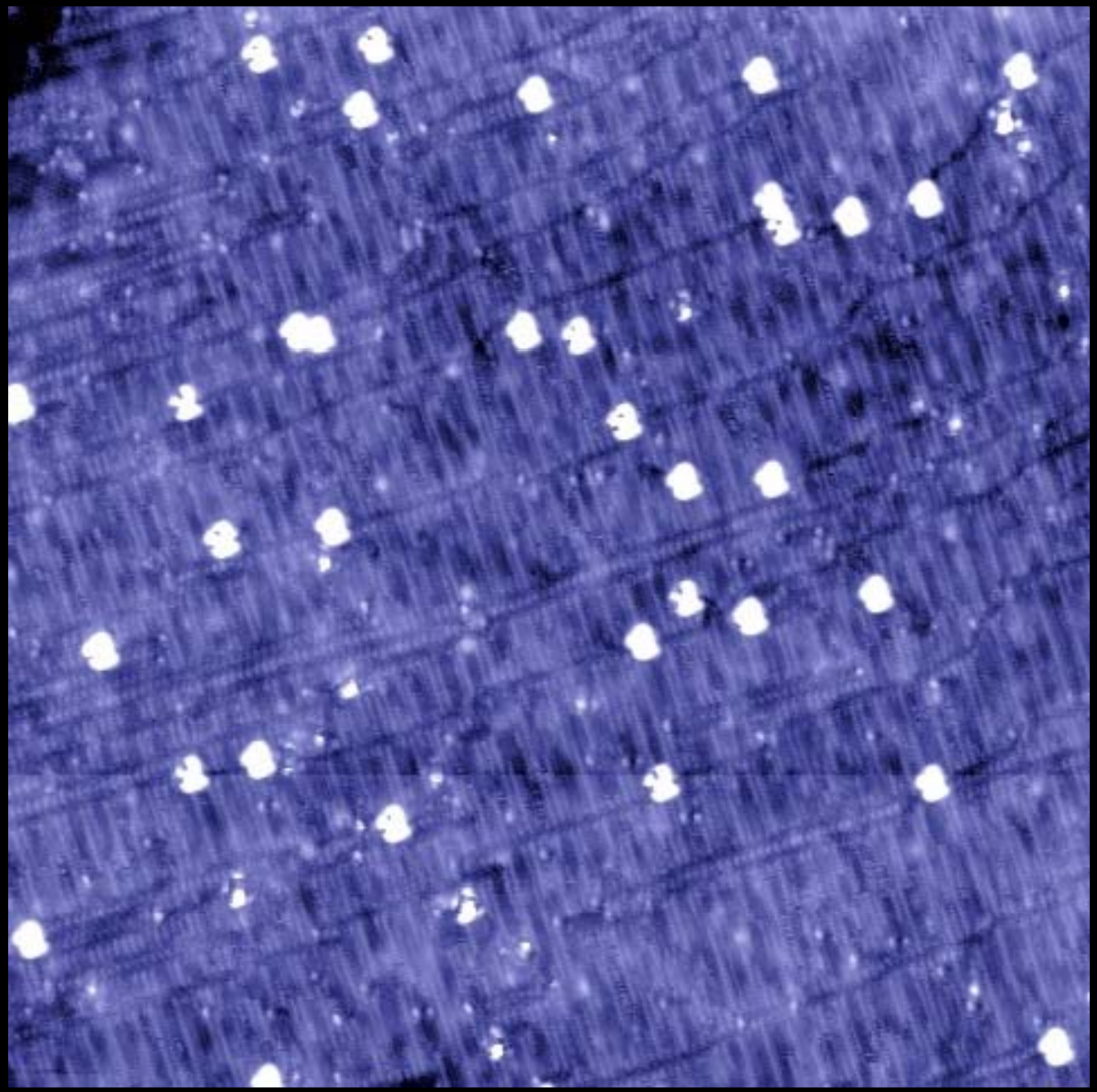
STS and Vortex Imaging in the Pnictide Superconductor $Ba(Co_xFe_{1-x})_2As_2$



Yi Yin

Martin Zech

Tess Williams

XiangFeng Wang

Gang Wu

Xianhui Chen

Jenny Hoffman

Thanks to:

NSF

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

UNITED STATES AIR FORCE

Who did all the work?

Yi Yin

Martin Zech

Tess Williams

Outline

Iron Pnictide Superconductors

→ Brief history

→ What are the big outstanding questions?

→ Where do we stand in answering these questions?

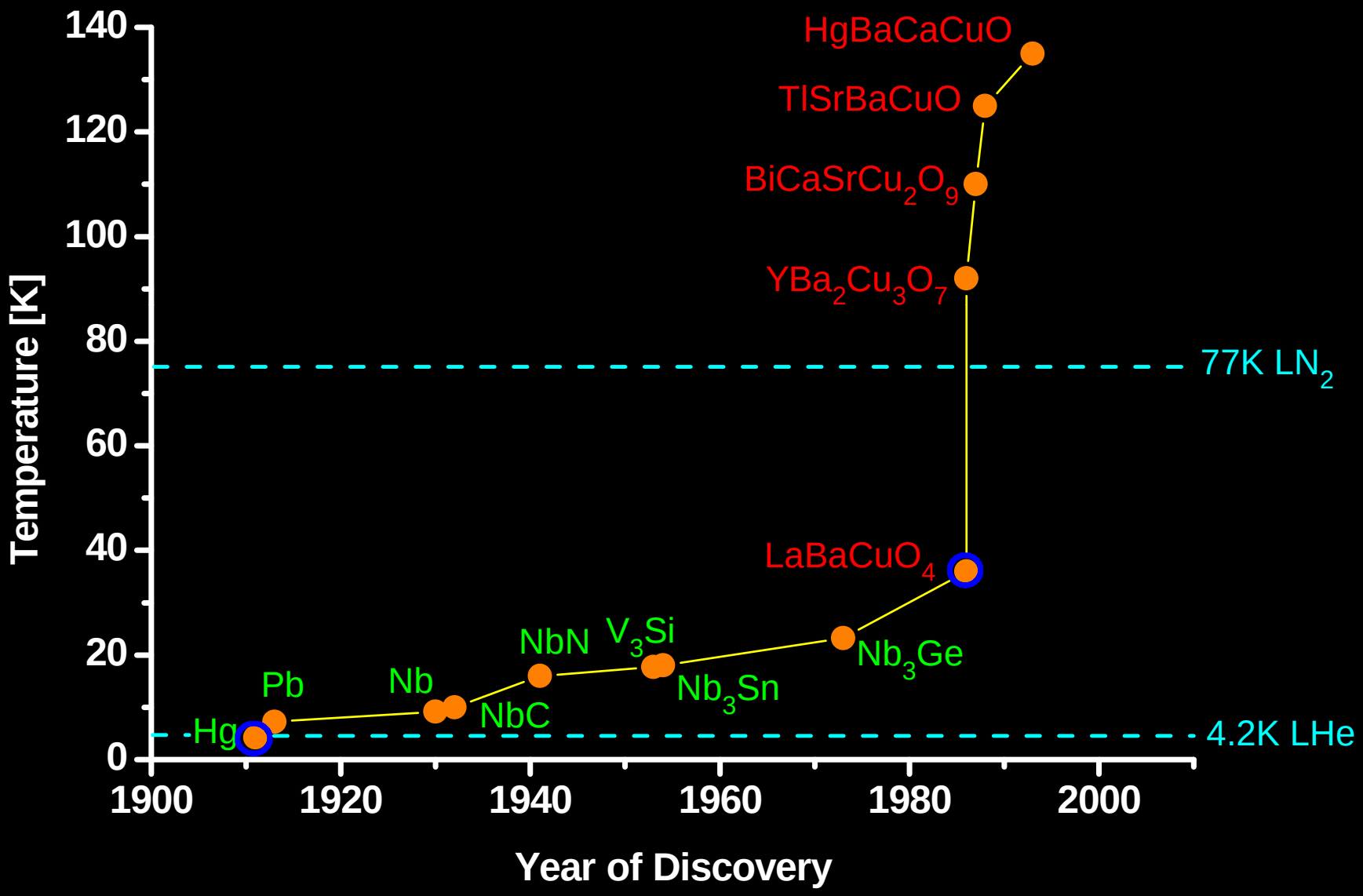
STM applied to iron pnictides

- surface considerations
- superconducting gap measurement
- vortex mapping

Direct comparison to cuprates

Outlook

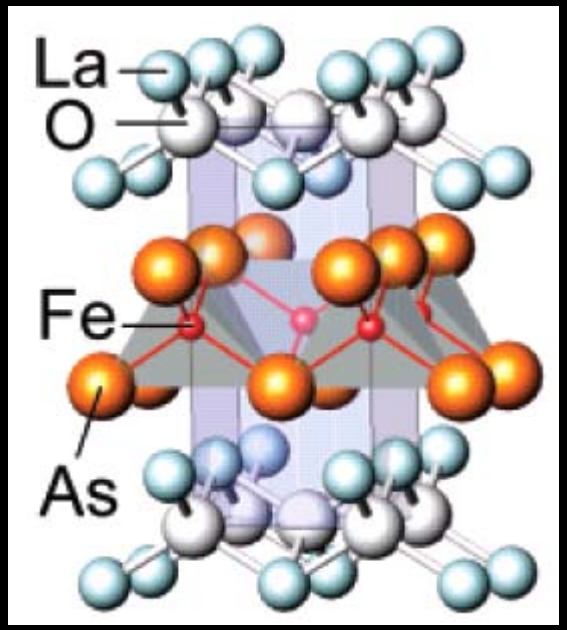
A Long History of Superconductivity



A New Revolution

Kamihara *et al*, J. Am. Chem. Soc. 130, 3296 (Feb 23, 2008)

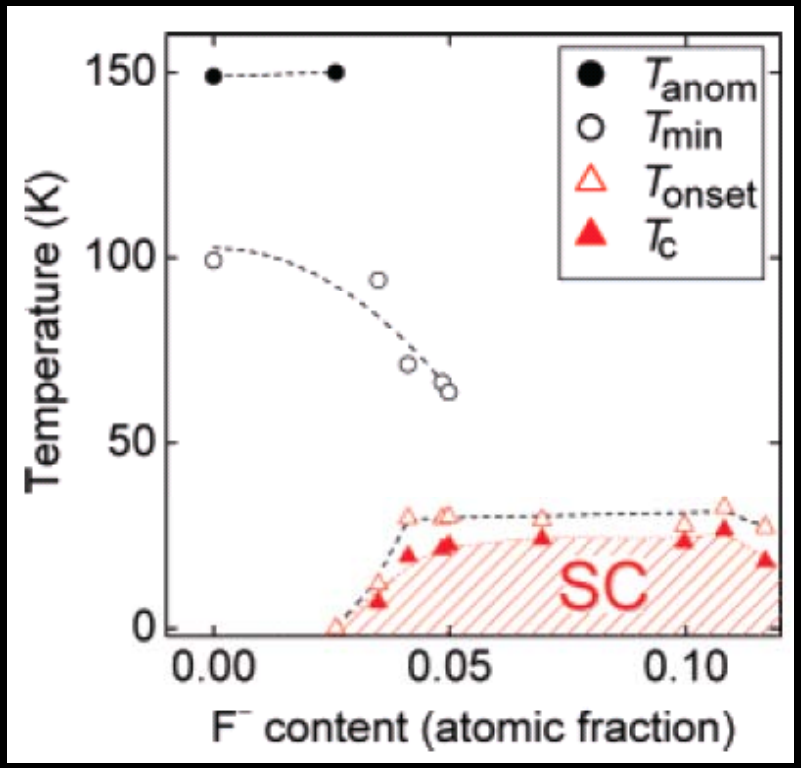
$LaFeAsO_{1-x}F_x$



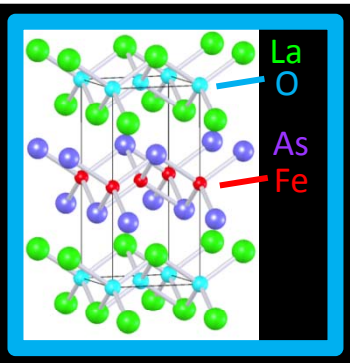
insulating layer

conducting layer

T_c=26K

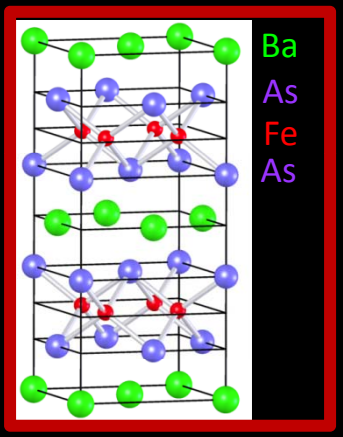


A Short History of Iron-Pnictide Superconductivity



1111

122



T_c (K)

60
50
40
30
20
10
0

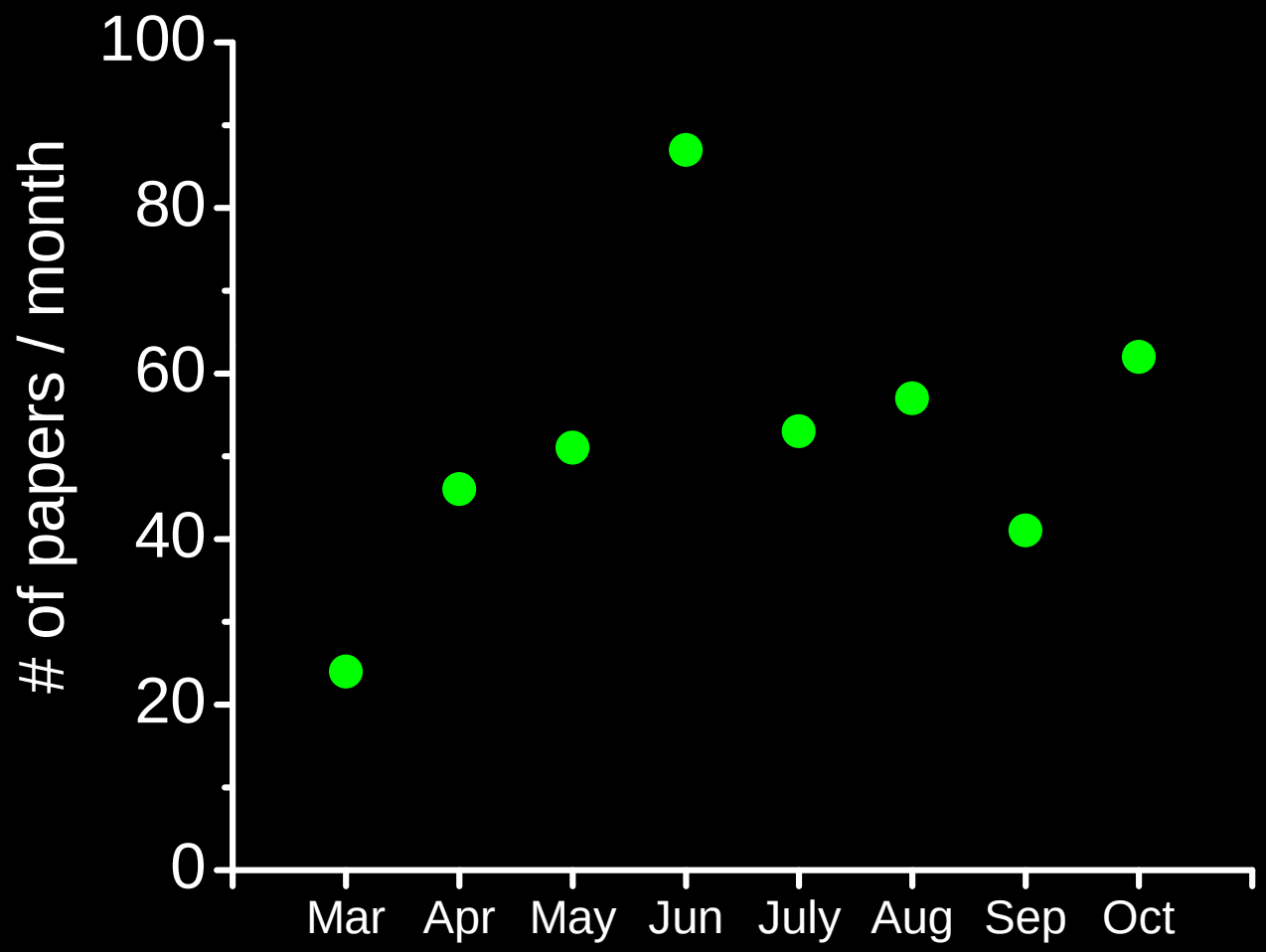
$SmFeAsO_{1-x}$
$Gd_{1-x}Th_xFeAsO$
$SmFeAsO_{1-x}F_x$
$PrFeAsO_{1-x}F_x$
$GdFeAsO_{1-x}$
$Tb_{1-x}Th_xFeAsO$
$NdFeAsO_{1-x}F_x$
$TbFeAsO_{1-x}F_x$
$DyFeAsO_{1-x}F_x$
$SmFeAsO_{1-x}F_x$
$CeFeAsO_{1-x}F_x$
$Sr_{1-x}K_xFe_2As_2$
$GdFeAsO_{1-x}F_x$
$Ba_{1-x}K_xFe_2As_2$
$Eu_{1-x}K_xFe_2As_2$
e-doped
$LaFeAsO_{1-x}F_x$
hole-doped
$La_{1-x}Sr_xFeAsO$
$Ca_{1-x}Na_xFe_2As_2$
$BaCo_xFe_{2-x}As_2$
$Eu_{1-x}La_xFe_2As_2$
$SrCo_xFe_{2-x}As_2$
$BaNi_xFe_{2-x}As_2$
$Li_{1-x}FeAs$
$FeSe_{0.5}Te_{0.5}$
$LaO_{1-x}F_xFeP$
LaOFeP
LaONiP
$BaNi_2P_2$
$LaO_{1-x}NiBi$
α-$FeSe_{1-x}$
α-FeSe
$SrNi_2As_2$

Feb Mar Apr May Jun Jul Aug Sep Oct Nov

2006-7

2008

Flood of papers…

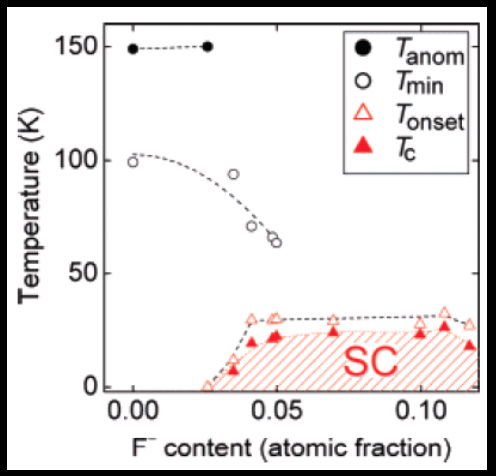


Why the excitement?

