Magnetyzm i nadprzewodnictwo w domieszkowanym $EuFe_2As_2$

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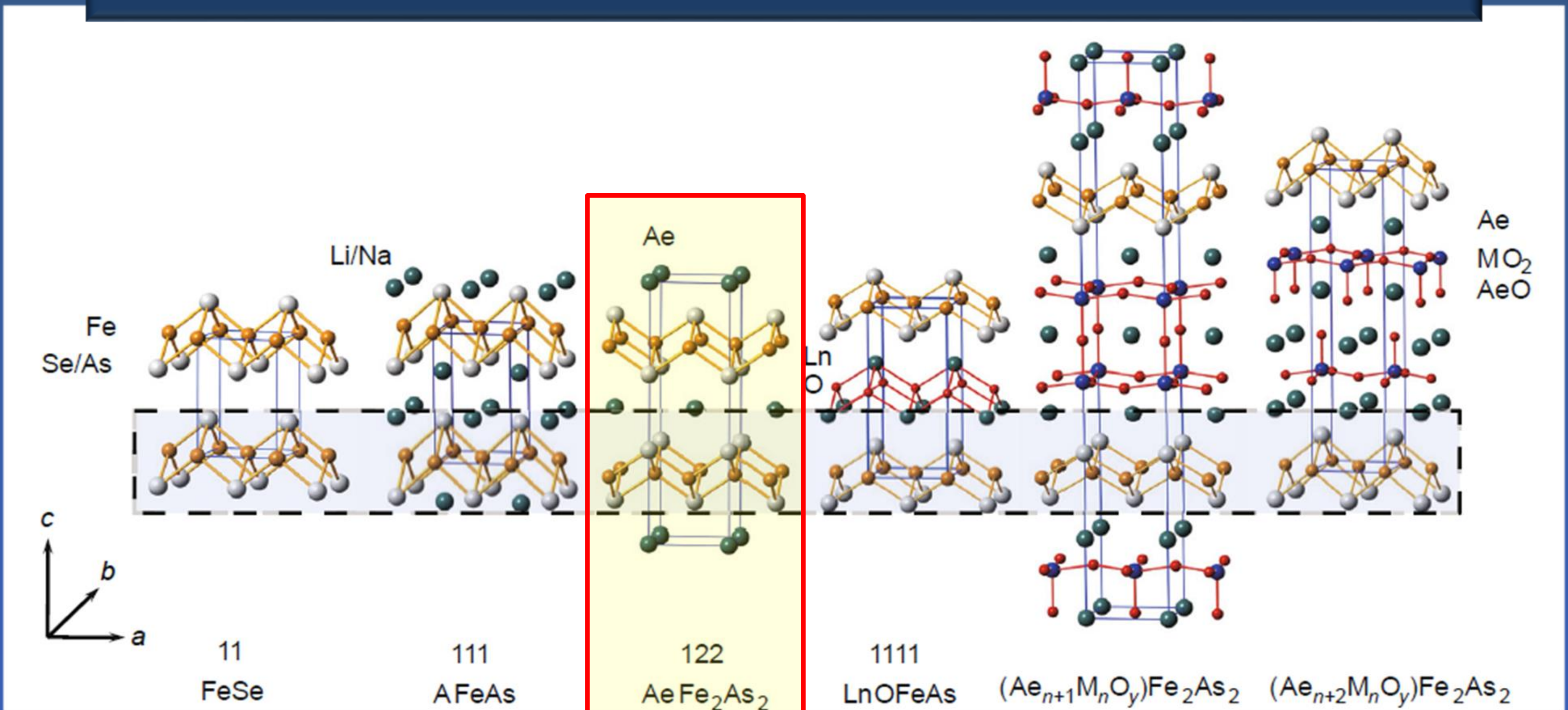
NARODOWE CENTRUM NAUKI

AGH Seminarium Wydziału Fizyki i Informatyki Stosowanej AGH Kraków 18-01-2019

Plan:

1. Podstawowe właściwości $EuFe_2As_2$
2. Wzrost monokryształów z metalicznych topników
3. Diagram fazowy $EuFe_2As_2$
   - wpływ pola magnetycznego
   - wpływ ciśnienia
4. Podstawienia chemiczne w $EuFe_2As_2$
   - domieszkowanie dziurowe – K, Na
   - domieszkowanie elektronowe – La
   - podstawienia izowalencyjne – Ca, Sr, Ba
   - podstawienia izowalencyjne – P
   - podstawienia metalami przejściowymi – Co, Ni, Ir, Ru, Rh…
5. Nadprzewodnictwo i magnetyzm w $EuFe_{2-x}Ni_xAs_2$ - wybrane przykłady
6. Spontaniczne worteksy
7. Poszukiwanie nadprzewodnictwa w $EuFe_{2-x}Ni_xAs_2$

Crystal structure of iron-based superconductors



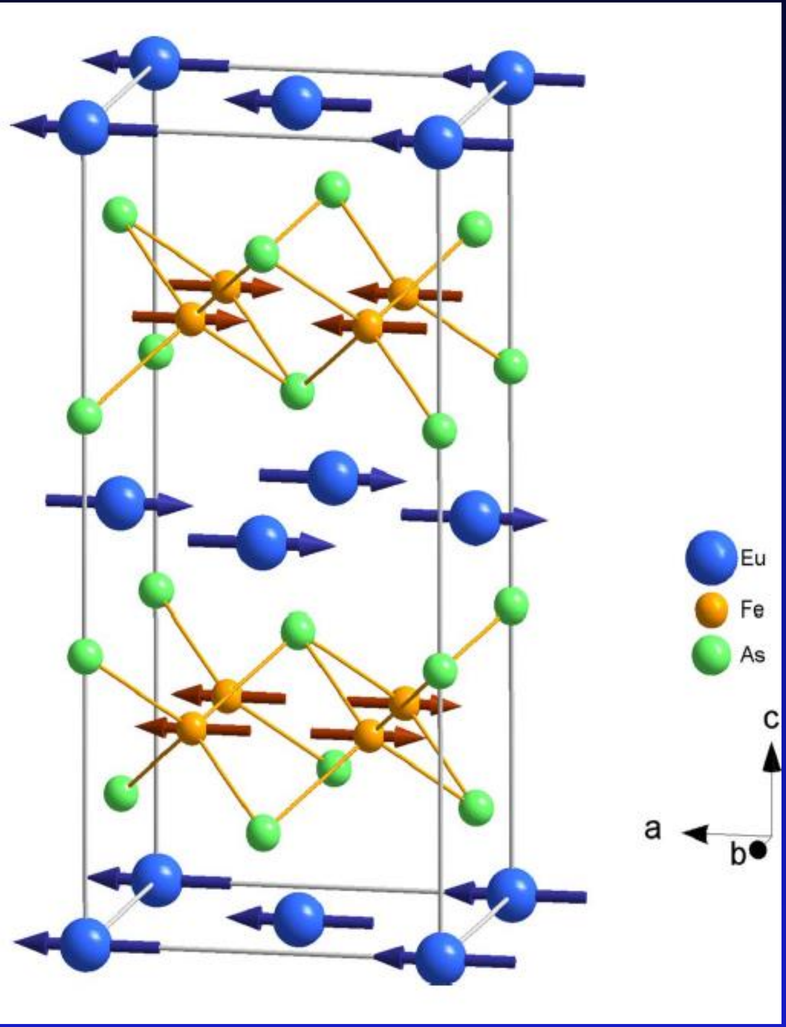
nonsuperconducting parent compounds

$BaFe_2As_2$
$SrFe_2As_2$
$CaFe_2As_2$
$EuFe_2As_2$

KFe_2As_2
$RbFe_2As_2$
$CsFe_2As_2$

low-Tc superconductors

Magnetic structure of $EuFe_2As_2$



Two magnetic sublattices

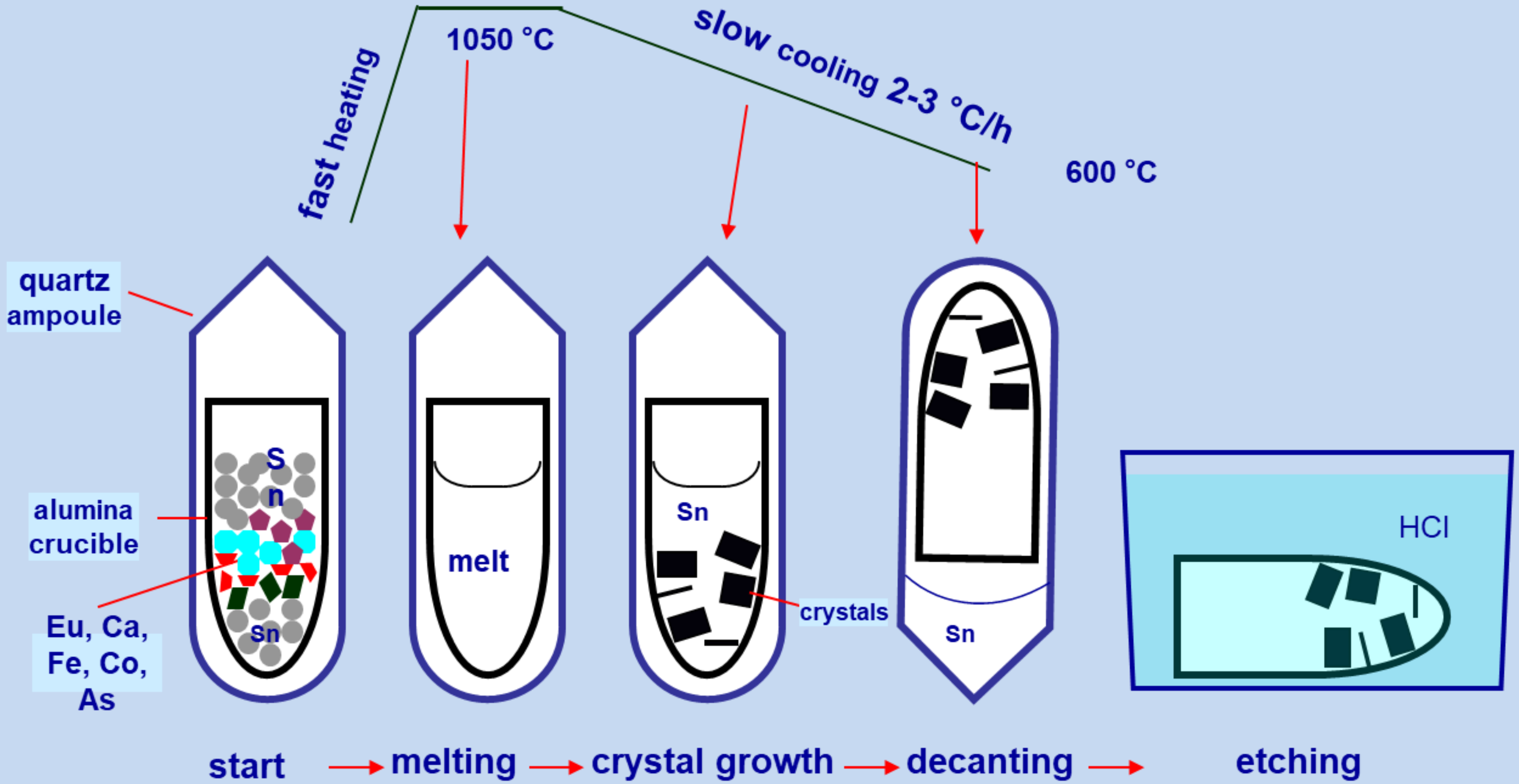
Fe^{2+} 3d itinerant electrons
Spin Density Wave
Fe saturation moment of 0.988 μ_B
aligned along the long *a* axis.
T_{SDW}=190 K

localised Eu^{2+} 4f electrons,
spin S=7/2 μ_{eff}= 7.94 μ_B
RKKY A-type antiferromagnet
T_N=19 K

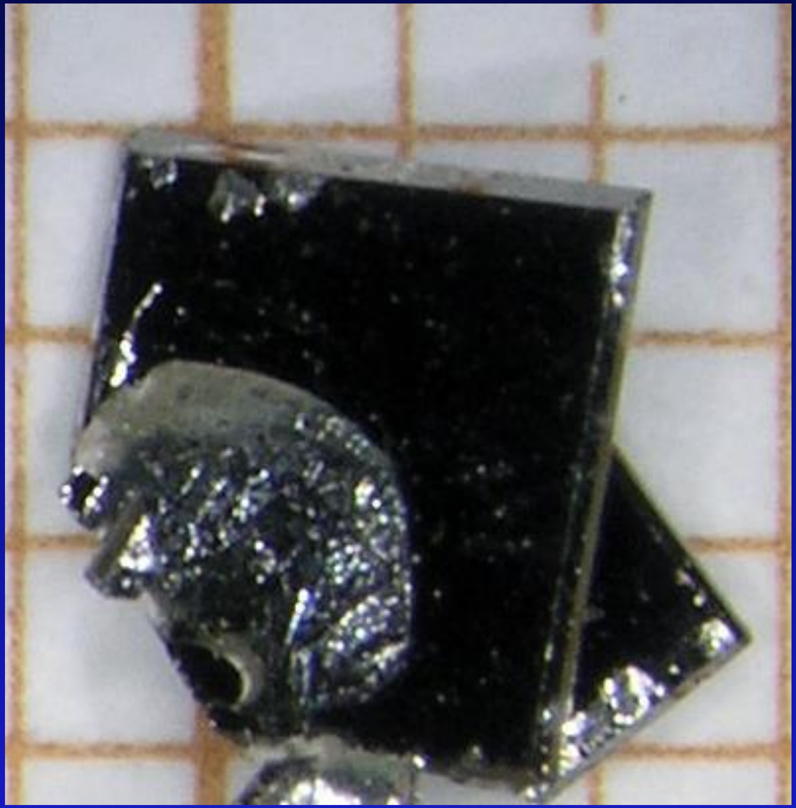
Xiao et al. PRB **80**, 174424 2009

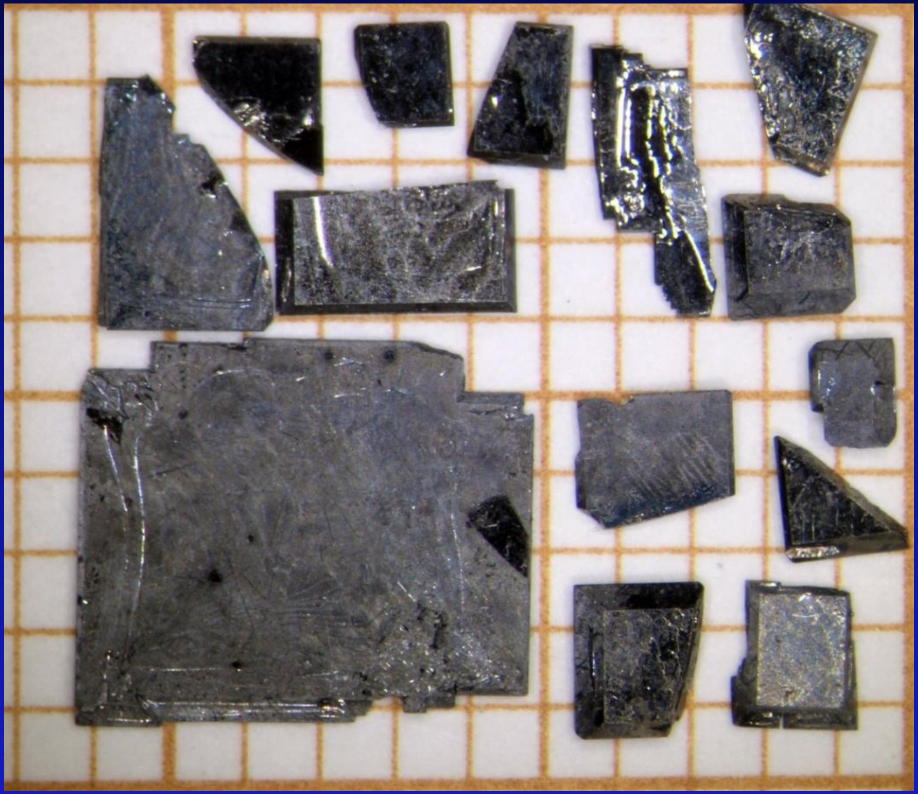
Growth of single crystals from Sn flux

Single crystals of doped $EuFe_2As_2$ with a size up to few millimeters were grown from Sn flux. Starting components: Eu,(Ca), Fe,(Co), As, and Sn were placed in alumina crucibles and sealed in silica tubes under reduced pressure of Ar. The ampoules were heated to 1050°C and slowly cooled down to 600°C, when liquid tin was decanted.



