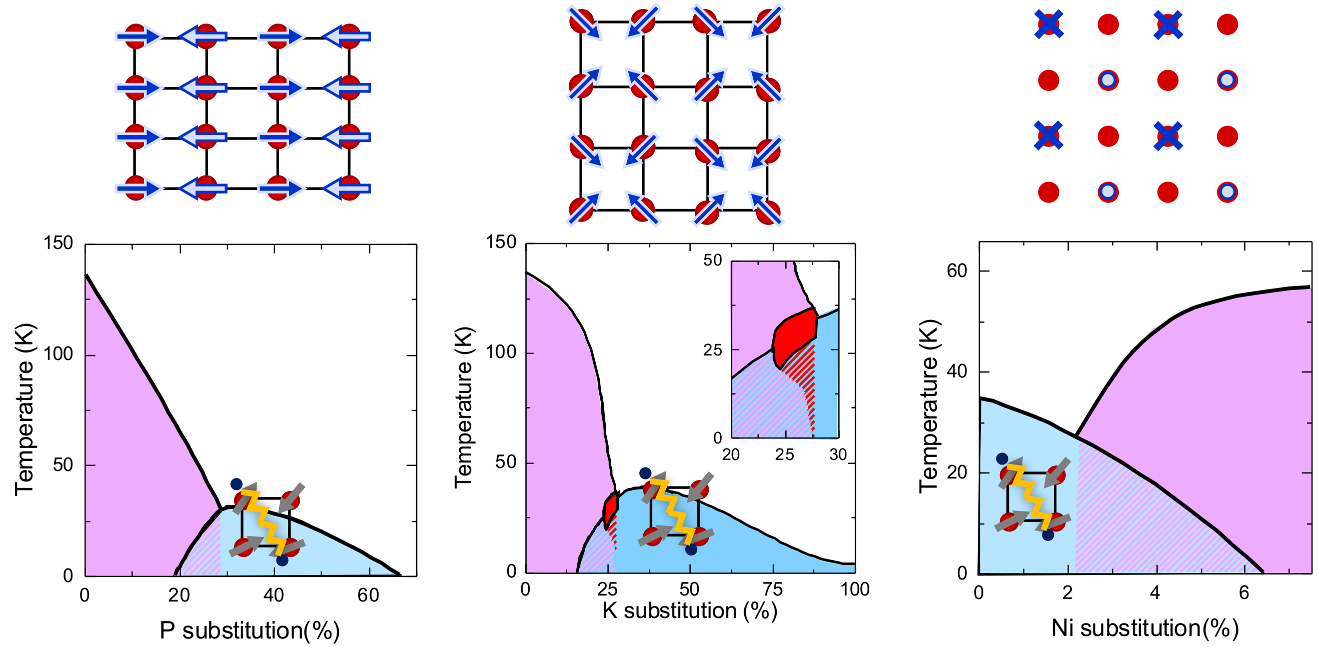
Iron-based materials



Tuning parameters

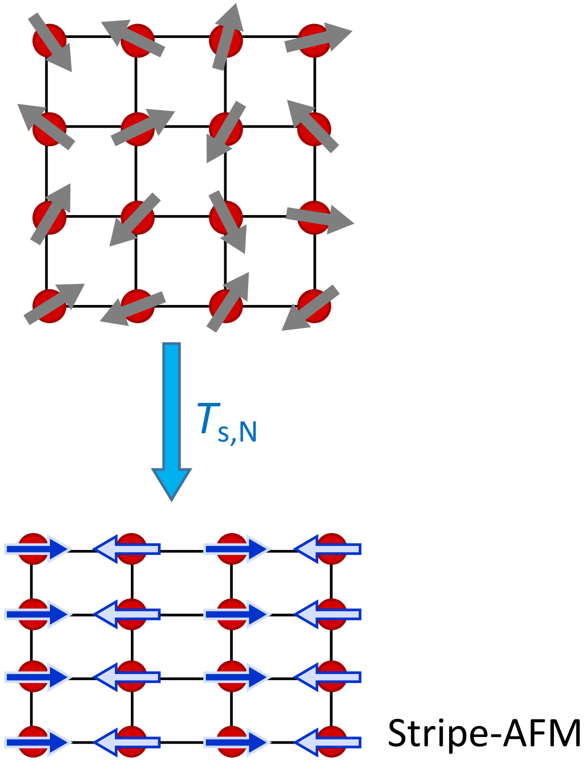


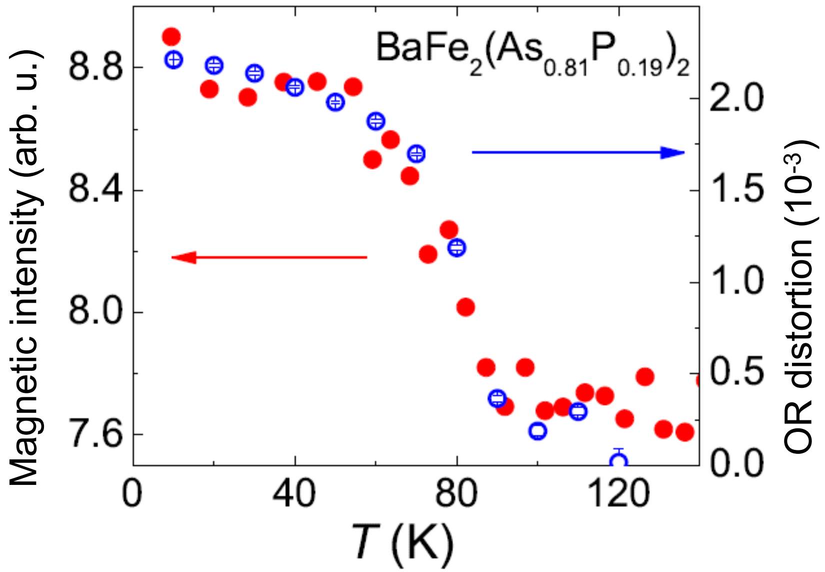
Phases



A. Böhmer, A. Kreyssig,
Phys. Unserer Zeit **48**, 70 (2017)

Magnetoelastic coupling

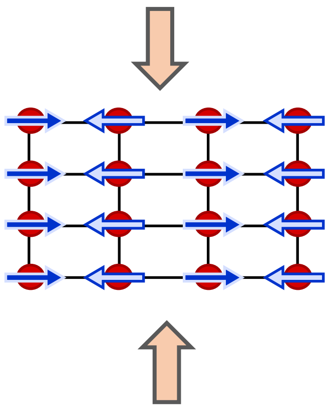


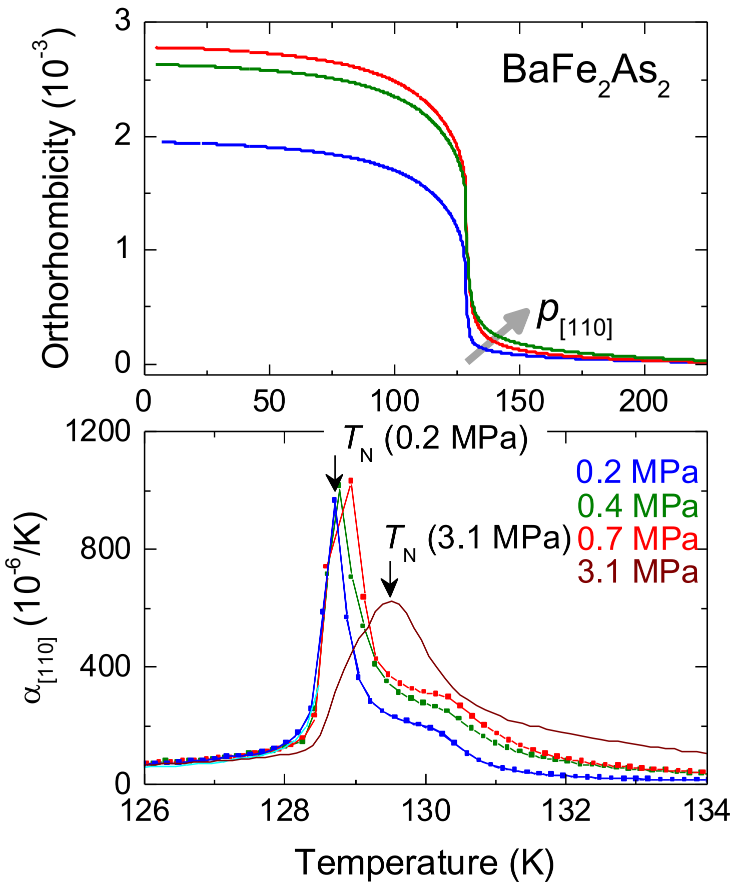


Allred et al., PRB **90**, 104513 (2014)

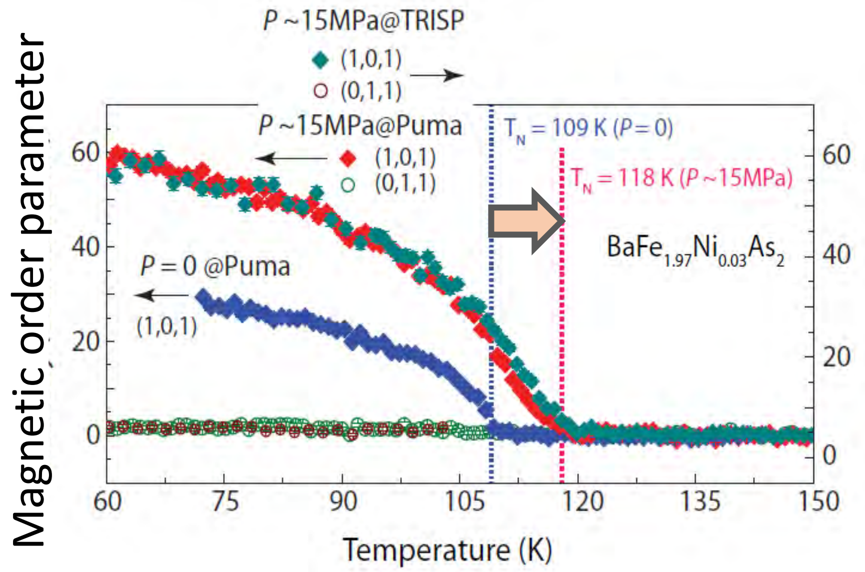
Stripe-type antiferromagnetism couples directly to structural distortion.
Facilitates elastic tuning of magnetic order.

Tune magnetic transition via uniaxial stress





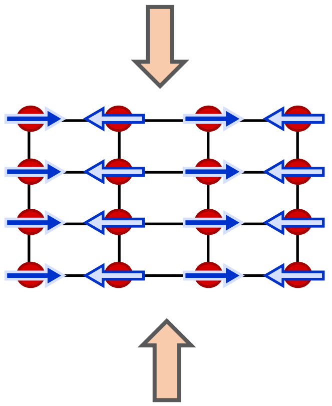
Böhmer et al., unpublished



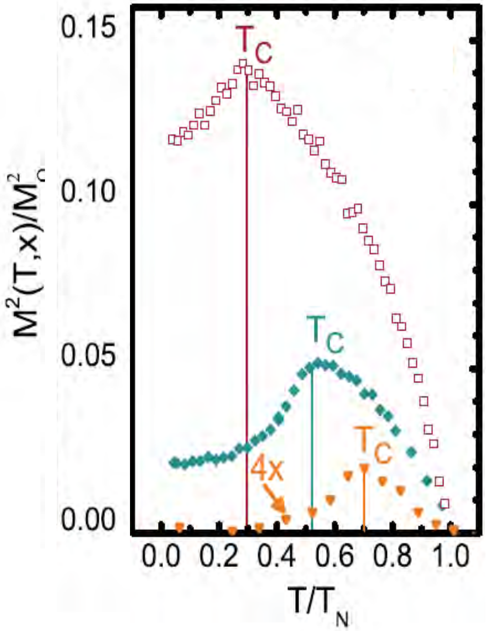
Lu et al., PRB **93**, 134519 (2016)

Tuning with uniaxial pressure

Effect on superconductivity

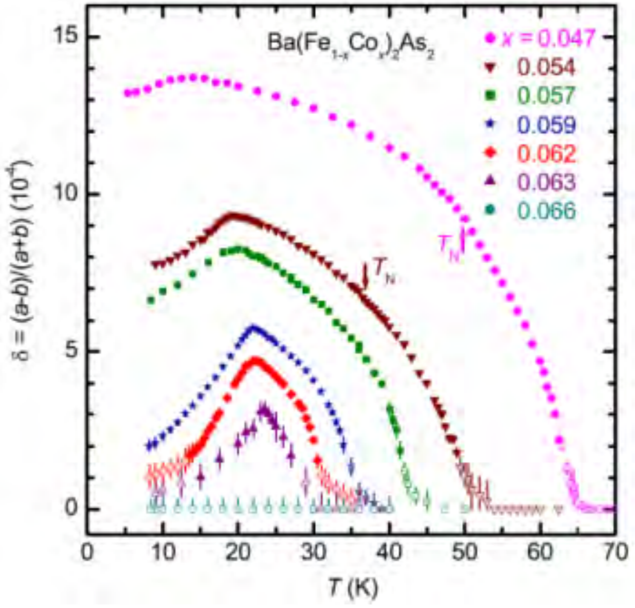


Ordered magnetic moment



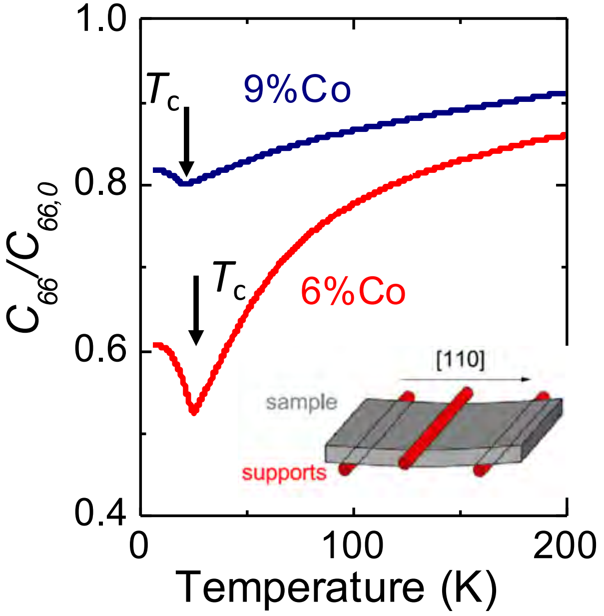
Fernandes et al., PRB 2010

Orthorhombic distortion



Nandi et al., PRL **104**, 057006 (2010)

Elastic shear modulus



Böhmer et al., PRL **112**, 047001 (2014)

- Competition between magnetism and superconductivity for the same electrons
- Results in a huge effect of superconductivity on lattice constants and elastic modulus
- T_{sc} highly sensitive to uniaxial deformation:

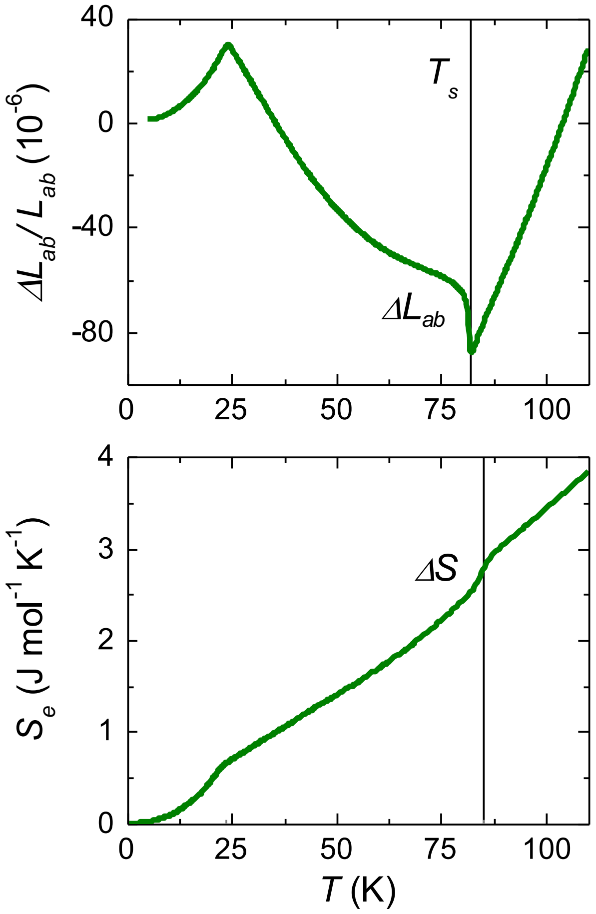
$$\frac{dT_{sc}}{d\varepsilon_a} - \frac{dT_{sc}}{d\varepsilon_b} \sim 9\ \mathrm{K}/10^{-3}$$ in $Ba(Fe_{0.955}Co_{0.045})_2As_2$ with T_{sc}=14 K

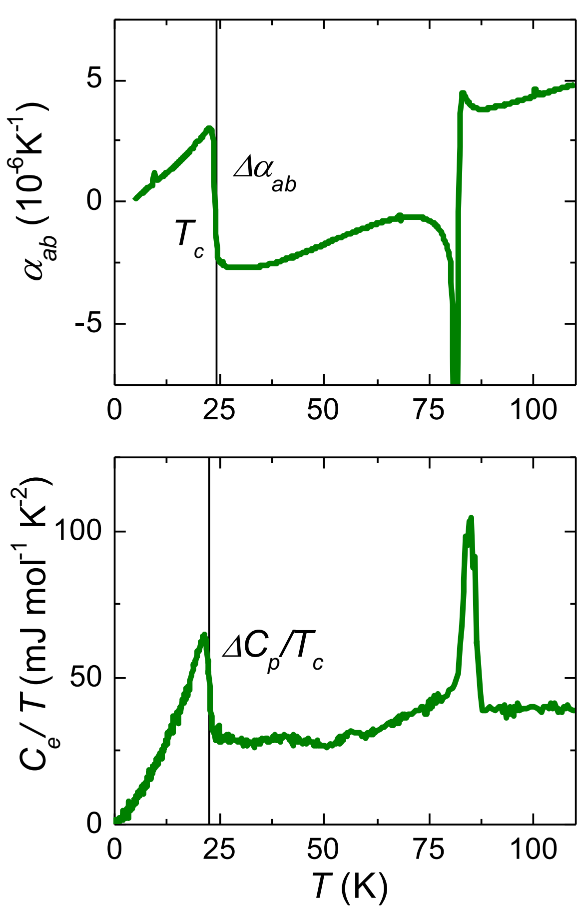
For tetragonal samples, see: Malinowski et al., arxiv: 1911.03390

What will anisotropic (symmetry-conserving) pressure do?

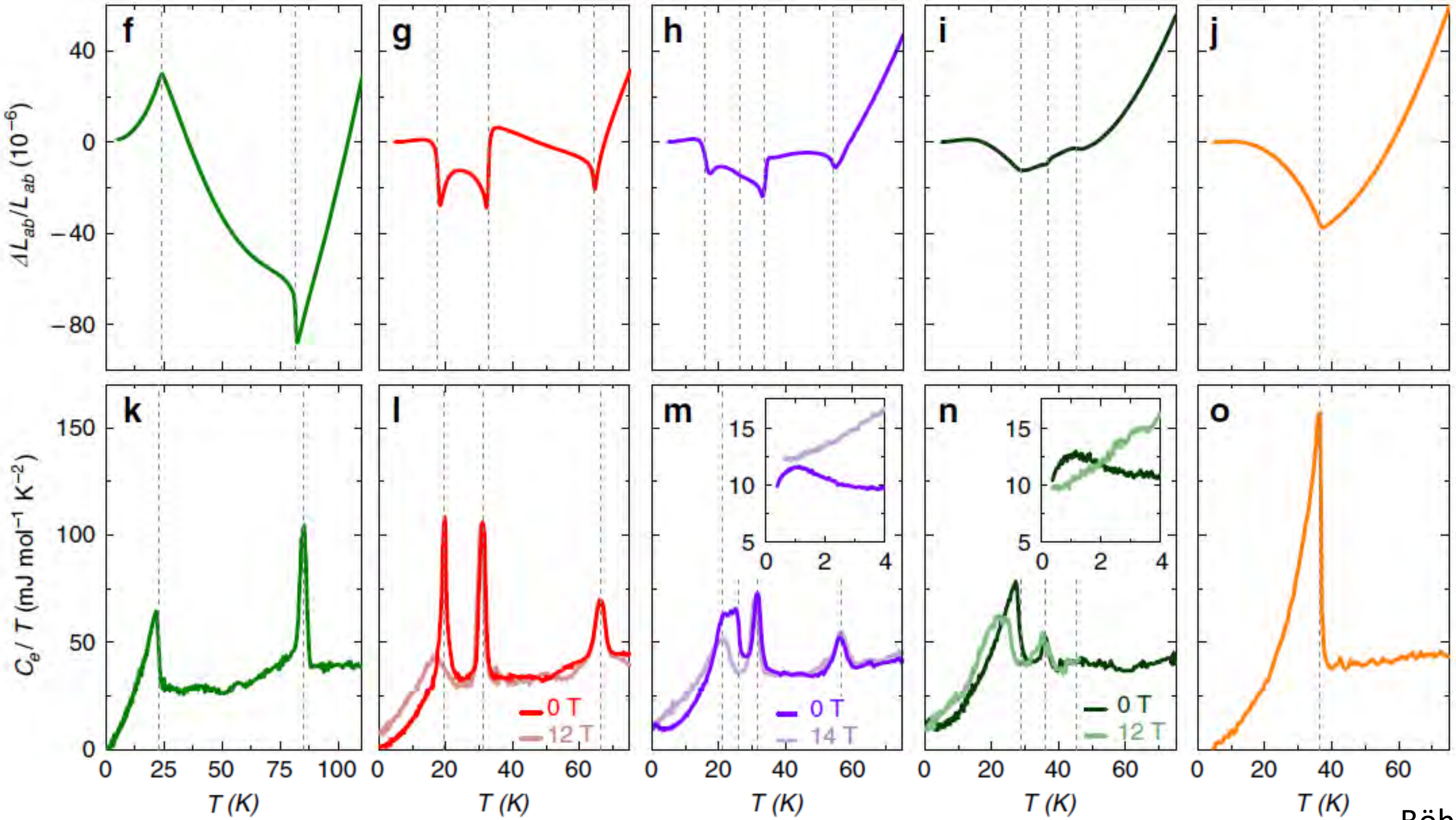
Clausius-Clapeyron (1st order transitions) $\frac{dT}{dp_i} = V_m \frac{\Delta L_i / L_i}{\Delta S}$

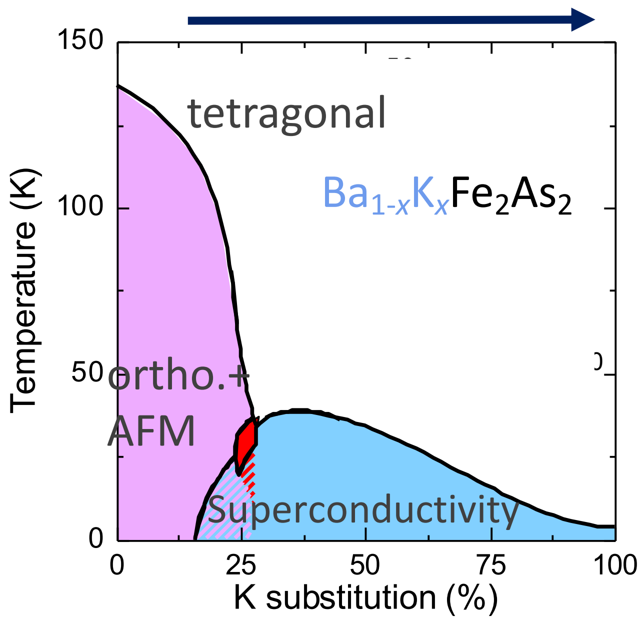
Ehrenfest (2nd order transitions) $\frac{dT}{dp_i} = V_m \frac{\Delta \alpha_i}{\Delta C_p / T_c}$





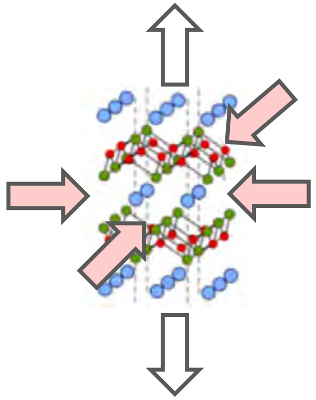
Pressure derivatives in hole-doped $Ba_{1-x}K_xFe_2As_2$

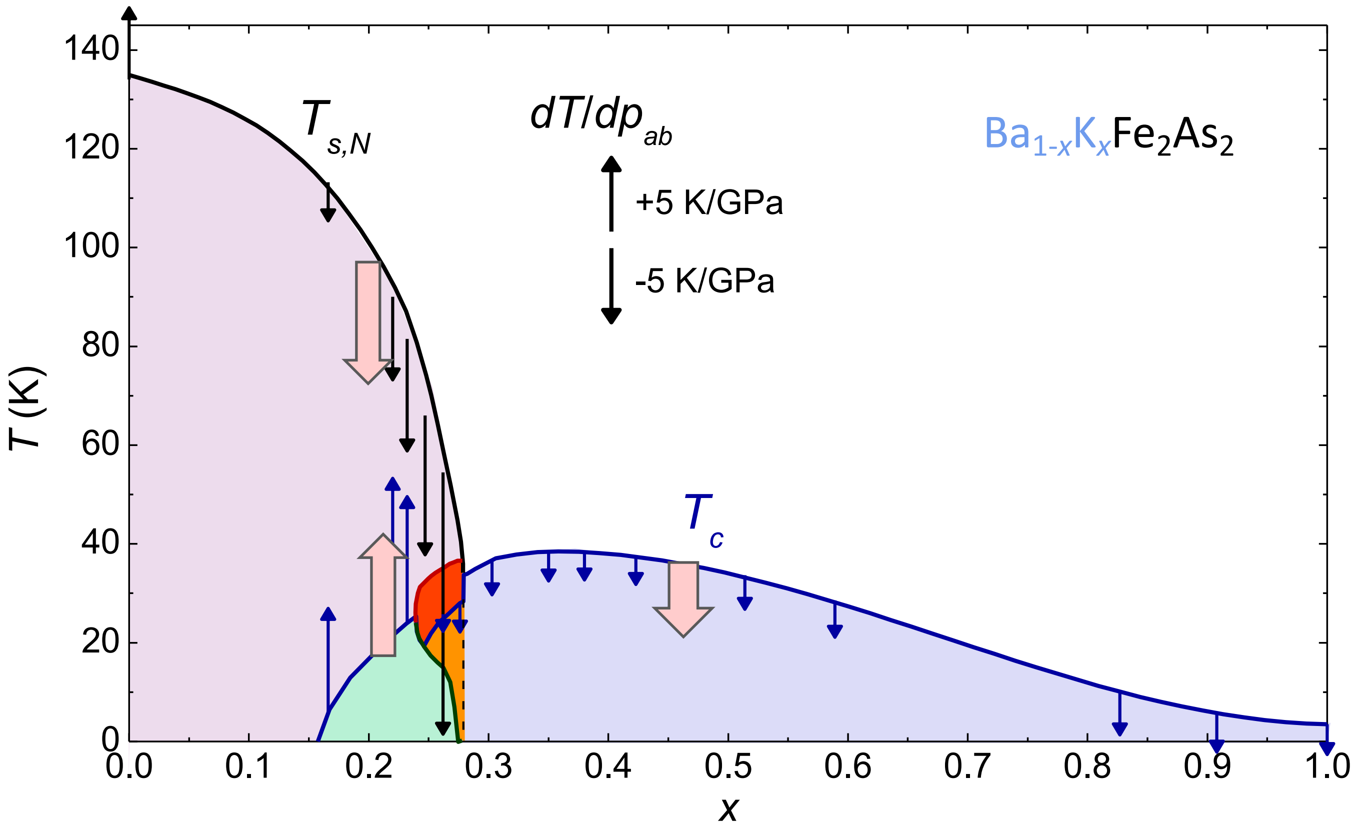




Böhmer et al., Nat. Commun. 6, 7911 (2015)

