Emergent Nematic State in Iron-based Superconductors

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Outline

***Introduction:**

High Temperature Superconductivity in Fe-pnictides
& Possible Nematic State in This Class of Materials

***Experimental**

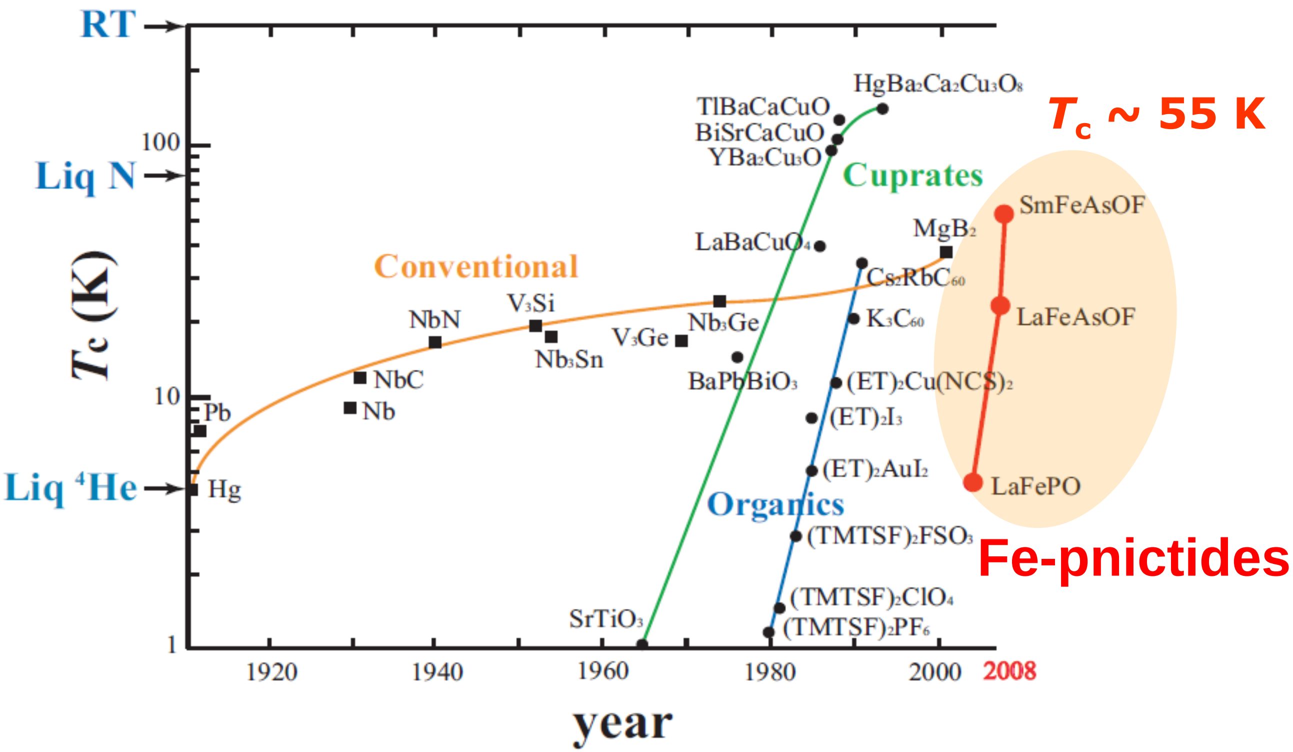
Magnetic Torque Measurements
Single Crystalline Synchrotron XRD

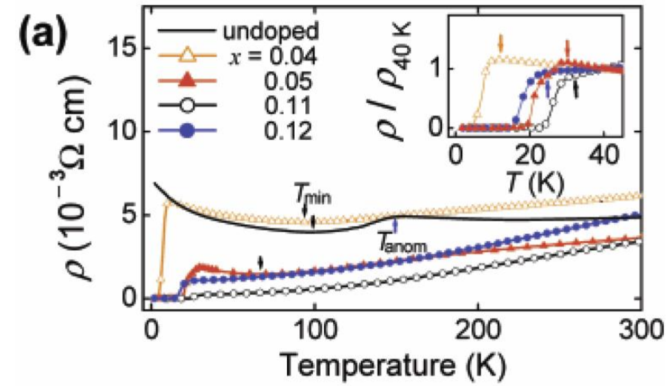
***Results & Discussion**

Evidence for the Electronic Nematic State

***Summary**

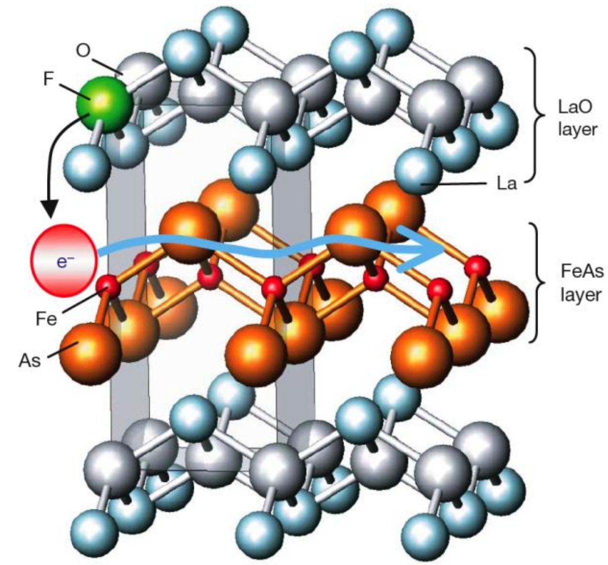
Superconductivity in Fe-Pnictides — Discovery





Y. Kamihara, *et al.*, JACS, **130**, 3296 (2008).

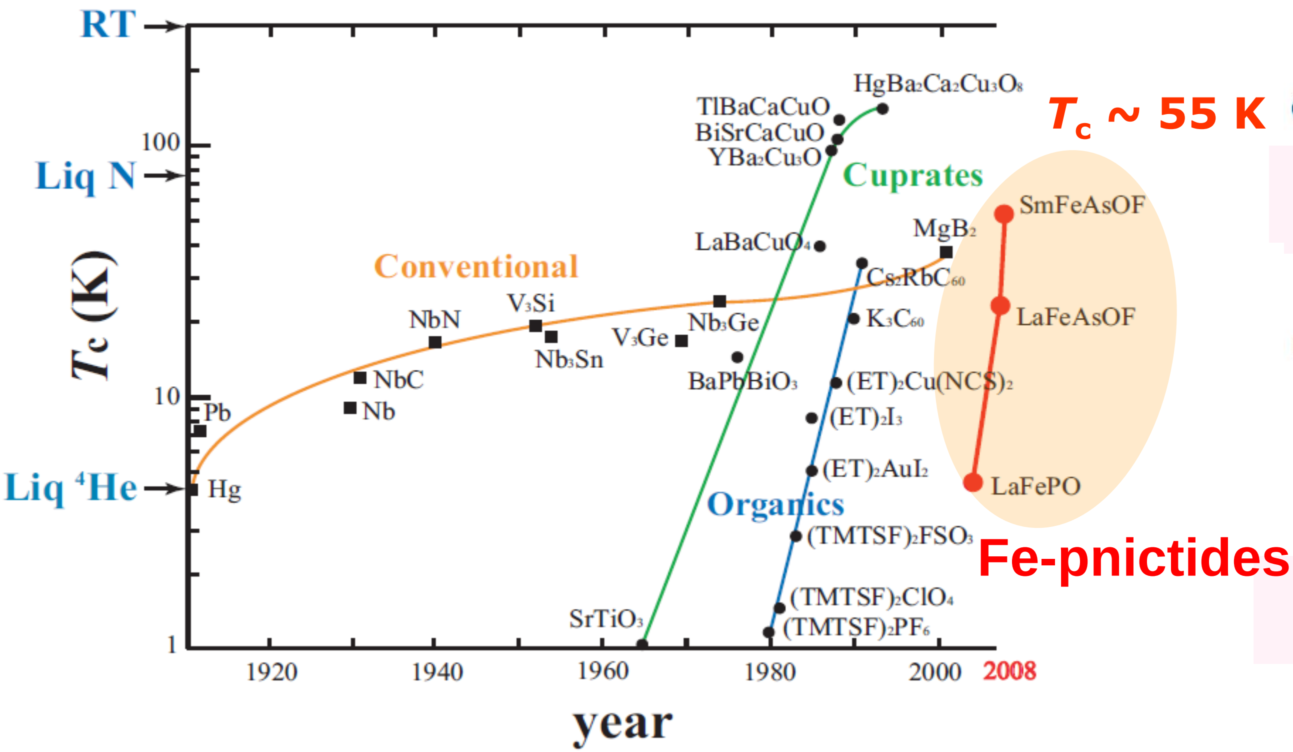
LaFeAs(O,F)
("1111")