Single crystals grown from Sn flux

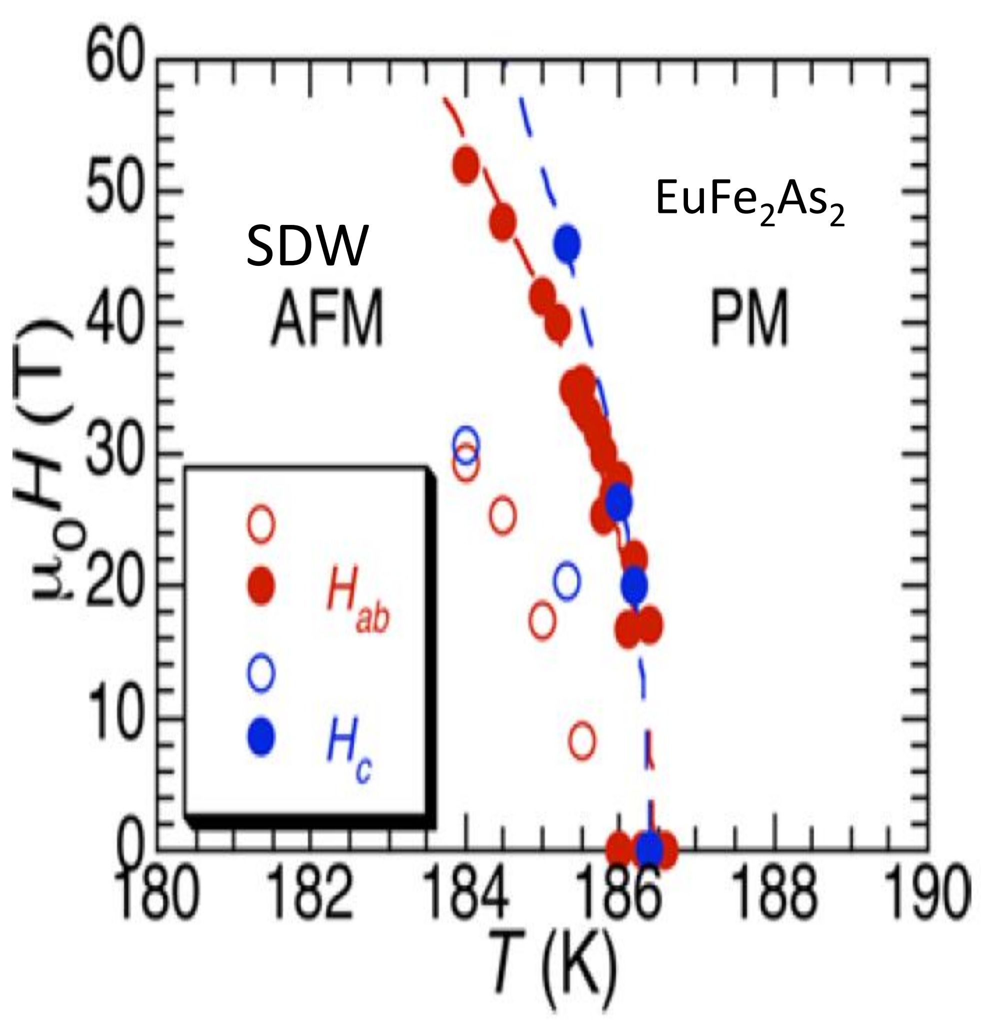




$EuFe_2As_2$

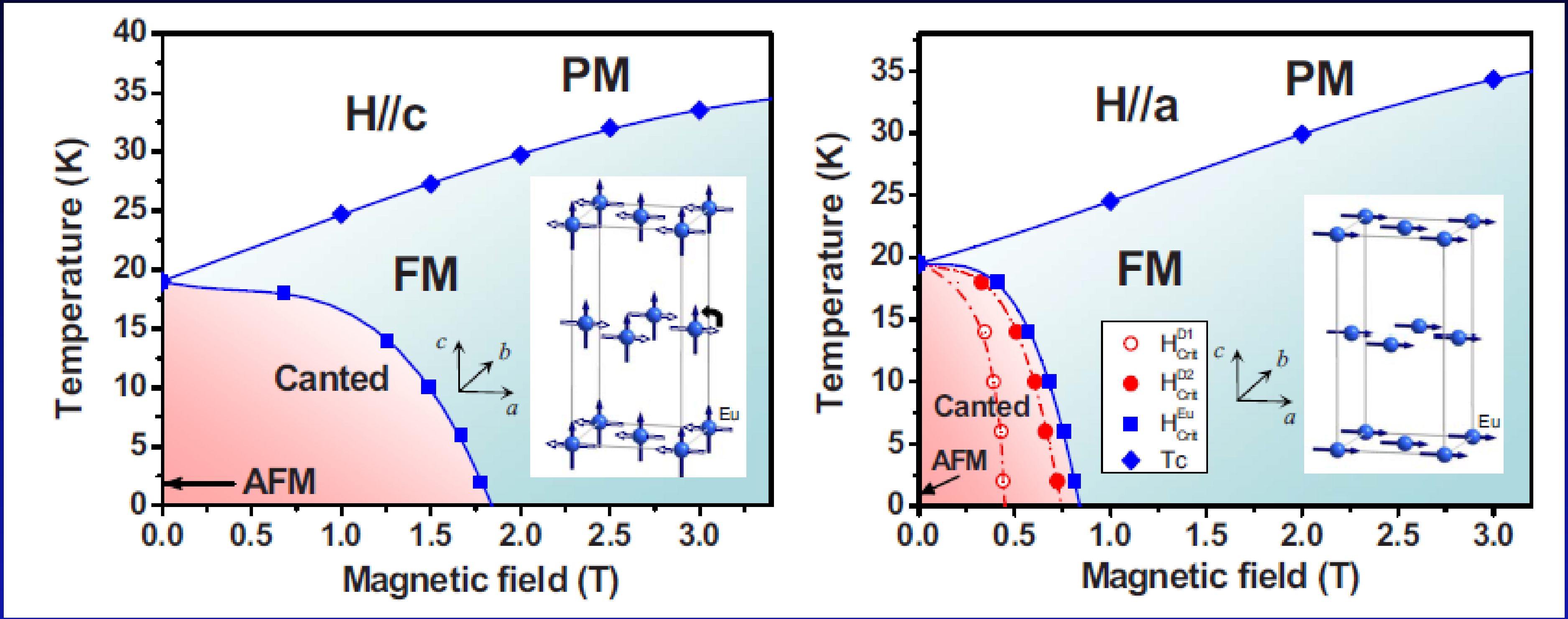
Effect of magnetic field on SDW ordering

Tokunaga et al. J. Low Temp. Phys. 159 (2010) 601



Simple extrapolation suggests that an **extremely high field (>500 T) is needed to suppress the AFM state** at low temperatures.

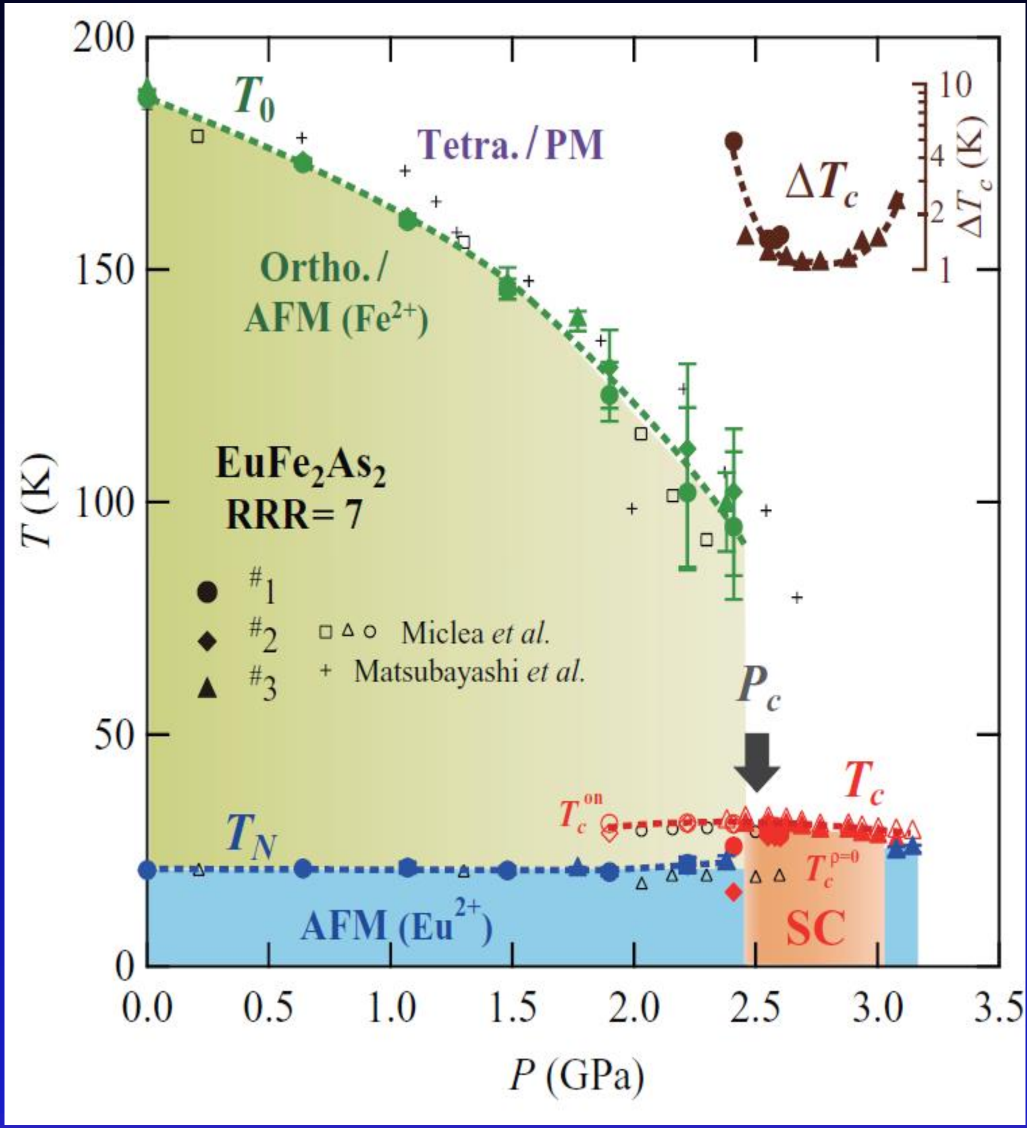
Effect of magnetic field on magnetic order in $EuFe_2As_2$



Xiao et al.PRB **81**, 220406R (2010)

- spin canting
- metamagnetic transitions
- field induced ferromagnetism

Effect of pressure



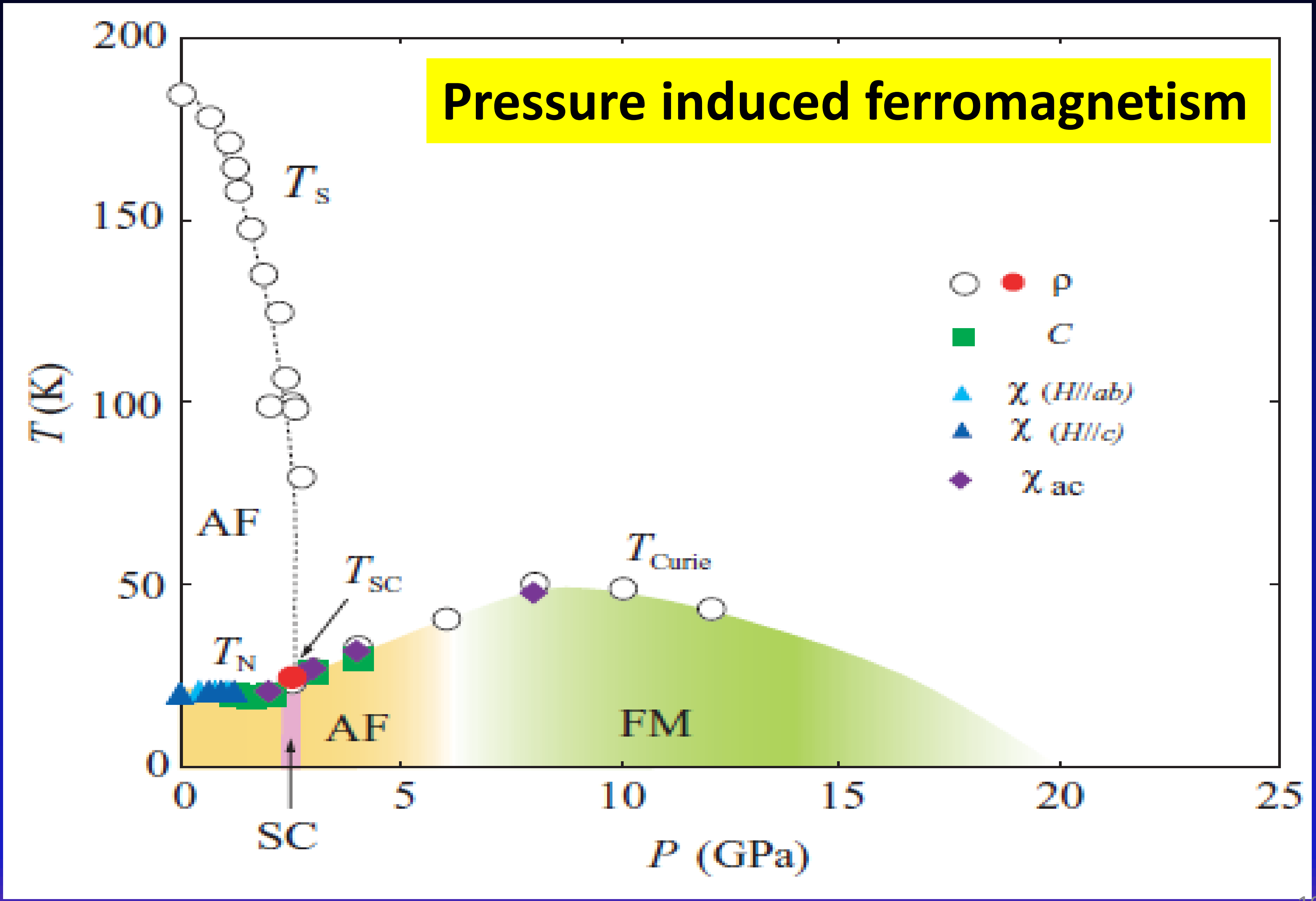
Pressure-suppressed SDW order

Persistent Eu^{2+} magnetic order

Pressure-induced superconductivity

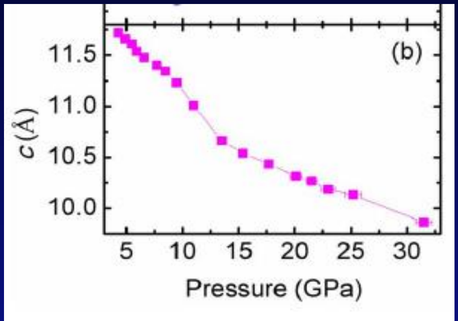
Kurita *et al.* PRB **83**, 214513 (2011)

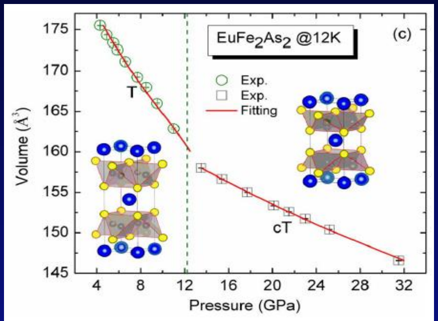
Effect of pressure

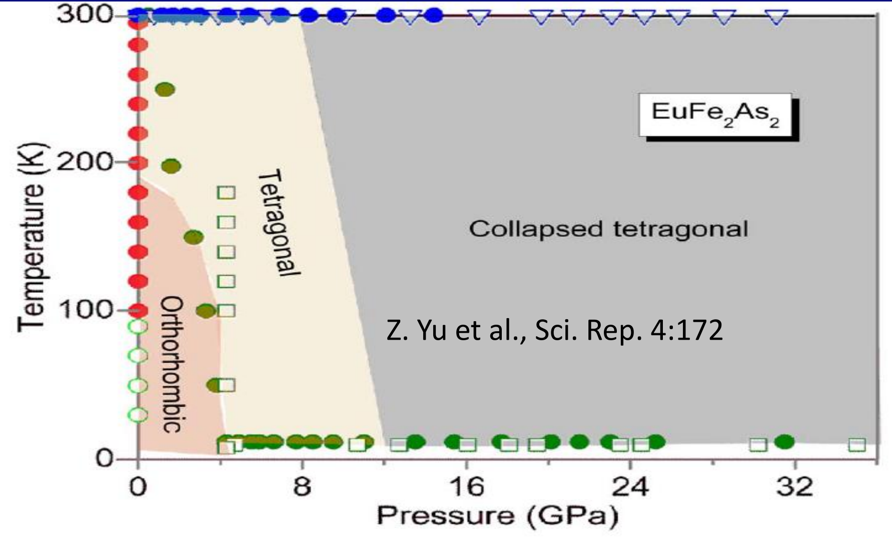


K. Matsubayashi et al., PRB 84, 024502 (2011)

Effect of pressure on $EuFe_2As_2$ crystal structure

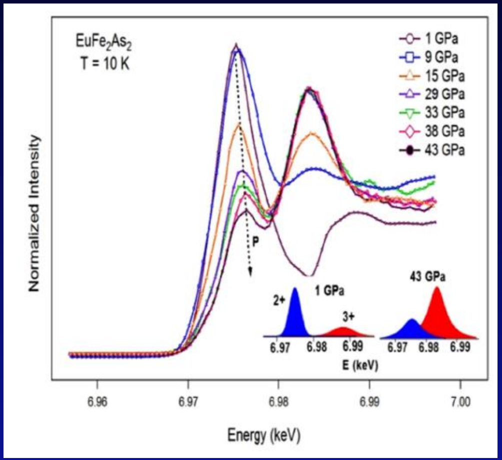






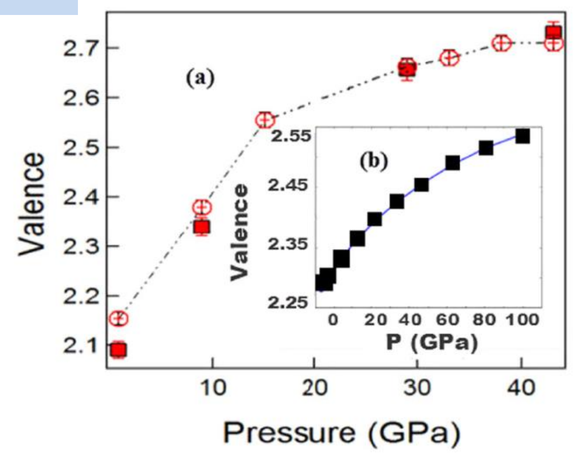
Pressure induced tetragonal-”collapsed tetragonal” phase transition

