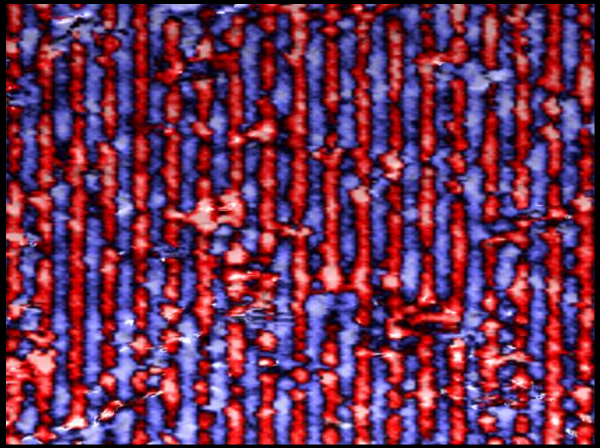
Imaging and Controlling Emergent States in Quantum Materials



Peter Wahl
University of St Andrews

Acknowledgements

Experiments:

Christopher Trainer, Chi Ming Yim, Ram Aluru, Haibiao Zhou, Antoine Essig, Jean-Philippe Reid (St Andrews)

Mostafa Enayat, Zhi-Xiang Sun, Udai Raj Singh, Stefan Schmaus (Stuttgart)

Samples:

Y. Liu, C.T. Lin, MPI Stuttgart

V. Tsurkan, J. Deisenhofer, A. Loidl, Universität Augsburg

Shun Chi, Doug Bonn, UBC Vancouver

Chris Stock, University of Edinburgh

Theory:

A. Yaresko, MPI Stuttgart

C. Heil and F. Giustino, Oxford University

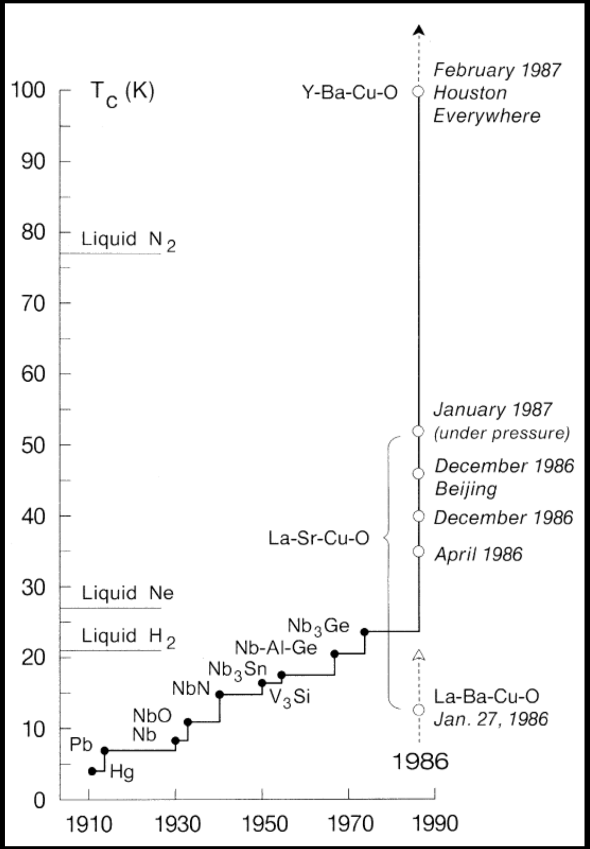
Funding:

Scottish Universities Physics Alliance

Netherlands Organization for Scientific Research (Rubicon Grant)

EPSRC

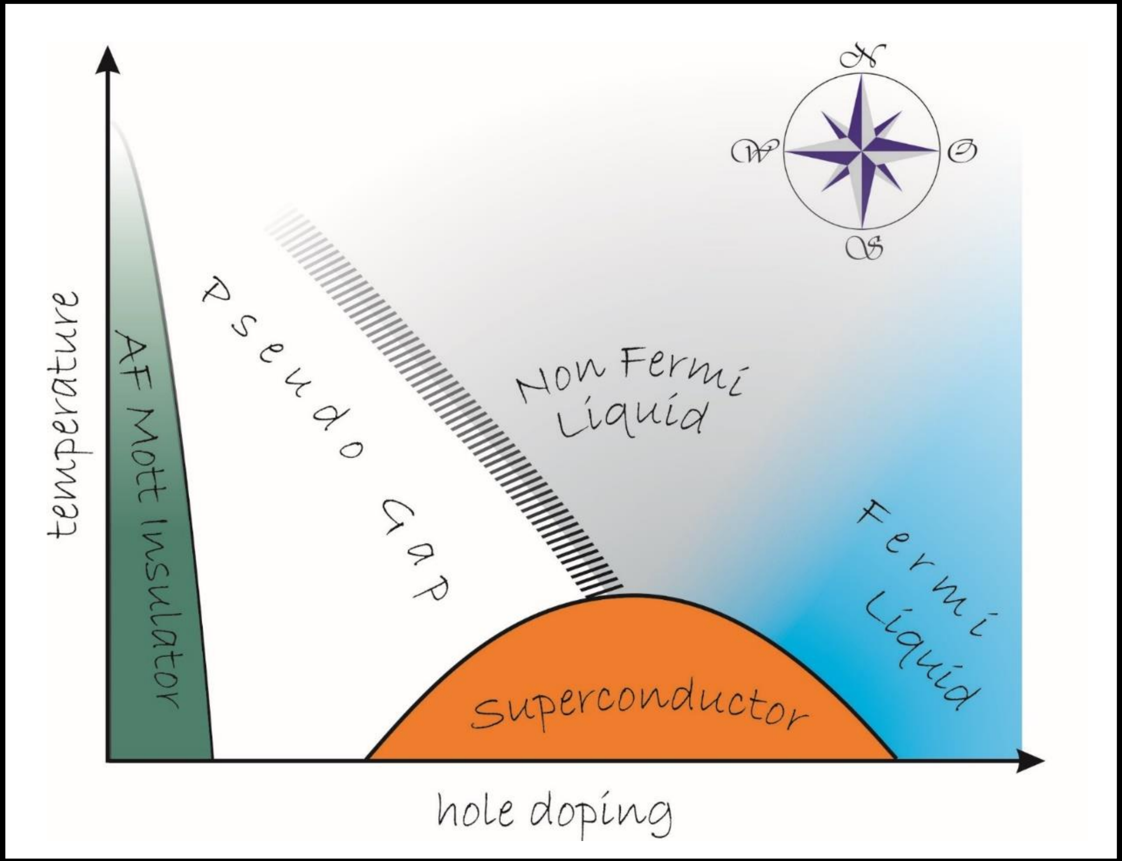
Quantum Materials - High Tc Superconductivity



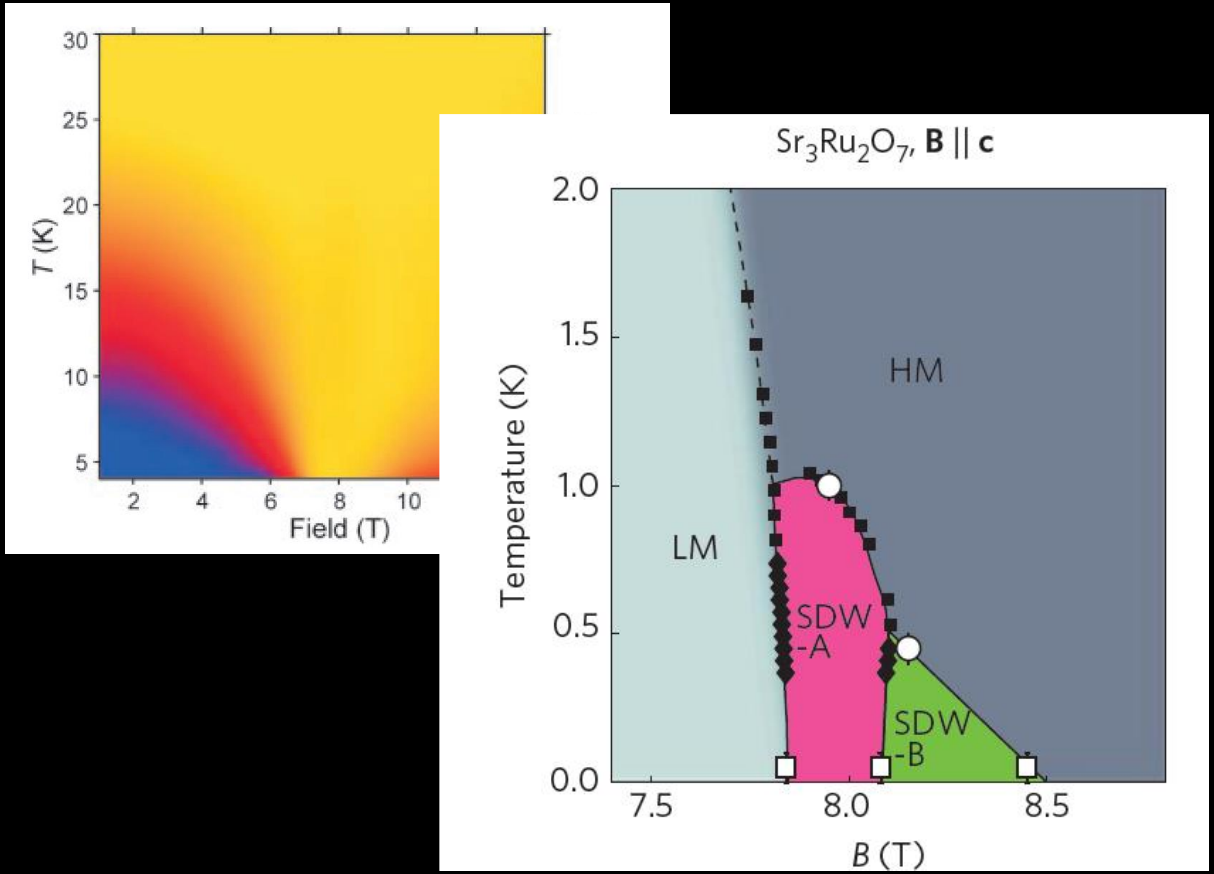
May 11, 1987

K.A. Müller and J.G. Bednorz, *Science* **237**, 1133 (1987)

Phase Diagrams of Quantum Materials



Nat. Phys. **8**, 514

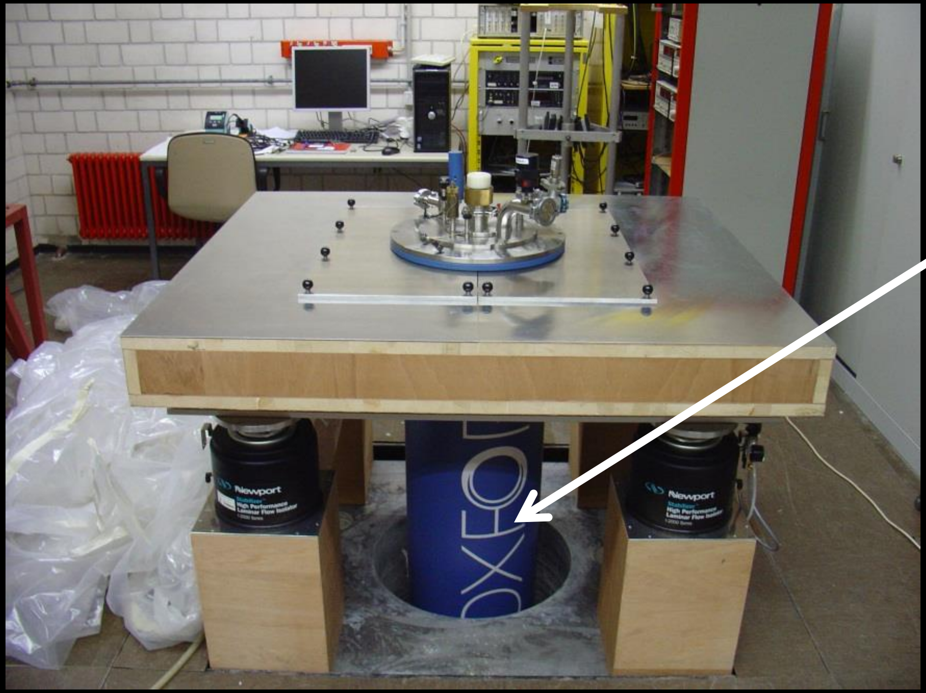


C. Lester *et al.*, Nat. Mat. **14**, 373 (2015)
S. Grigera *et al.*, Science **294**, 329 (2001)

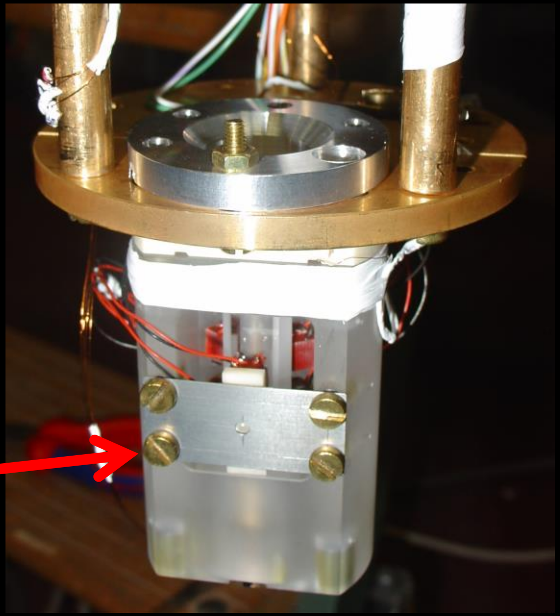
Instrumentation

- 1.6K (to ~20K) 16T SI STM
- 7mK(MXC), 14T SI-STM, hold time up to ~140h
- 1.6K, 9/5T vector magnet

All with sample exchange and *in-situ* sample cleavage.



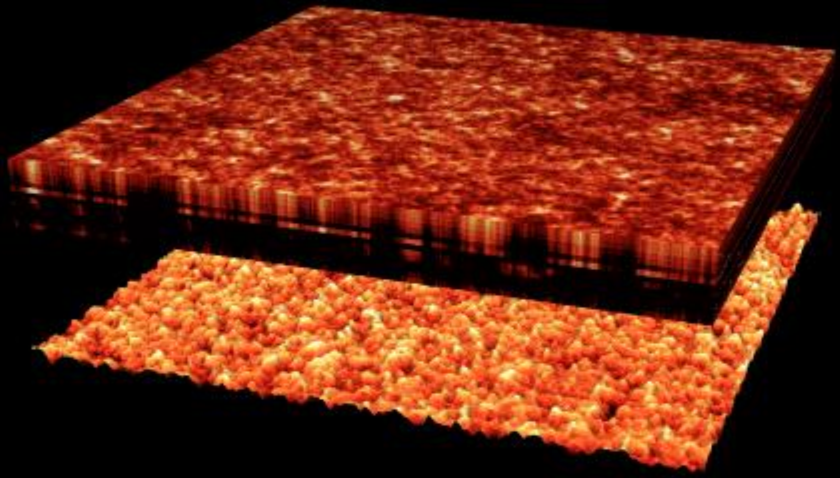
Magnet dewar

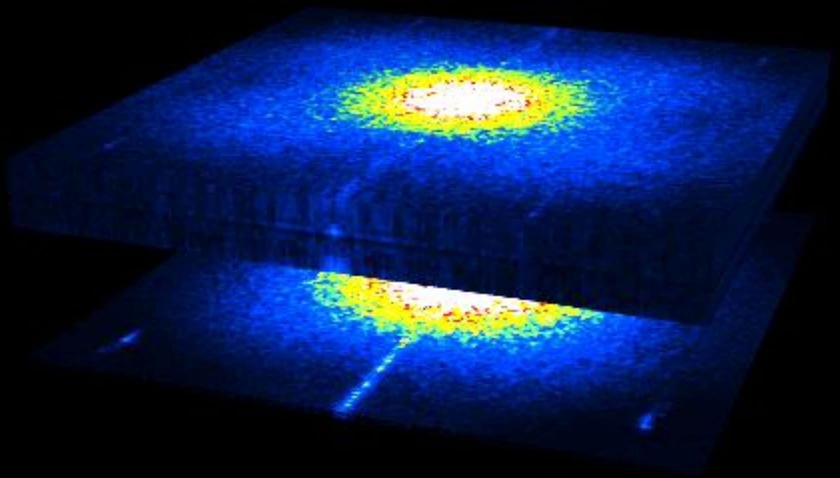


STM head

Rev. Sci. Instr. **82**, 113708 (2011); Rev. Sci. Instr. **84**, 013708 (2013); Rev. Sci. Instrum. **88**, 093705 (2017)

Spectroscopic Mapping





Spatial map of
local excitations:

- Local gap size
- Effect of defects
- Inelastic excitations
- Local ordering

FFT

Periodic effects:

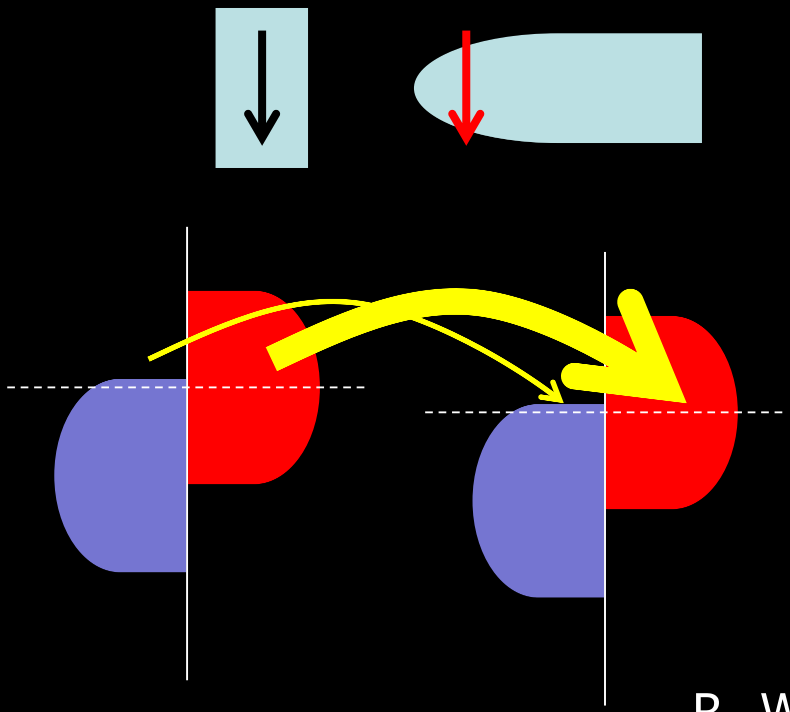
- Quasiparticles
- CDWs
- Lattice distortions

Spin-polarized STM

With a magnetic tip on a magnetic sample:

$$I(V) \propto \int_{-\infty}^{+\infty} \left(\rho_s^{\uparrow}(E)\rho_t^{\uparrow}(E-eV) + \rho_s^{\downarrow}(E)\rho_t^{\downarrow}(E-eV) \right) T(E,V,z)\left(f(E-eV,T_t) - f(E,T_s) \right) \mathrm{d}E$$

Sample LDOS Tip LDOS



R. Wiesendanger, Rev. Mod. Phys. 81, 1495

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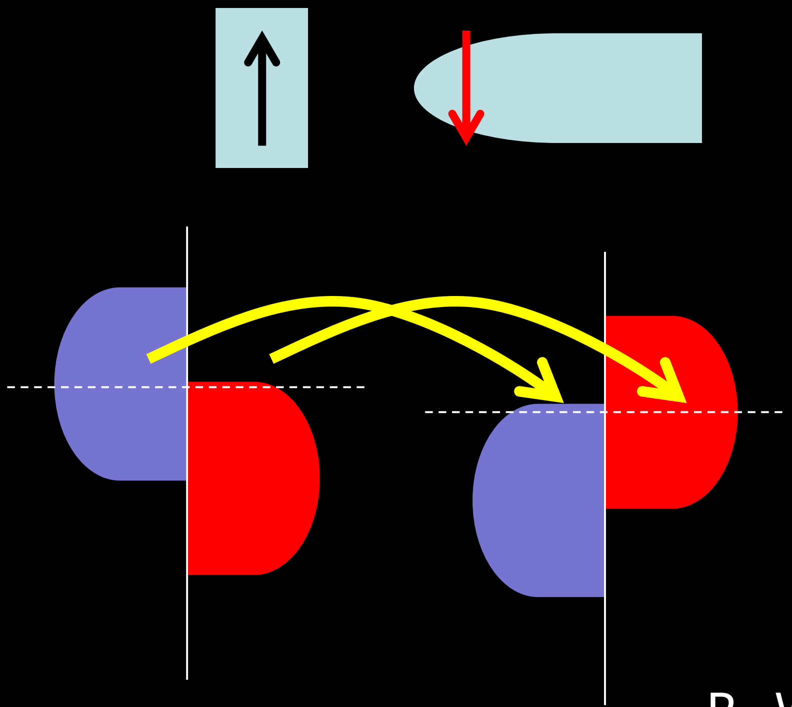
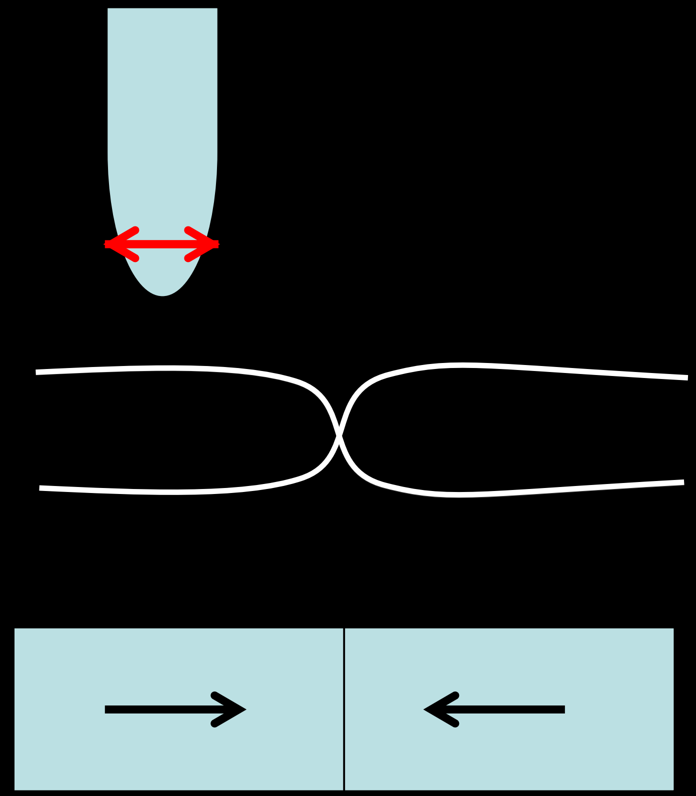


In constant current mode: tip will approach

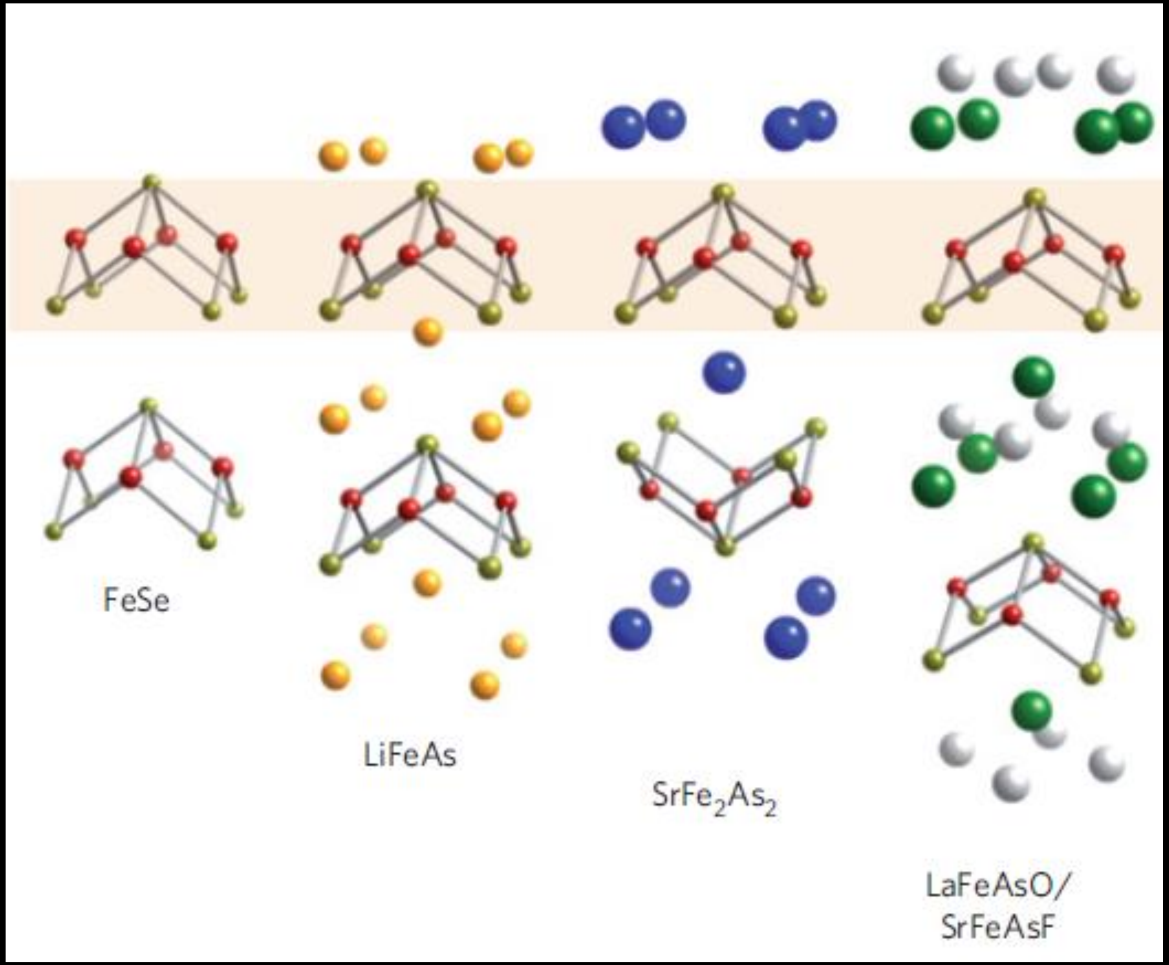
R. Wiesendanger, Rev. Mod. Phys. 81, 1495

What is the Smoking Gun of Magnetic Imaging with STM ?