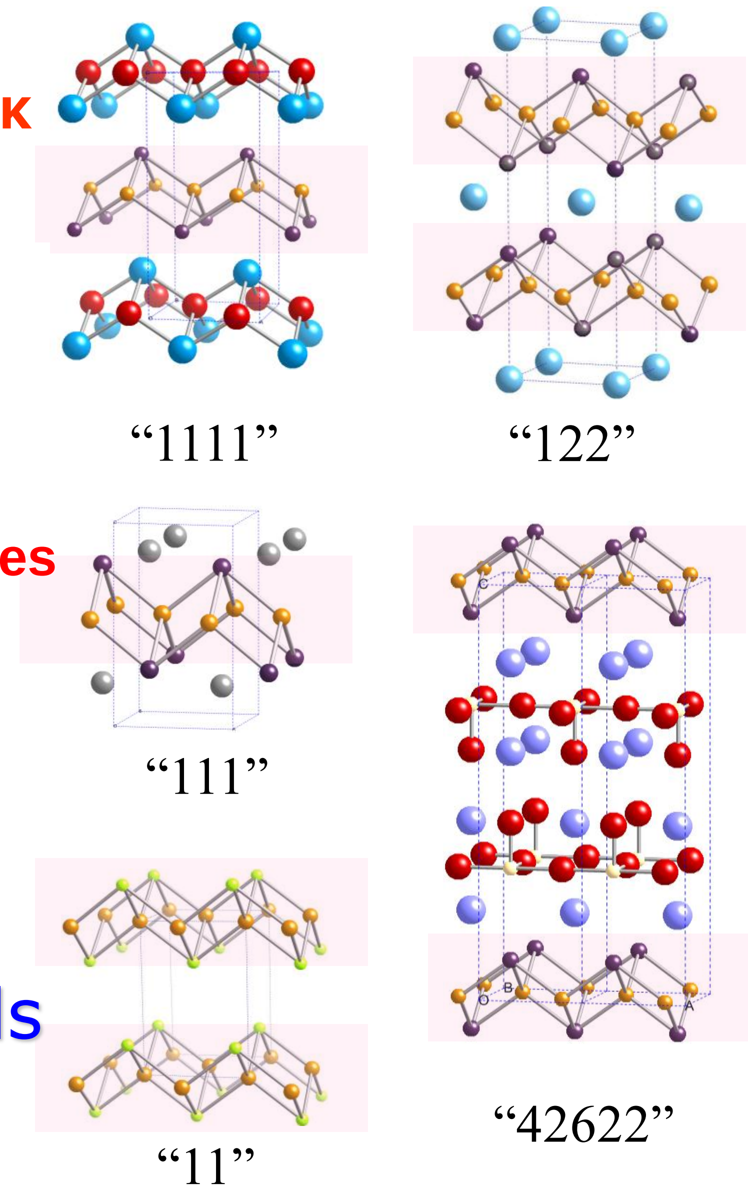


H. Takahashi *et al.*, Nature **453**, 376 (2008).

The Second Generation Materials of High-T_c Superconductivity

Superconductivity in Fe-Pnictides — Family



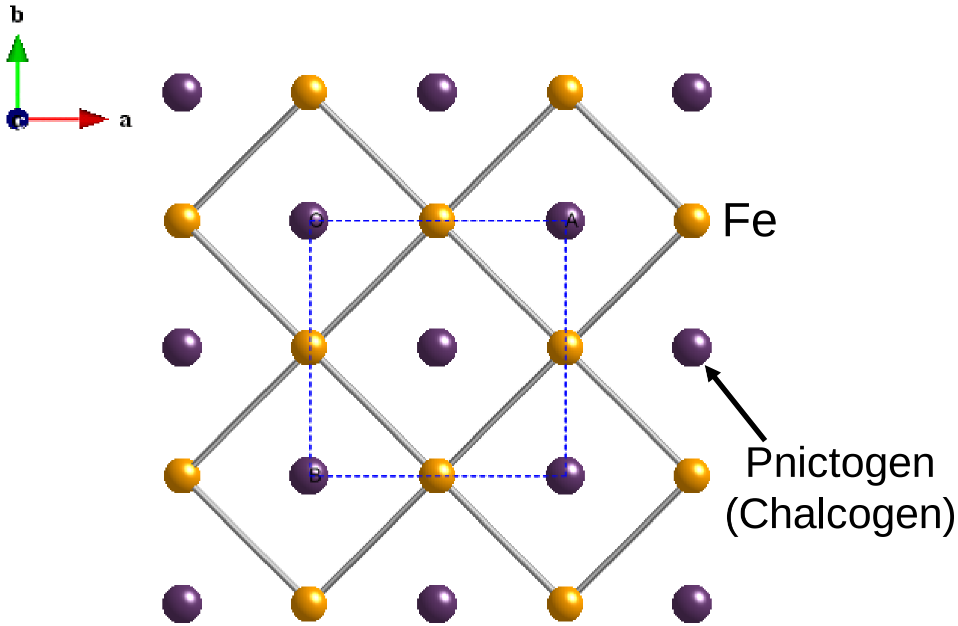


The Second Generation Materials of High-T_c Superconductivity

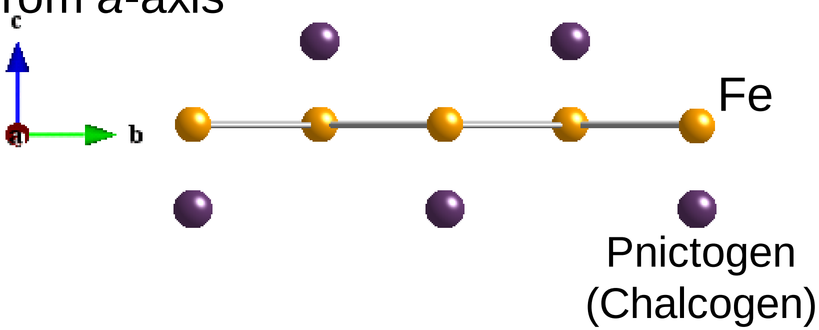
Superconductivity in Fe-Pnictides — Family

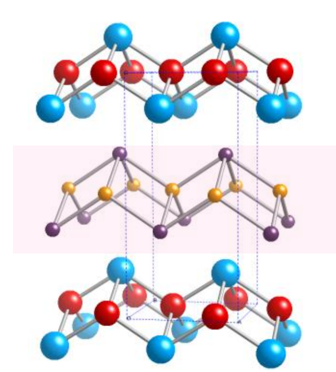
- 2D square lattice of Fe-atoms

From *c*-axis



From *a*-axis





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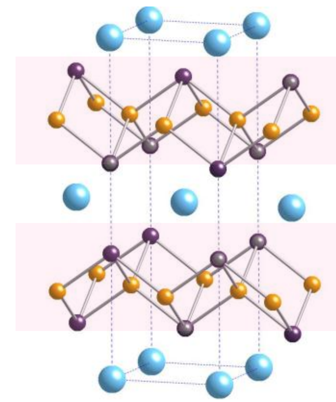
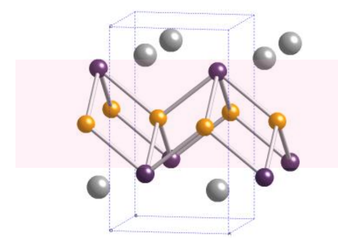


“122”



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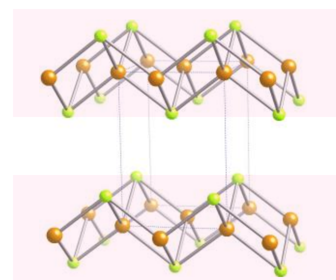

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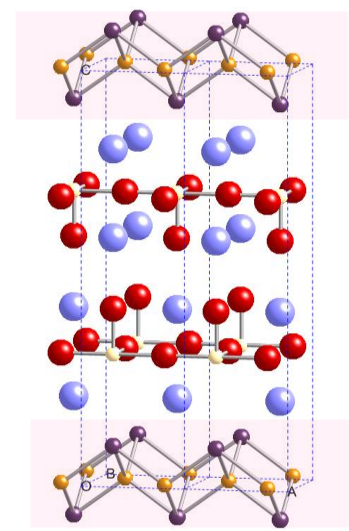

“42622”

Phase Diagram

Parent compounds

Structural transition (T_S) & AFM transition (T_N)