Effect of pressure on Eu-ion valence in $EuFe_2As_2$



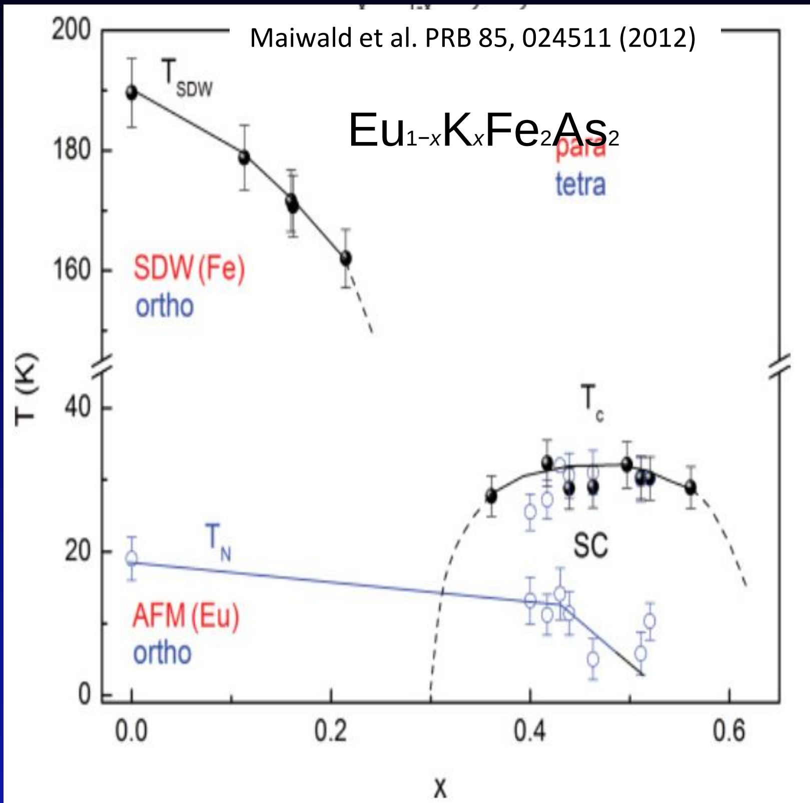
X-ray absorption spectra

Kumar et al. Appl. Phys. Lett. 104, 042601 (2014)

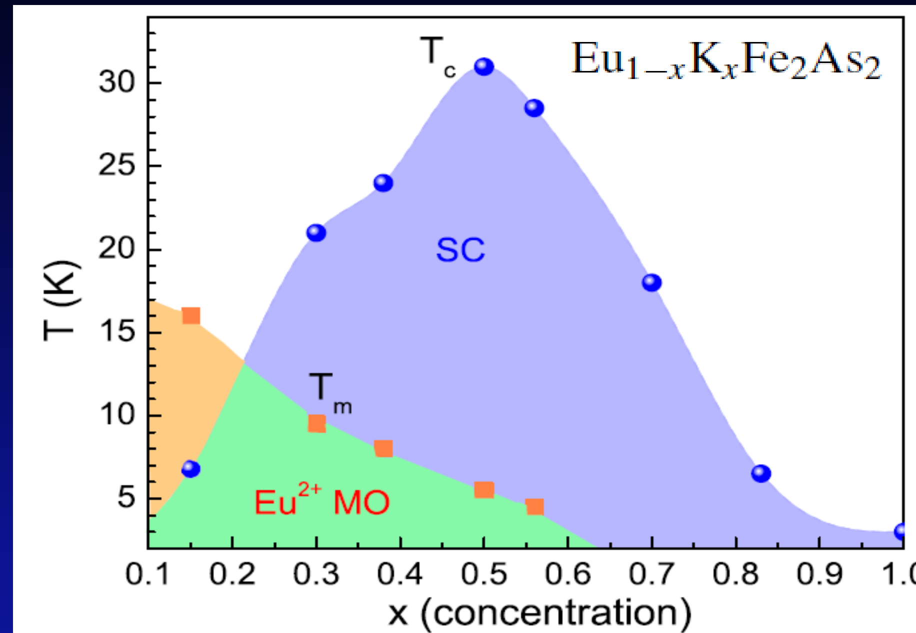


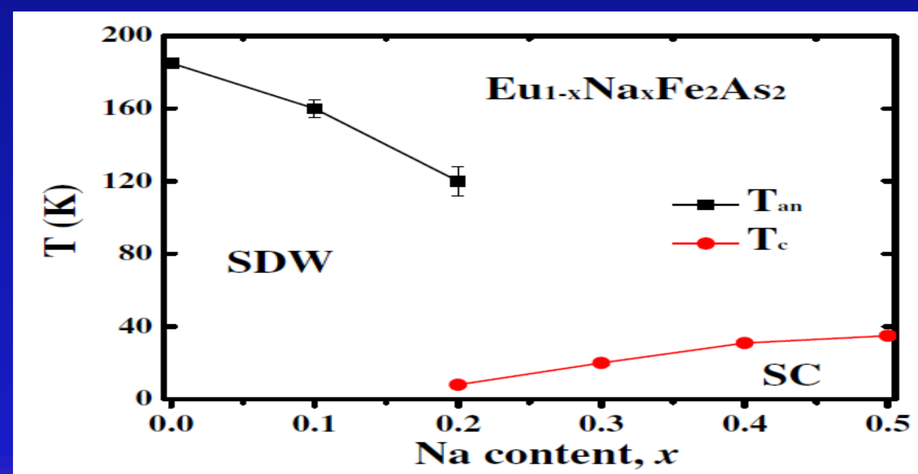
Conversion of Eu^{2+} to Eu^{3+} under pressure

K, Na-substitution



Anupam et al. J. Phys.: Condens. Matter 23 (2011) 455702





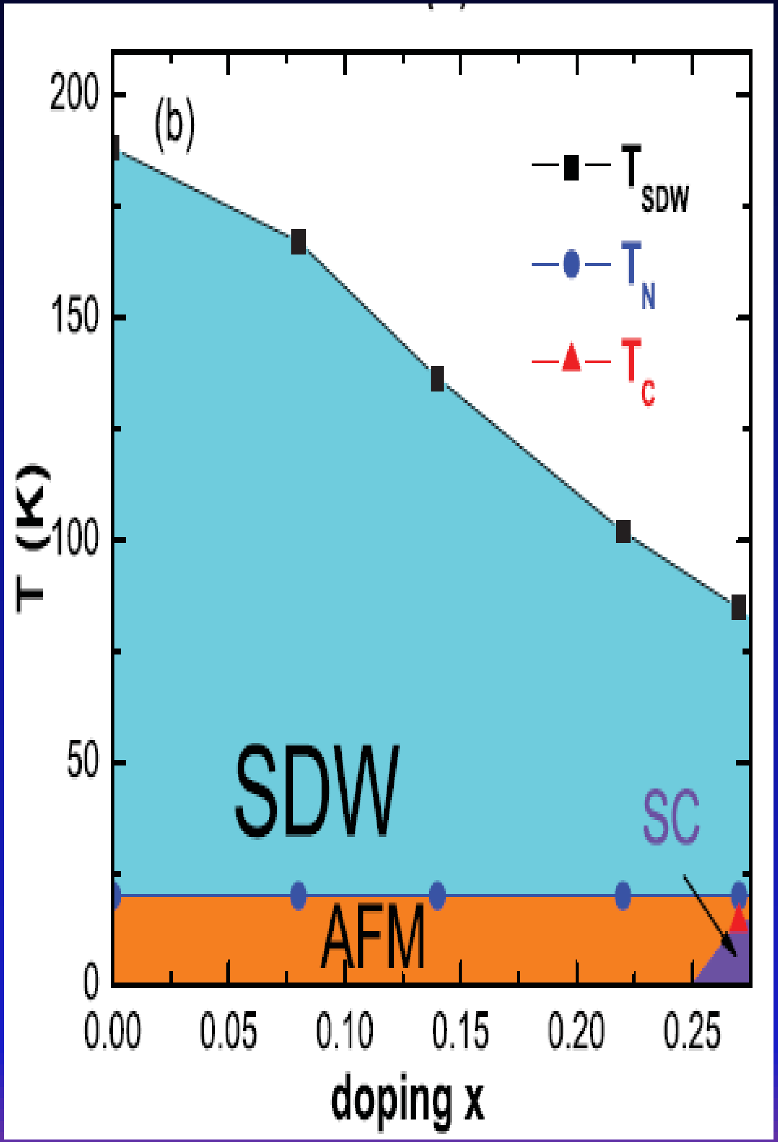
Y.Qi et al. , *New Journal of Physics* **14** (2012) 033011

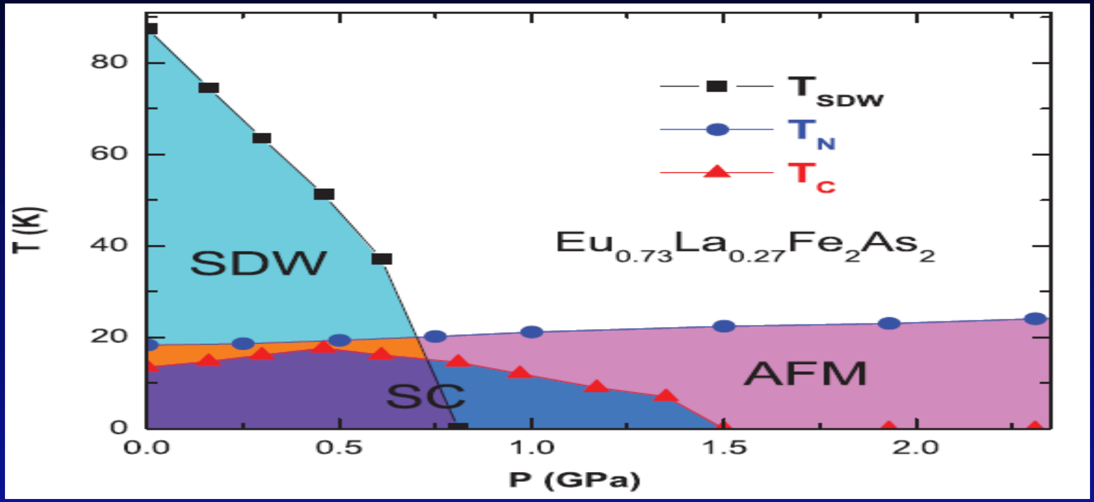
hole doping:

- SDW is suppresed
- Eu^{2+} AF order disappears
- appearence of superconductivity

La-substitution

M. Zhang et al., PRB 85, 092503 (2012)



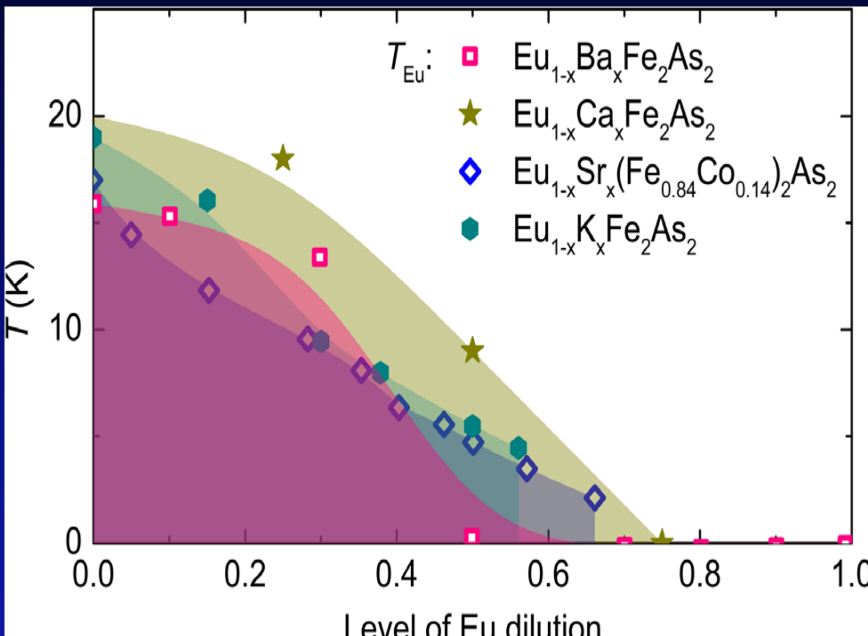


Electron doping:

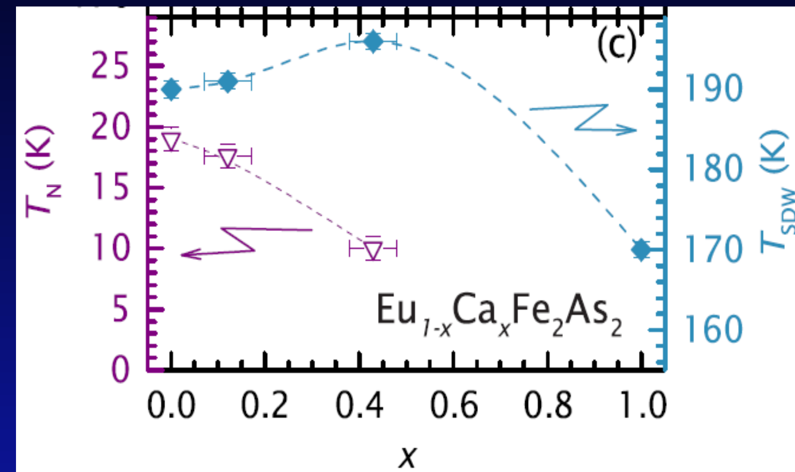
- SDW suppression
- superconductivity

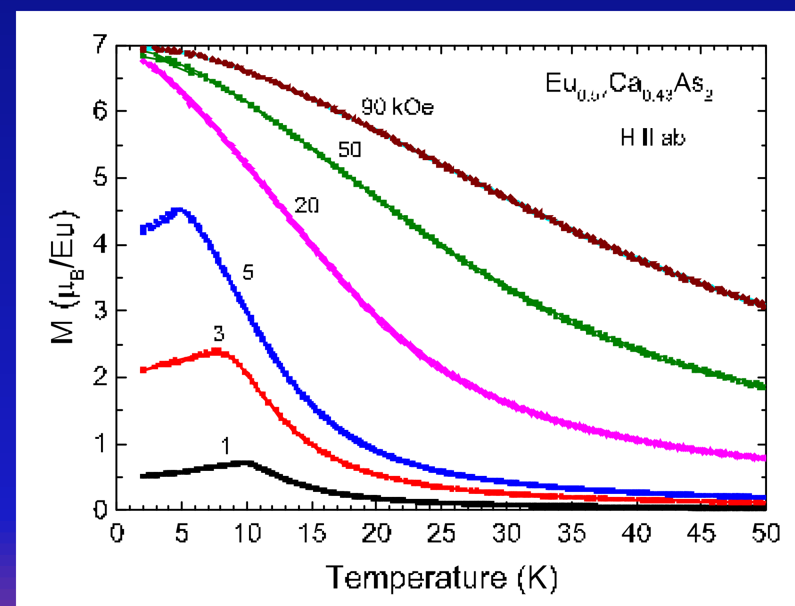
Dilution of Eu-sublattice with nonmagnetic ions

Zapf and Dressel, Rep. Prog. Phys. **80** (2017) 016501



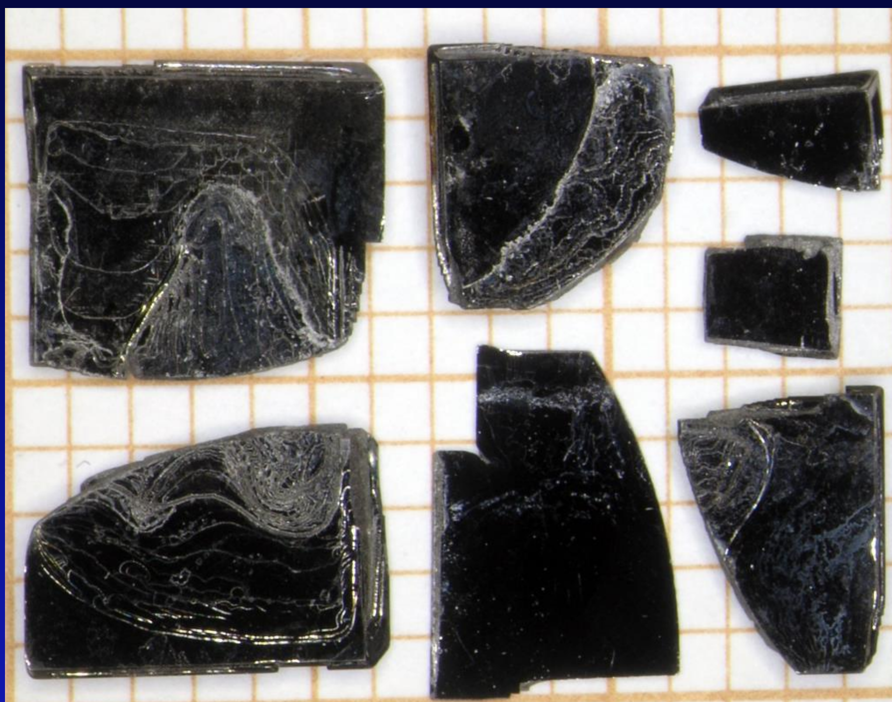
*L. M. Tran et al. PRB **98**, 104412 (2018)*