Effect of biaxial in-plane pressure

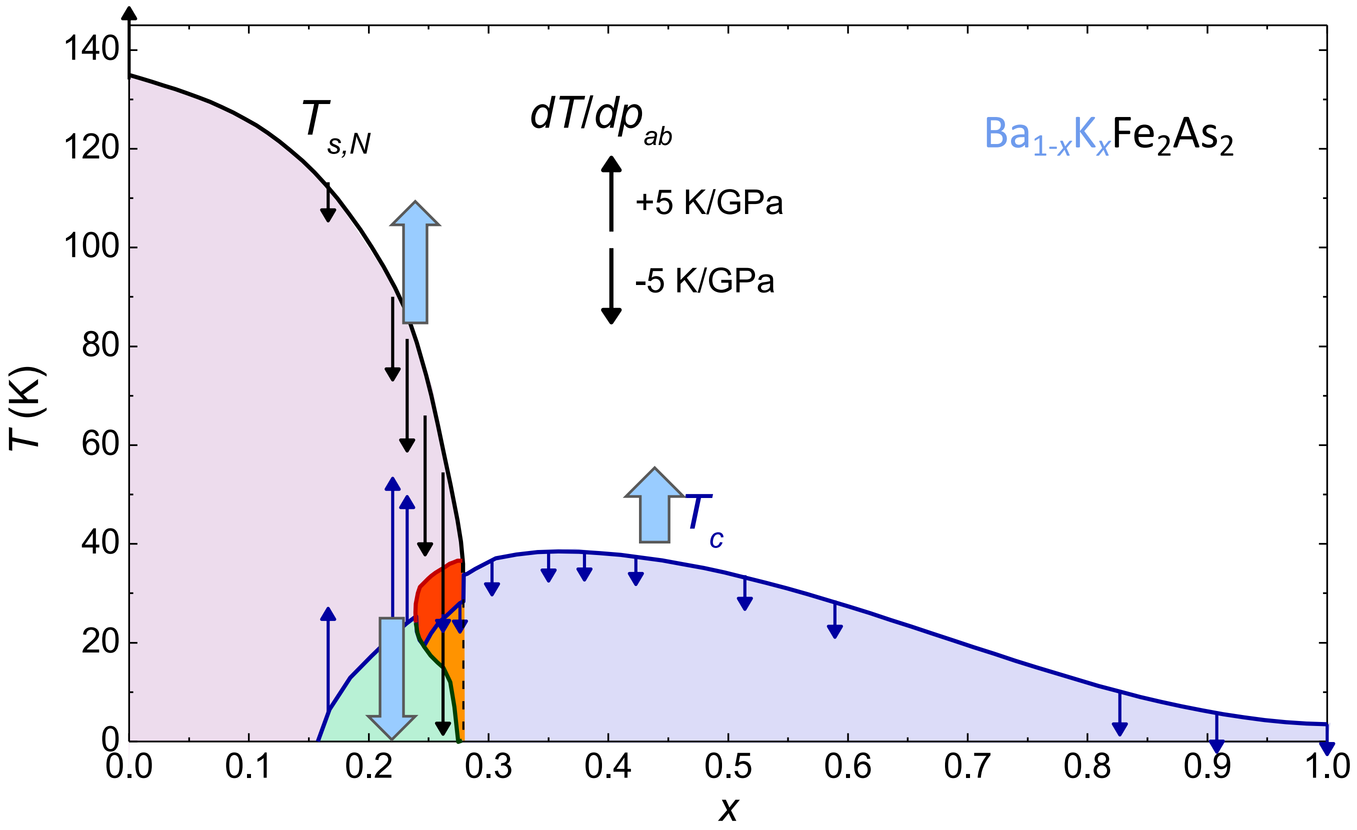


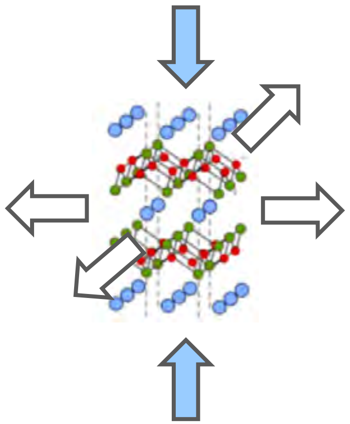


Opposite pressure derivatives of T_{AFM} and T_{sc}: one phase is stabilized at the expense of the other

Böhmer et al., Nat. Commun. 6, 7911 (2015)

Effect of *c*-axis pressure





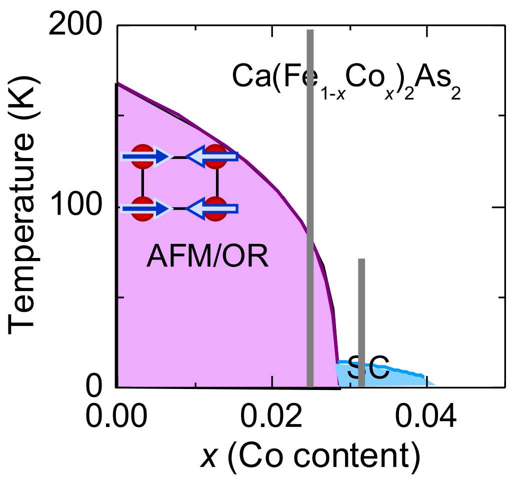
The "best" structural tuning is via the *c*/*a*-ratio

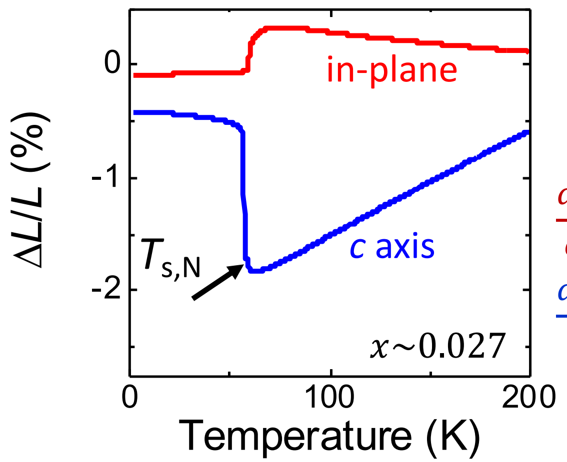
Opposite sign of pressure derivatives $dT/d\sigma_{ab}$ and $dT/d\sigma_c$

See: Meingast et al., PRL 2012
Böhmer, PhD thesis

Uniaxial pressure derivatives from thermal expansivity of $Ca(Fe,Co)_2As_2$

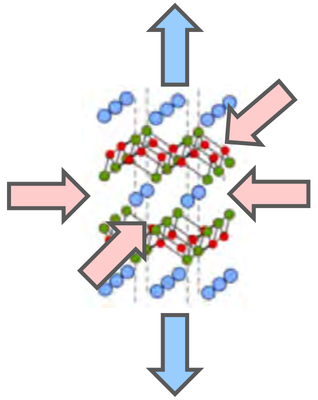
Tuning via biaxial strain





$$\frac{dT_{s,N}}{dP_{ab}} \sim 1000 \text{ K/GPa}$$

$$\frac{dT_{s,N}}{dP_{c}} \sim -3000 \text{ K/GPa}$$



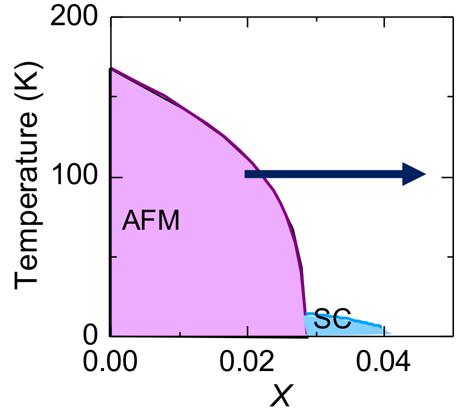
$Ca(Fe,Co)_2As_2$ is incredibly sensitive to the *c/a* ratio!

$$\frac{dT_{c}}{dP_{ab}} \sim 70 \text{ K/GPa}$$

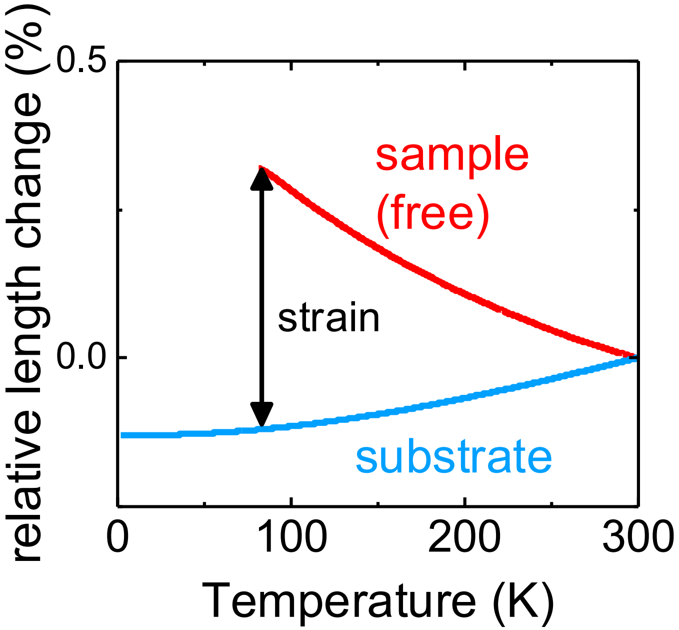
$$\frac{dT_{c}}{dP_{c}} \sim -200 \text{ K/GPa}$$

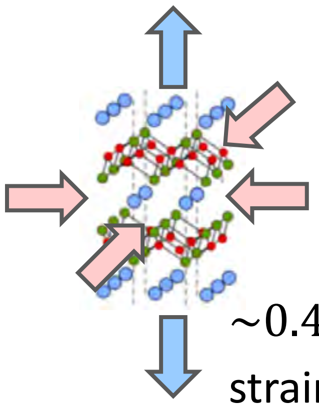
Bud'ko et al., Phys. Rev. B 88, 064513 (2013)

Tune $Ca(Fe_{1-x}Co_x)_2As_2$ via biaxial strain



Sample fixed to a glass substrate

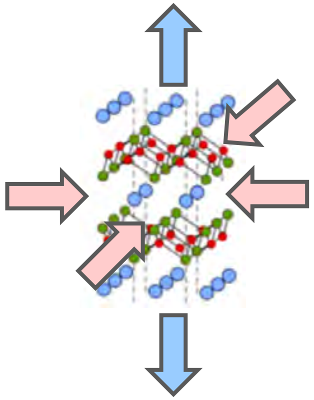


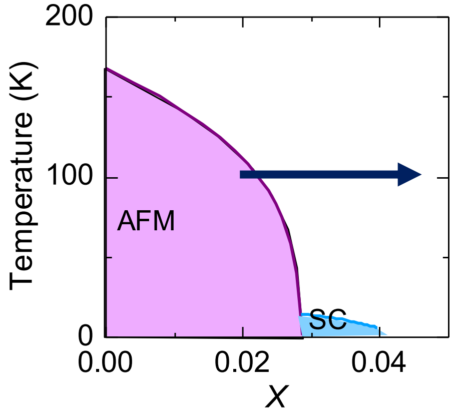


~0.4% in-plane strain "applied"

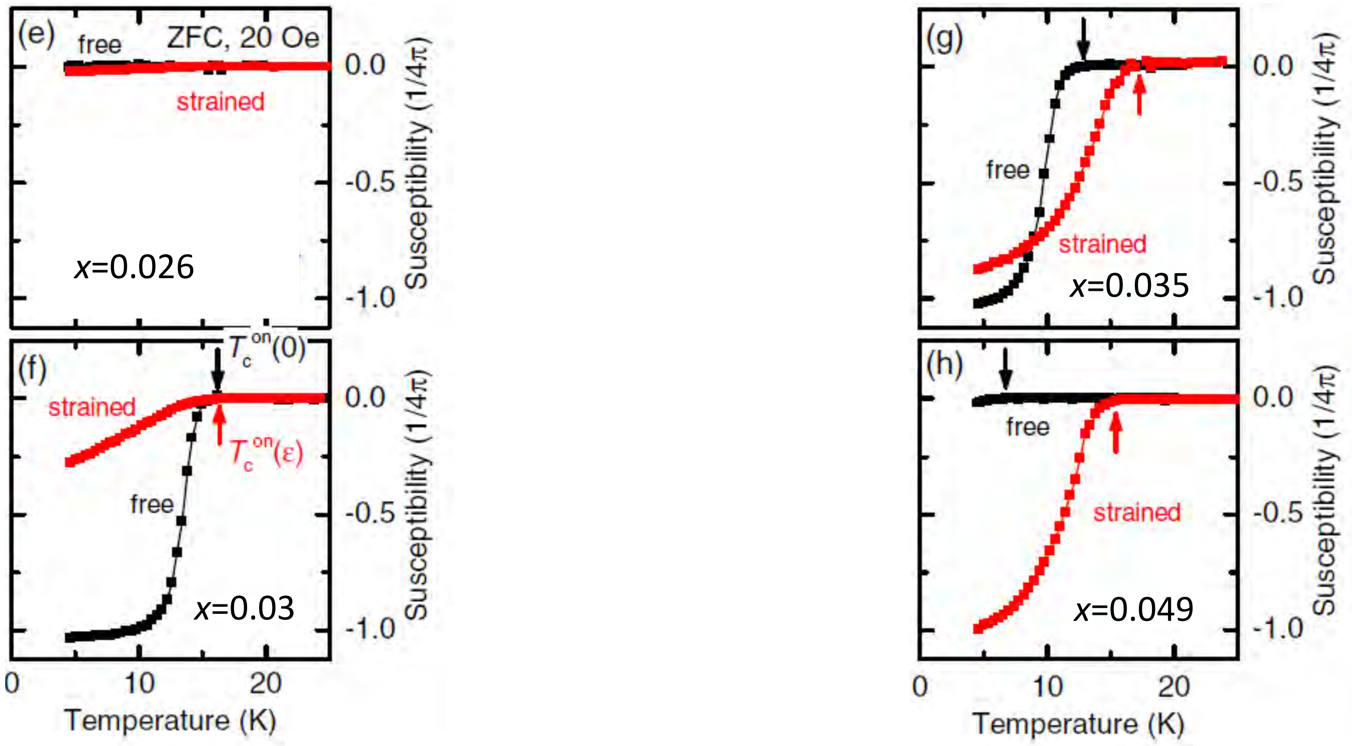
Böhmer et al., PRL **118**, 107002 (2017)

Tune $Ca(Fe_{1-x}Co_x)_2As_2$ via biaxial strain



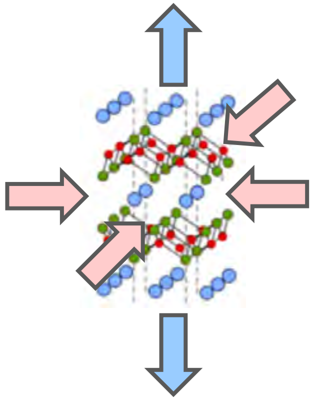


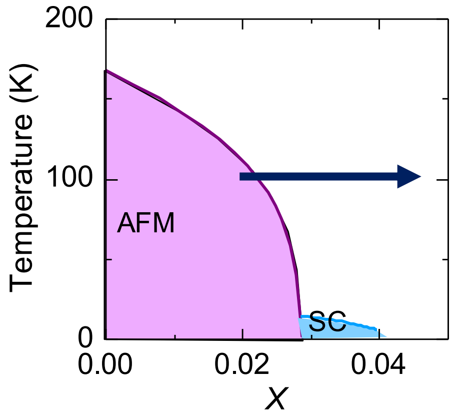
diamagnetic shielding



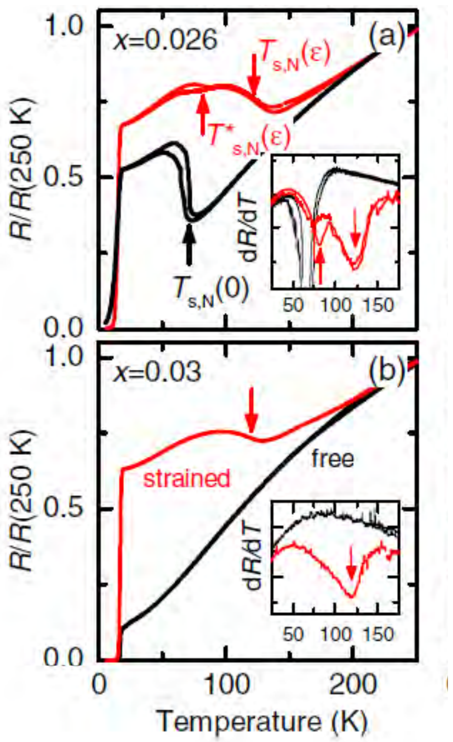
Superconductivity can be suppressed or induced

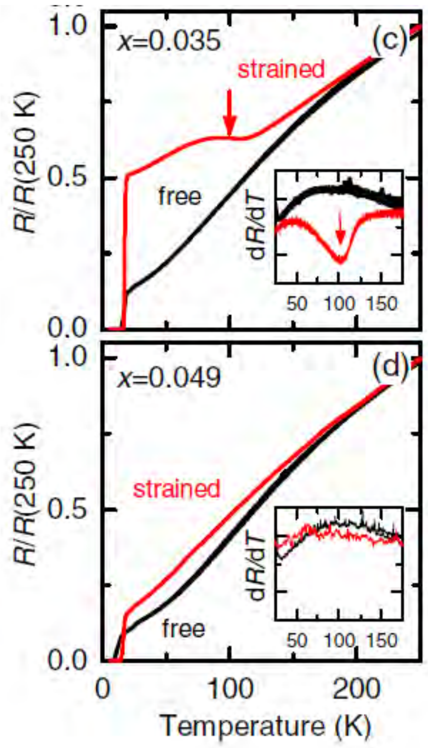
Tune $Ca(Fe_{1-x}Co_x)_2As_2$ via biaxial strain





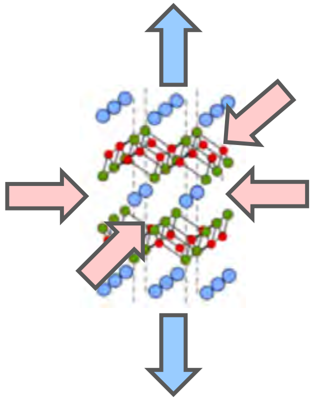
electrical resistance

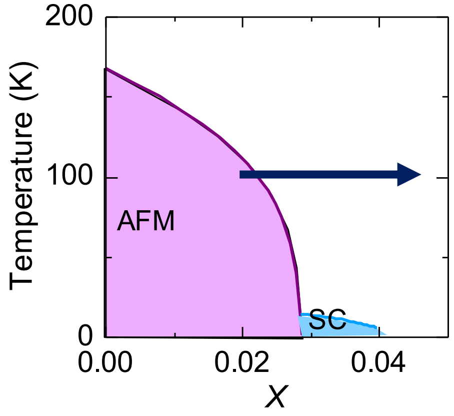


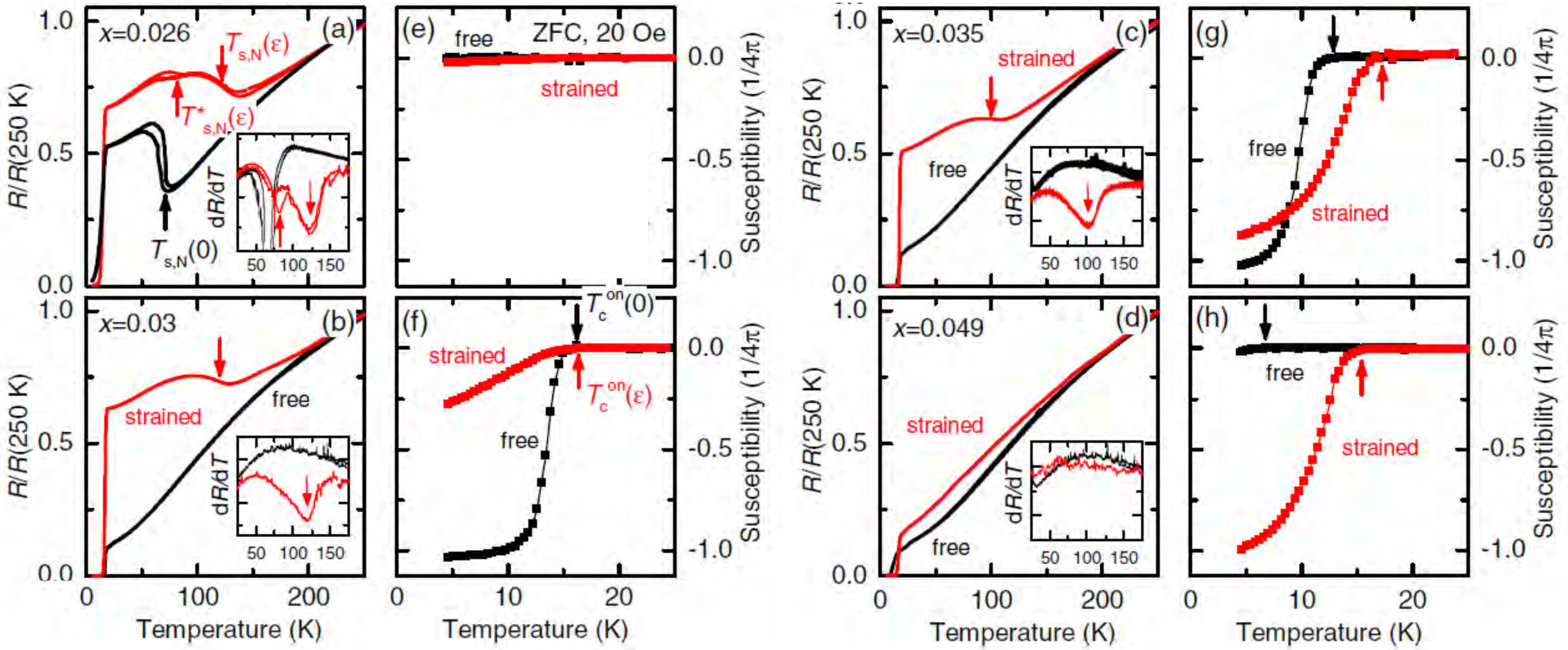


High-temperature transition shifted or induced

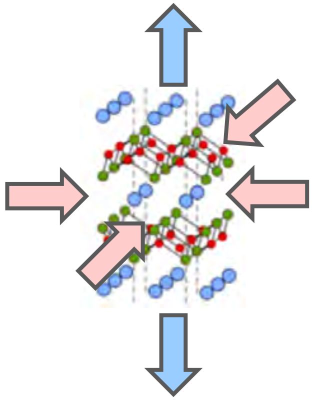
Tune $Ca(Fe_{1-x}Co_x)_2As_2$ via biaxial strain