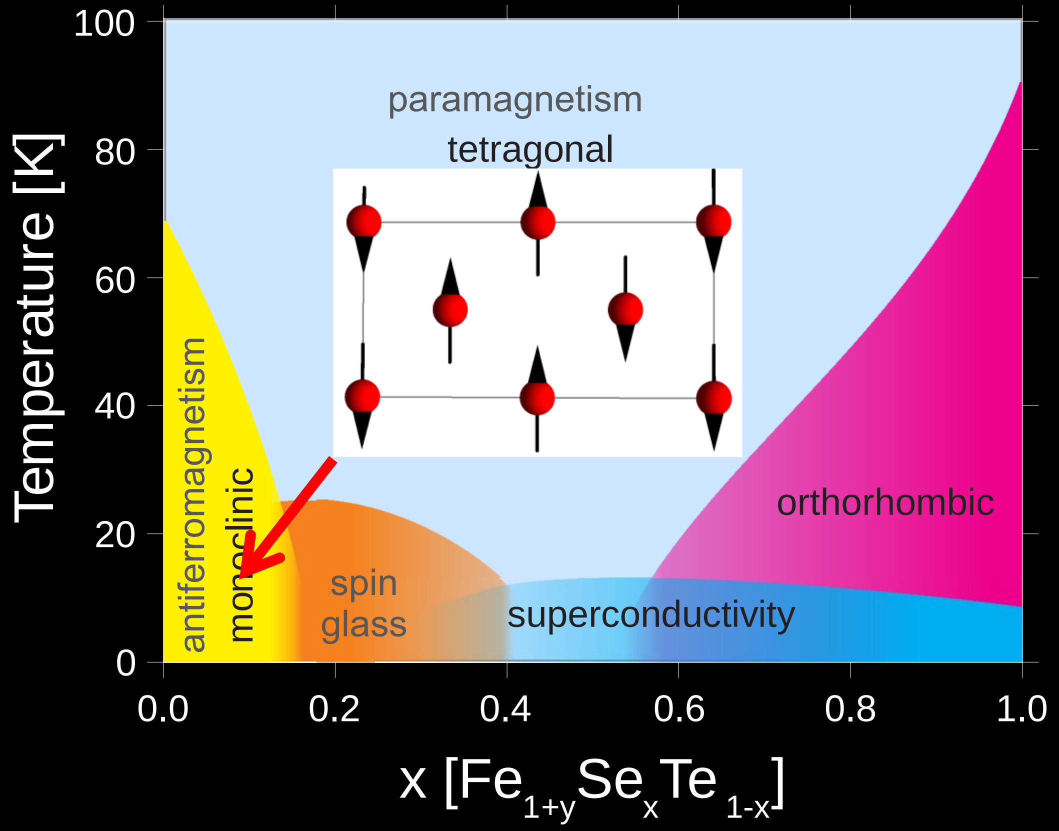
1. Change the magnetization of the tip
2. image the same place with the same tip

Iron-based Superconductors



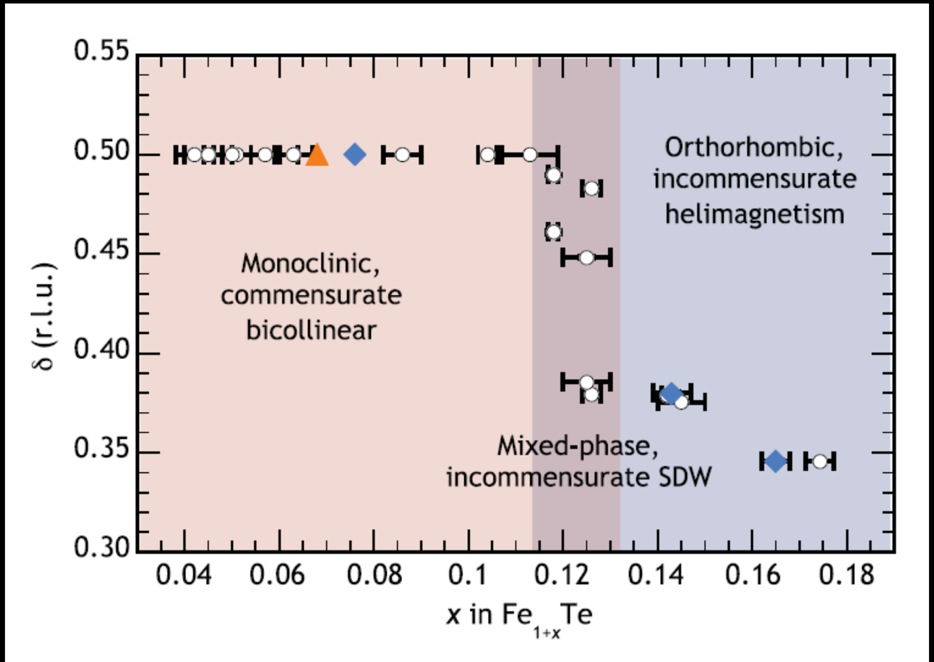
Paglione&Greene, *Nat. Phys.* **6**, 645 (2010)

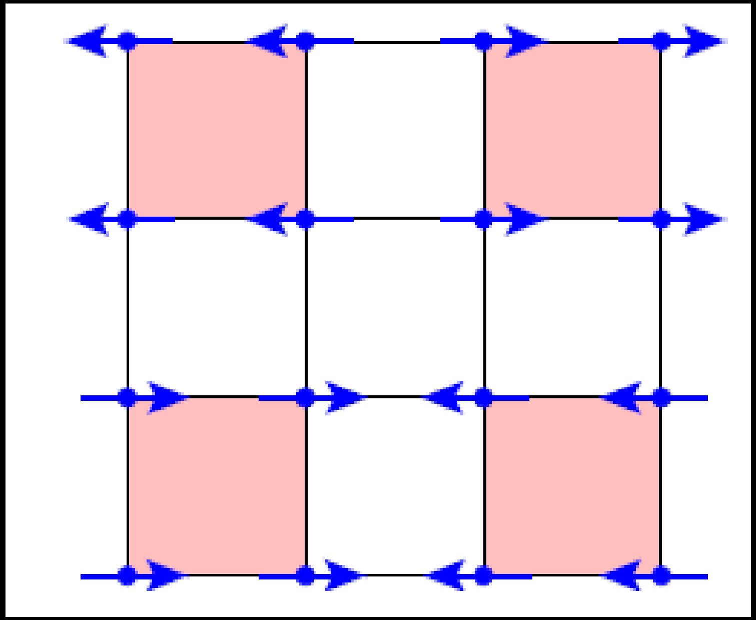
Phase Diagram



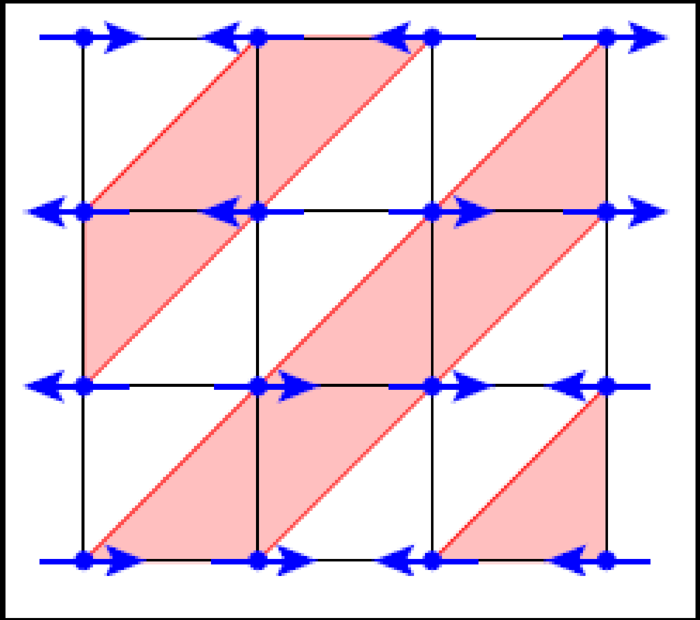
N. Katayama *et al.*, *J. Phys. Soc. Jpn.* **79**, 113702 (2010);
Y. Mizuguchi and Y. Takano, *J. Phys. Soc. Jpn.* **79**, 102001 (2010)

Phase Diagram





Plaquette Order



Diagonal Double Stripe Order

Origin of complex magnetic order:

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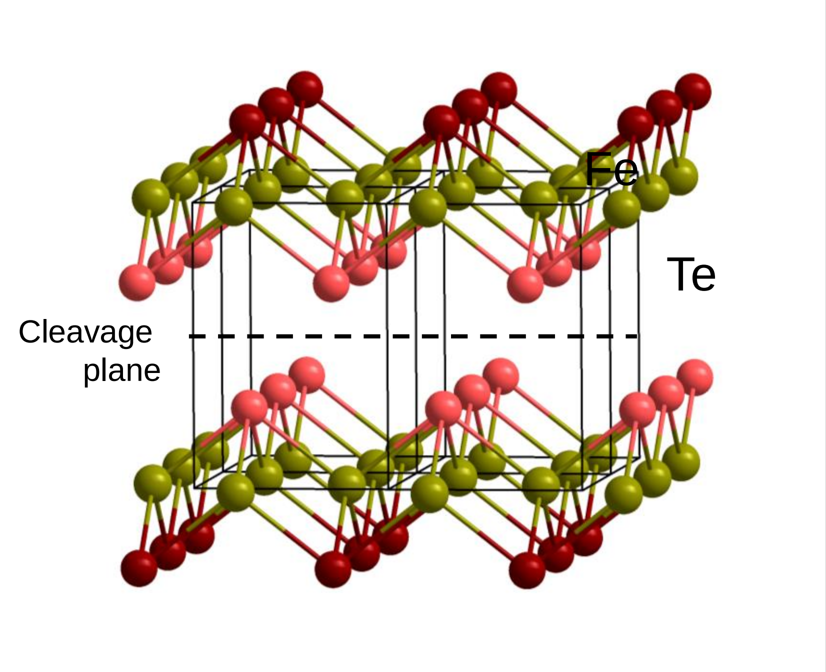
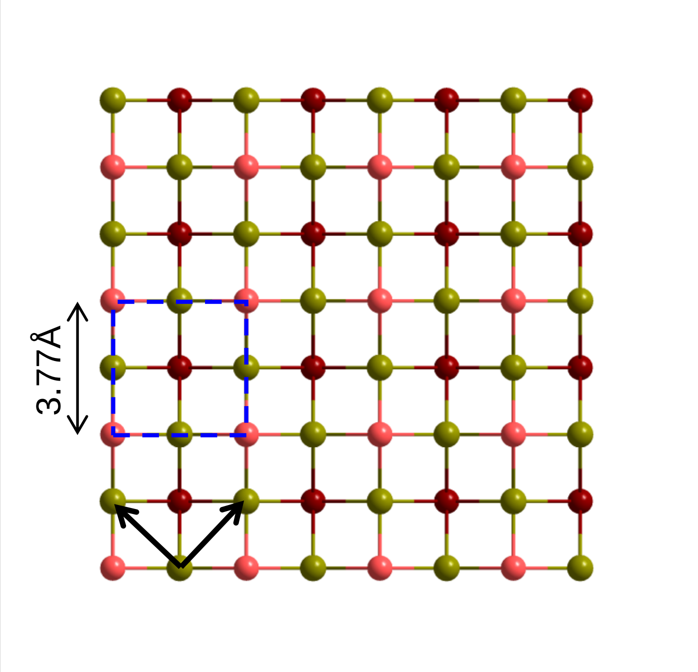
- Structural distortion driving double-stripe order (Glasbrenner et al., Nat. Phys. 11, 954)

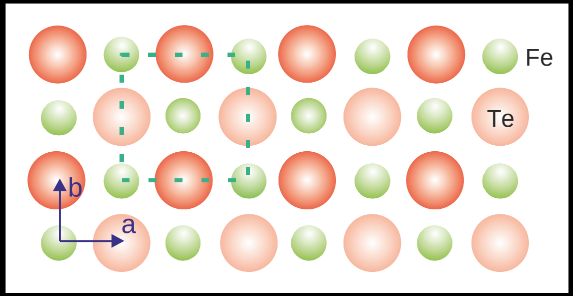
E.E. Rodriguez *et al.*, Phys. Rev. B84, 064403 (2011)

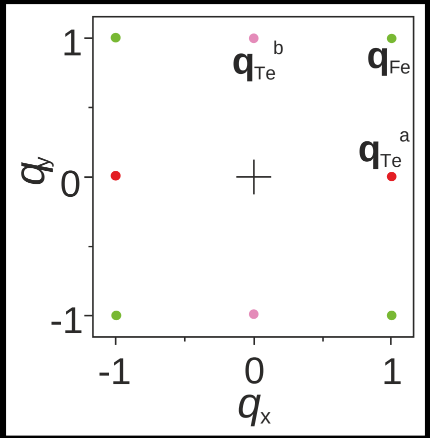
$Fe_{1+\delta}Te$

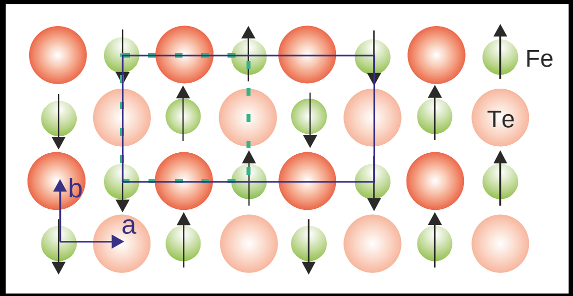




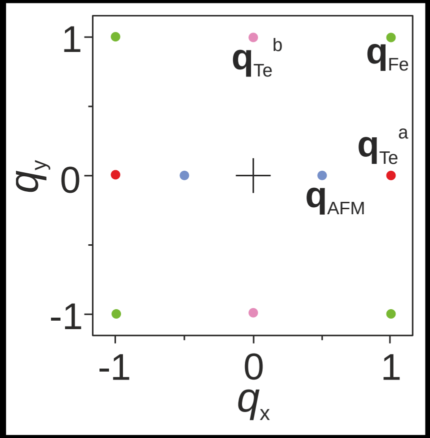
Stripes in FeTe







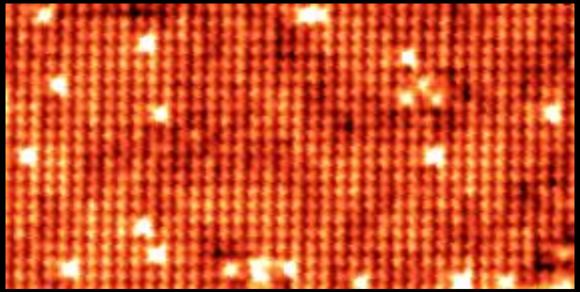
Magnetic structure deduced from Neutron Scattering

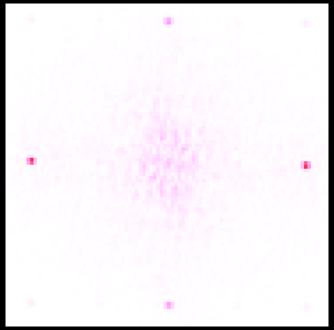


Expected Pattern in Fourier Space

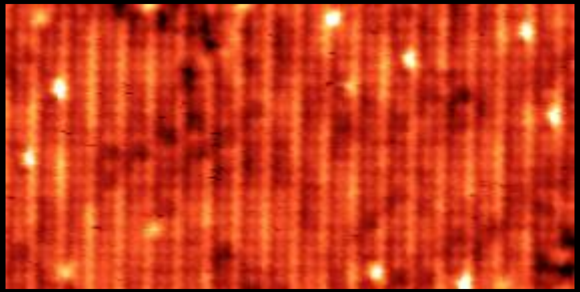
Stripes in FeTe

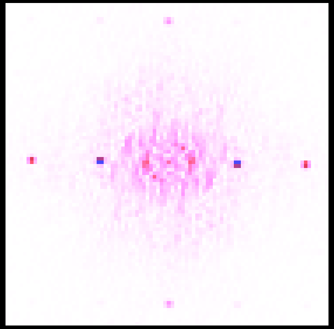
Non-magnetic tip





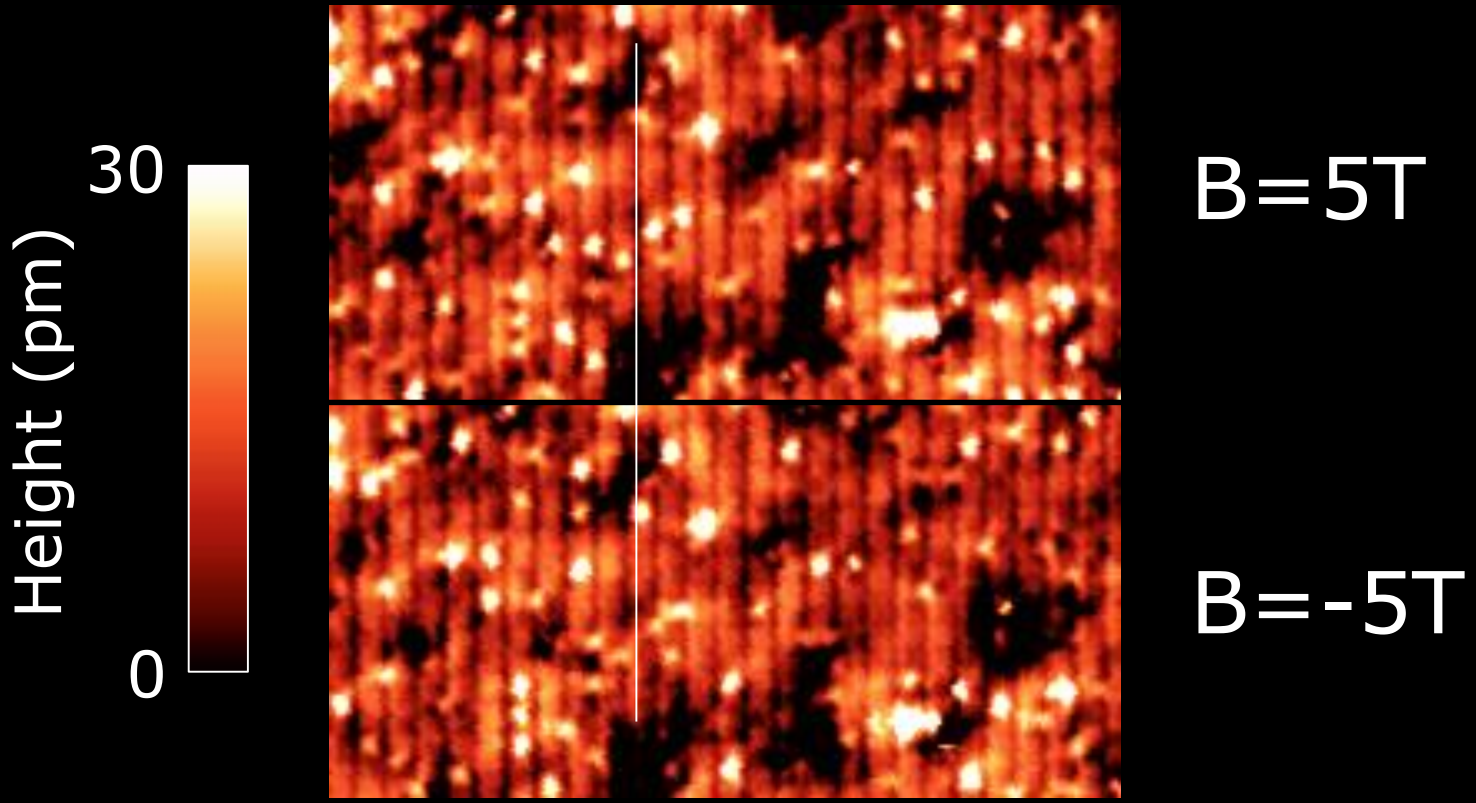
Magnetic tip



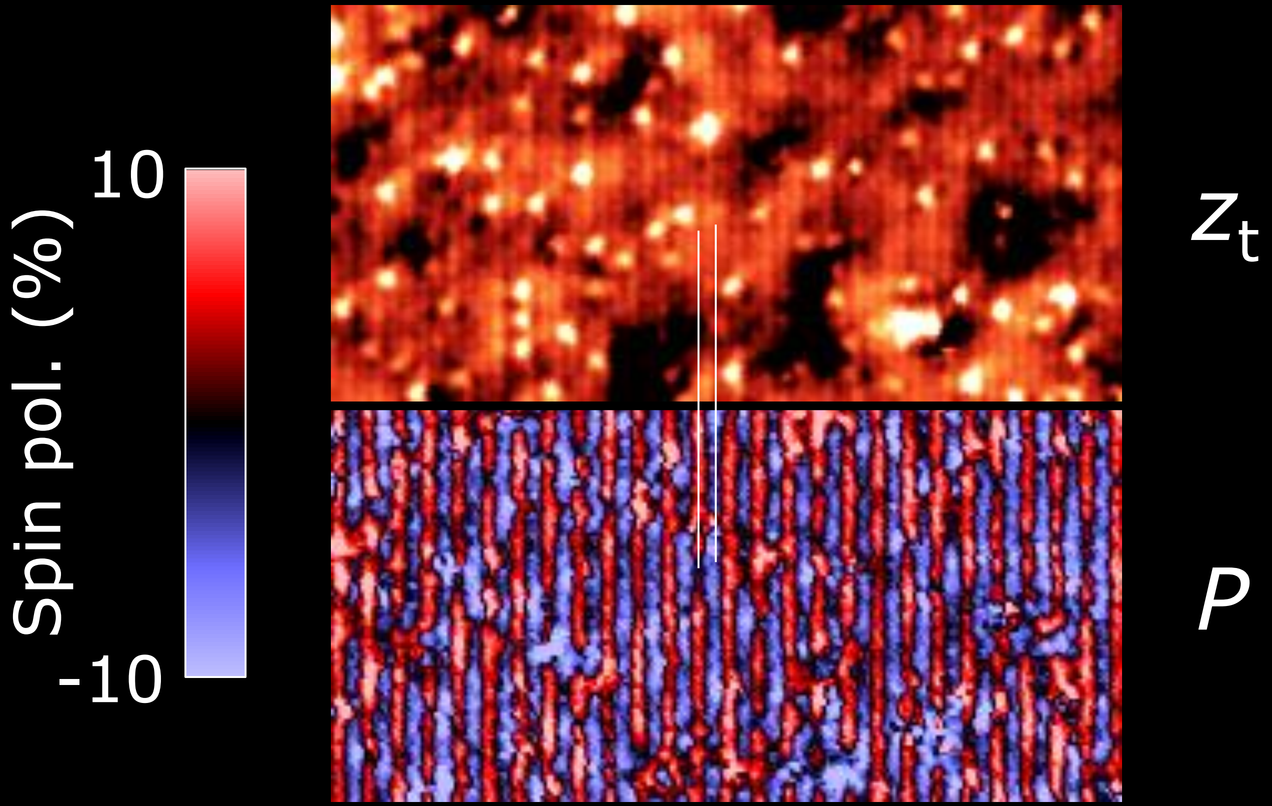


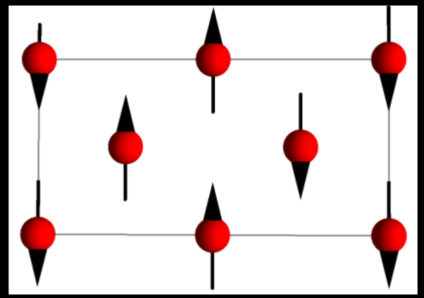
Some Fe defects gone …

Magnetic Field



Magnetic Field

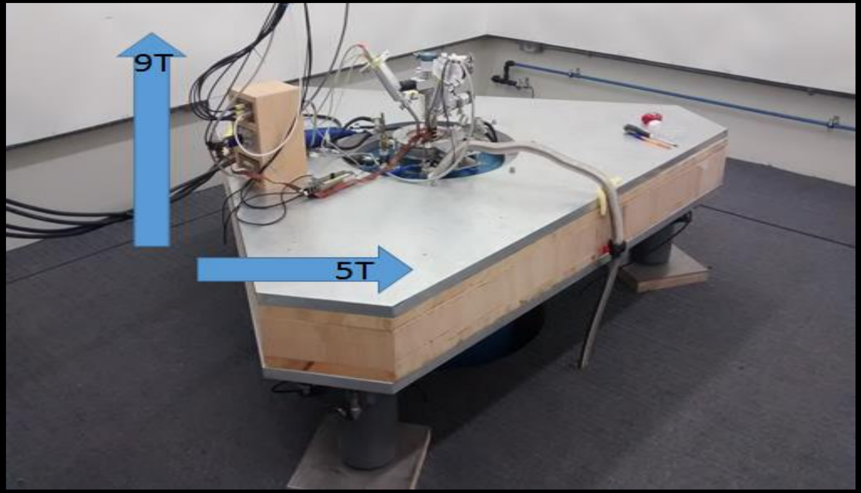


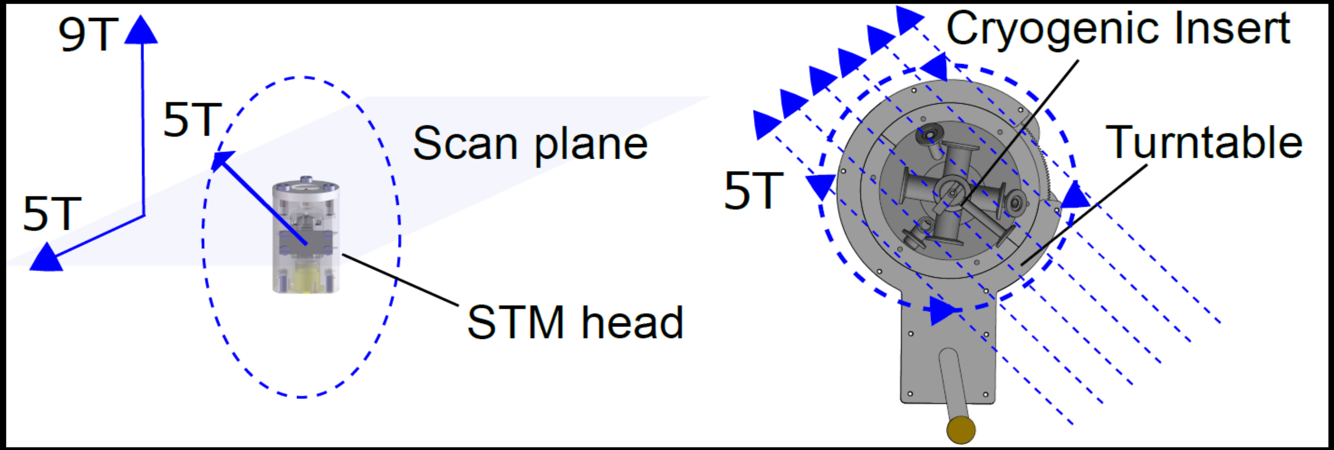


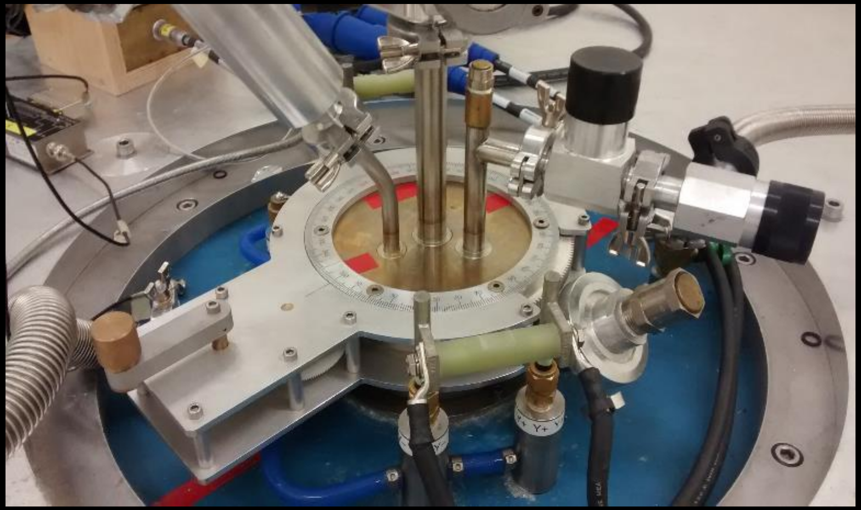
Largest spin polarization between Te atoms !