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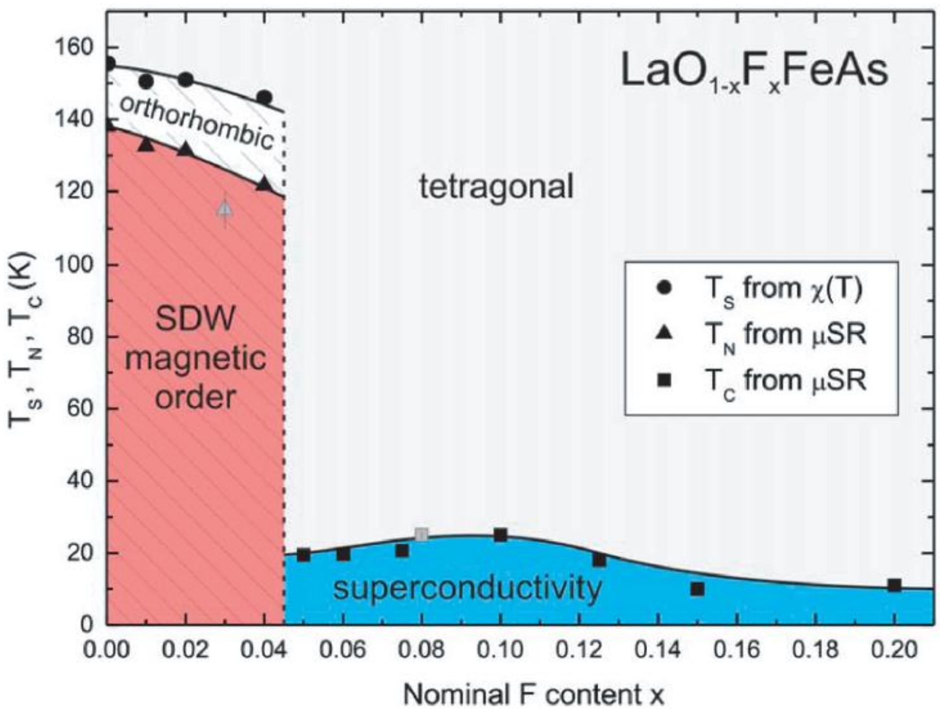
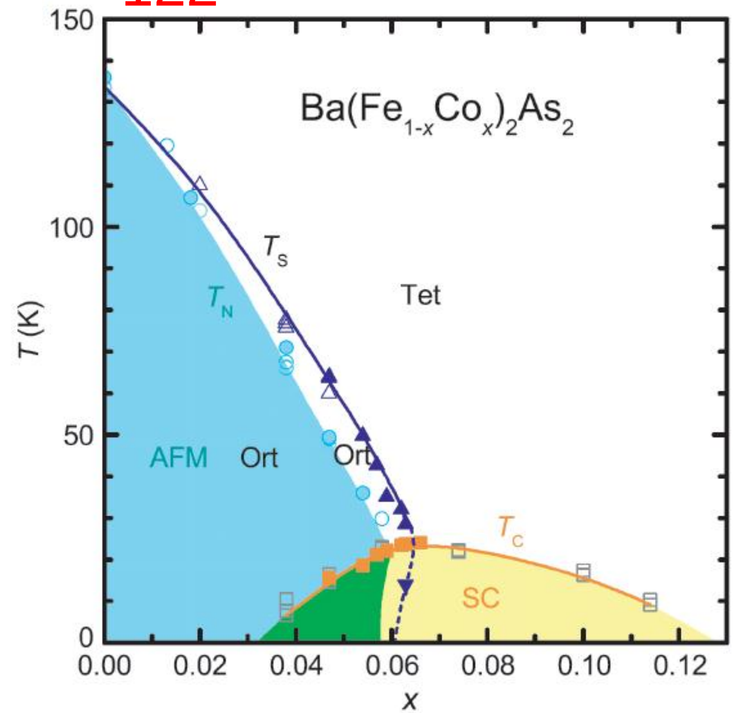


H. Luetkens *et al*., Nature Materials **8**, 305 (2009).

"122"



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

The magneto-structural transition is suppressed by doping or applying pressure.

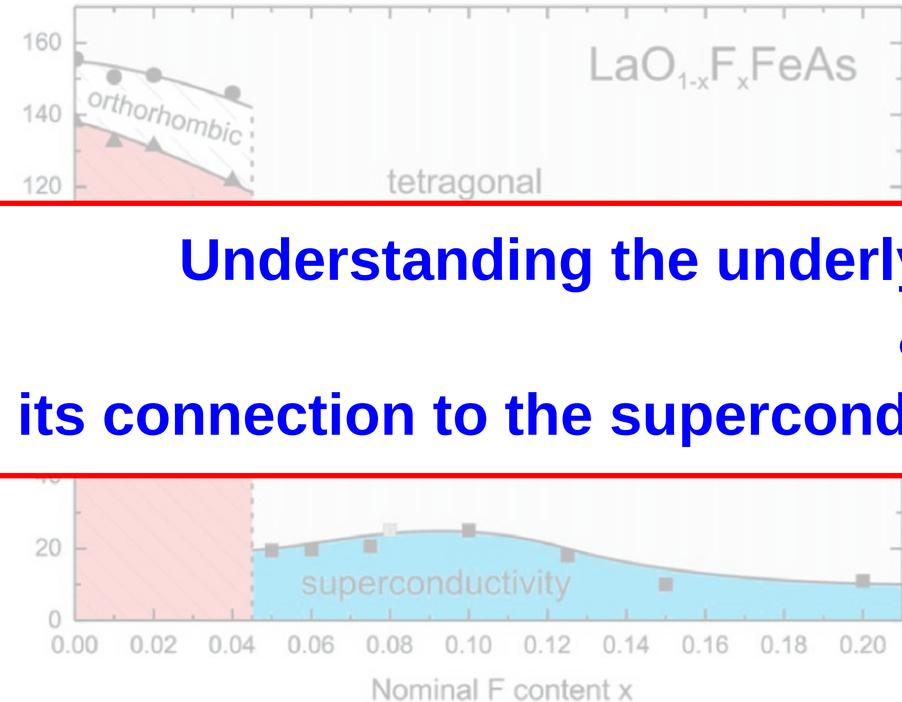
Superconductivity in a close proximity to magneto-structural order.

Phase Diagram

Parent compounds

Structural transition (T_S) & AFM transition (T_N)

"1111"



H. Luetkens *et al*., Nature Materials **8**, 305 (2009).

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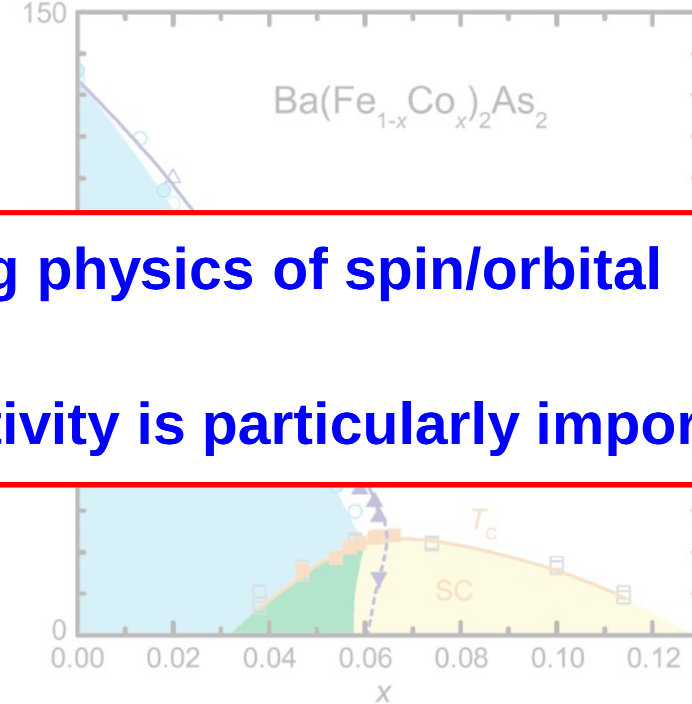


S. Nandi *et al*., PRL **104**, 057006 (2010).

Understanding the underlying physics of spin/orbital

&

its connection to the superconductivity is particularly important.

The magneto-structural transition is suppressed by doping or pressure.

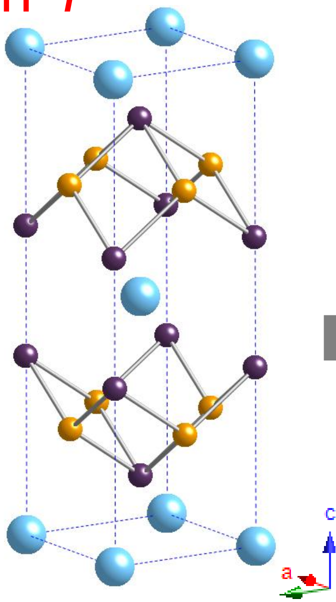
Superconductivity in a close proximity to magneto-structural order.

Phase Diagram

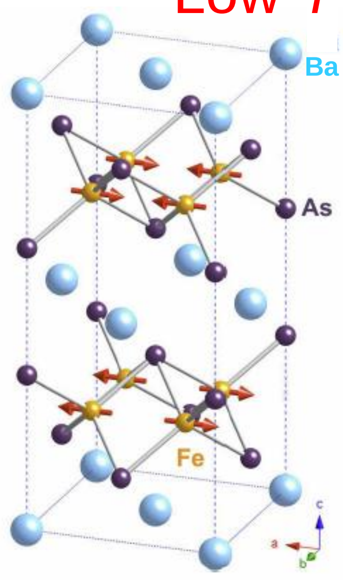
Parent compounds

Structural transition (T_S) & AFM transition (T_N)