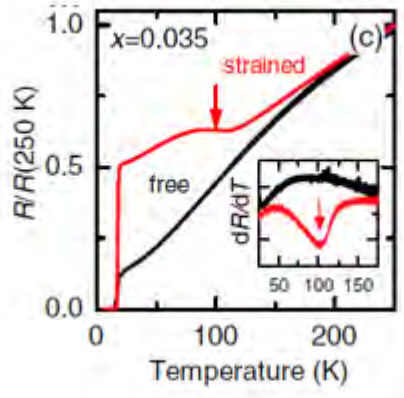


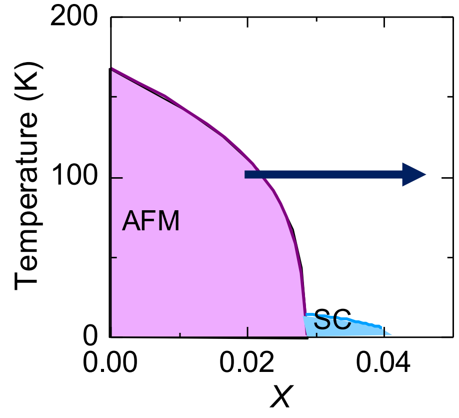


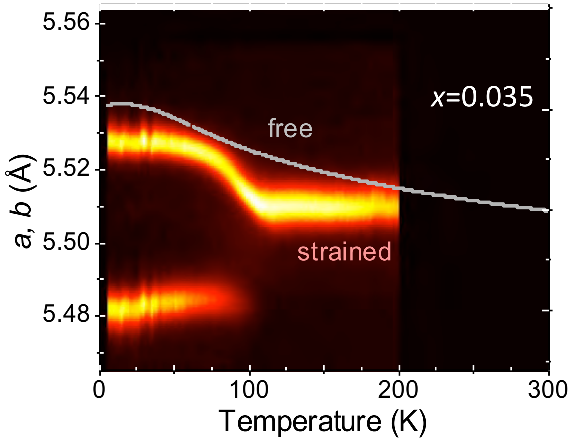


The strain-induced transition

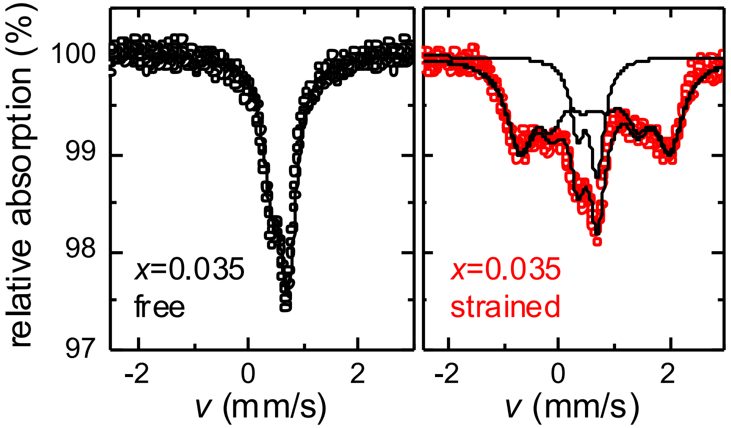






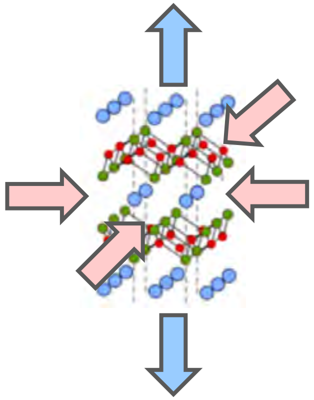


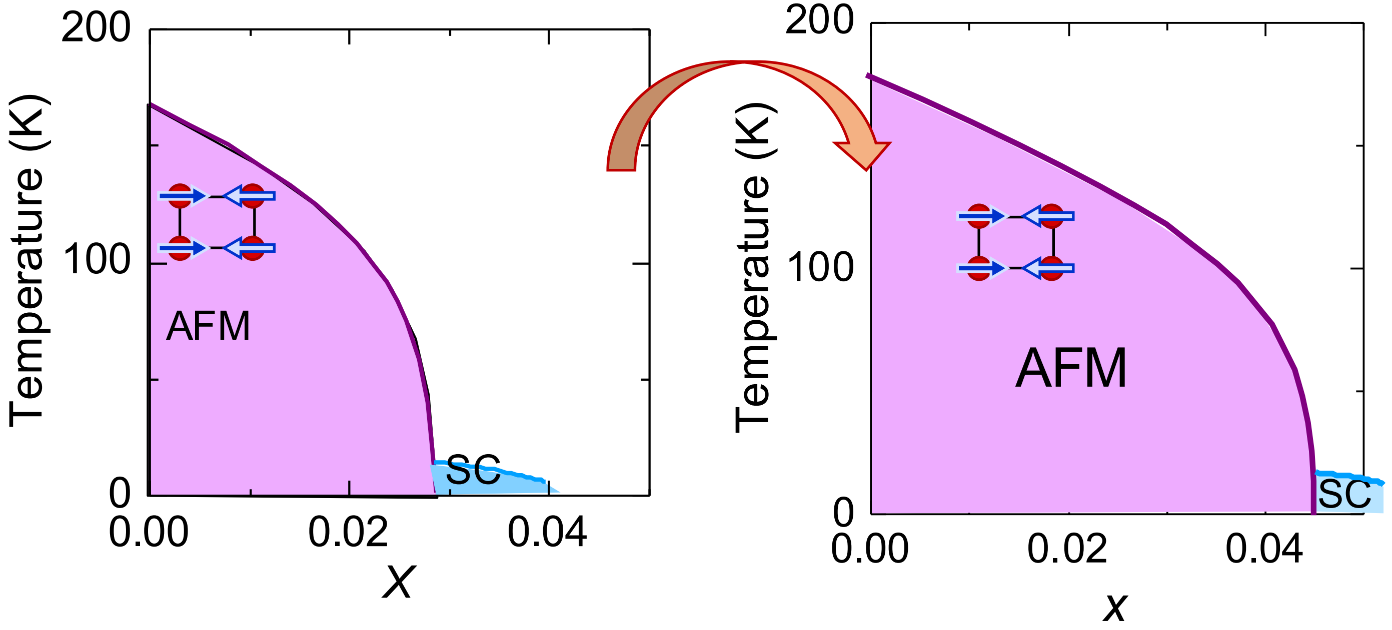
Strain induced
structural transition



Strain induced
magnetic order

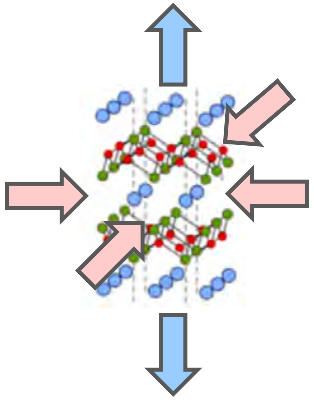
Manipulation of the phase diagram

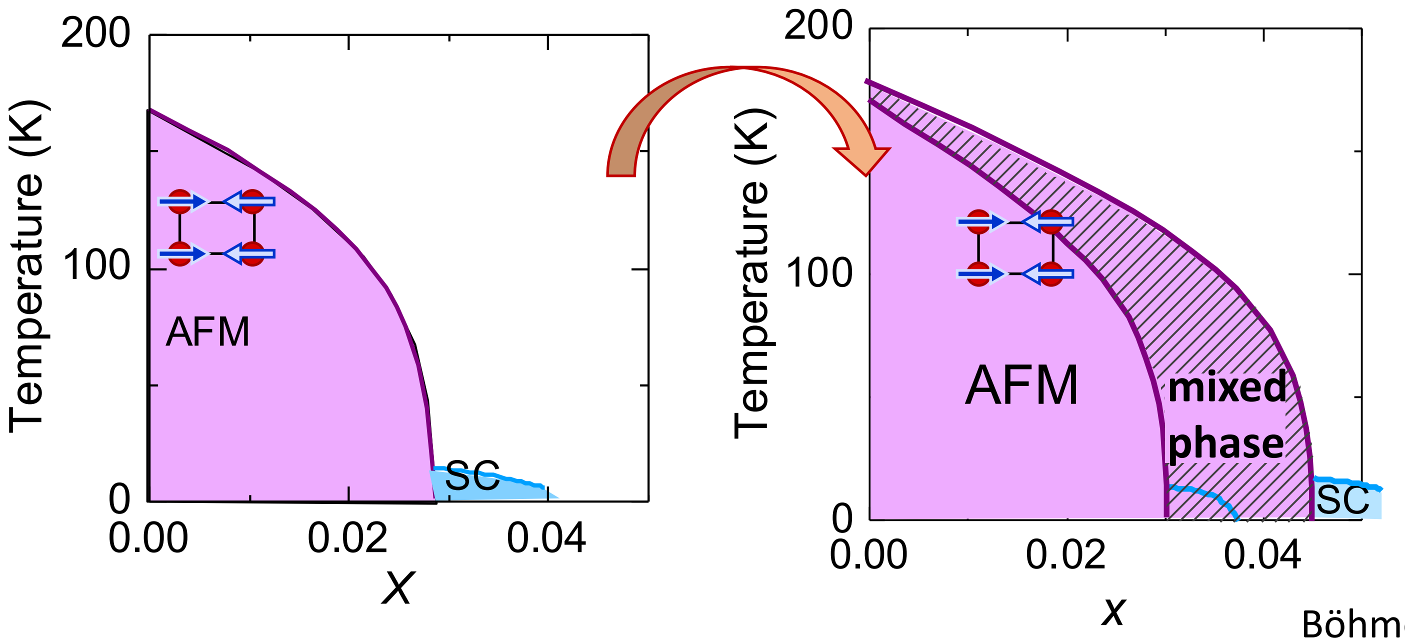




Böhmer et al., PRL **118**, 107002 (2017)

Manipulation of the phase diagram



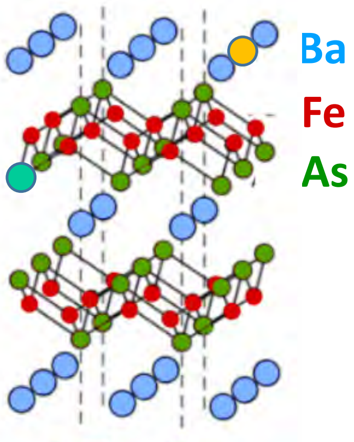


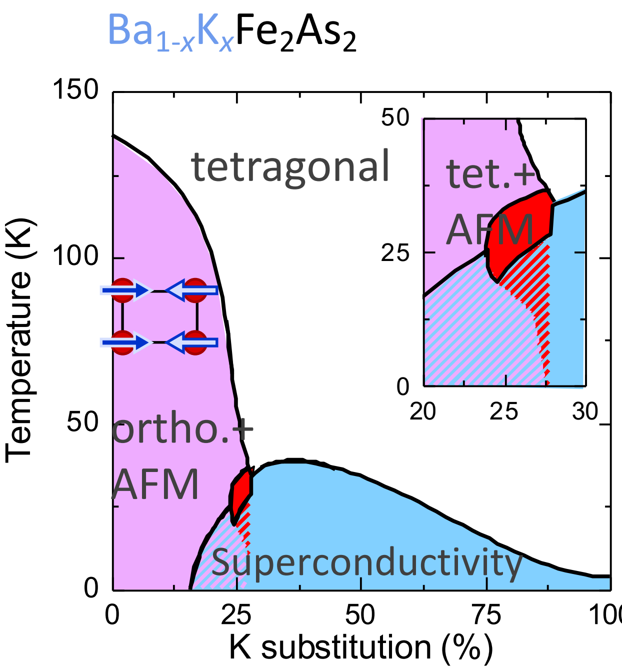
Consequence of fixed *strain not stress*

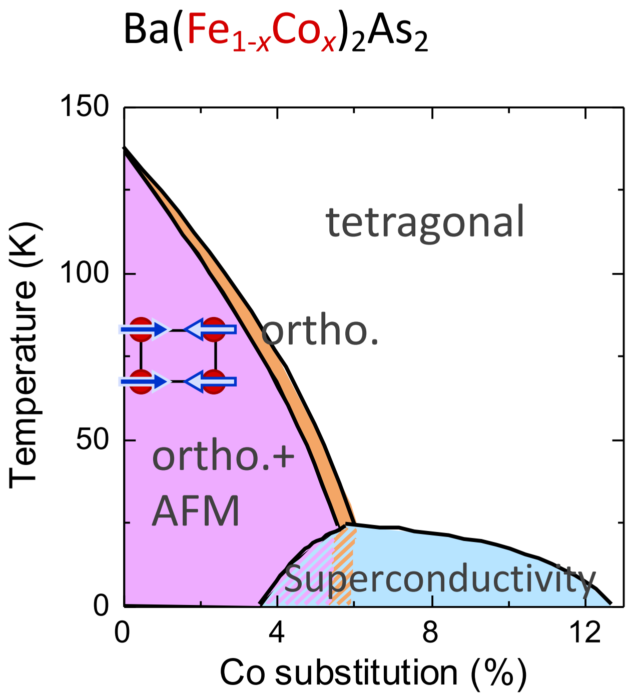
Böhmer et al., PRL **118**, 107002 (2017)
See: Fente et al., PRB **97**, 014505 (2018)

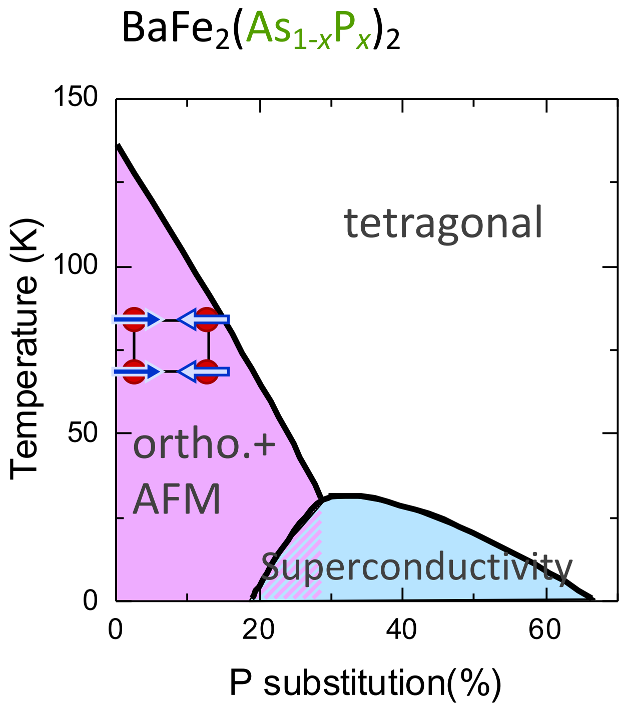
Phase diagram variants

Tuning via chemical composition



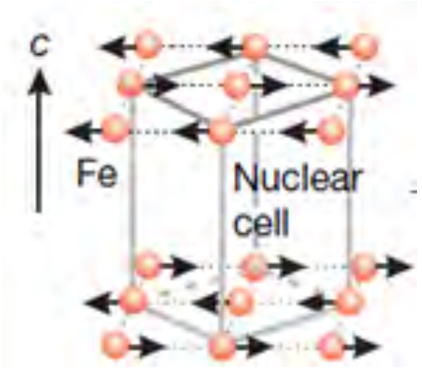




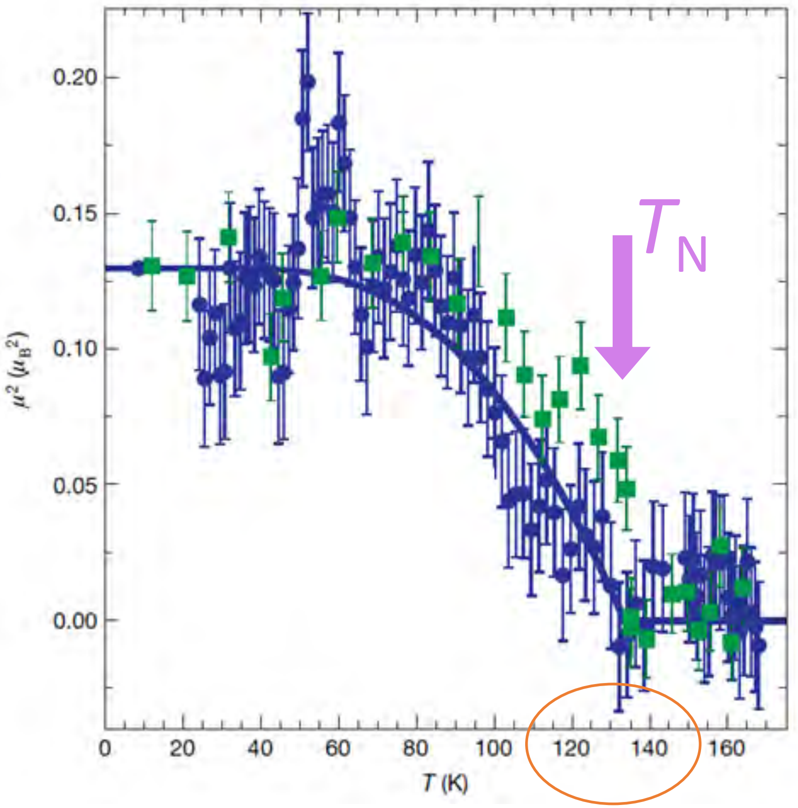


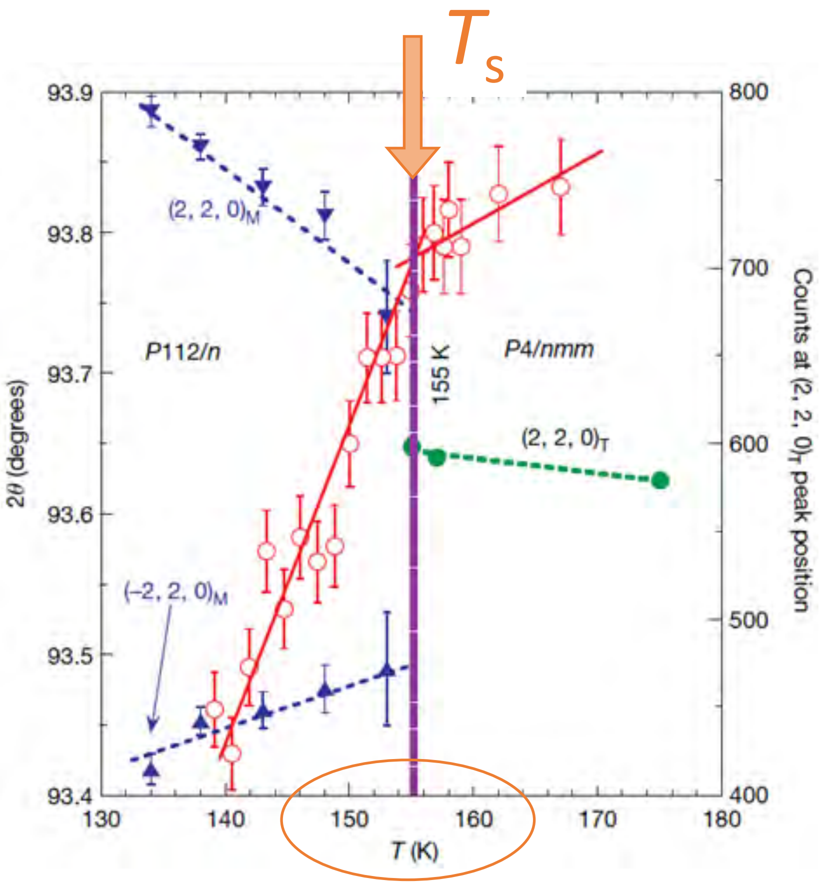
Which magnetic phases can occur in these systems?
How can they be tuned/stabilized?
How do they couple to the crystal lattice?

A surprise in the very beginning…



$\boldsymbol{Q} = (\pi, 0)$

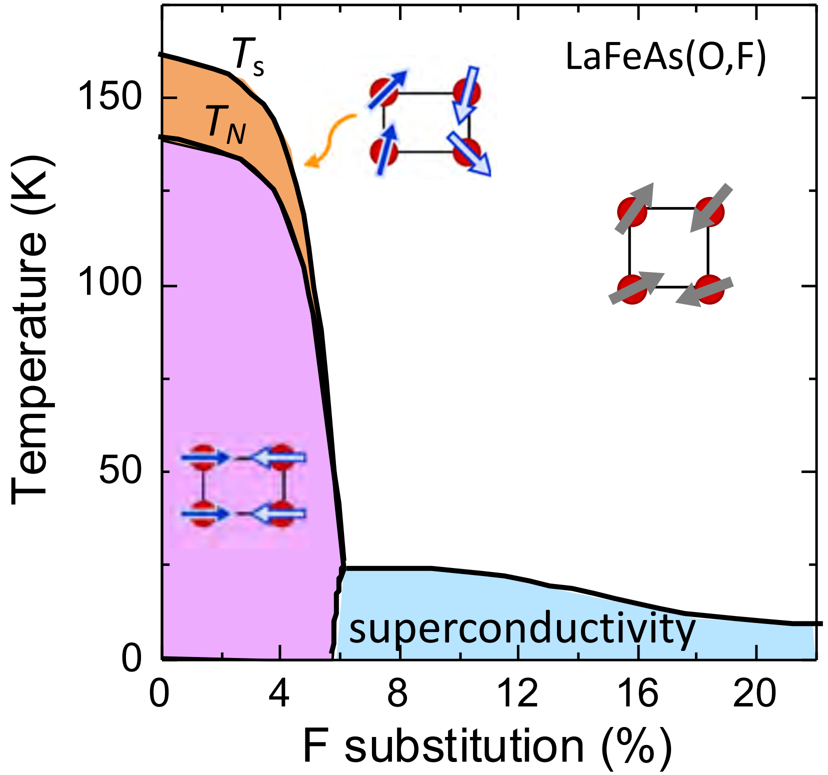


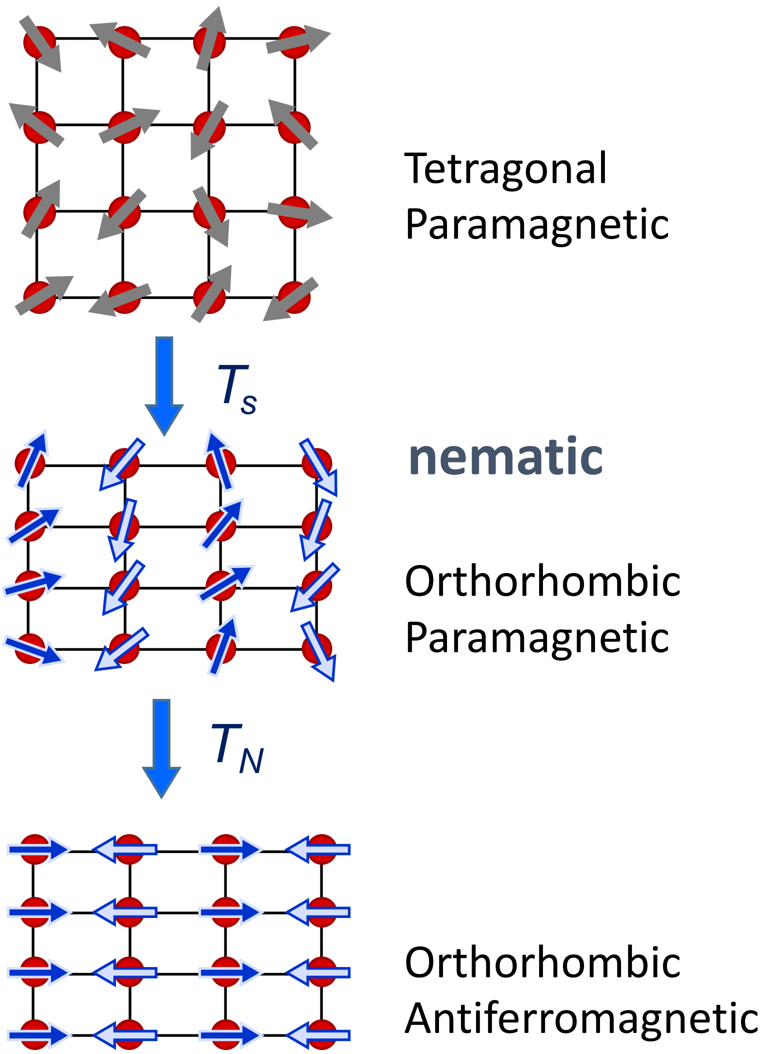


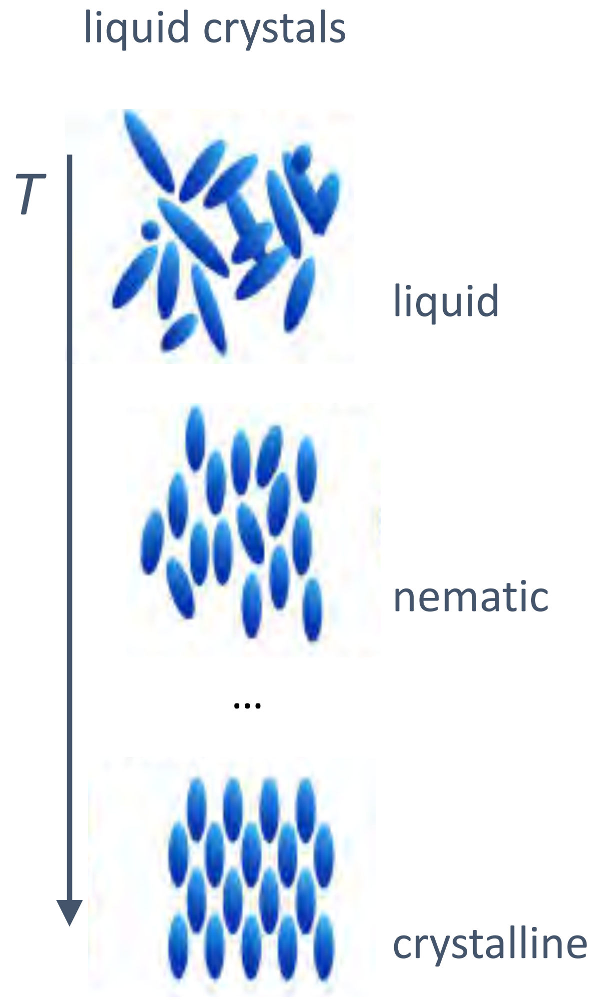
De la Cruz et al., Nature **453**, 899 (2008)

- Magnetic transition is expected to result in a structural transition
- But the structural transition occurs at a higher temperature, T_s>T_{AFM}

Sequence of magnetic and structural transitions



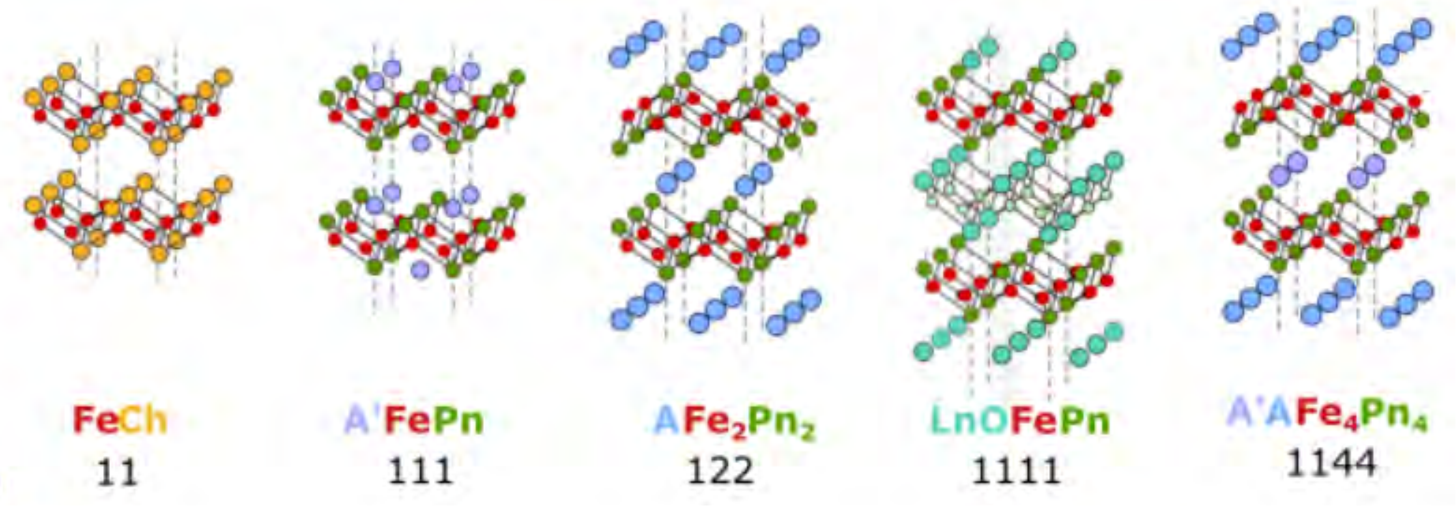




Luetkens et al., Nat. Mat. **8**, 305 (2009)

Ni et al., PRB **78**, 214515 (2008)
Chu et al., PRB **79**, 014506 (2009)
Lester et al., PRB **79**, 144523 (2009)
...