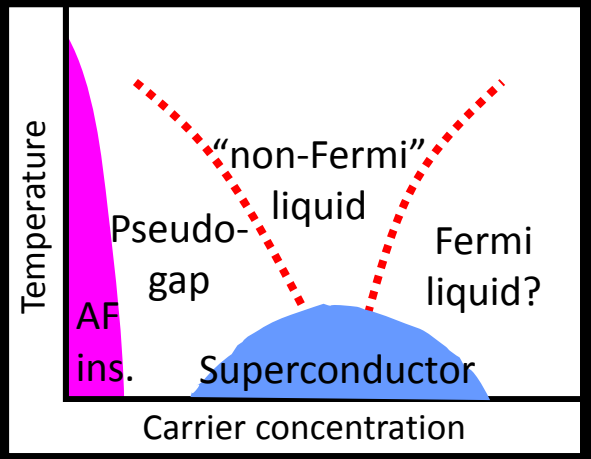
1) Physics
   - A second chance to get it right!
   - A foil for cuprates

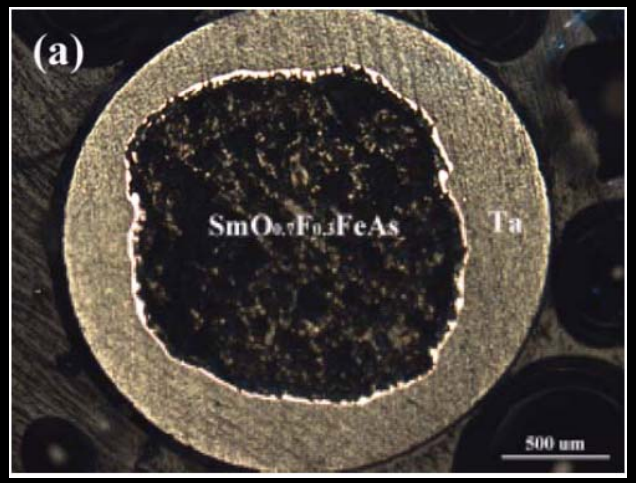
2) Applications
   - Low anisotropy
   - High H_{c2}
   - Strong pinning

$LaFeAsO_{1-x}F_x$



Cuprates





$SmO_{0.7}F_{0.3}FeAs$ wires fabricated by powder-in-tube method

T_c=52K, J_c up to 3900 A/cm^2, extrapolated H_{c2} up to 120T
(J_c within grains ~ 2x10^5 A/cm^2)

Zhaoshun Gao, Super. Sci. Tech. 21, 112001 (2008)

Big Unanswered Questions

(1) What is the pairing symmetry?

(2) What is the role of spin?

(3) Quantify & understand H_{c2} and vortex pinning?

Big Unanswered Questions

(1) What is the pairing symmetry?

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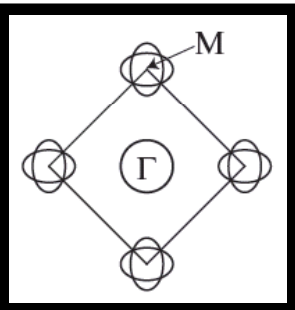
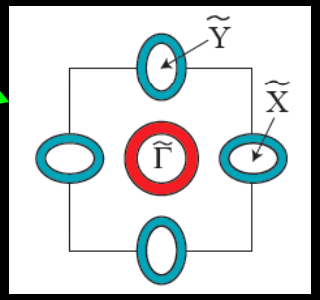
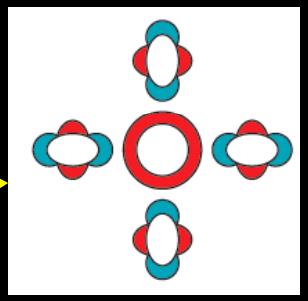
Theory: What is the pairing symmetry?

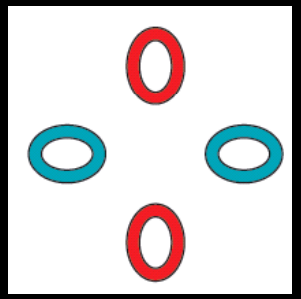


(1) nodeless extended s-wave (s±)
- Mazin, PRL 101, 057003 (2008)
- Wang, PRL 102, 047005 (2009)
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)

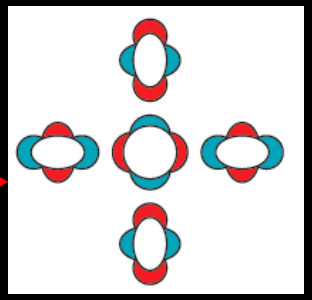




(2) nodal s-wave
- Kuroki, PRL 101, 087004 (2008)

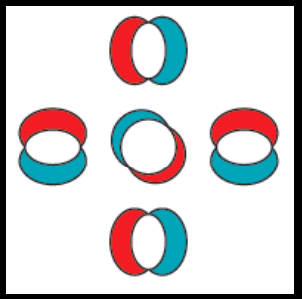


(3) nodeless d
- Kuroki, PRL 101, 087004 (2008)



(4) d_{x2-y2} order
- Yao, Li & Wang, New J. Phys. 11, 025009 (2009)

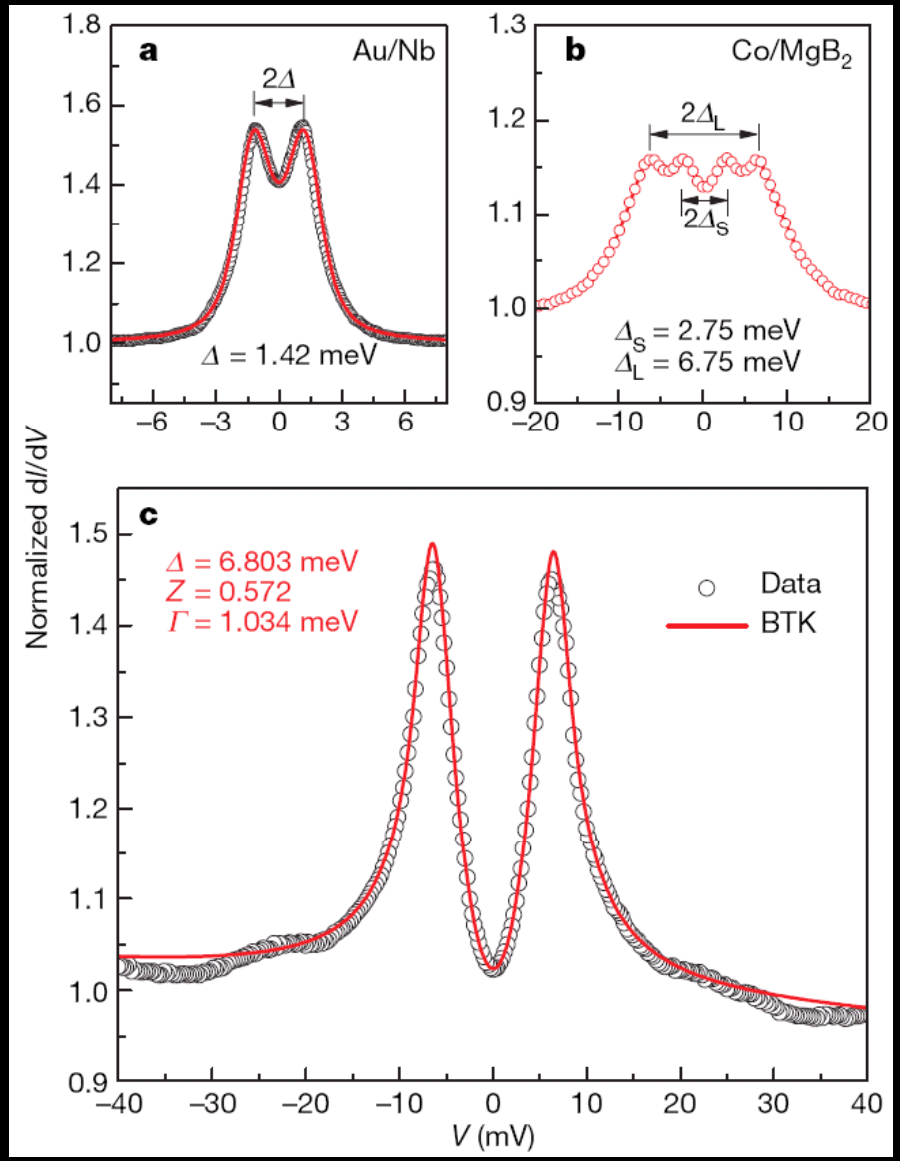
(5) nodal intraband p order
- Lee & Wen, PRB 78, 144517 (2008)



(6) interband p order
- Dai, PRL 101, 057008 (2008)

figures borrowed from from Hicks, … Moler, JPSJ 78, 013708 (2009)

Andreev: What is the pairing symmetry?



$SmFeAsO_{0.85}F_{0.15}$ with $T_c = 42$ K

Gap: $2\Delta = 13.34 \pm 0.3$ meV

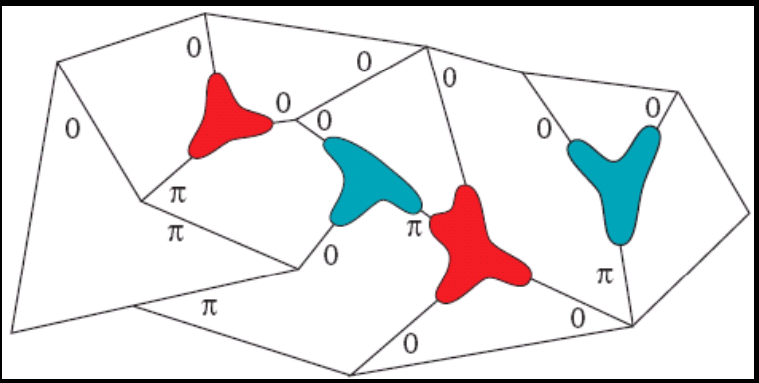
Reduced Gap: $2\Delta/k_B T_c = 3.68$
(compare to 3.53 for pure BCS)

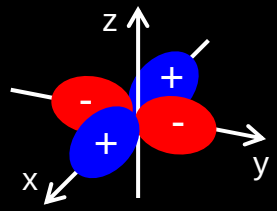
Conclude from fit: nodeless gap

Chen, Nature 453, 1224 (2008)

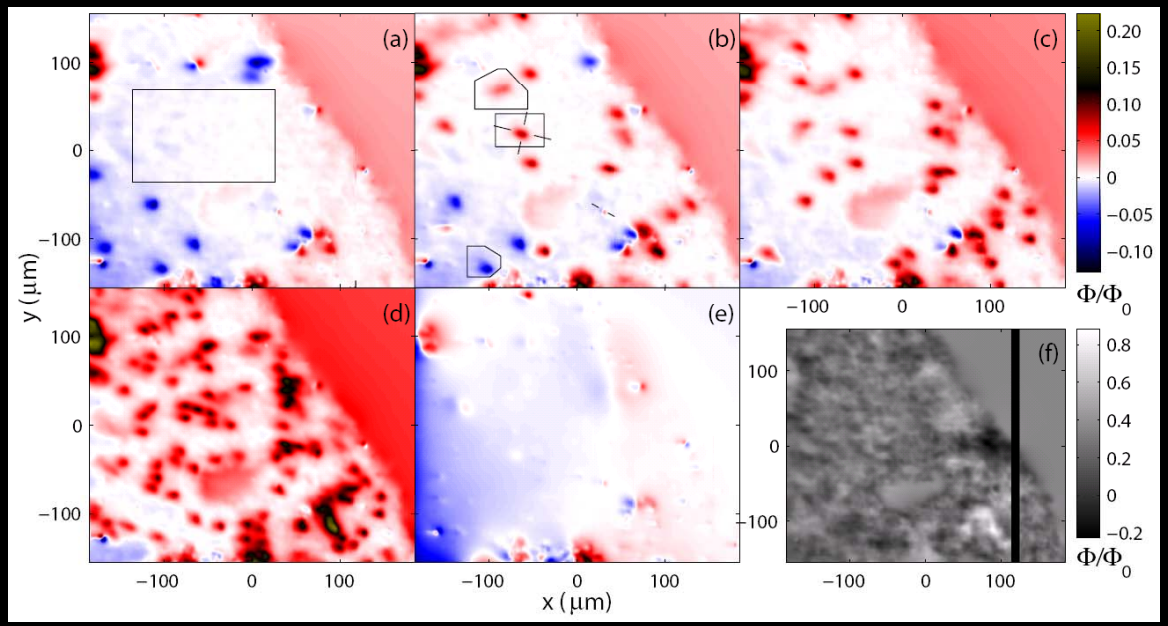
Scanning SQUID: what is the pairing symmetry?

Polycrystalline material would have many grain boundaries.
In some symmetry scenarios, e.g. d_{x2-y2}
some grain boundaries would flip sign of order parameter
→ trap fractional flux!



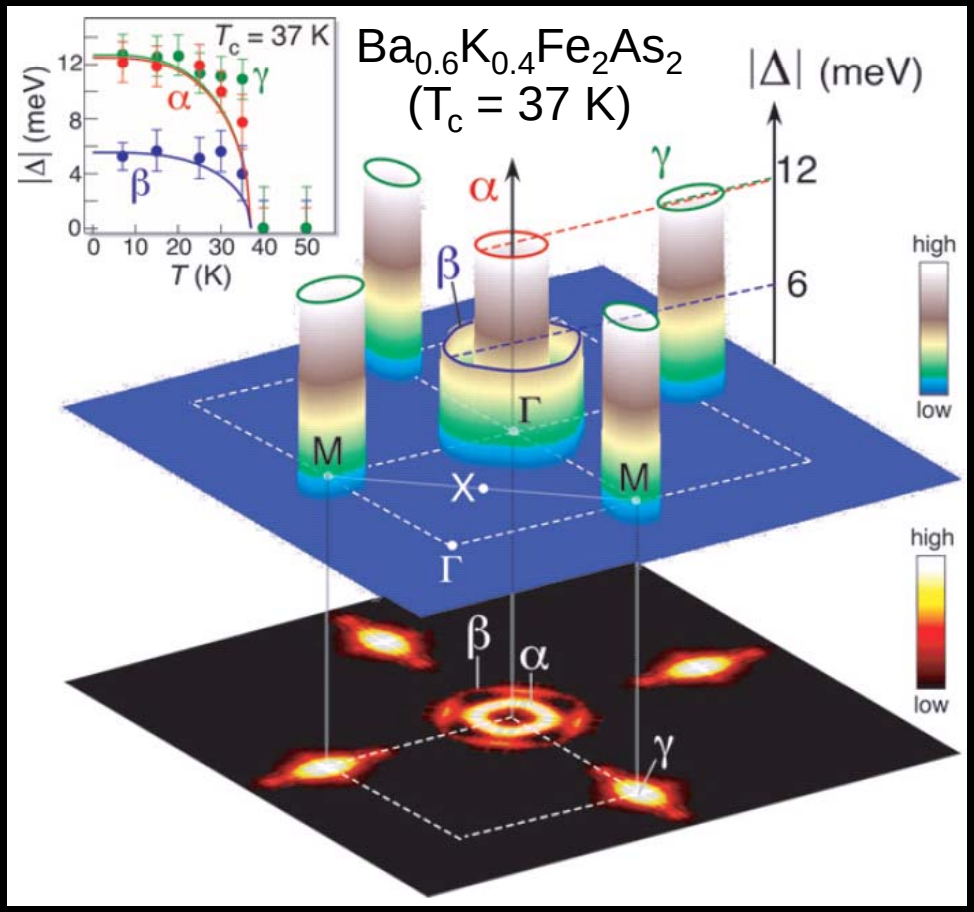


$NdFeAsO_{0.94}F_{0.06}$ (T_c = 48 K)
No Fractional Vortices Observed!



