RUHR-UNIVERSITÄT BOCHUM

NEMATIC FLUCTUATIONS IN IRON-BASED SUPERCONDUCTORS WITHOUT STRIPE-TYPE MAGNETISM

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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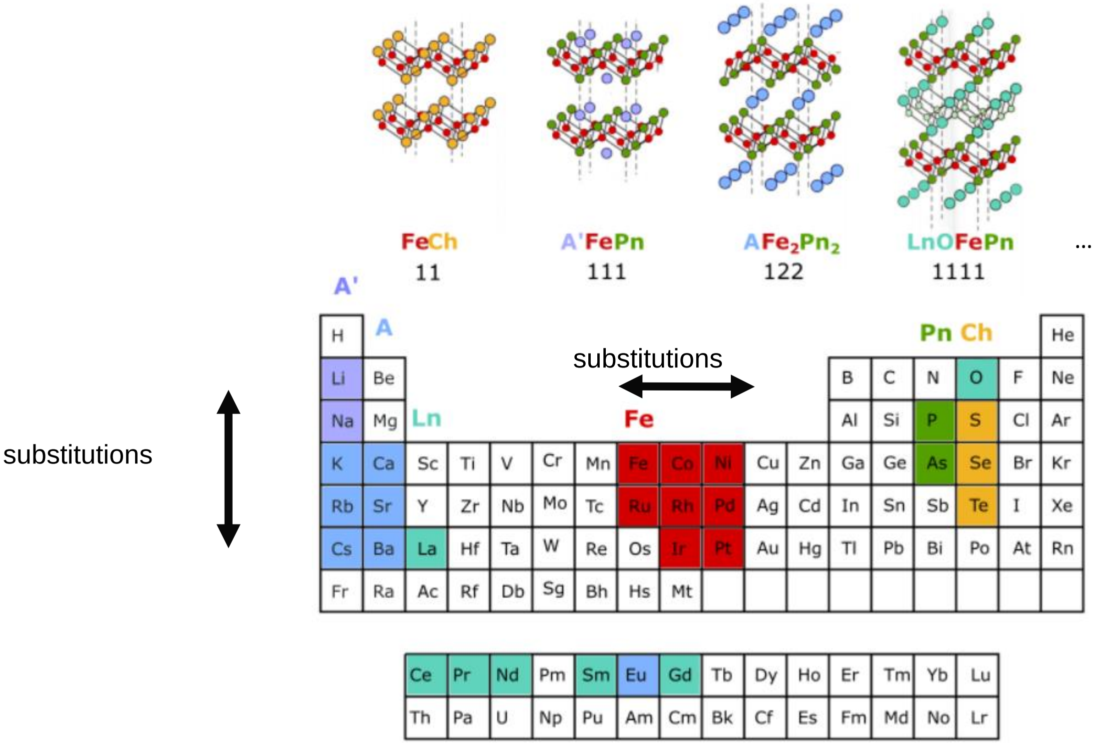
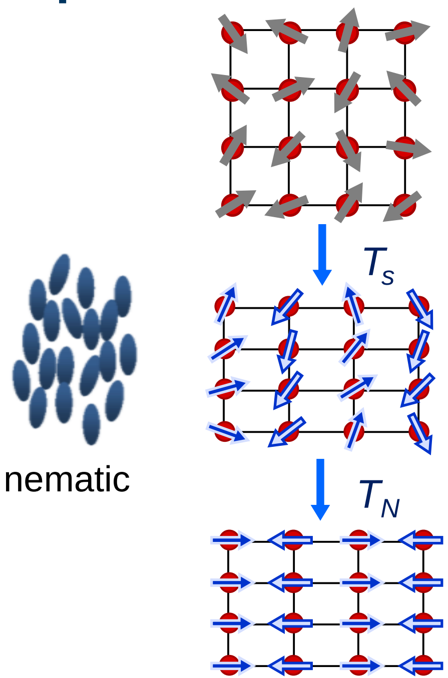
DFG SFB/TRR288 ELASTO-Q-MAT
Helmholtz Impuls- und Vernetzungsfond
Ames Laboratory, US DOE, under contract No. DE-AC02-07CH11358

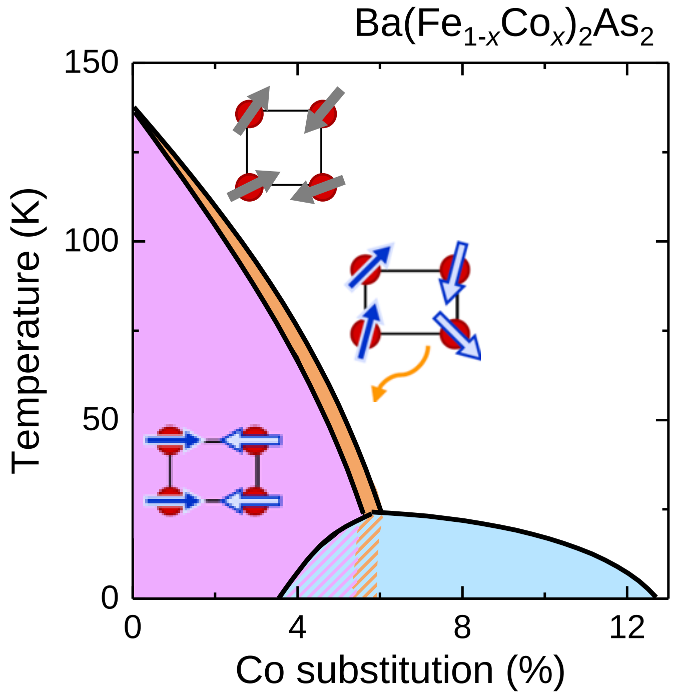
A large variety of iron-based materials



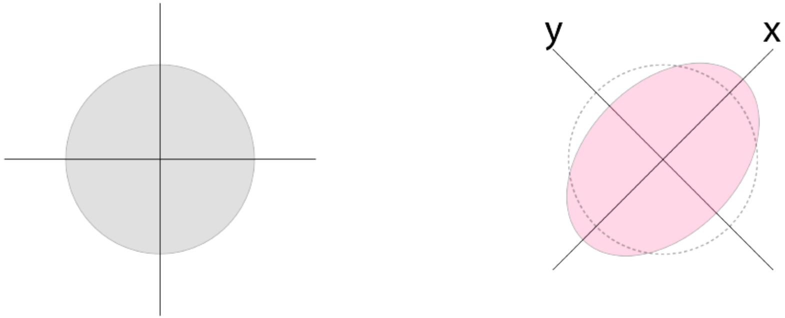
A. Böhmer, A. Kreyssig,
Phys. Unserer Zeit **48**, 70 (2017)

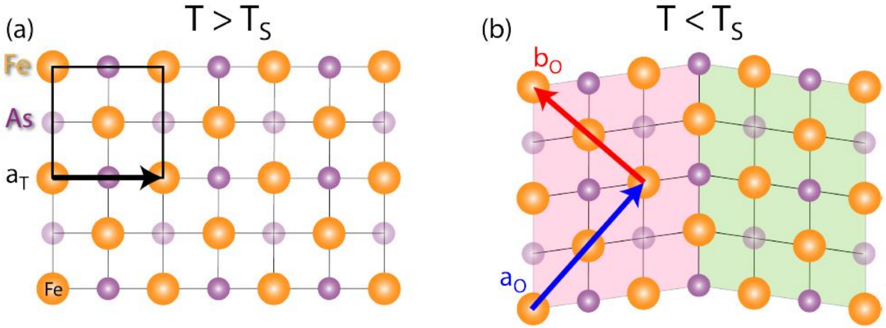
Typical phase diagram of 122 iron-based compounds





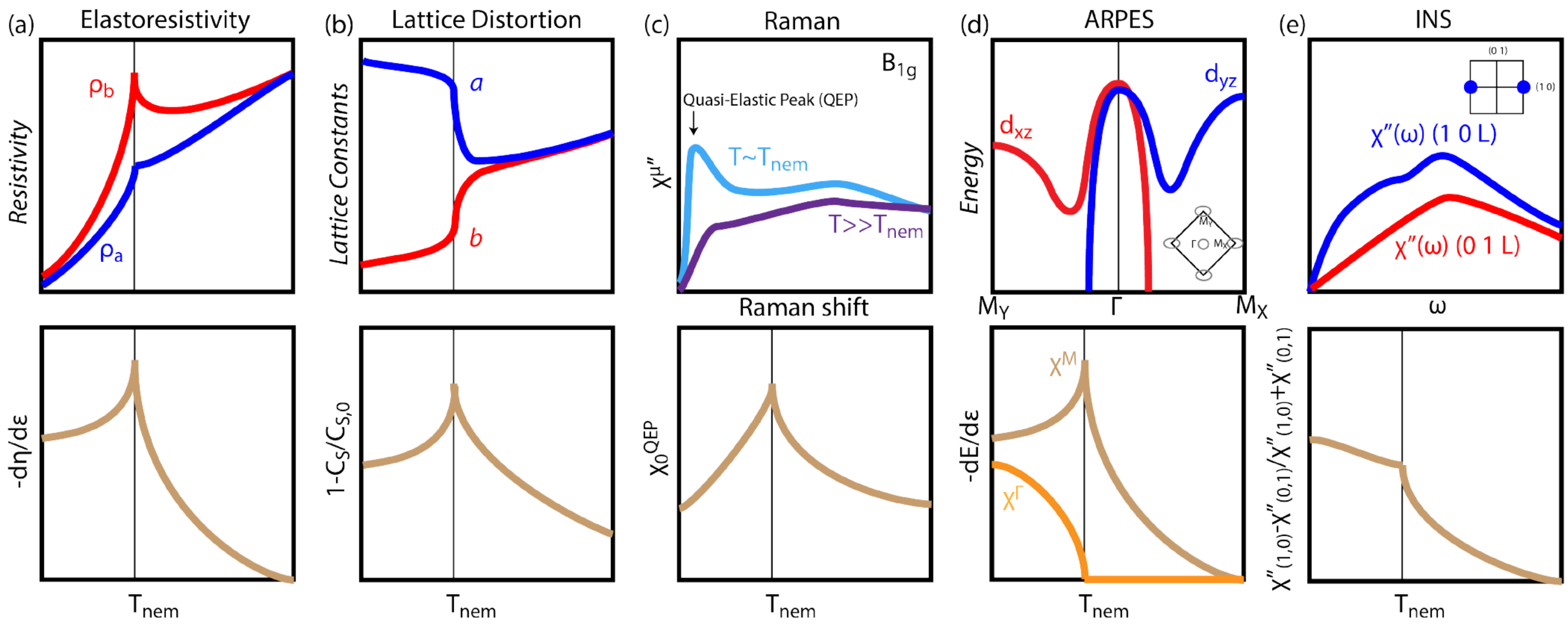
Nematicity in iron-based superconductors





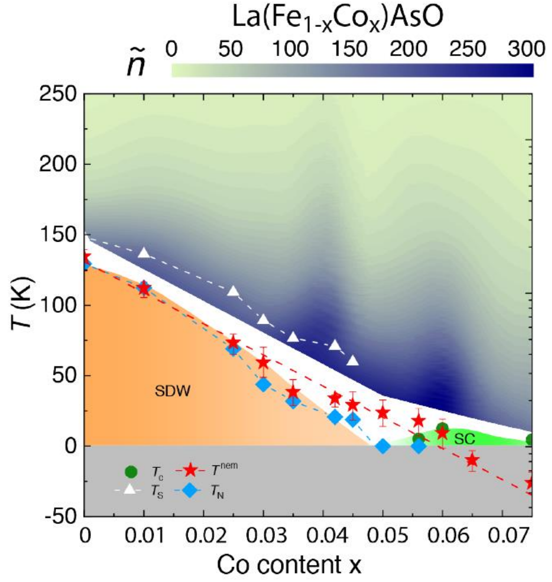
A. Böhmer, J.-H. Chu, S. Lederer and M. Yi, (in preparation)

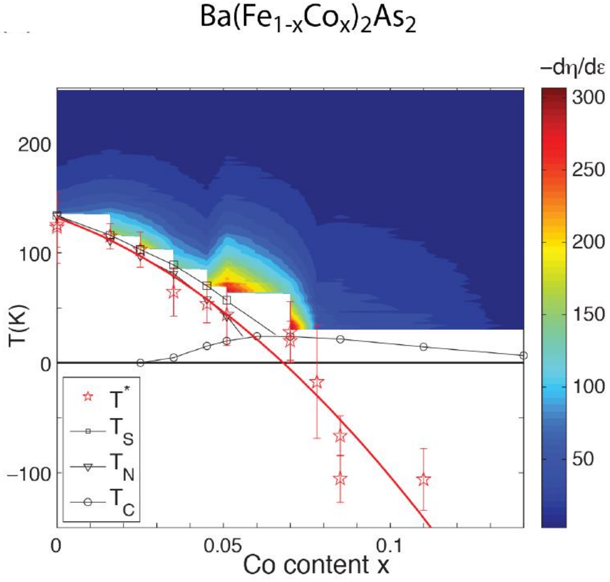
Model character of the iron-based systems (since 2008)

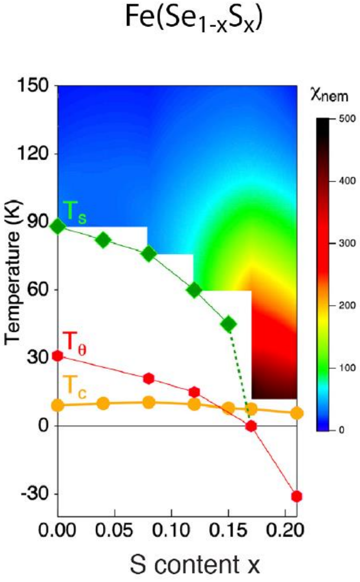


A. Böhmer, J.-H. Chu, S. Lederer and M. Yi, (in preparation)

Role of nematic fluctuations in superconducting pairing?