Nematic phase is very common



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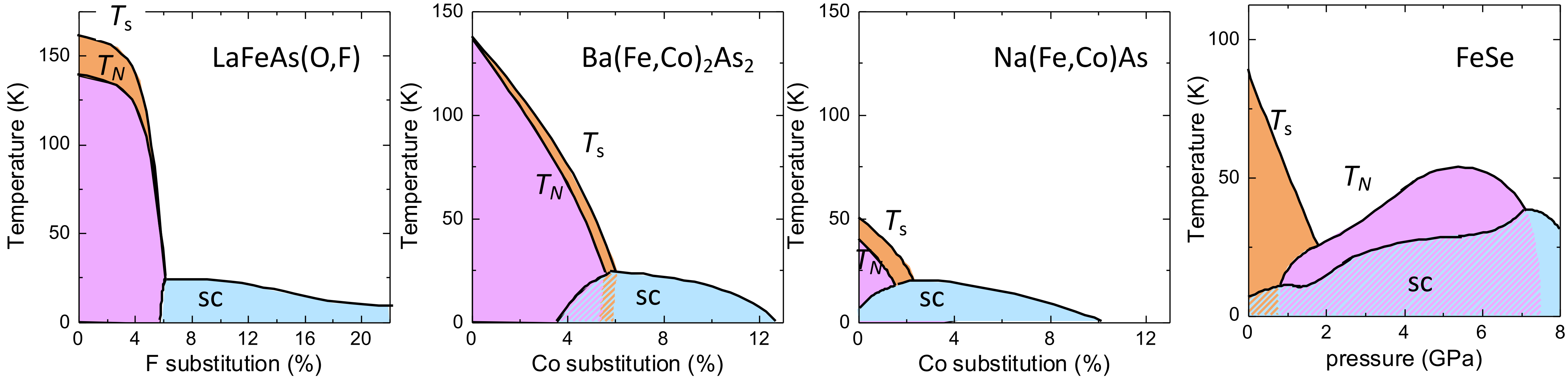
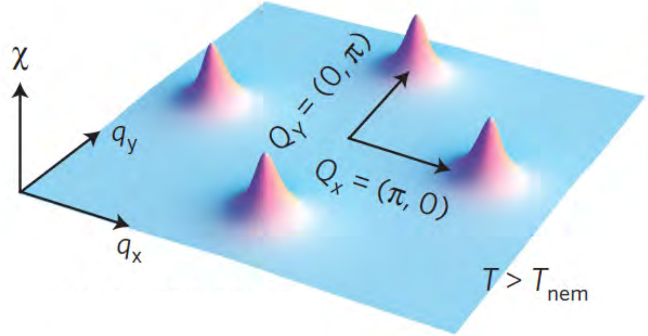


Special nature of magnetism in iron-based materials

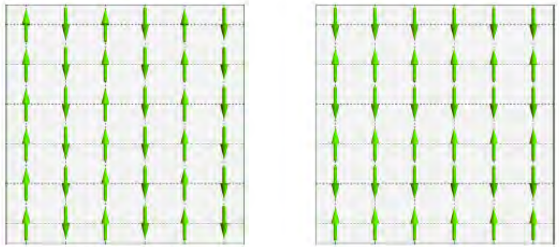
- Antiferromagnetic fluctuations characterized by a pair of wavevectors:
  $\boldsymbol{Q_X} = (\pi, 0), \boldsymbol{Q_Y} = (0, \pi)$
- These are symmetry-equivalent for the tetragonal system



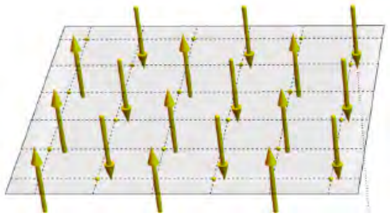
SDW can be described as:

$$\boldsymbol{M}(\boldsymbol{r}) = \boldsymbol{M}_1 \cos(\boldsymbol{Q_X r}) + \boldsymbol{M}_2 \cos(\boldsymbol{Q_y r})$$

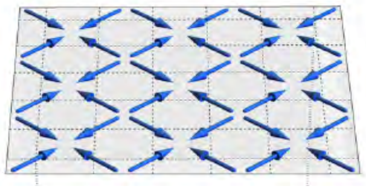
Various types of commensurate magnetic order are possible from these wavevectors



Stripe-type AFM



“C4” magnetic order



Spin-vortex crystal

Lorenzana et al., Phys. Rev. Lett. 101, 186402 (2008)
Eremin, Chubukov, Phys. Rev. B 81, 024511 (2010)

Fernandes, Kivelson, and Berg, PRB **93**, 014511 (2016)
Fernandes, Orth, Schmalian ARCMP 10, 133 (2019)

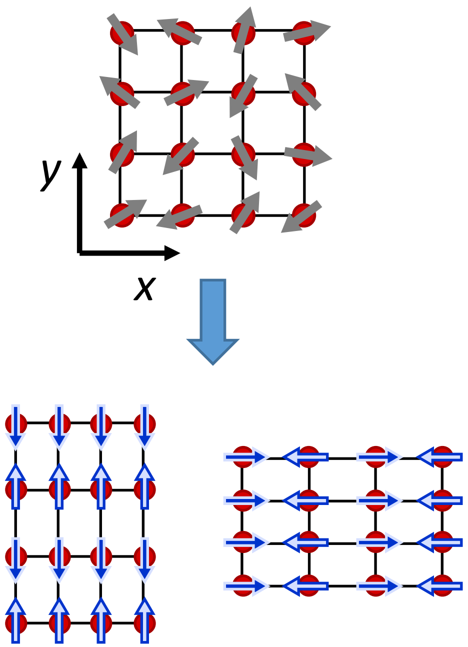
Note: Leave aside materials that feature magnetic fluctuations with other wavevectors such as $Fe_{1+y}Te$, $K_xFe_{2-y}Se_2$

Option 1: stripe-type spin-density wave (SSDW)

$\boldsymbol{M}(\boldsymbol{r}) = \boldsymbol{M}_1 \cos(\boldsymbol{Q}_X \boldsymbol{r}) + \boldsymbol{M}_2 \cos(\boldsymbol{Q}_y \boldsymbol{r})$, $\boldsymbol{Q}_X = (\pi, 0), \boldsymbol{Q}_Y = (0, \pi)$

with

$\boldsymbol{M}_1 = \boldsymbol{0}$ or $\boldsymbol{M}_2 = \boldsymbol{0}$



$\boldsymbol{M}_1 = 0$ $\boldsymbol{M}_2 = 0$

Intertwined order:

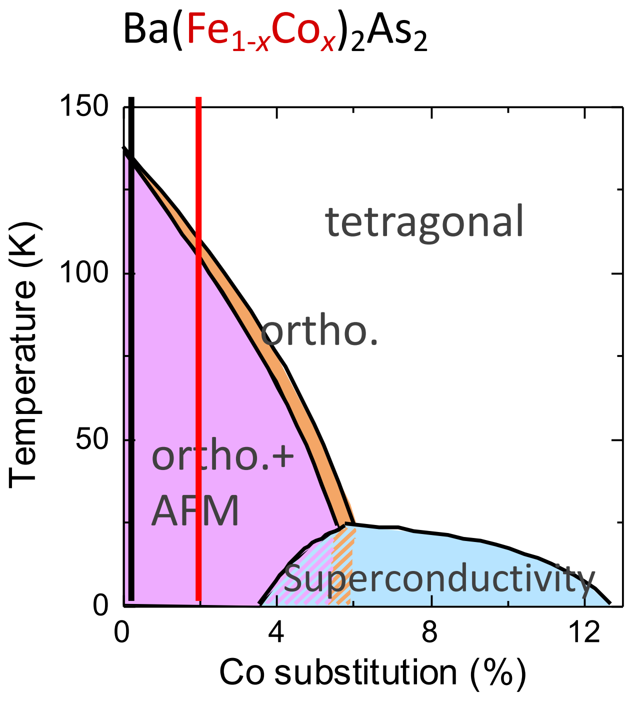
- New order Ising-type parameter (*nematic*)
$$\varphi = \boldsymbol{M}_1^2 - \boldsymbol{M}_2^2$$

- Reduced rotational symmetry couples to lattice distortion: tetragonal-to-orthorhombic

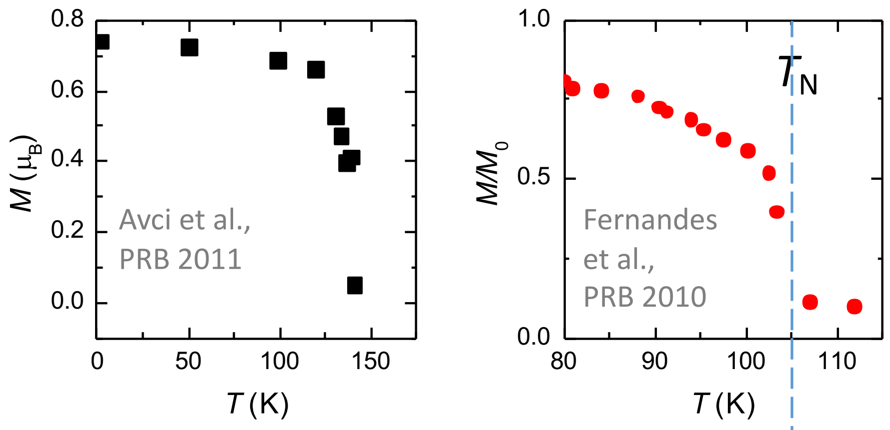
- φ "gets its own life" from magnetic fluctuations and induces nematic transition with $T_{\text{nem}} \geq T_{AFM}$

Fernandes et al., PRL **105**, 157003 (2010)
Fernandes and Schmalian, Supercond. Sci. Technol. **25**, 084005 (2012)

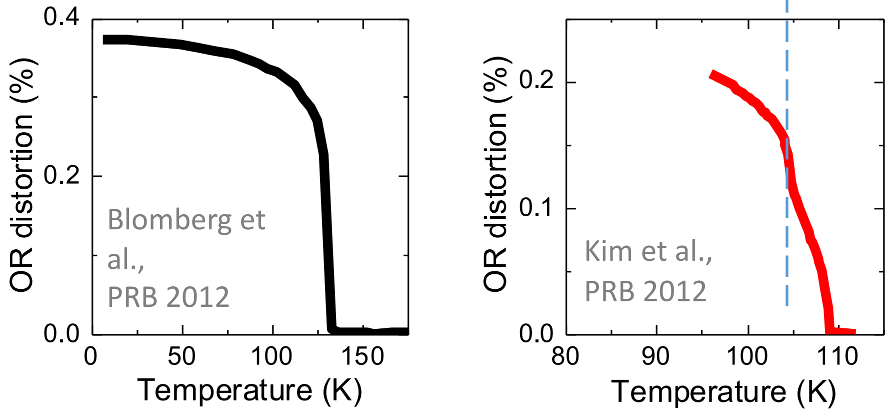
Coupled but separated nematic order emerges



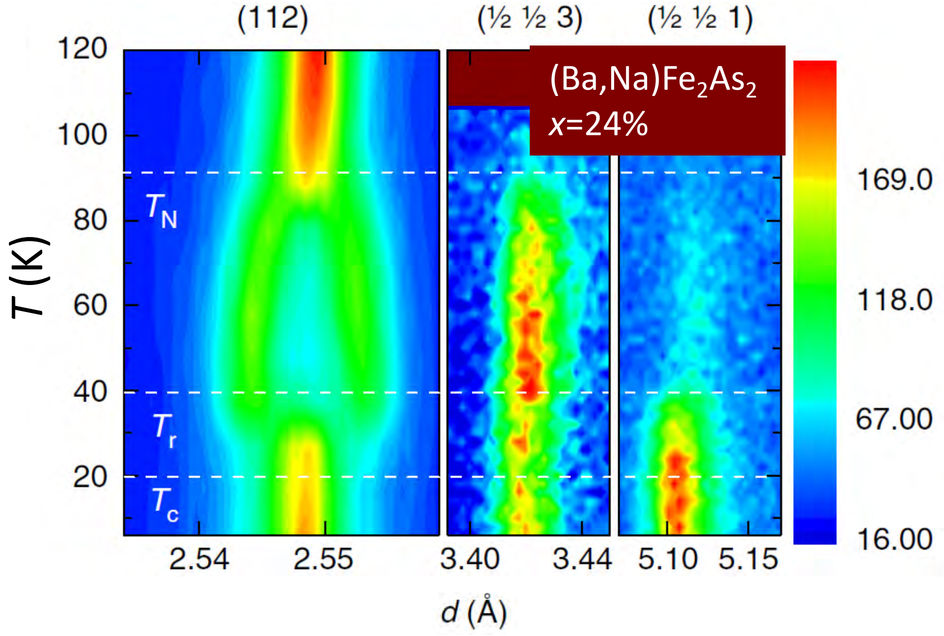
Magnetic order parameter

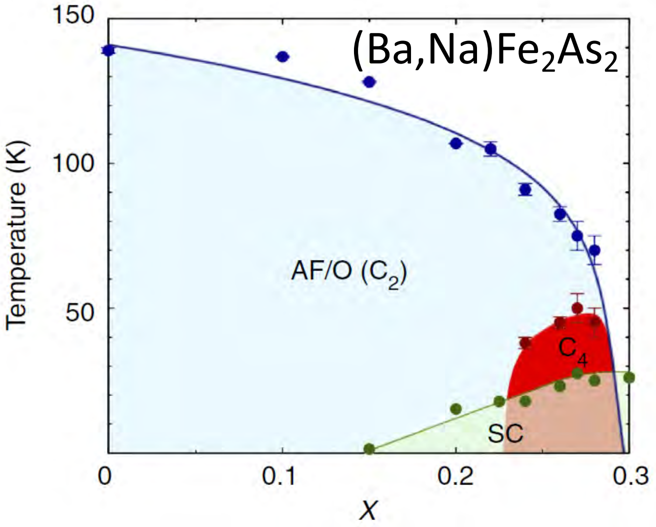


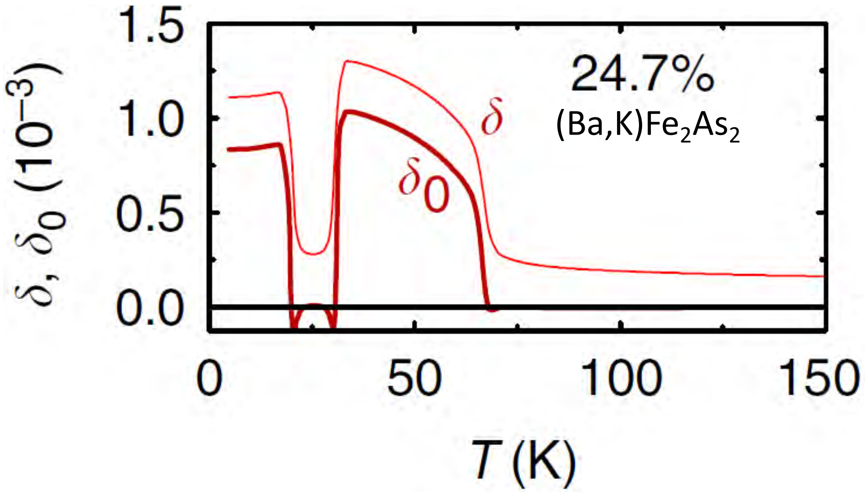
Nematic order parameter

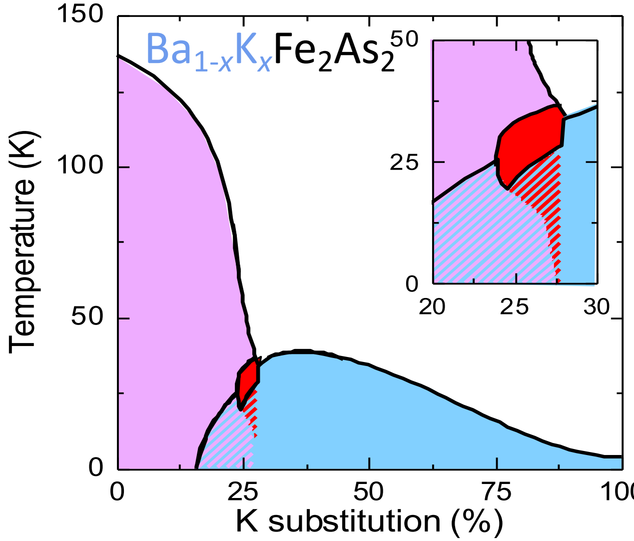


A surprisingly tetragonal magnetic phase









Avci et al., Nat. Comm. **5**, 3845 (2014)

Böhmer et al., Nature Comm. **6**, 7911, (2015)

Discovery of a “new phase”: Hassinger et al., PRB **86**, 1405052 (2012)

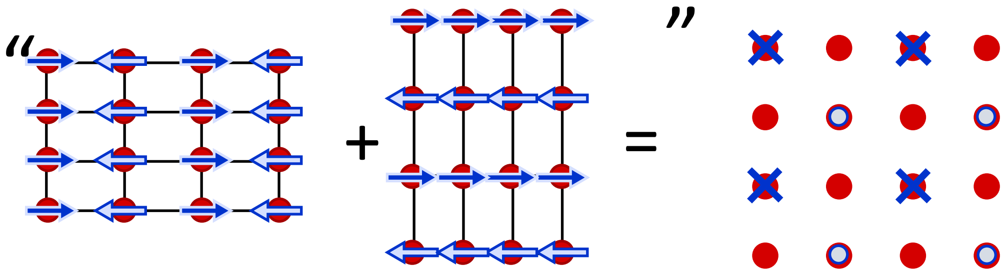
Option 2: spin-charge density wave, “C4” phase

$\boldsymbol{M}(\boldsymbol{r}) = \boldsymbol{M}_1\cos(\boldsymbol{Q}_X\boldsymbol{r}) + \boldsymbol{M}_2\cos(\boldsymbol{Q}_y\boldsymbol{r})),\ \boldsymbol{Q}_X = (\pi, 0), \boldsymbol{Q}_Y = (0, \pi)$

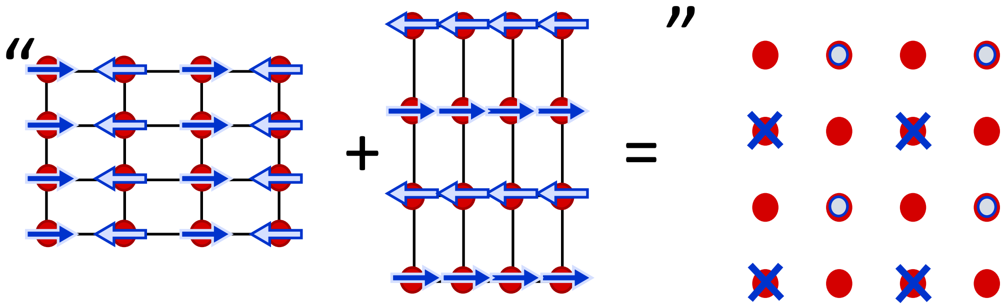
with

$\boldsymbol{M}_1 = +\boldsymbol{M}_2$ or $\boldsymbol{M}_1 = -\boldsymbol{M}_2$

Choice: $\boldsymbol{M}_1 = +\boldsymbol{M}_2$



Choice: $\boldsymbol{M}_1 = -\boldsymbol{M}_2$



Intertwined order

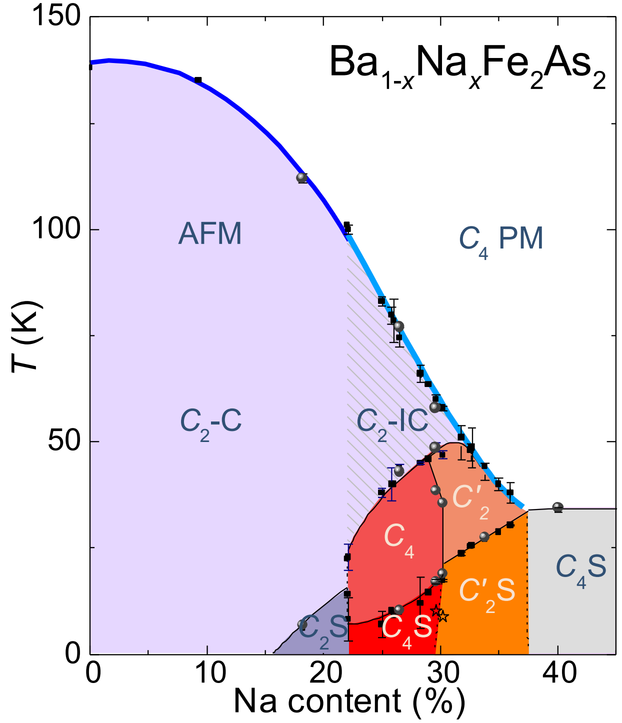
- Reduced translational symmetry
- Scalar order parameter:

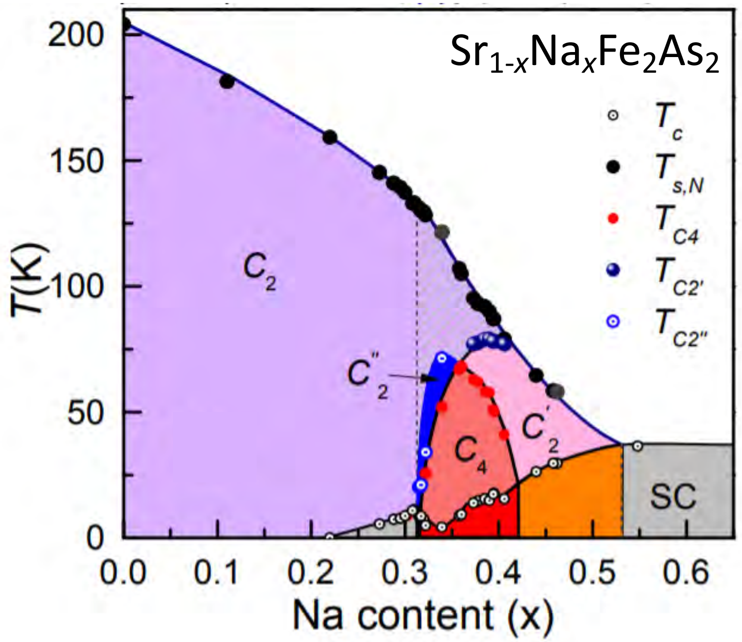
$$\varphi = \boldsymbol{M}_1 \cdot \boldsymbol{M}_2$$

- Couples to charge density! i.e., SCDW

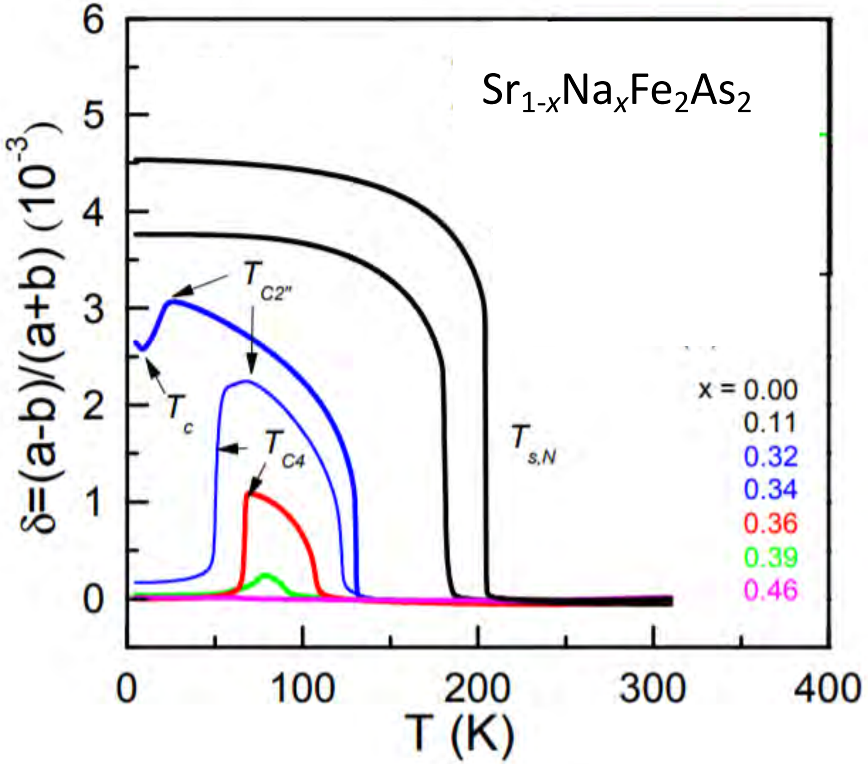
See: Yi et al., Phys. Rev. Lett. **121**, 127001 (2018)
“Spectral Evidence for Emergent Order in $Ba_{1-x}Na_xFe_2As_2$”

It can be much more complex





Orthorhombic distortion is a sensitive measure!



High-resolution dilatometry

C_2’ and C_2’’ phases: precise nature is unclear

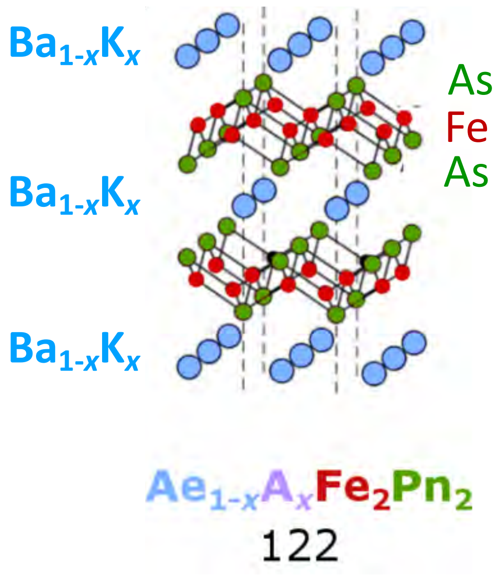
Textured phases?

L. Wang et al., PRB 93, 014514 (2016)

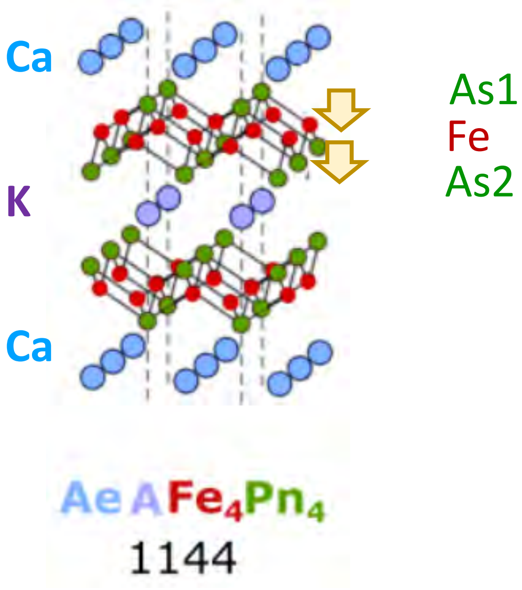
L. Wang et al., JPSJ 88, 104710 (2019)

See: Morten Christensen, Brian Andersen, Rafael Fernandes et al.

$CaK(Fe,Ni)_4As_4$: a 1144 material



vs.