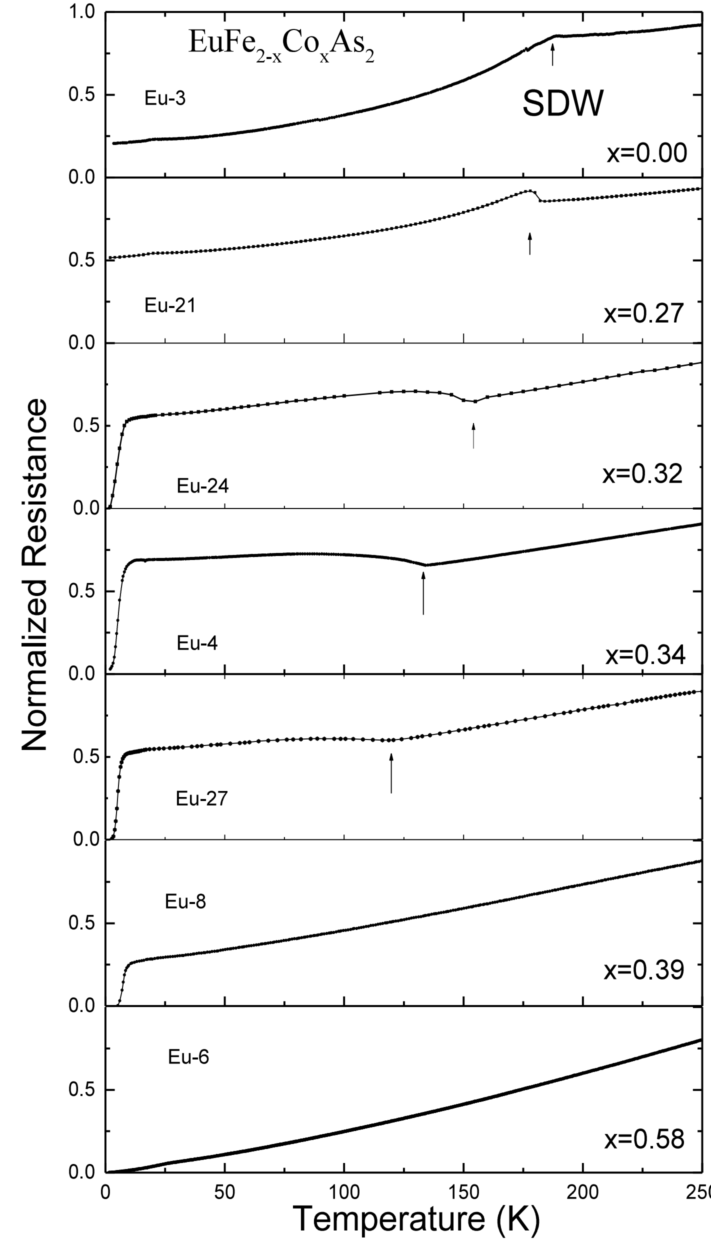


- Disappearance of magnetic order of Eu^{2+}
- SDW order remains intact

Co-substitution: $EuFe_{2-x}Co_xAs_2$



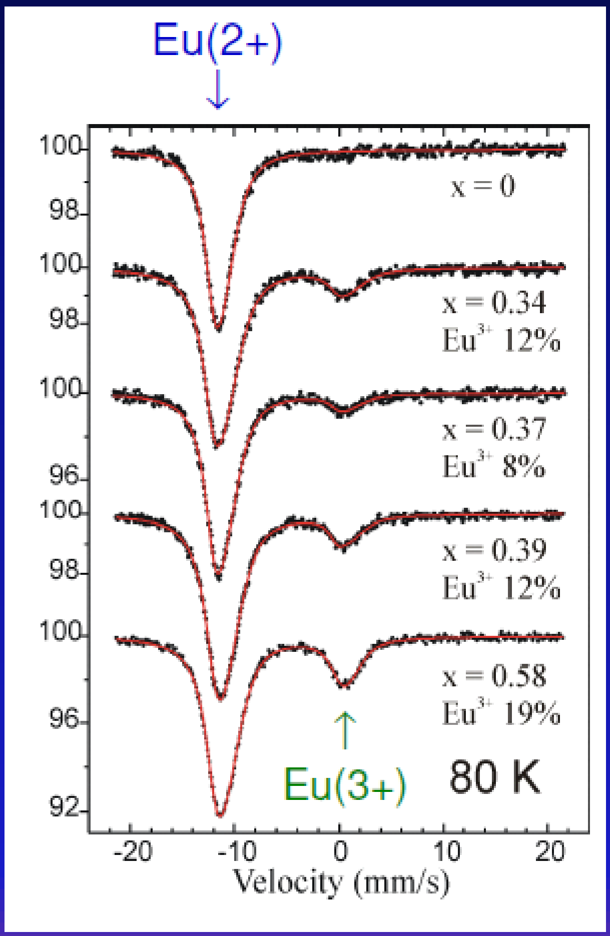
Single crystals of $EuFe_{2-x}Co_xAs_2$ grown from Sn flux

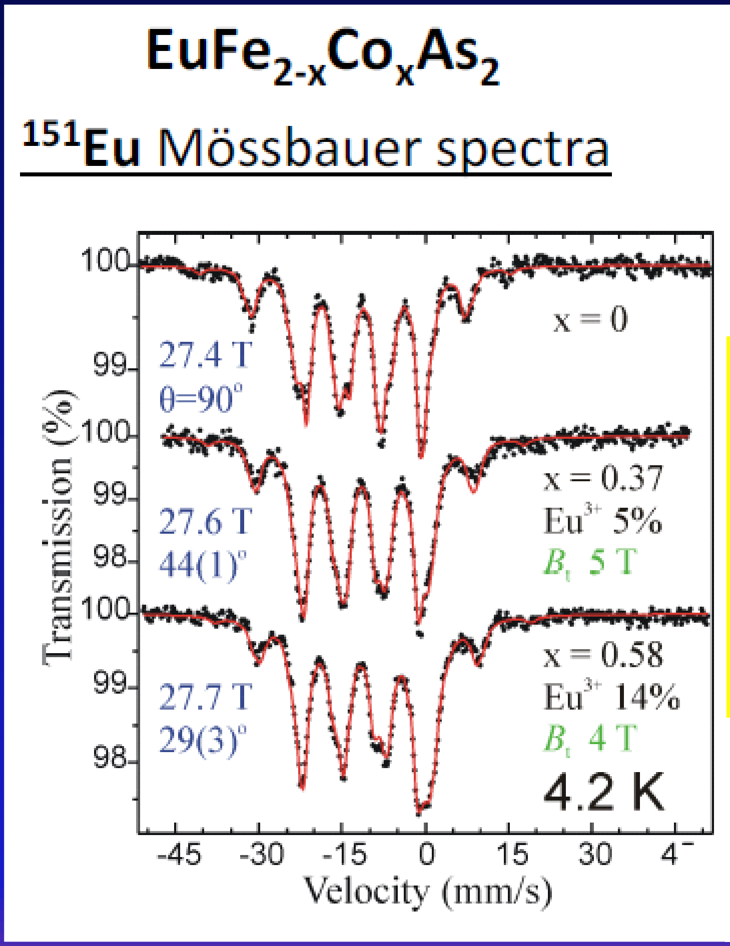


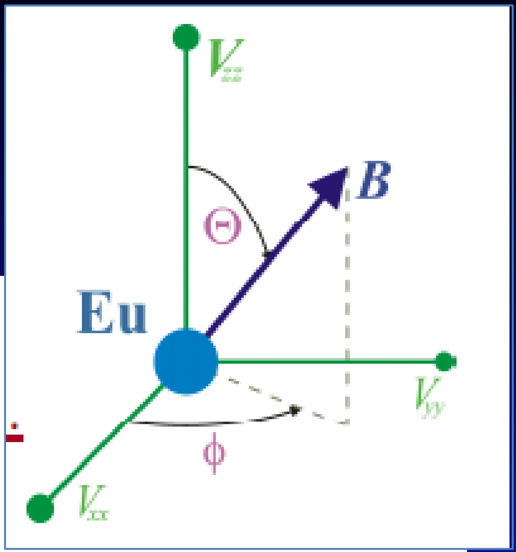
Electrical resistivity

Mössbauer spectroscopy of $EuFe_{2-x}Co_xAs_2$

A.Błachowski et al., Phys. Rev. B **84**, 174503 (2011)

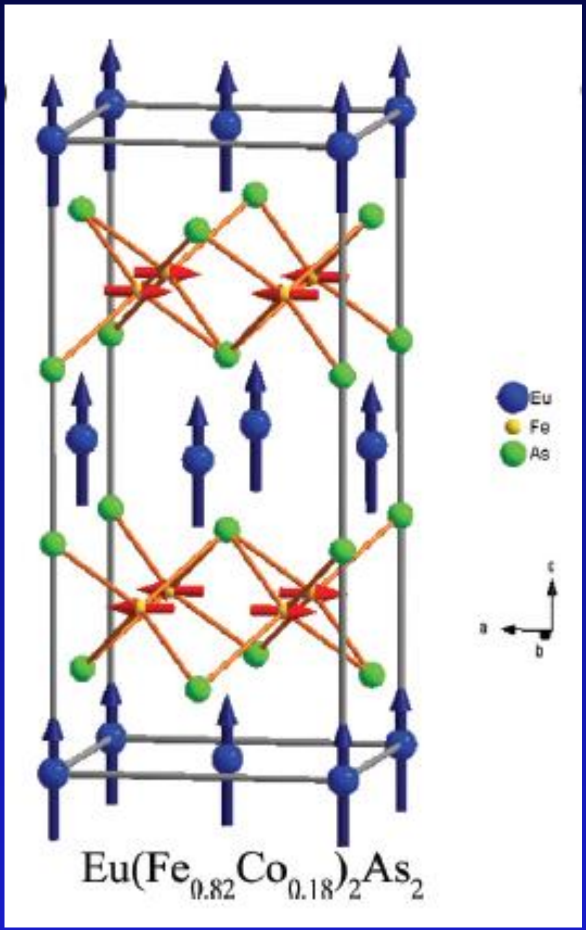






Eu^{2+} moments rotate from ab-plane toward c-axis direction

Magnetic structure of $Eu(Fe_{0.82}Co_{0.18})_2As_2$ (single-crystal neutron diffraction)



long-range ferromagnetic order of the Eu^{2+} moments along the *c* direction

T_C = 17 K

no incommensurate magnetic reflections corresponding to the helical arrangement of the Eu^{2+} spins are observed

Antiferromagnetism of the Fe^{2+} moments still survives

tetragonal-to-orthorhombic structural transition is observed

transition temperatures of the Fe spin-density-wave (SDW) order and the structural phase transition are significantly suppressed to T_{SDW} = 70 K and T_S = 90 K

Superconducting T_{SC}=8 K

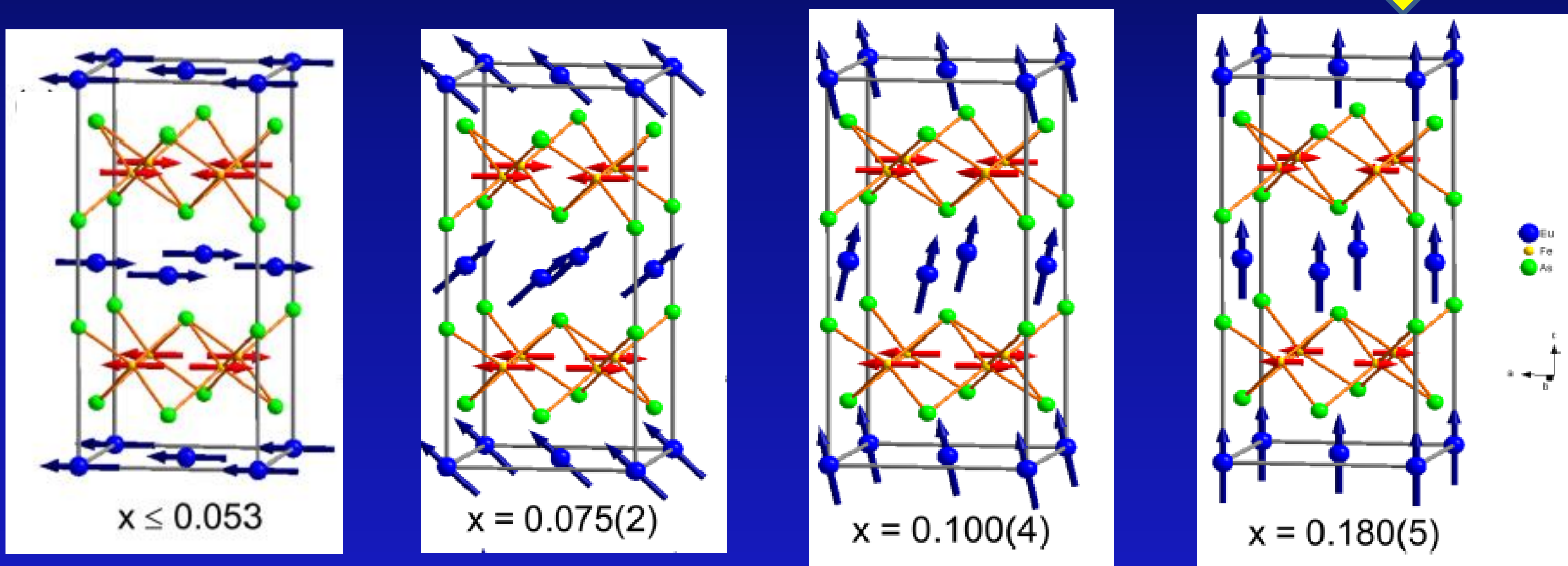
Jin et al., Phys.Rev. B 88, 214516 (2013)

Effect of Co-doping on Eu^{2+} magnetic ordering in $Eu(Fe_{1-x}Co_x)_2As_2$ single crystals

Neutron diffraction

- ferromagnetic Eu^{2+} moment of $6.2\mu_B$ purely along the c direction
- Fe^{2+} moment is estimated to be $0.63(4)\ \mu_B$

W. T. Jin et al., Phys. Rev. B **94**, 184513 (2016)



Co concentration x →

A-type antiferromagnet → **canted AF** → **ferromagnet**

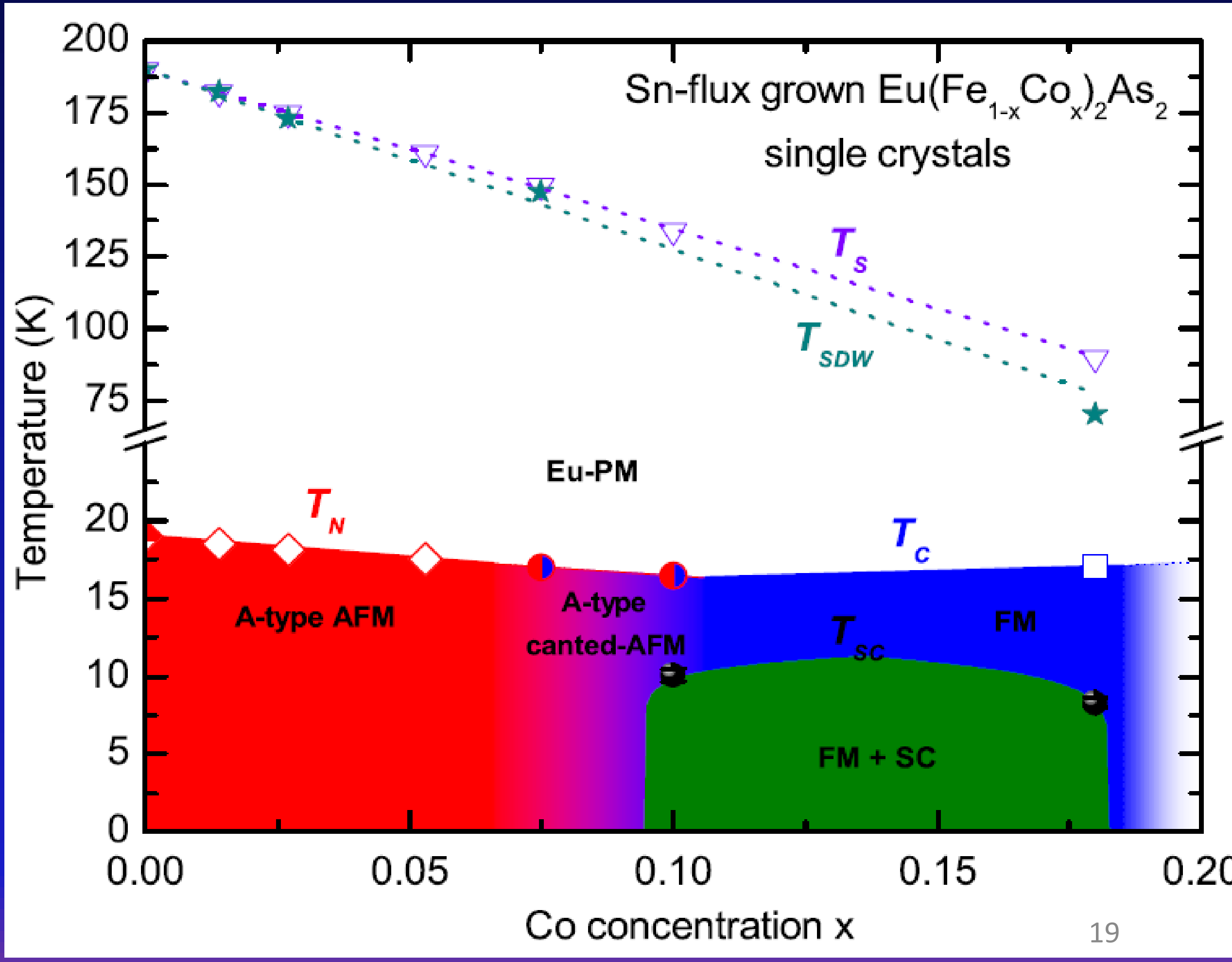
Magnetic phase diagram of $Eu(Fe_{1-x}Co_x)_2As_2$
(Sn-flux-grown single crystals)