Science **345**, 653 (2014)
Phys. Rev. B **91**, 161111 (2015)

STM in a Vectormagnet



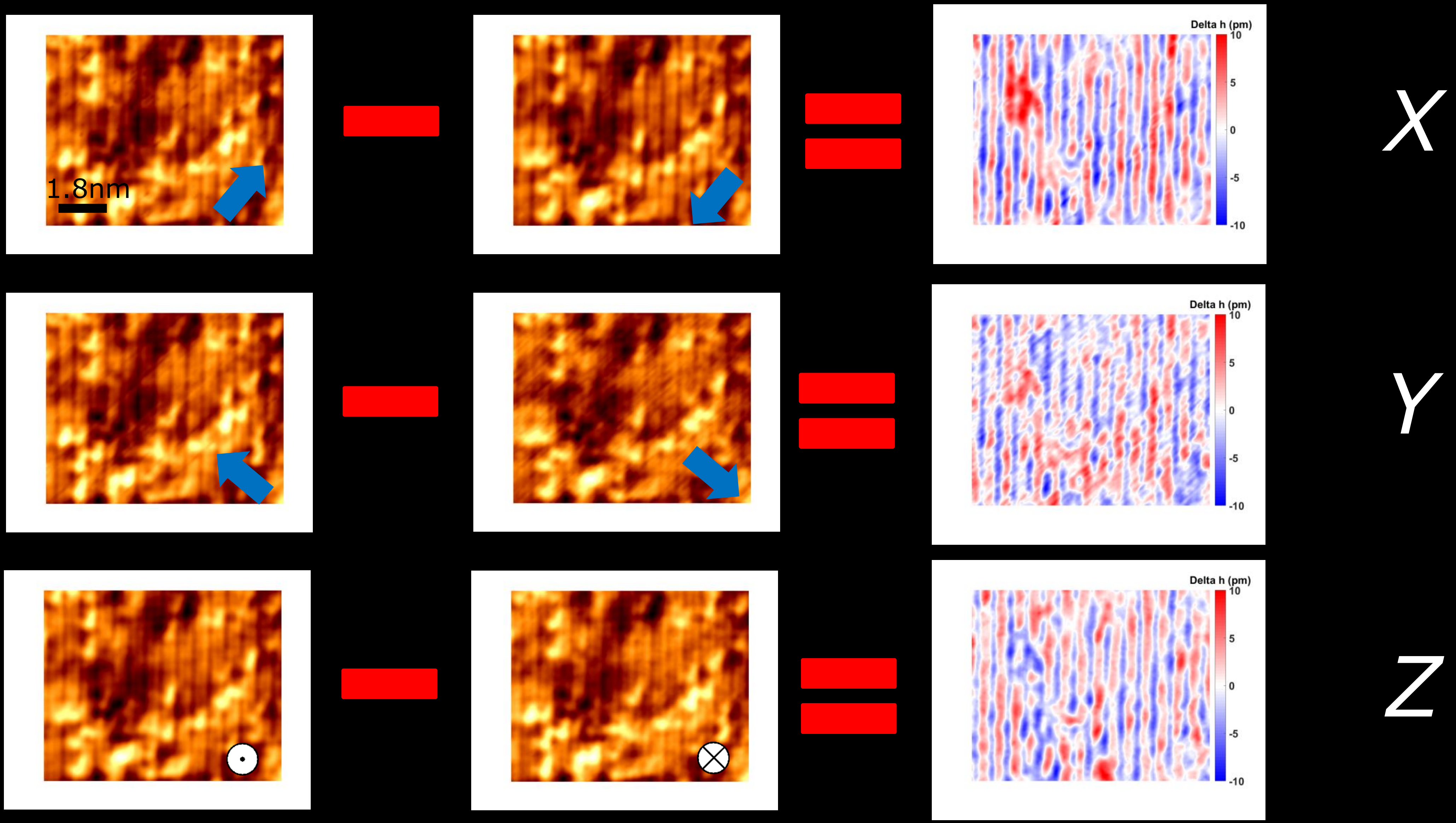




Full 3D rotation of 5T

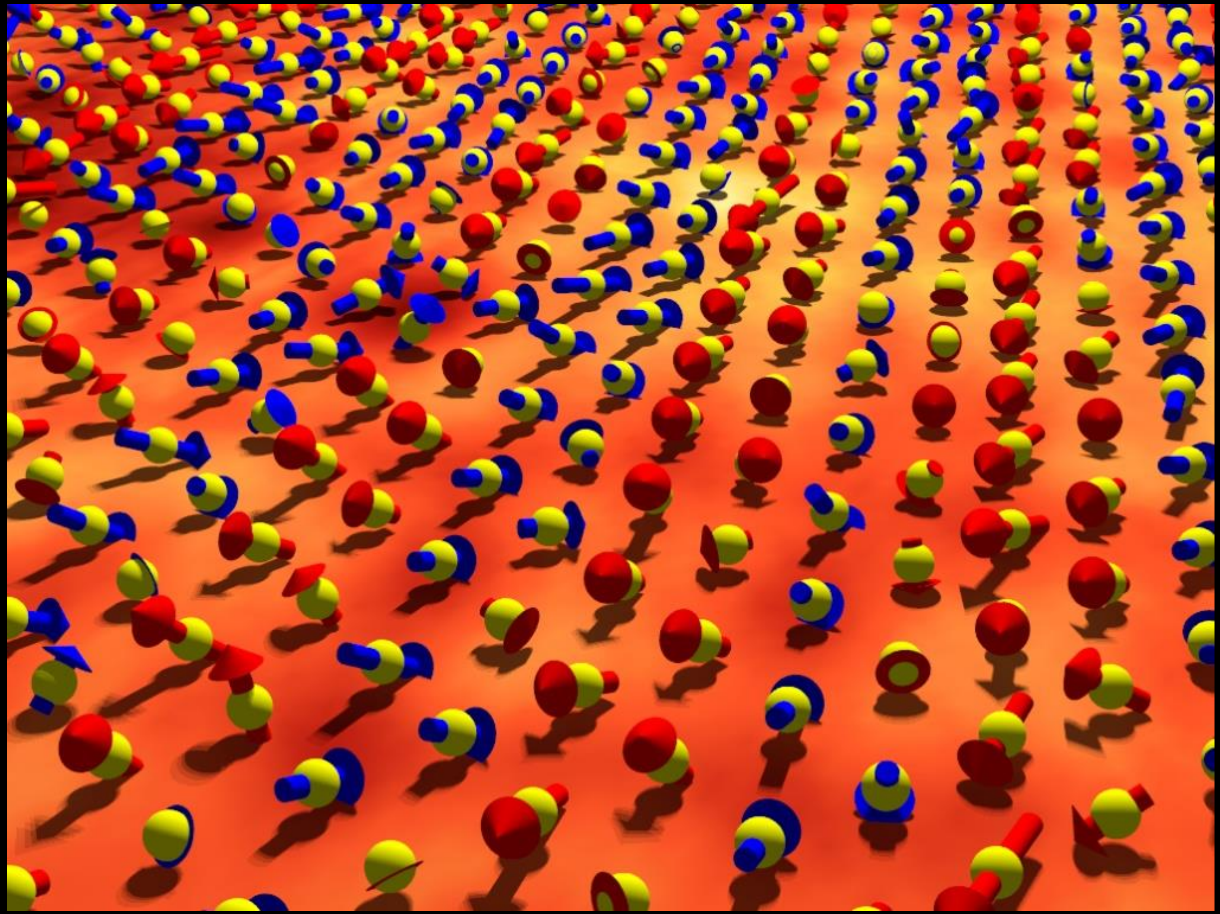
Rev. Sci. Instr. 88, 093705 (2017)

Results: Low excess Fe – $Fe_{1.06}Te$

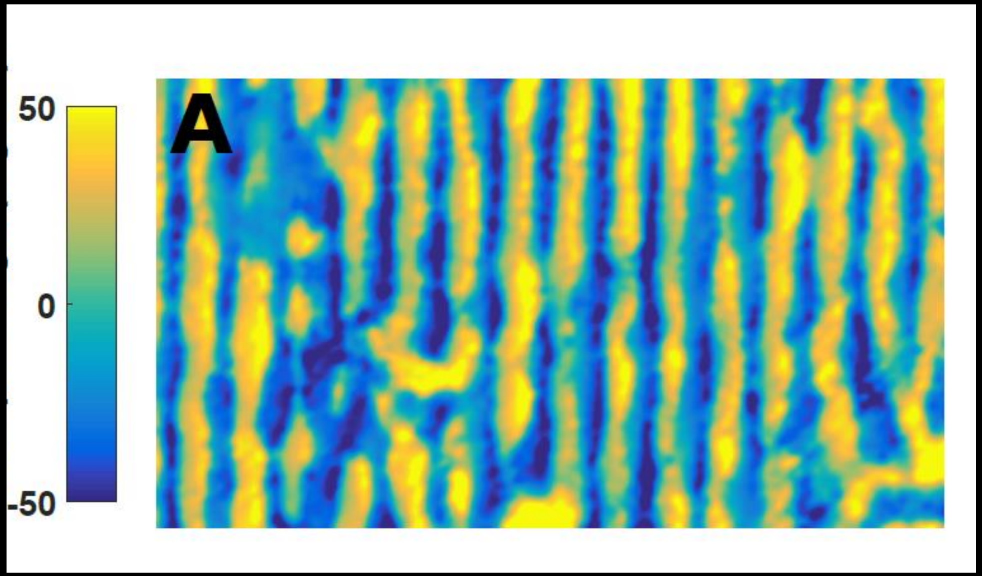


C.Trainer et al. arxiv/1802.05978

Reconstructing the magnetic structure



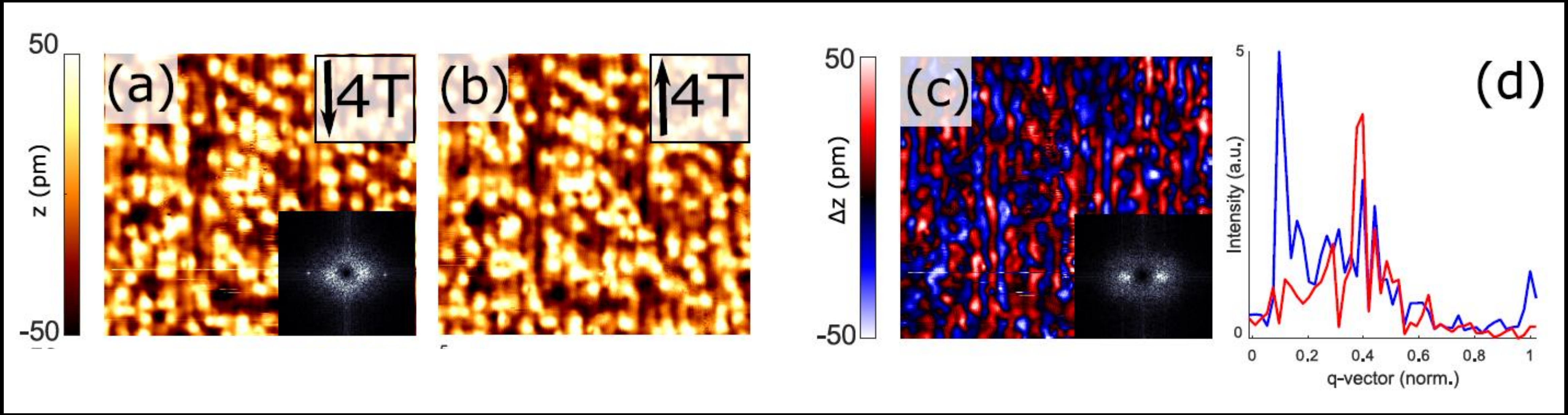
Out of plane angle (degrees)



- out of plane component of 31°
- Same periodicity, but different magnetization direction than neutron scattering

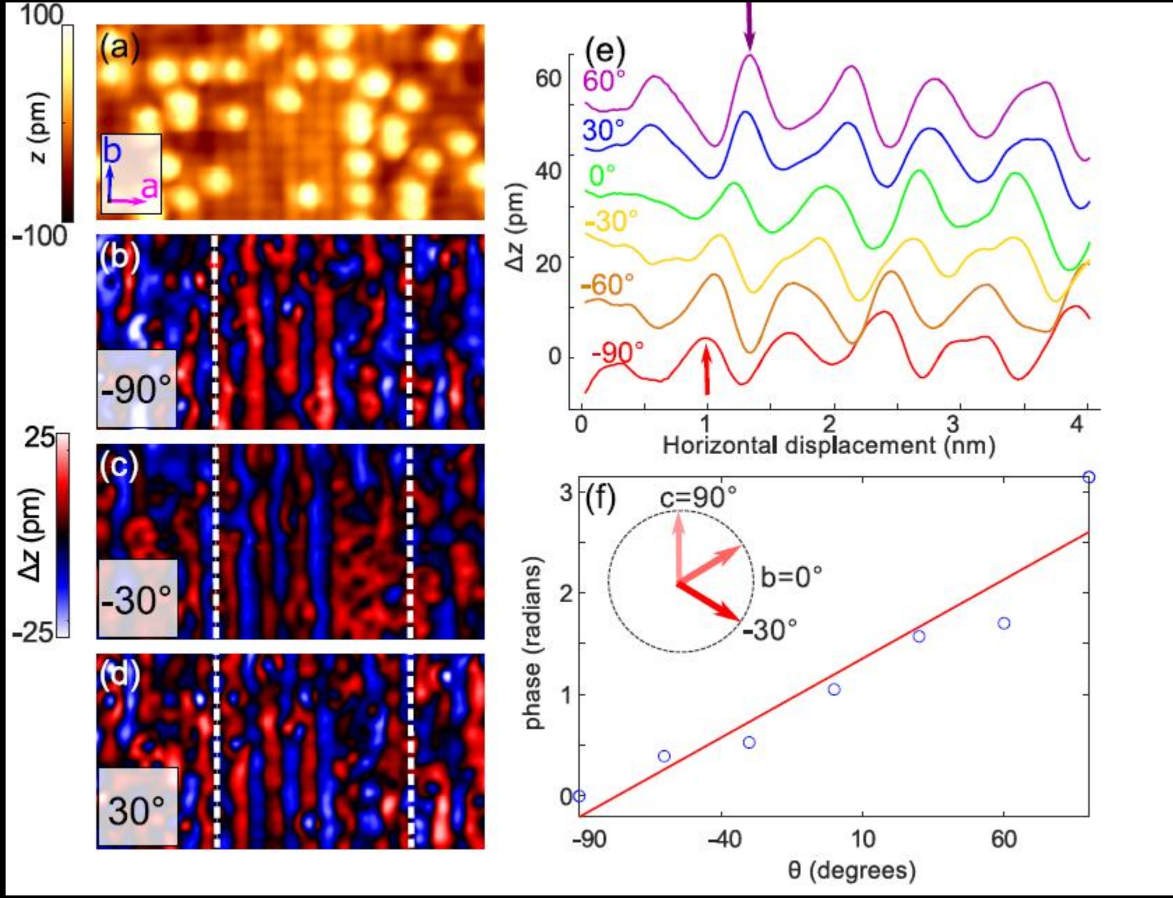
see also Hänke *et al*, Nat. Commun. 8, 13939

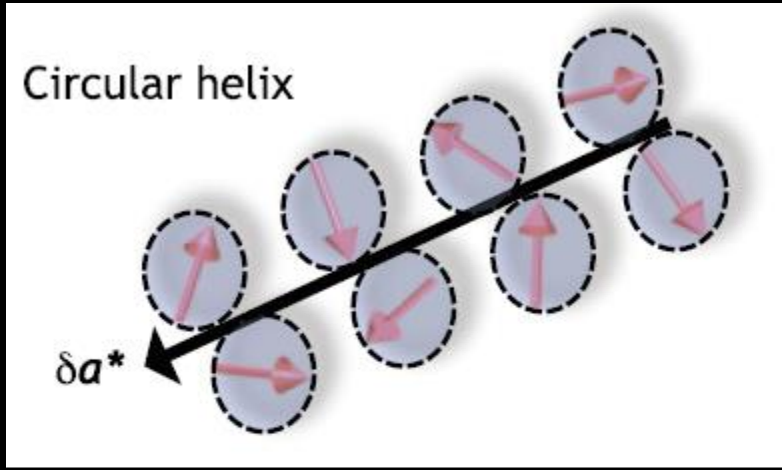
Magnetic order at high excess Fe concentations $x>0.12$



Incommensurate order with $q=0.4$.

Magnetic order at high excess Fe concentations x>0.12

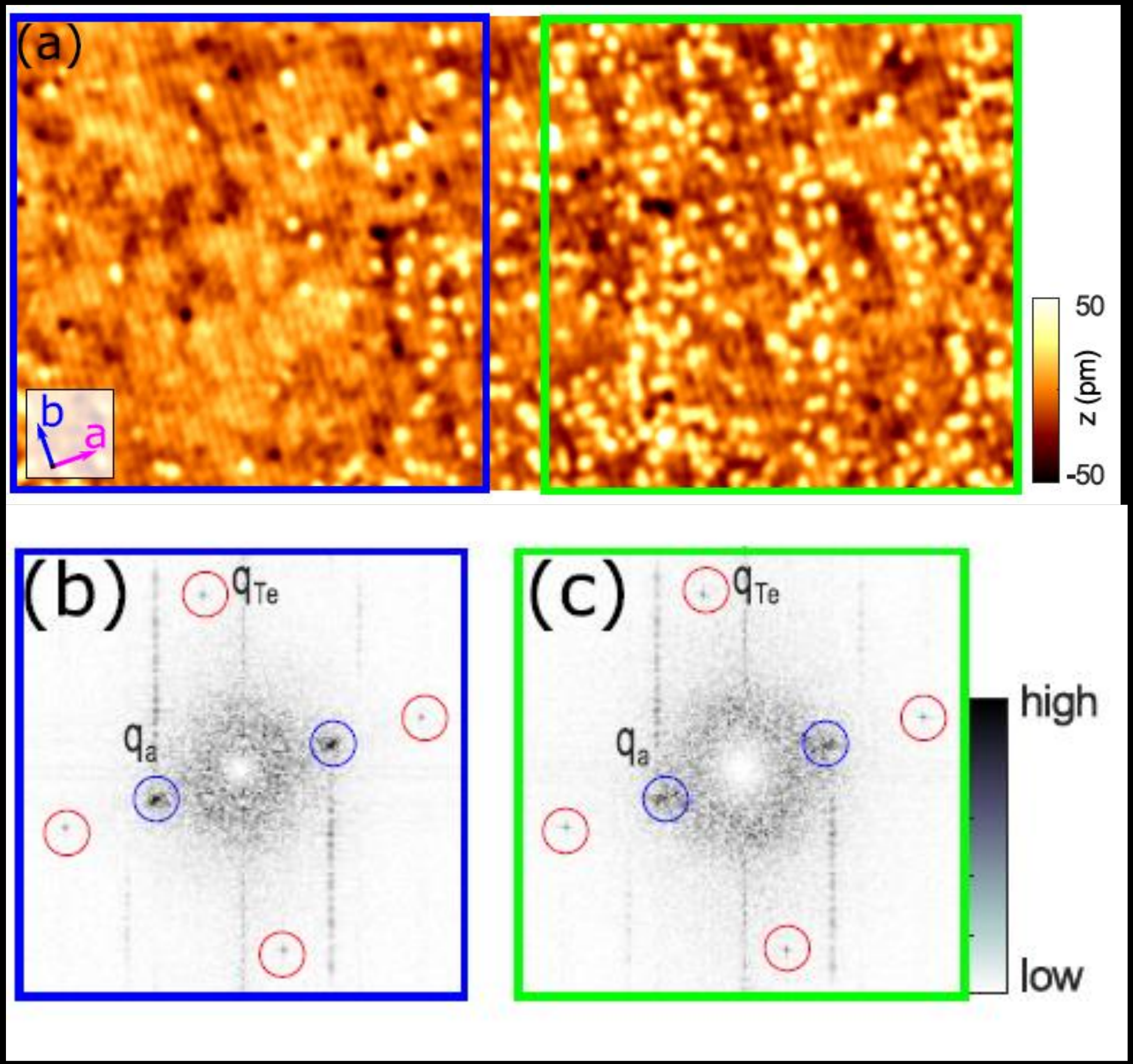


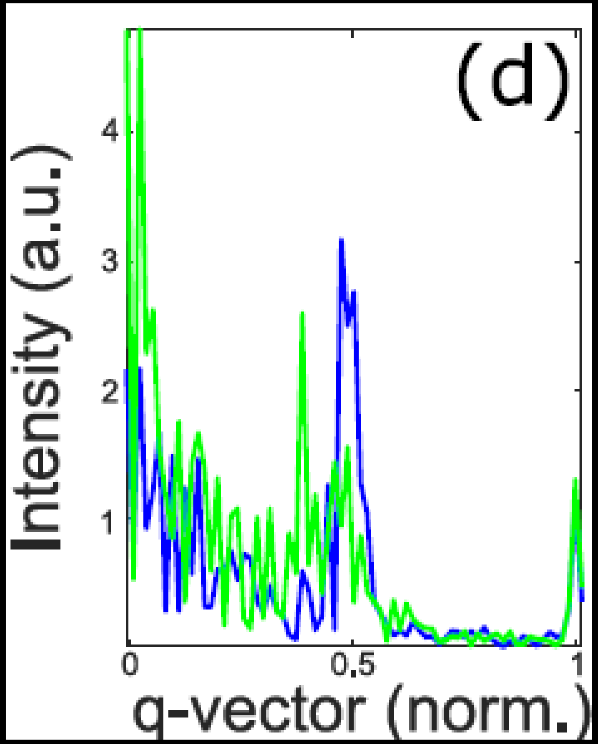


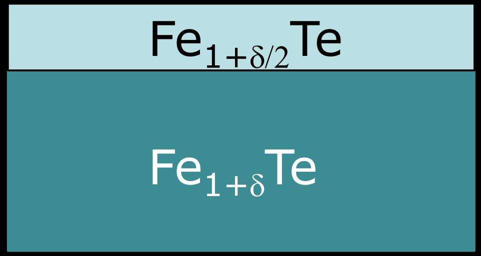
Spin spiral!