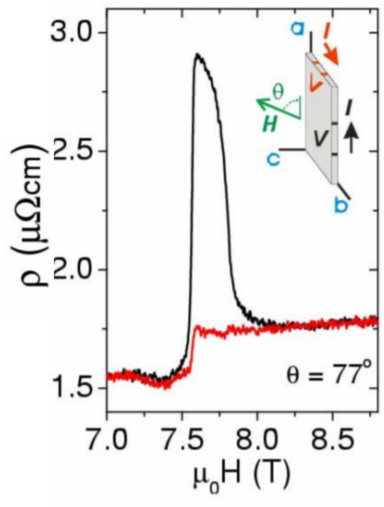




Hong et al., Phys. Rev. Lett. **125**, 067001 (2020)
Chu et al., Science **337**, 710 (2012)
Hosoi et al., PNAS **113**, 8139 (2016)

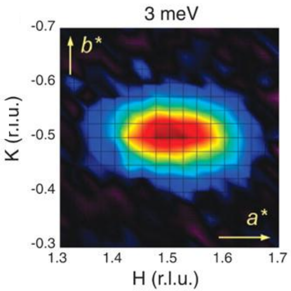
Multiple observations of electronic anisotropy

$Sr_3Ru_2O_7$



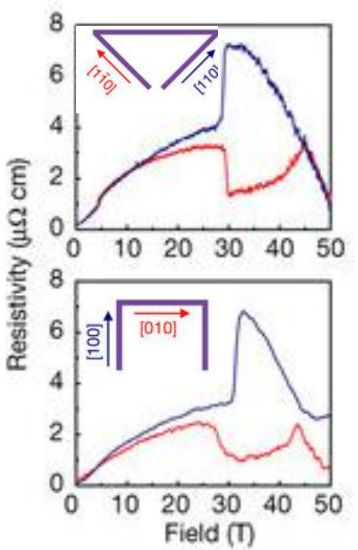
Borzi et al., Science **315,** 214 (2007)

$YBa_2Cu_3O_{6.45}$



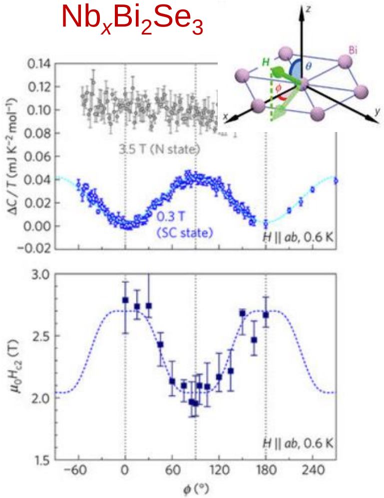
Hinkov et al., Science **319**, 597 (2008)

$CeRhIn_5$



Ronning et al., Nature **548**, 313 (2017)

$Cu_xBi_2Se_3$
$Sr_xBi_2Se_3$
$Nb_xBi_2Se_3$



Yonezawa et al., Nature Physics **13**, 123 (2017)

$Sr,BaNi_2As_2$

$CeAuSb_2$

Magic-angle twisted bilayer graphene

CsV_3Sb_5

…

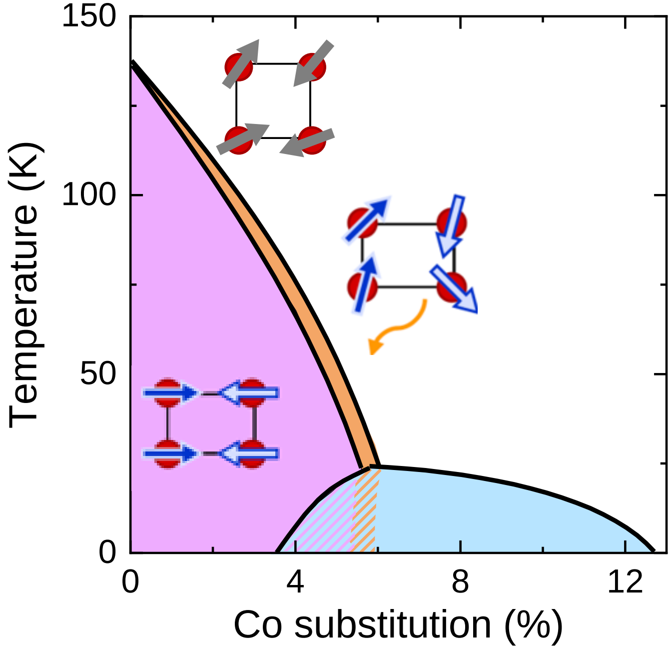
Eckberg et al., Nature Physics **16**, 346 (2020)

Seo et al, Phys. Rev. X **10,** 011035 (2020)

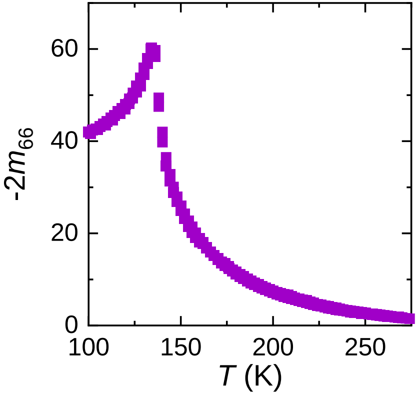
Cao et al., Science **372**, 264 (2021)

Xiang et al., arxiv 2104.06909 (2021)

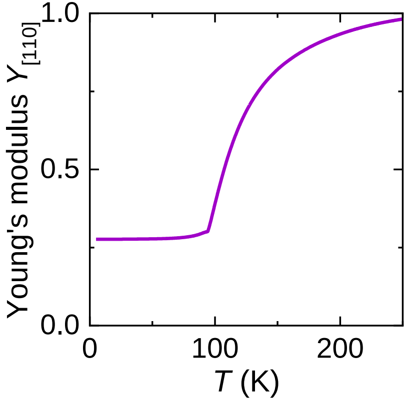
„Nematicity standard“: $Ba(Fe_{1-x}Co_x)_2As_2$



Elastoresistance

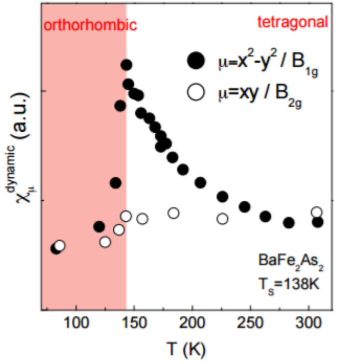


Shear modulus



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

Electronic Raman



Gallais et al., Comptes Rendus Physique (2016)

Iron-based materials with no stripe-type magnetic order?

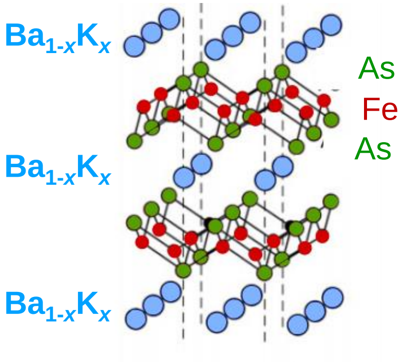
$CaK(Fe_{1-x}Ni_x)_4As_4$

$A Fe_2As_2$, A = K, Rb, Cs

A special derivative structure type of iron-based superconductors

122

$(Ba_{1-x}K_x)Fe_2As_2$

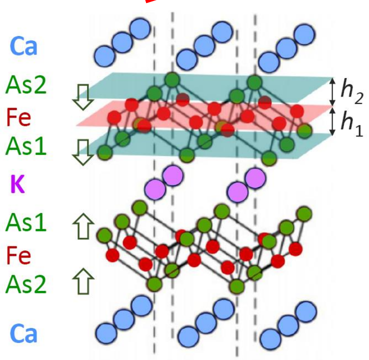


vs.

1144

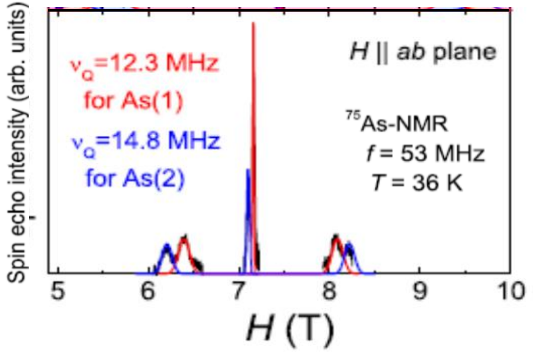
$CaKFe_4As_4$

(not ~~$Ca_{0.5}K_{0.5}Fe_2As_2$~~)



Iyo et al., JACS 2016

Two inequivalent As sites

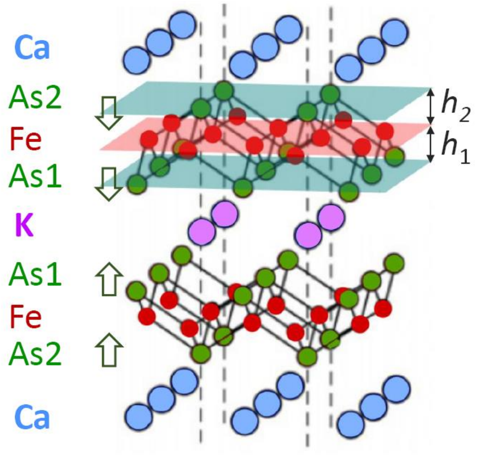


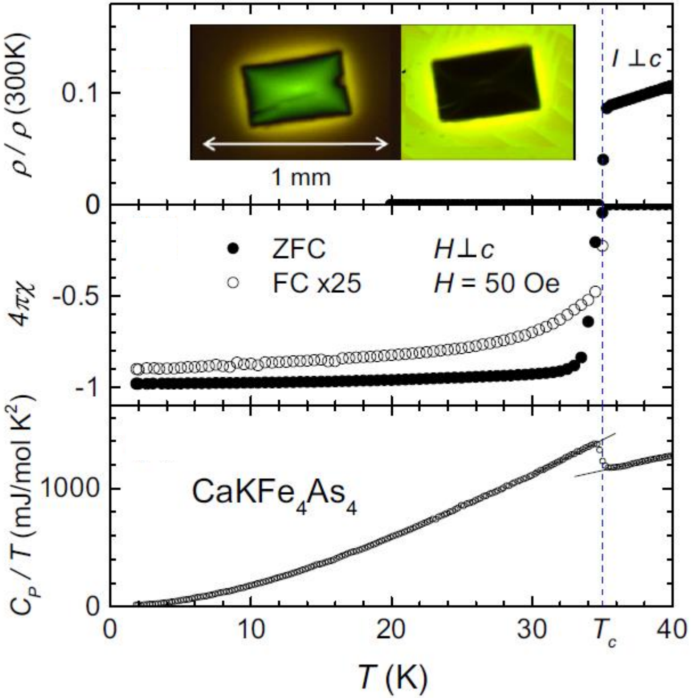
Cui et al, PRB **96**, 104512 (2017)

$$h_1 = 1.4124(4)\ \text{Å}$$
$$h_2 = 1.3951(4)\ \text{Å}$$
$$h_1 - h_2 = 0.0173(8)\ \text{Å}$$