High-T



Low-T



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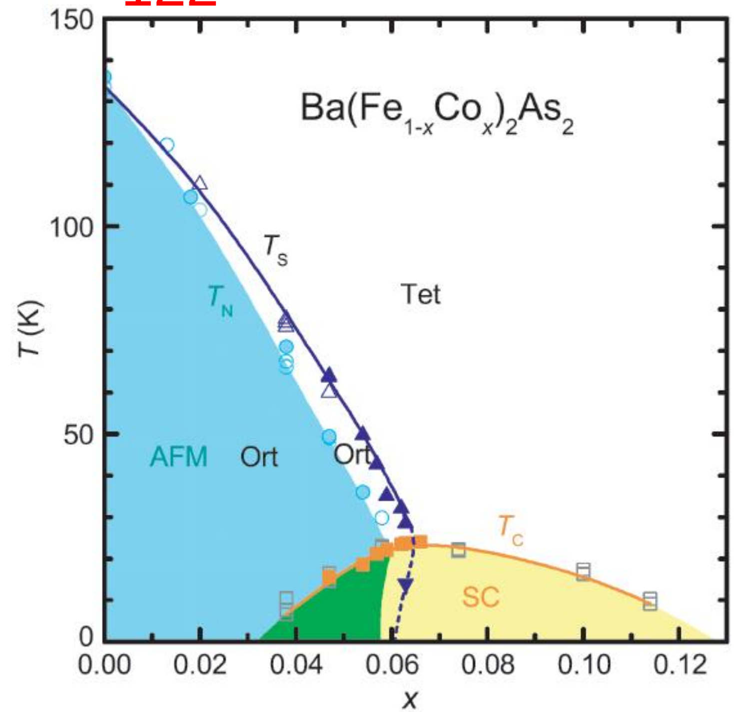
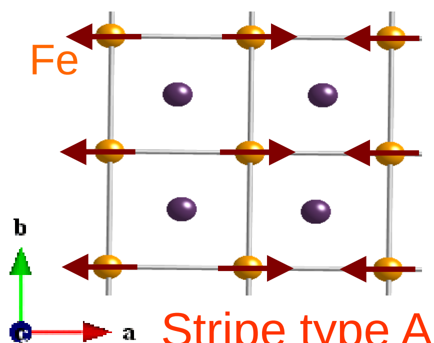


Tetragonal
Paramagnetic

Orthorhombic.
Antiferromagnetic

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



Stripe type AFM

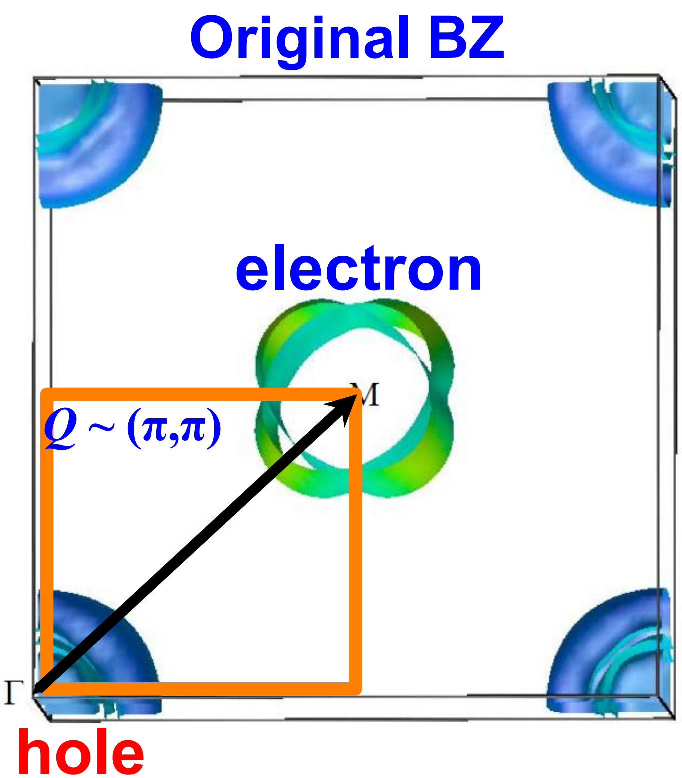
Symmetry Breaking

Theoretical approach: Itinerant Picture

Fermi Surface

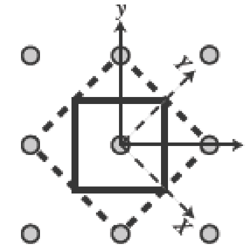
Five-fold degenerate Fe 3*d* orbitals participate: *XZ/YZ, XY, 3Z²-R², X²-Y²*

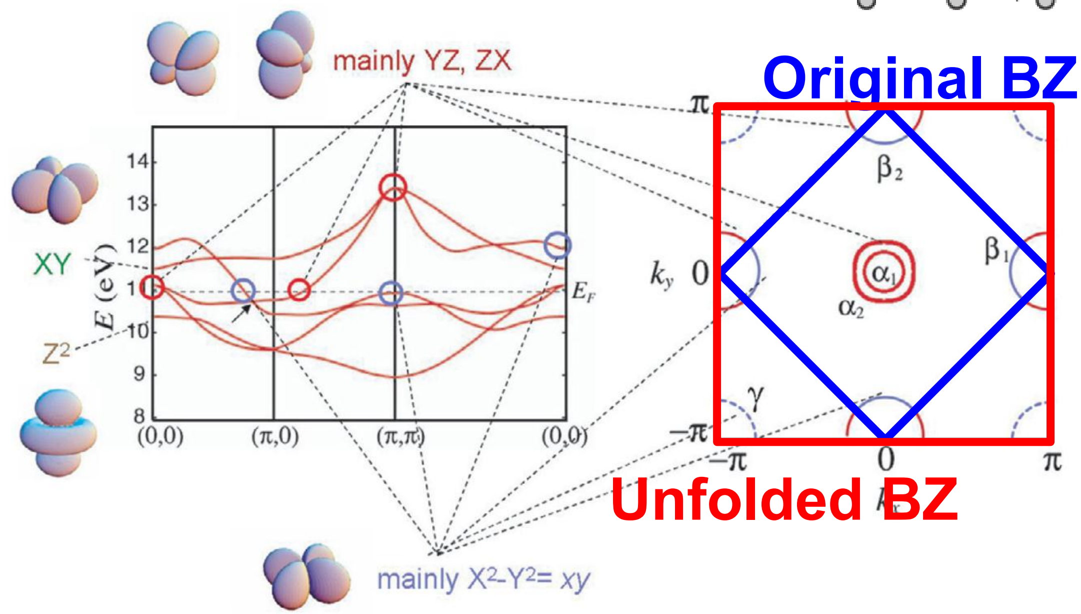
→ **Multiband** electronic structure with well-separated **hole** and **electron** sheets



D.J. Singh and M.H. Du, Phys. Rev. Lett. **100**, 237003 (2008).

Good nesting between hole and electron sheets

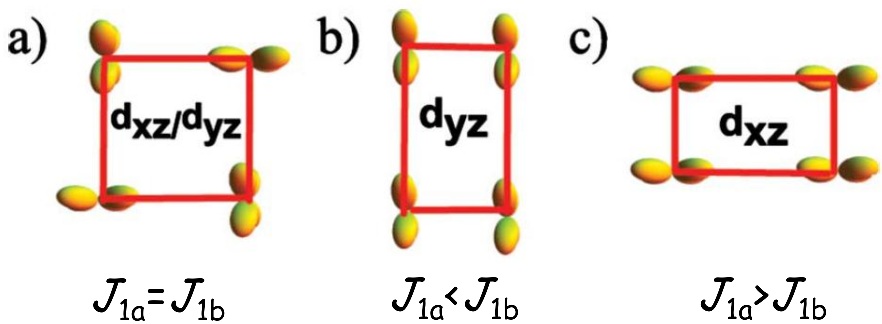




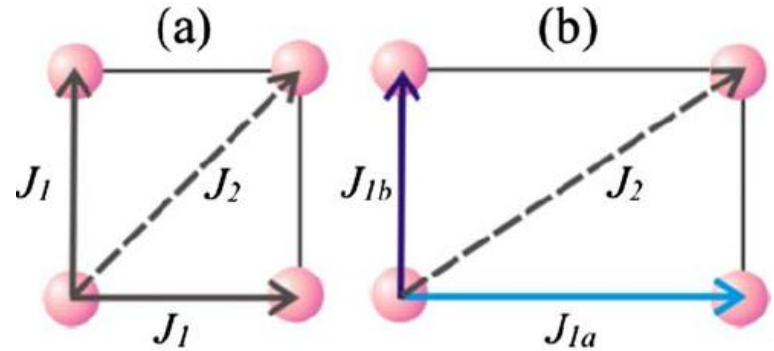
K. Kuroki *et al*., New J. Phys. **11**, 025017 (2009).

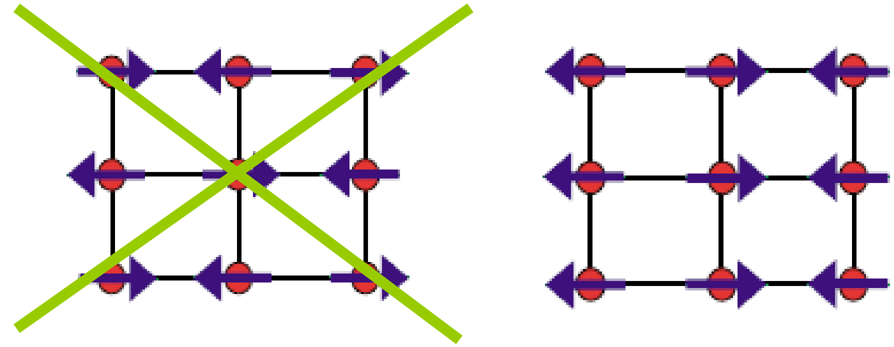
Theoretical approach: Localized Picture

Frustration between J1 and J2 and its removal by orbital ordering



Lv et al., PRB **80**, 224506 (2009).
PRB **82**, 045125 (2010).