- spin spiral rotating in the bc plane
- full agreement with neutron scattering

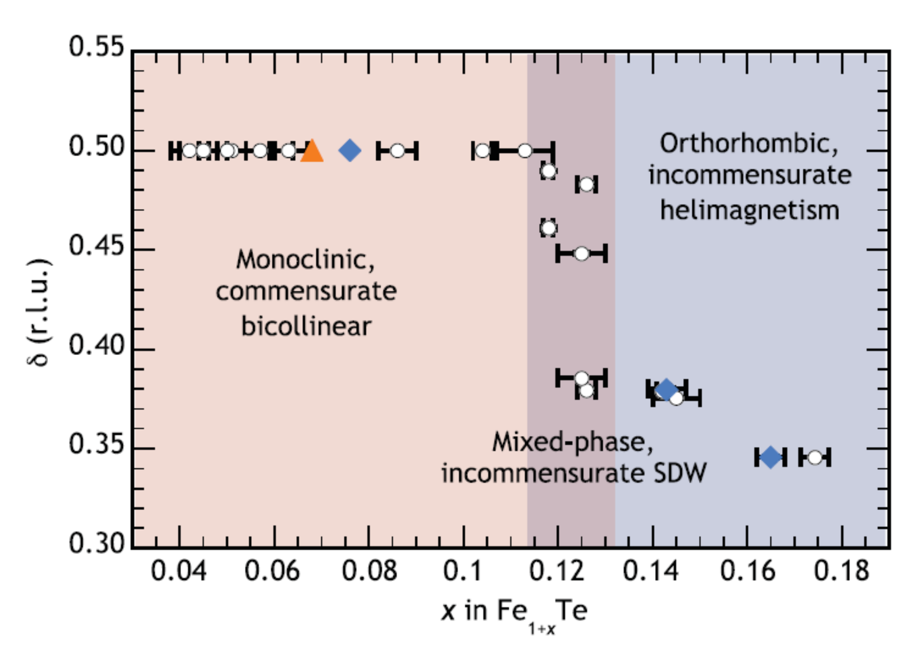
Effect of removing surface Fe

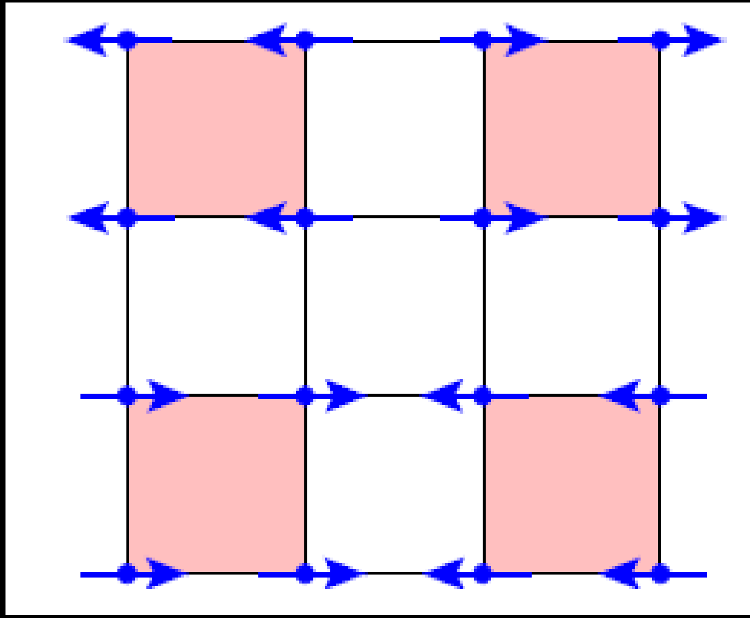




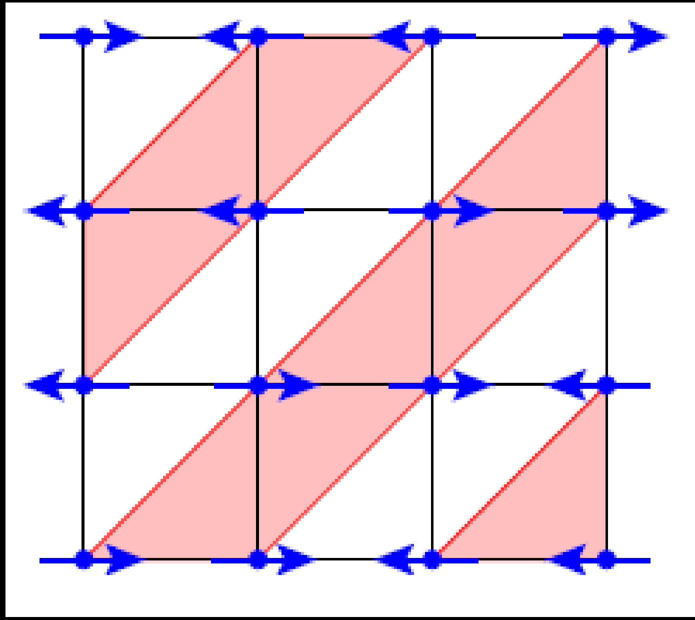


Phase Diagram





Plaquette Order



Diagonal Double Stripe Order

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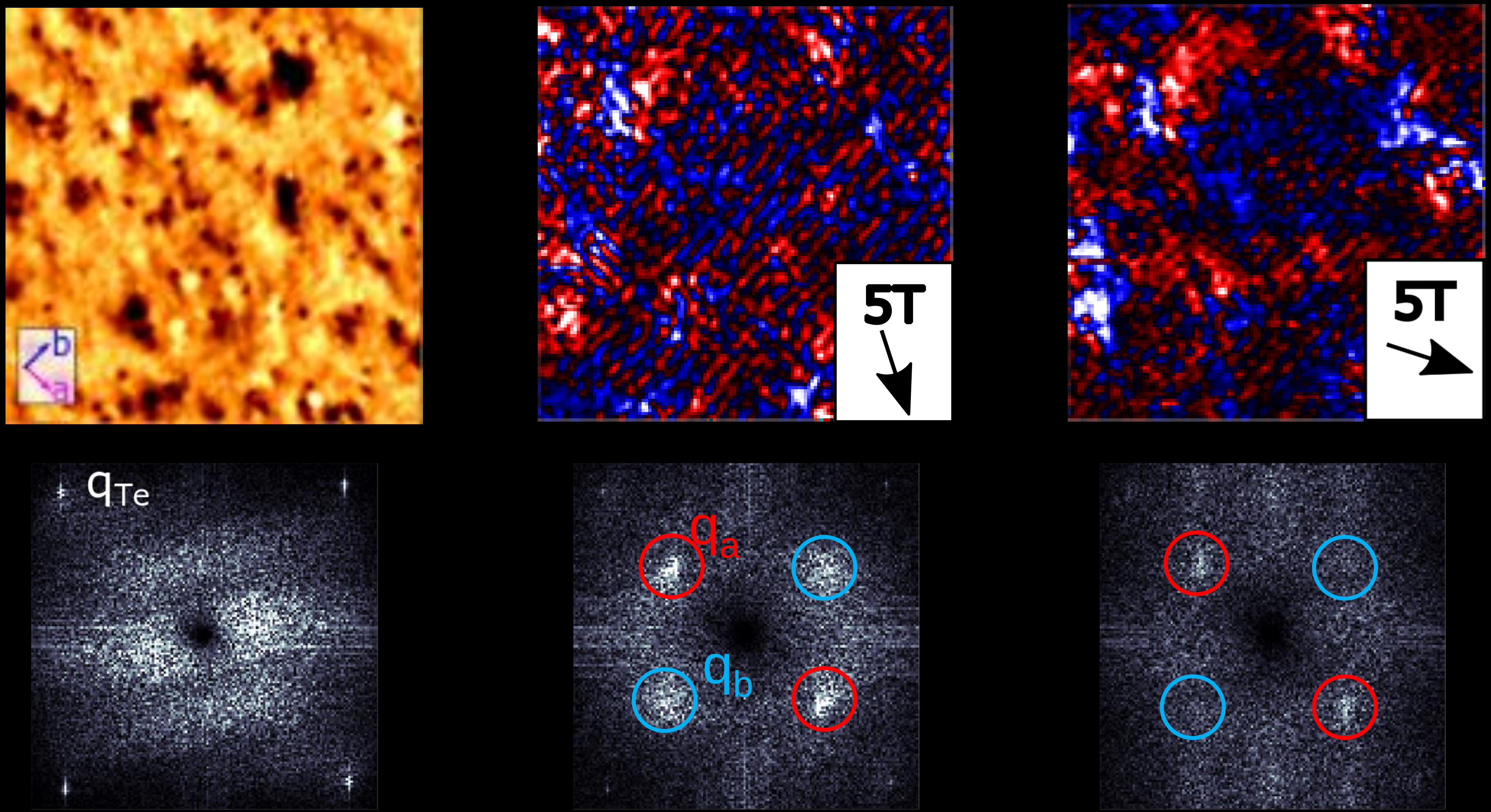
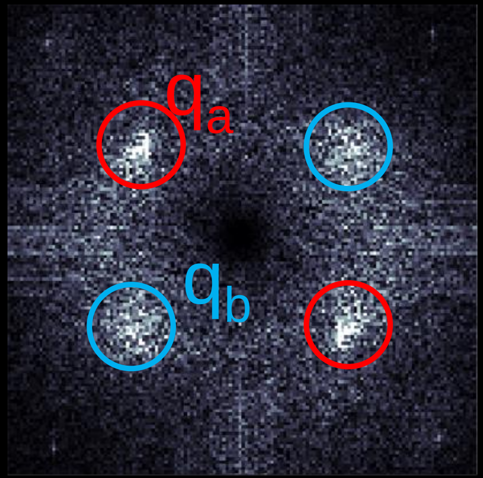
- Structural distortion driving double-stripe order (Glasbrenner et al., Nat. Phys. 11, 954)

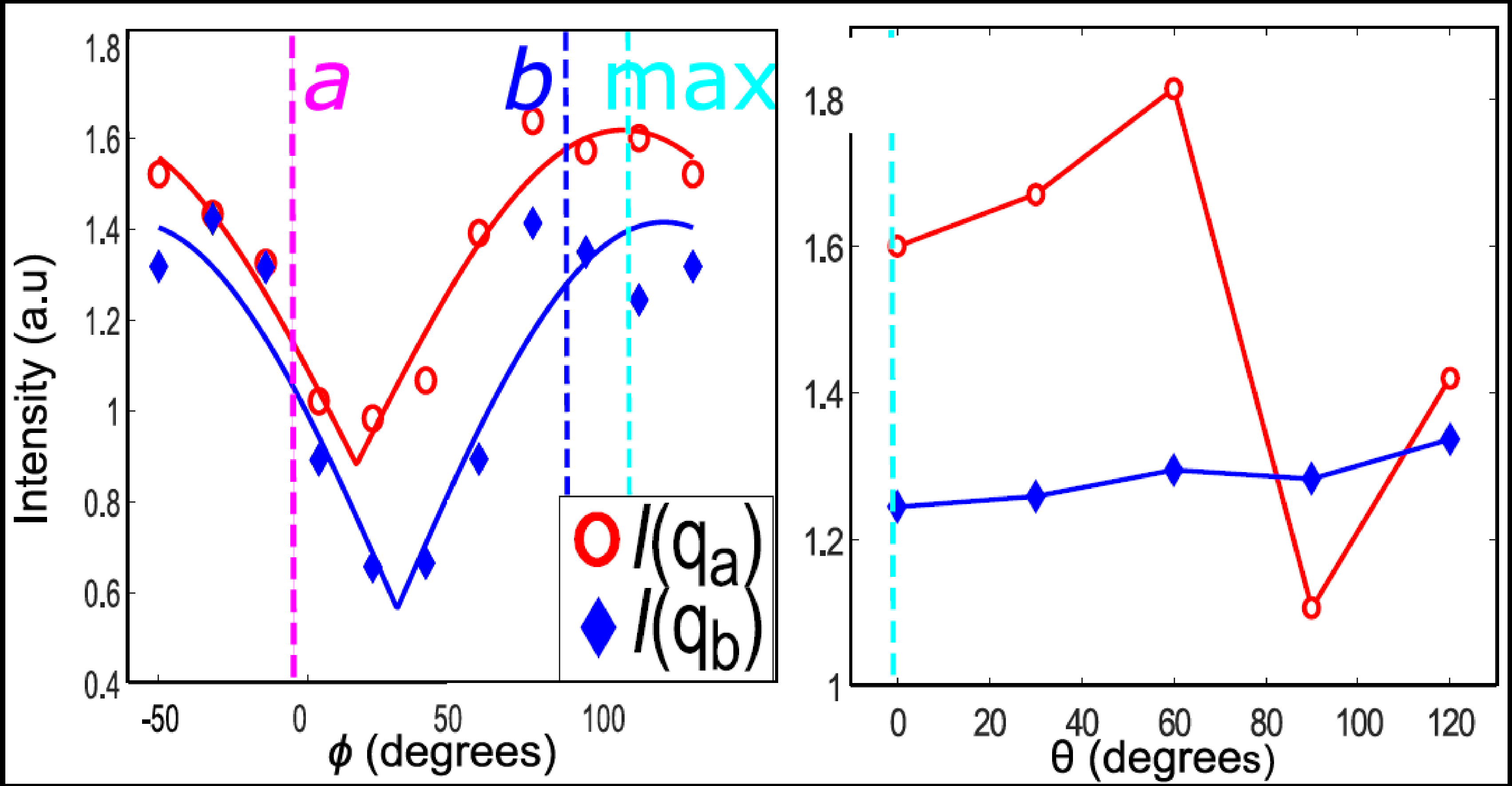
E.E. Rodriguez *et al.*, Phys. Rev. B84, 064403 (2011)

Magnetic structure of $Fe_{1.1}Te/Fe_{1.2}Te$

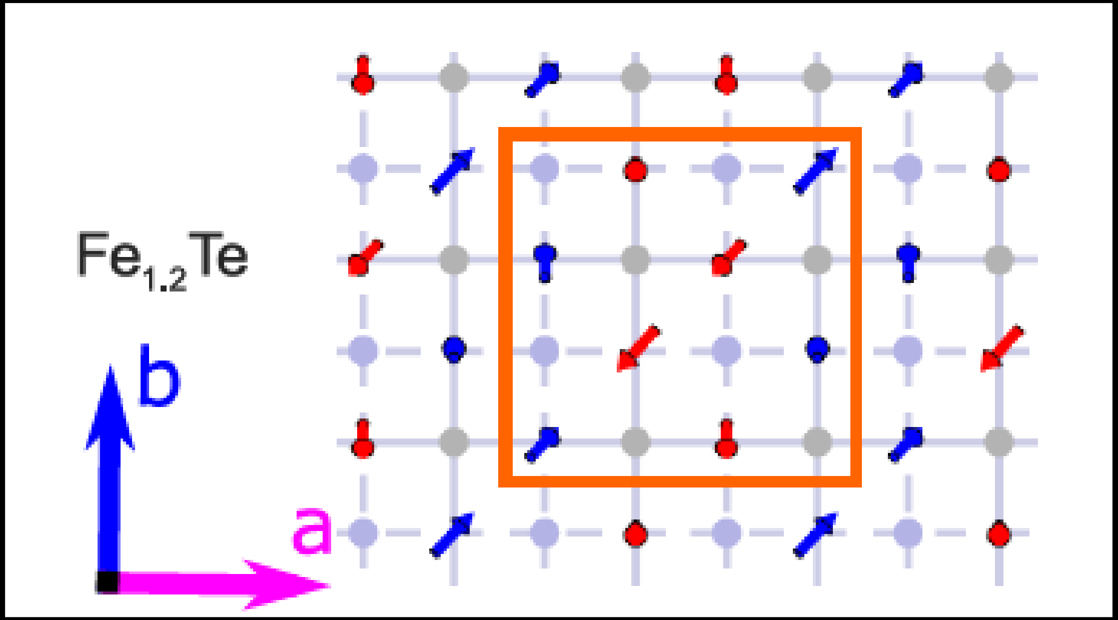


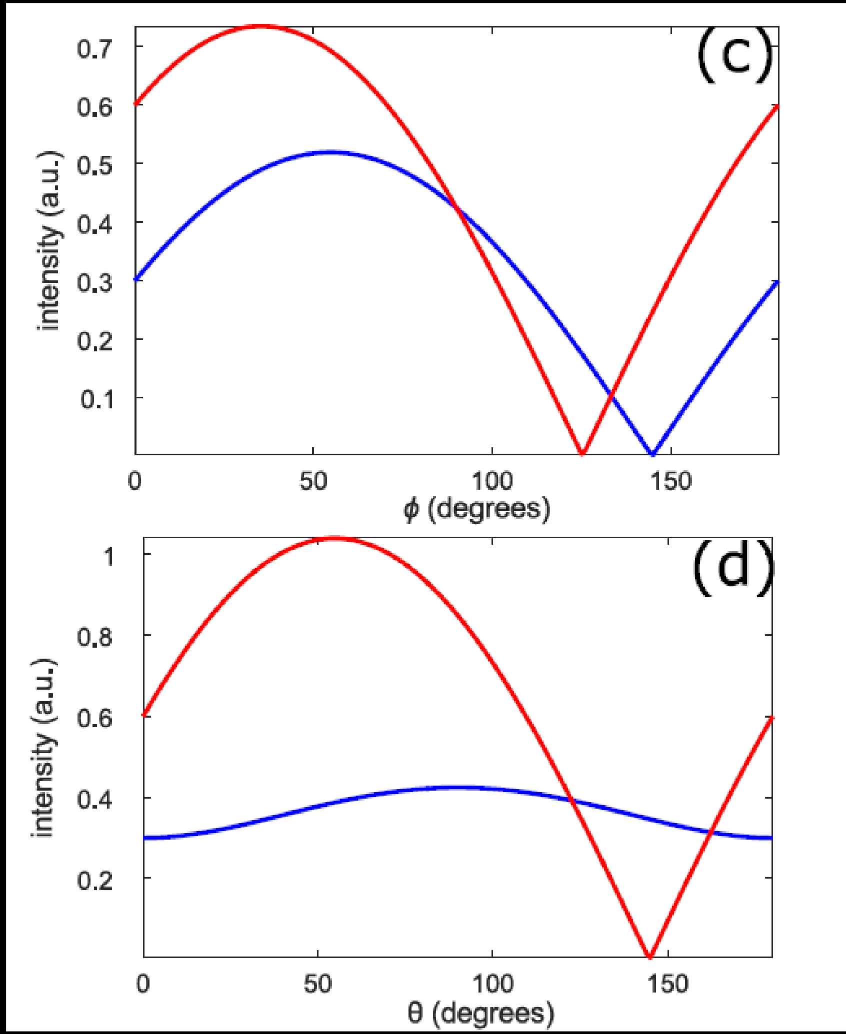
Relationship with field angle





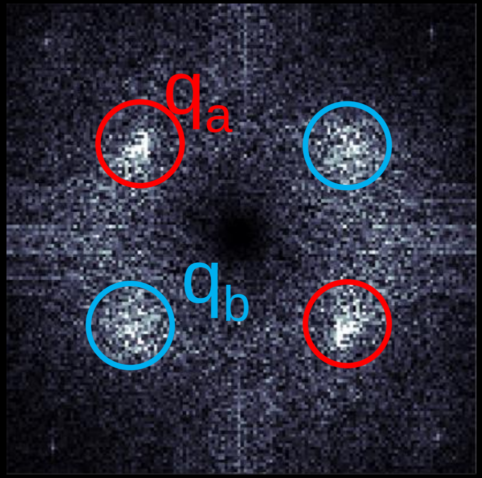
Resulting structure



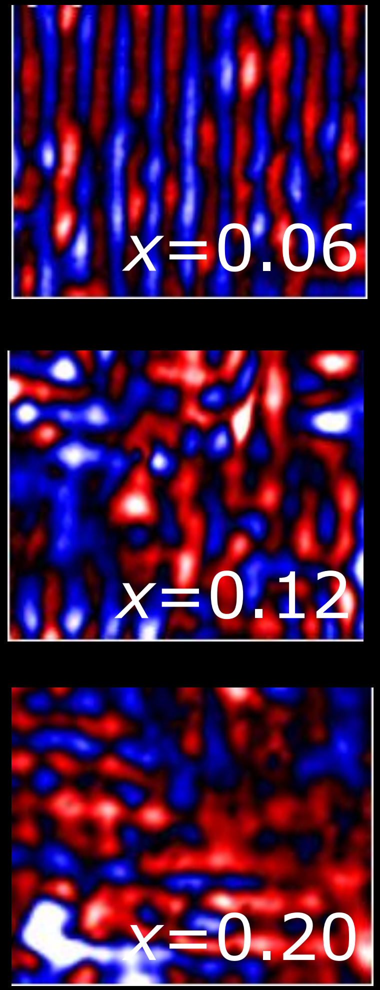


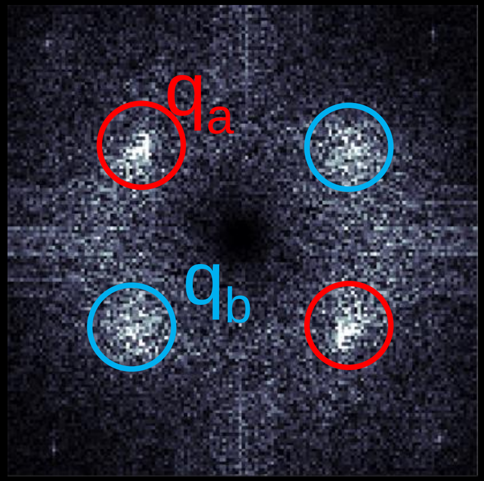
Spins order in a complex staggered structure forming two different spin spirals along both Fe-Fe directions.