Böhmer et al., arXiv:2011.13207

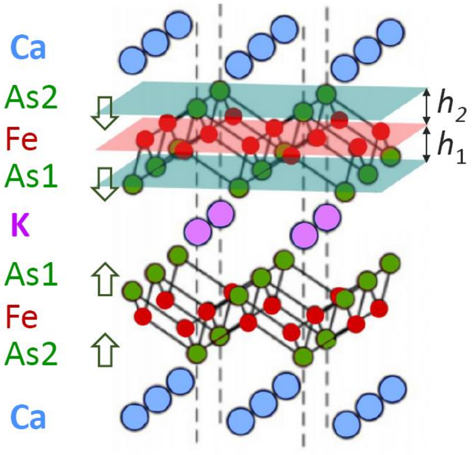
Superconductivity in $CaKFe_4As_4$

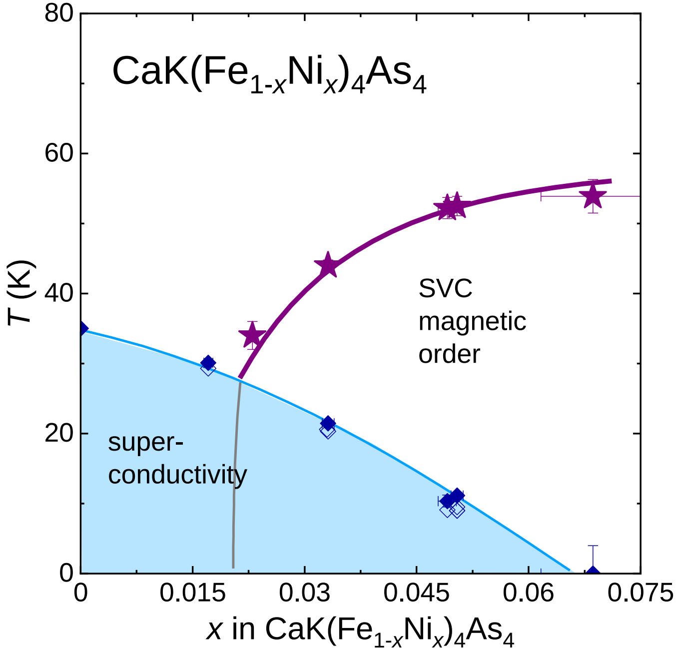




Meier et al., Phys. Rev. B, 94, 064501 (2016)

Magnetic order achieved by electron-doping

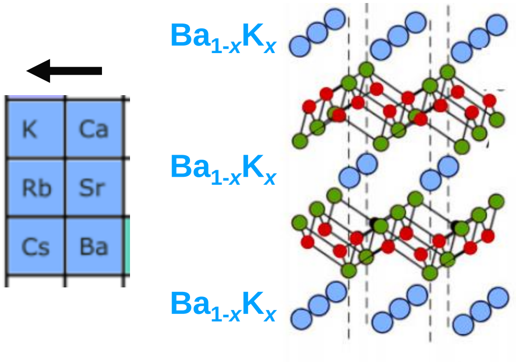




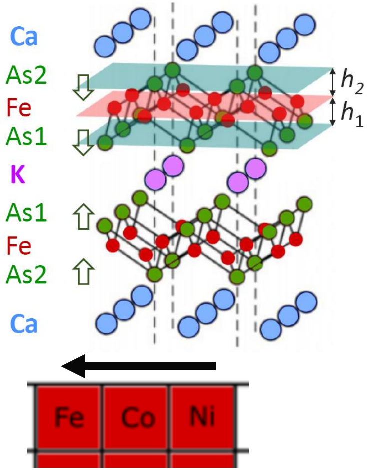
Meier et al., npj Quantum Materials **3**, 5 (2018)

Comparison: hole-doped 122 and electron-doped 1144

$(Ba_{1-x}K_x)Fe_2As_2$

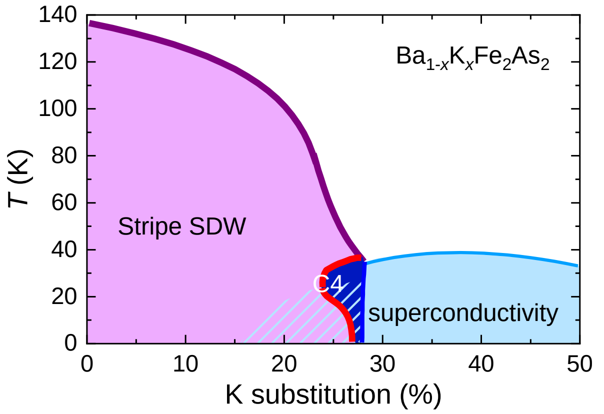


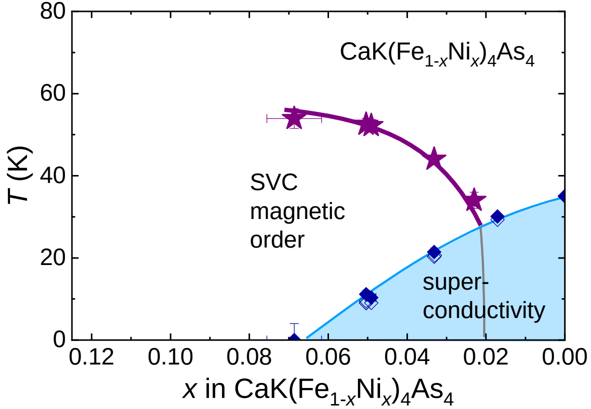
$CaKFe_4As_4$



Meier et al., Phys. Rev. B, 94, 064501 (2016)

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

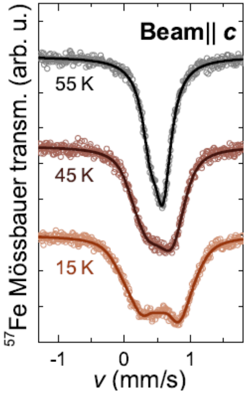




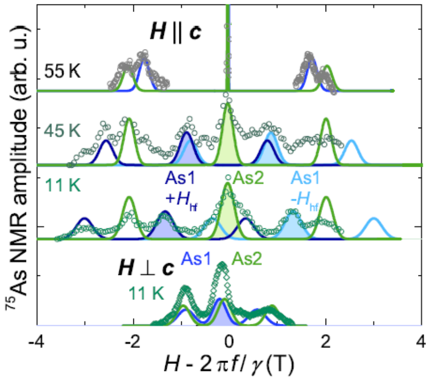
Different magnetic order types

Experimental evidence

Mössbauer



NMR

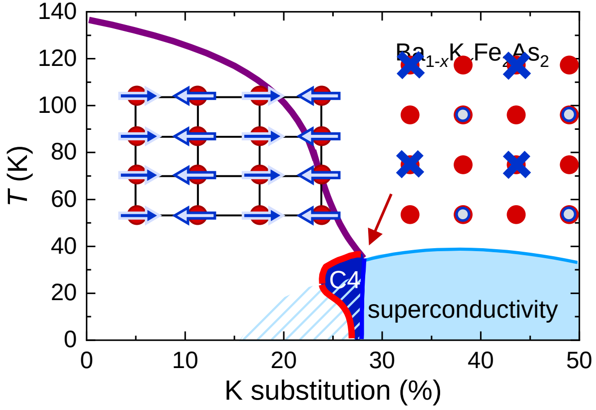


W. Meier et al., npj Quantum Materials **3**, 5 (2018)

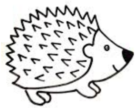
Neutron diffraction

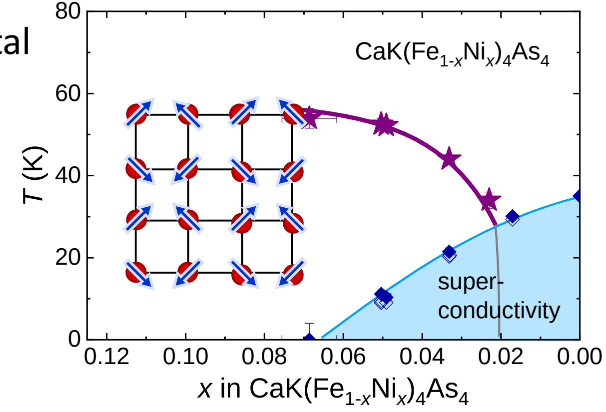
Kreyssig et al, Phys. Rev. B **97**, 224521 (2018)

Stripe-type magnetic order



Spin-vortex crystal magnetic order, hedgehog type





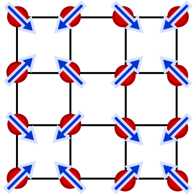
Magnetic phases in Ginzburg-Landau parameter space

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

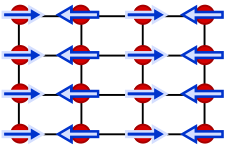
$$\boldsymbol{Q}_X = (\pi, 0), \boldsymbol{Q}_Y = (0, \pi)$$

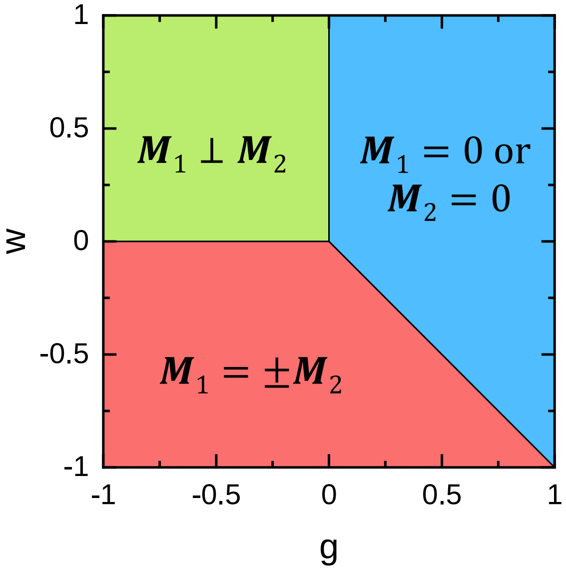
$$\mathcal{F} = r_0 \left(\mathrm{M}_1^2 + \mathrm{M}_2^2\right) + \frac{u}{2}\left(\mathrm{M}_1^2 + \mathrm{M}_2^2\right)^2 - \frac{g}{2}\left(\mathrm{M}_1^2 - \mathrm{M}_2^2\right)^2 + 2w\left(\mathrm{M}_1 \cdot \mathrm{M}_2\right)^2$$

Spin-vortex crystal

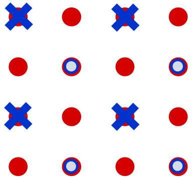


Stripe-spin density wave





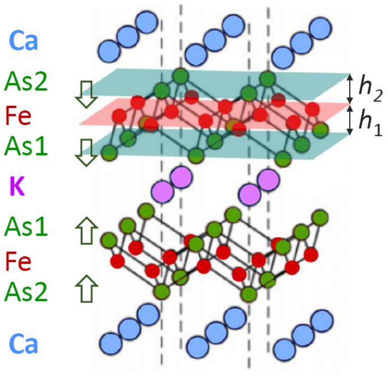
Spin-charge density wave



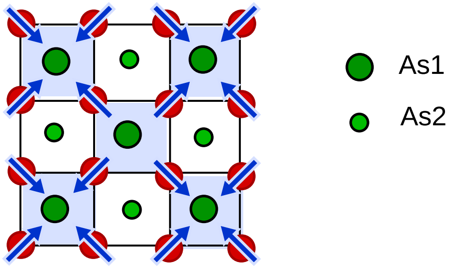
Fernandes, Kivelson, and Berg, PRB **93**, 014511 (2016)