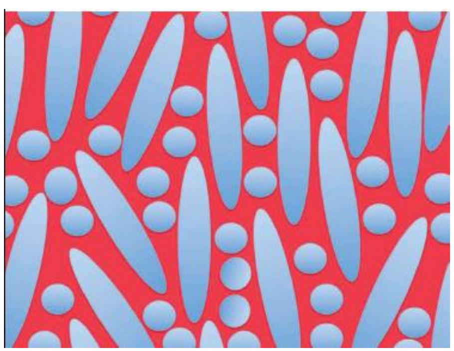




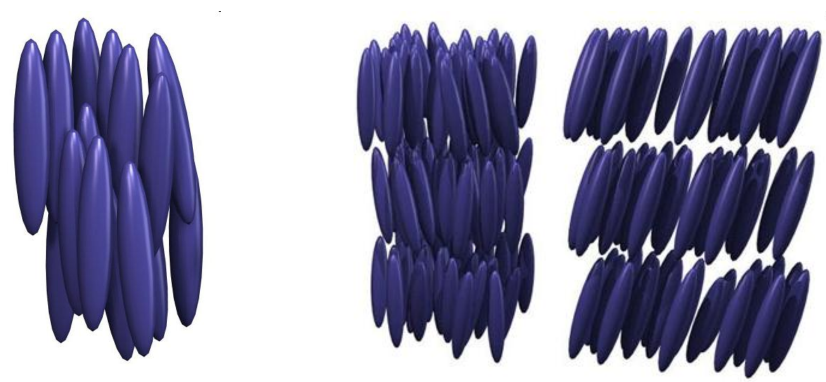
Chen *et al.*, PRB **80**, 180418(R) (2009).

Broken Rotational Symmetry

Electronic Nematic State



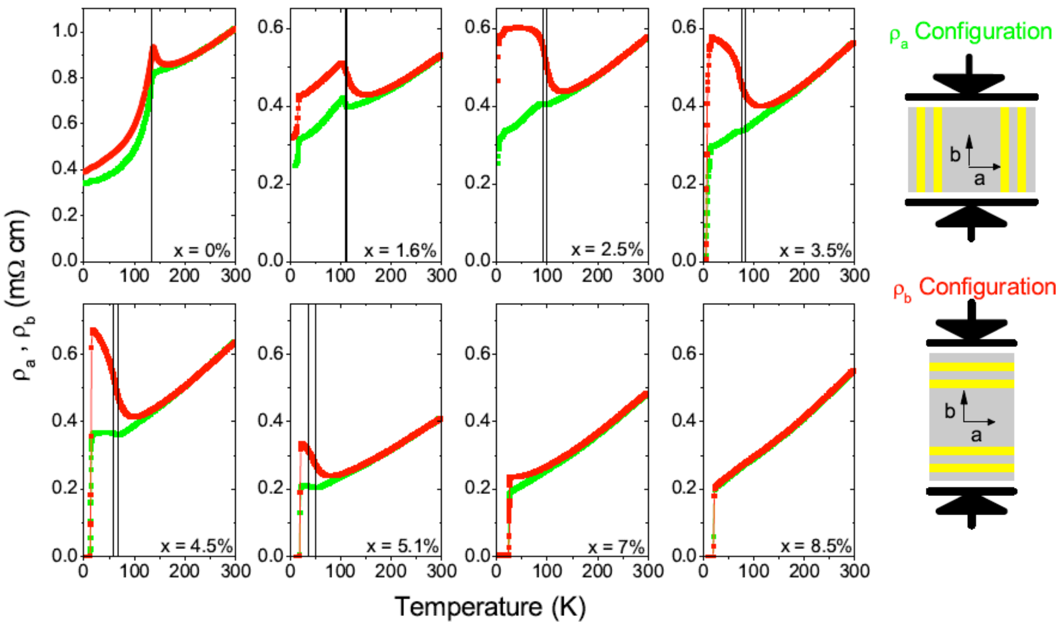
E. Fradkin *et al.*, Science **327**, 155 (2010).



Nematic & Smectic in Liquid Crystals (Wikipedia)

Experiments Suggesting the Electronic Nematic State

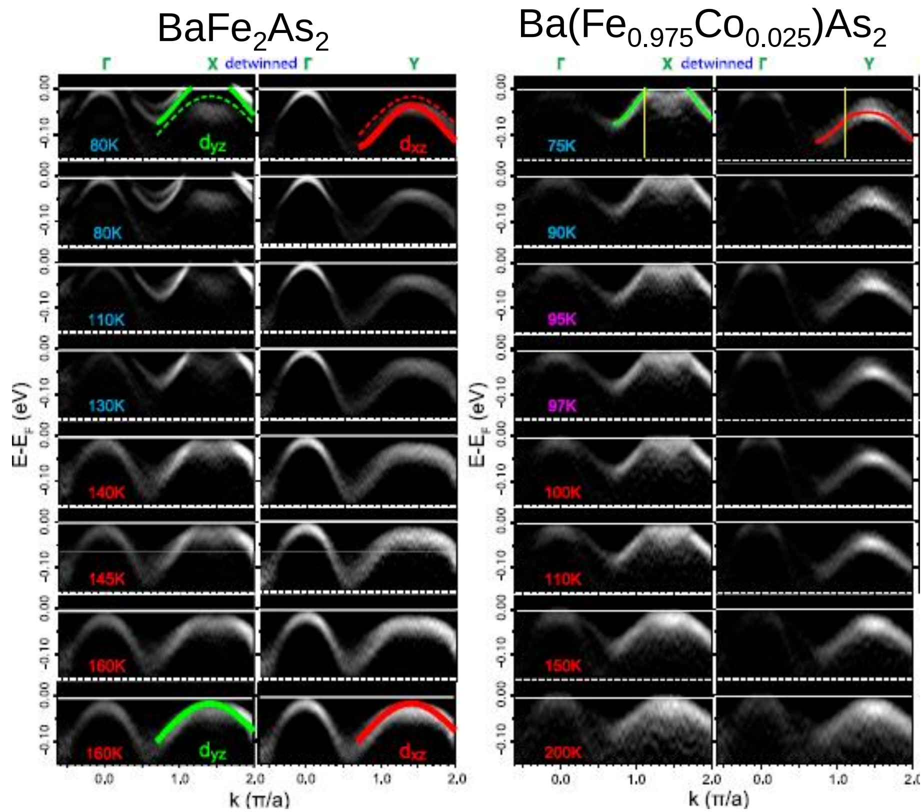
Resistivity J. Chu *et al*. Science (2010).

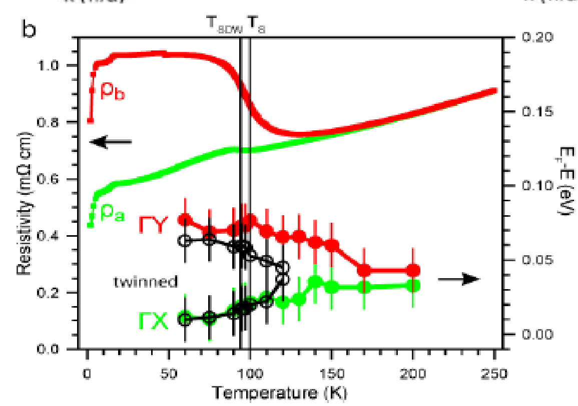


ρ_b > ρ_a above T_s

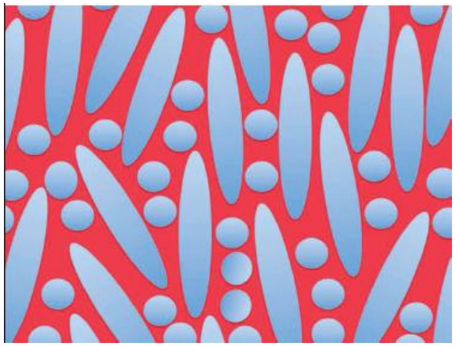
Finite in-plane anisotropy above T_s in detwinned crystals.

ARPES M. Yi et al., PNAS (2011).





Questions on the Electronic Nematic State



Electronic Nematic

1. Intrinsic?
2. Thermodynamic phase?
3. Connections to the Magneto-Structural transition and Superconductivity?

Ultra-Precise Torque Magnetometry

&

Single Crystalline Synchrotron XRD

Experiment 1: Magnetic torque measurements

$$\boldsymbol{\tau} = \mu_0 \boldsymbol{M} V \times \boldsymbol{H}$$

$$M_i = \sum_j \chi_{ij} H_j$$

$\boldsymbol{\tau}$: magnetic torque
V: sample volume
$\boldsymbol{M}$: magnetization
$\boldsymbol{H}$: applied Field