W. T. Jin et al., PRB **94**, 184513 (2016)

suppression of SDW order

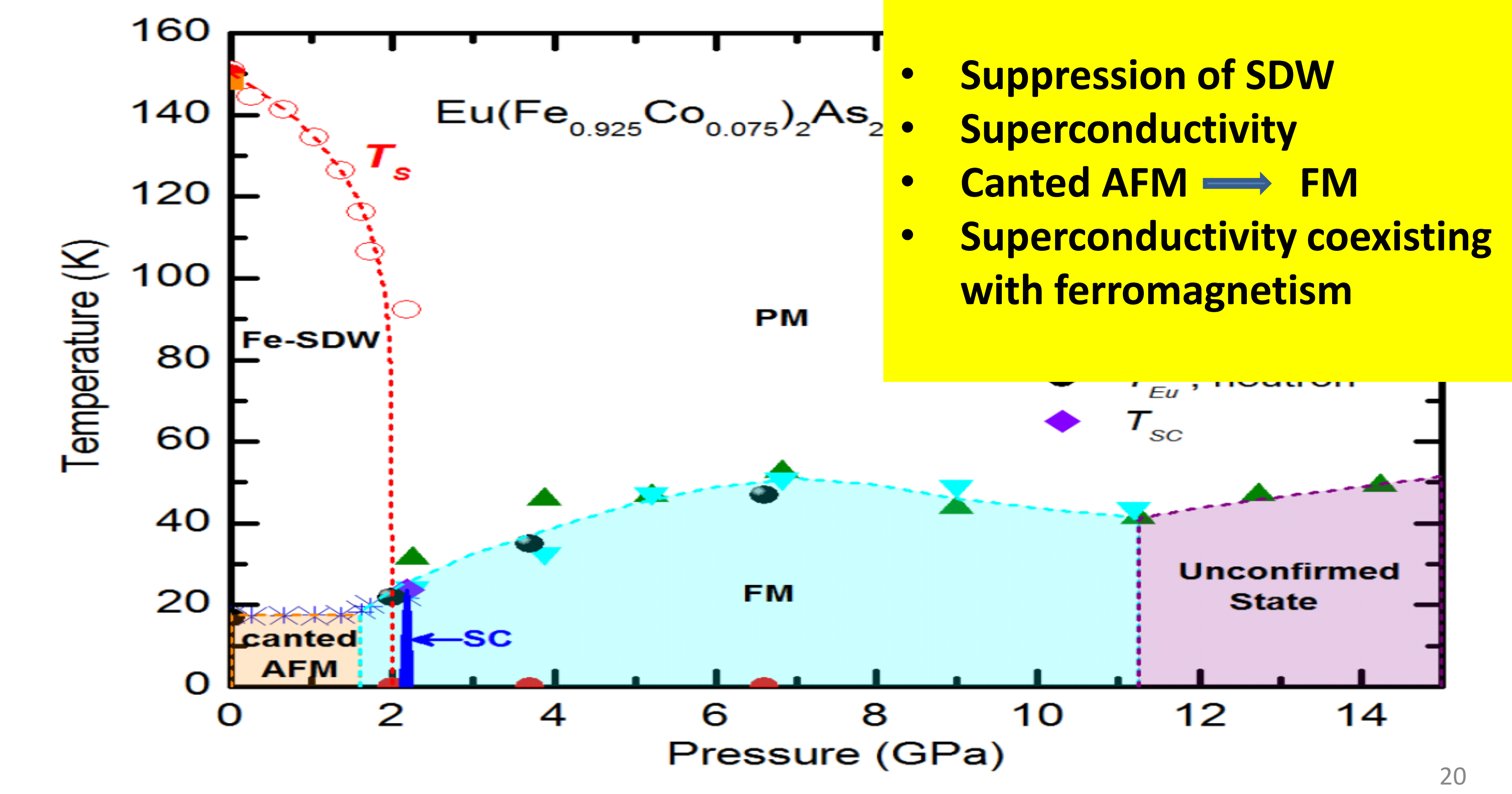
superconductivity competes with Fe SDW antiferromagnetic order

superconductivity coexists with Eu ferromagnetism



Hydrostatic pressure effects on the static magnetism in $Eu(Fe_{0.925}Co_{0.075})_2As_2$

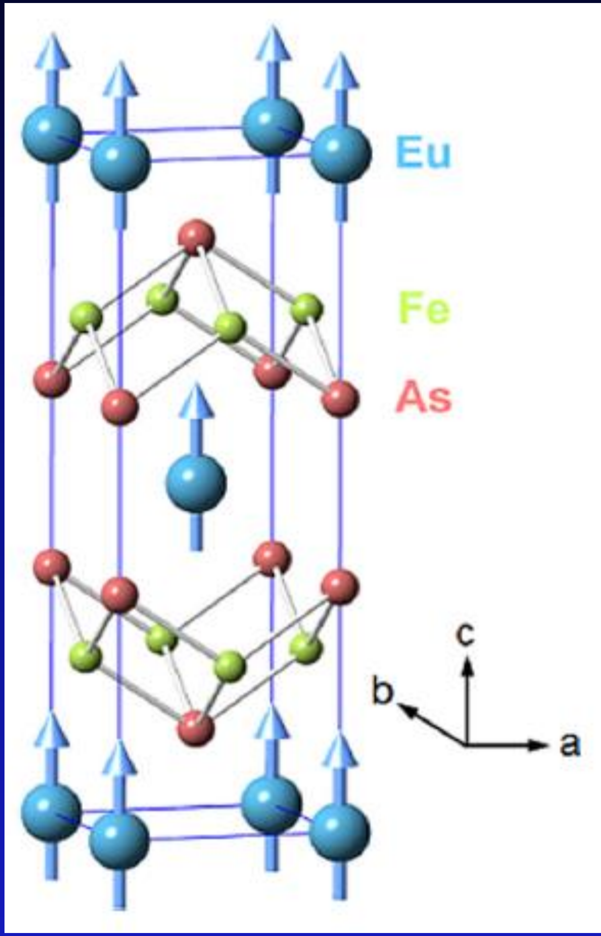
W. T. Jin et al., Scientific Reports | 7: *3532* |

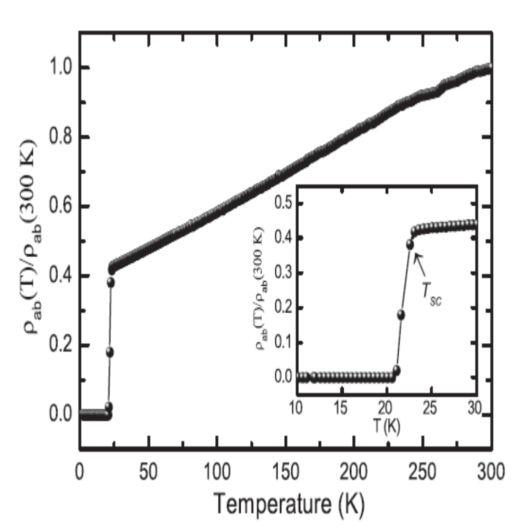


- **Suppression of SDW**
- **Superconductivity**
- **Canted AFM ⟹ FM**
- **Superconductivity coexisting with ferromagnetism**

Ferromagnetic $Eu(Fe_{0.86}Ir_{0.14})_2As_2$

*V. K. Anand et al., PRB **91** 094427 (2015)*



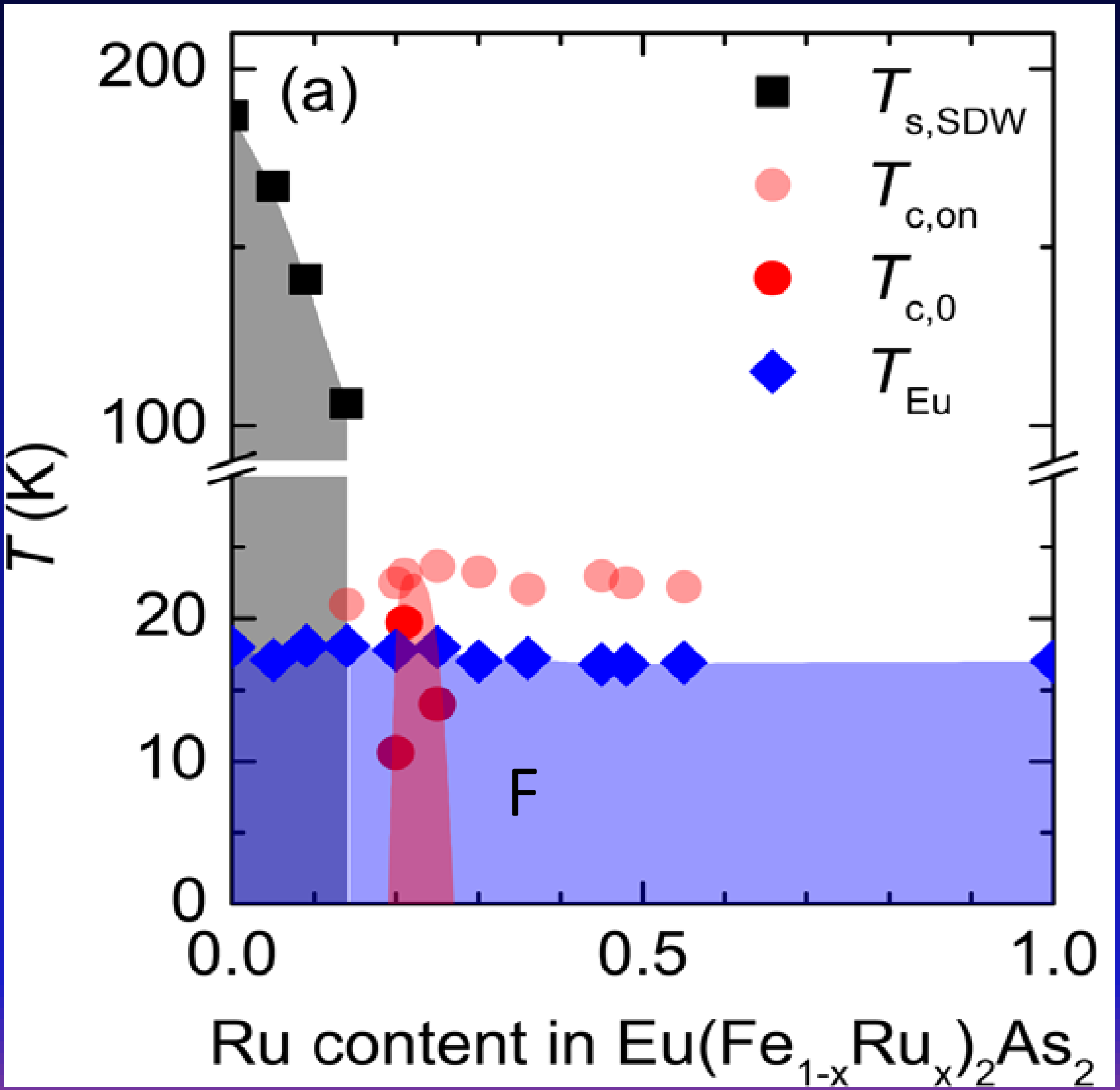


The body centered tetragonal chemical and magnetic unit cell (space group I4/mmm).

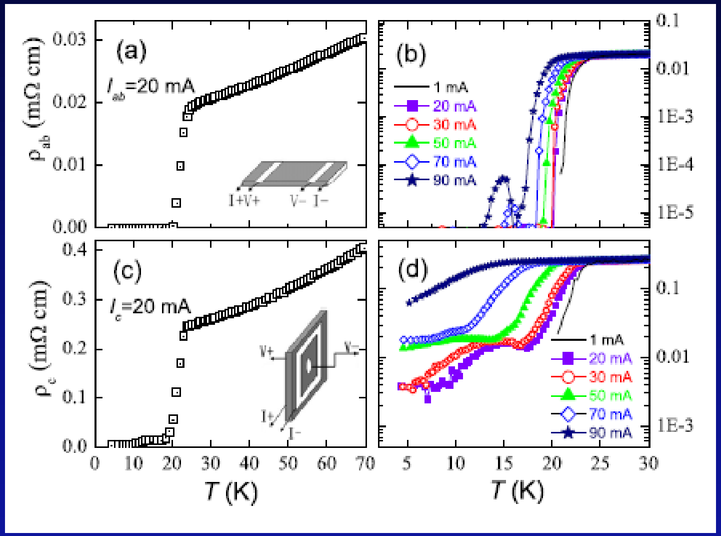
ferromagnetically coupled Eu moments are aligned along the c axis with a magnetic propagation wave vector k = (0, 0, 0) and ordered moment of 6.29(5) μ_B at 1.8 K.

$Eu(Fe_{0.75}Ru_{0.25})_2As_2$ ferromagnetic superconductor

Jiao et al., J. Phys.: Conf. Ser. 400 (2012) 022038



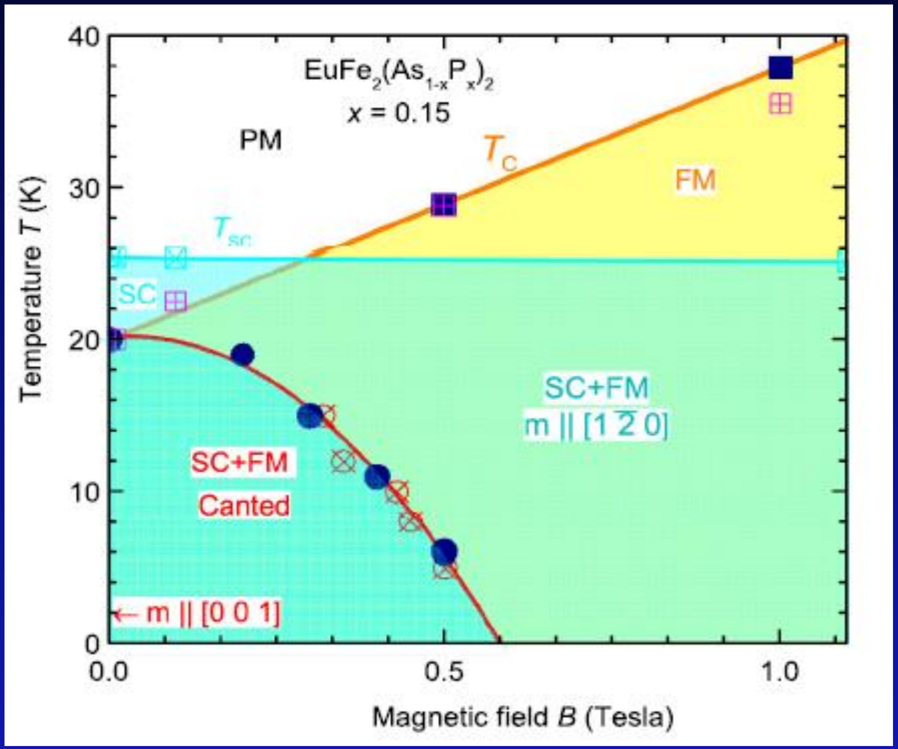
Jiao et al., EPL, 95 (2011) 67007



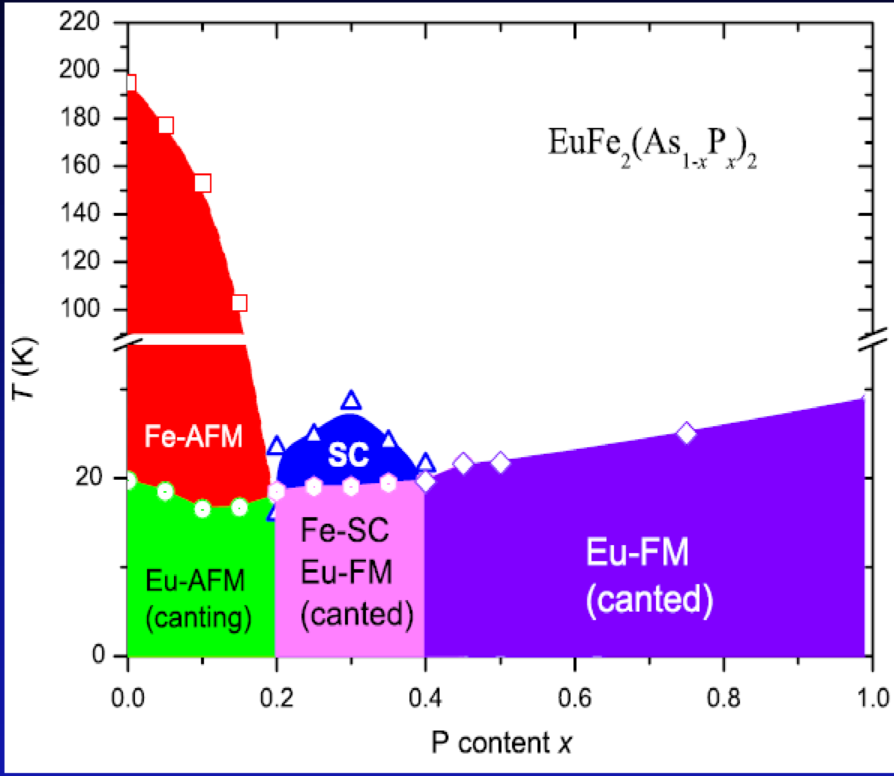
T_{SC} =23 K
Mossbauer data indicate that the Eu^{2+} spins order ferromagnetically below 19.5 K with the moments tilted 20° from the c-axis.