Consequence of inequivalent As-sites in the 1144 crystal structure

$CaKFe_4As_4$



P4/mmm



Symmetry-breaking field

- characterized by $\boldsymbol{\eta} = \eta\hat{z}$
- couples to SVC phase:

$$F \sim -\boldsymbol{\eta} \cdot (\boldsymbol{M}_1 \times \boldsymbol{M}_2)$$

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

Magnetic phases in Ginzburg-Landau parameter space

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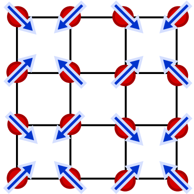
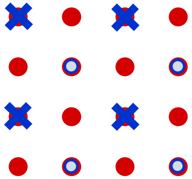
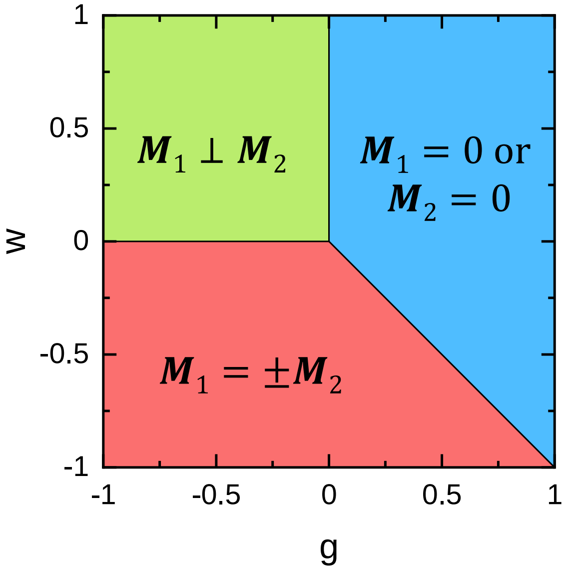
Spin-vortex crystal

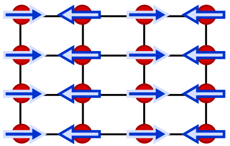


Spin-charge density wave





Stripe-spin density wave



Fernandes, Kivelson, and Berg, PRB **93**, 014511 (2016)

Magnetic phases in Ginzburg-Landau parameter space

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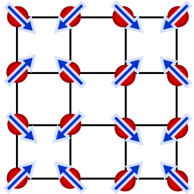
$$\boldsymbol{Q}_X = (\pi, 0), \boldsymbol{Q}_Y = (0, \pi)$$

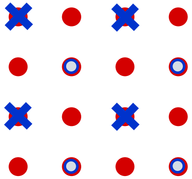
$$\mathcal{F} = r_0 \left(\mathrm{M}_1^2 + \mathrm{M}_2^2\right) + \frac{u}{2}\left(\mathrm{M}_1^2 + \mathrm{M}_2^2\right)^2 - \frac{g}{2}\left(\mathrm{M}_1^2 - \mathrm{M}_2^2\right)^2 + 2w\left(\mathrm{M}_1 \cdot \mathrm{M}_2\right)^2 - \eta\left(\mathrm{M}_1 \times \mathrm{M}_2\right) \cdot \hat{z},$$

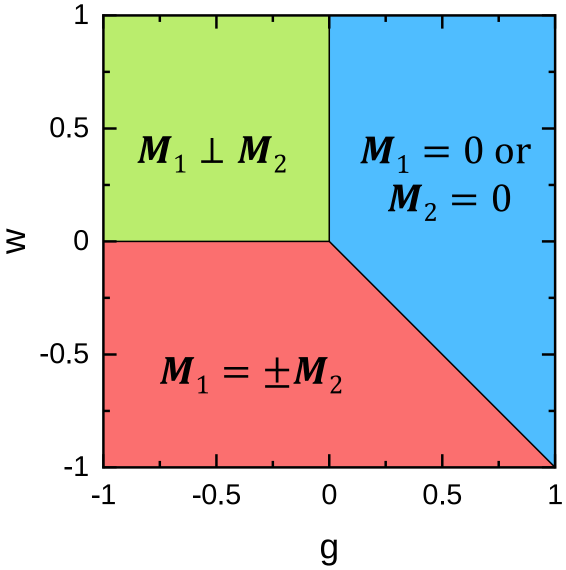
Effect on nematic fluctuations?

Spin-vortex crystal

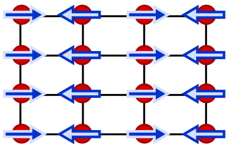


Spin-charge density wave



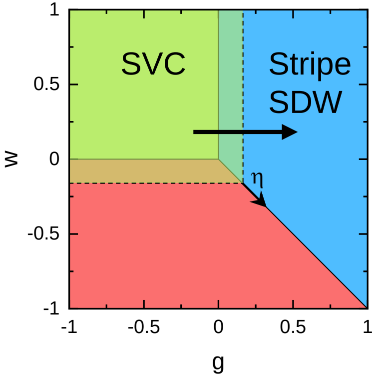


Stripe-spin density wave



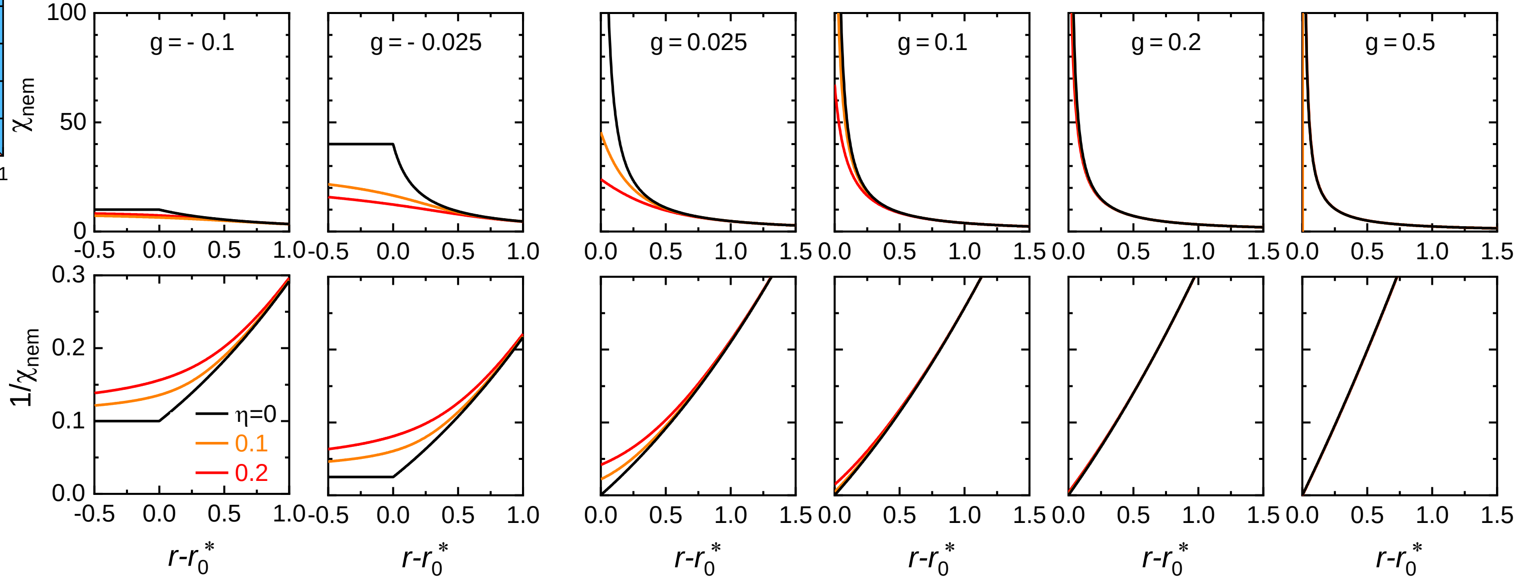
Fernandes, Kivelson, and Berg, PRB **93**, 014511 (2016)

Expectation for nematic susceptibility



Ginzburg-Landau, 2 dimensions

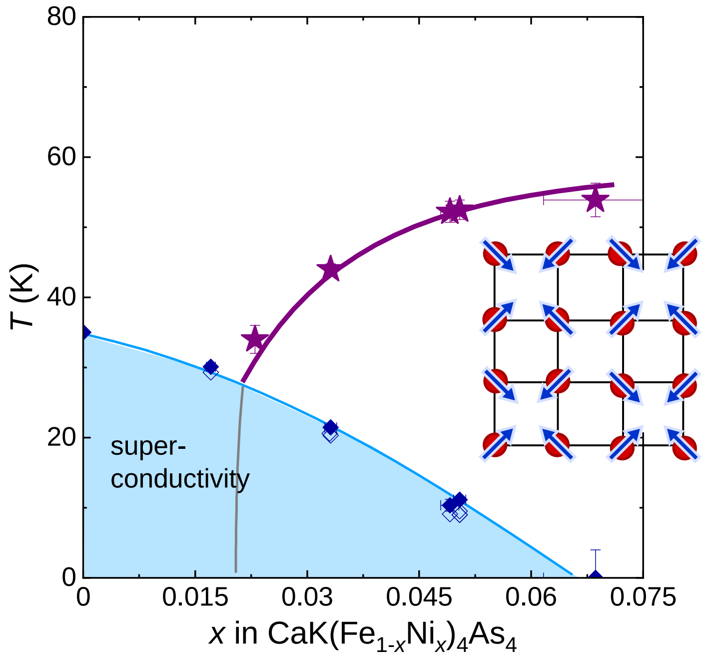
M. Christensen, Fei Chen



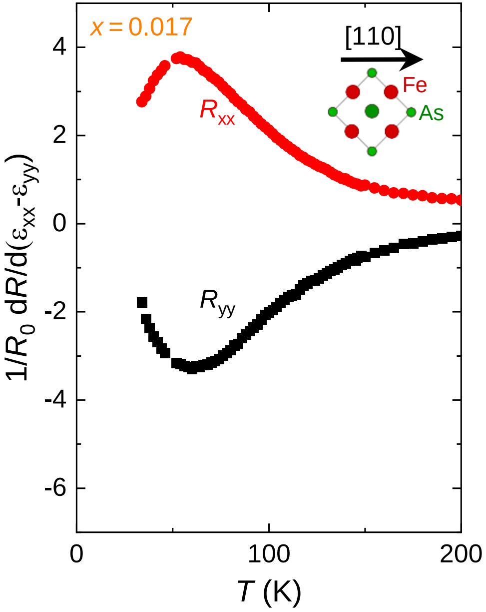
Böhmer et al., arXiv:2011.13207

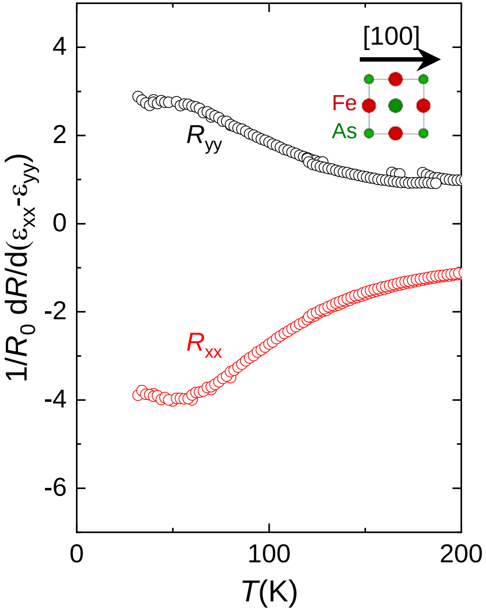
Experimental study of the nematic susceptibility

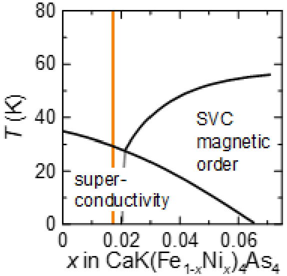
- Elastoresistance
- Elastic modulus

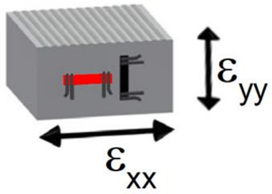


Elastoresistance of $CaK(Fe_{1-x}Ni_x)_4As_4$









$$m_{B_{2g}} = k \cdot \chi_{\text{nem}}^{B_{2g}}$$

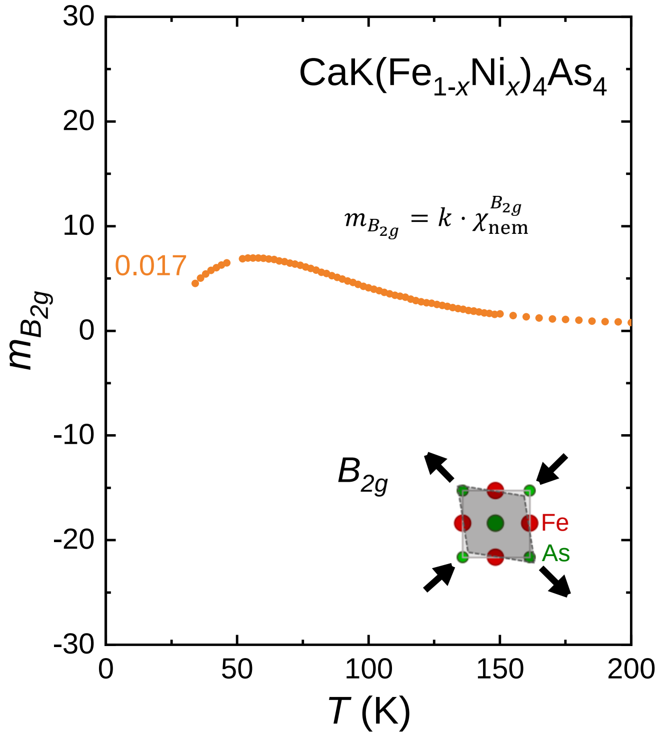
$$m_{A_{1g}} = \frac{1}{1-\nu_{[100]}}\left[\frac{d(\Delta R/R_0)_{[100]}}{d\varepsilon_{[100]}} + \frac{d(\Delta R/R)_{[010]}}{d\varepsilon_{[100]}}\right]$$