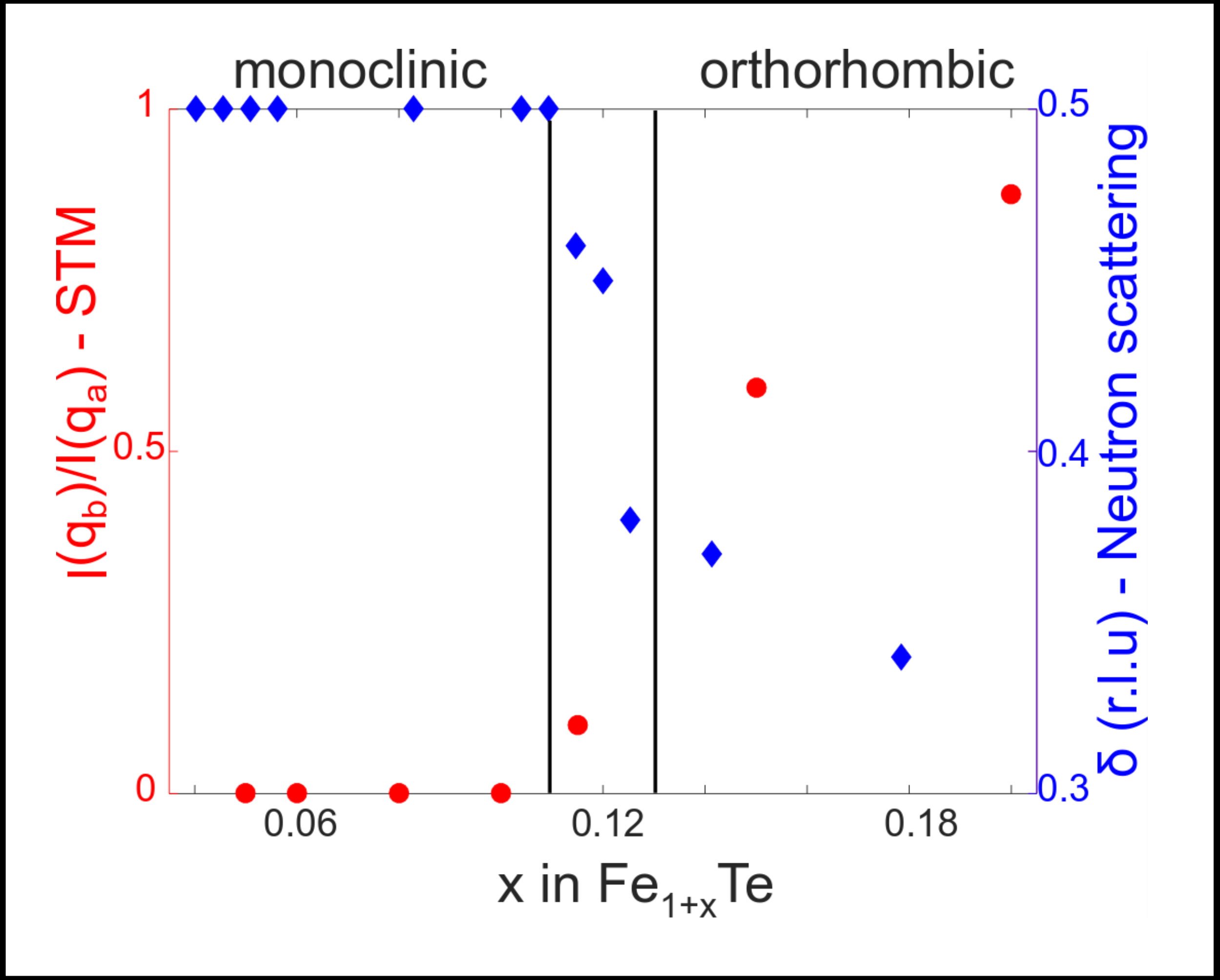
Construcing a magnetic phase diagram



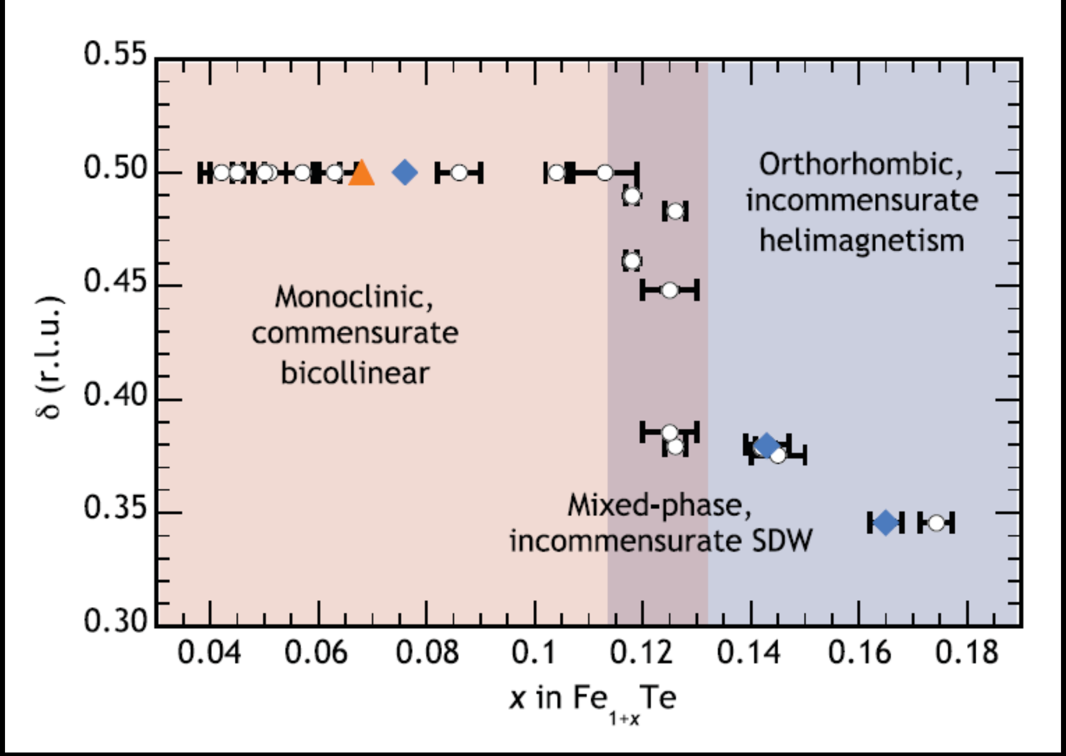
Magnetic Phase Diagram

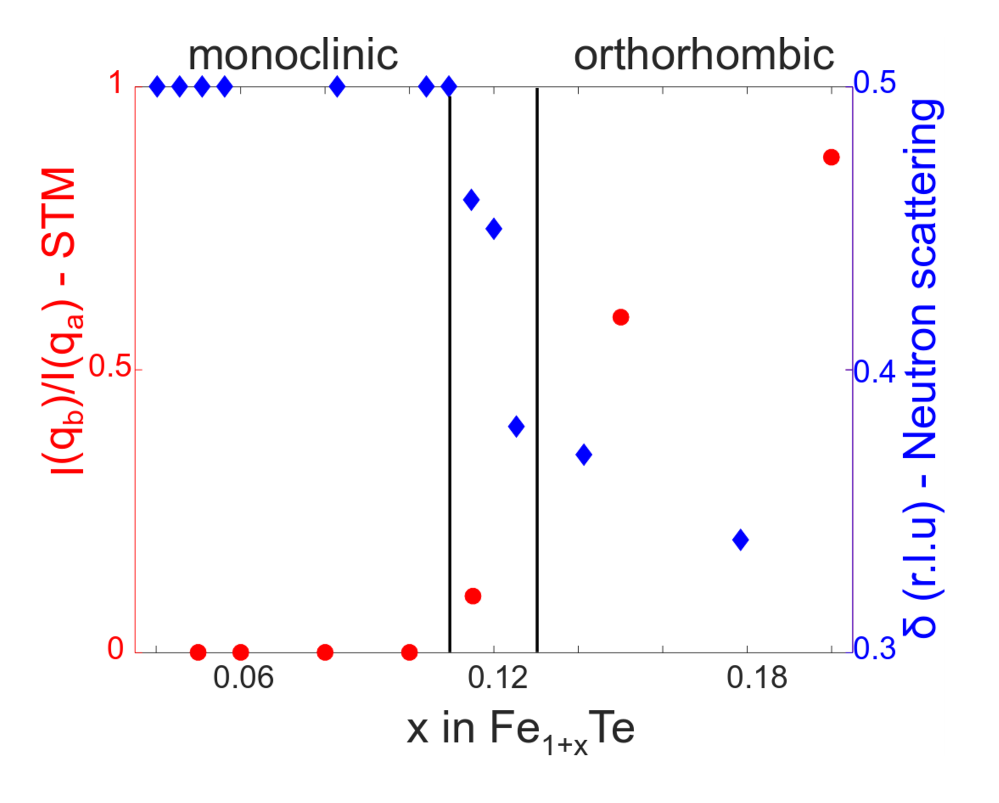






Phase Diagram





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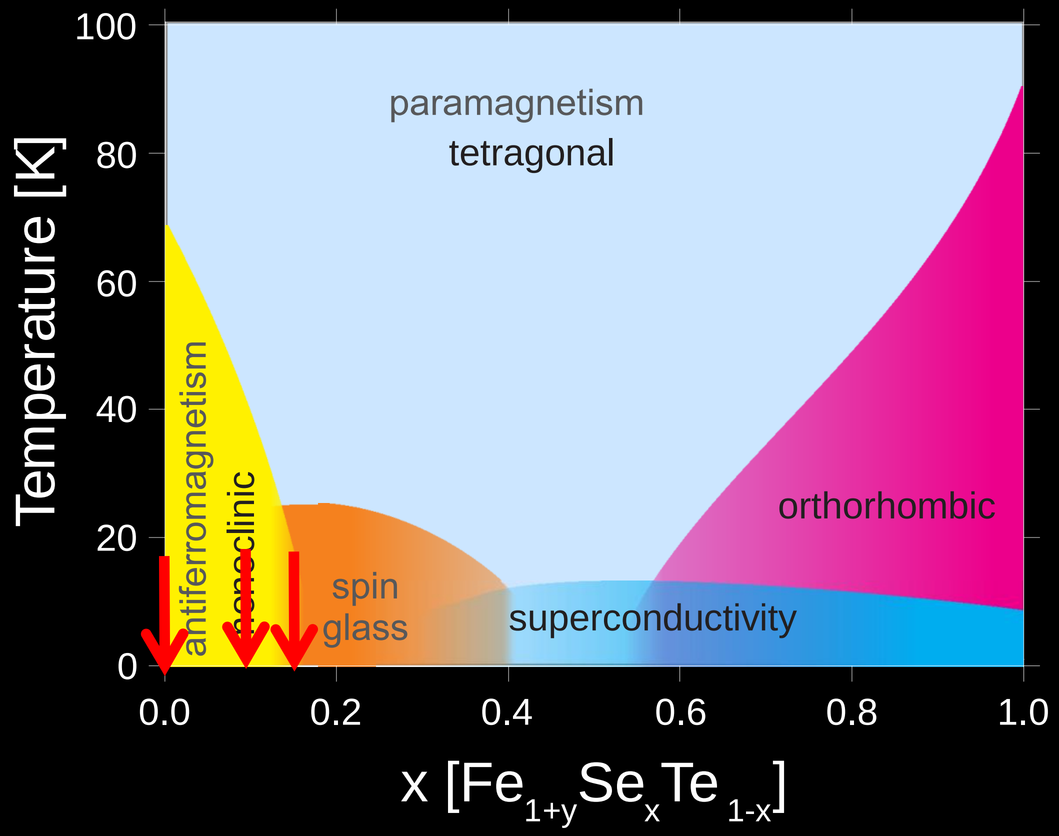
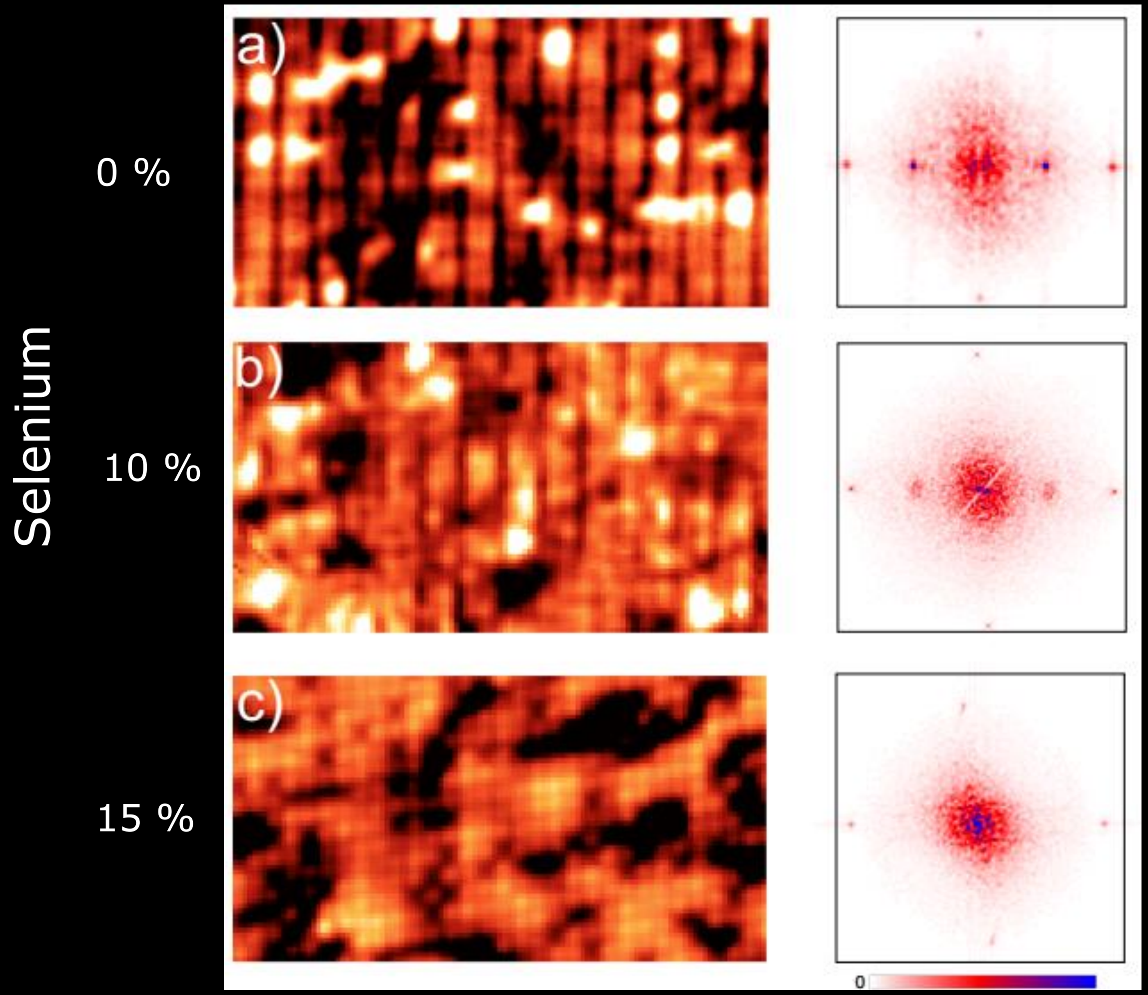
E.E. Rodriguez *et al.*, Phys. Rev. B84, 064403 (2011)

Phase Diagram





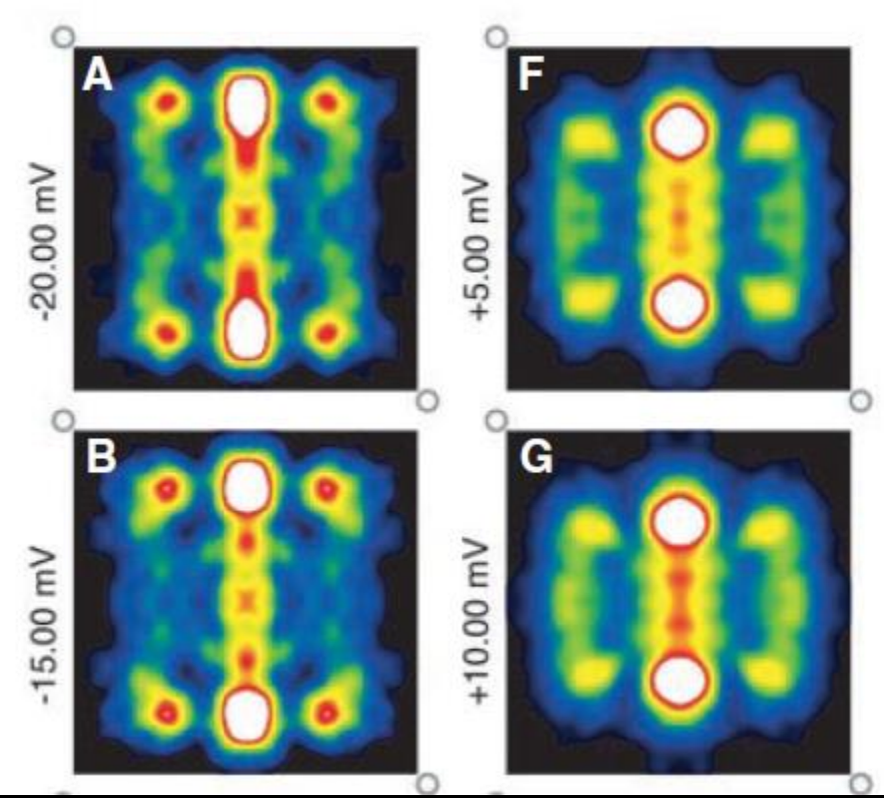
N. Katayama *et al.*, *J. Phys. Soc. Jpn.* **79**, 113702 (2010);
Y. Mizuguchi and Y. Takano, *J. Phys. Soc. Jpn.* **79**, 102001 (2010)

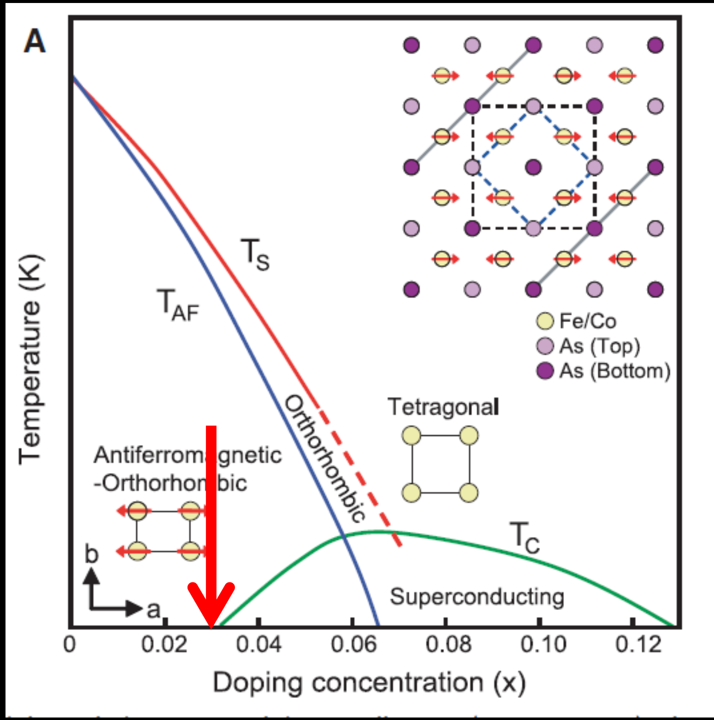
see Aluru et al., arxiv/1711.10389

Controlling Symmetry Breaking Electronic States

Symmetry Breaking Electronic States in Iron Pnictides

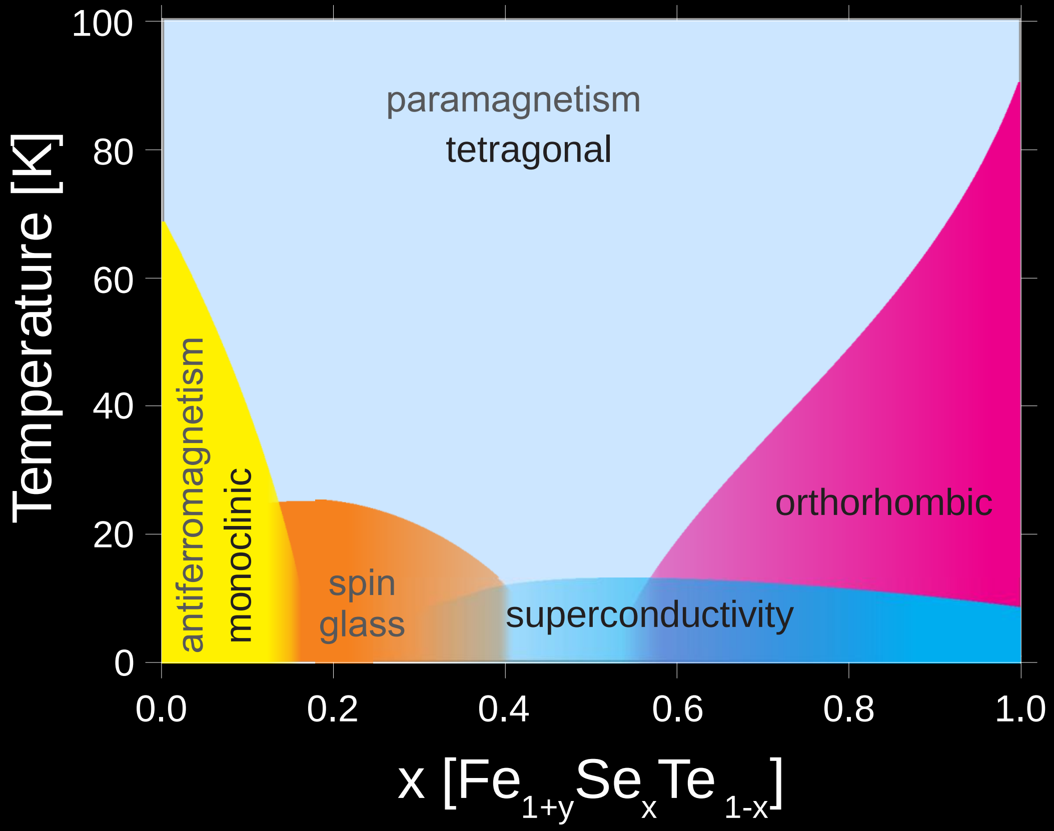
$Ca(Fe_{0.97}Co_{0.03})_2As_2$

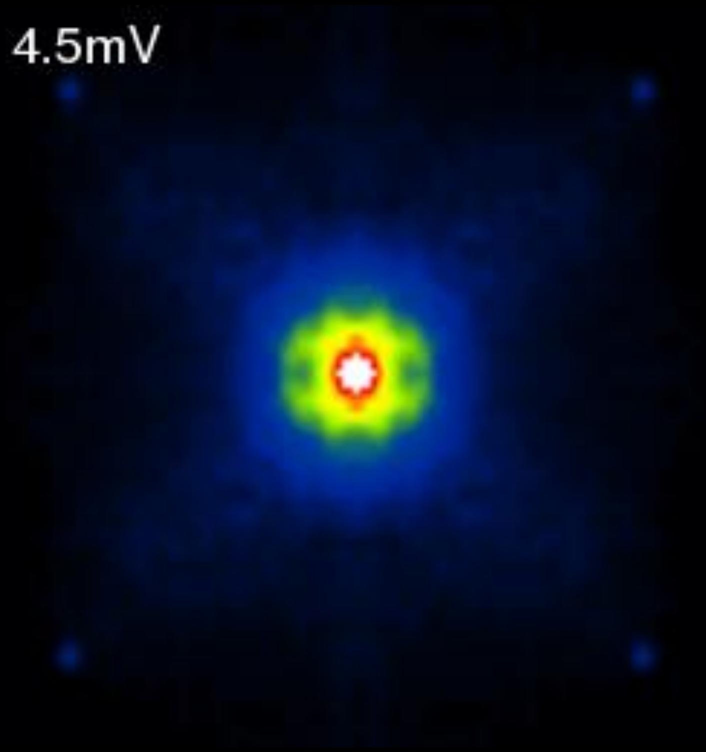




T.-M. Chuang *et al.*, Science **327**, 181 (2010)

Symmetry breaking QPI

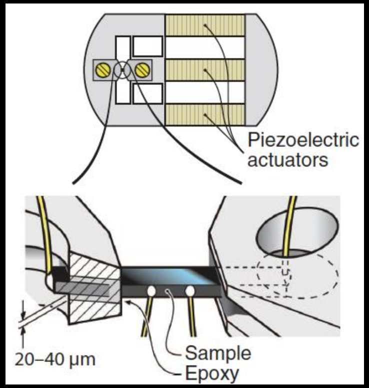


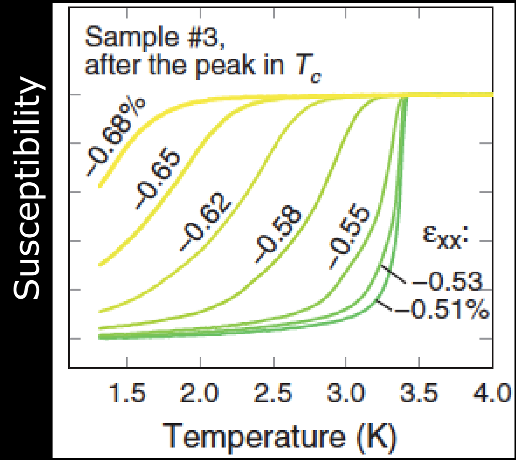


excess iron atoms that reside between the iron-chalcogenide planes. A possible explanation for the symmetry-breaking excitations seen in our sample is strain, for example, building up during cooldown because of thermal contraction, which might impose a small asymmetry in the orbital couplings. High sensitivity of iron-based superconductors to small strains

Sci. Adv. **1**, e1500206 (2015)

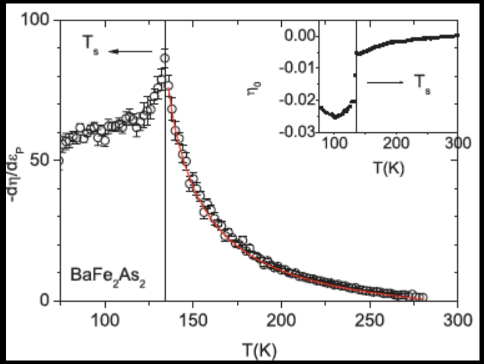
Strain-tuning in quantum materials

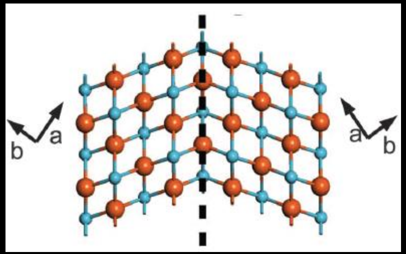




Strain-induced enhancement of Superconductivity

Steppke A *et al.*, *Science*, **355**, eaaf9398 (2017)

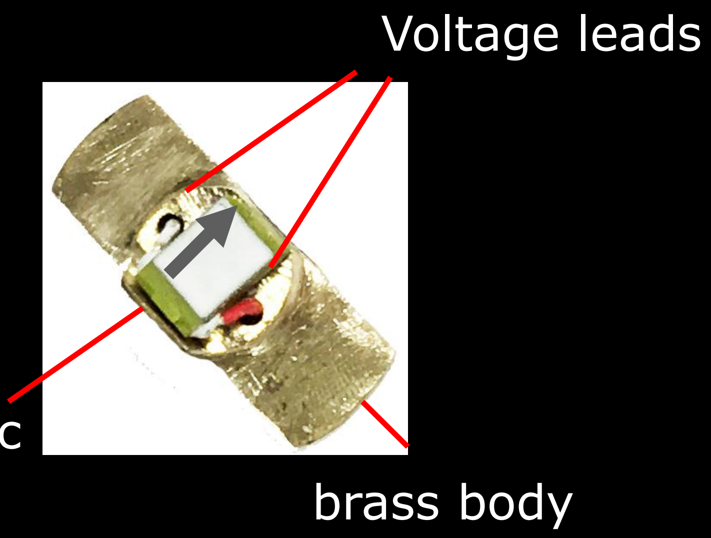


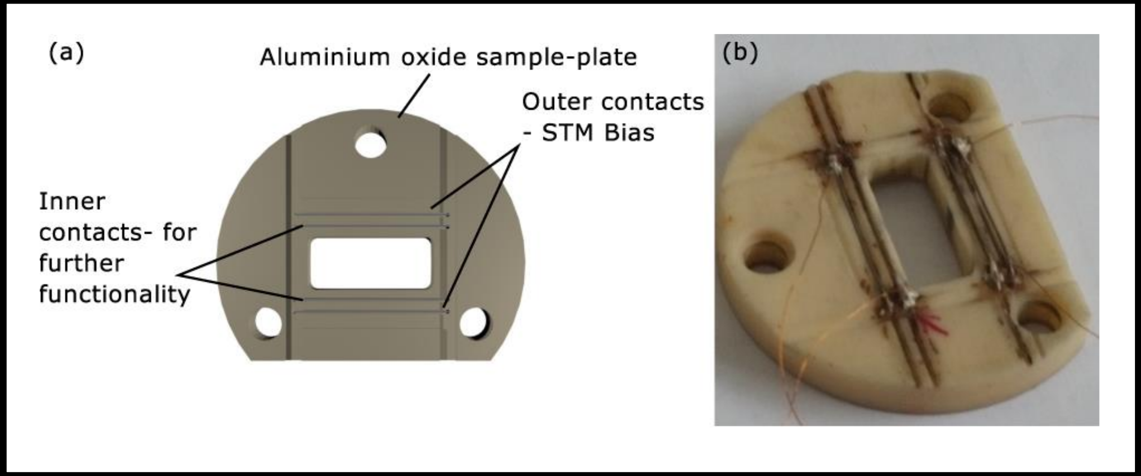


Divergent nematic response in BaFe2As2

Chu JH *et al.*, *Science*, **337**, 710 (2012)