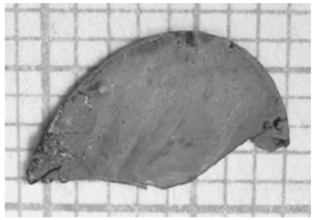


I4/mmm

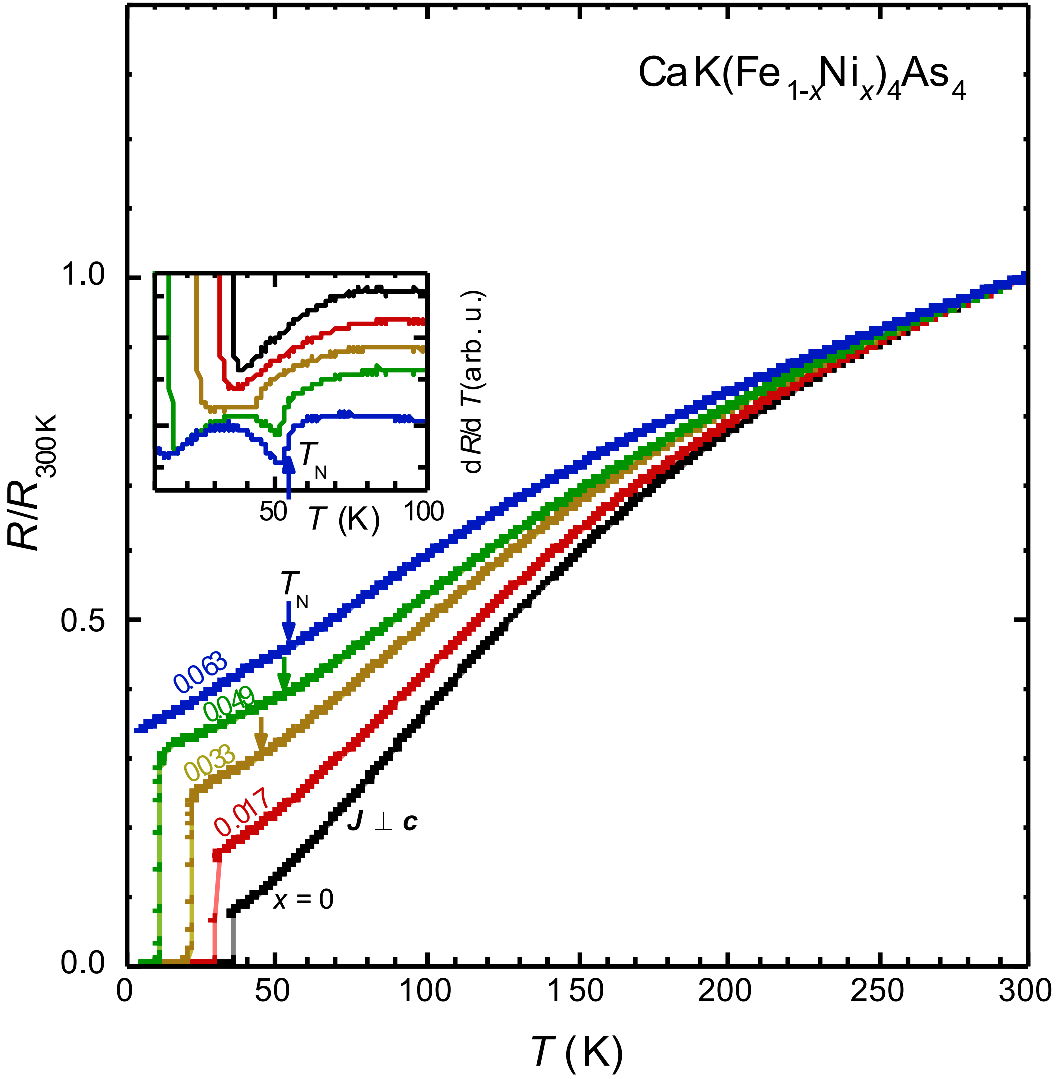
P4/mmm

Iyo et al., *J. Am. Chem. Soc.* 138, 3410 (2016)

Meier et al., Phys. Rev. B 94, 064501 (2016)
Meier et al., Phys. Rev. Materials 1, 013401 (2017)

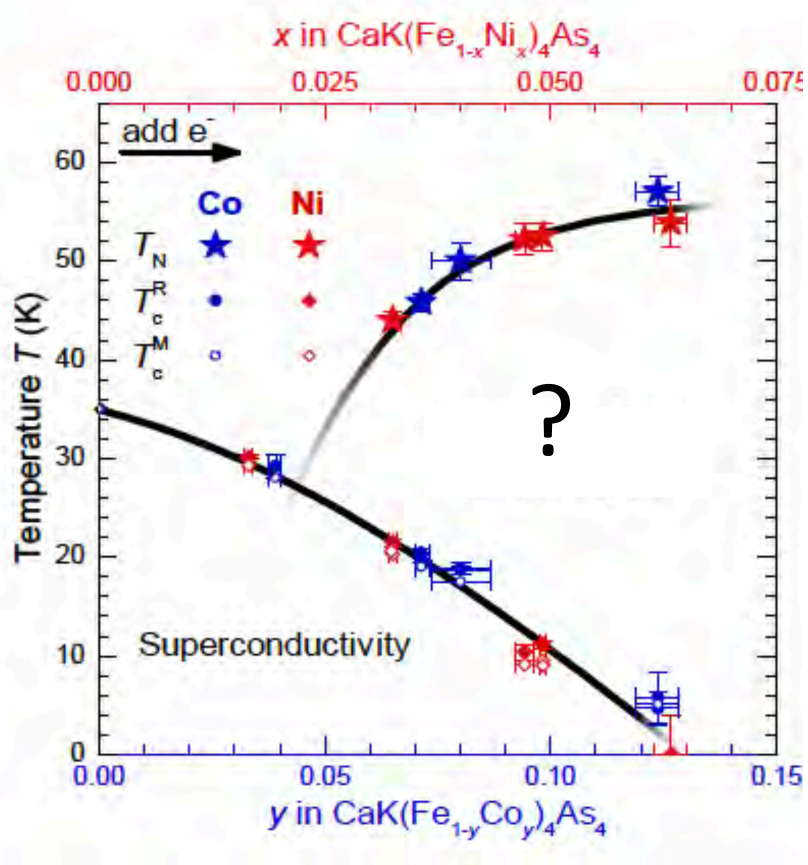


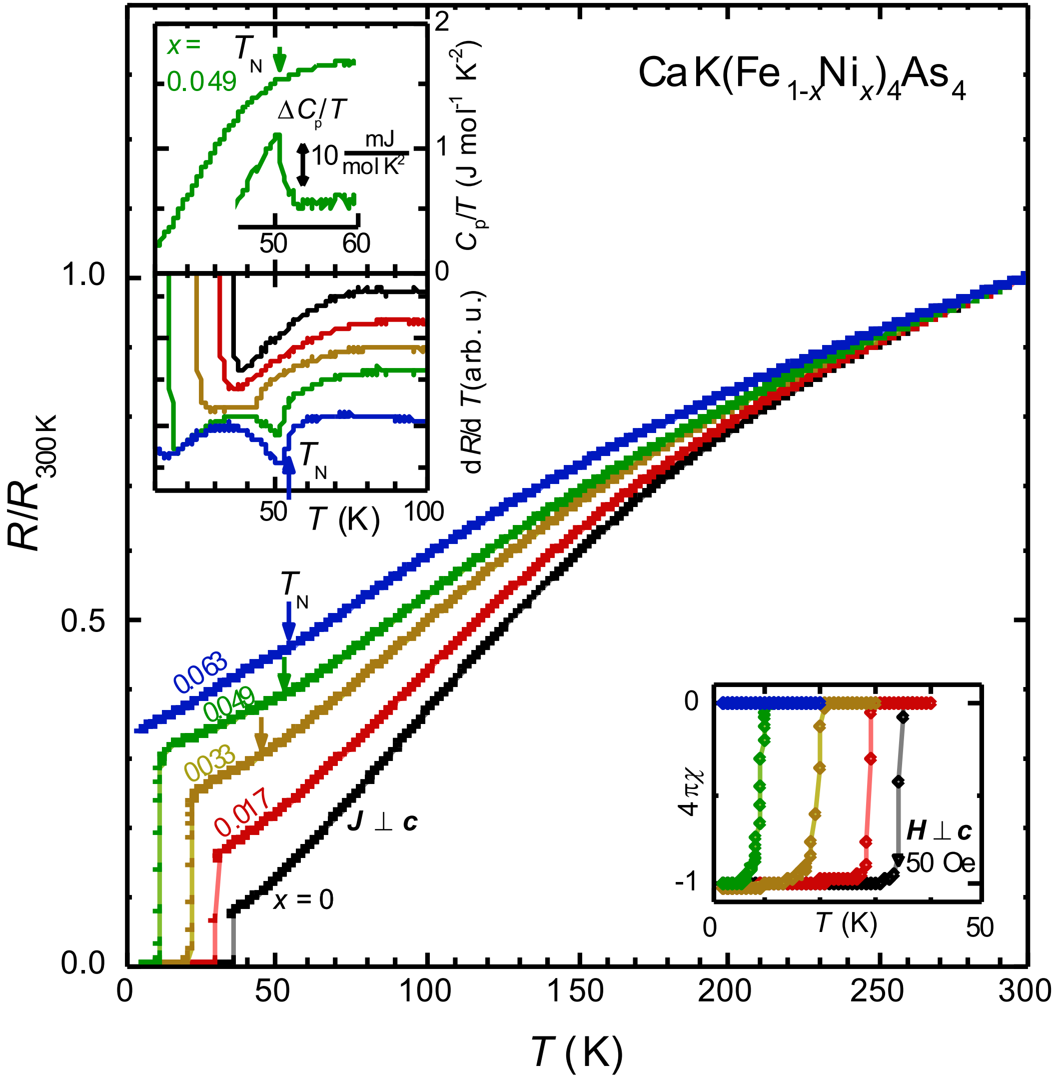
$CaK(Fe,Ni)_4As_4$: second-order phase transition



W. Meier et al., npj Quantum Materials **3**, 5 (2018)

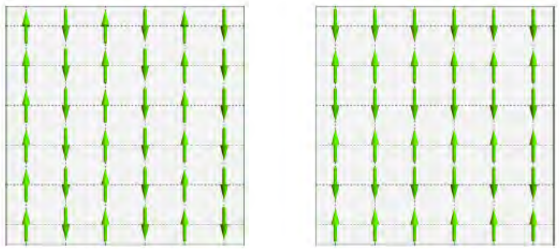
$CaK(Fe,Ni)_4As_4$: second-order phase transition



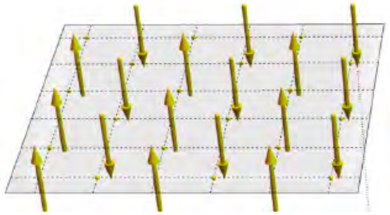


W. Meier et al., npj Quantum Materials **3**, 5 (2018)

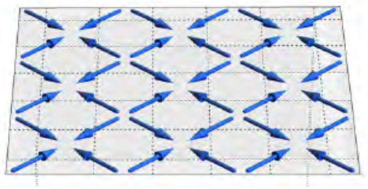
Various types of commensurate magnetic order are possible



Stripe-type AFM



“C4” magnetic order



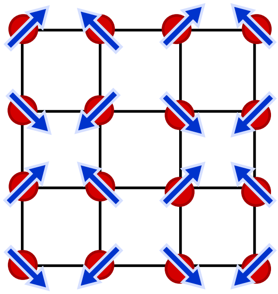
Spin-vortex crystal

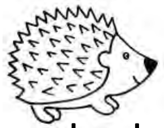
Lorenzana et al., Phys. Rev. Lett. 101, 186402 (2008)
Eremin, Chubukov, Phys. Rev. B 81, 024511 (2010)

Fernandes, Kivelson, and Berg, PRB **93**, 014511 (2016)
Fernandes, Orth, Schmalian ARCMP 10, 133 (2019)

Spin-vortex crystal magnetic order identified in $CaK(Fe,Ni)_4As_4$

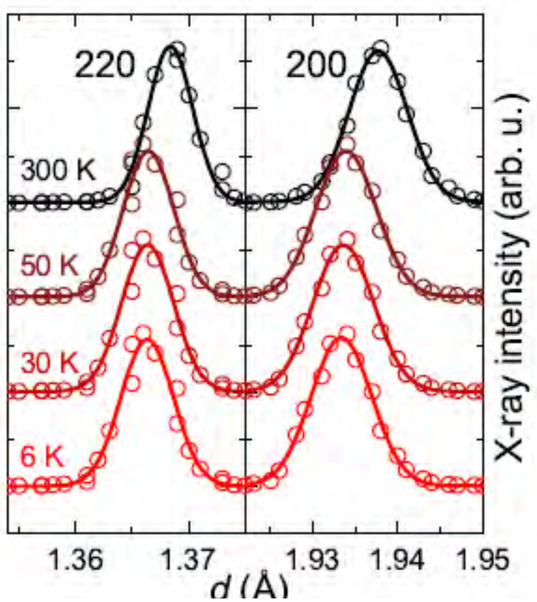
- Tetragonal and magnetically ordered -> not nematic
- Mössbauer spectra indicate a magnetic moment on all iron sites -> not the SCDW
- NMR spectra provide strong evidence for “option 3”: spin-vortex crystal structure



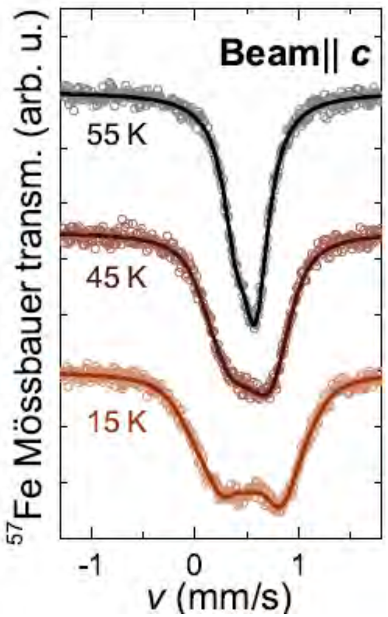


hedgehog-type

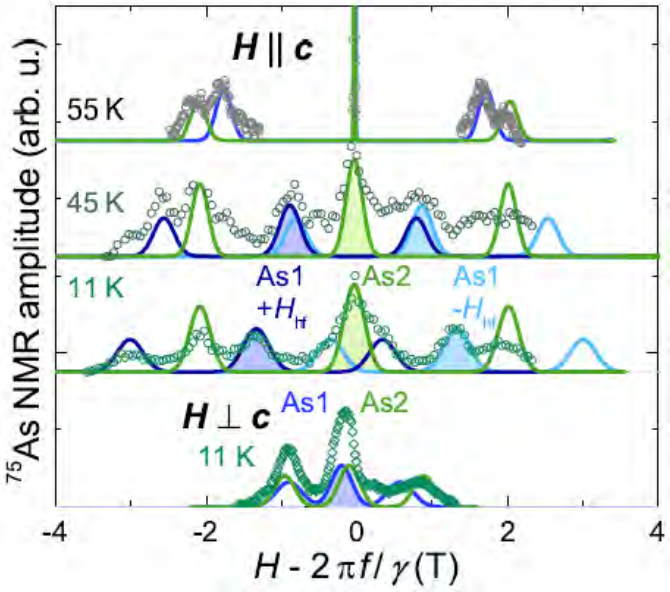
x-ray diffraction



Mössbauer

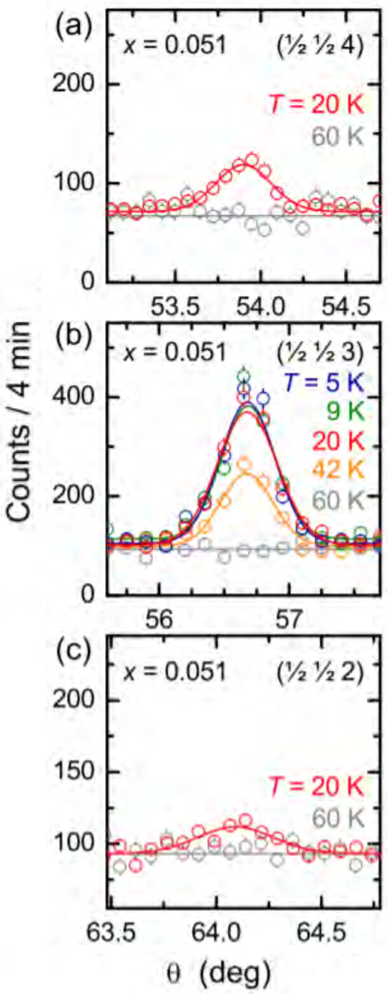


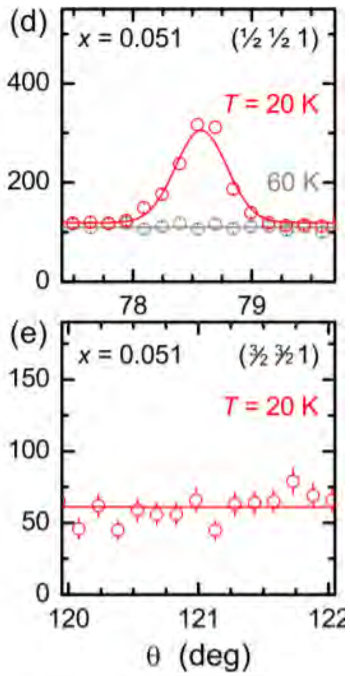
NMR

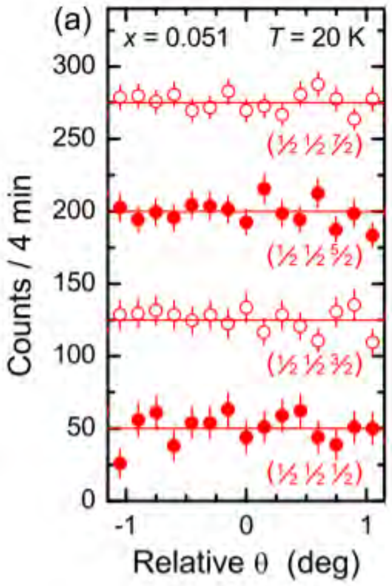


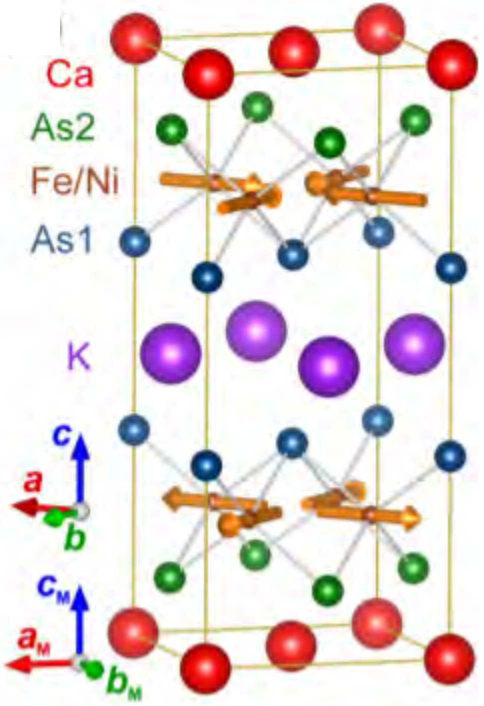
W. Meier et al., npj Quantum Materials **3**, 5 (2018)

Confirmation from neutron diffraction









AFM Bragg peak	Measurement: $x=$ 0.033 $T=$ 25 K	Measurement: $x=$ 0.051 $T=$ 20 K	Calculation: Hedgehog SVC in $(\boldsymbol{ab})$ plane: $\boldsymbol{\mu}_i \parallel \boldsymbol{\tau}_i$ — AFM along $\boldsymbol{c}$	Hedgehog SVC — FM along $\boldsymbol{c}$	Loops SVC in $(\boldsymbol{ab})$ plane: $\boldsymbol{\mu}_i \perp \boldsymbol{\tau}_i$ — AFM along $\boldsymbol{c}$	Loops SVC — FM along $\boldsymbol{c}$	SCDW $\boldsymbol{\mu}_i \parallel \boldsymbol{c}$ — AFM along $\boldsymbol{c}$	SCDW — FM along $\boldsymbol{c}$
$(\frac{1}{2}\frac{1}{2}4)$	22	18	19	80	26	107	13	54
$(\frac{1}{2}\frac{1}{2}3)$	143	144	130	17	207	26	155	20
$(\frac{1}{2}\frac{1}{2}2)$	12	6	9	164	21	384	24	441
$(\frac{1}{2}\frac{1}{2}1)$	69	95	99	1	634	8	1071	14
$(\frac{3}{2}\frac{3}{2}1)$	<2	<2	1	0.1	32	0.4	63	1

A. Kreyssig et al., PRB 97, 224521 (2018)

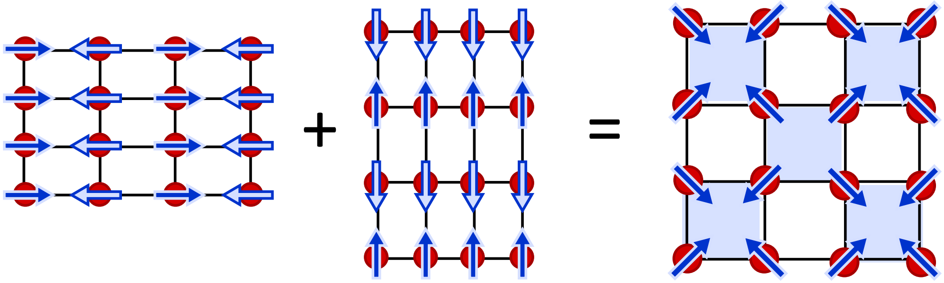
Option 3: The spin-vortex crystal (SVC)

$\boldsymbol{M}(\boldsymbol{r}) = \boldsymbol{M}_1\cos(\boldsymbol{Q}_X\boldsymbol{r}) + \boldsymbol{M}_2\cos(\boldsymbol{Q}_y\boldsymbol{r})), \boldsymbol{Q}_X = (\pi, 0), \boldsymbol{Q}_Y = (0, \pi)$

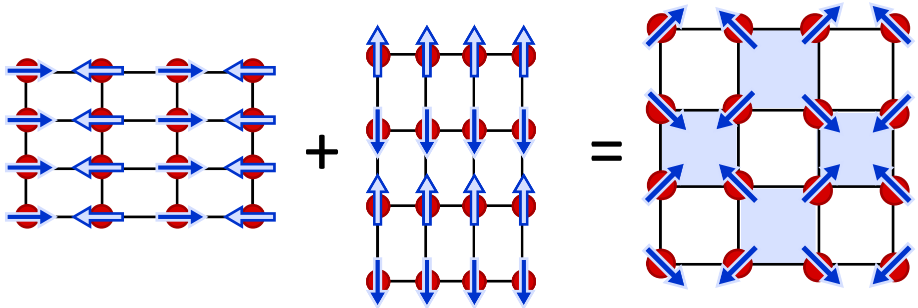
with

$\boldsymbol{M}_1 \perp \boldsymbol{M}_2$

Choice $\boldsymbol{M}_2$ “to the right” of $\boldsymbol{M}_1$



Choice $\boldsymbol{M}_2$ “to the left” of $\boldsymbol{M}_1$



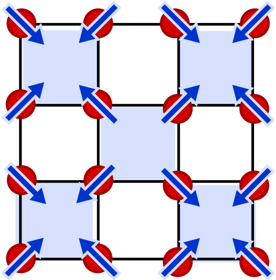
Intertwined order

- Reduced translational symmetry
- Chiral order parameter:
  $\boldsymbol{\varphi} = \boldsymbol{M}_1 \times \boldsymbol{M}_2$
- “Spin-vorticity-density wave”

Why realized in 1144-type material?

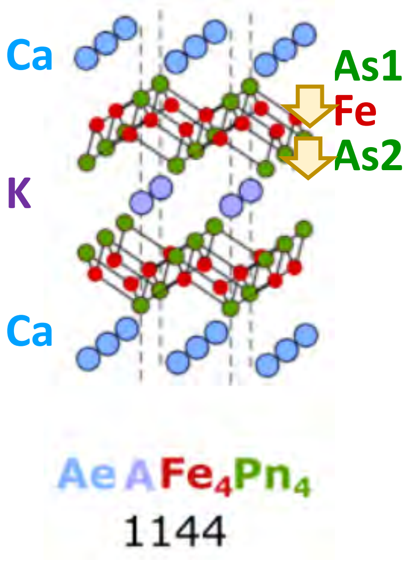
Intertwined order

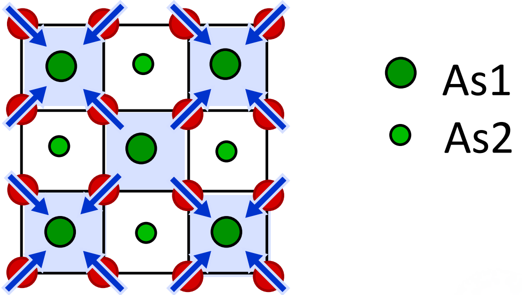
- Reduced translational symmetry
- Chiral order parameter:
  $$\varphi = \boldsymbol{M}_1 \times \boldsymbol{M}_2$$
- “Spin-vorticity-density wave”



Particular symmetry of the 1144-type structure

- Inequivalent As1 and As2-sites provide a symmetry-breaking field, $\boldsymbol{\eta}$
- It couples to the spin-vorticity density wave, $F \sim -\boldsymbol{\eta} \cdot (\boldsymbol{M}_1 \times \boldsymbol{M}_2)$



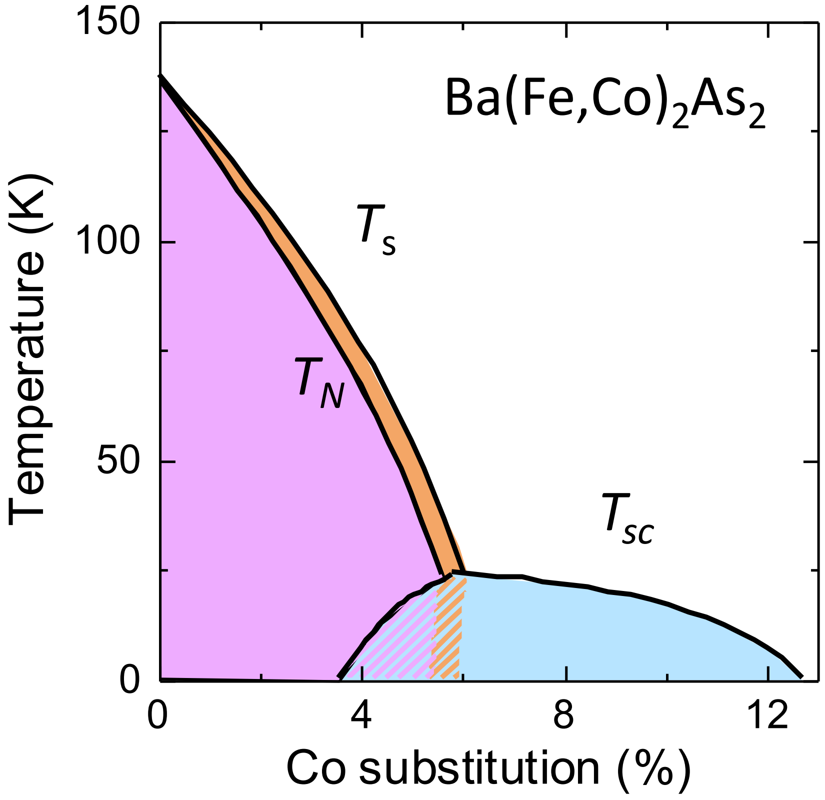


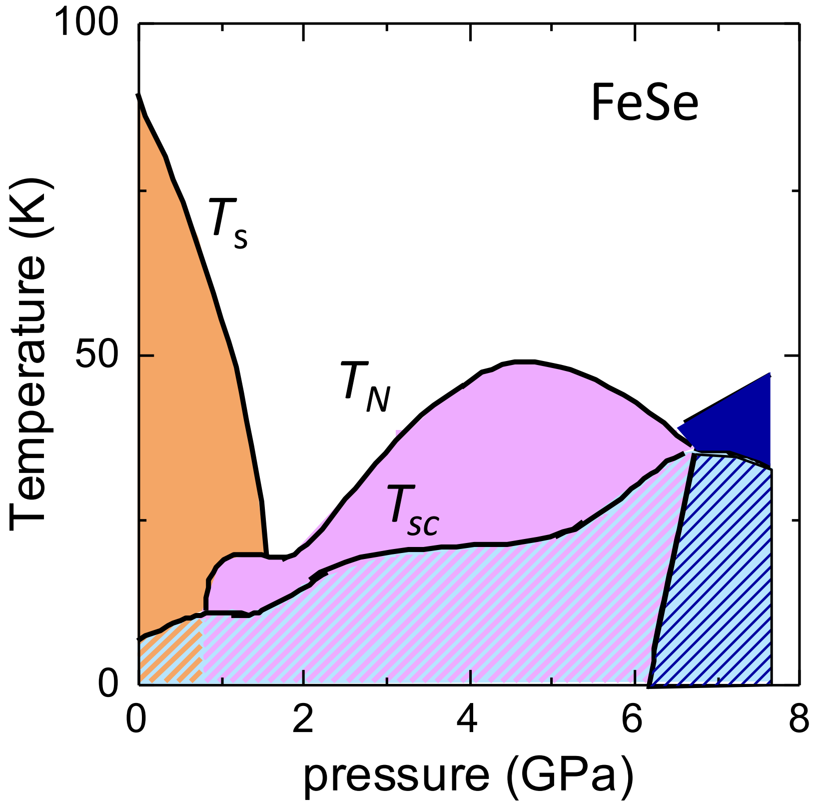
“Tuning” with the internal crystal structure