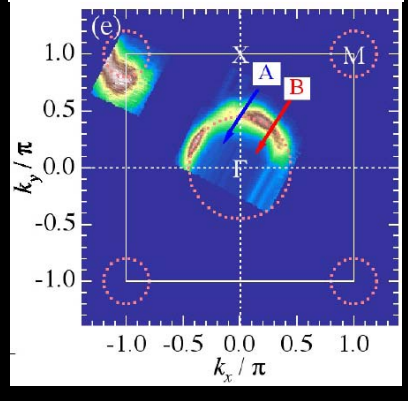
Hicks, … Moler, JPSJ 78, 013708 (2009)

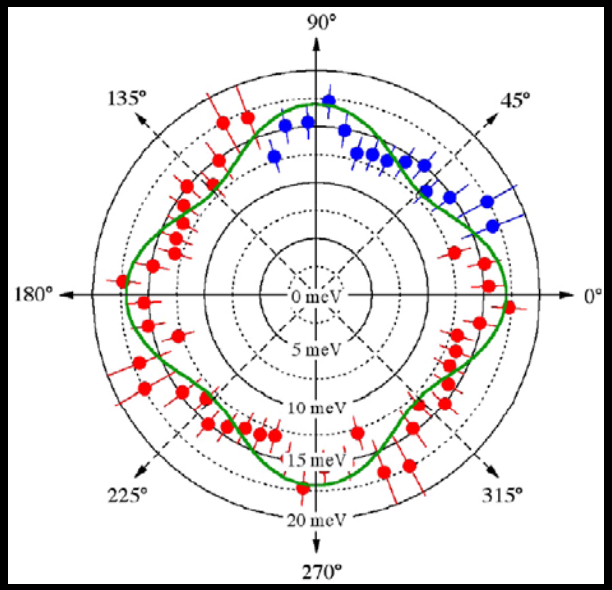
ARPES: What is the pairing symmetry?



Ding, EPL 83, 47001 (2008)

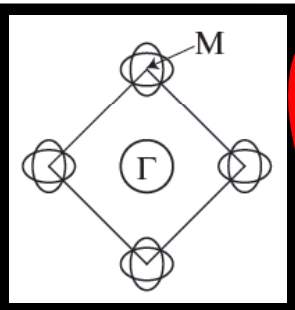
$NdFeAsO_{0.9}F_{0.1}$
(T_c = 53 K)



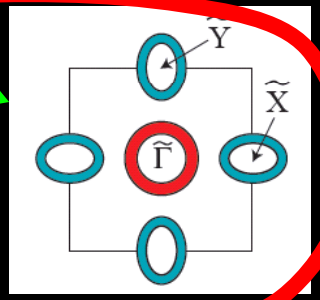


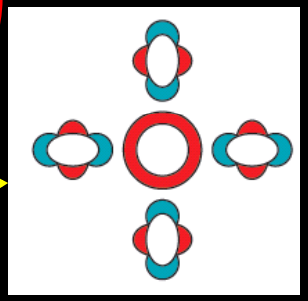
Kondo, PRL 101, 147003 (2008)

Converging on s± symmetry?

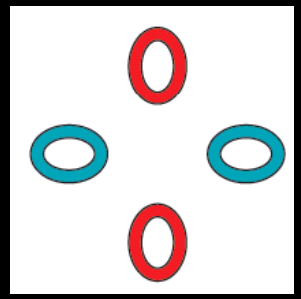


(1) nodeless extended s-wave (s±)
- Mazin, PRL 101, 057003 (2008)
- Wang, PRL 102, 047005 (2009)
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)

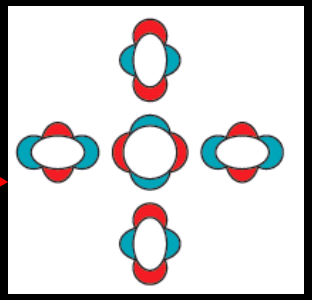




(2) nodal s-wave
- Kuroki, PRL 101, 087004 (2008)



(3) nodeless d
- Kuroki, PRL 101, 087004 (2008)



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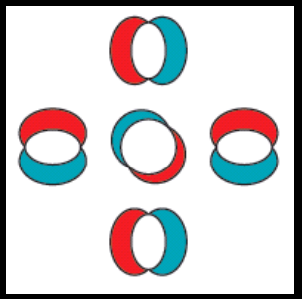

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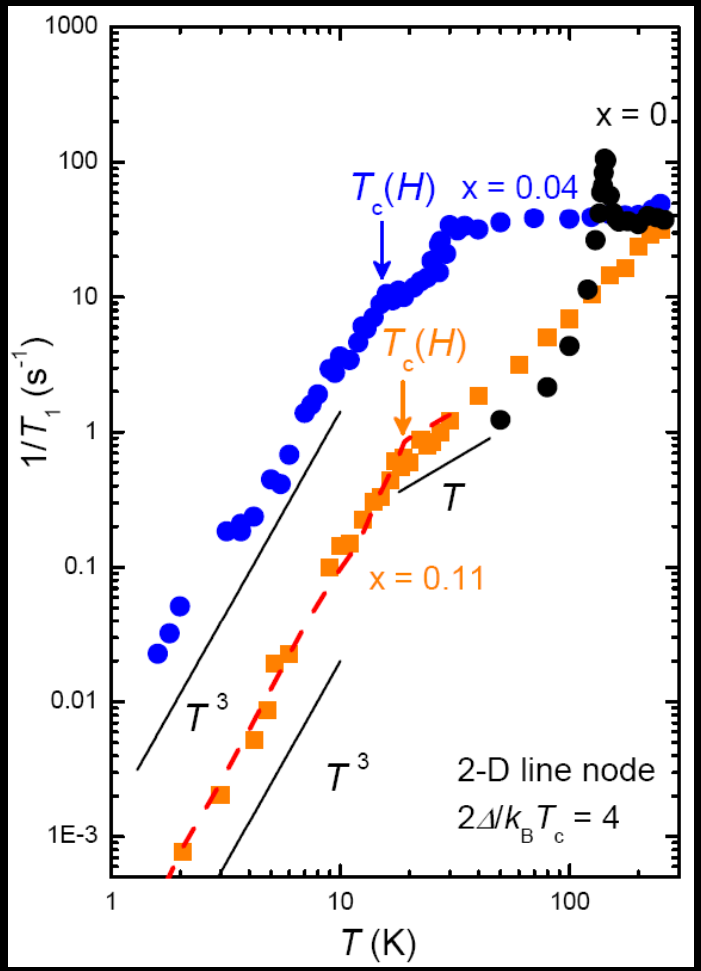
figures borrowed from from Hicks, … Moler, JPSJ 78, 013708 (2009)

NMR: what is the pairing symmetry?

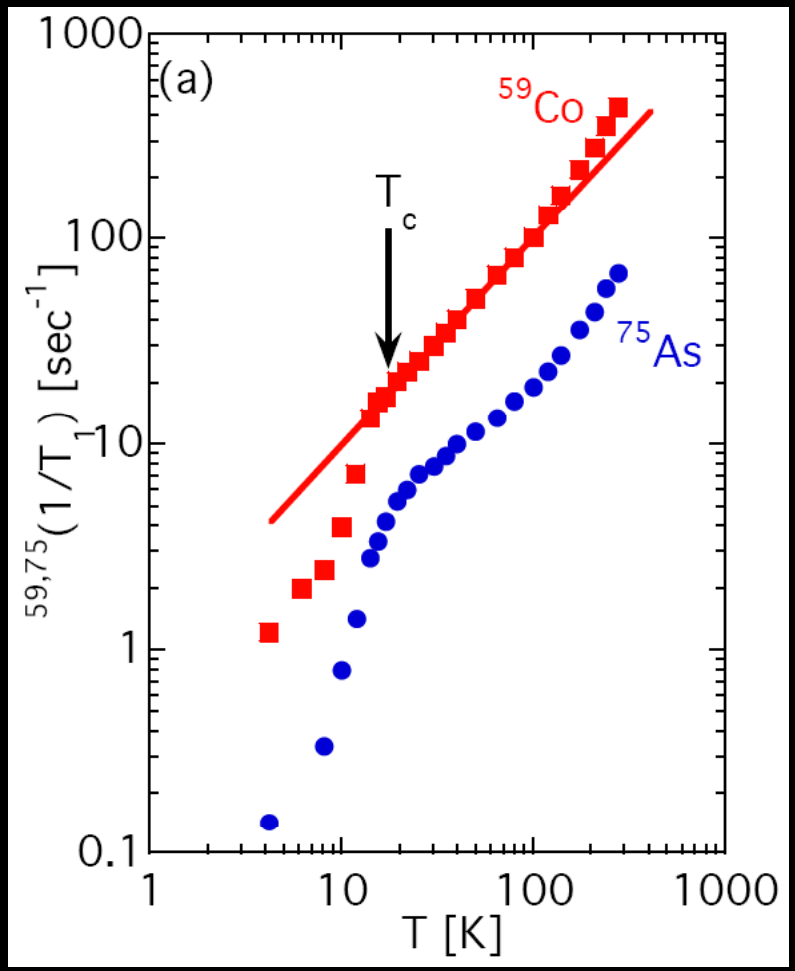
$La(O_{1-x}F_x)FeAs$



Ning, arXiv:0804.4765, to appear in J. Phys. Soc. Jpn.

"suggests 2-dim line nodes in gap"

$Ba(Co_xFe_{1-x})_2As_2$

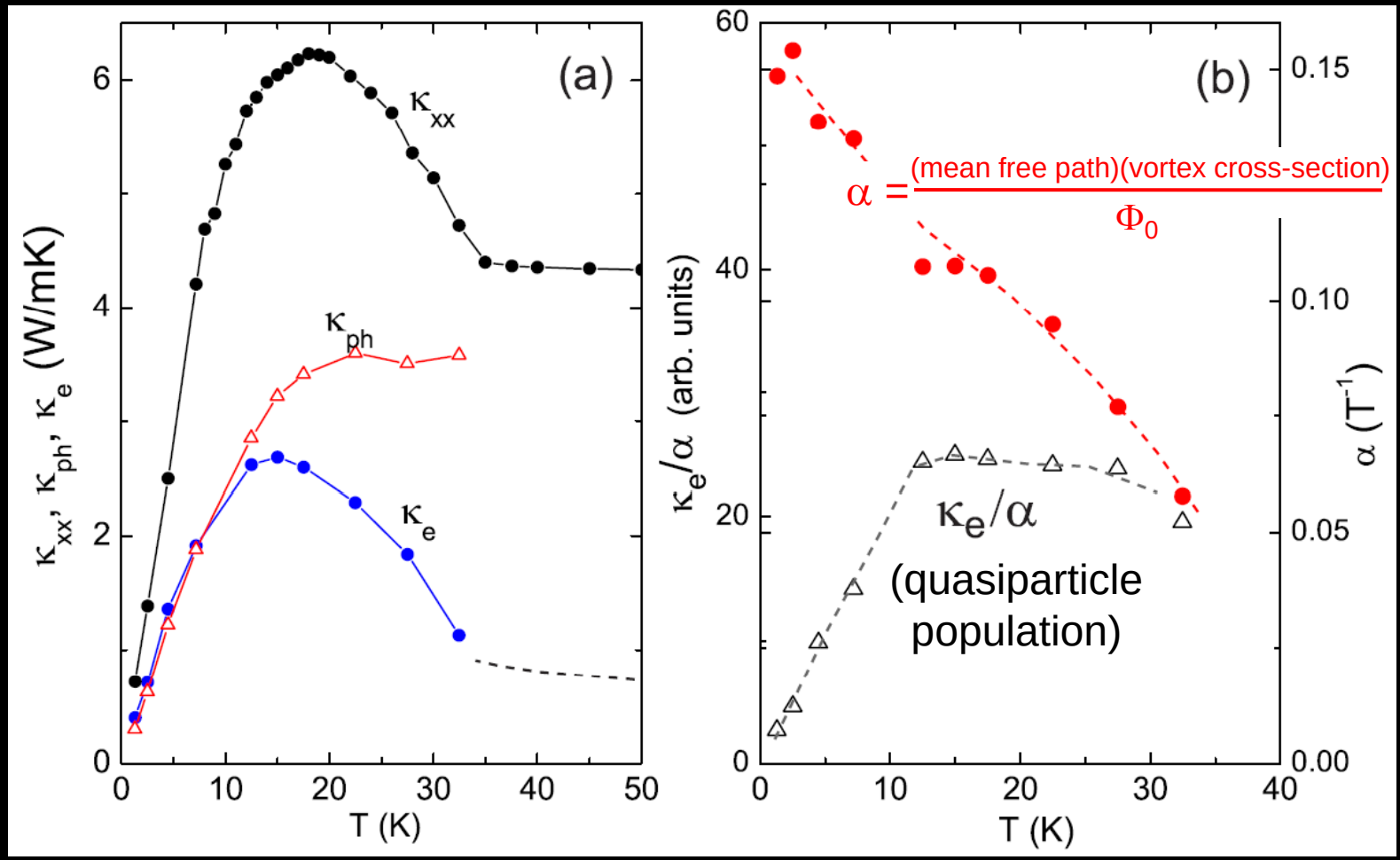


Ning, J. Phys. Soc. Jpn. 77, 103705 (2008).

"rules out spin-triplet pairing; qualitatively similar to d-wave cuprates"

Thermal transport: what is the pairing symmetry?

$(Ba_{1-x}K_x)Fe_2As_2$, T_c=37K



Checkelsky, arXiv:0811:4668

Other Evidence For Gap Nodes

- Specific heat in $LaFeAsO_{0.9}F_{0.1-\delta}$
  [Mu *et al*, Chin. Phys. Lett. 25, 2221 (2008)]
- H_{c1} measurements in $LaFeAsO_{0.9}F_{0.1}$
  [Ren *et al*, arXiv: 0804.1726]
- point contact spectroscopy in $LaFeAsO_{0.9}F_{0.1-\delta}$
  [Shan *et al*, Europhys. Lett. 83, 57004 (2008)]
- μSR in $LaFeAsO_{1-x}F_x$
  [Luetkens *et al*, Phys. Rev. Lett. 101, 097009 (2008)]
- NMR in $LaFeAsO_{1-x}F_x$
  [Ahilan *et al*, Phys. Rev. B 78, 100501 (2008),
  Grafe *et al*, Phys. Rev. Lett. 101, 047003 (2008),
  Nakai *et al*, J. Phys. Soc. Jap. 77, 073701 (2008)]
- NMR in $LaFeAsO_{1-y}$ and $NdFeAsO_{1-y}$
  [Mukuda *et al*, J. Phys. Soc. Jap. 77, 093704 (2008)]
- NMR in FeSe
  [Kotegawa *et al*, J. Phys. Soc. Jap. 77, 113703 (2008)]
- Thermal Hall conductivity in $Ba_{1-x}K_xFe_2As_2$
  [Checkelsky *et al*, arXiv: 0811.4668]
- Penetration depth λ in $Ba(Co_xFe_{1-x})_2As_2$
  [Gordon *et al*, arXiv: 0810.2295, Martin *et al*, arXiv:0902.1804]
- Penetration depth λ in LaFePO, Nd-1111, La-1111
  [Fletcher *et al*, arXiv: 0812.3858, Martin *et al*, arXiv:0903.2220]

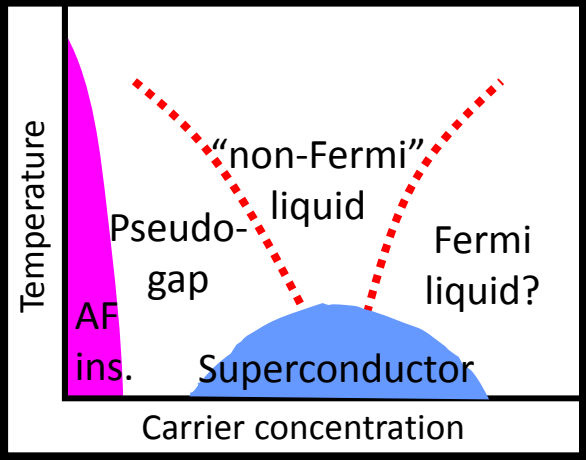
Big Unanswered Questions

(1) What is the pairing symmetry?