STM Strain-device





- Strain due to anisotropic thermal contraction (300 -> 4 K) ~ ≤0.3%
- Strain levels achieved by voltage tuning were ≤0.01%

Rev. Sci. Instr. 88, 093705 (2017)

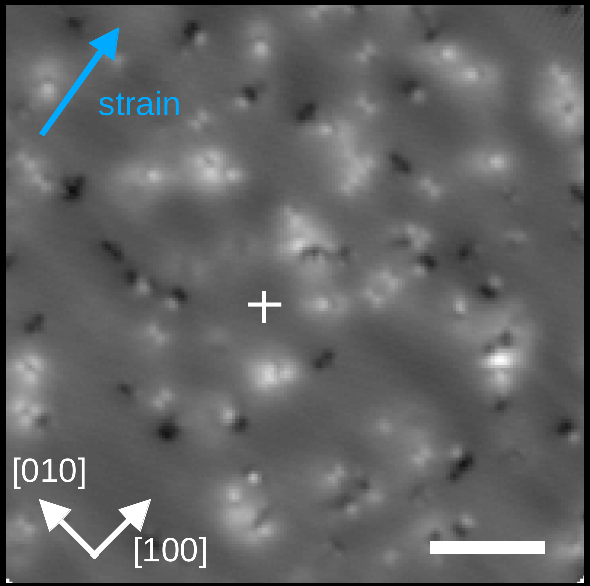
STM Strain-device

Voltage leads

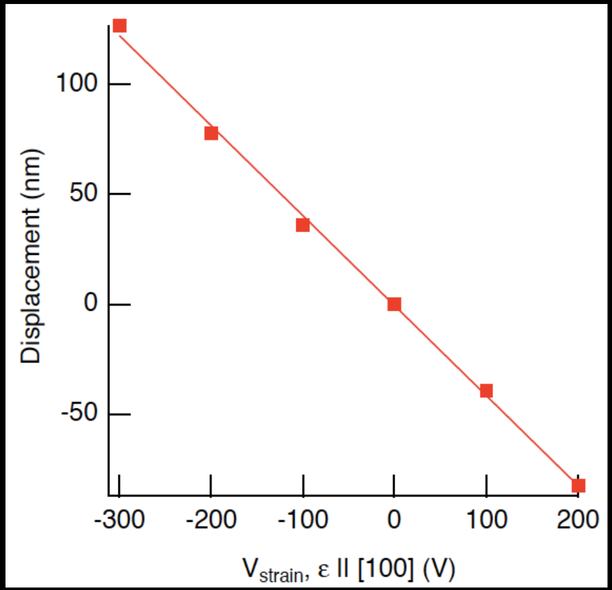
piezo-electric
actuator

brass body

- Strain due to anisotropic thermal contraction (300 -> 4 K) ~ ≤0.3%
- Strain levels achieved by voltage tuning were ≤0.01%

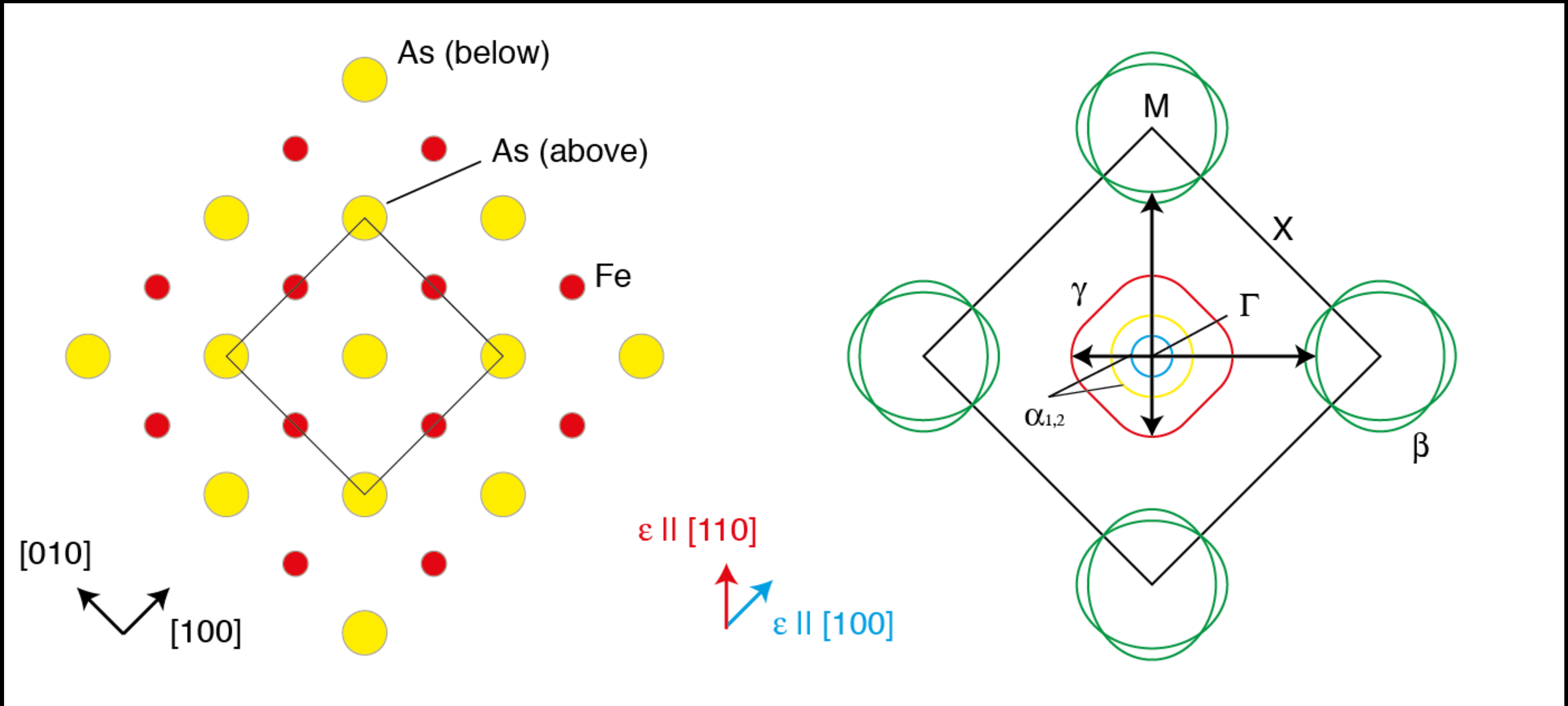


LiFeAs

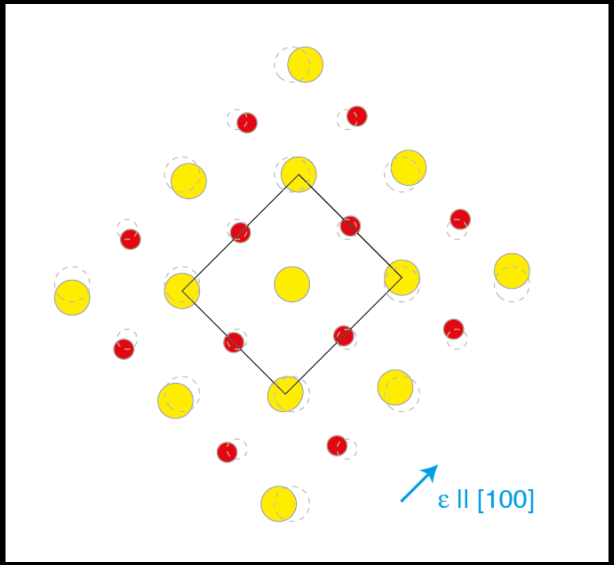


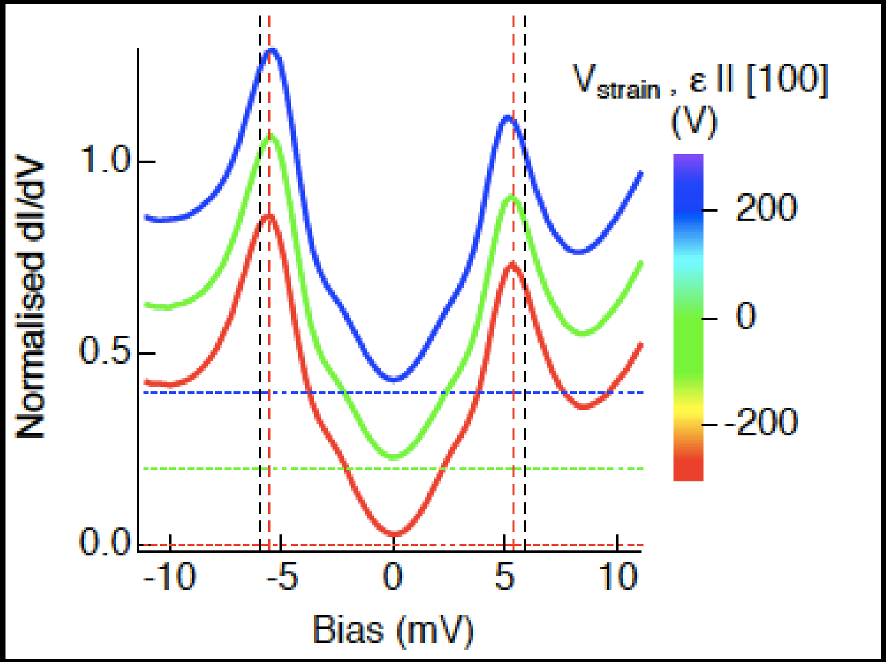
FOV displacement
demonstrates strain tuning

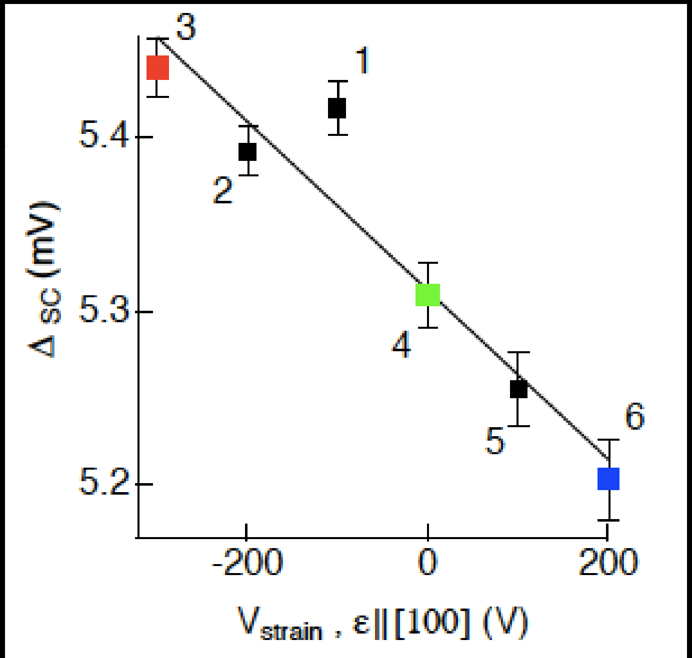
Structure of LiFeAs



Strain along [100]

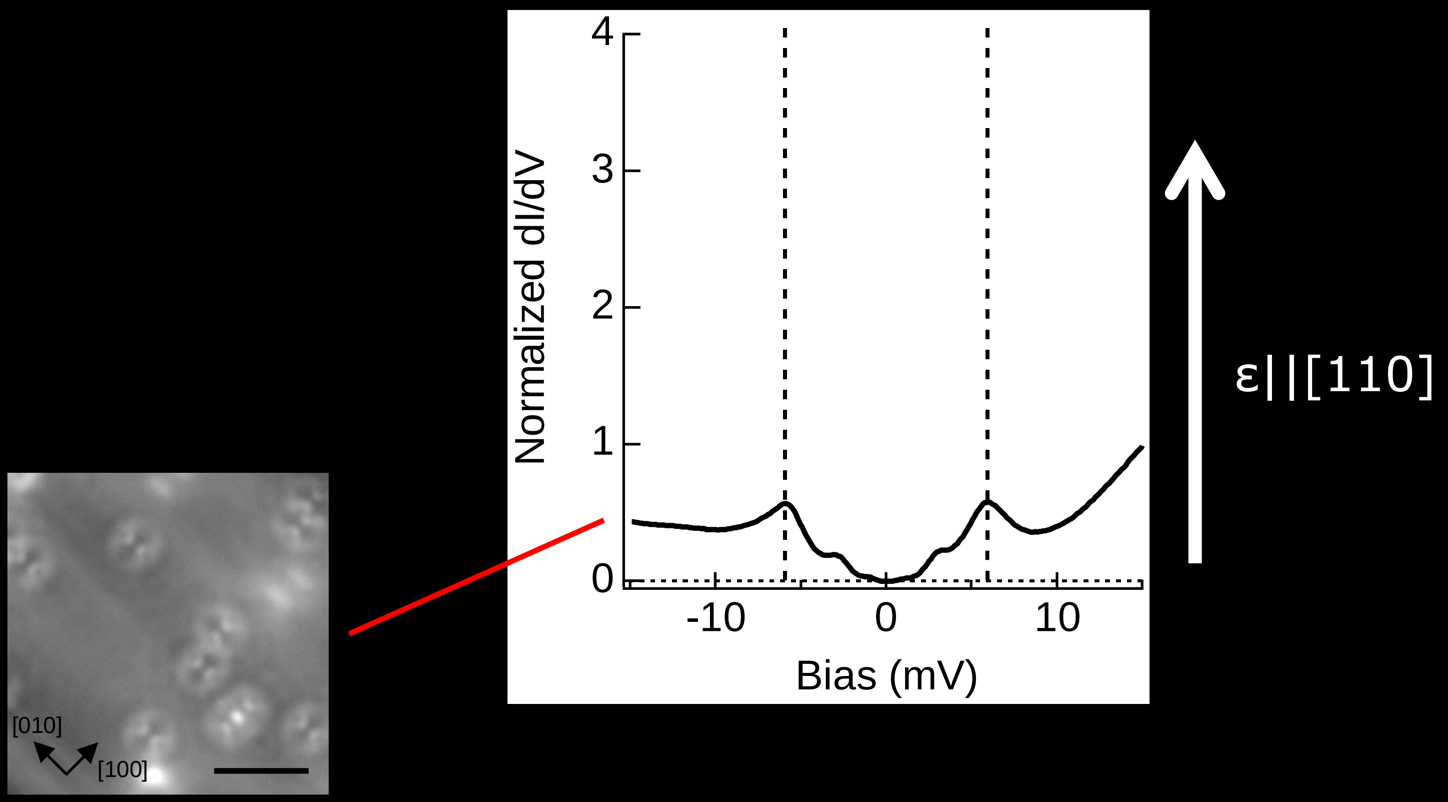




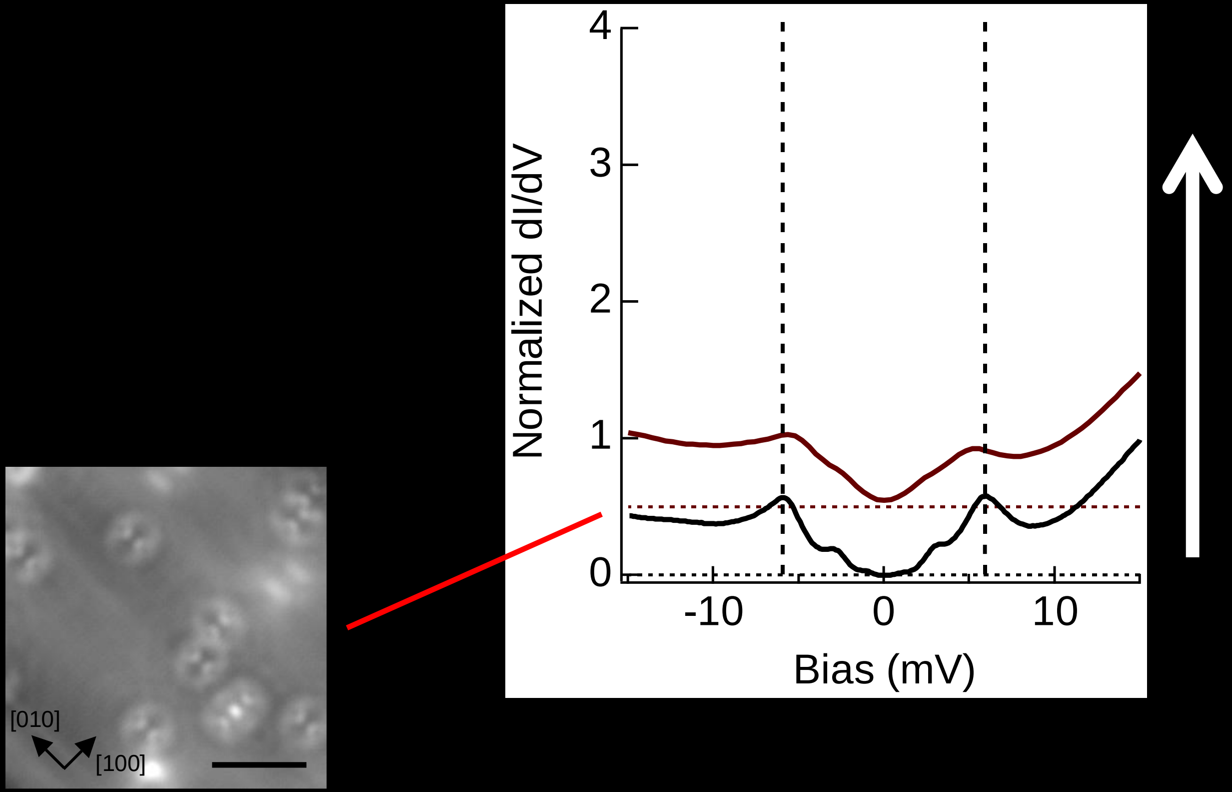


black dashed - unstrained (±5.8 mV)
red-dashed - V = -300 V

Strain along [110]

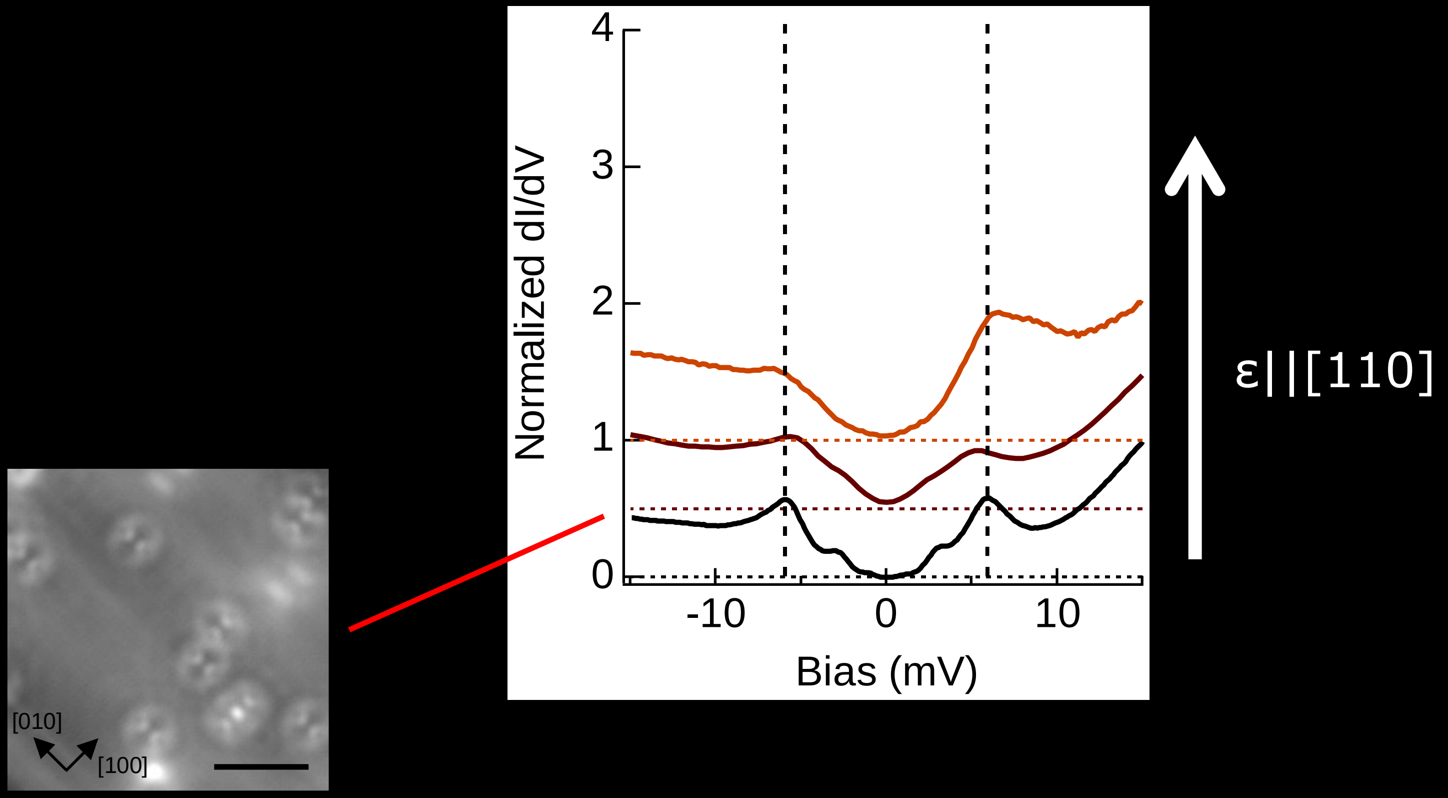


Strain along [110]

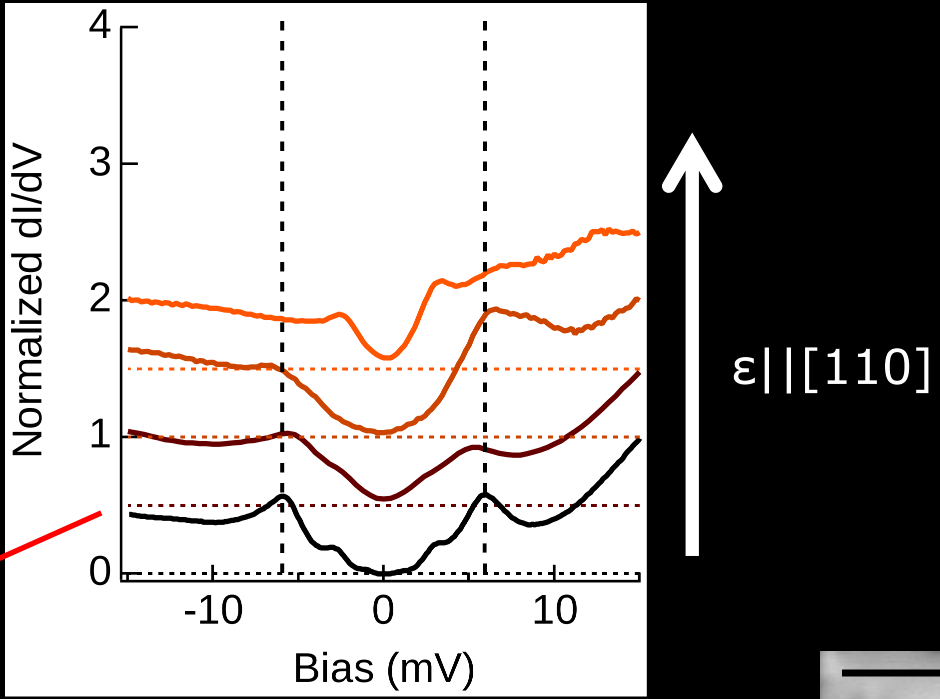


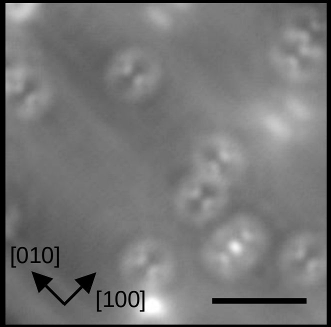
ε||[110]

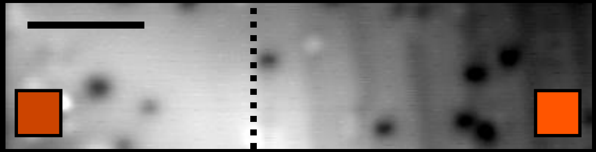
Strain along [110]