Isovalent P-substitution $EuFe(As_{1-x}P_x)_2$

Nandi et al., PRB **89**, 014512 (2014)



Cao et al. J. Phys.: Condens. Matter 23 (2011) 464204

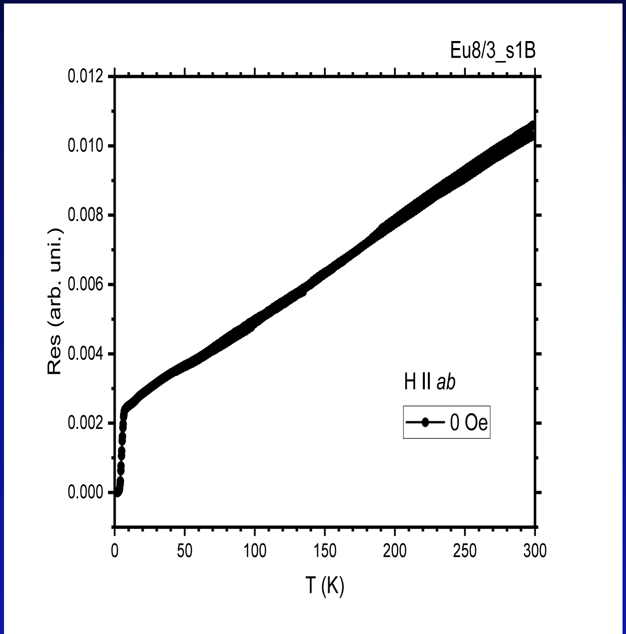


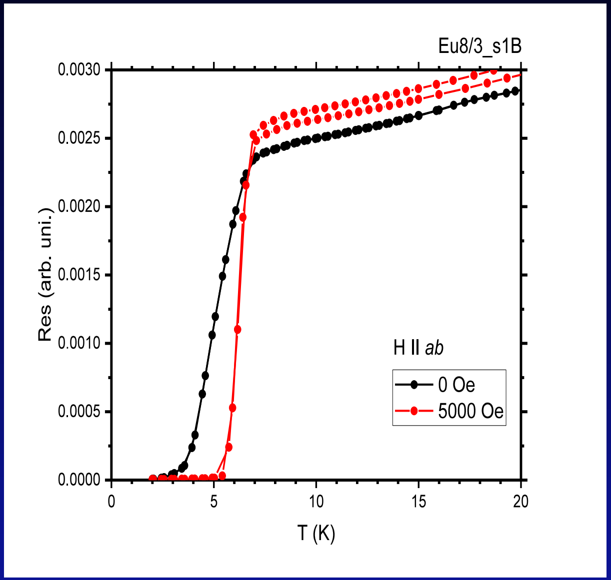
Superconductivity induced by partial substitution of P into As positions

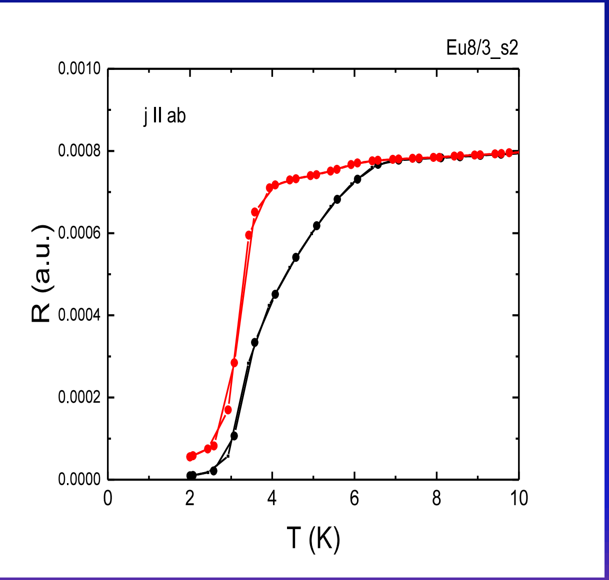
AFM ⟹ Ferromagnetism

Superconductivity coexists with ferromagnetism

Peculiar properties of Sn-flux-grown $Eu(Fe_{0.81}Co_{0.19})_2As_2$ single crystals

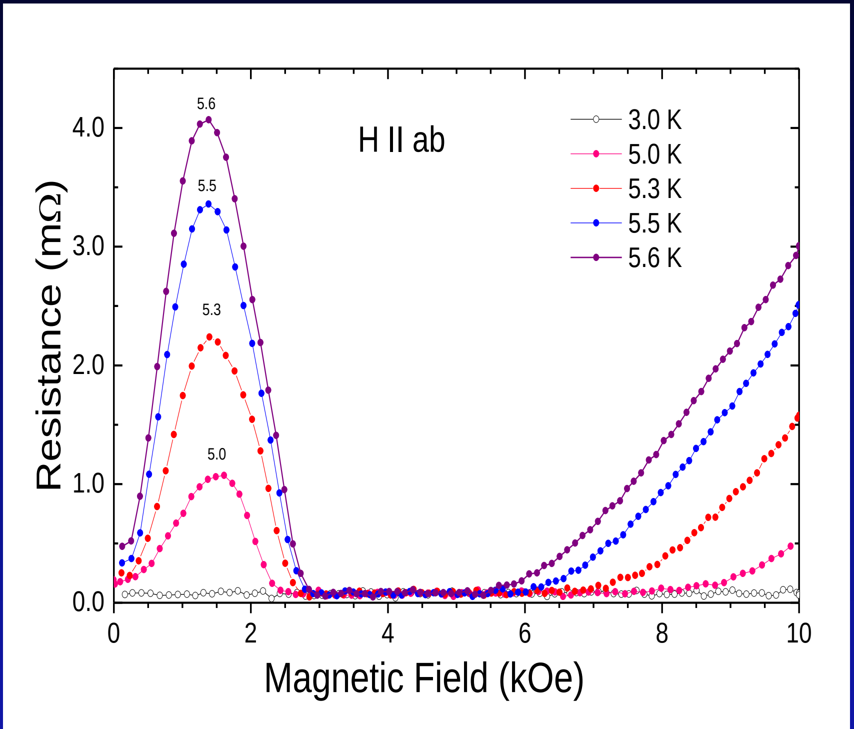


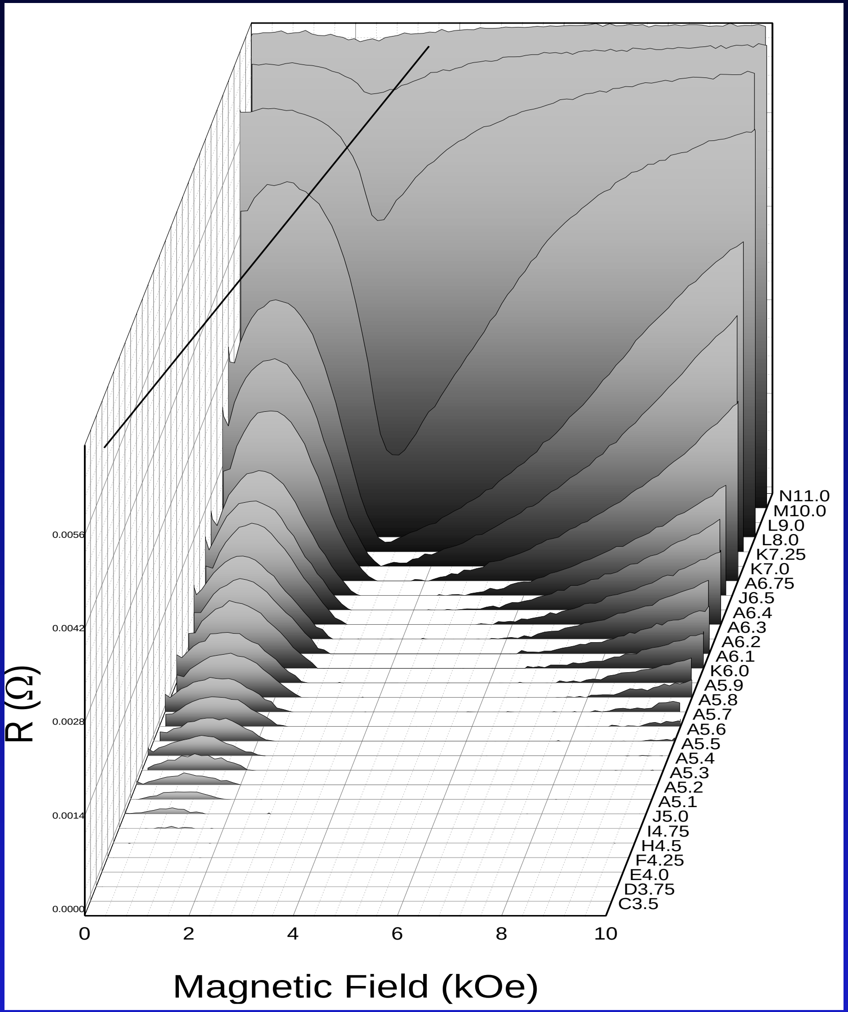




Magnetic field enhancement of superconductivity ?!

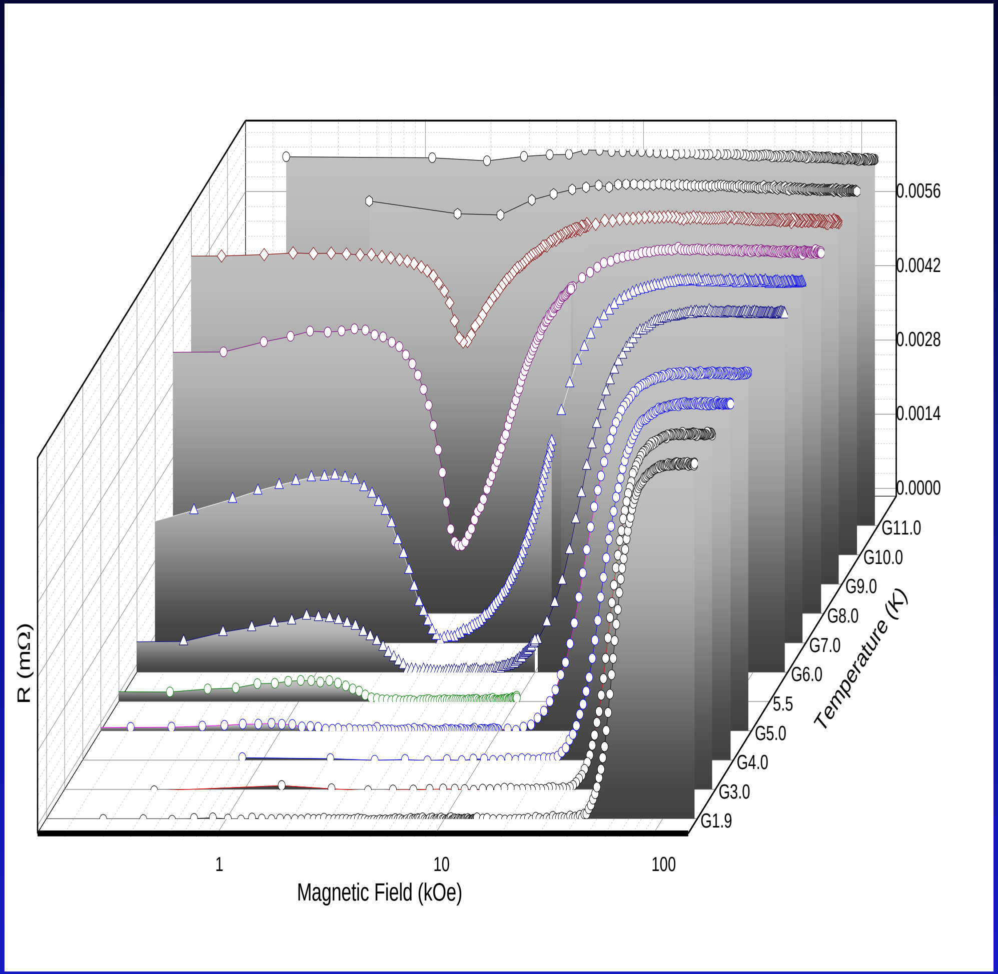
Peculiar properties of Sn-flux-grown $Eu(Fe_{0.81}Co_{0.19})_2As_2$ single crystals

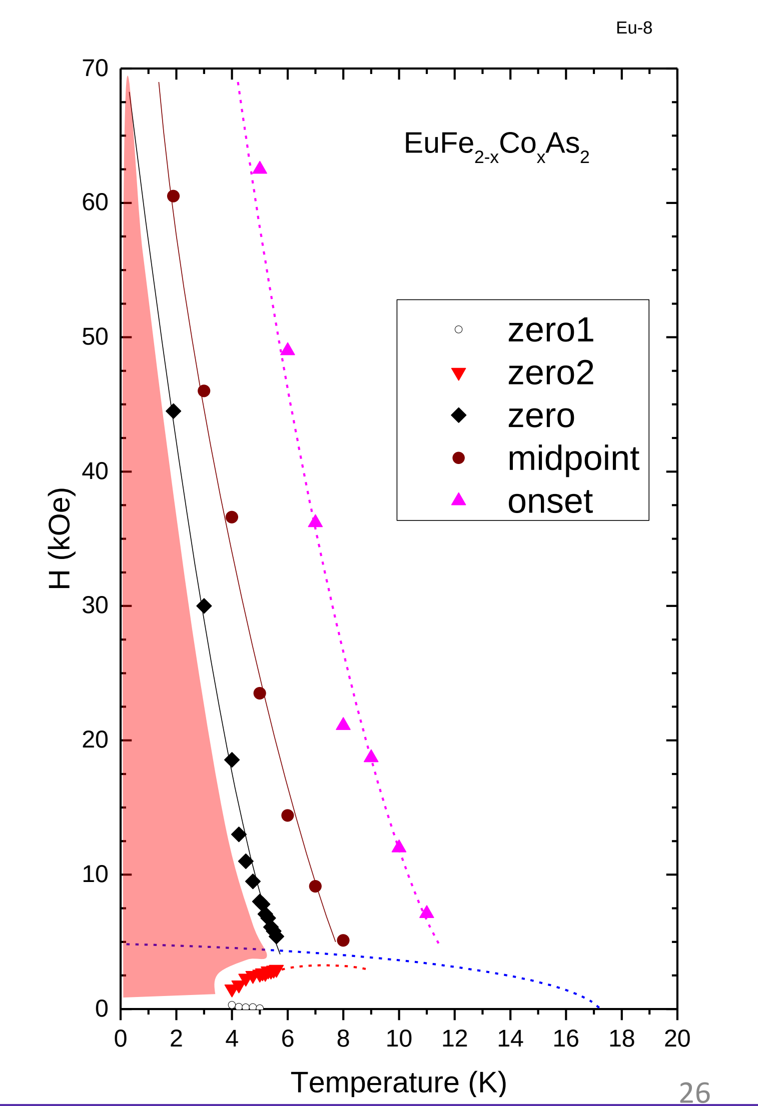




Resistivity „peak” most likely corresponds to the flux flow effect

Peculiar properties of Sn-flux-grown $Eu(Fe_{0.81}Co_{0.19})_2As_2$ single crystals