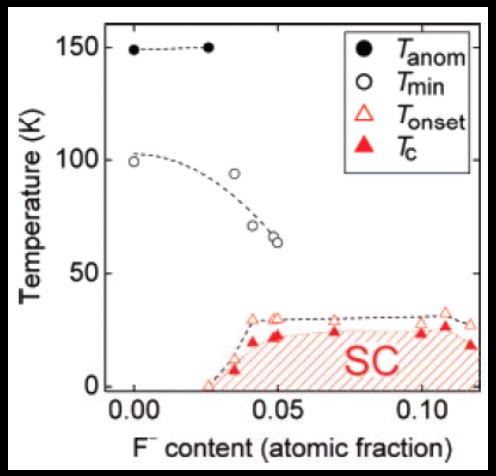
(2) What is the role of spin?

(3) Quantify & understand H_{c2} and vortex pinning?

Cuprates



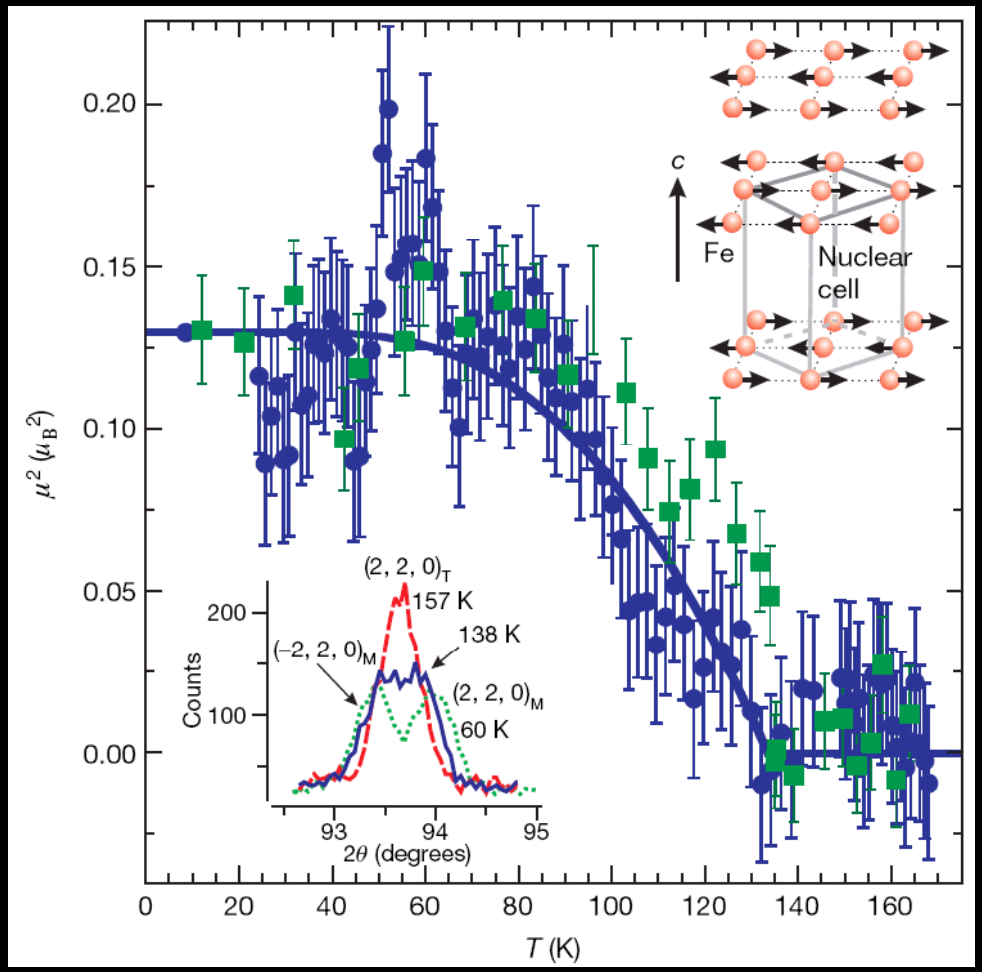
$LaFeAsO_{1-x}F_x$



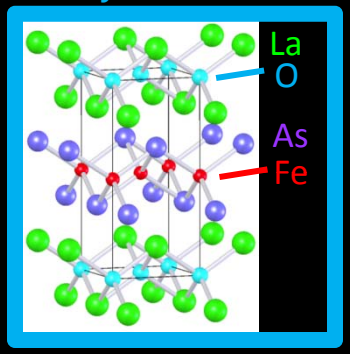
Neutron Scattering: What is the role of spin?

$LaO_{1-x}F_xFeAs$

- x=0: Structural ordering: 138K
- x=0: Collinear antiferromagnetic spin ordering: 137K
- Doping suppresses both, allows superconductivity.

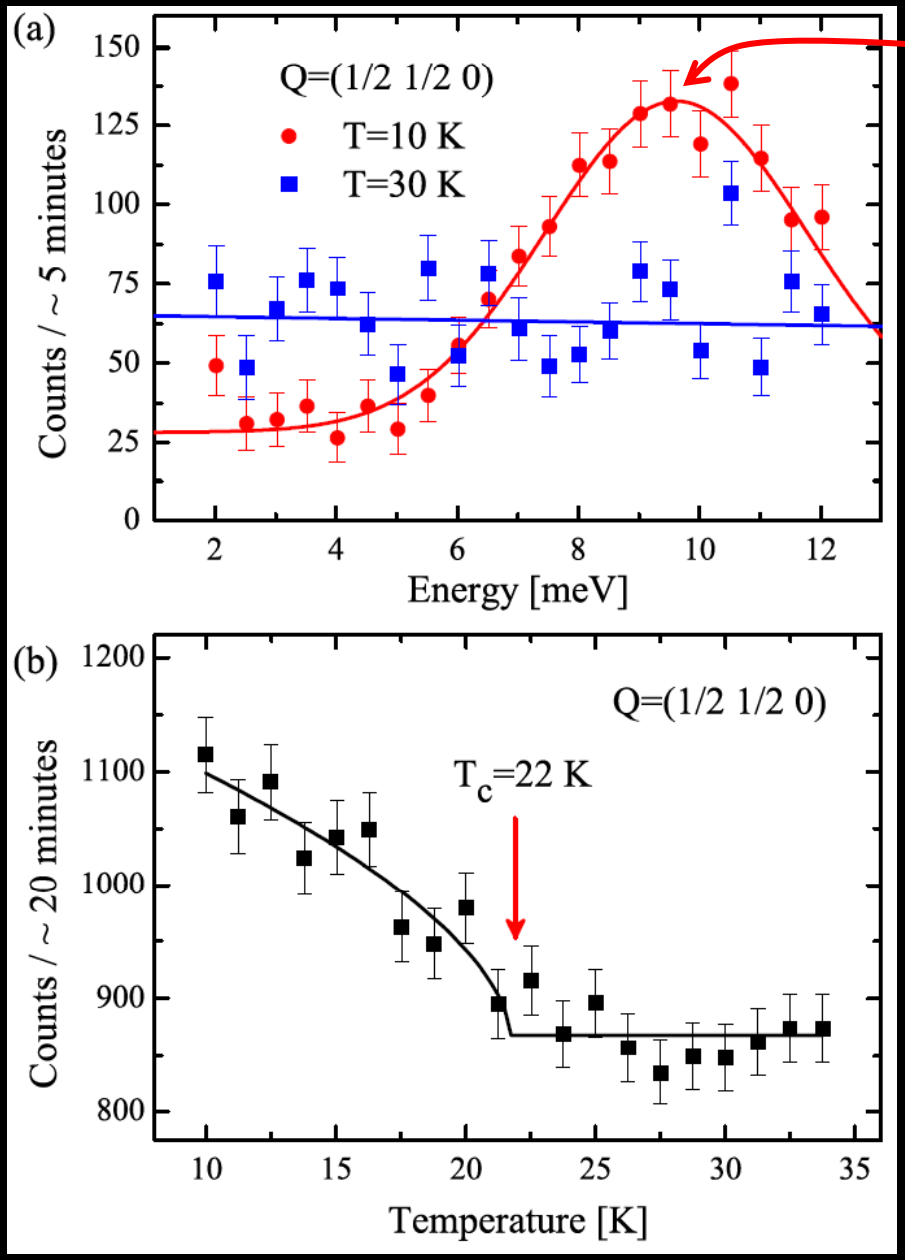


full crystal structure



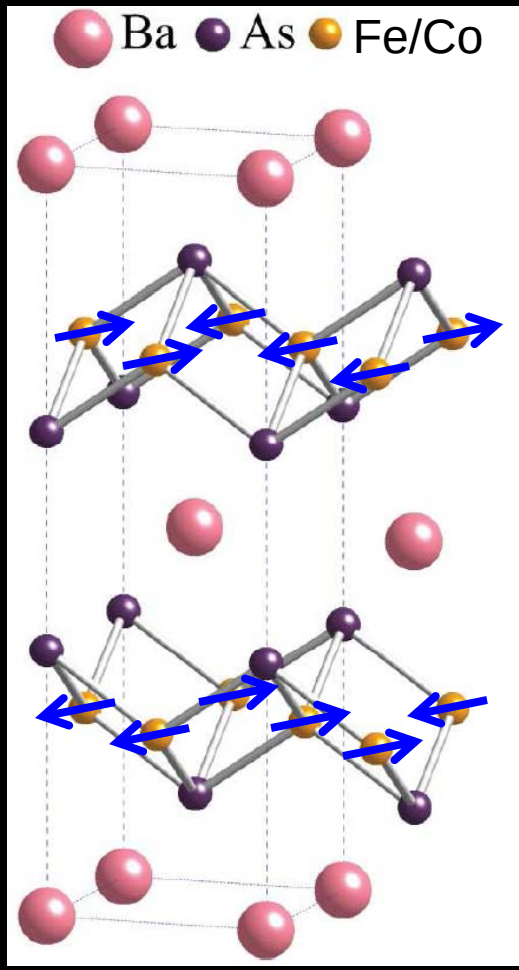
de la Cruz *et al*, Nature 453, 899 (2008)

Inelastic Neutron Scattering



magnetic resonance energy ~ $5k_BT_c$

$BaFe_{1.84}Co_{0.16}As_2$



Lumsden, arXiv:0811:4755

Big Unanswered Questions

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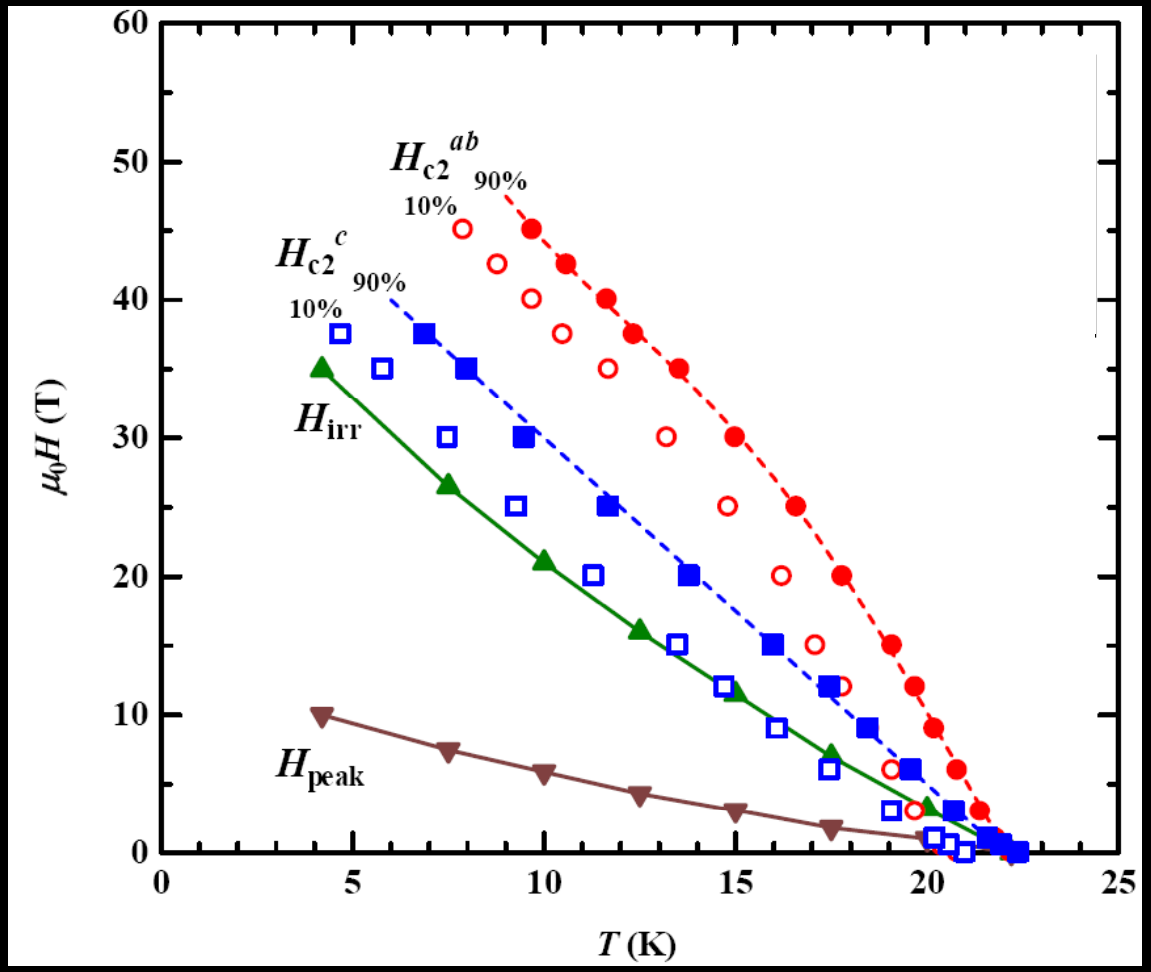
(2) What is the role of spin?

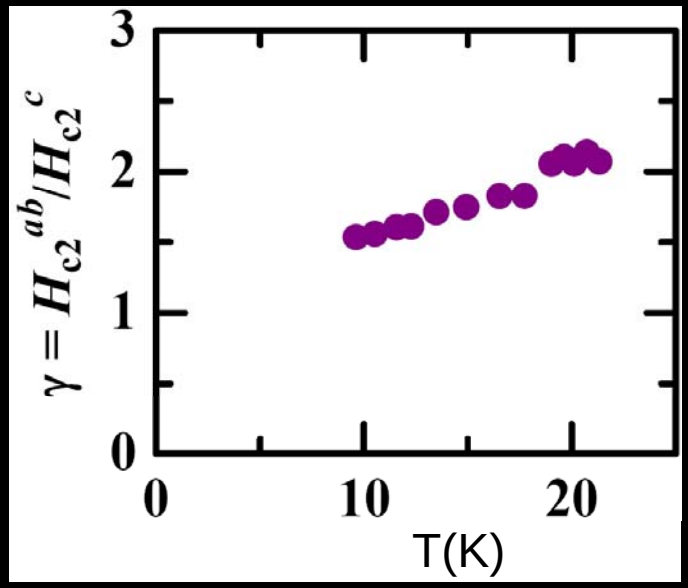
(3) Quantify & understand H_{c2} and vortex pinning?

Vortex pinning: low anisotropy, high H_{c2}

$Ba(Co_xFe_{1-x})_2As_2$ (T_c = 22K)



anistropy: γ = 1.5-2



strong pinning, speculation that it comes from nanoscale pinning sites,
e.g. Co dopant inhomogeneities → need a local tool to study these materials!

Yamamoto, APL 94, 062511 (2009)

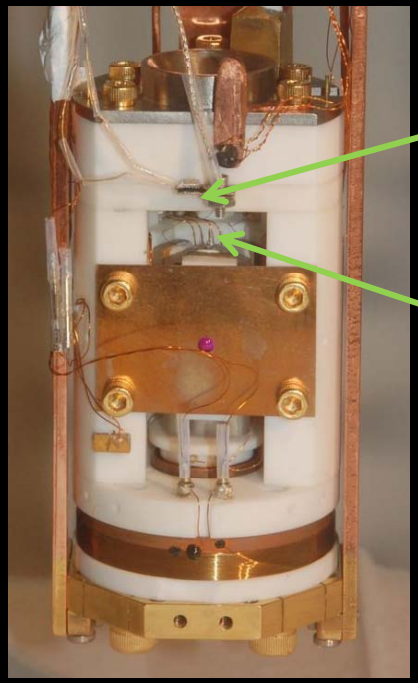
Big Unanswered Questions – Our Contributions

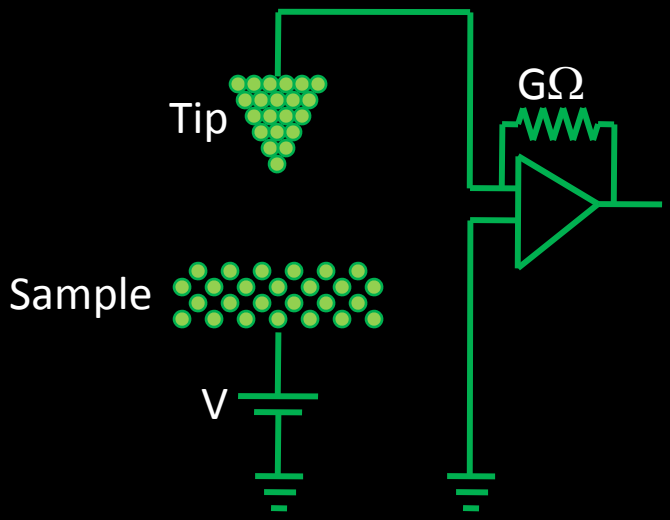
(1) What is the pairing symmetry?