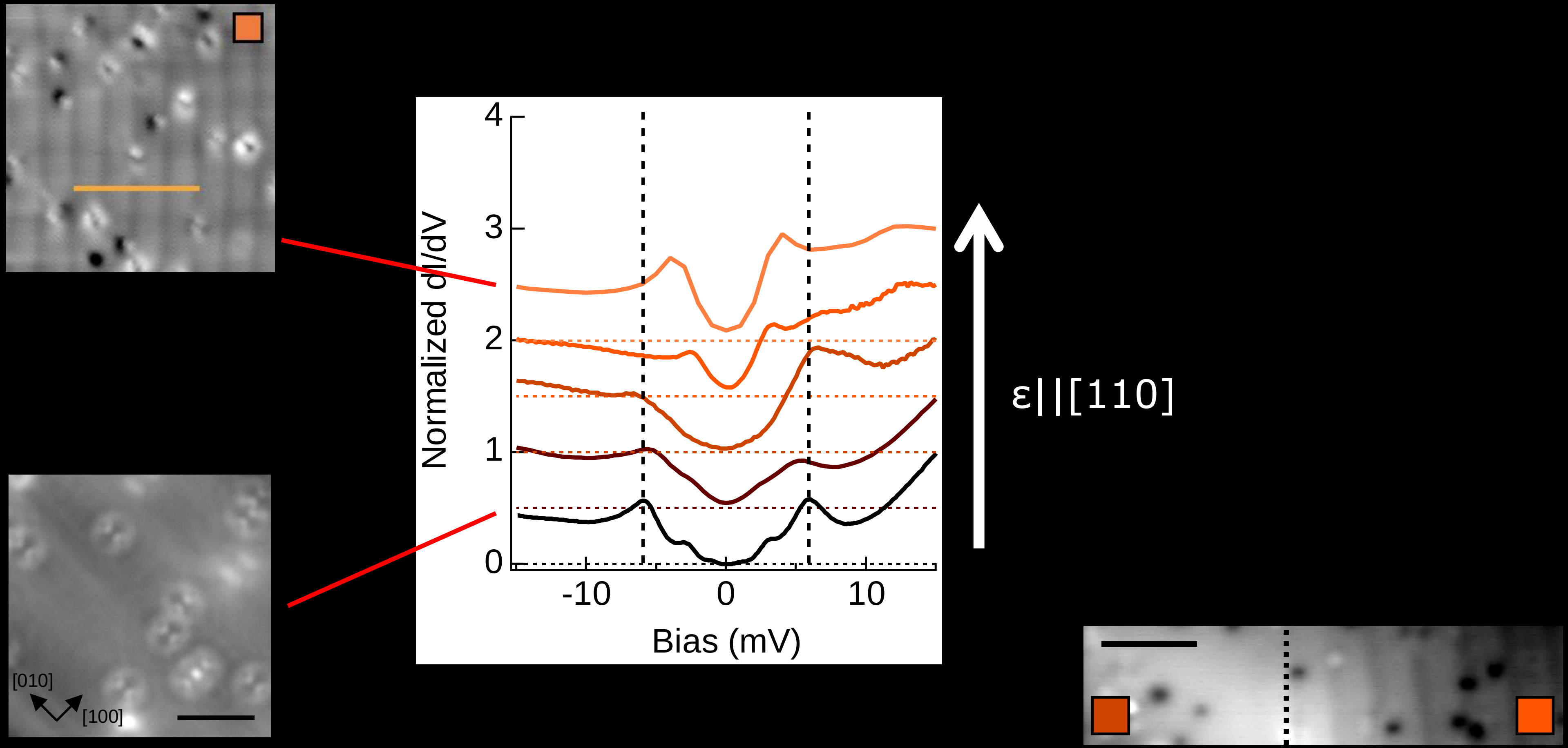
Strain along [110]



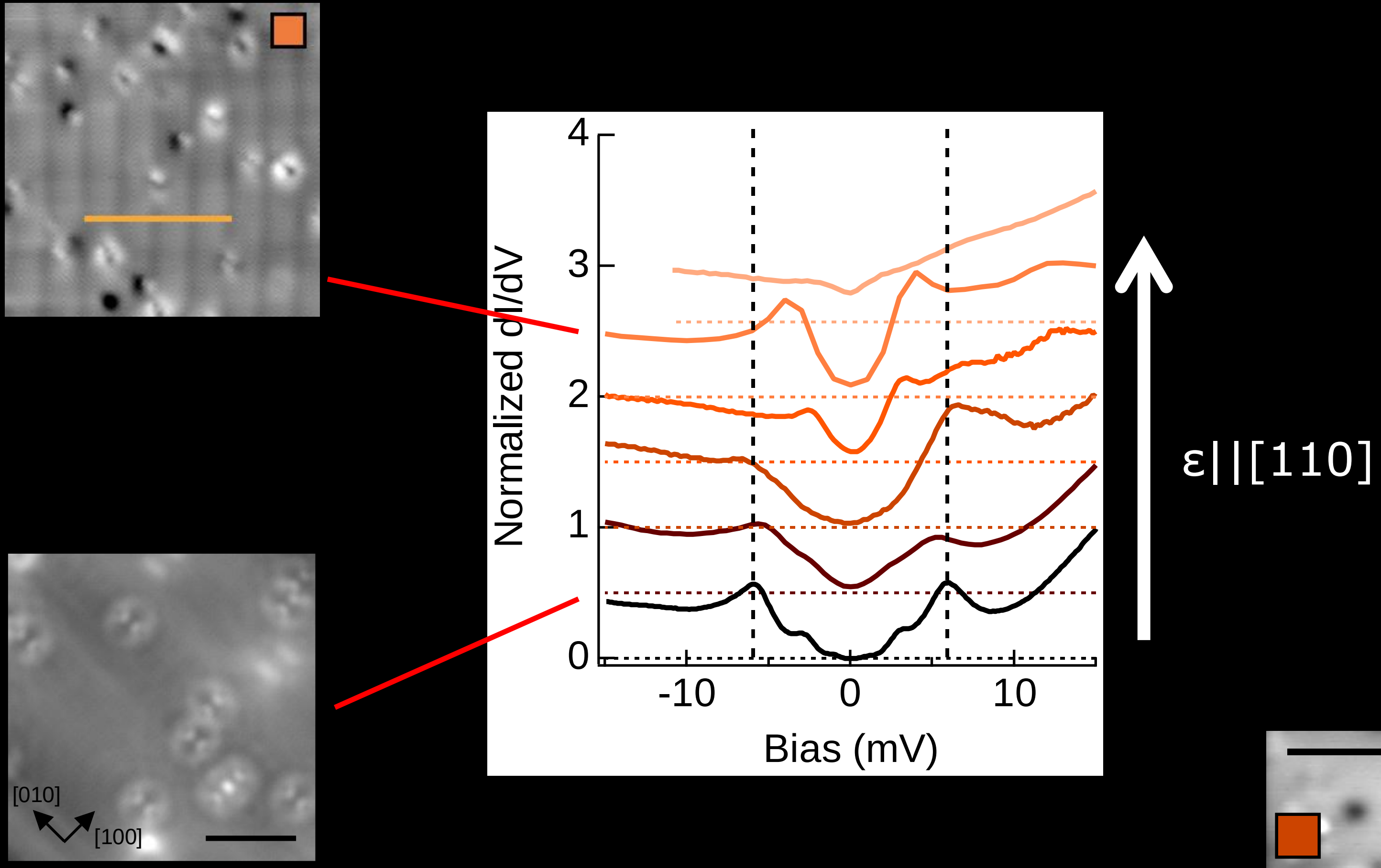


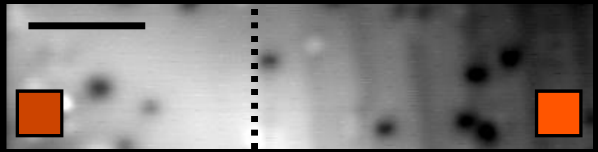


Strain along [110]

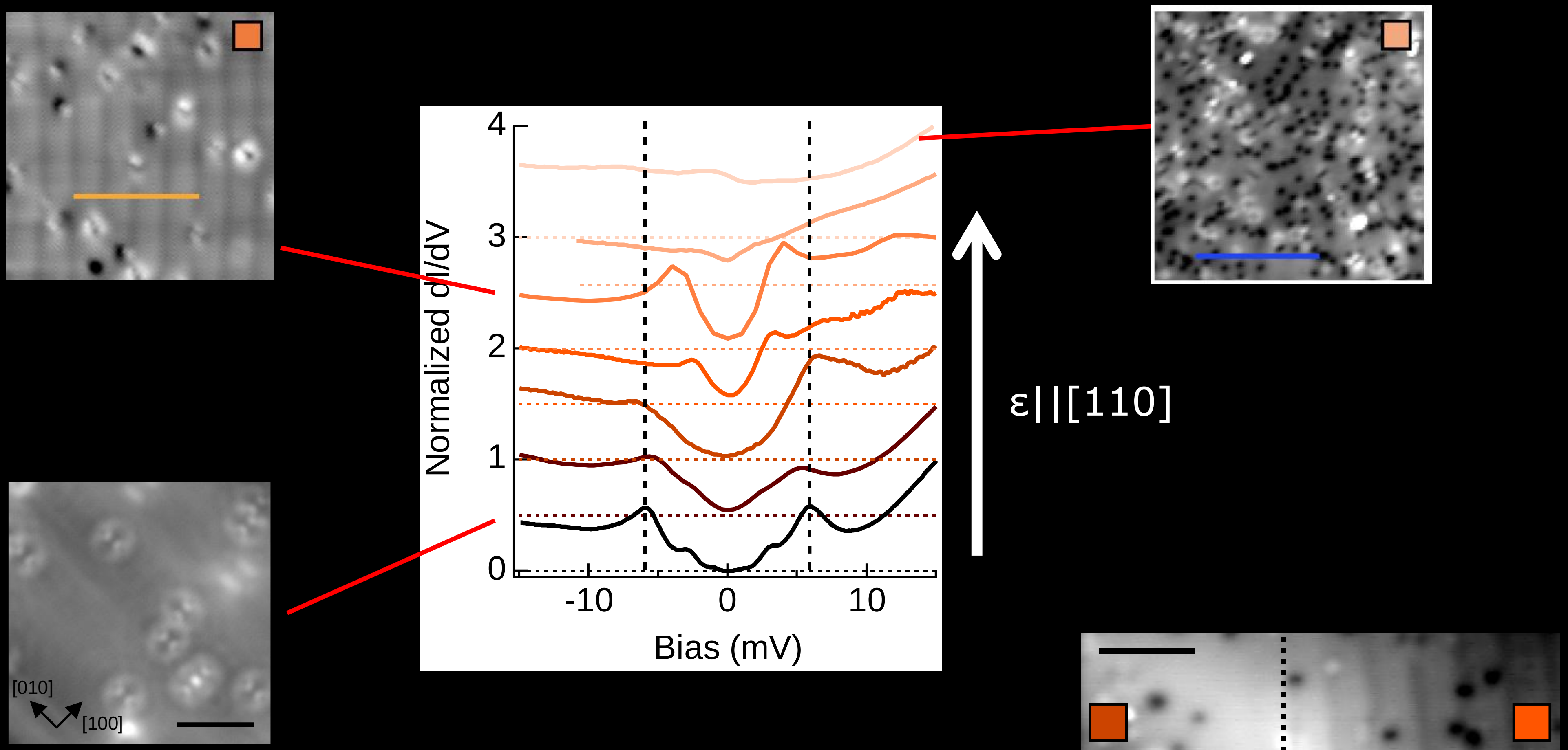


Strain along [110]

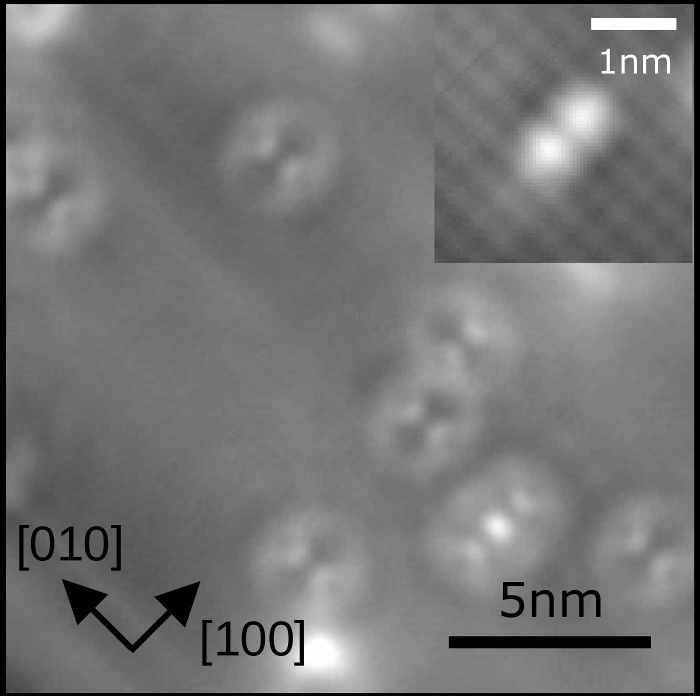




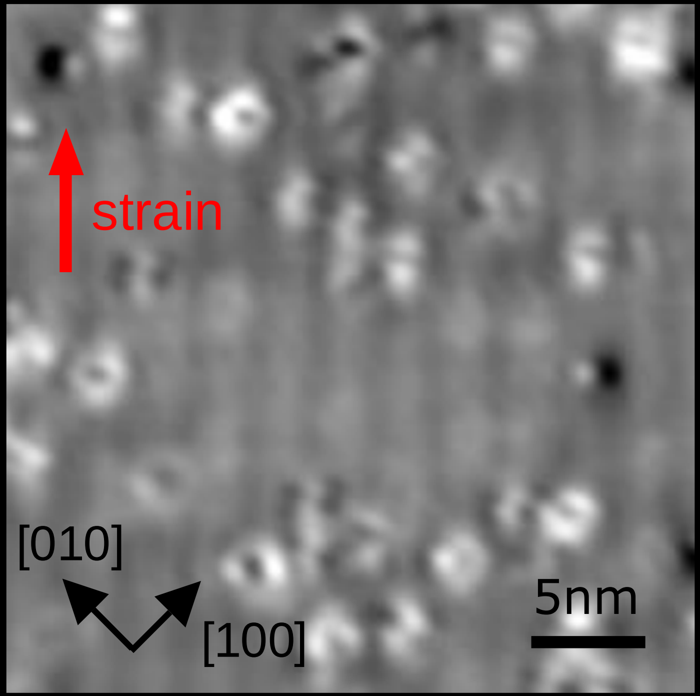
Strain along [110]



Modulated Phase in strained LiFeAs

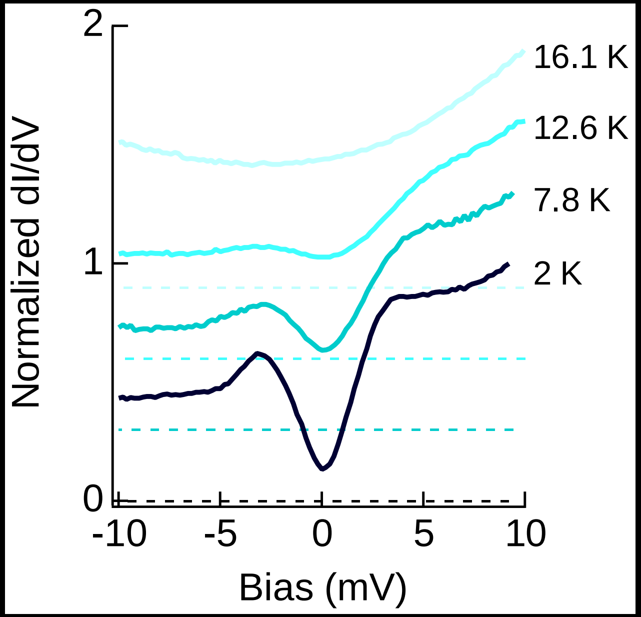


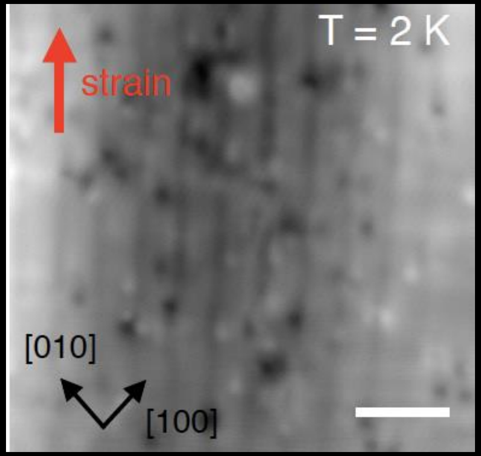
Unstrained LiFeAs
15 mV, 0.25 nA
Inset: -50 mV, 0.3nA

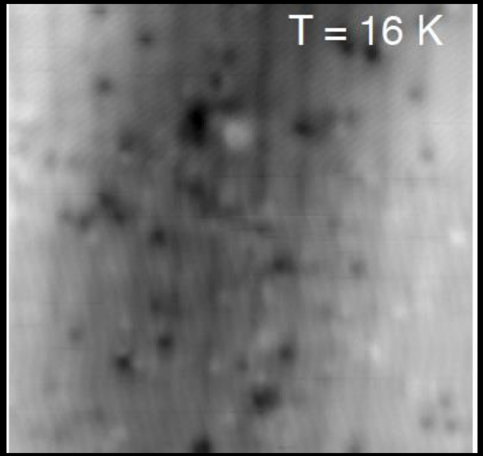


Modulated phase (periodicity ~2.7 nm)
15 mV, 50pA

Origin of the modulation



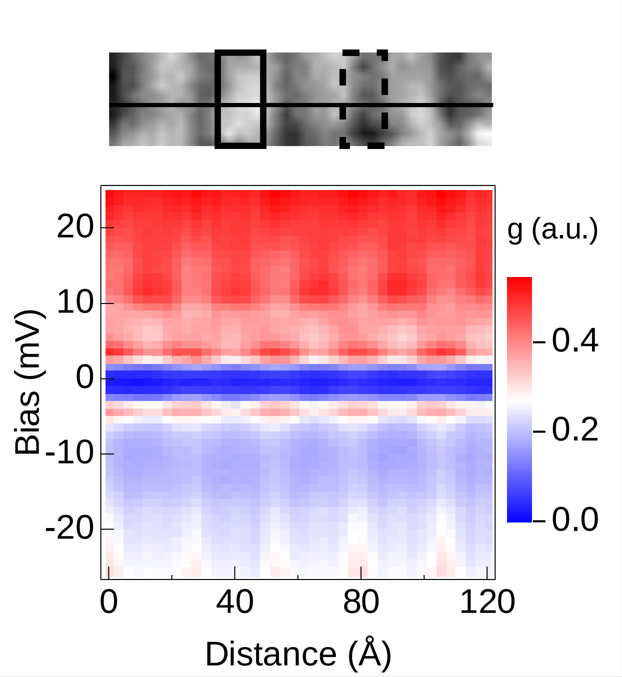


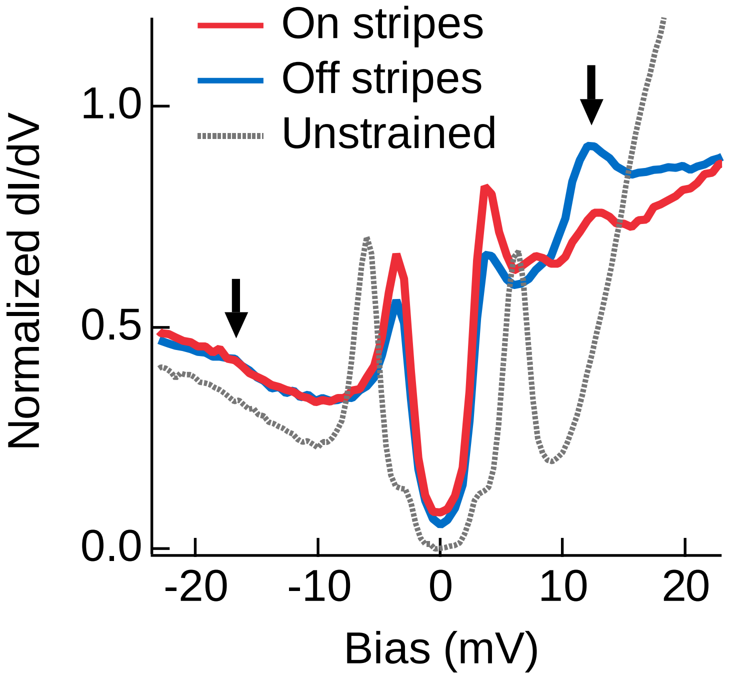


Setpoints: 20 mV, 50 pA

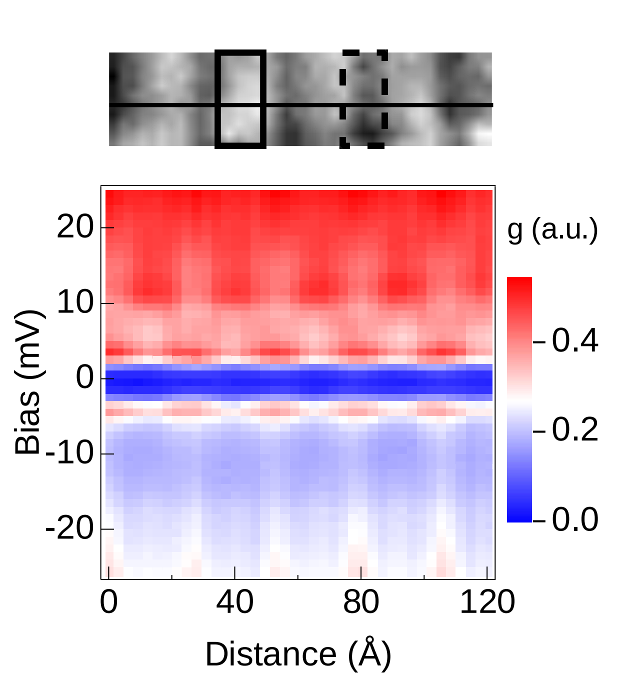
Superconductivity forms on top of modulated state