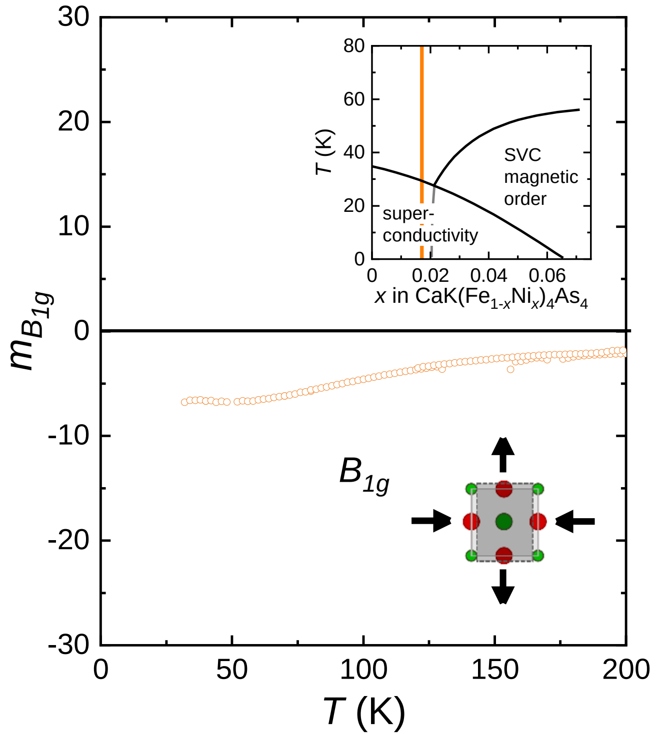
$$= \frac{1}{1-\nu_{[110]}}\left[\frac{d(\Delta R/R_0)_{[110]}}{d\varepsilon_{[110]}} + \frac{d(\Delta R/R)_{[\bar{1}10]}}{d\varepsilon_{[110]}}\right]$$

$$m_{B_{1g}} = \frac{1}{1+\nu_{[100]}}\left[\frac{d(\Delta R/R_0)_{[100]}}{d\varepsilon_{[100]}} - \frac{d(\Delta R/R)_{[010]}}{d\varepsilon_{[100]}}\right]$$

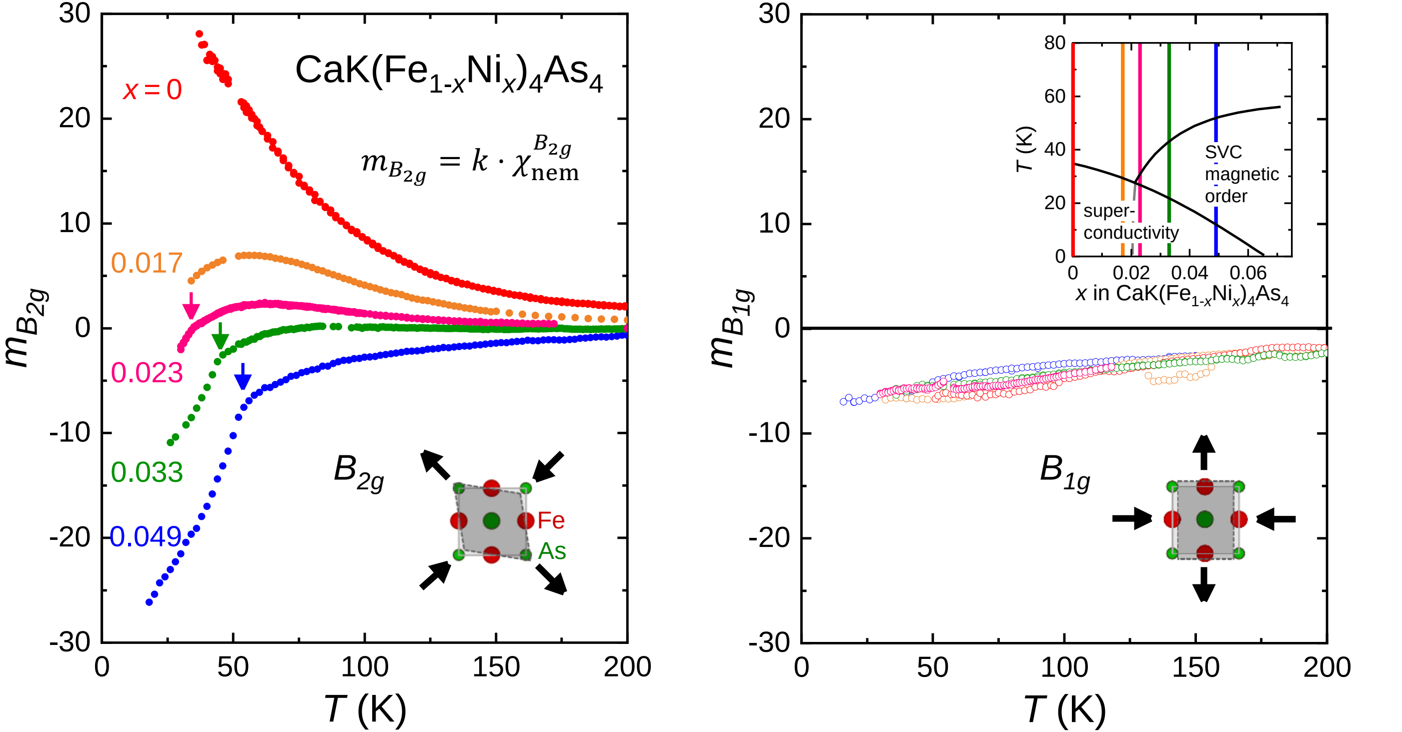
$$m_{B_{2g}} = \frac{1}{1+\nu_{[110]}}\left[\frac{d(\Delta R/R_0)_{[110]}}{d\varepsilon_{[110]}} - \frac{d(\Delta R/R)_{[\bar{1}10]}}{d\varepsilon_{[110]}}\right]$$

Elastoresistance of $CaK(Fe_{1-x}Ni_x)_4As_4$



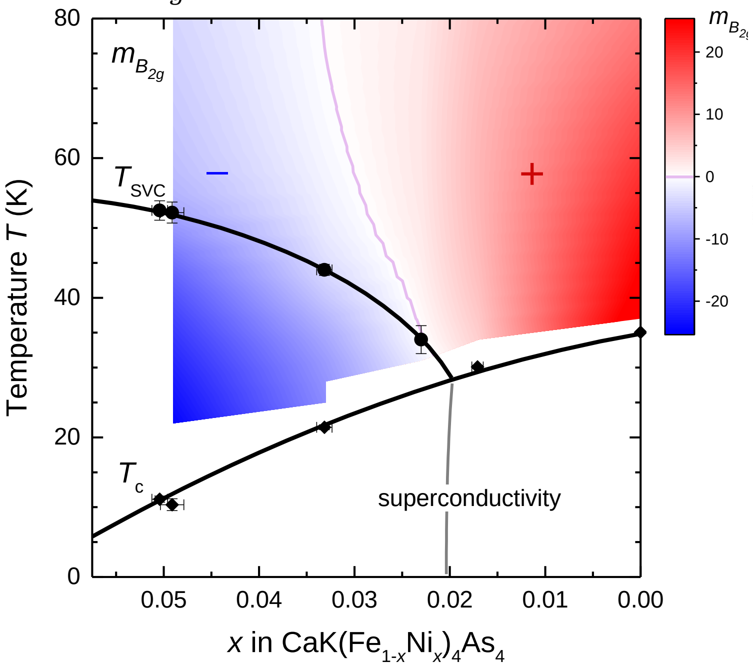


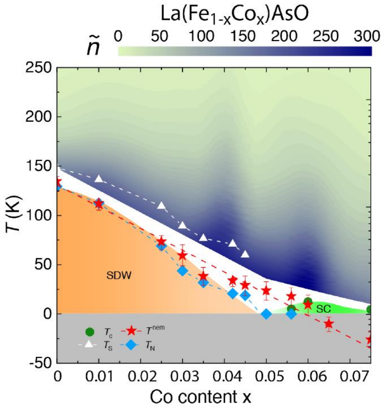
Elastoresistance of $CaK(Fe_{1-x}Ni_x)_4As_4$

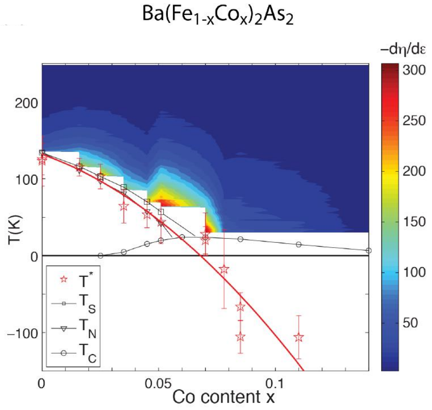


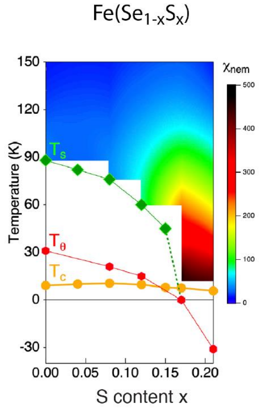
Unexpected(?) sign change of the elastoresistance

$$m_{B_{2g}} = k \cdot \chi_{\text{nem}}^{B_{2g}}$$

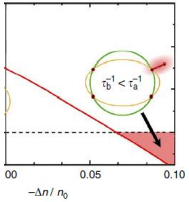








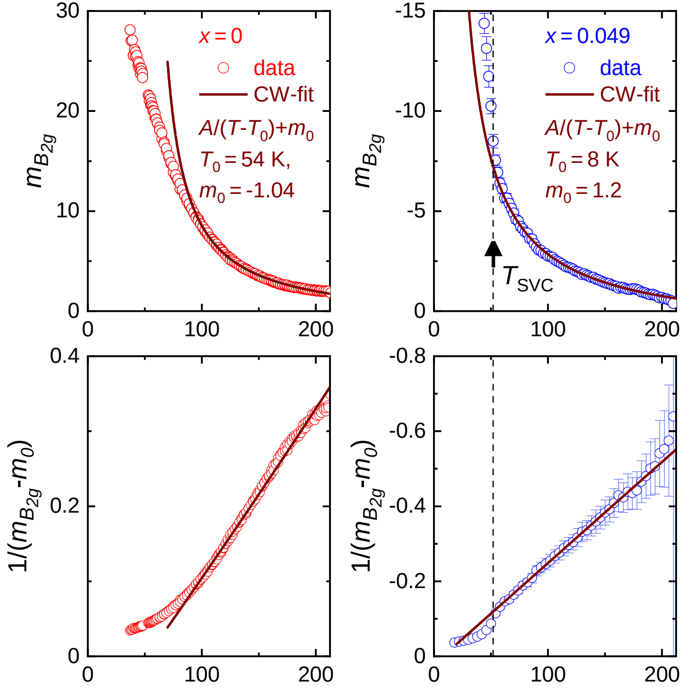
Hong et al., Phys. Rev. Lett. **125**, 067001 (2020)
Chu et al., Science **337**, 710 (2012)
Hosoi et al., PNAS **113**, 8139 (2016)