Thermodynamic Quantity

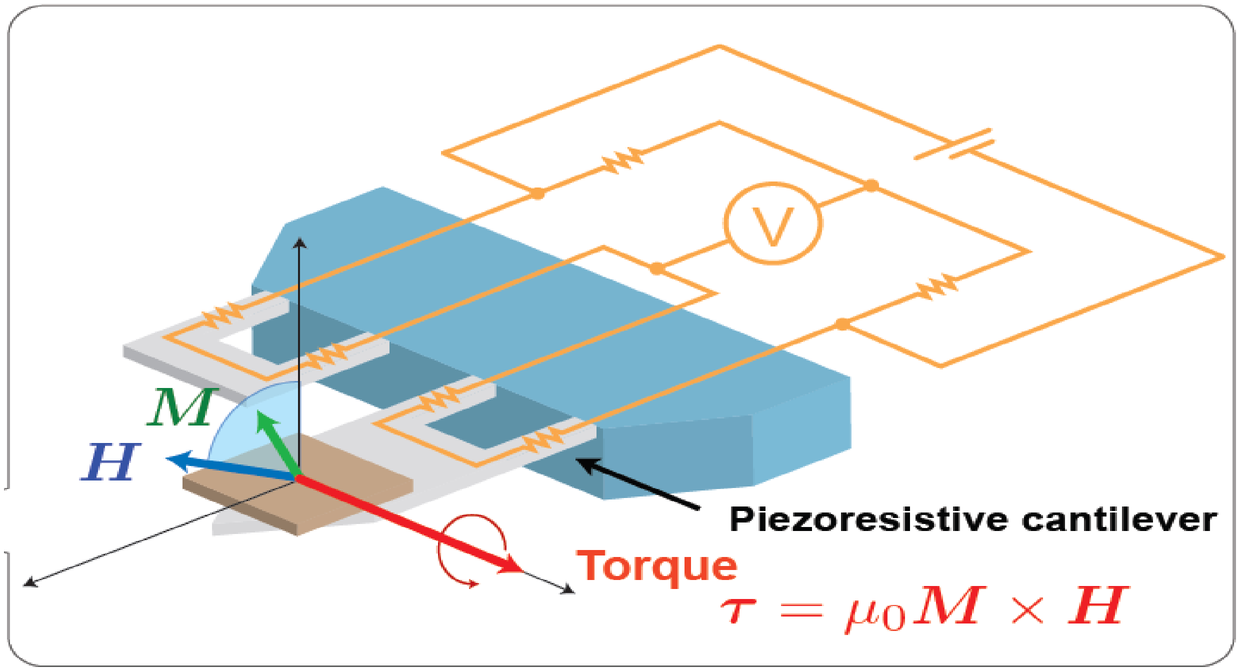
Micro-piezoresistive cantilever

Very high sensitivity
- torque $5\text{x}10^{-12}$ e.m.u.
- SQUID 10^{-8} e.m.u.

(at $\mu_0 H$=4T)

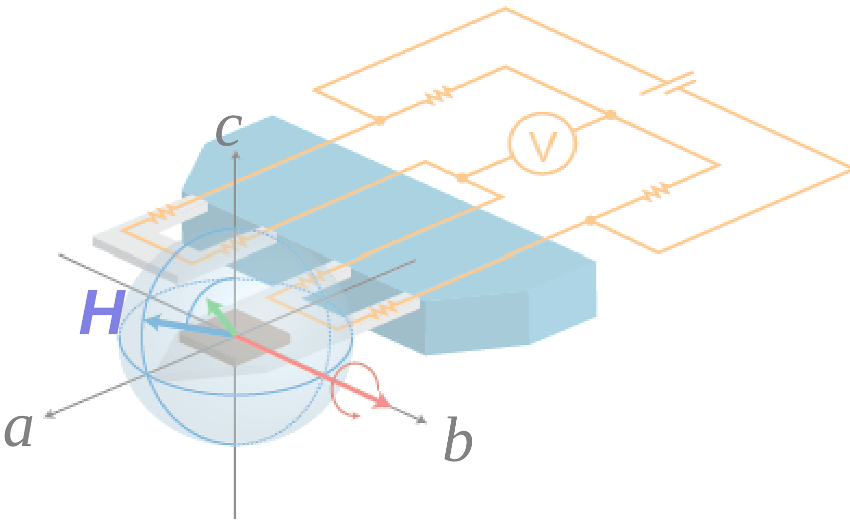
Change in the piezoresistance

→ **Magnetic Torque**



Experiment 1: Magnetic torque measurements

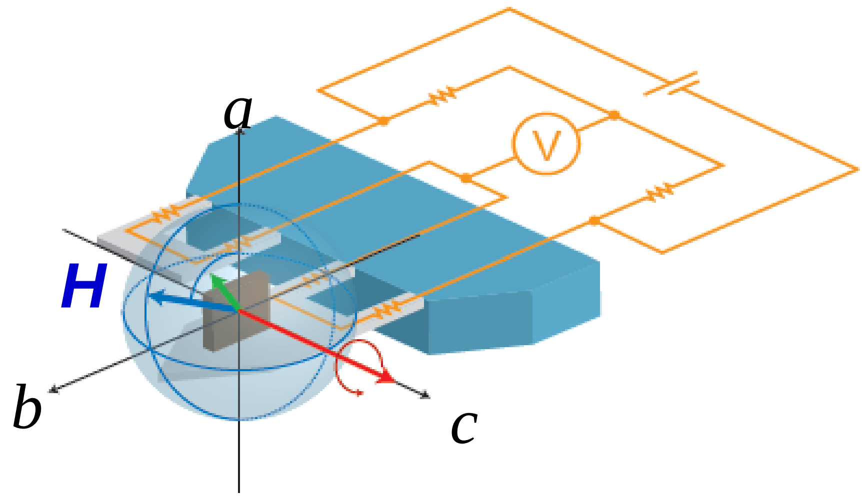
θ scan



Field Rotation within the *ac*-plane

$$\tau_{2\theta} = \frac{1}{2}\mu_0 H^2 V \Delta\chi_{ca} \sin 2\theta$$

ϕ scan



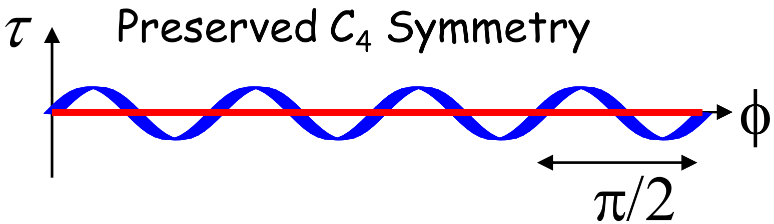
Field Rotation within the *ab*-plane

$$\tau_{2\phi} = \frac{1}{2}\mu_0 H^2 V \left[(\chi_{aa} - \chi_{bb}) \sin 2\phi - 2\chi_{ab} \cos 2\phi\right]$$

Experiment 1: Magnetic torque measurements

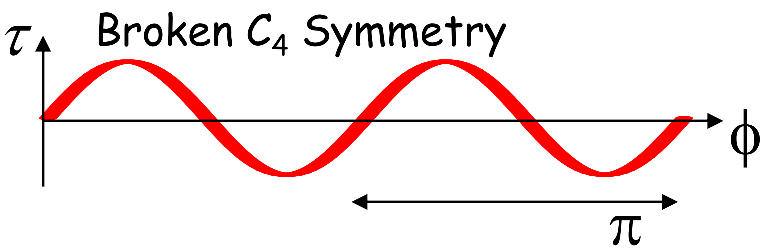
Preserved tetragonal symmetry

$\chi_{aa} = \chi_{bb}, \chi_{ab} = 0 \Rightarrow \tau_{2\phi} = 0$

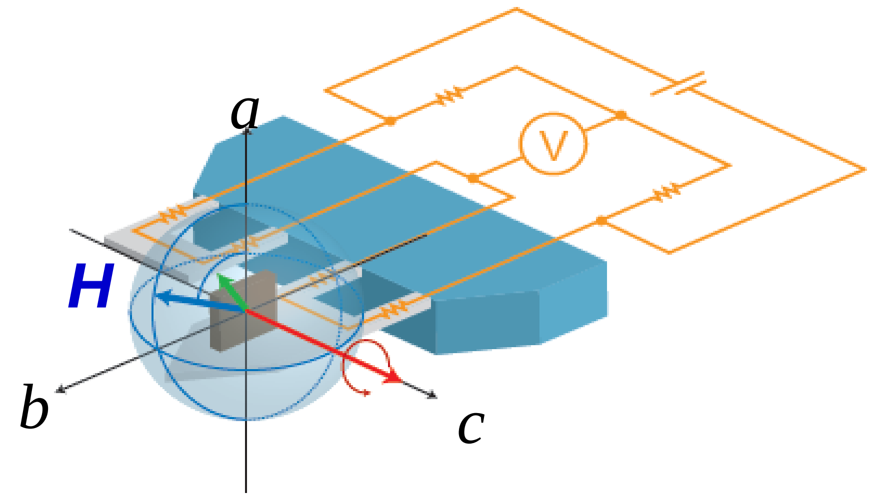


Broken rotational symmetry

$\chi_{aa} \neq \chi_{bb}$, or $\chi_{ab} \neq 0 \Rightarrow \tau_{2\phi} \neq 0$



ϕ scan



Field Rotation within the *ab*-plane

$$\tau_{2\phi} = \frac{1}{2}\mu_0 H^2 V \left[(\chi_{aa} - \chi_{bb}) \sin 2\phi - 2\chi_{ab} \cos 2\phi\right]$$