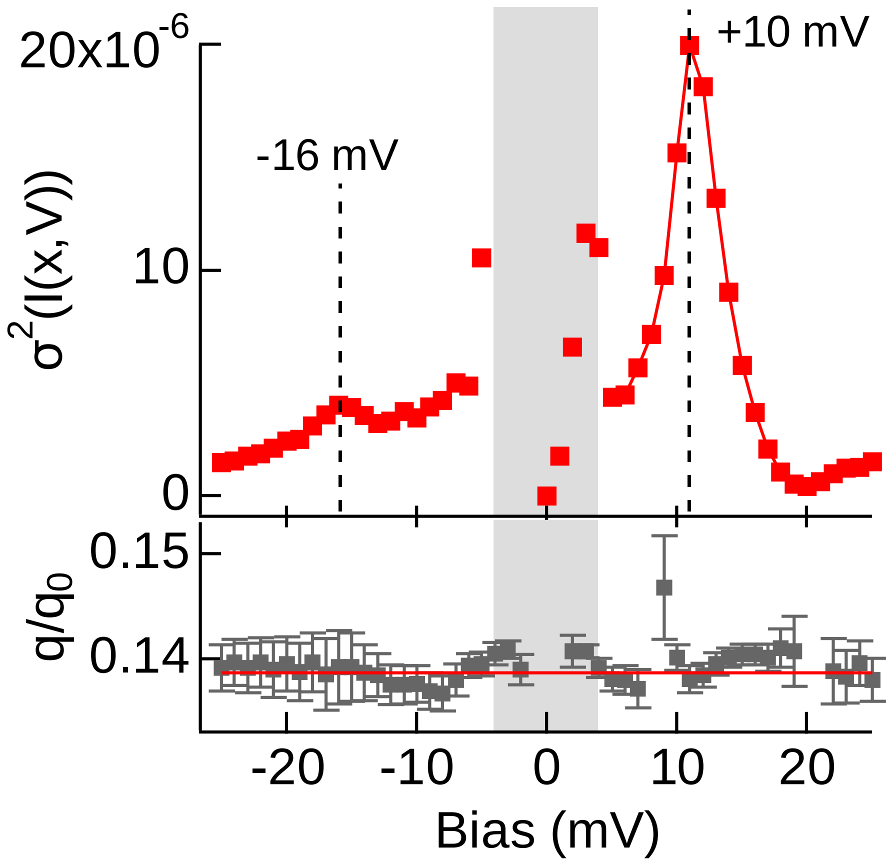
Modulated superconductivity



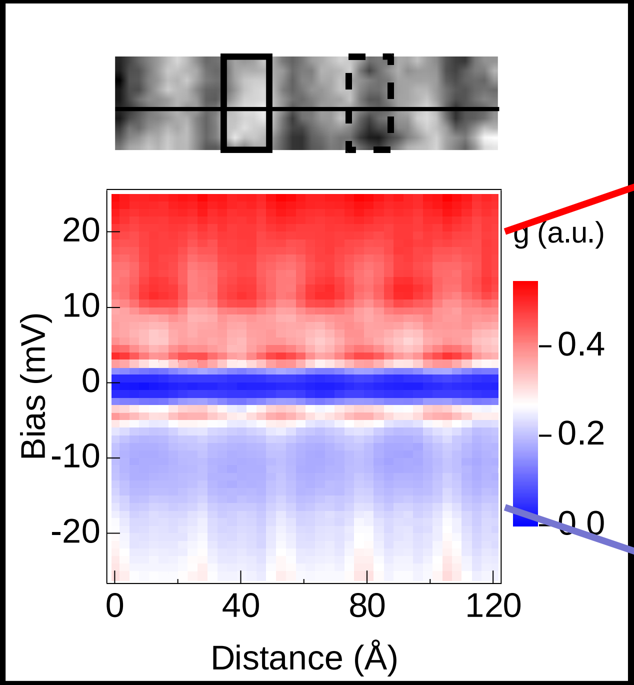


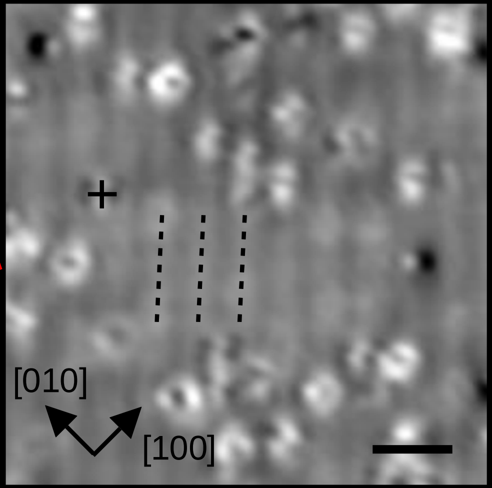
Modulated superconductivity



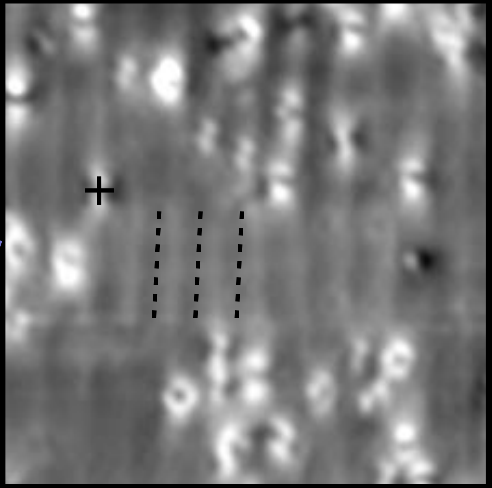


Modulated superconductivity



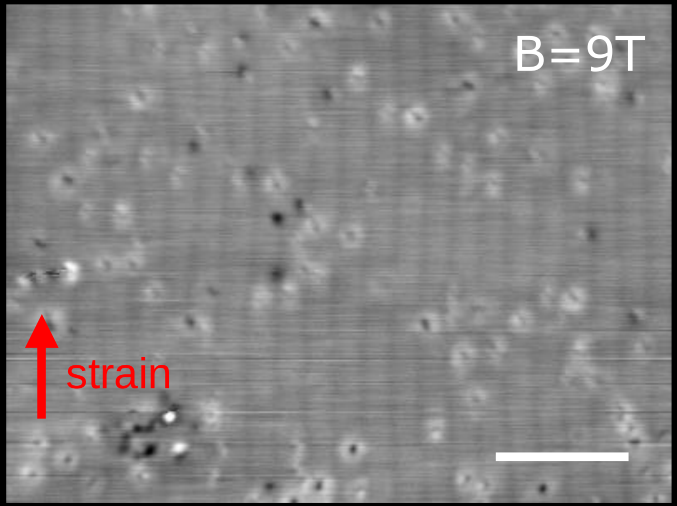


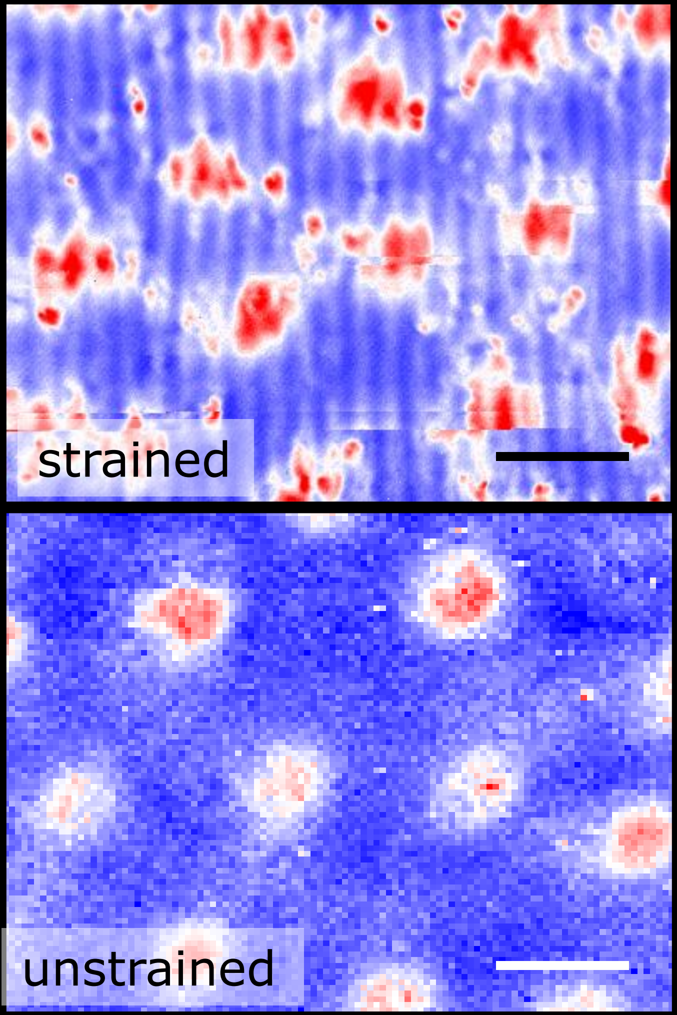
positive bias

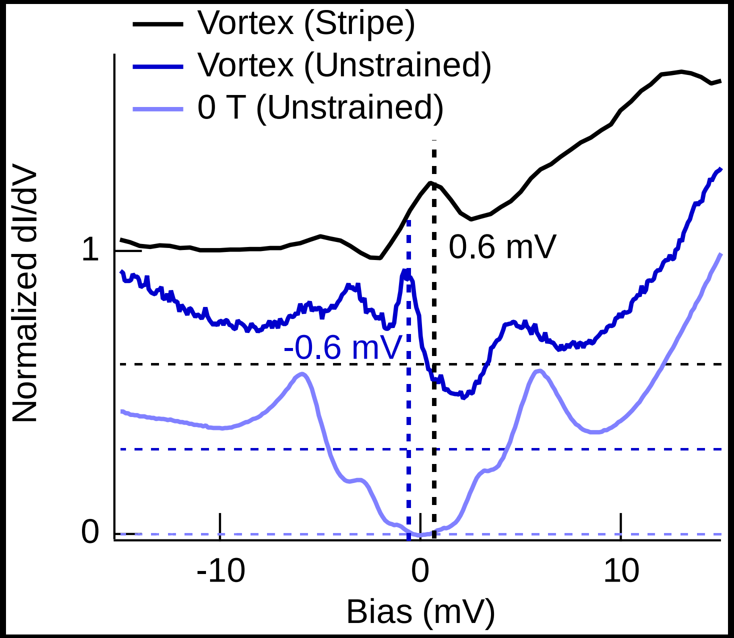


negative bias

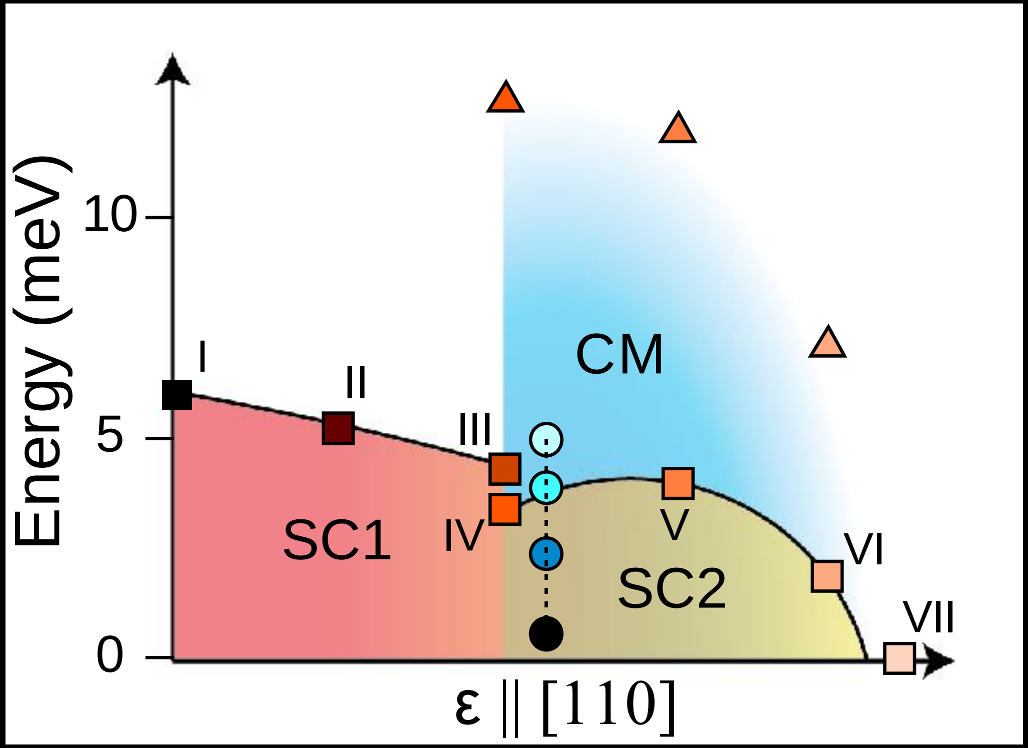
Vortex cores in modulated phase





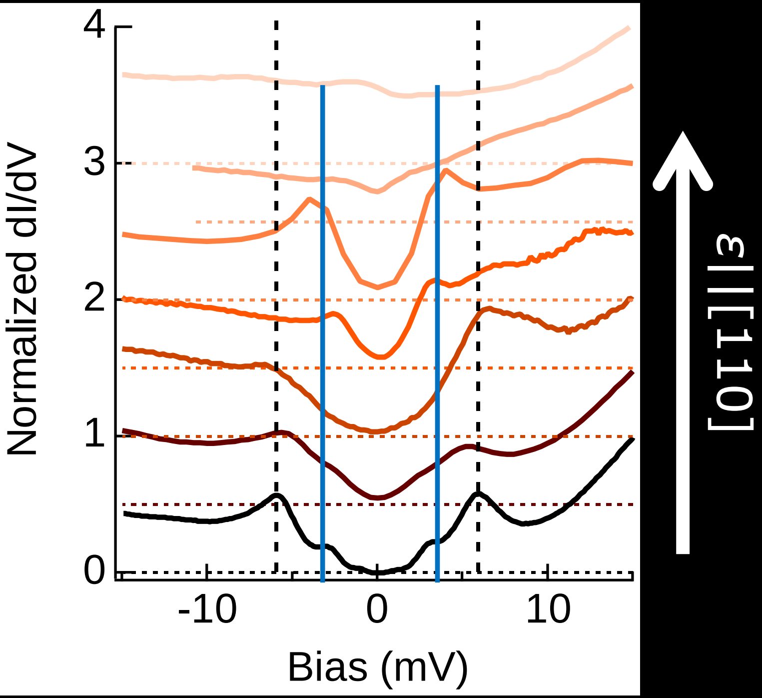


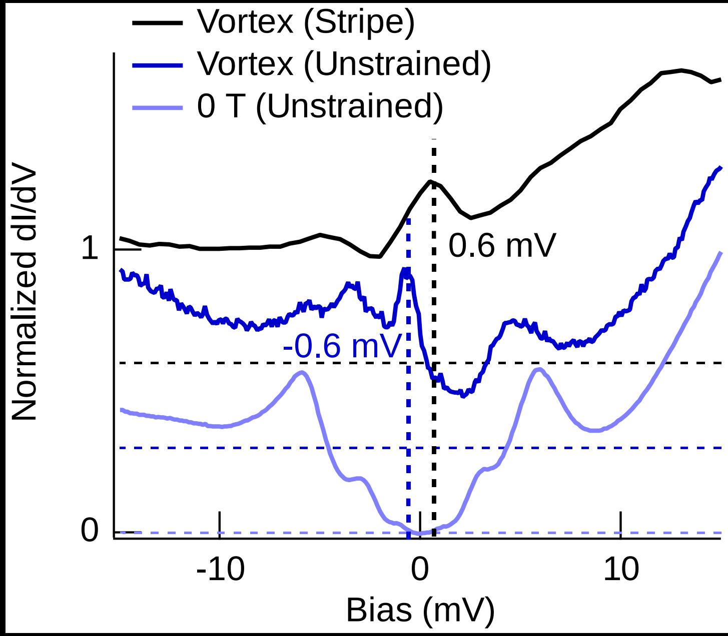
Phase diagram

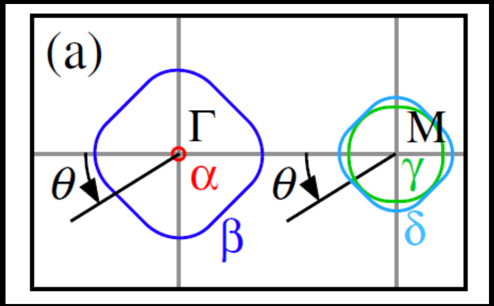


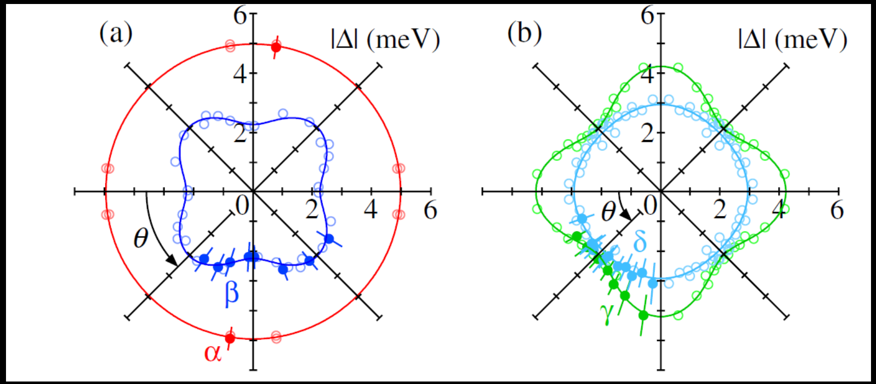
Nature Communications 9, 2602 (2018)

Reconstruction of the Fermi surface?



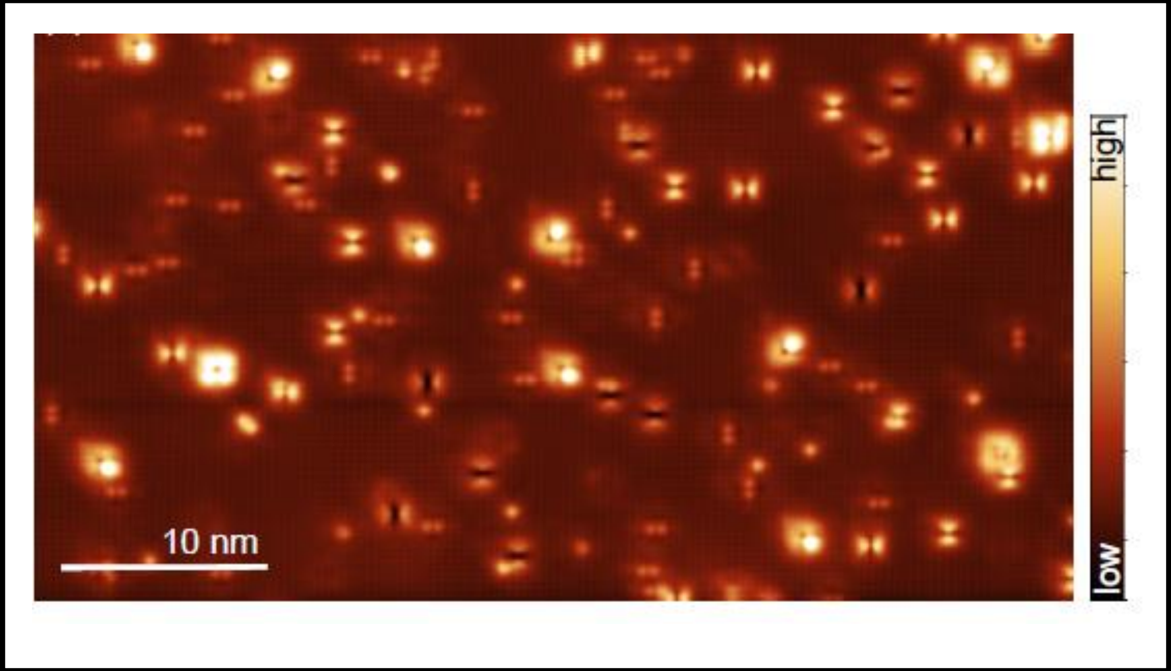


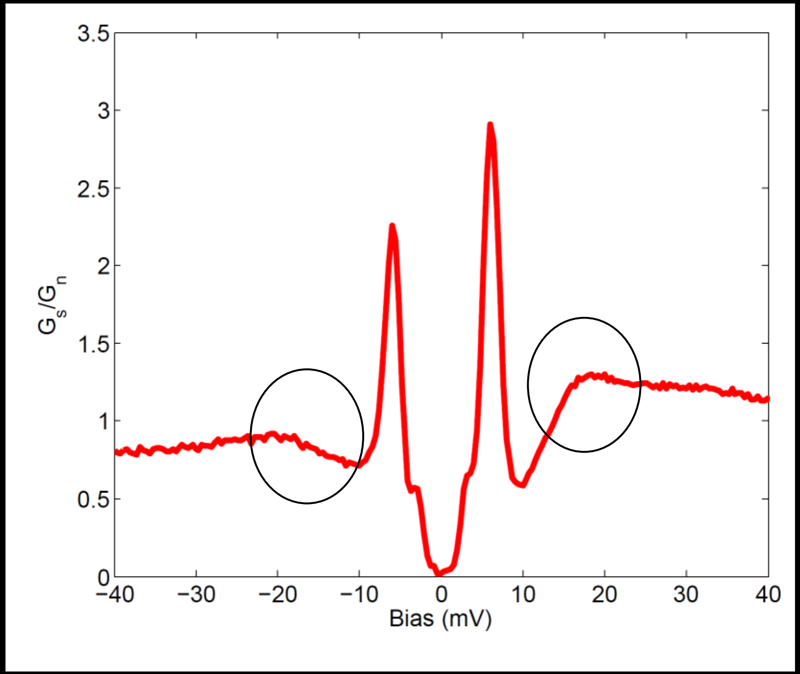




Umezawa *et al.*, Phys. Rev. Lett. **108**, 037002 (2012), also Allan *et al.* Science **336**, 563 (2012)

Dip-hump features – coupling to the spin resonance

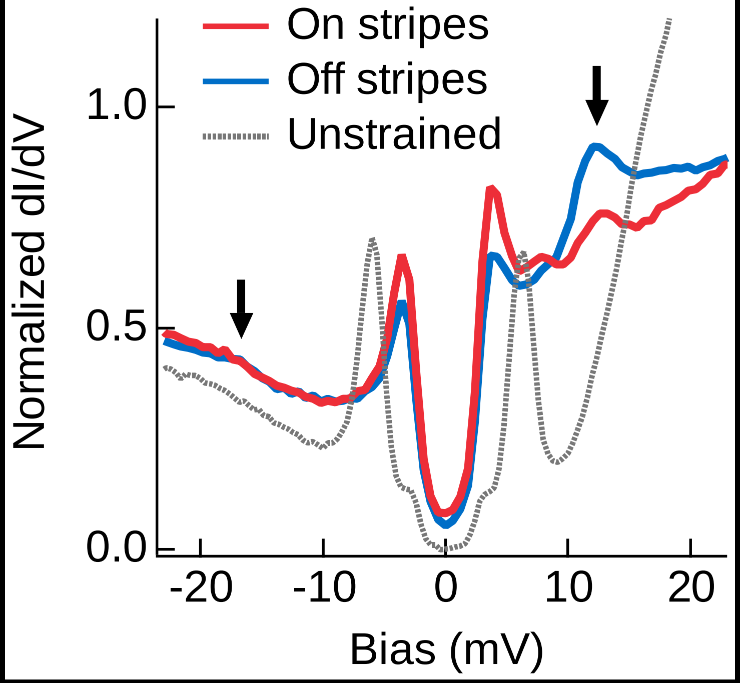


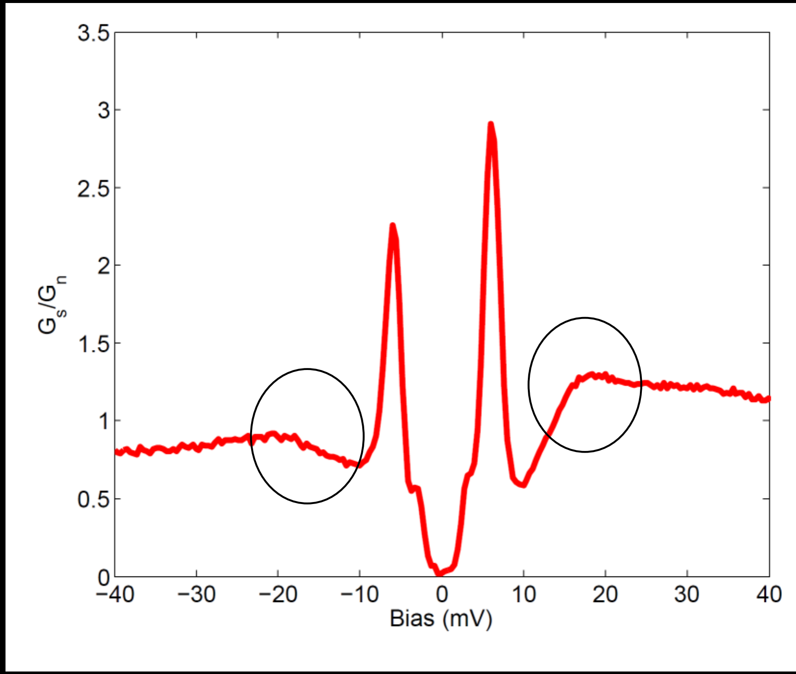


Replica features due to inelastic tunneling

Nat. Commun. **8**, 15996 (2017)

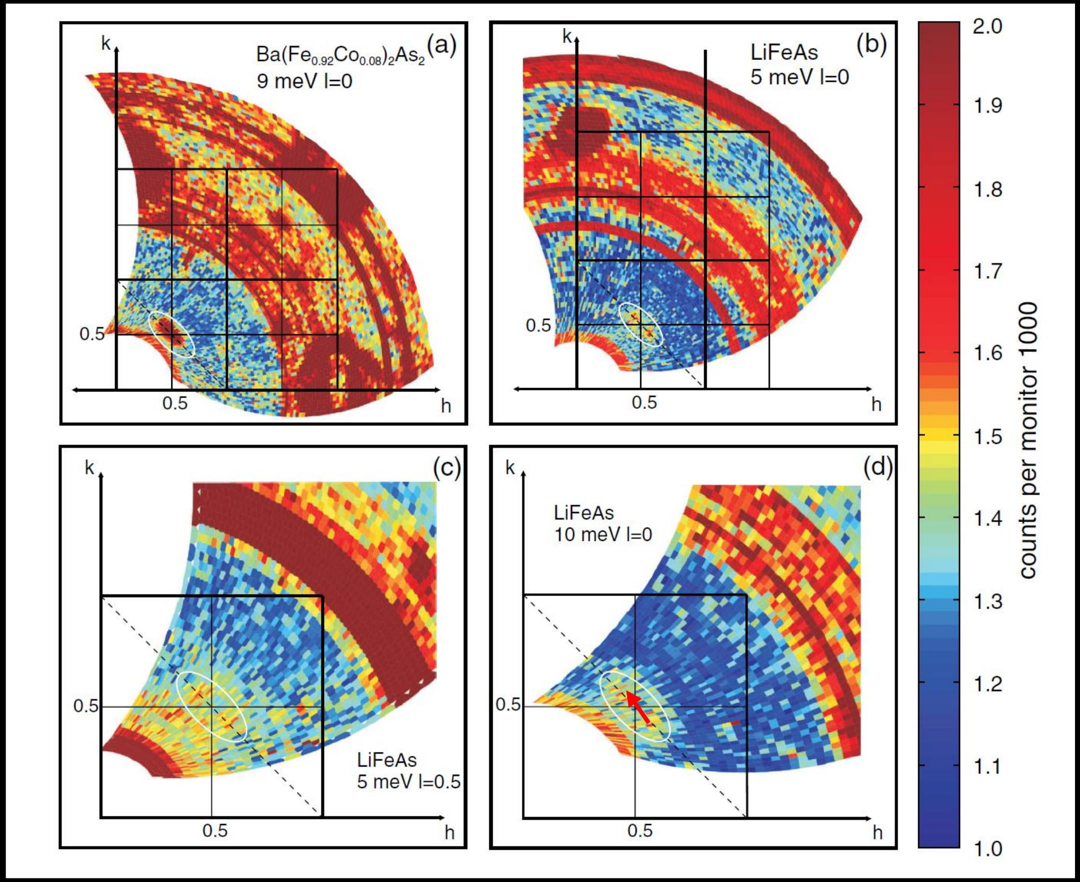
Dip-hump features – coupling to the spin resonance





Nat. Commun. **8**, 15996 (2017)

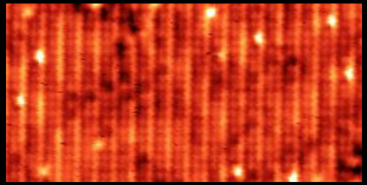
Spin Resonance



δ~±0.07

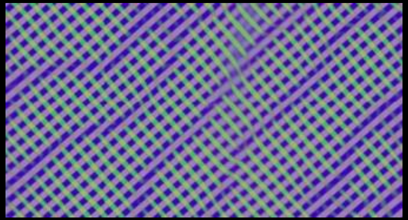
N. Qureshi *et al.*, *Phys. Rev. Lett.* **108**, 117001 (2012)
see also A.E. Taylor *et al.*, *Phys. Rev. B* **83**, 220514 (2011)

Summary

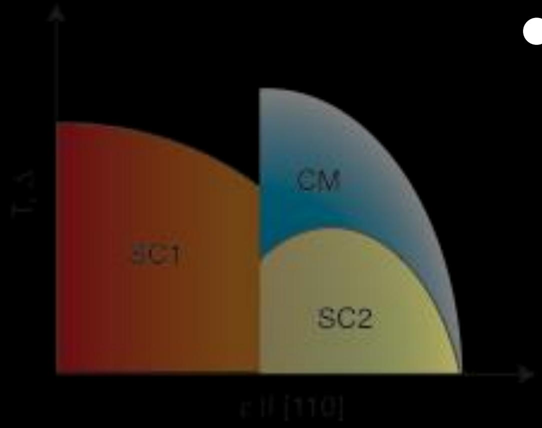


- Magnetic imaging of emergent orders

- Manipulation of surface magnetic order



- Strain-tuning of emergent phases



The End