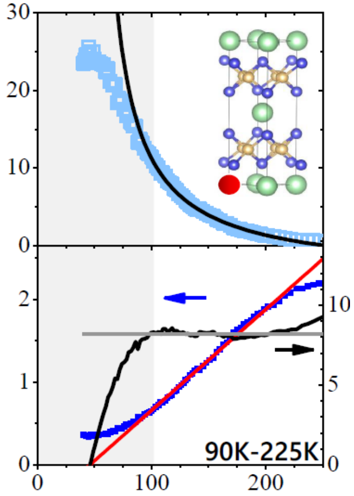
See:
Blomberg et al., Nat. Commun. 4, 1914 (2013)
Sanchez et al., arXiv:2006.09444

Temperature dependence of the elastoresistance

optimum T_c 1144 | "underdoped" 1144

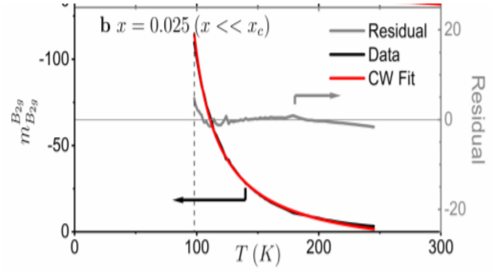


Optimally doped $Ba_{1-x}K_xFe_2As_2$



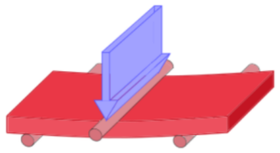
Kuo et al., Science **352**, 958 (2016)

Underdoped $Ba(Fe,Co)_2As_2$



Palmstrom et al.,
arxiv 1912.07574 (2020)

Bending modulus of $CaK(Fe,Ni)_4As_4$

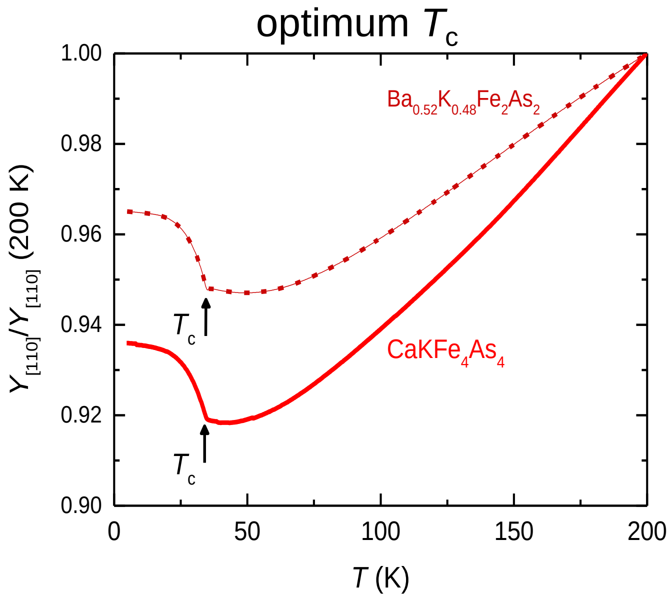


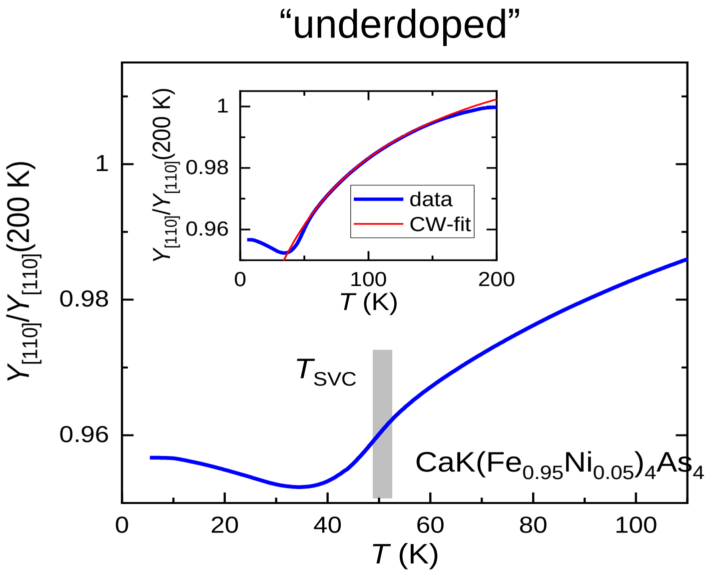
$$Y_{[110]} = 4\left(\frac{1}{C_{66}} + \frac{1}{\gamma}\right)^{-1}$$

$$\gamma = \frac{C_{11}+C_{12}}{2} - \frac{C_{13}^2}{C_{33}}$$

$$\frac{C_{66}}{C_{66,0}} = 1 - \frac{\lambda^2}{C_{66,0}}\chi_{\mathrm{nem}}$$

Three-point bending in a capacitance dilatometer
See: Böhmer et al., PRL **112**, 047001 (2014)

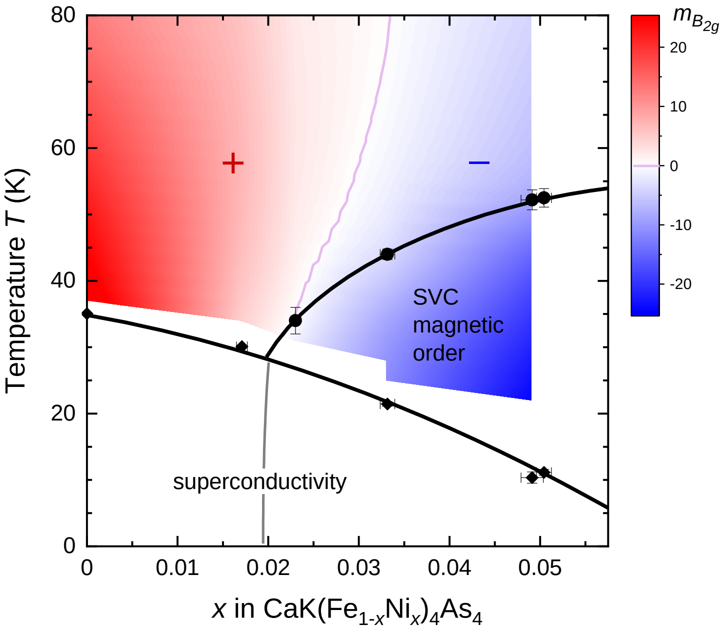




Summary: Evolution of nematic fluctuations in $CaK(Fe_{1-x}Ni_x)_4As_4$

- “Sub-Curie-Weiss” *T*-dependence
- Very similar to $Ba_{0.5}K_{0.5}Fe_2As_2$
- Consequence of almost degenerate magnetic orders?

More hole-doped?



- Nematic fluctuations finite but far from critical
- Curie-Weiss-like temperature dependence

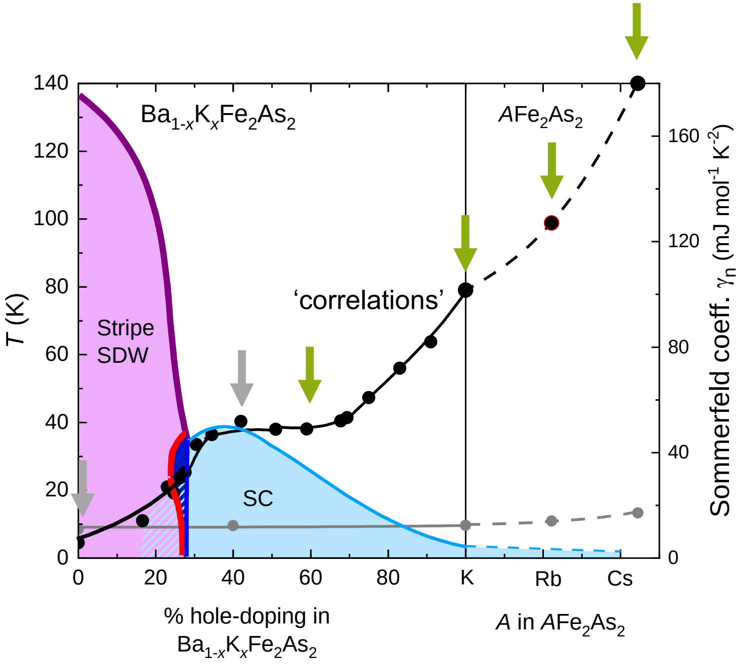
$$m_{B_{2g}} = k \cdot \chi_{nem}^{B_{2g}}$$

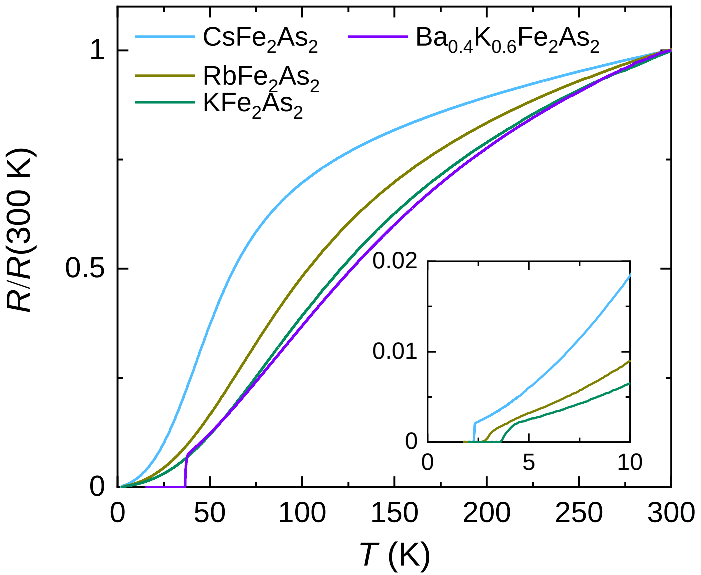
Prefactor of elastoresistance:

- Clear doping dependence
- Likely temperature dependent

Böhmer et al., arXiv:2011.13207

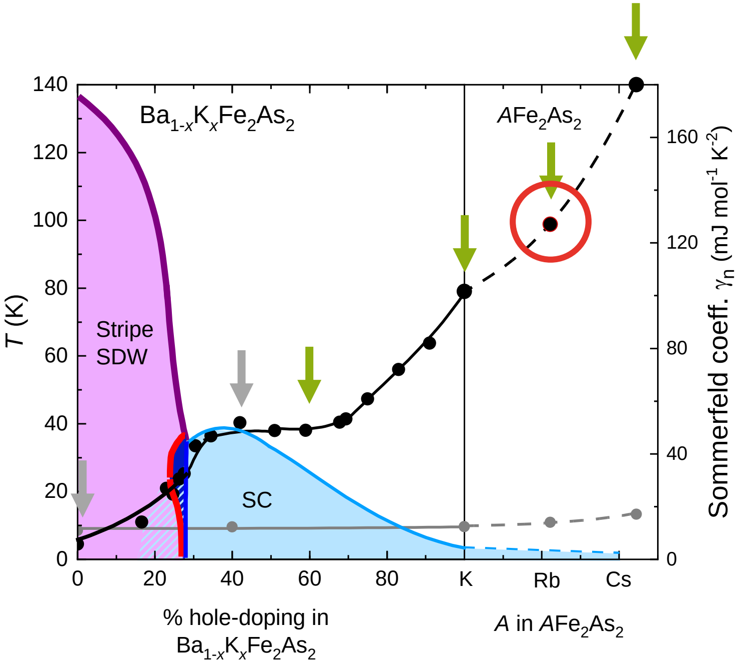
The "extremely hole-doped" AFe_2As_2 (A=K,Rb,Cs)



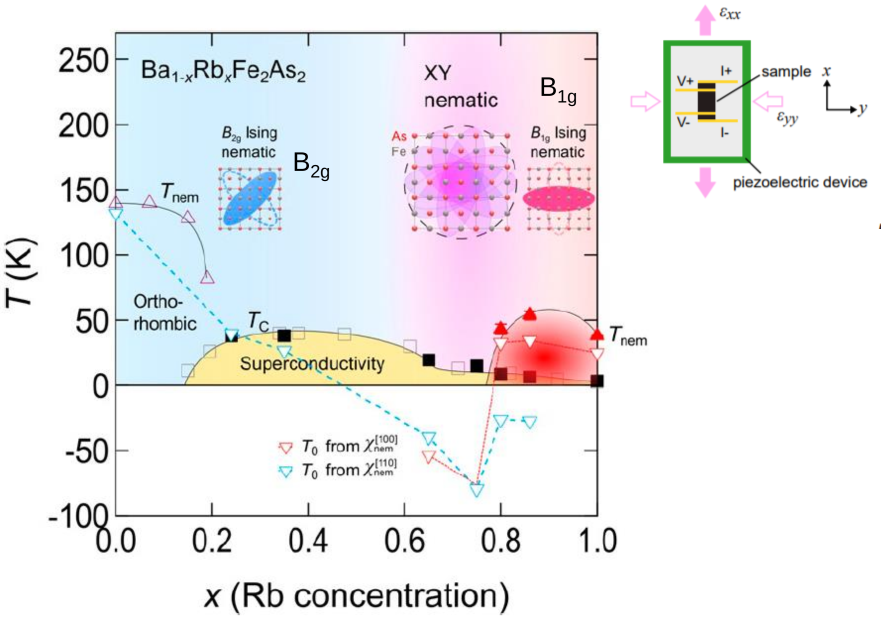


Hardy et al., PRB **94**, 025113 (2016)

Change of nematic direction?