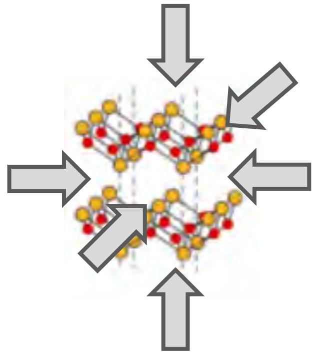
Rafael Fernandes, Cristian Batista

FeSe: a mysterious compound

Tuning with hydrostatic pressure







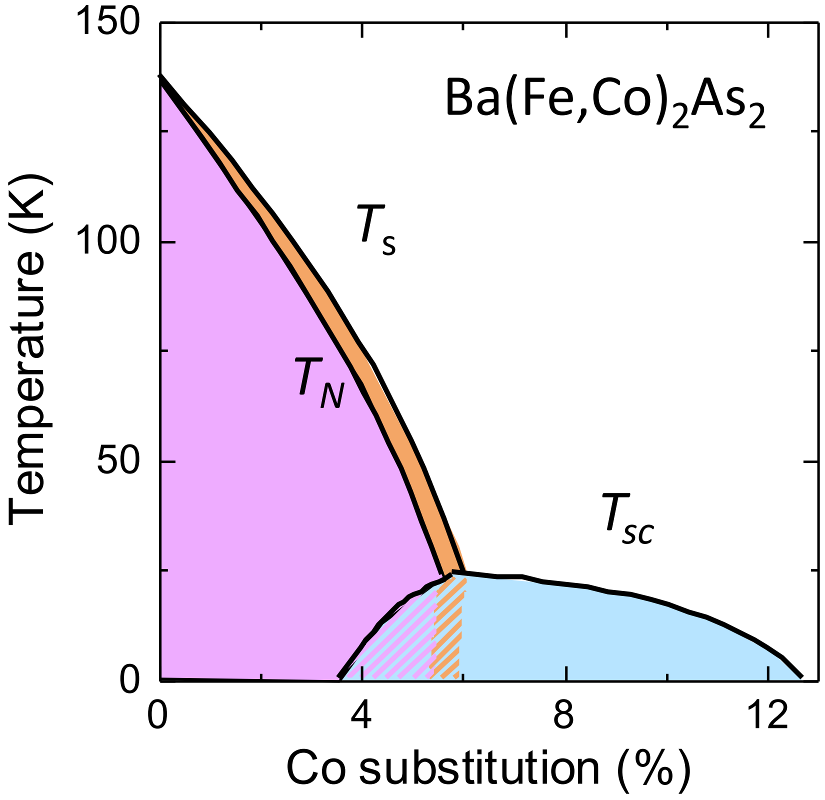
Sun et al., Nat Commun (2015)
Miyoshi et al., JPSJ (2014)

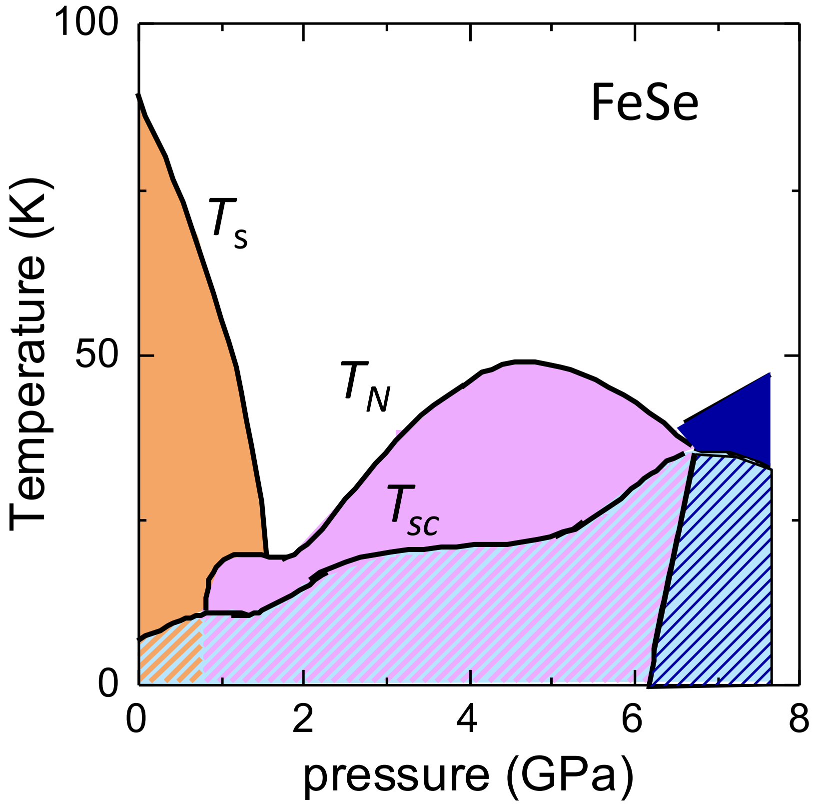
Böhmer*, Kothapalli* *et al.*, PRB 100, 064515 (2019)

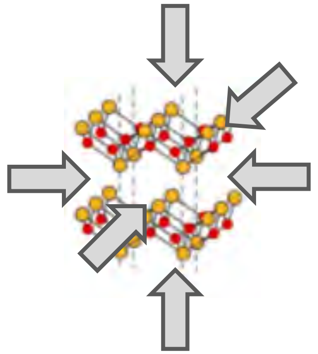
- Can FeSe and 122-type materials be compared? – many ambient-pressure properties are similar
- What is the relation between nematicity and magnetism and superconductivity in FeSe under pressure?

FeSe: a mysterious compound

Tuning with hydrostatic pressure







Sun et al., Nat Commun (2015)
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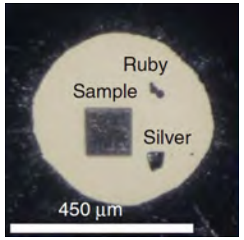
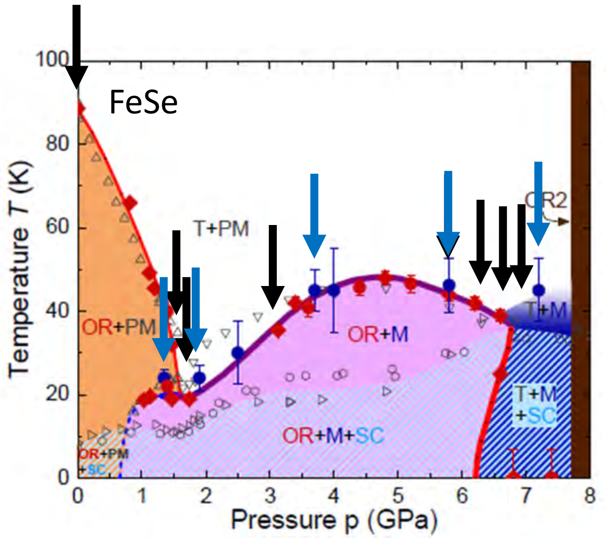
Böhmer*, Kothapalli* *et al.*, PRB 100, 064515 (2019)

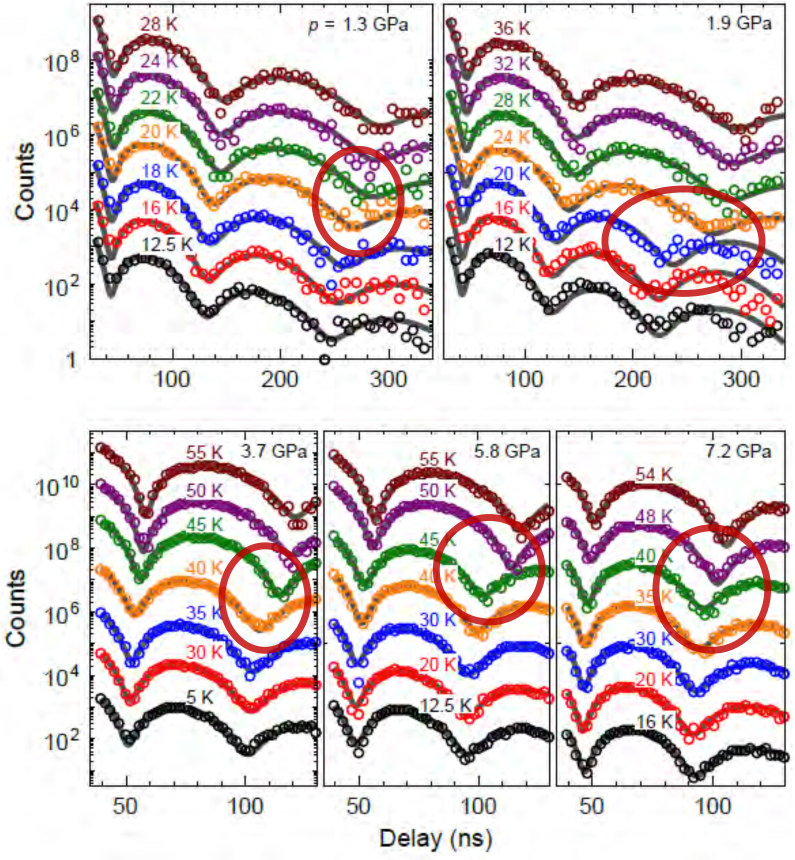
- Can FeSe and 122-type materials be compared? – many ambient-pressure properties are similar
- What is the relation between nematicity and magnetism and superconductivity in FeSe under pressure?

Lattice parameters and magnetic order in FeSe under pressure

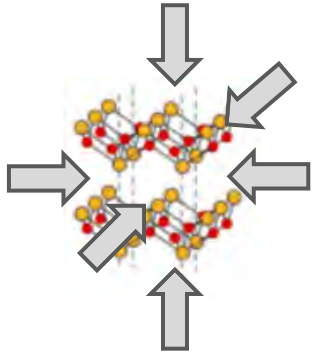


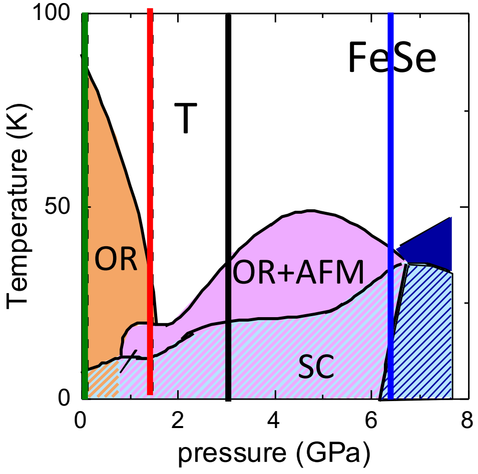


Kothapalli*, Böhmer* *et al.*, Nat. Comm. **7**, 12728 (2016)
Böhmer*, Kothapalli* *et al.*, PRB 100, 064515 (2019)

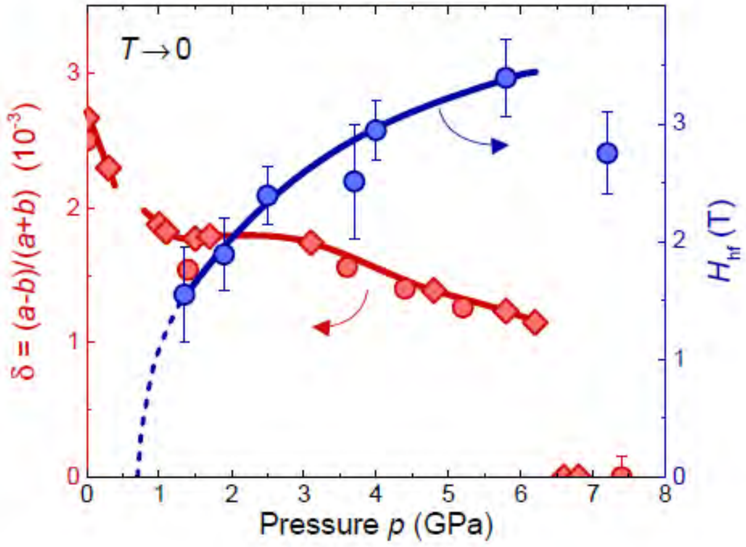


Evolution of orthorhombic distortion

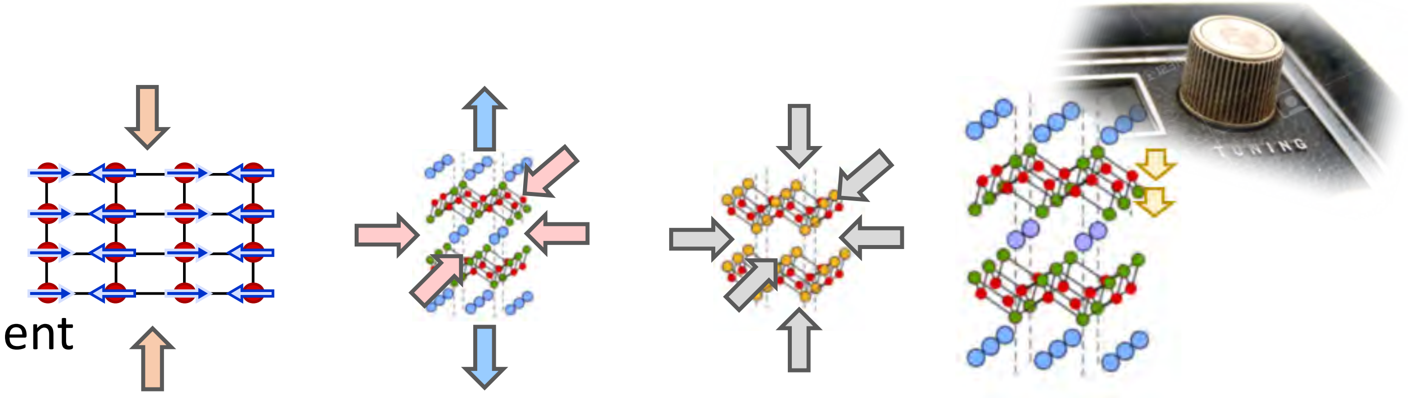




- Compatible with a dome of stripe-type magnetism
- A tetragonal magnetic phase at high pressure
- Order parameter coupling and phase diagram topology is a consequence of symmetry, not mechanism



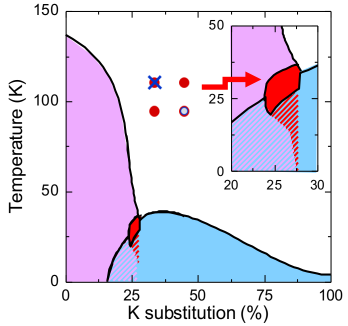
Conclusions

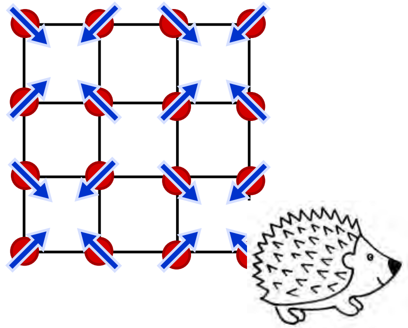


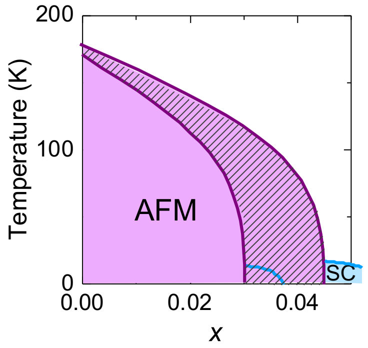
Diverse magnetic structures from a two-component magnetic order parameter

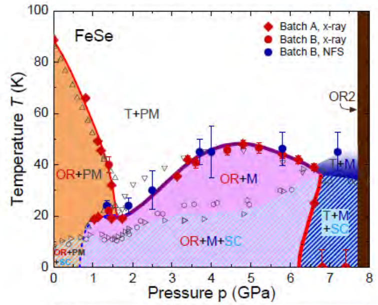
Interesting intertwined orders emerge

A well-characterized material class that is highly sensitive to elastic tuning









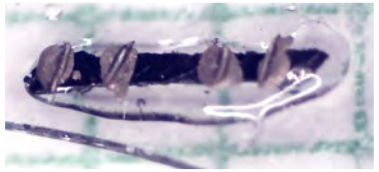
Nematicity/nematic susceptibility:
Anna Böhmer and Christoph Meingast, Comptes Rendus Physique **17**, 90, (2016) [review]

Spin-vortex crystal in $CaK(Fe,Ni)_4As_4$:
W. Meier et al., npj Quantum Materials **3**, 5 (2018)

Phase interplay in FeSe:
Anna Böhmer and Andreas Kreisel, Journal of Physics: Condensed Matter, **30**, 023001 (2017) [topical review]

Iron-based materials, broad audience:
Anna Böhmer and Andreas Kreyssig, Physik in unserer Zeit **48**, 70 (2017) [in German]

Consequences of imposing *strain not stress*



$L_{substrate}=L_{sample}$

T, strained

vs.

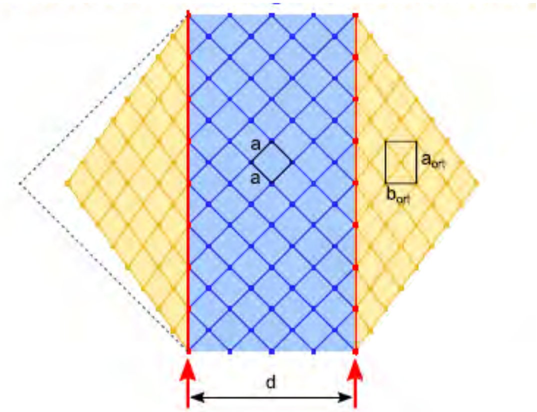
OR	T	OR	T	OR	T	OR	T

T=tetragonal, paramagnetic
OR=orthorhombic, stripe-SDW

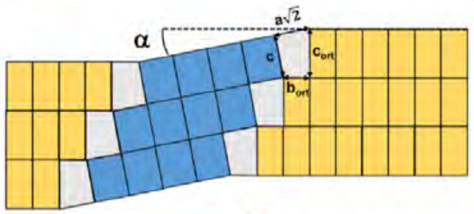
Possible domains

top view

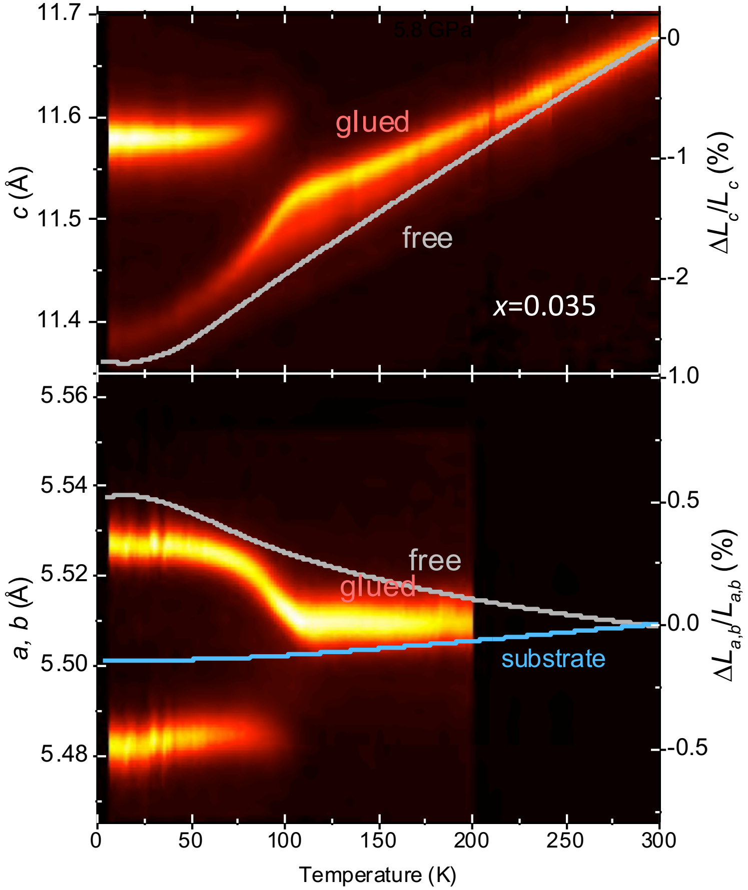
OR T OR



side view

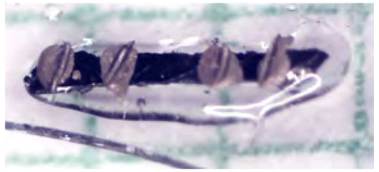


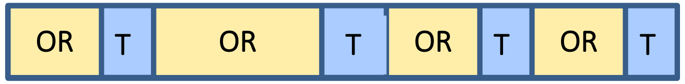
OR T OR



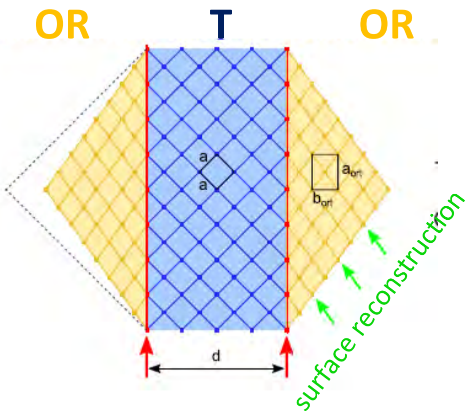
Observation of unusual domains in strained $Ca(Fe_{1-x}Co_x)_2As_2$

Fente, Correa-Orellana, Böhmer,..., Suderow
PRB **97**, 014505 (2018)

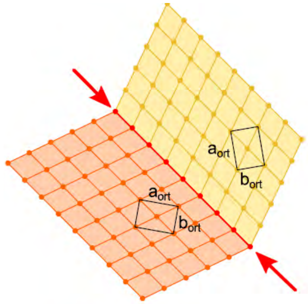




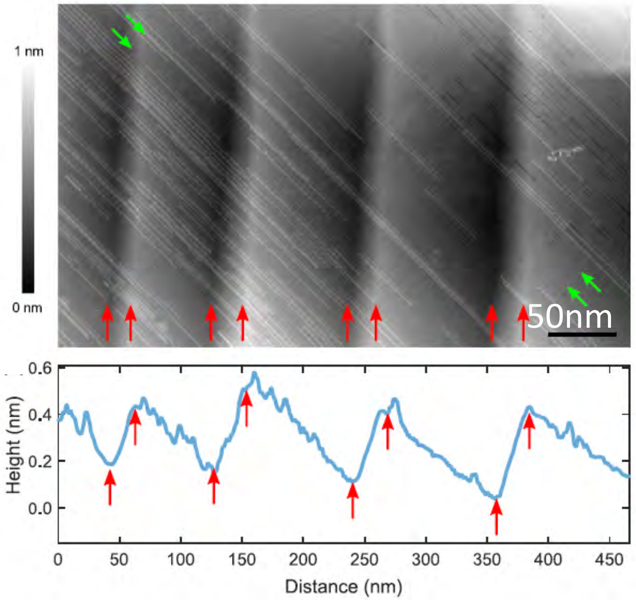
top view

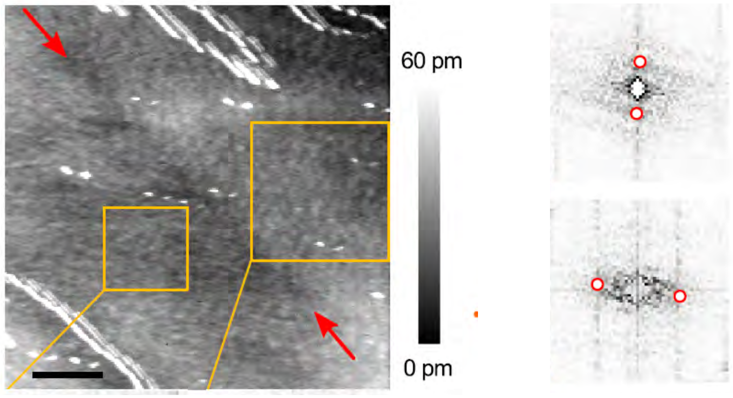


Large domains are orthorhombic below ~70 K

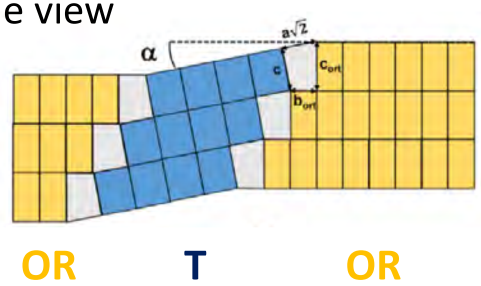


AFM topography





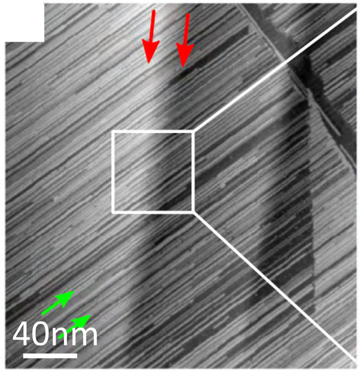
side view



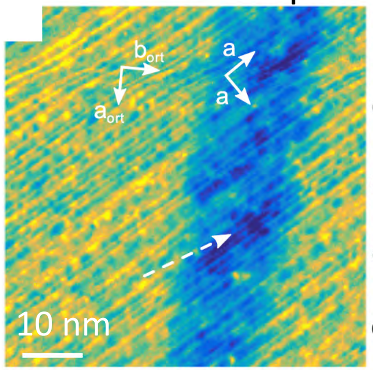
Nanoscale superconducting domains

Fente, Correa-Orellana, Böhmer,..., Suderow
PRB **97**, 014505 (2018)