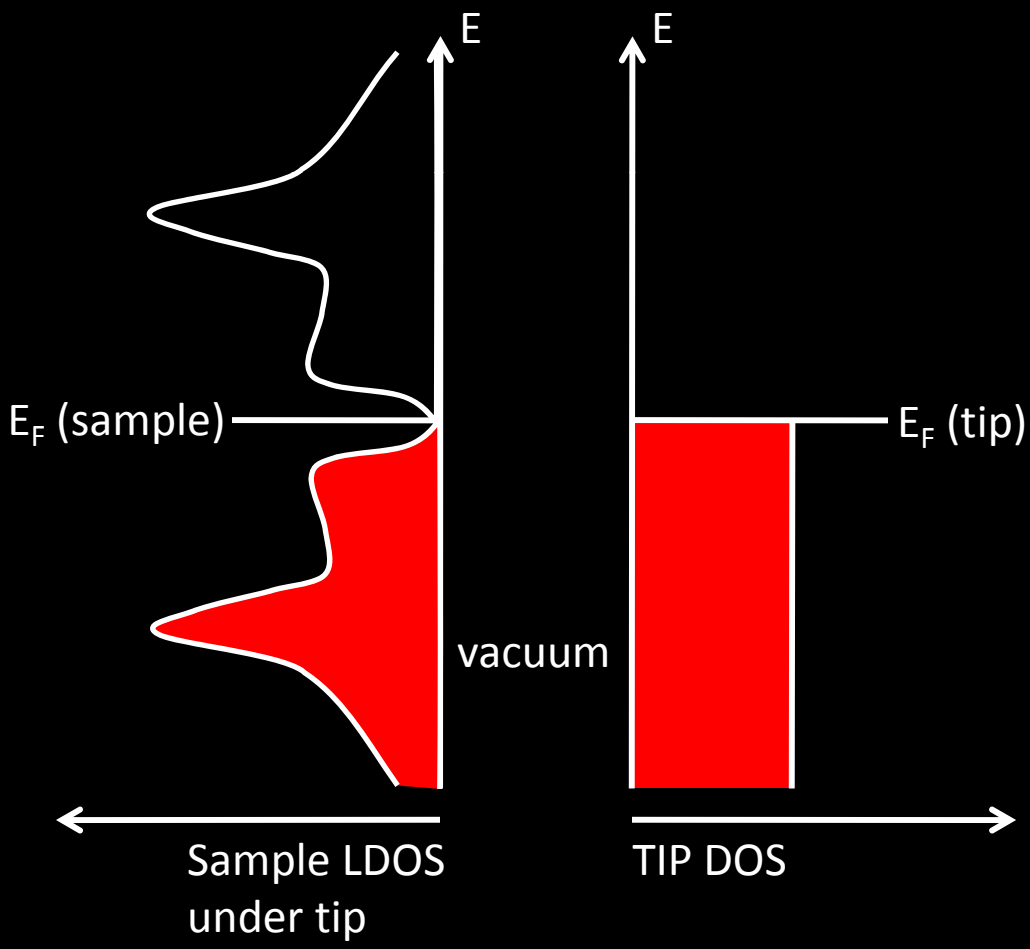
(2) What is the role of spin? → will have to wait…

(3) Quantify & understand H_{c2} and vortex pinning?