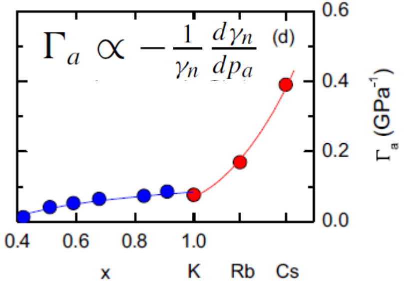


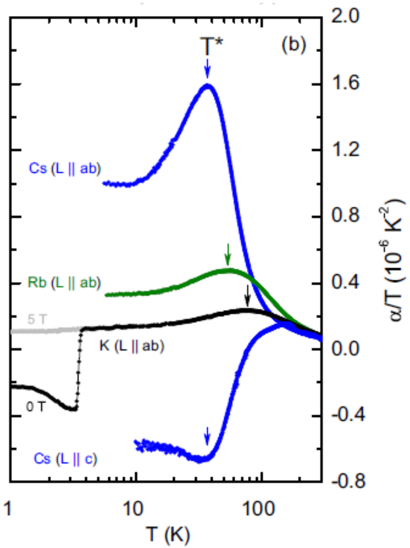
Hardy et al., PRB **94**, 025113 (2016)



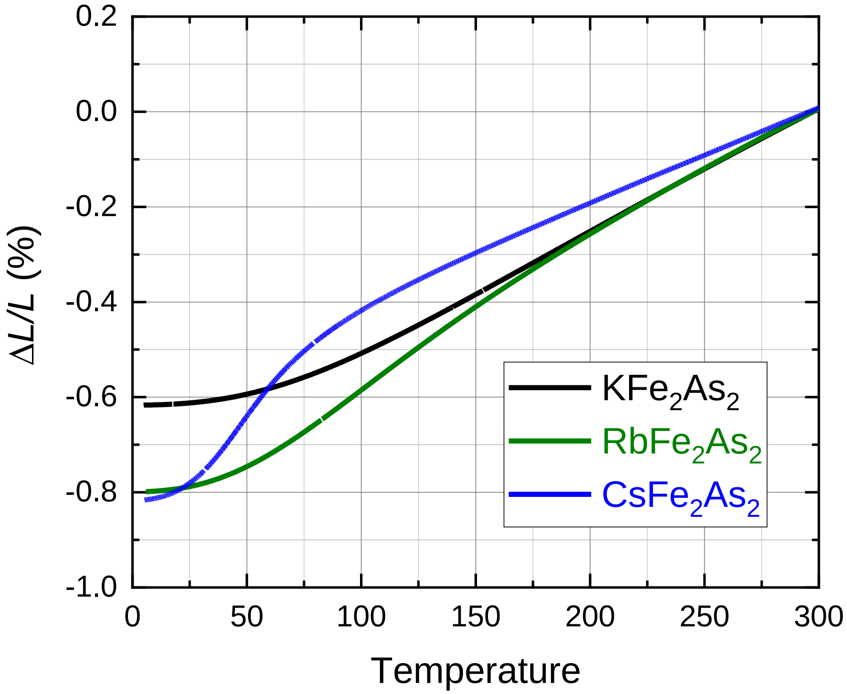
Ishida et al., PNAS, 117, 6424–6429, (2020)

Strain dependence and thermal expansion



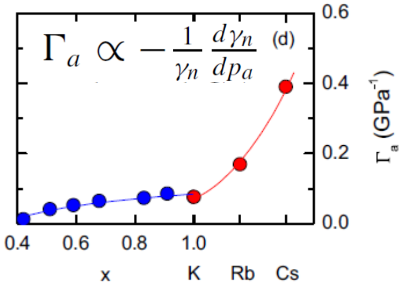


$$\alpha = \frac{1}{V}\frac{dV}{dT} = -\frac{dS}{dp}$$

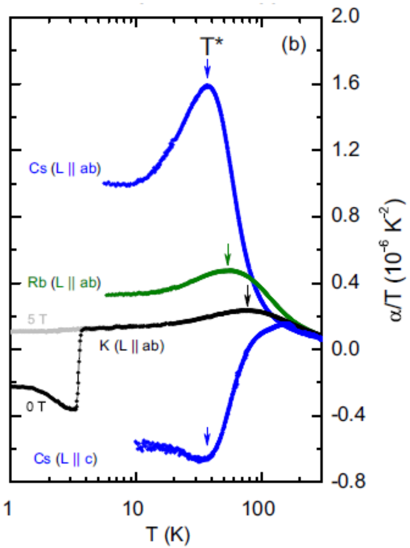


Hardy et al., PRB **94**, 025113 (2016)

Strain dependence and thermal expansion

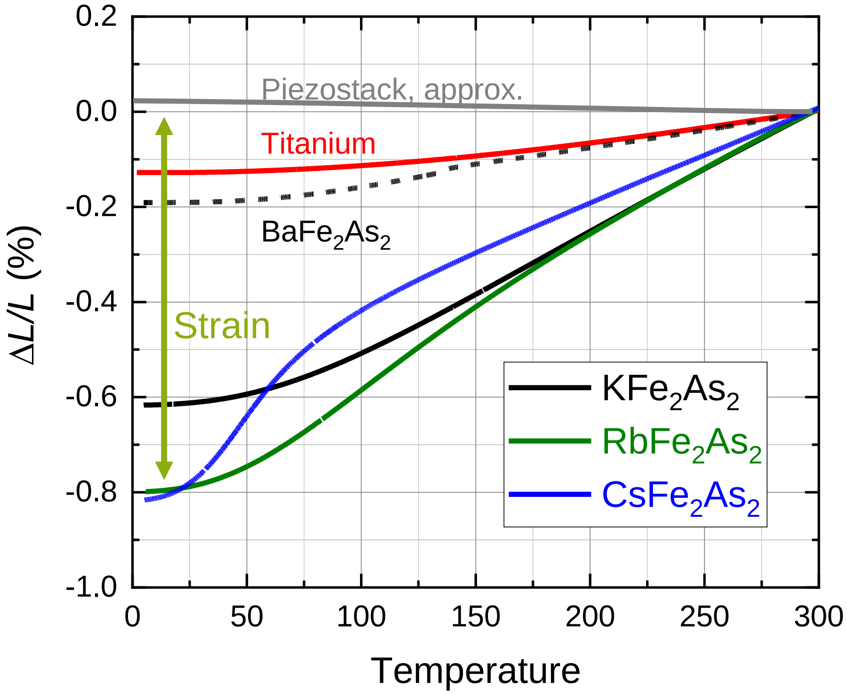


$$\Gamma_a \propto -\frac{1}{\gamma_n}\frac{d\gamma_n}{dp_a}$$



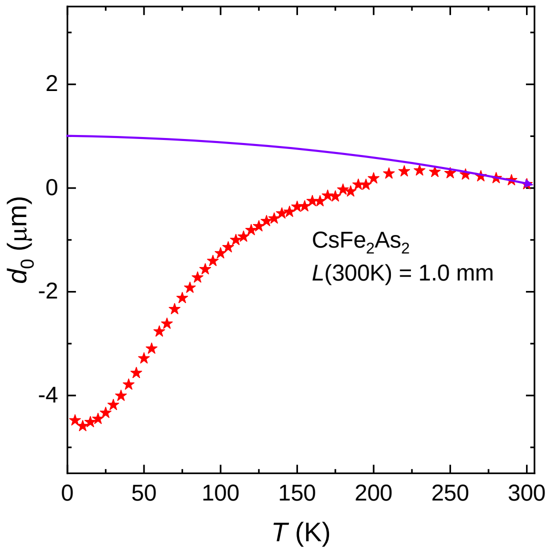
$$\alpha = \frac{1}{V}\frac{dV}{dT} = -\frac{dS}{dp}$$

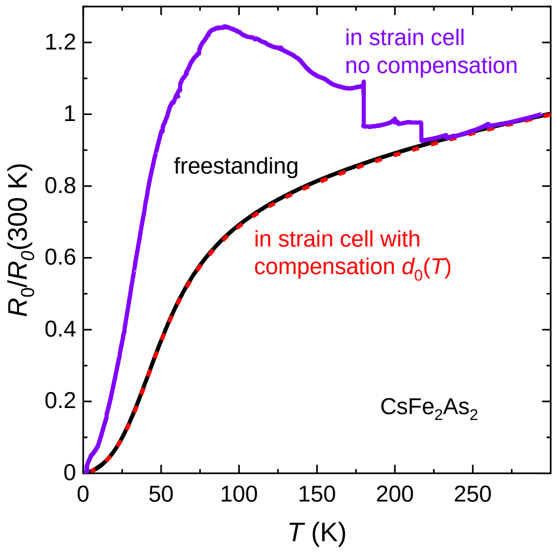
Hardy et al., PRB **94**, 025113 (2016)

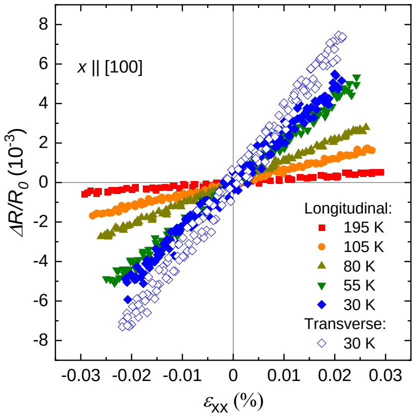


Successful active strain compensation

Razorbill
CS100, CS120

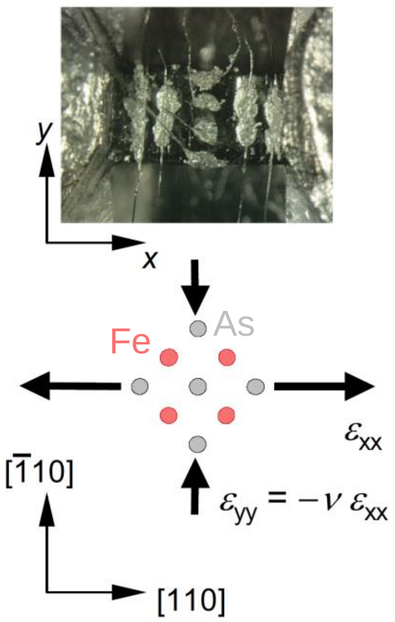


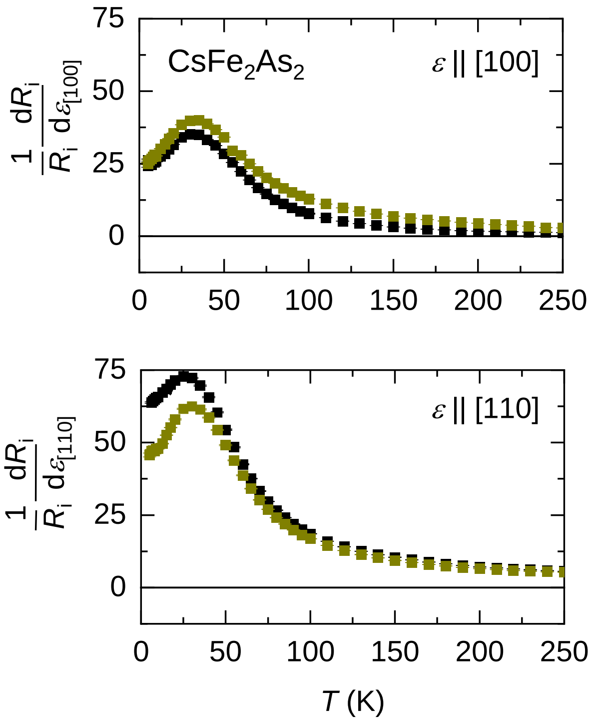


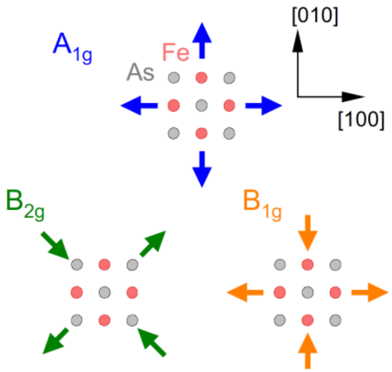


Wiecki et al., Phys. Rev. Lett. **125**, 187001 (2020)