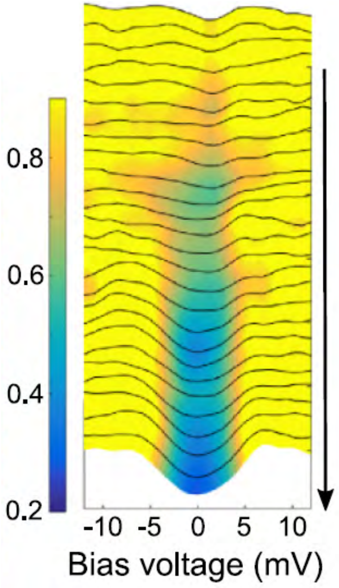
STM topography

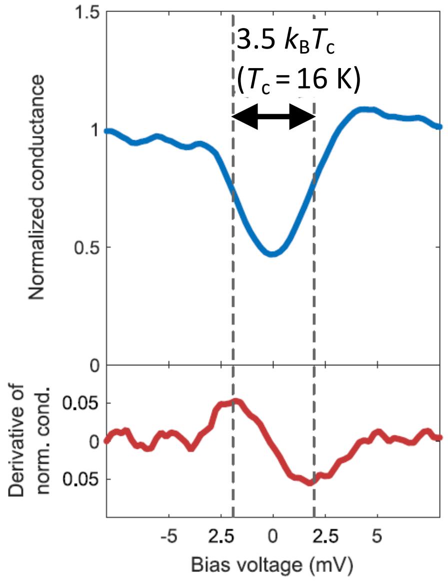


STM zero-bias conductance map

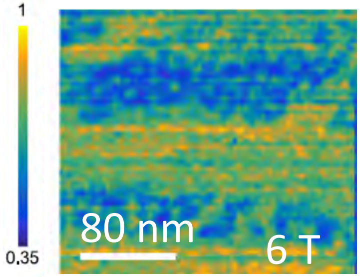


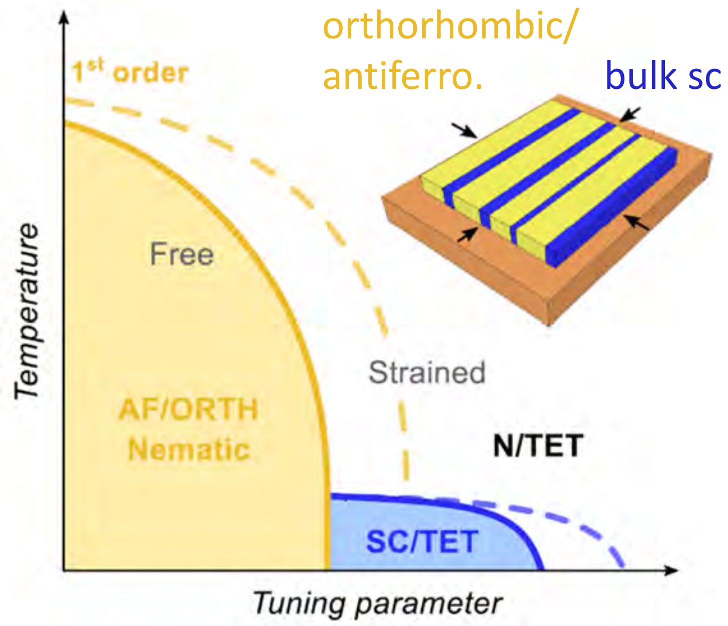
superconducting gap





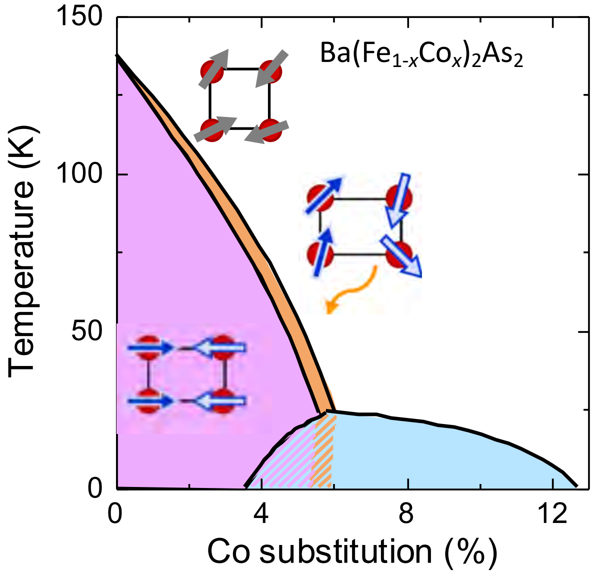
vortices



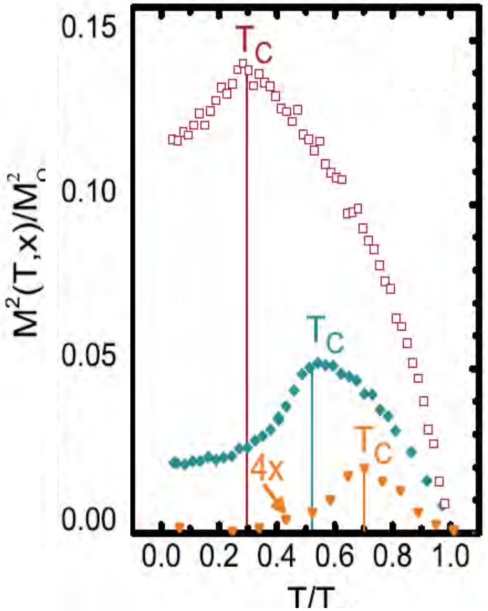


A strain-induced nm-scale domain structure of alternating orthorhombic/antiferromagnetic and tetragonal/superconducting regions

Competing with superconductivity

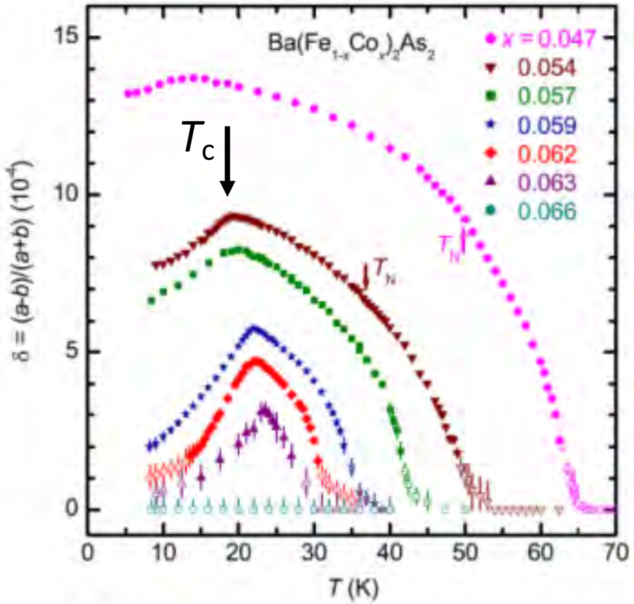


Magnetic order parameter



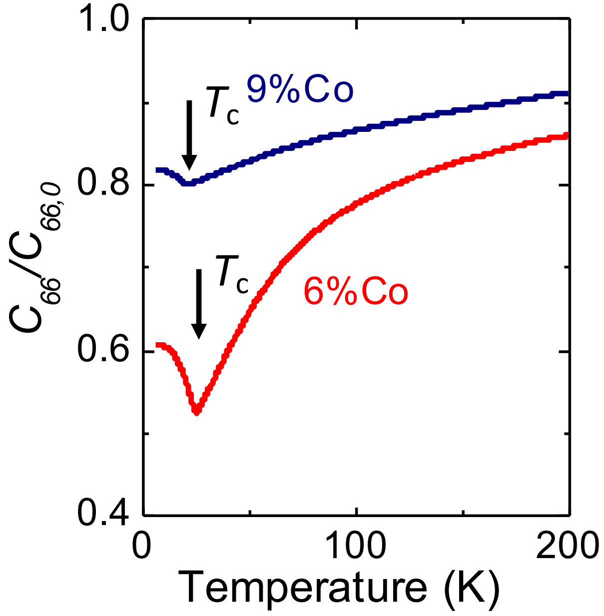
Fernandes et al., PRB 2010

Orthorhombic distortion (Nematic order parameter)



Nandi et al., PRL **104**, 057006 (2010)

Shear modulus (Nematic susceptibility)

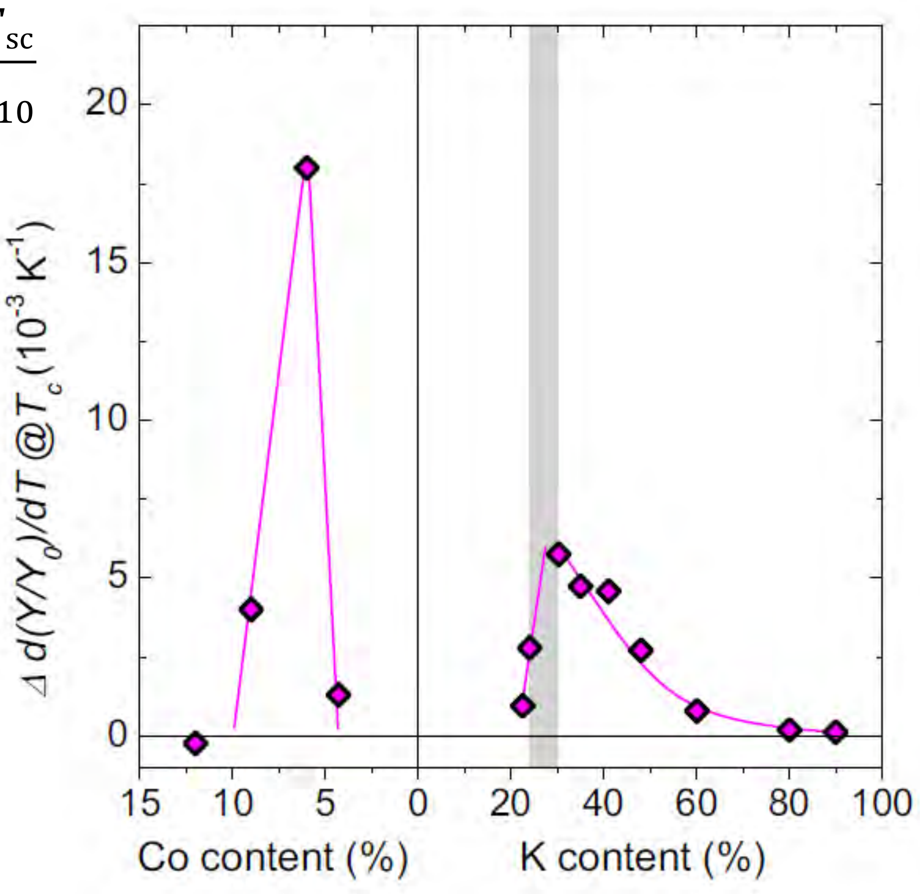


Böhmer et al., PRL **112**, 047001 (2014)

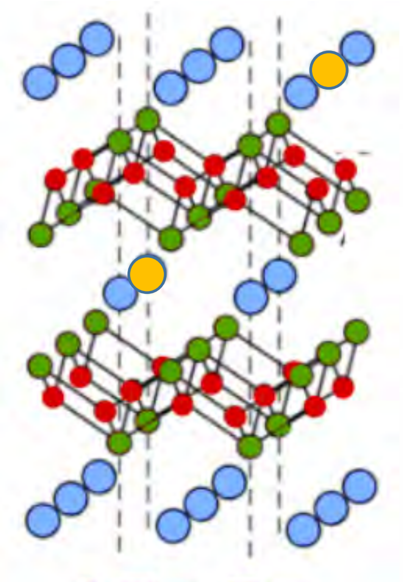
- Coexistence of superconductivity and magnetism/nematicity in a single phase
- Competition for the same electrons
- Results in a huge effect of superconductivity on lattice constants and elastic modulus

Resulting tunability of T_{sc}

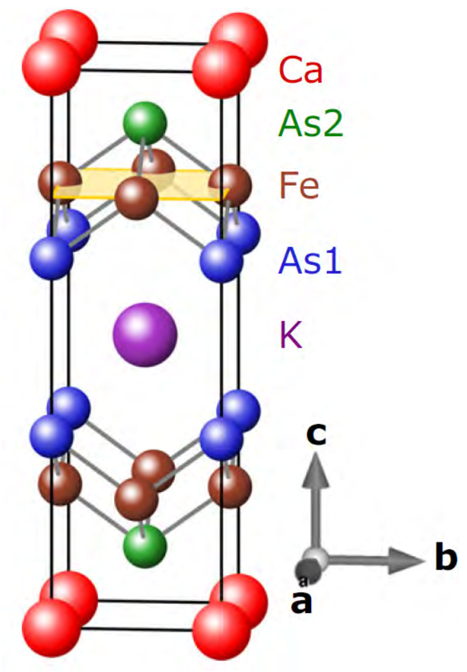
$$\sim -\frac{d^2 T_{\mathrm{sc}}}{d\sigma_{110}^2}$$



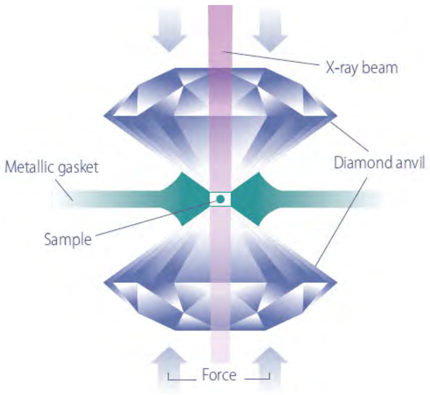
Tuning via chemical composition



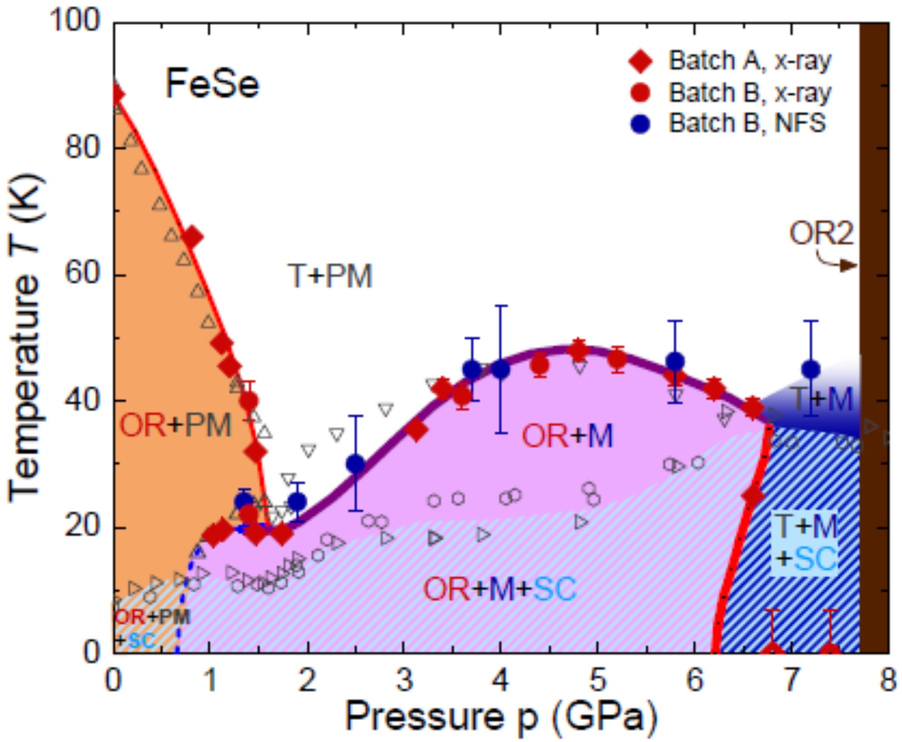
“Tuning” via the internal crystal structure

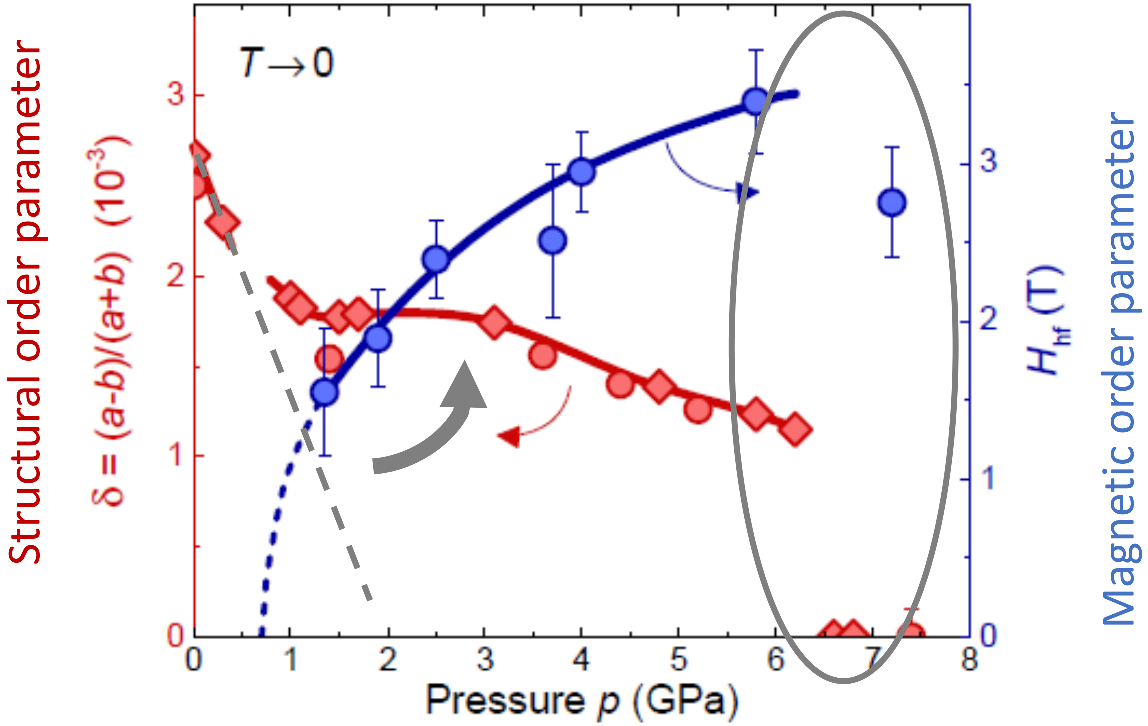


Tuning with hydrostatic pressure



Detailed phase diagram and order parameter evolution

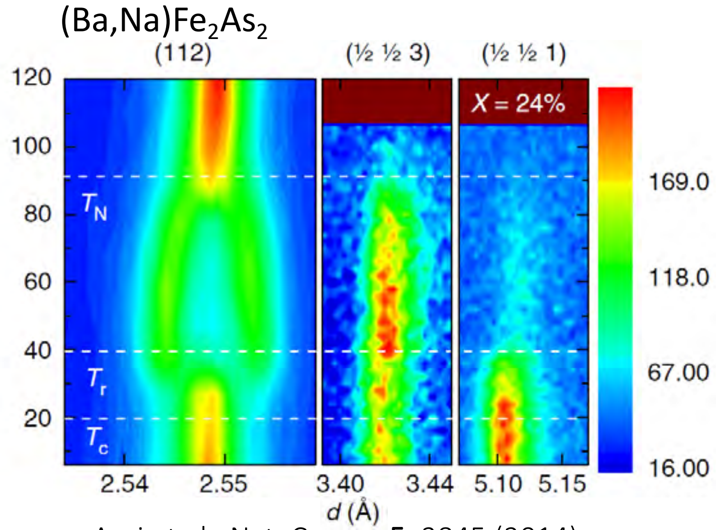




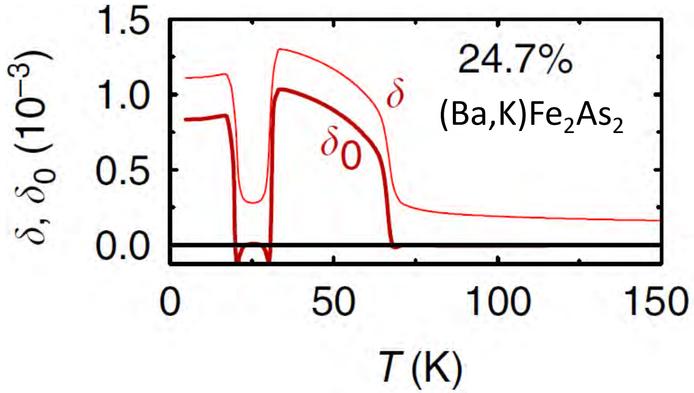
- Cooperative coupling of magnetic order and orthorhombic distortion
- Coupling breaks down at higher pressures

Böhmer et al., (under review)

Identification of spin-charge density wave order

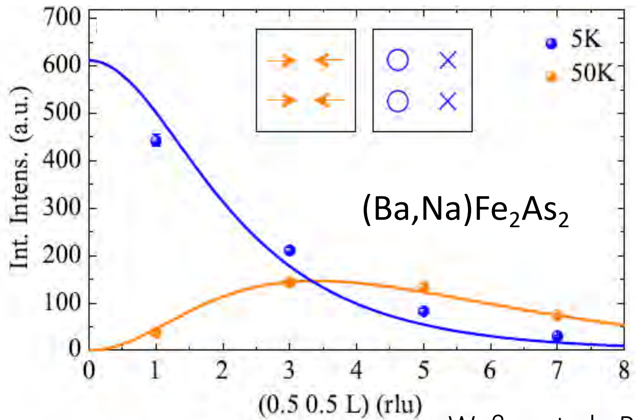


Avci et al., Nat. Comm. **5**, 3845 (2014)



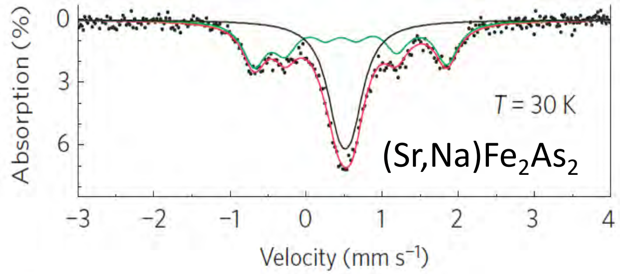
Böhmer et al., Nature Comm. **6**, 7911, (2015)

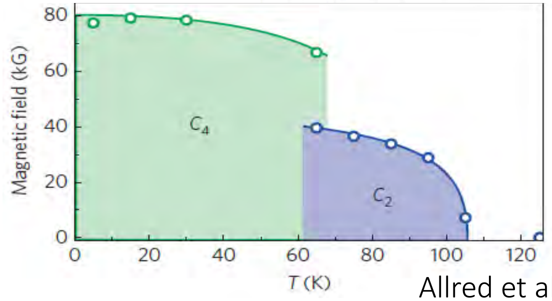
Tetragonal!



Waßer et al., PRB **91**, 060505 (2015)

Out-of-plane moments!

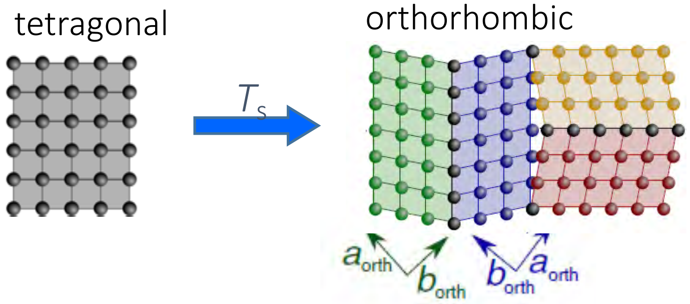




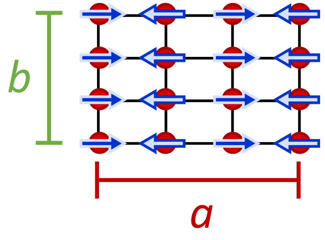
Allred et al., Nat. Phys. **12**, 493 (2016)

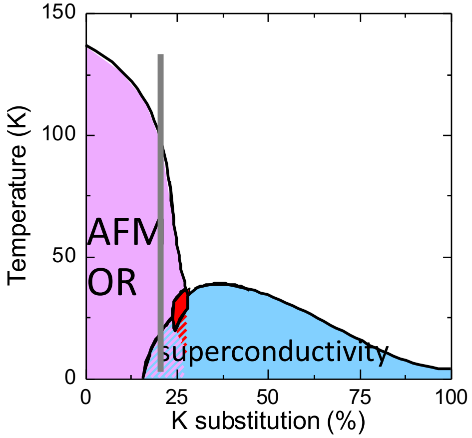
Two distinct magnetic Fe-sites!