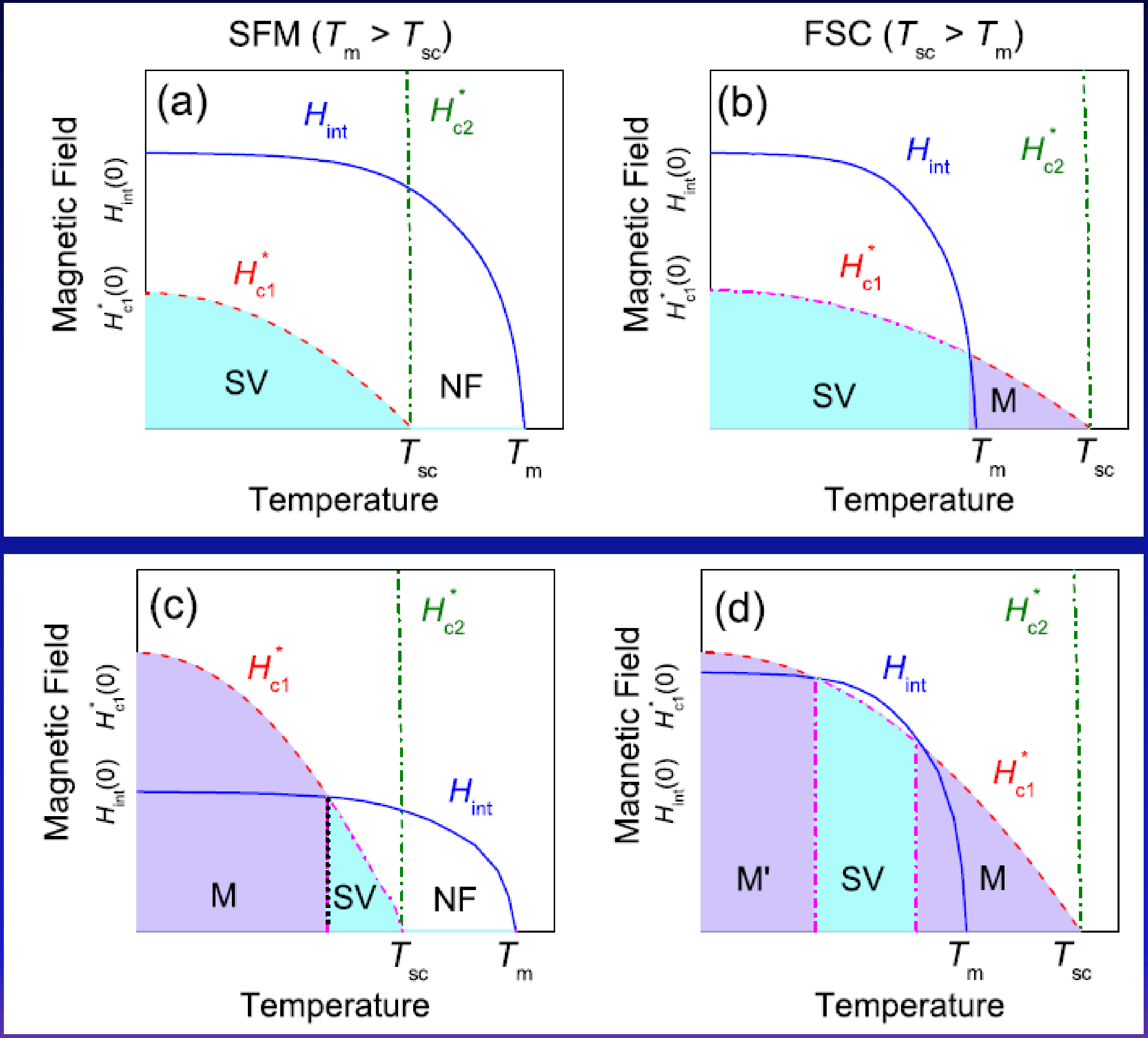




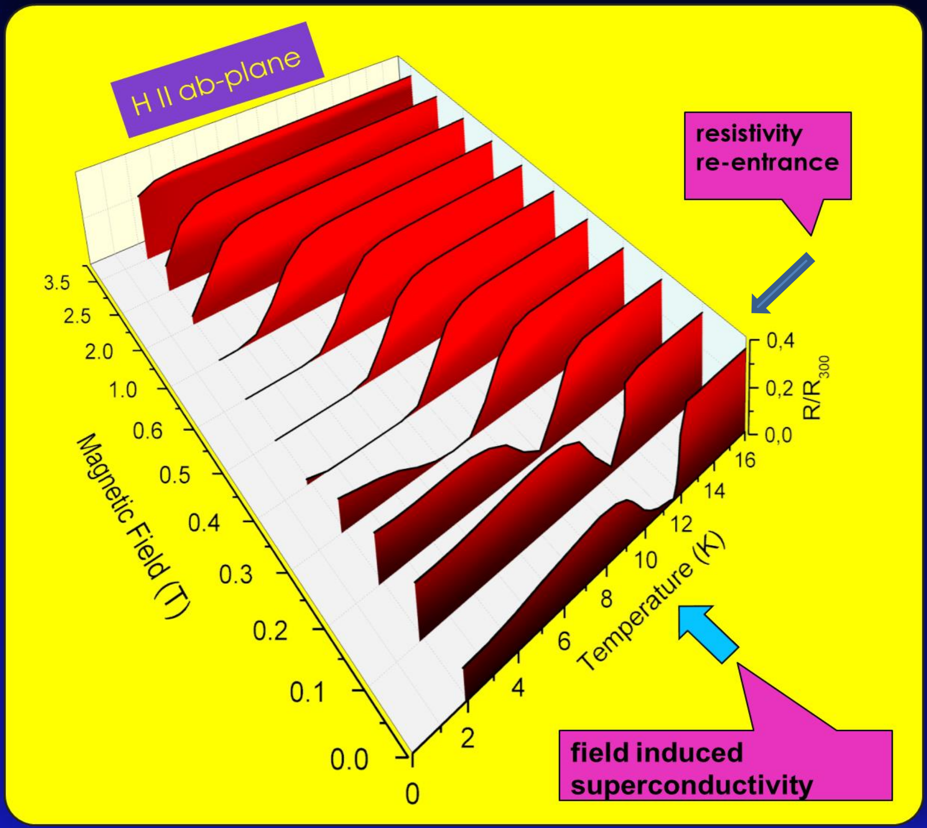
Bukowski et al., *(SCTE 2010 Annecy)*

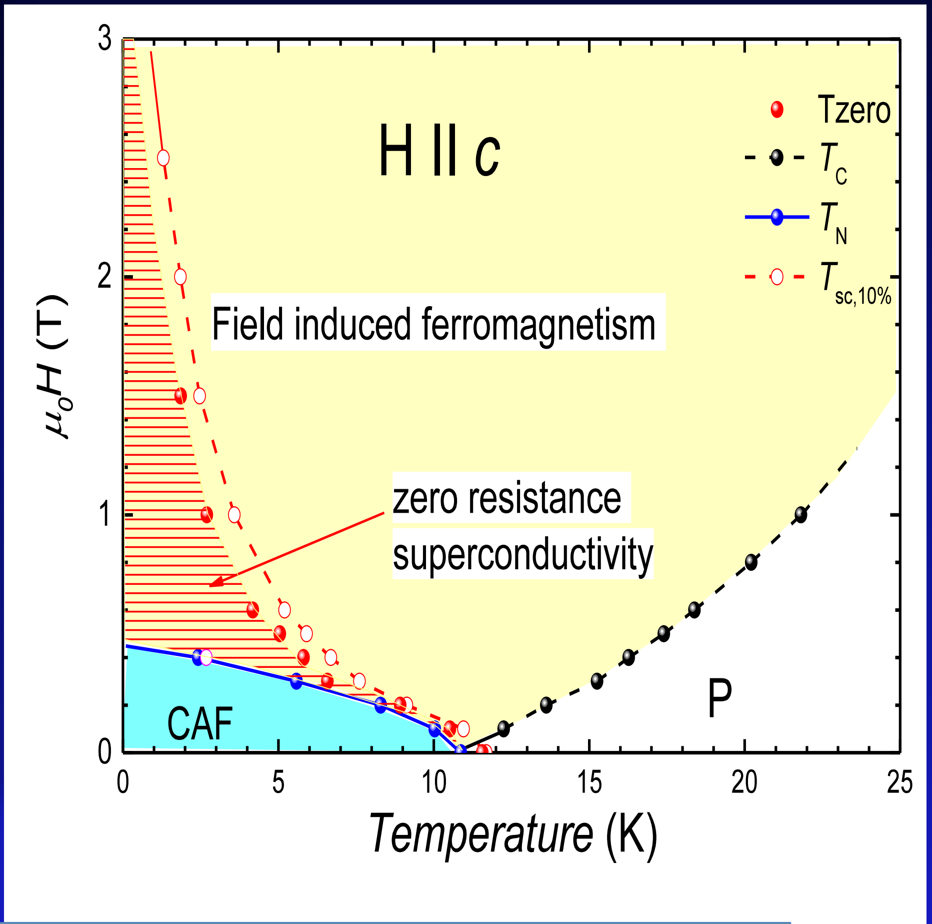
Spontaneous vortex state in ferromagnetic superconductor

W-H Jiao et al., npj Quantum Materials (2017) 2:50



Peculiar properties of Sn-flux-grown $Eu_{0.73}Ca_{0.27}(Fe_{0.87}Co_{0.13})_2As_2$ single crystals





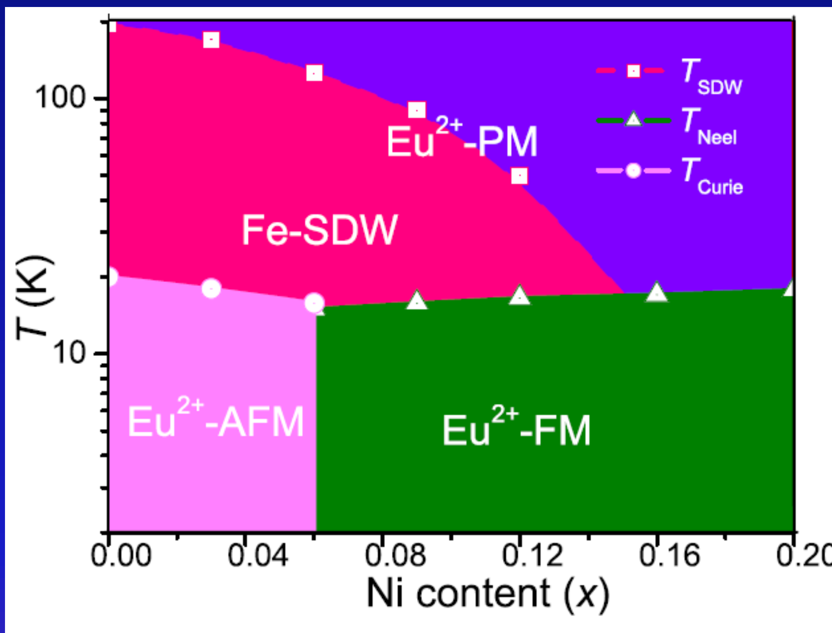
Zero-resistance superconductivity is suppressed in antiferromagnetic region and coexists with field induced ferromagnetism

Search for superconductivity in Ni-substitututed $EuFe_2As_2$

I Nowik et al. New Journal of Physics ***13*** *(2011) 023033*

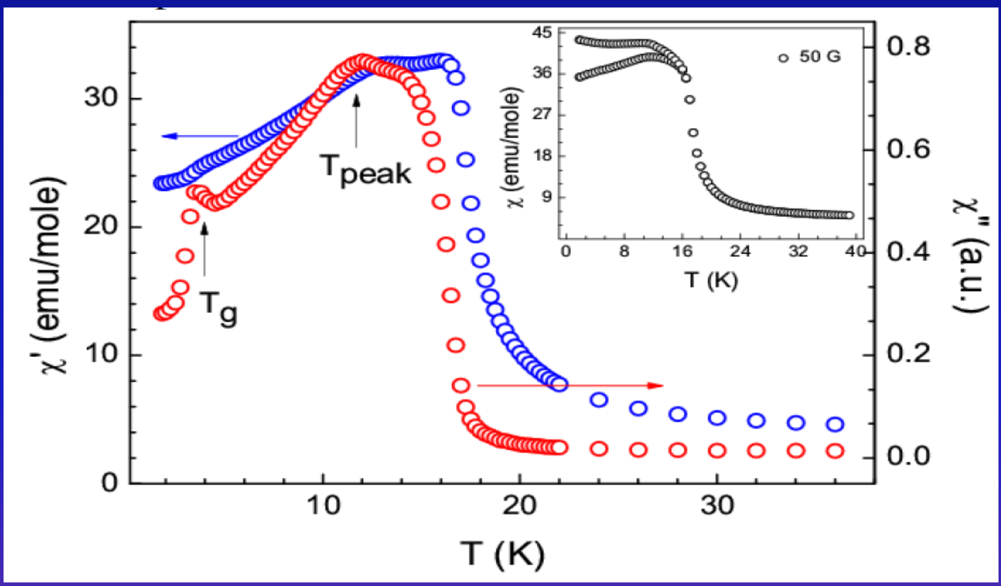
Polycrystalline material

Mössbauer studies of $Eu(Fe_{0.9}Ni_{0.1})_2As_2$ and $Eu(Fe_{0.89}Co_{0.11})_2As_2$, in particular the Eu negative quadrupole interaction and the tilting of H_{eff} from the *c*-axis, are almost the same. This indicates a similar magnetic structure regardless of whether the system is normal conducting or SC



Zhi Ren et al. PRB 79, 094426(2009)

Anupam et al. AIP Conf. Proc. 1349, 1293-1294 (2011)



Superconductivity not detected

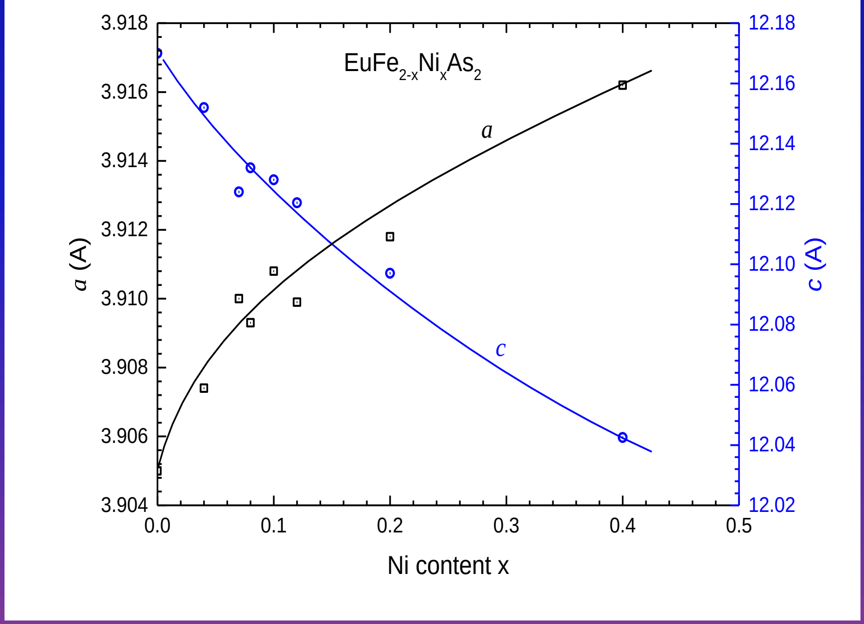
In EuFe1.9Ni0.1As2 in addition to FM transition, two more transitions were observed. = 3.5 K. The broad transition at T_{peak} =11.5 K could be due to the transition from FM to AFM state. The transition at T_g *=3.5 K* could be due to the spin glass ordering, which might arise due to the competition between FM and AFM ordering and hence leads to the spin freezing at *Tg*.

Ni substitution in $EuFe_2As_2$

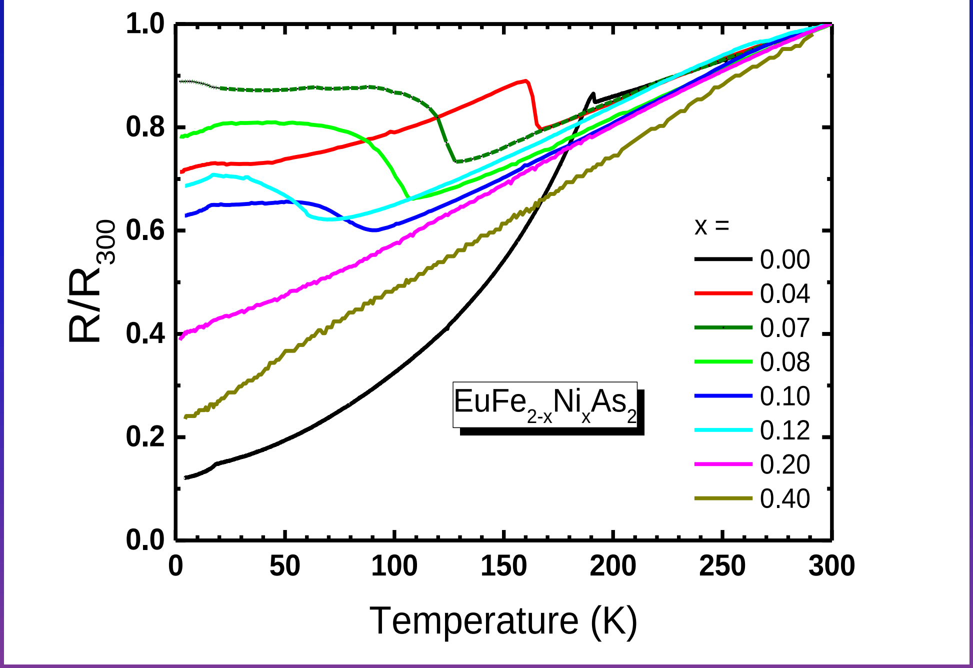
Single crystals of $EuFe_{2-x}Ni_xAs_2$ grown from Sn flux (up to x=0.4)