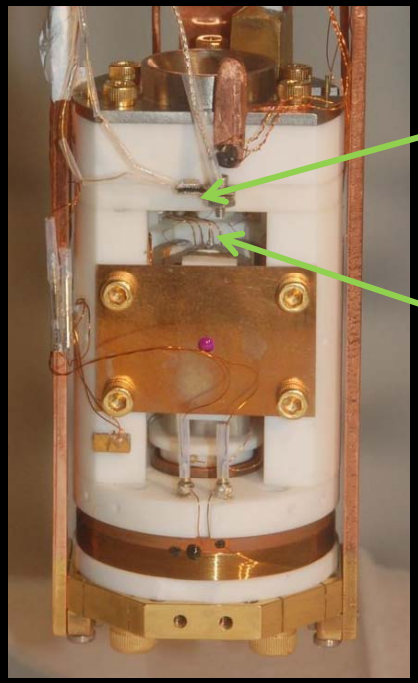
Introduction to STM



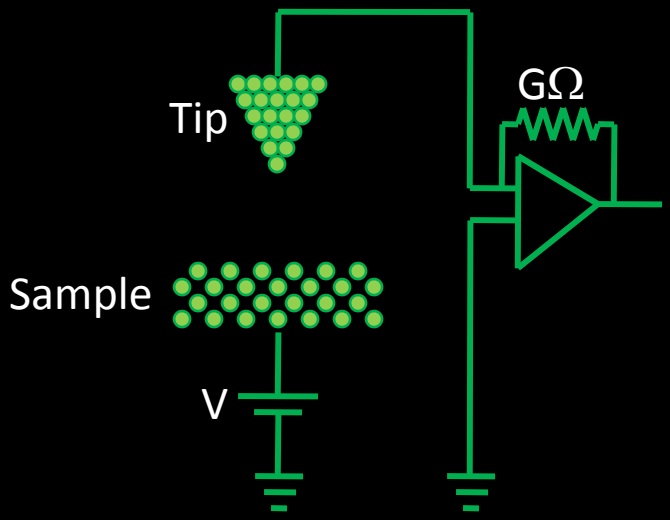


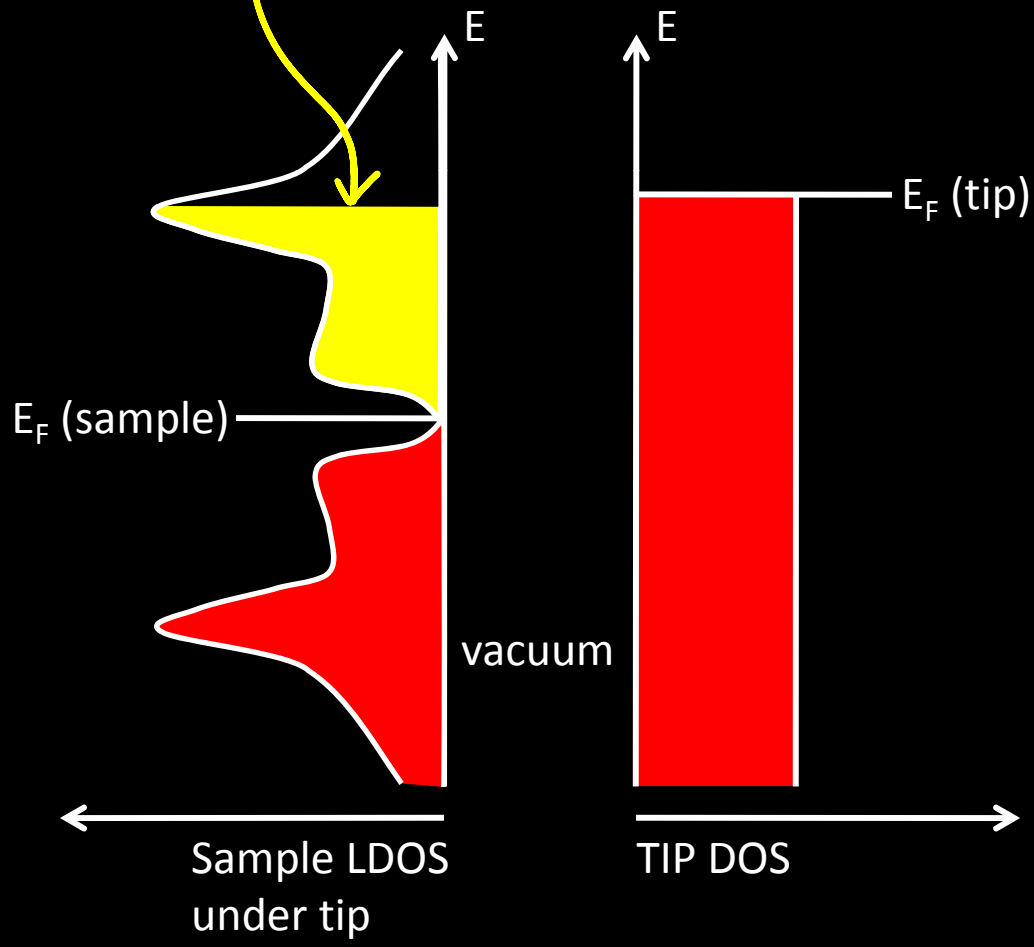


Introduction to STM

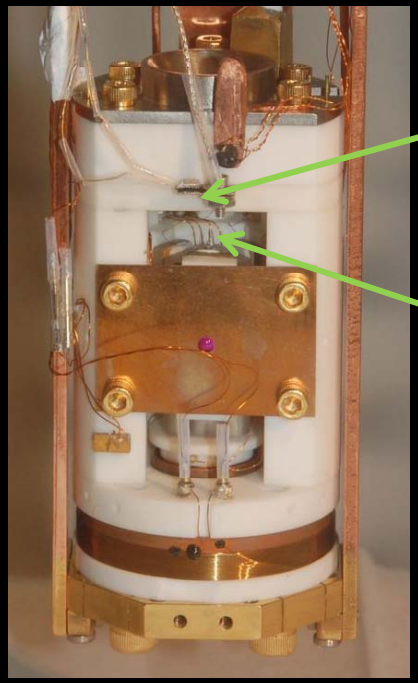


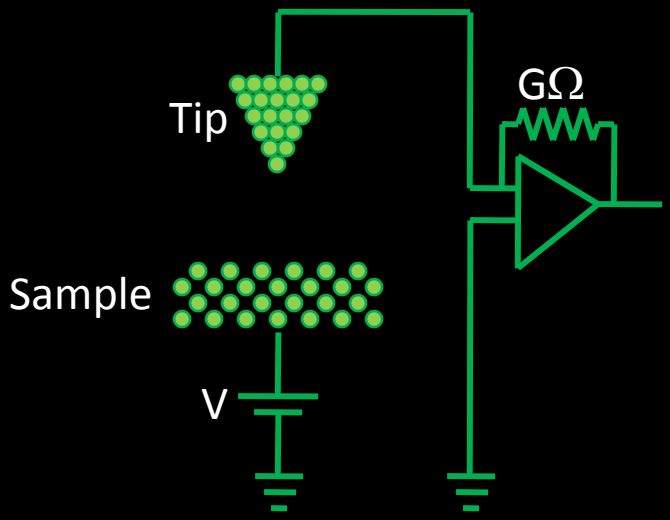
$$I(V) = \int_{E_F}^{eV} LDOS(E)\,dE$$



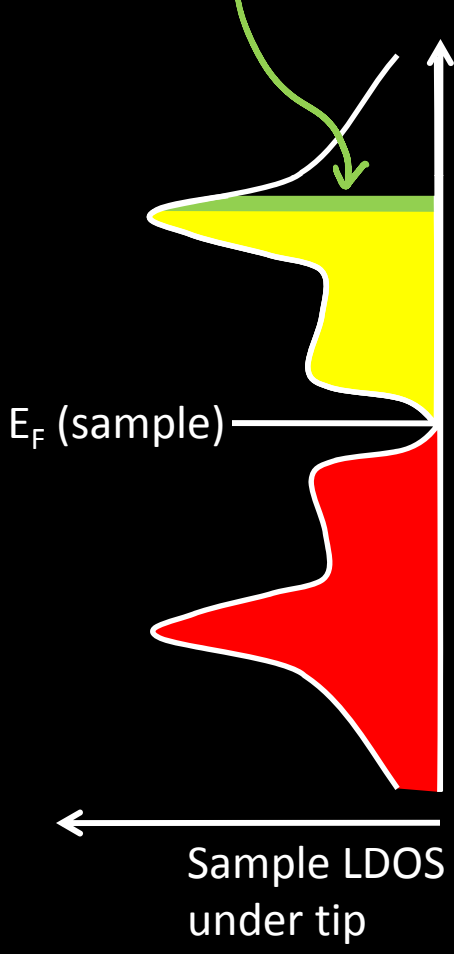


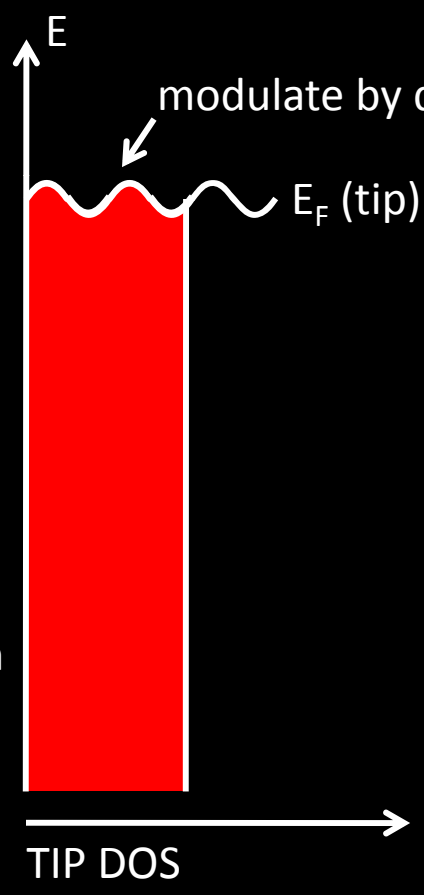
Introduction to STM



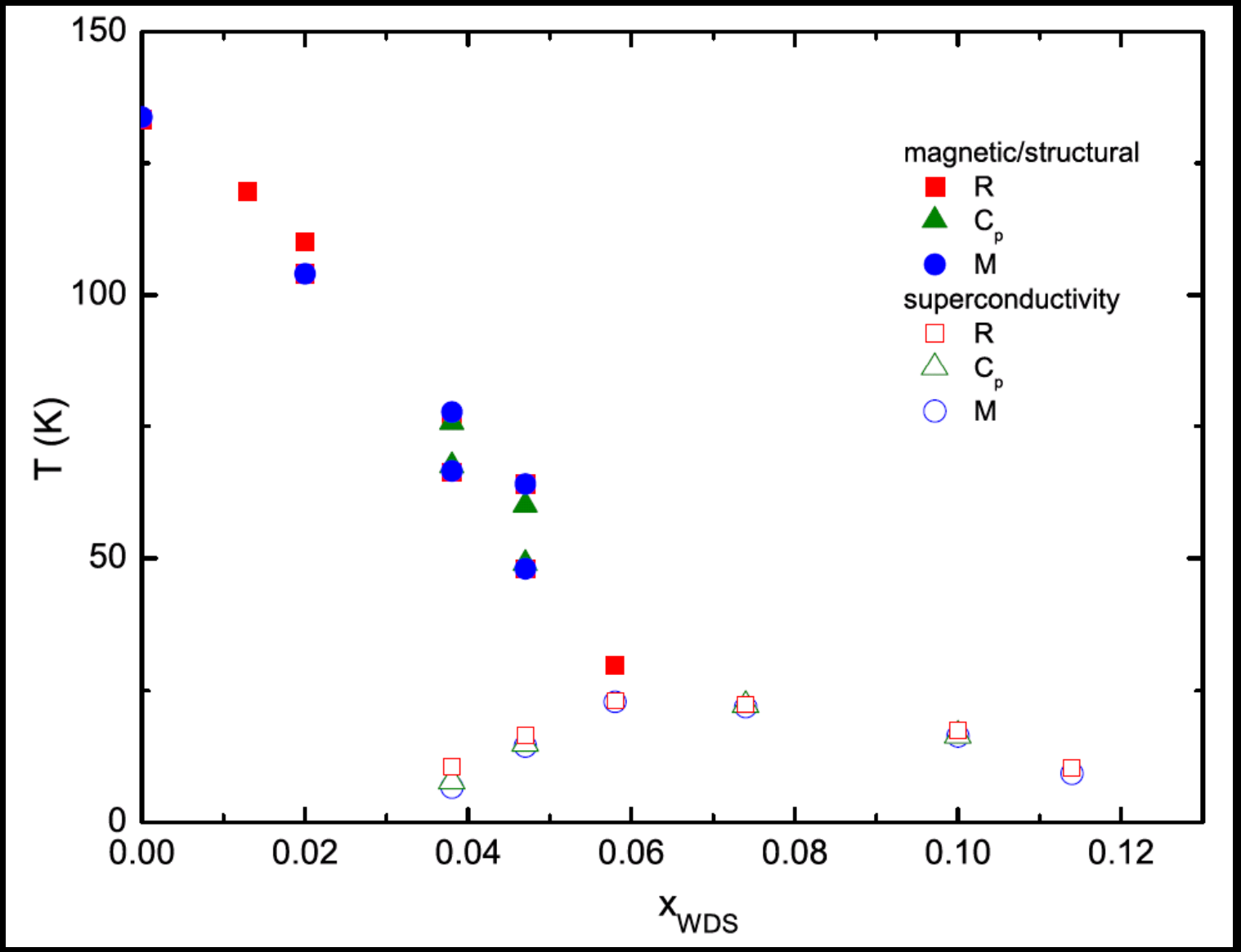


$\frac{dI}{dV} \propto LDOS(eV)$



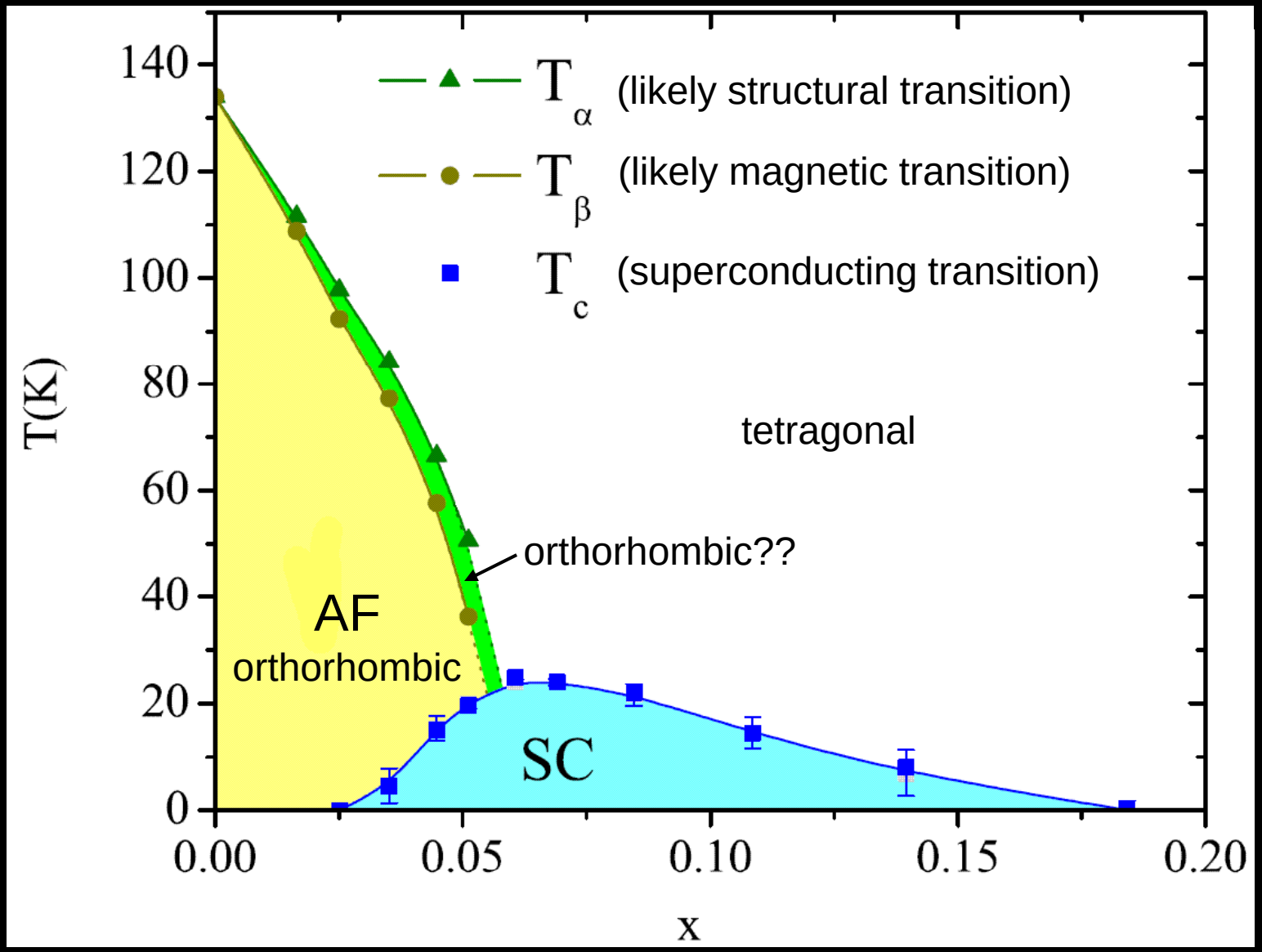


$Ba(Co_xFe_{1-x})_2As_2$ Phase Diagram



Ni … Canfield, arXiv:0811.1767

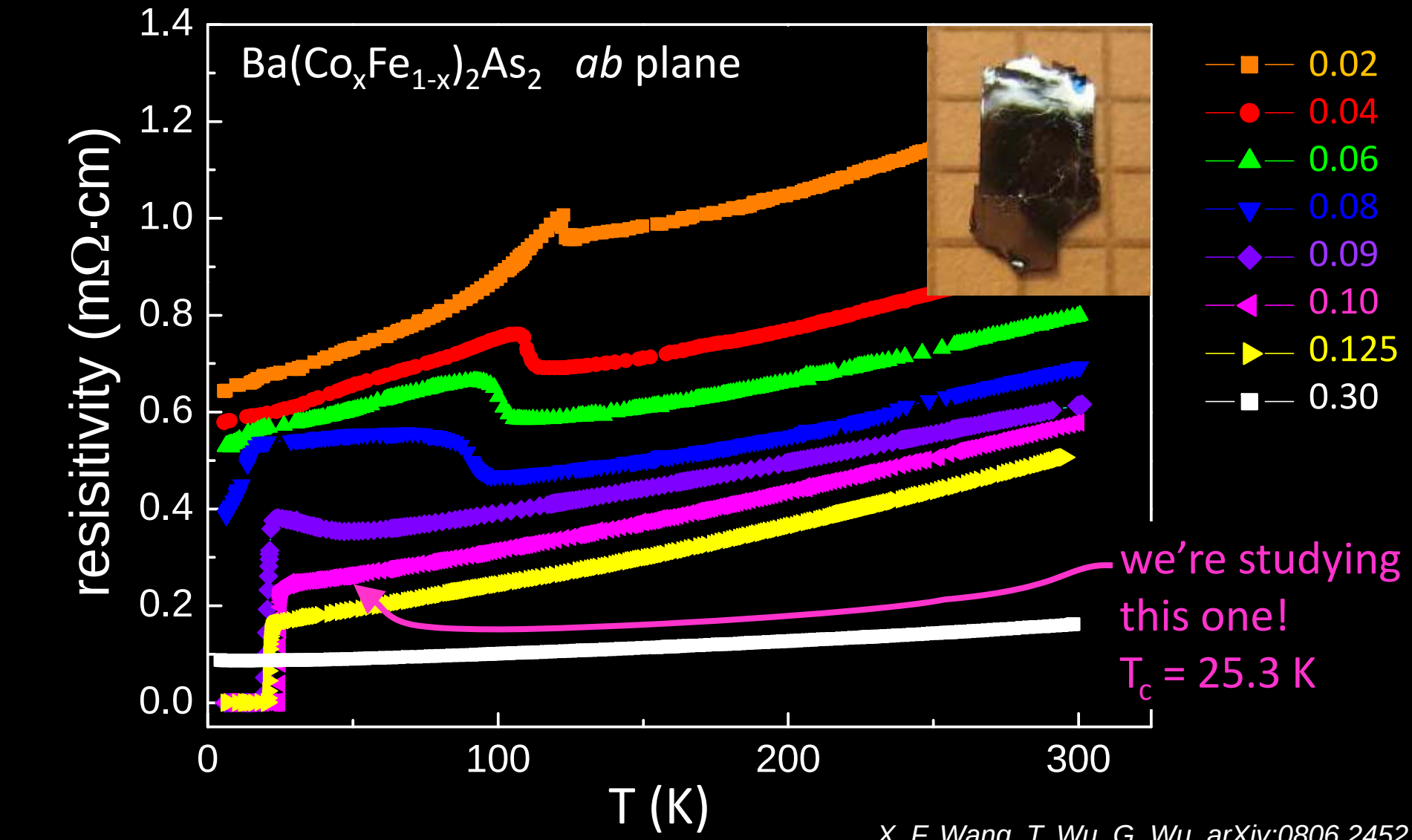
$Ba(Co_xFe_{1-x})_2As_2$ Phase Diagram



Chu *et al*, Phys. Rev. B 79, 014506 (2009)

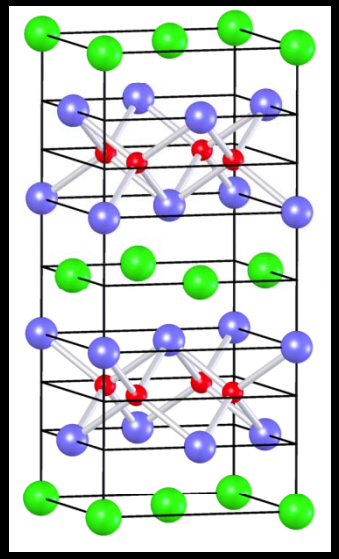
Resistivity of our $Ba(Co_xFe_{1-x})_2As_2$

single crystals grown by Prof. XianHui Chen

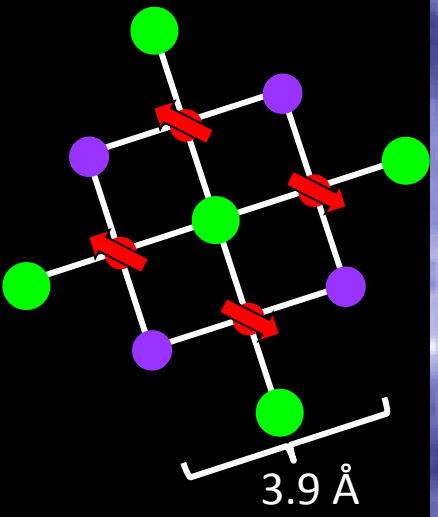


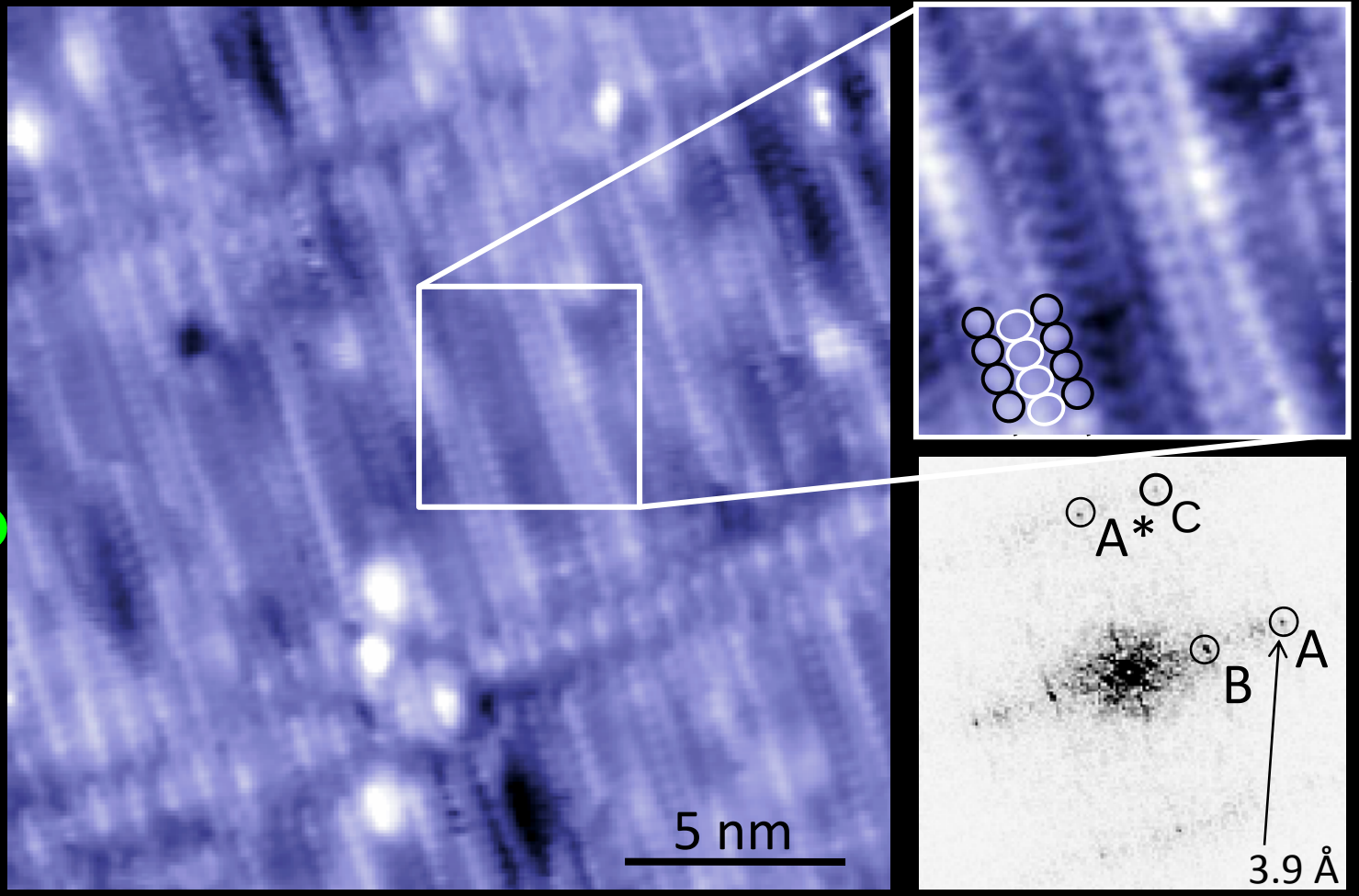
X. F. Wang, T. Wu, G. Wu, arXiv:0806.2452 to be published in Phys. Rev. Lett.

Atomic Resolution Topography



$Ba(Co_xFe_{1-x})_2As_2$
(x=0.1 nominal, T_c=25.3K)

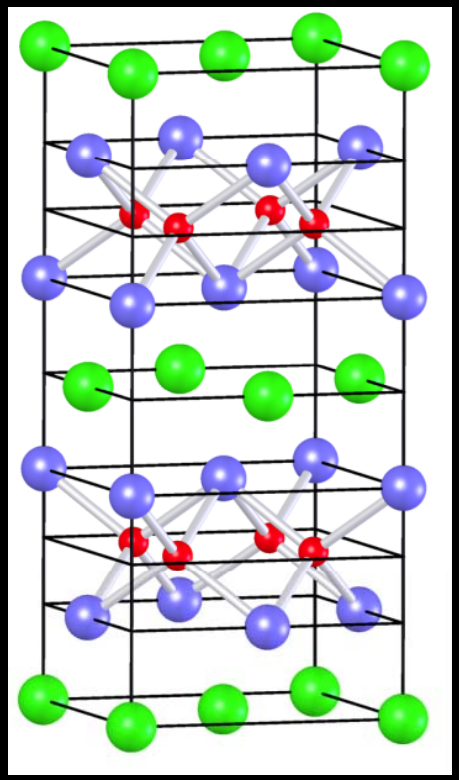




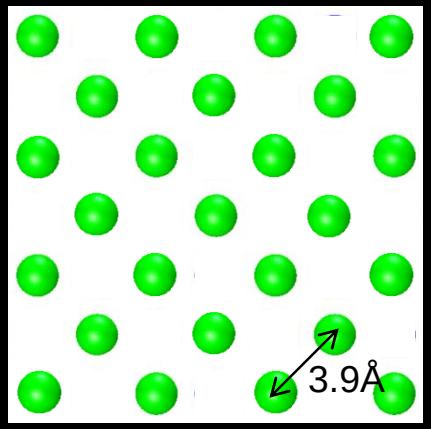
$Ba(Co_xFe_{1-x})_2As_2$ cleavage plane?

Ba (2+)

As
Fe
} (1-)

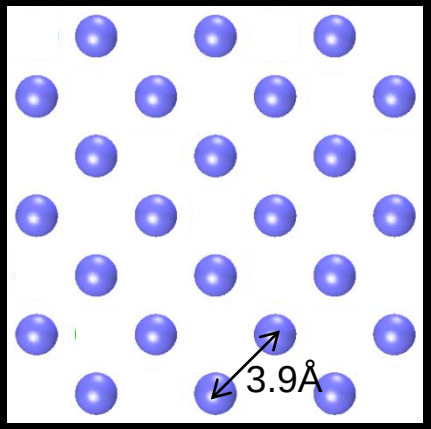


all Ba remain?



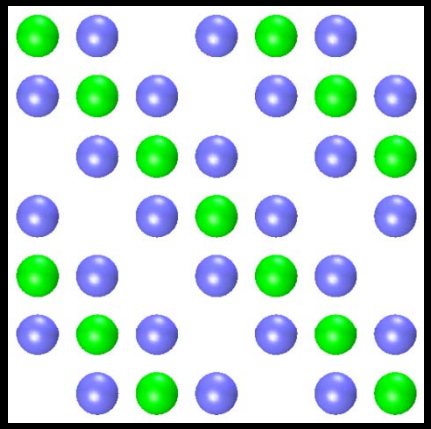
→ top Ba layer has charge 1+

all Ba removed?