Direct probe of the In-plane Anisotropy without detwining

Experiment 1: Magnetic torque measurements

$$\boldsymbol{\tau} = \mu_0 \boldsymbol{M} V \times \boldsymbol{H}$$

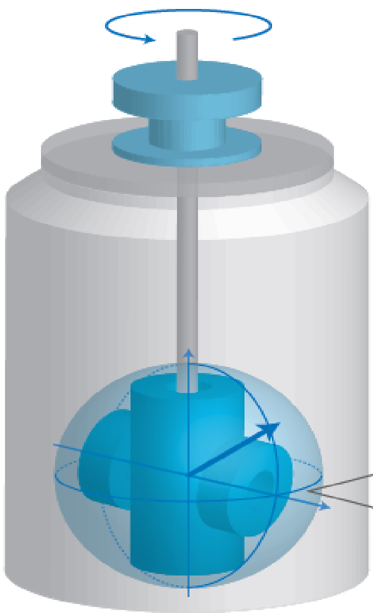
$$M_i = \sum_j \chi_{ij} H_j$$

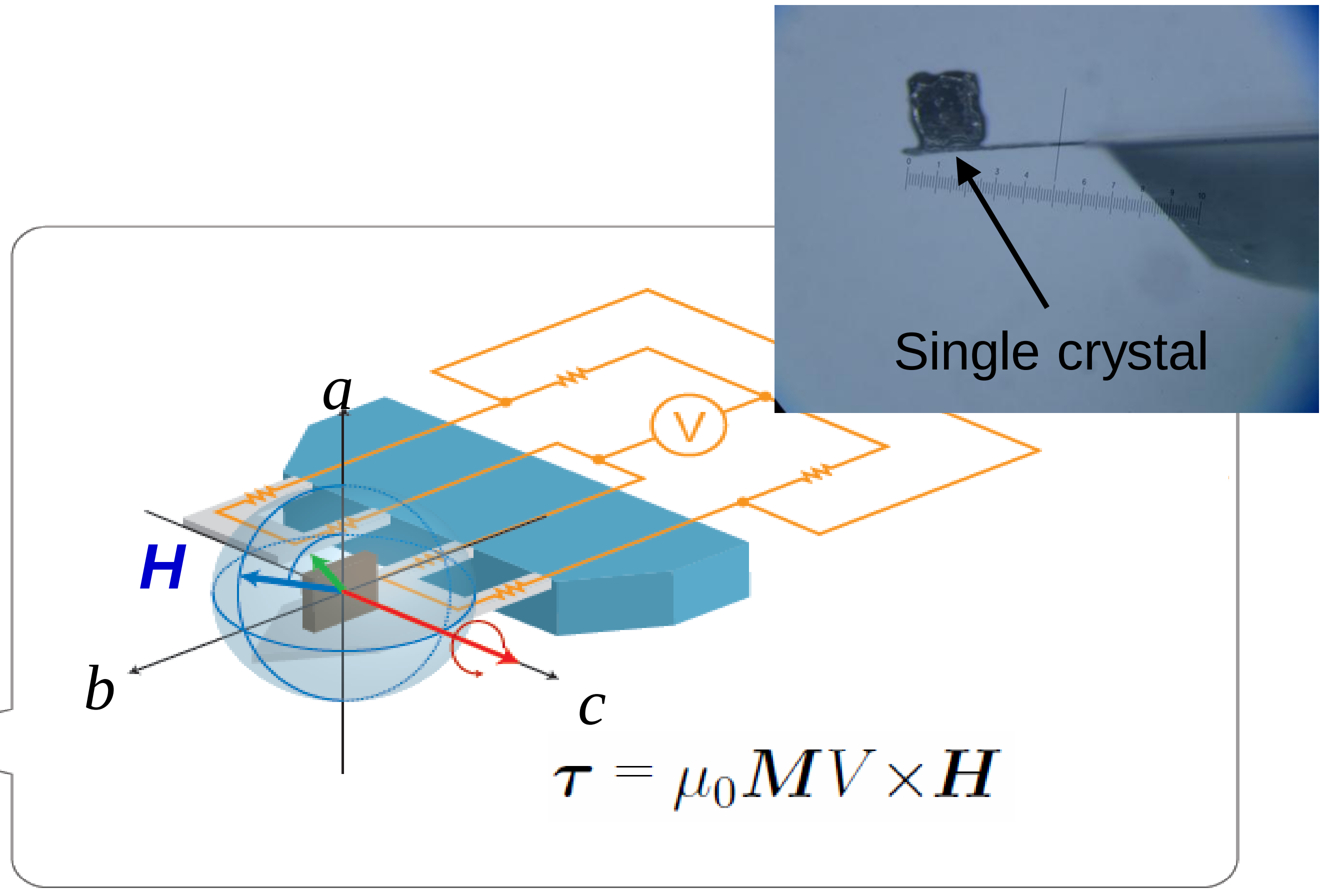
$\boldsymbol{\tau}$: magnetic torque
V: sample volume
$\boldsymbol{M}$: magnetization
$\boldsymbol{H}$: applied Field

Thermodynamic Quantity

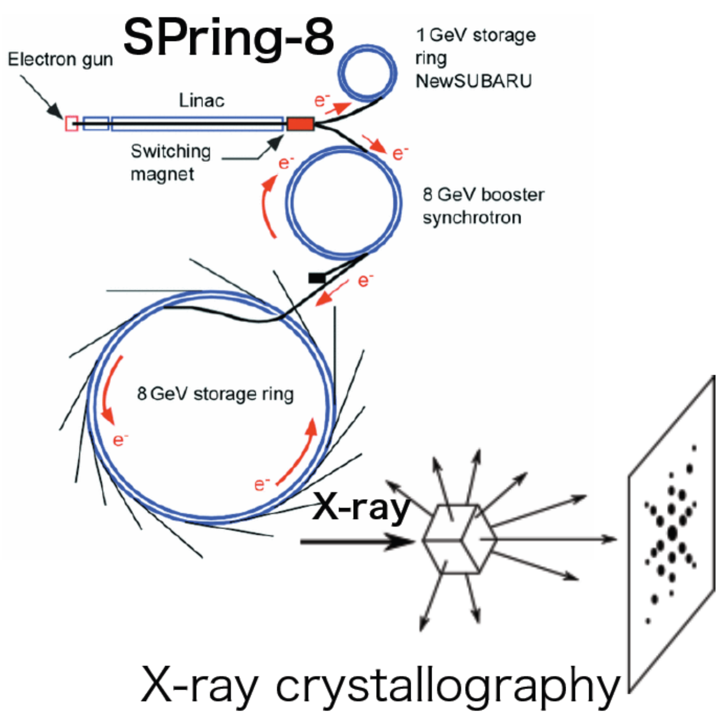
Vector magnet and mechanical rotator system

We can rotate ***H*** continuously within the *ab* plane with a misalignment less than 0.02 deg.





Experiment 2: Single Crystalline Synchrotron XRD



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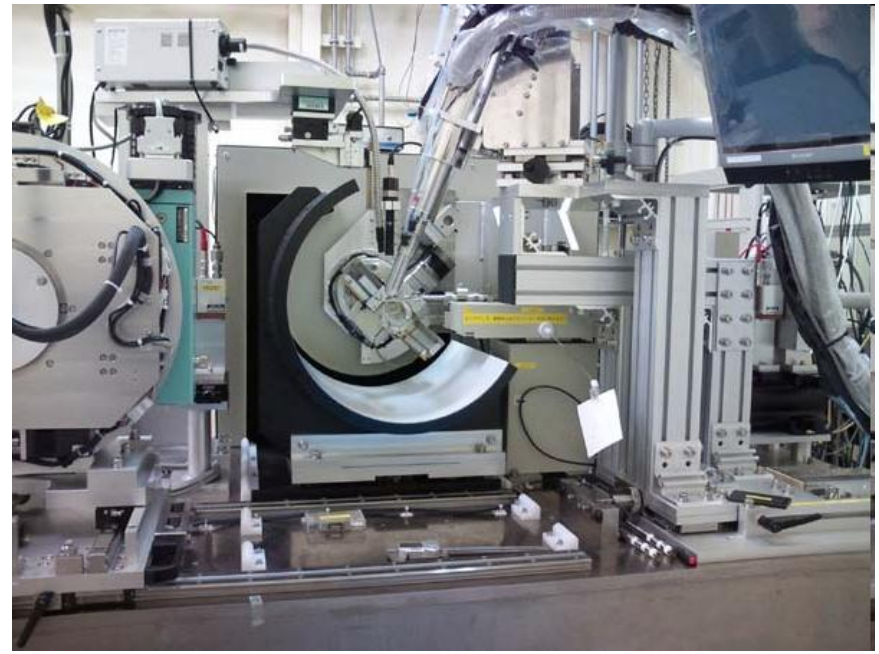
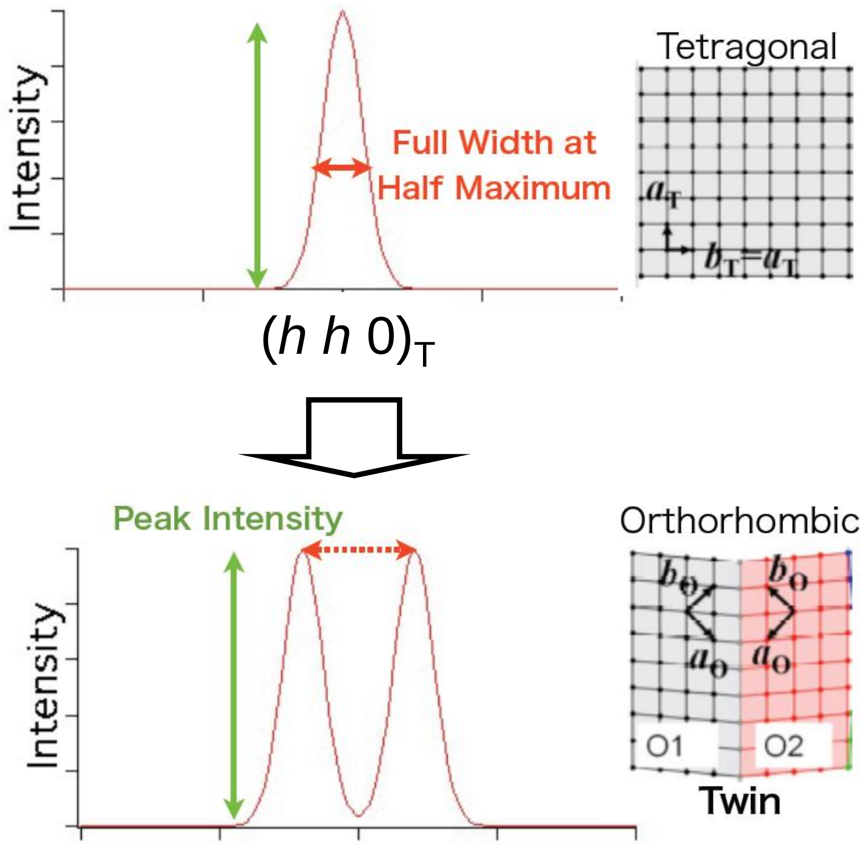