Chemical composition-determined from EDS data

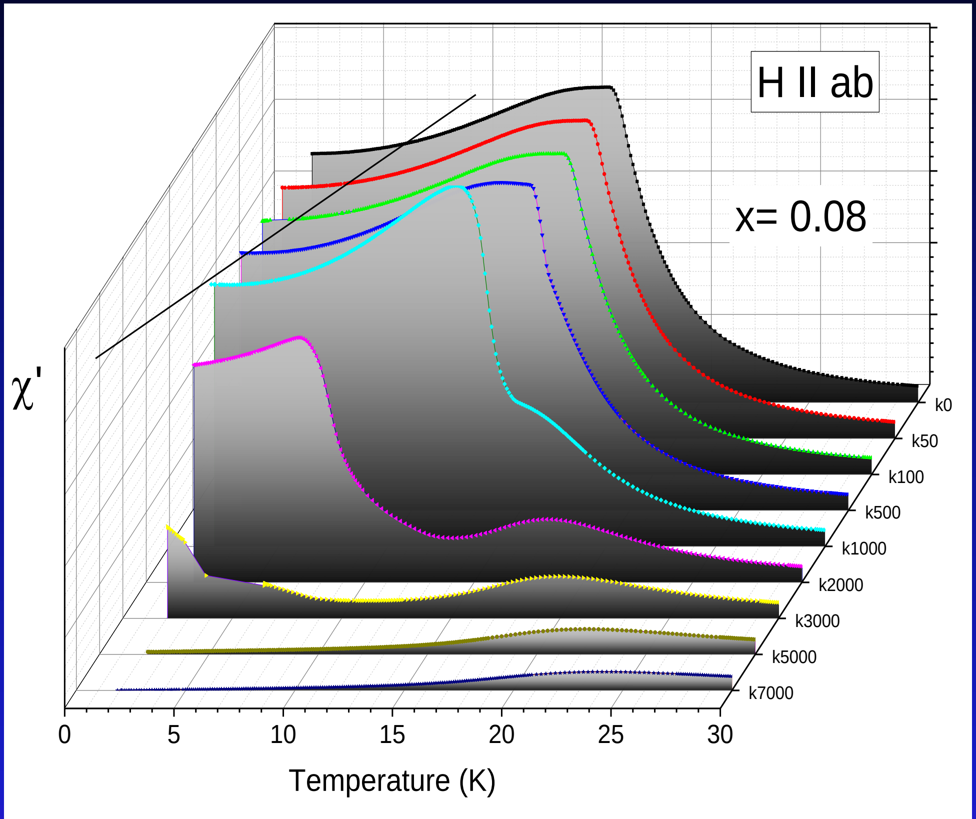
Lattice parameters



Electrical resistivity

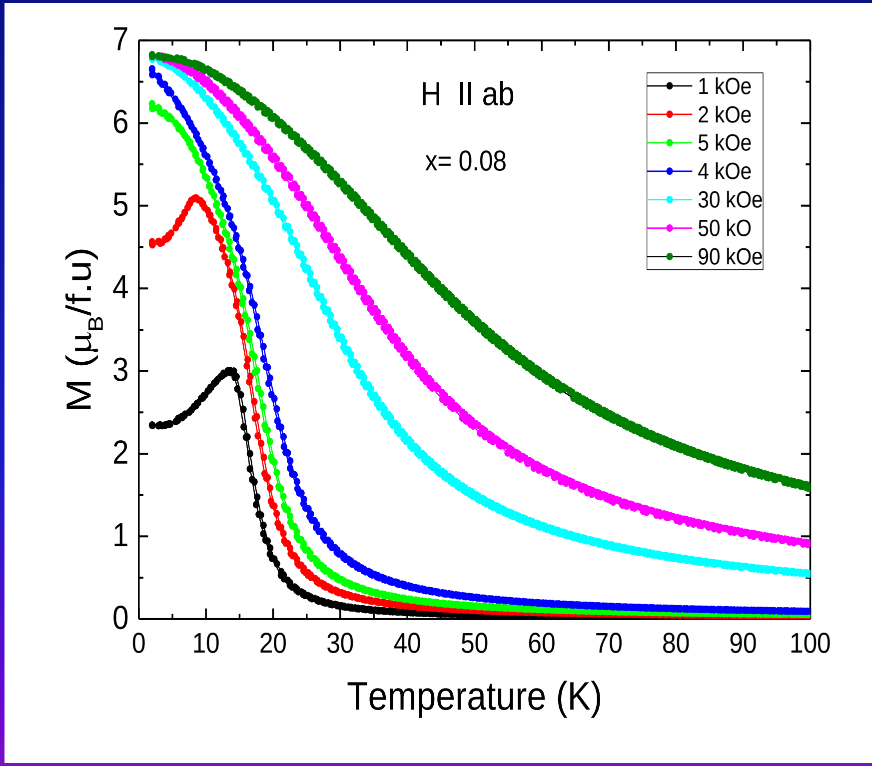


Magnetic properties of $EuFe_{1.92}Ni_{0.08}As_2$

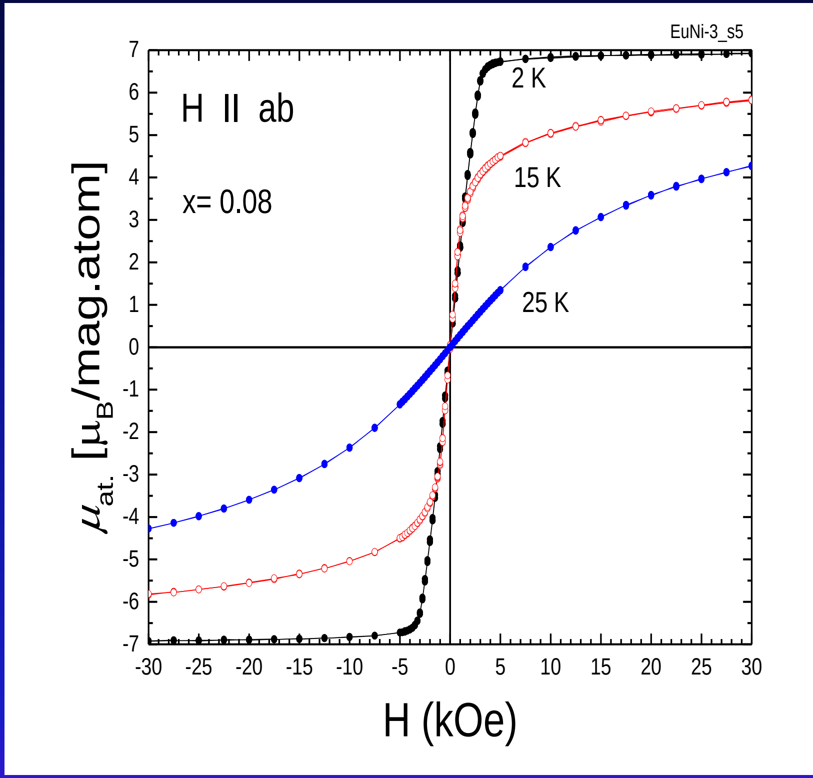


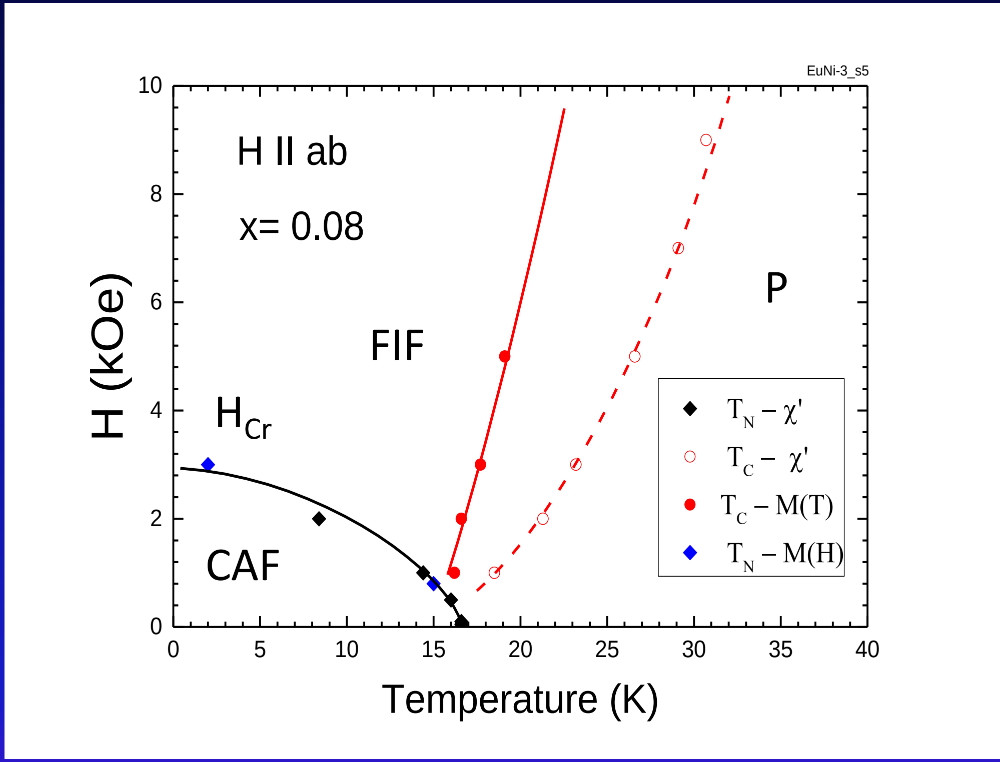
AC-susceptibility vs. Temperature in various magnetic fields

Magnetization vs. Temperature in various magnetic fields



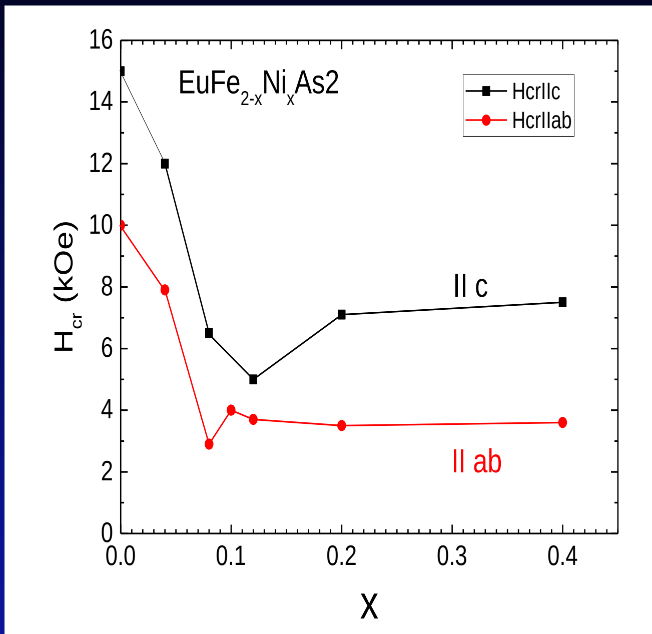
Magnetic properties of $EuFe_{1.92}Ni_{0.08}As_2$

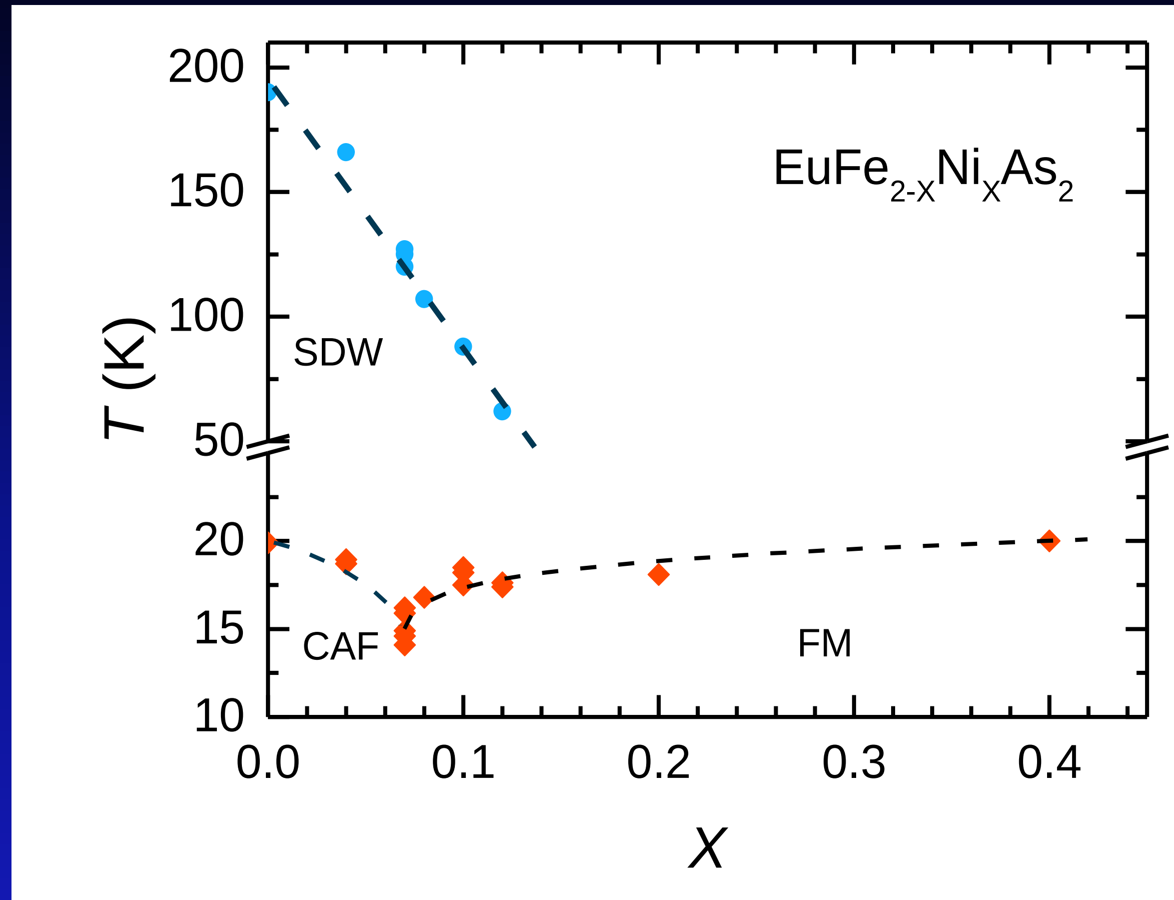




Field –dependent magnetization in various temperatures

Magnetic phase diagram of $EuFe_{2-x}Ni_{x2}As_2$





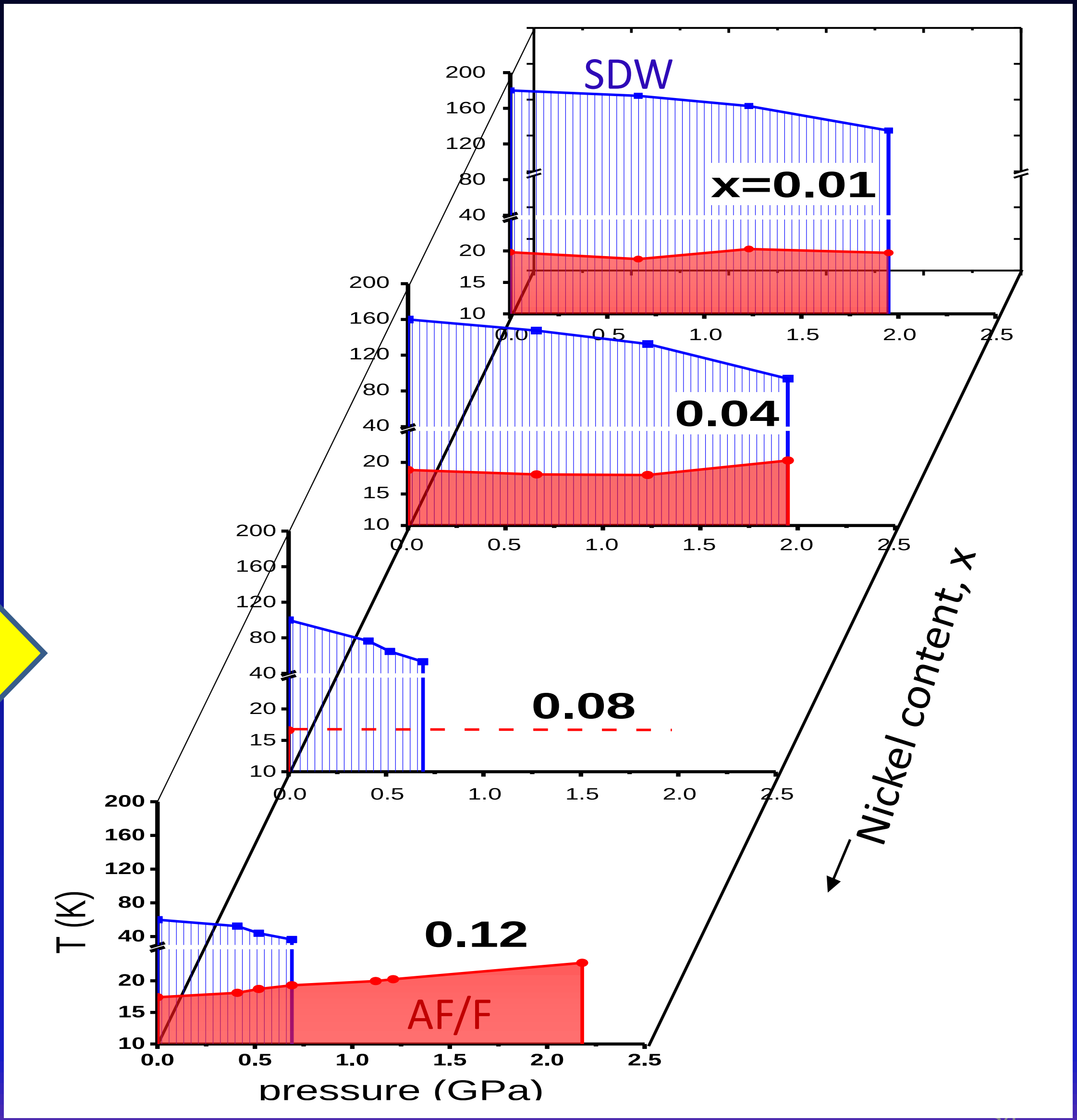
Absence of superconductivity above 1.8 K

Magnetism of Eu in $EuFe_{2-x}Ni_xAs_2$ is very similar to that in $EuFe_{2-x}Co_xAs_2$ and seems to be not responsible for the absence of superconductivity.

Search for superconductivity in $EuFe_{2-x}Ni_xAs_2$ under high pressure

Resistivity measured using piston-cylinder pressure cell

no evidence of superconductivity under pressure down to 2 K



Doped $EuFe_2As_2$

- Magnetic field easily aligns Eu^{2+} spins along the direction of the applied field (field induced ferromagnetism)
- Hydrostatic perssure, transition metal substitutions, and P substitution suppress SDW order, induce superconductivity and change magnetic order of Eu^{2+} moments from antiferro- to ferromagnetic
- Superconductivity coexists both with AF and F order of Eu^{2+} system

Coexistence of superconductivity and magnetism,
Zero-resistance as an effect of applied magnetic field,
High anisotropy,
Magnetic field sensitive electronic transport ,
Spontaneous superconducting vortices,
- potentially interesting for spintronics and other electronic applications

Collaboration:

Presented unpublished results obtained in fruitfull collaboration with:

Michał Babij
Lan Maria Tran
Daniel Gnida
Piotr Wiśniewski

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