→ top As layer has charge 1-

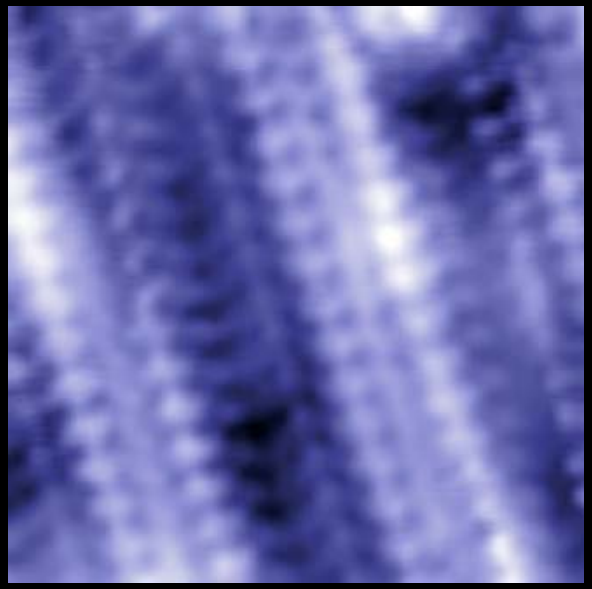
½ Ba removed, ½ Ba remain?



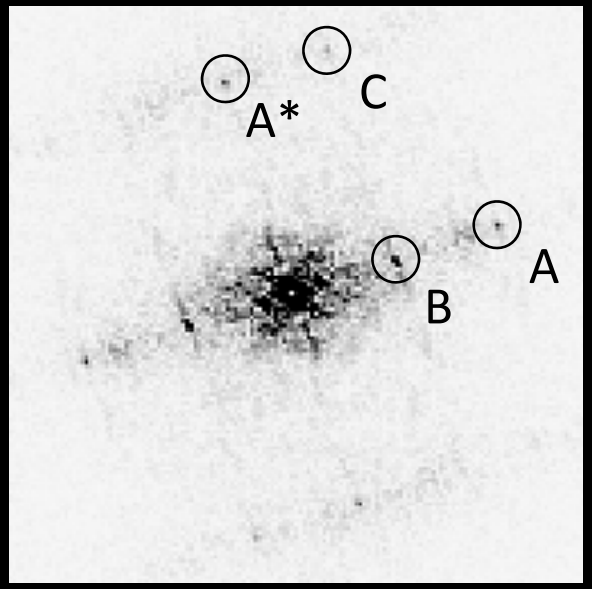
→ top layer is charge neutral

Fourier Transform Analysis

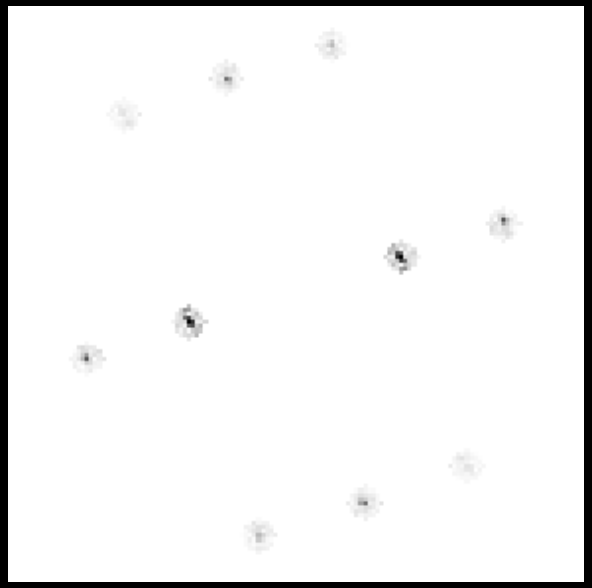
Raw data:



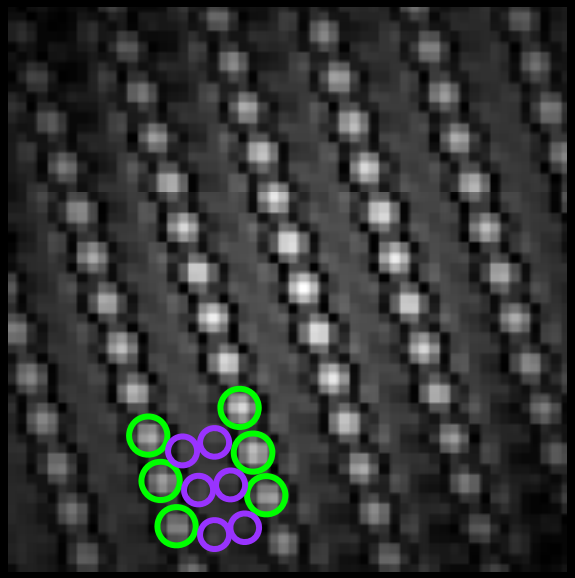
Fourier transform



filter

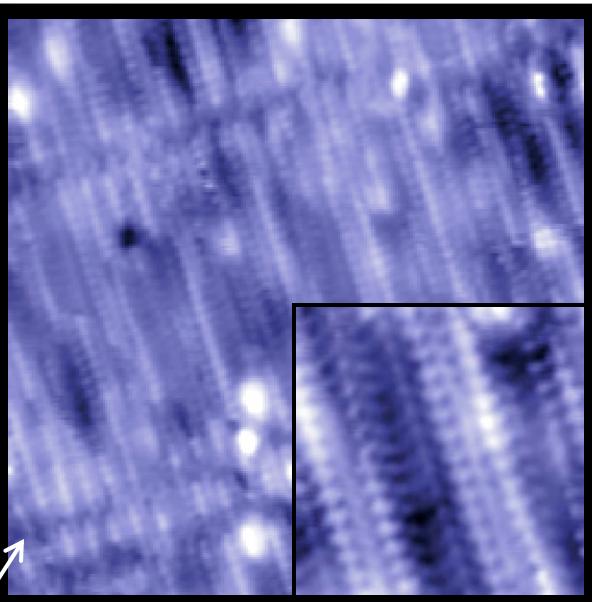


inverse Fourier transform

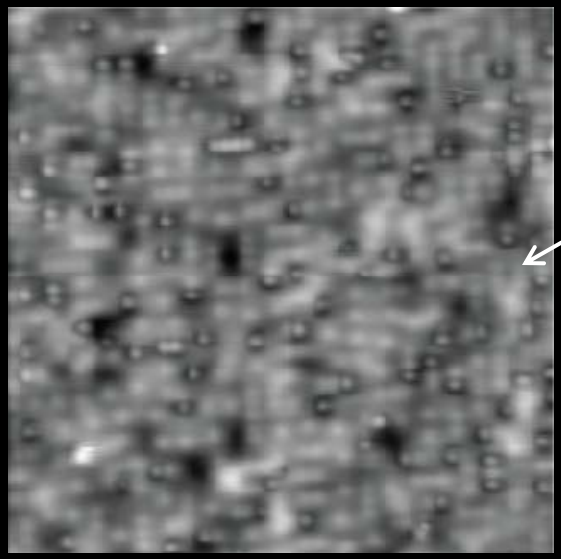


Topography Comparison

5 nm



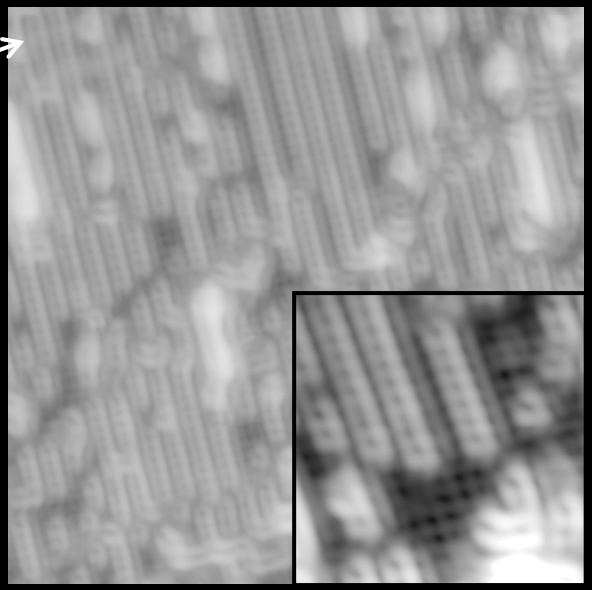
Yin *et al*, THIS WORK
PRL 102, 097002 (2009)



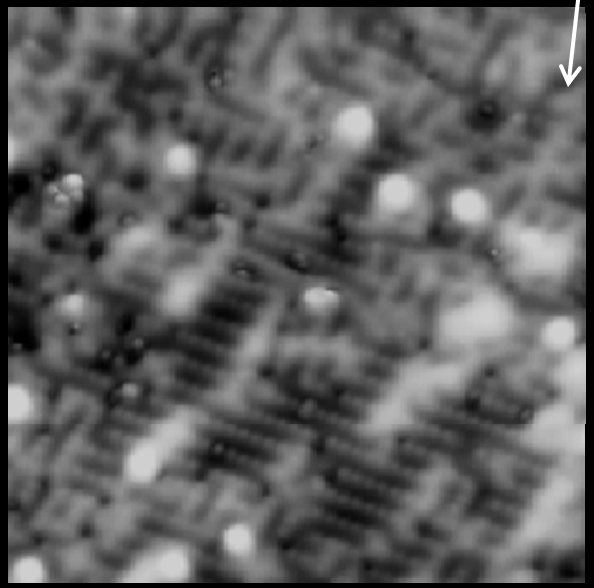
Massee *et al*, arXiv:0812.4539

300K cleave

low-T
cleave
(~ 30K)