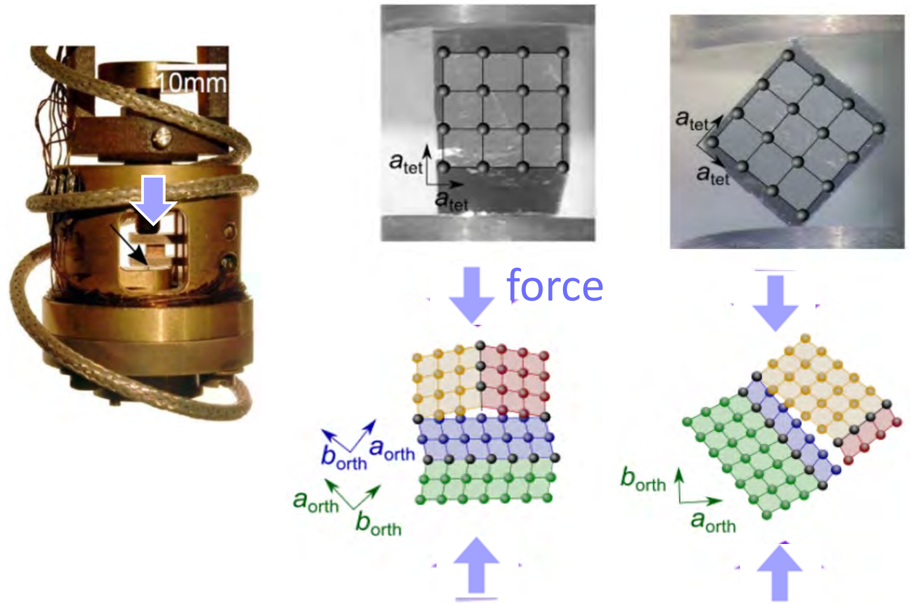
Orthorhombic distortion via dilatometry



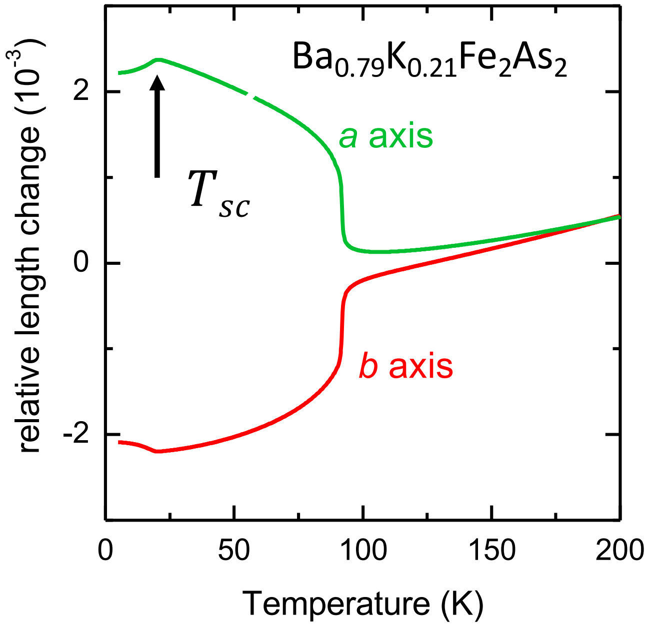
Regular domain structure

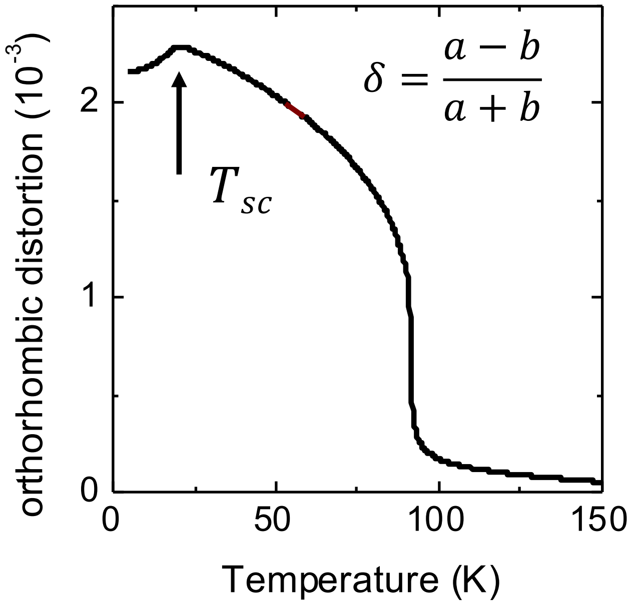






Use of uniaxial force for in-situ detwinning



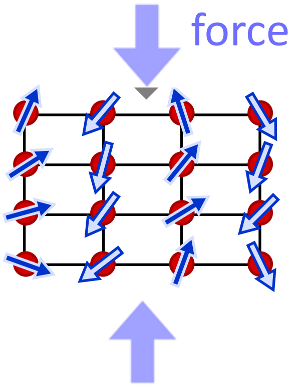


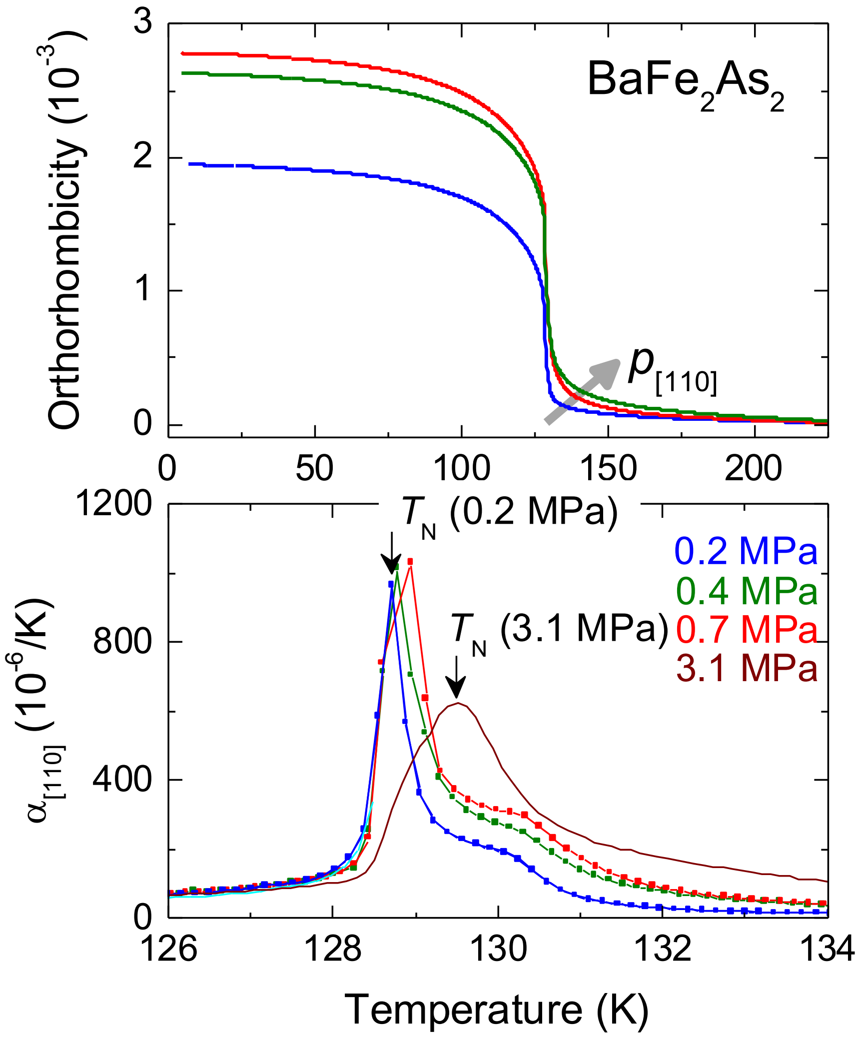
Orthorhombic distortion significantly decreases below T_{sc}

Competition between superconductivity and orthorhombicity/stripe-type magnetism.

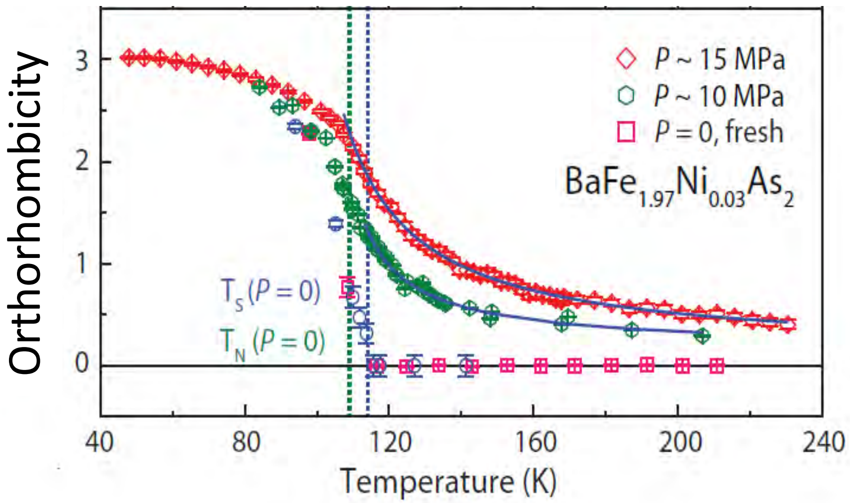
A. E. Böhmer et al., Nature Communications **6**, 7911 (2015)

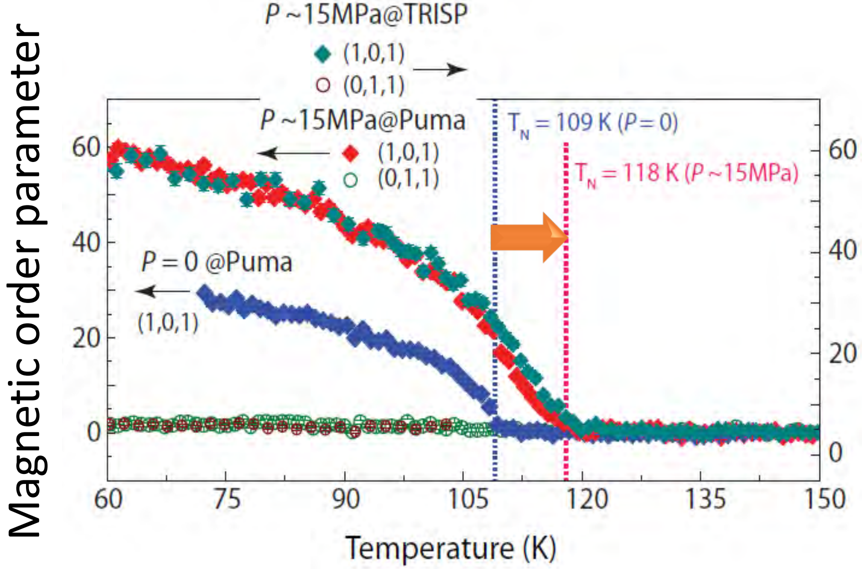
Tune stripe-AFM transition via “conjugate” uniaxial stress





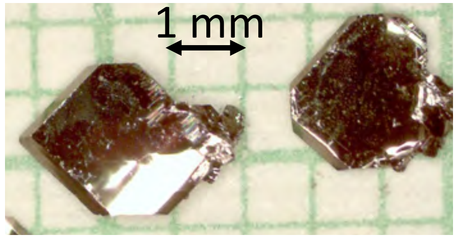
Böhmer et al., unpublished

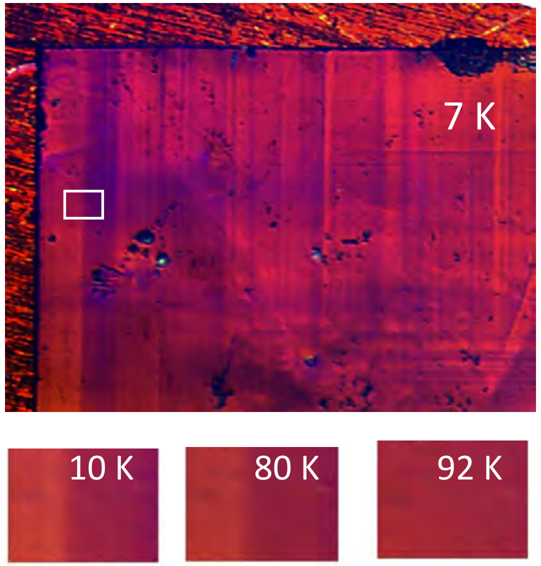




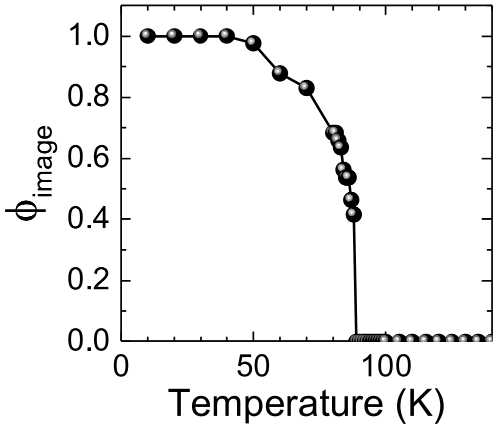
Lu et al., PRB **93**, 134519 (2016)

Tetragonal-to-orthorhombic transition of FeSe

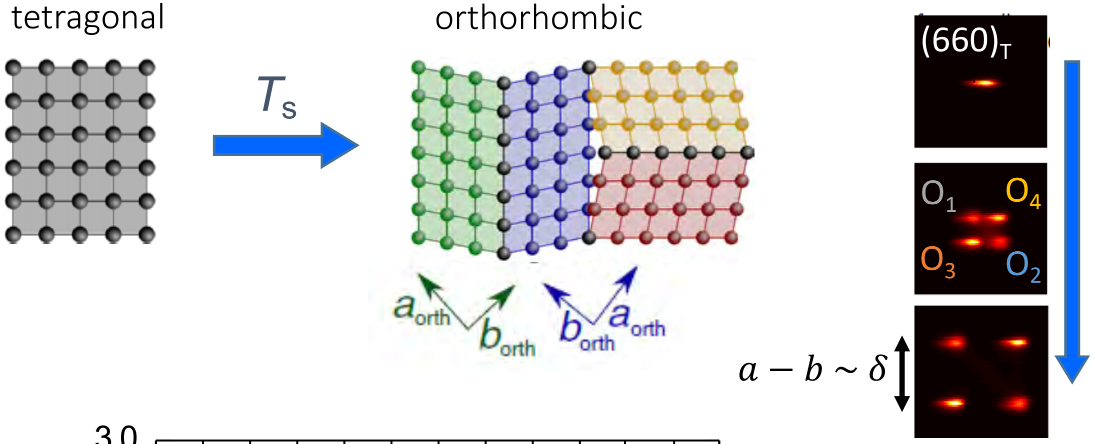


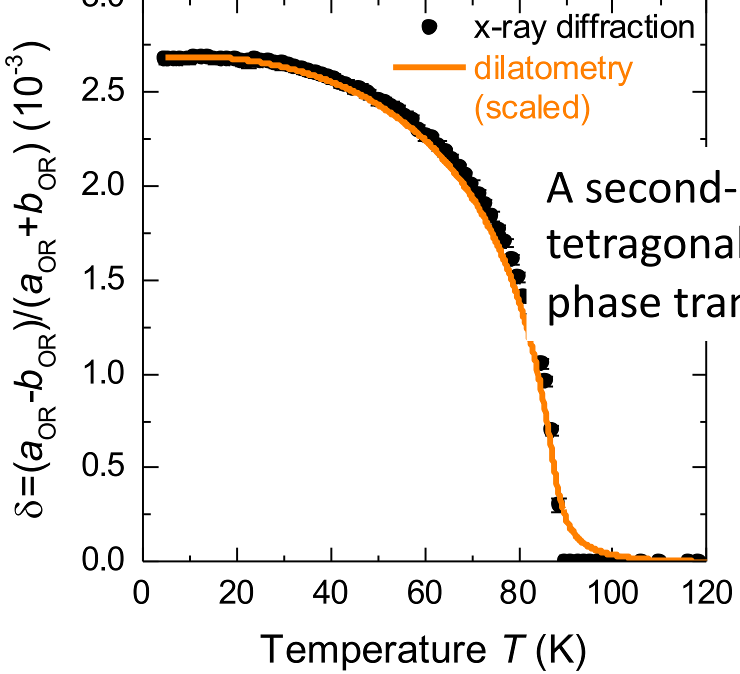


Color difference:



Tanatar, Böhmer et al., PRL 2016



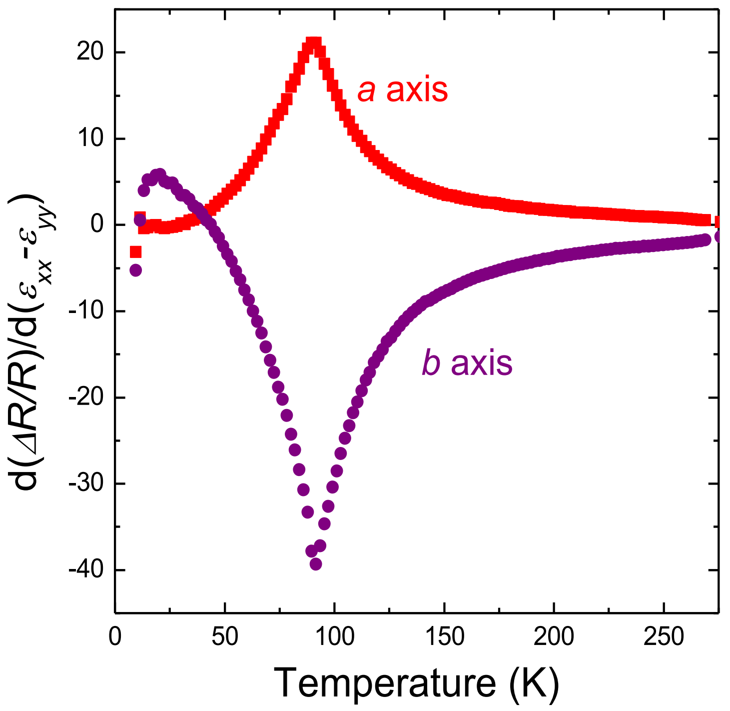


A second-order tetragonal-to-orthorhombic phase transition

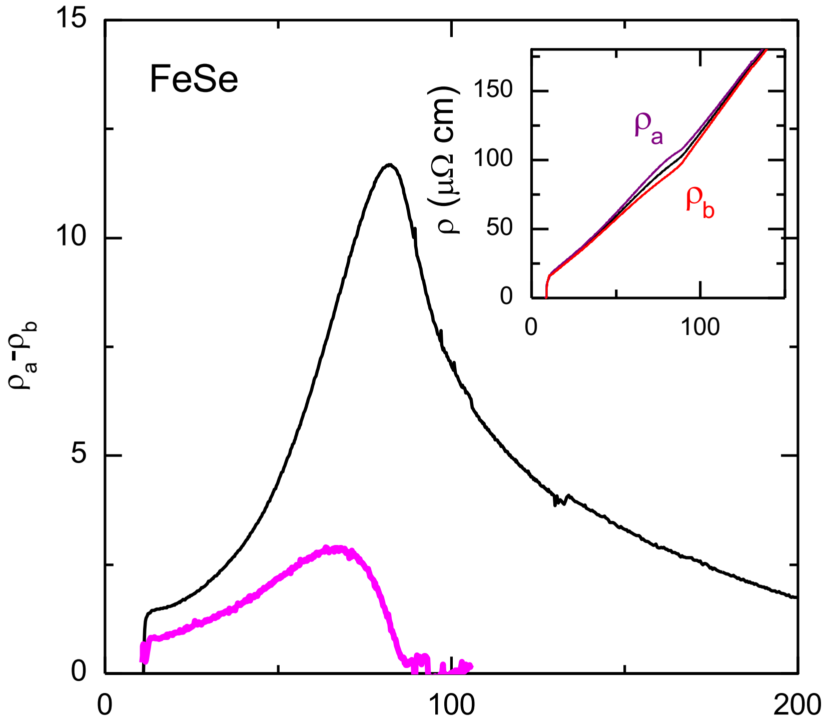
Böhmer et al., PRB 2013

Nematicity of FeSe

Elastoresistivity

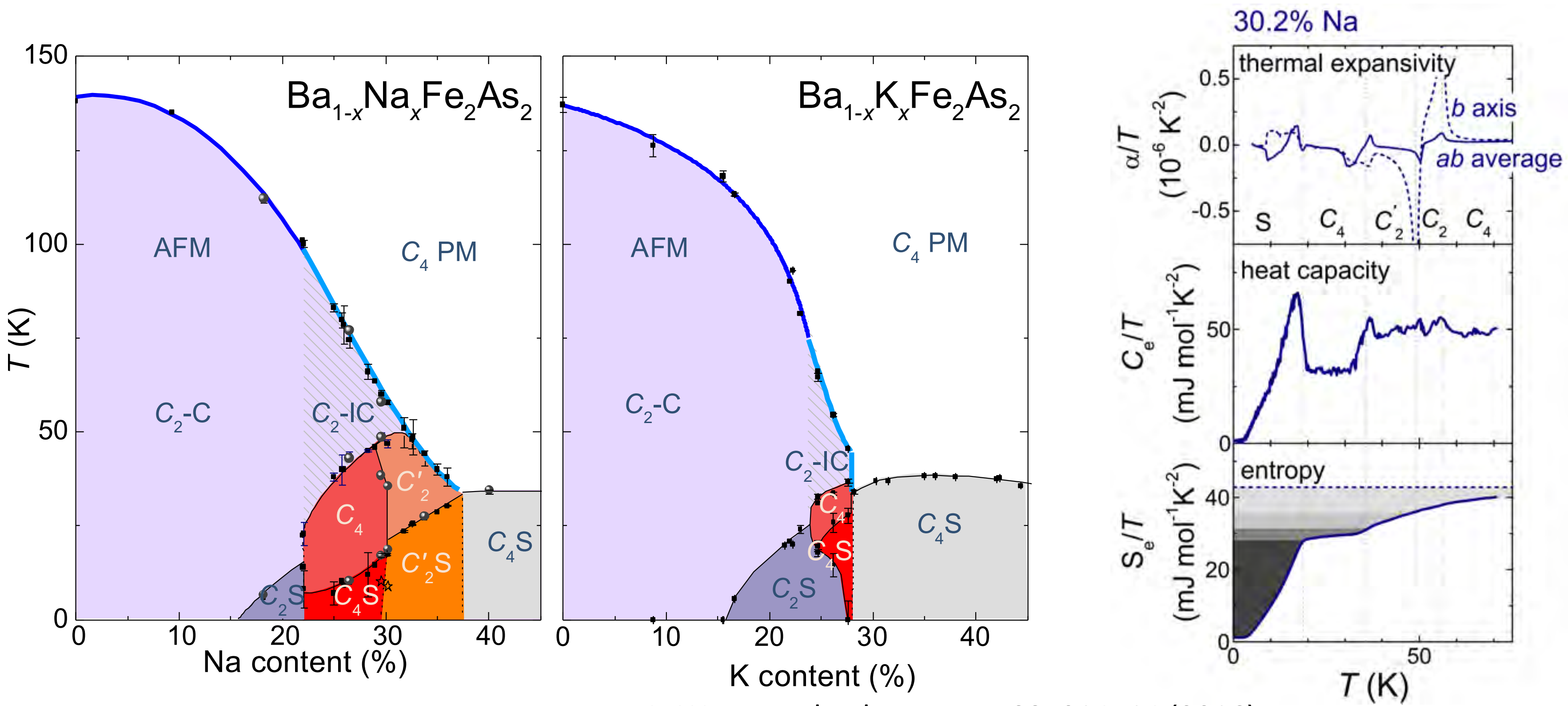


Resistivity anisotropy



Tanatar, Böhmer, et al., Phys. Rev. Lett. **117**, 127001 (2016).

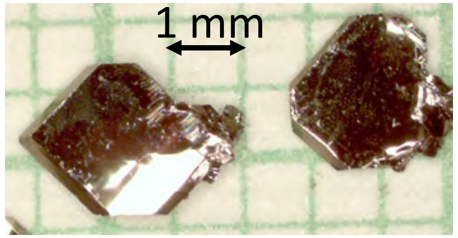
Unidentified phases: open questions

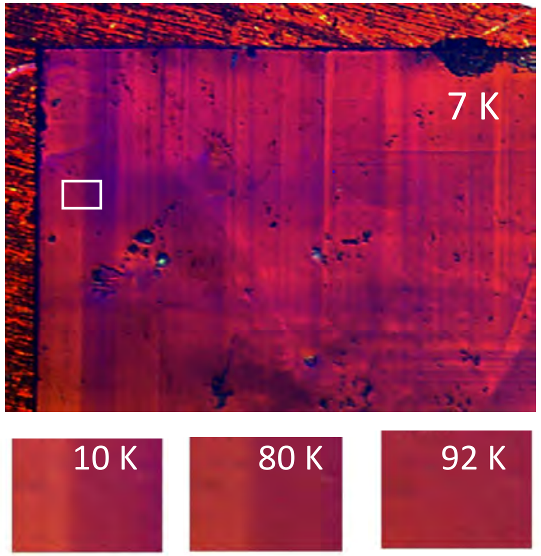


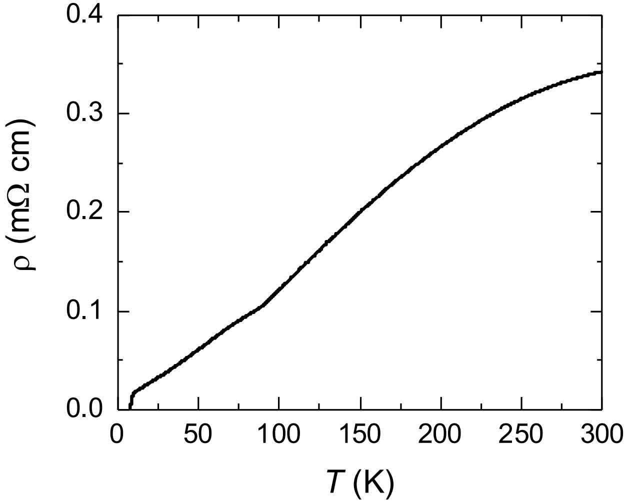
L. Wang et al., Phys. Rev. B 93, 014514 (2016)

- Incommensurate magnetic order?
- Different moment orientations?
- Different *c*-axis coupling?

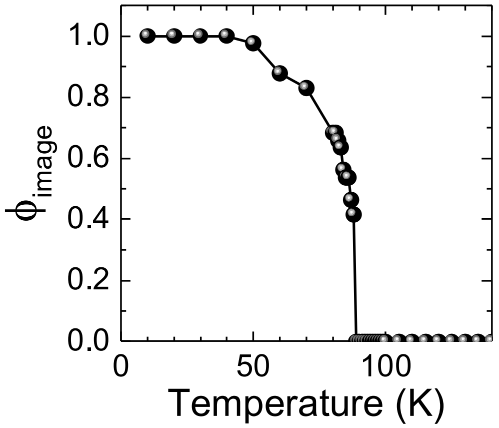
Tetragonal-to-orthorhombic transition of FeSe



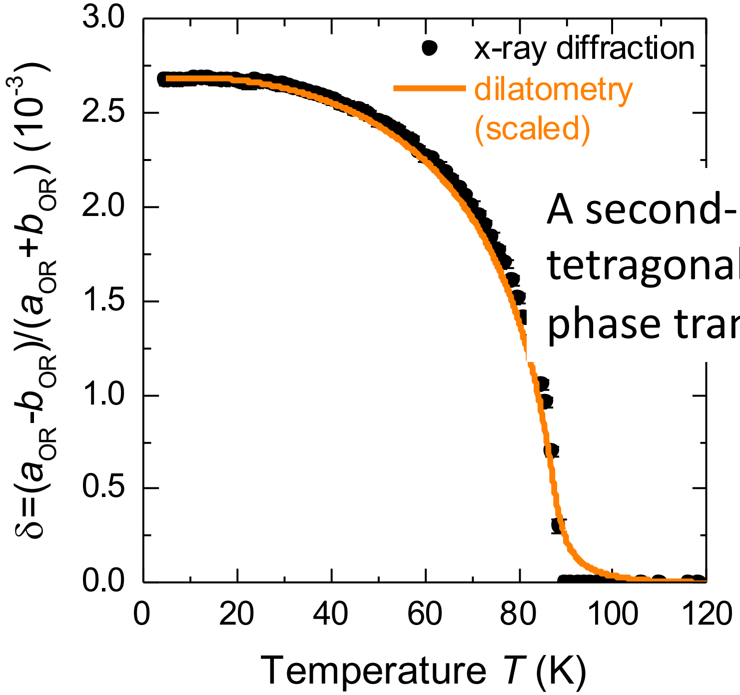




Color difference:



Tanatar, Böhmer et al., PRL 2016



A second-order tetragonal-to-orthorhombic phase transition

Böhmer et al., PRB 2013