Experiment 2: Single Crystalline Synchrotron XRD



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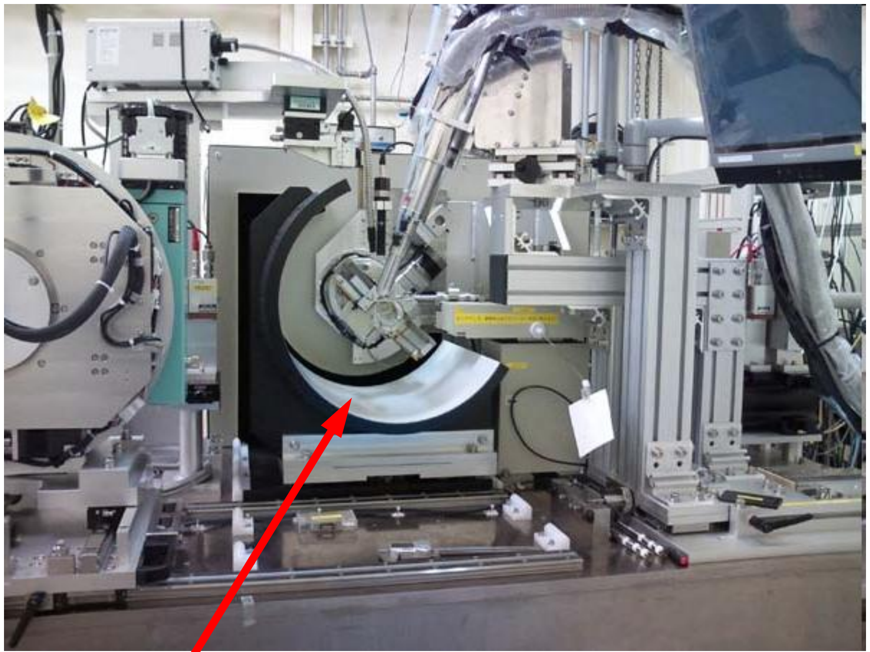


Equipped with a large cylindrical image-plate camera

(350 mm x 683 mm)

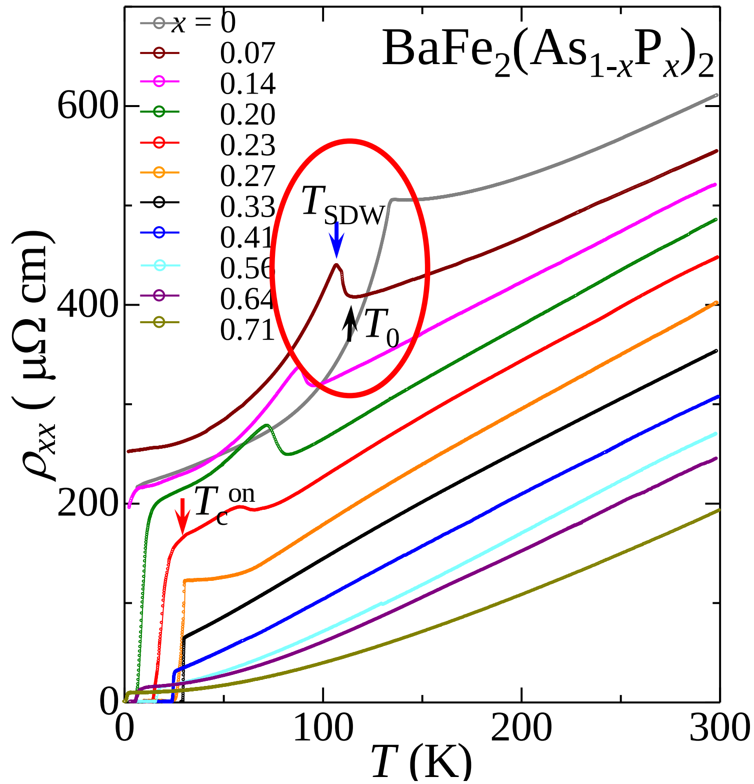
Higher order peaks $(7\ 7\ 0)_T$ or $(8\ 8\ 0)_T$

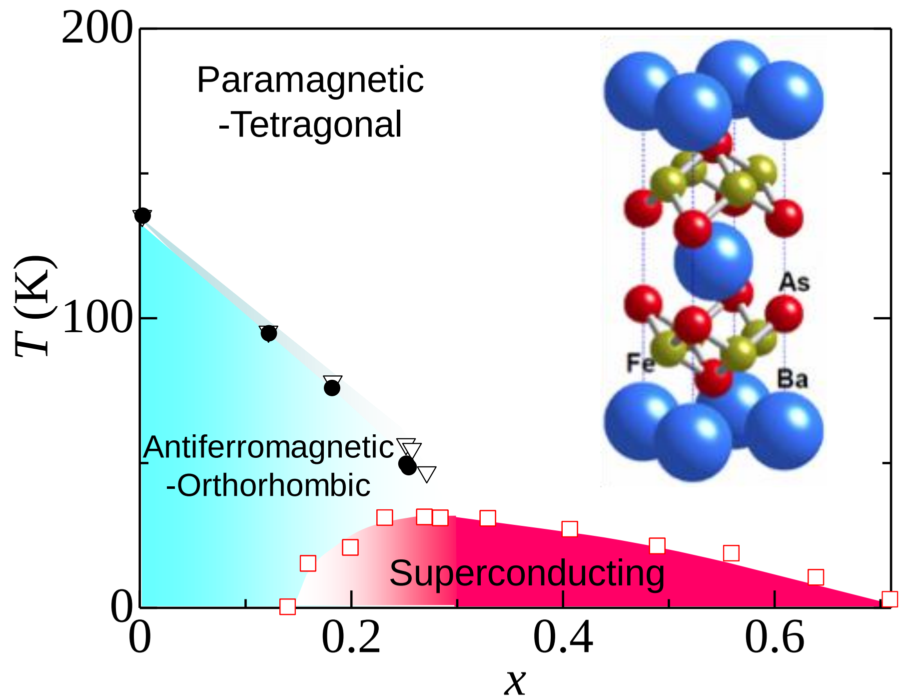
2θ values:

-60 deg $< 2\theta <$ 145 deg

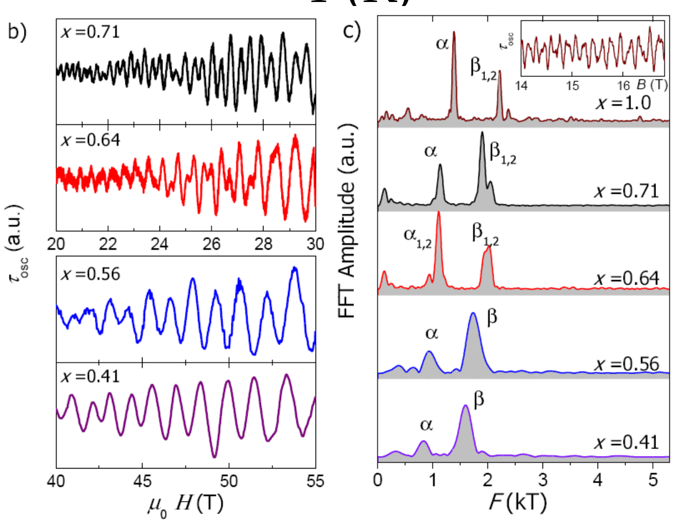
Sensitive experiments to the orthorhombic distortions.

System: $BaFe_2(As_{1-x}P_x)_2$





SK *et al.*, PRB **81**, 184519 (2010).
H. Shishido *et al.*, PRL **104**, 057008 (2010).



- Clear Anomalies at T_s & T_{SDW}
- Pure crystals are available

  Quantum oscillations are observed in a wide range (0.38 < x < 1.0)

An ideal system to study Iron-pnictides

Data are omitted because they are unpublished.