Symmetry-resolved elastoresistance







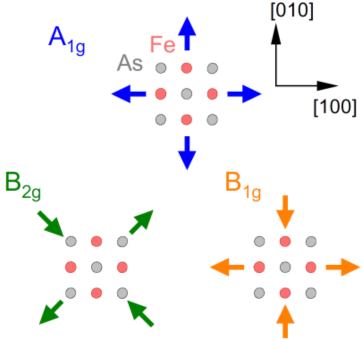
$$m_{A_{1g}} = \frac{1}{1-\nu_{[100]}}\left[\frac{d(\Delta R/R_0)_{[100]}}{d\varepsilon_{[100]}} + \frac{d(\Delta R/R)_{[010]}}{d\varepsilon_{[100]}}\right]$$

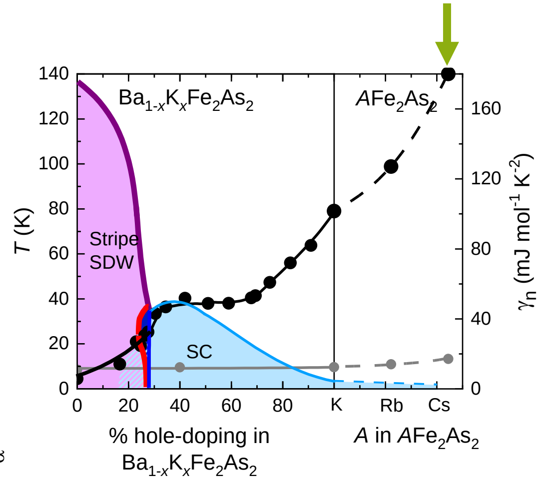
$$= \frac{1}{1-\nu_{[110]}}\left[\frac{d(\Delta R/R_0)_{[110]}}{d\varepsilon_{[110]}} + \frac{d(\Delta R/R)_{[\bar{1}10]}}{d\varepsilon_{[110]}}\right]$$

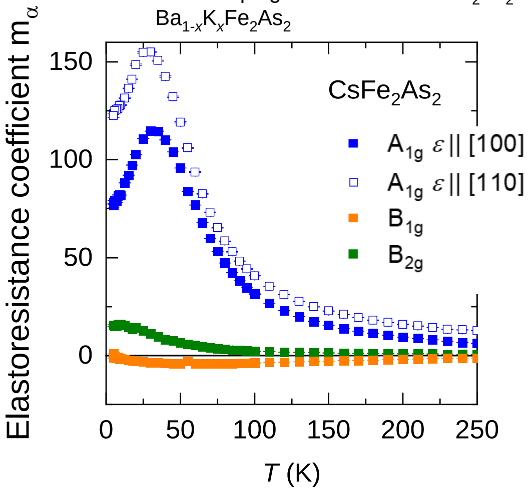
$$m_{B_{1g}} = \frac{1}{1+\nu_{[100]}}\left[\frac{d(\Delta R/R_0)_{[100]}}{d\varepsilon_{[100]}} - \frac{d(\Delta R/R)_{[010]}}{d\varepsilon_{[100]}}\right]$$

$$m_{B_{2g}} = \frac{1}{1+\nu_{[110]}}\left[\frac{d(\Delta R/R_0)_{[110]}}{d\varepsilon_{[110]}} - \frac{d(\Delta R/R)_{[\bar{1}10]}}{d\varepsilon_{[110]}}\right]$$

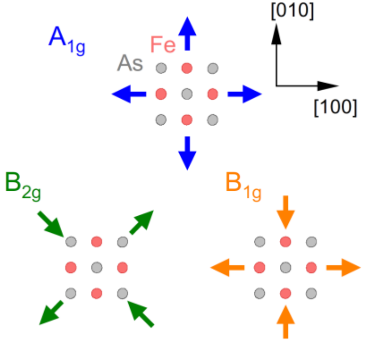
Elastoresistance evolution

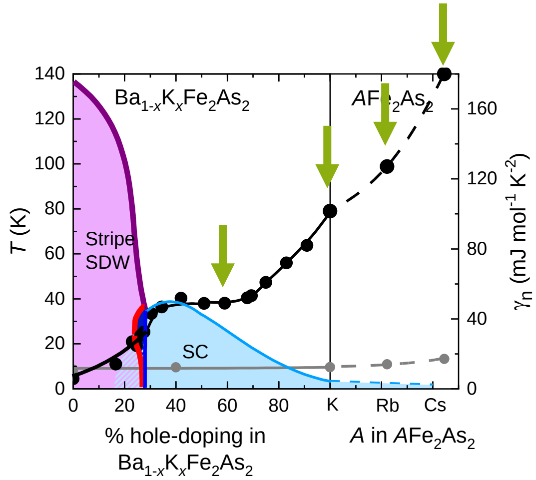




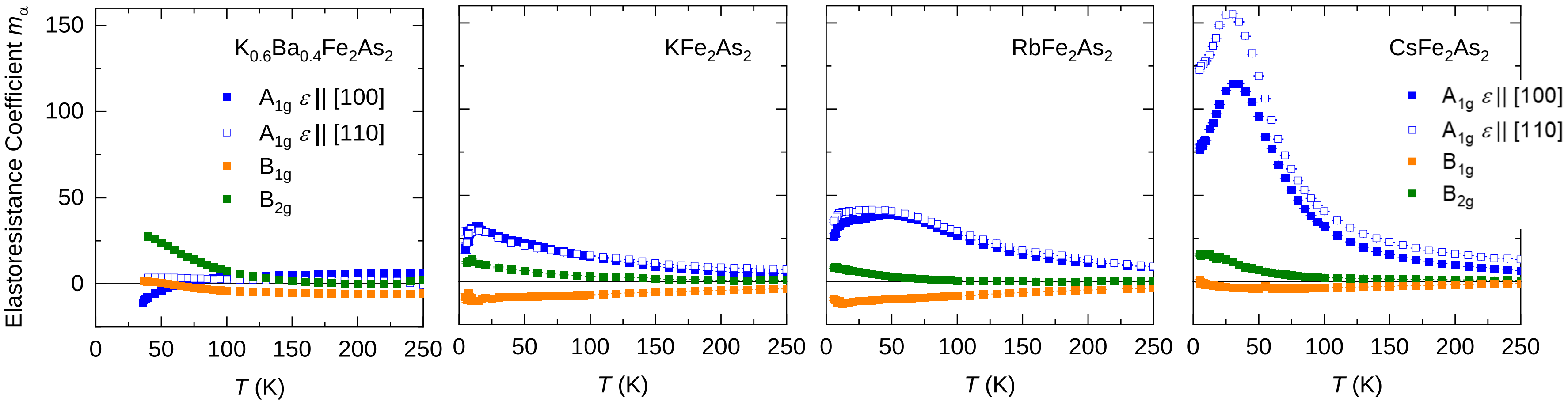


Elastoresistance evolution

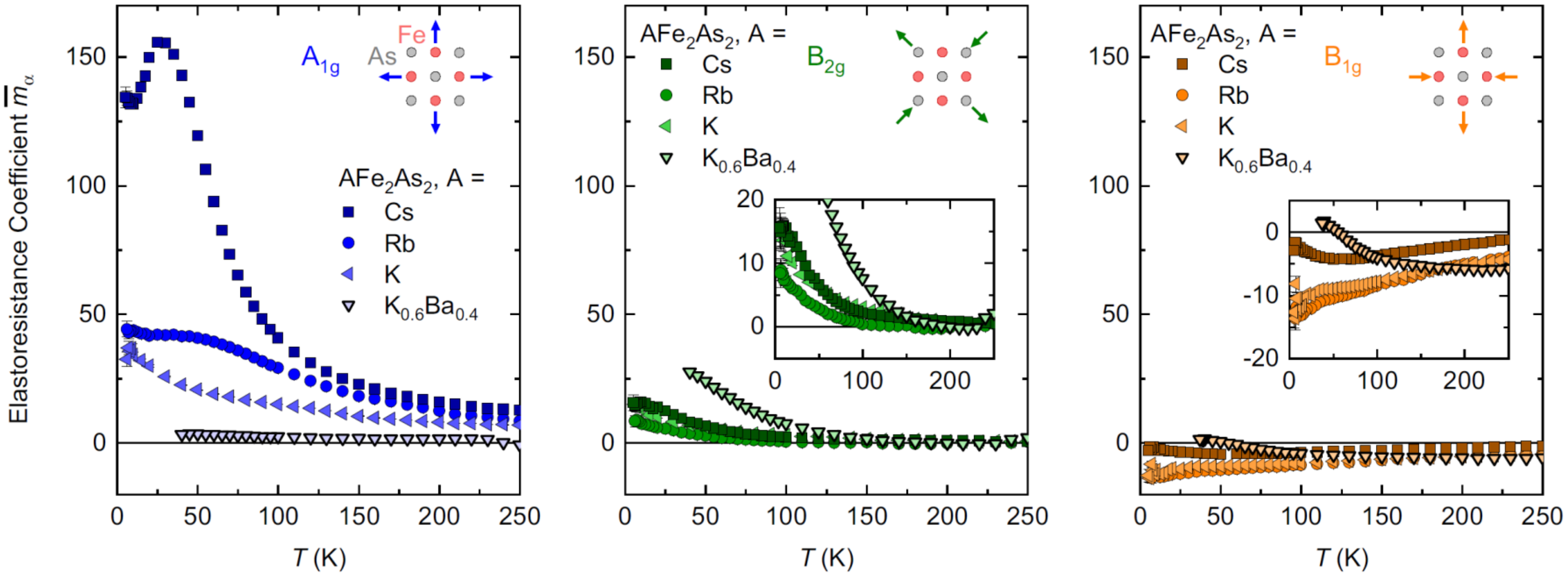




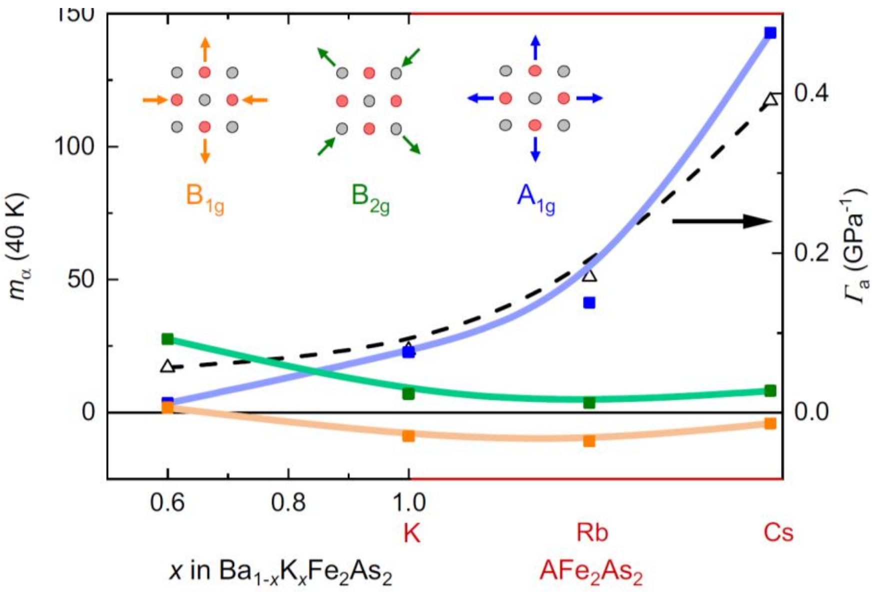
Wiecki et al., Nature Communications **12**, 4824 (2021)



Elastoresistance evolution



Wiecki et al., Nature Communications **12**, 4824 (2021)



Emerging symmetric strain response and weakening nematic fluctuations in strongly hole-doped iron-based superconductors,

P. Wiecki, M. Frachet, A.-A. Haghighirad, T. Wolf, C. Meingast, R. Heid and A. E. Böhmer, Nature Communications **12**, 4824 (2021)

(Weak) nematic behavior in iron-based materials also in less obvious cases