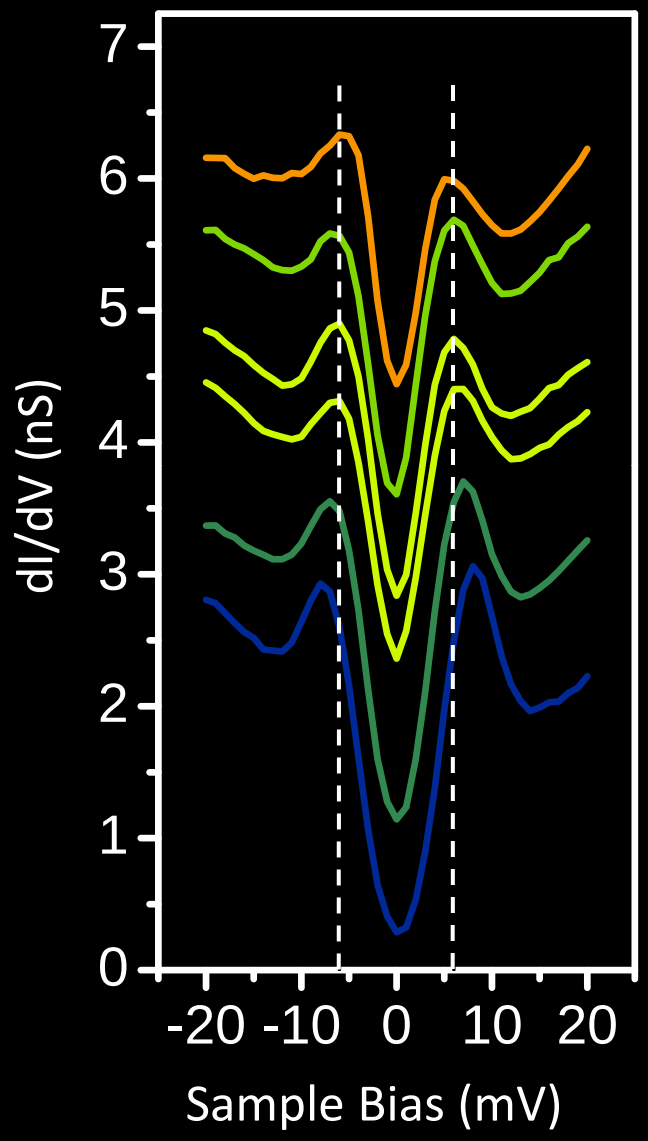


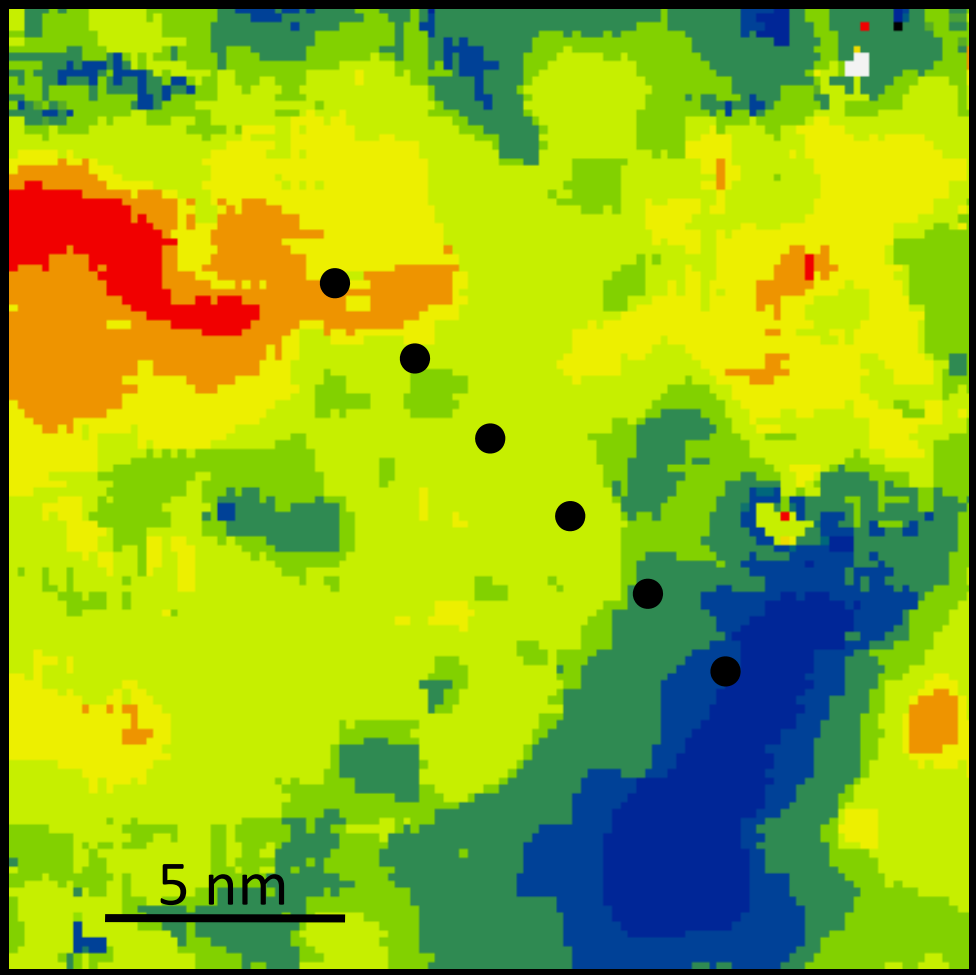
Boyer *et al*, arXiv:0806.4400

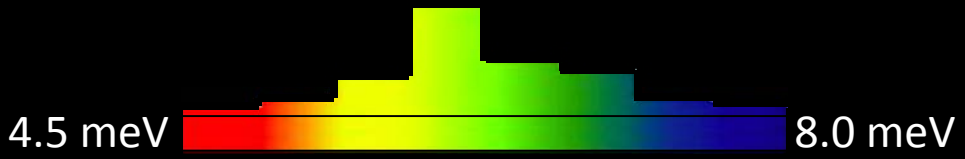


Hsieh *et al*, arXiv:0812.2289

Gap Mapping



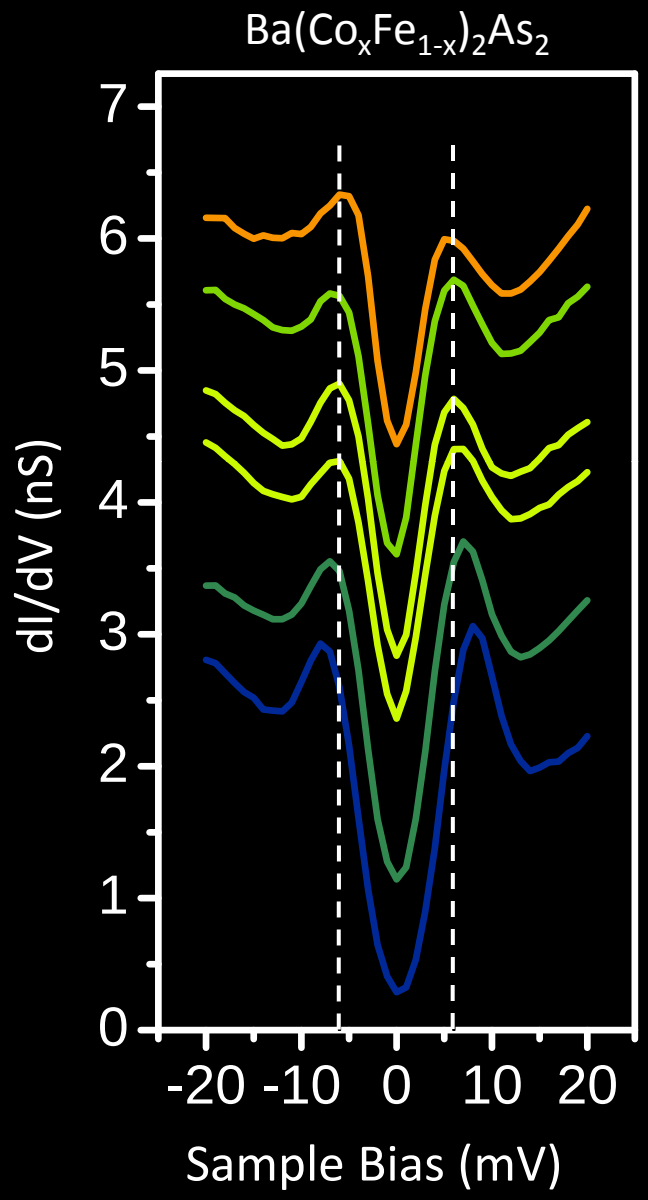


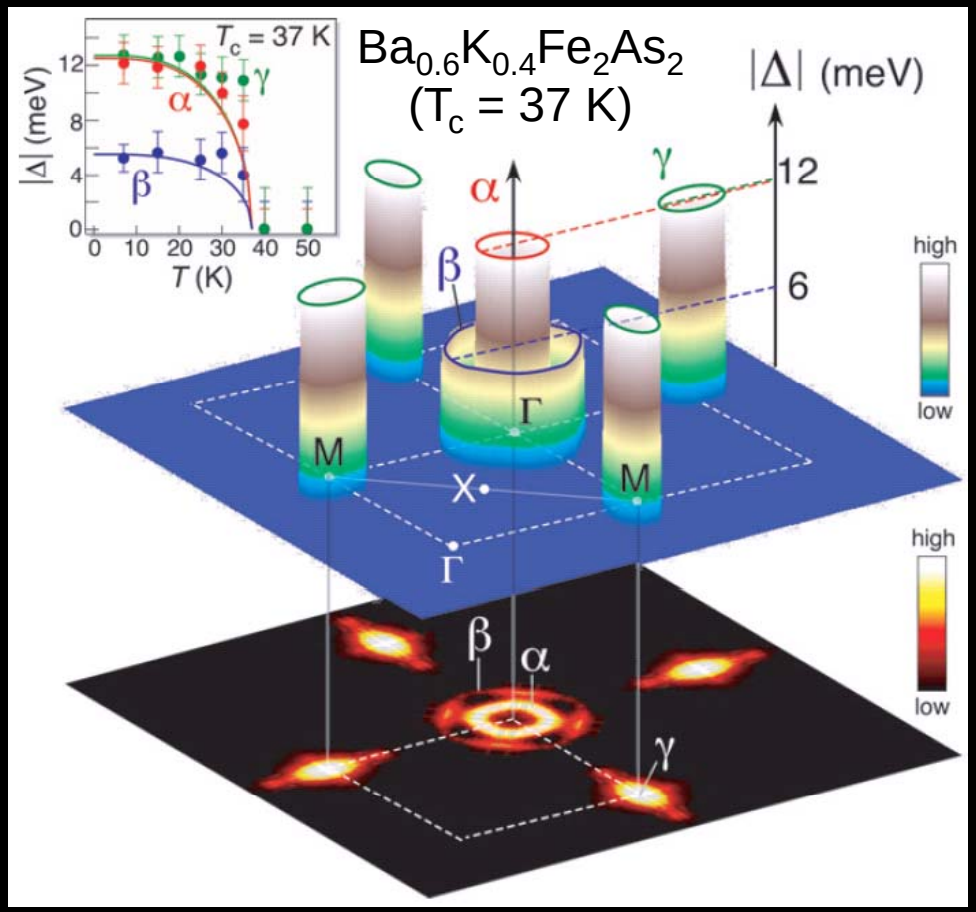


measurements at T=6K; k_BT = 0.5 meV
dV modulation = 1.5 meV

$\overline{\Delta}$ = 6.25 ± 0.73 meV (12% variation)

Comparison to ARPES?

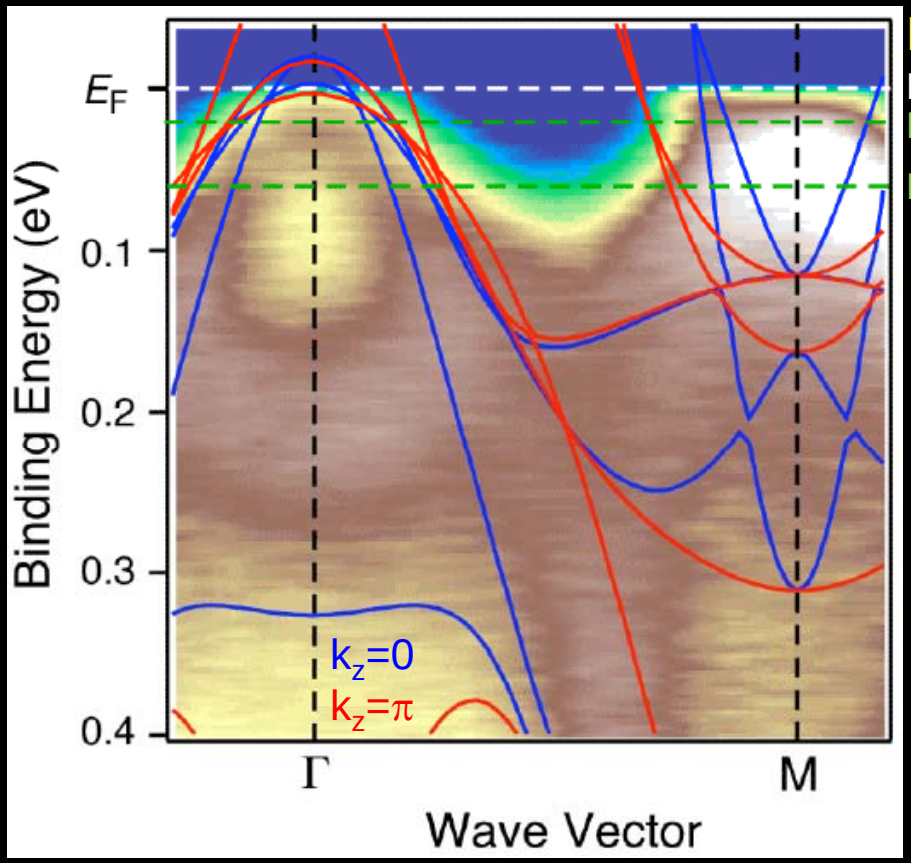




Ding, EPL 83, 47001 (2008)

Comparison to ARPES

Rigid band model substantiated by
C. Liu *et al*, PRL 101, 177005 (2008)

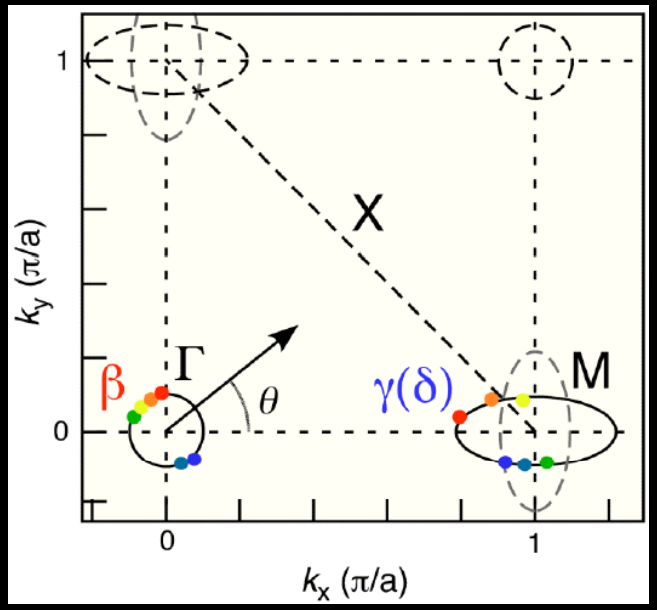


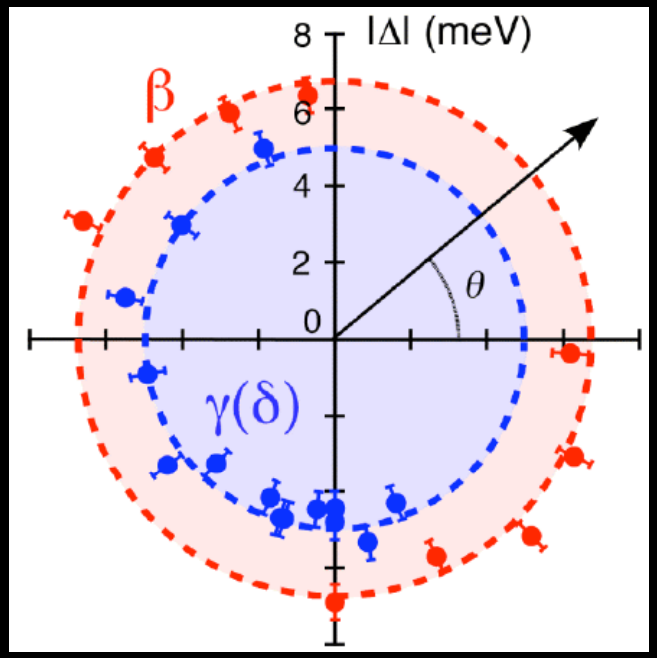
Fermi surfaces:

$BaCo_{0.15}Fe_{1.85}As_2$

$BaFe_2As_2$

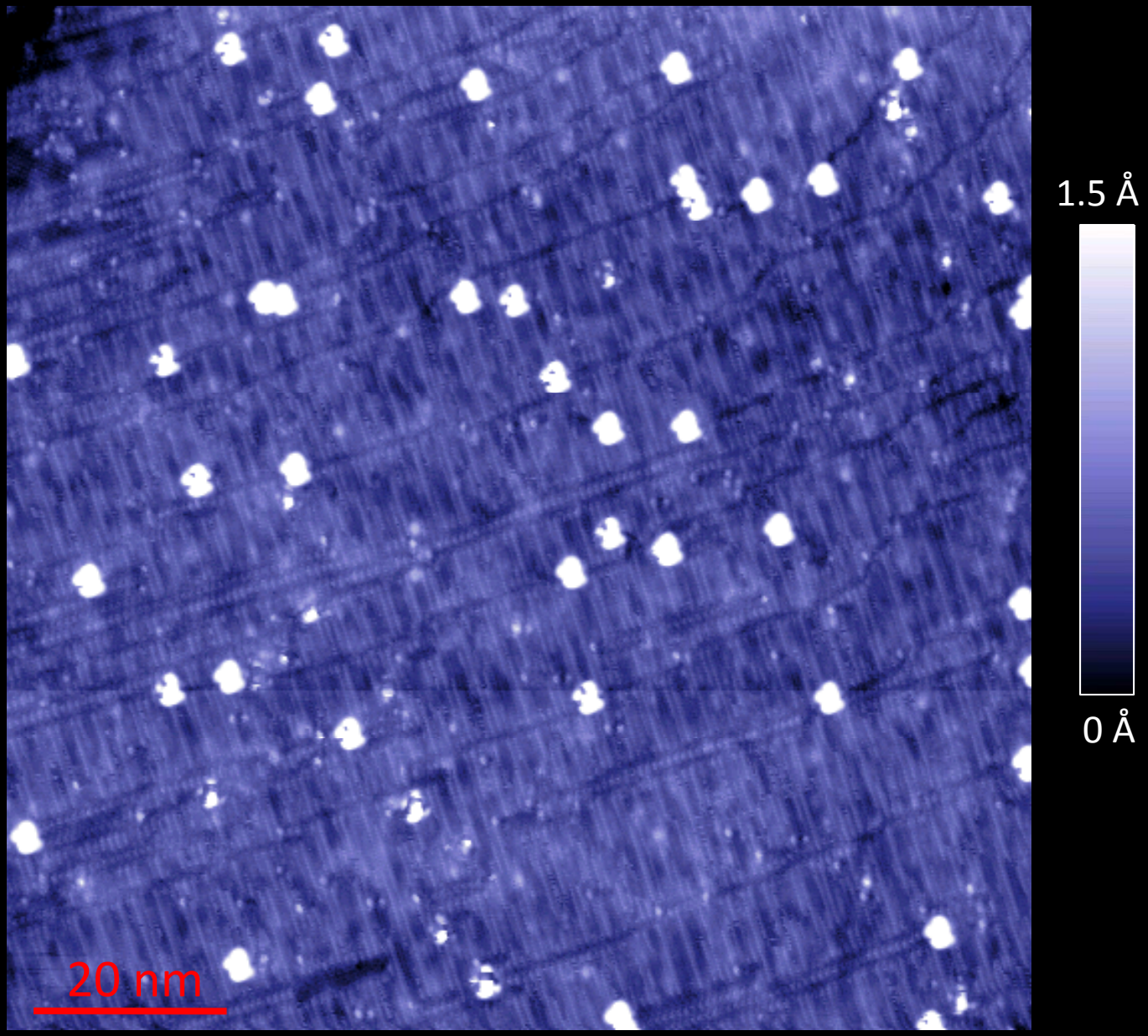
$Ba_{0.6}K_{0.4}Fe_2As_2$





Terashima *et al*, arXiv:0812.3704

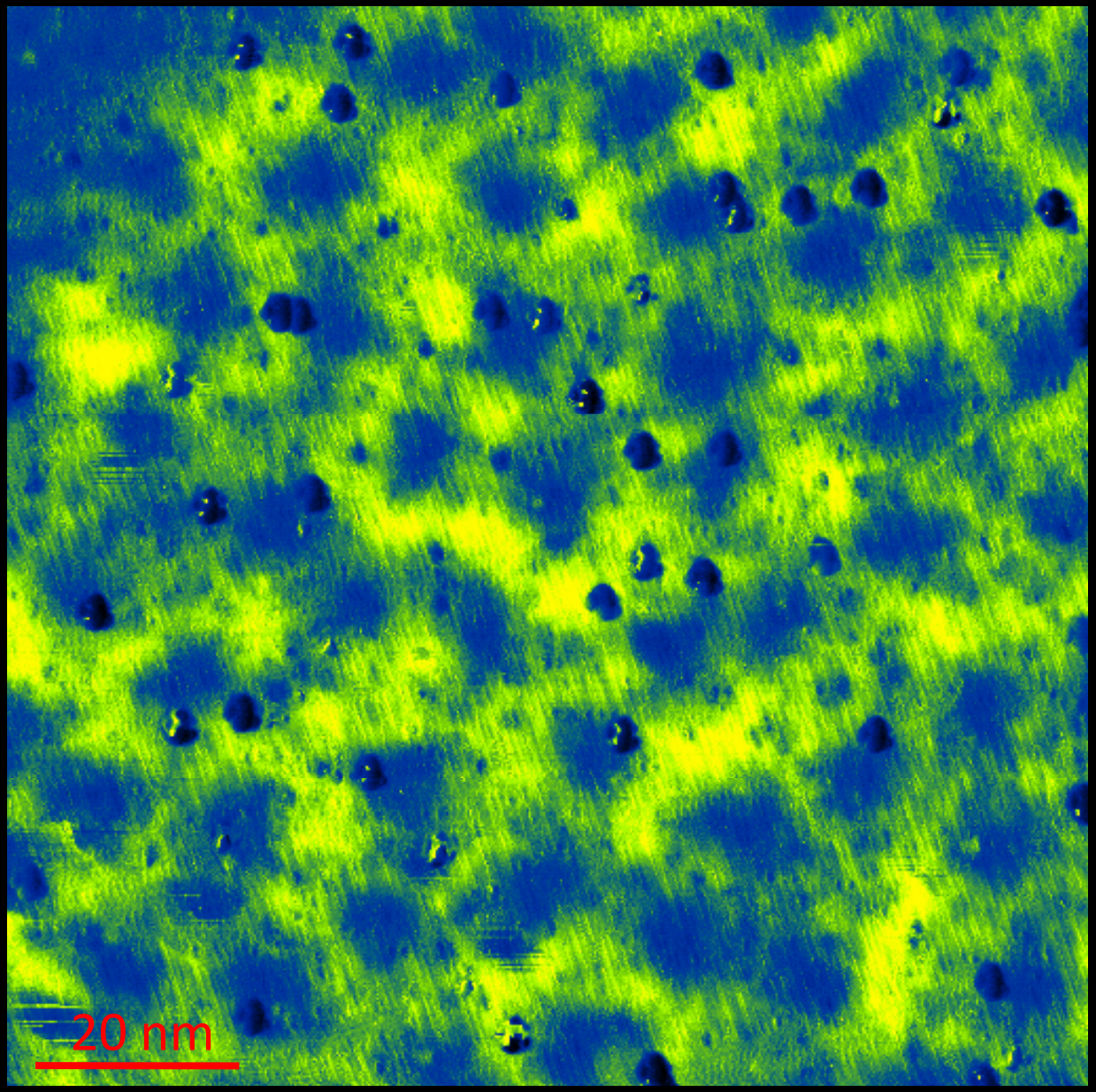
Topography



Vortices at 9T

dI/dV at 5 mV

(approximate coherence peak energy)



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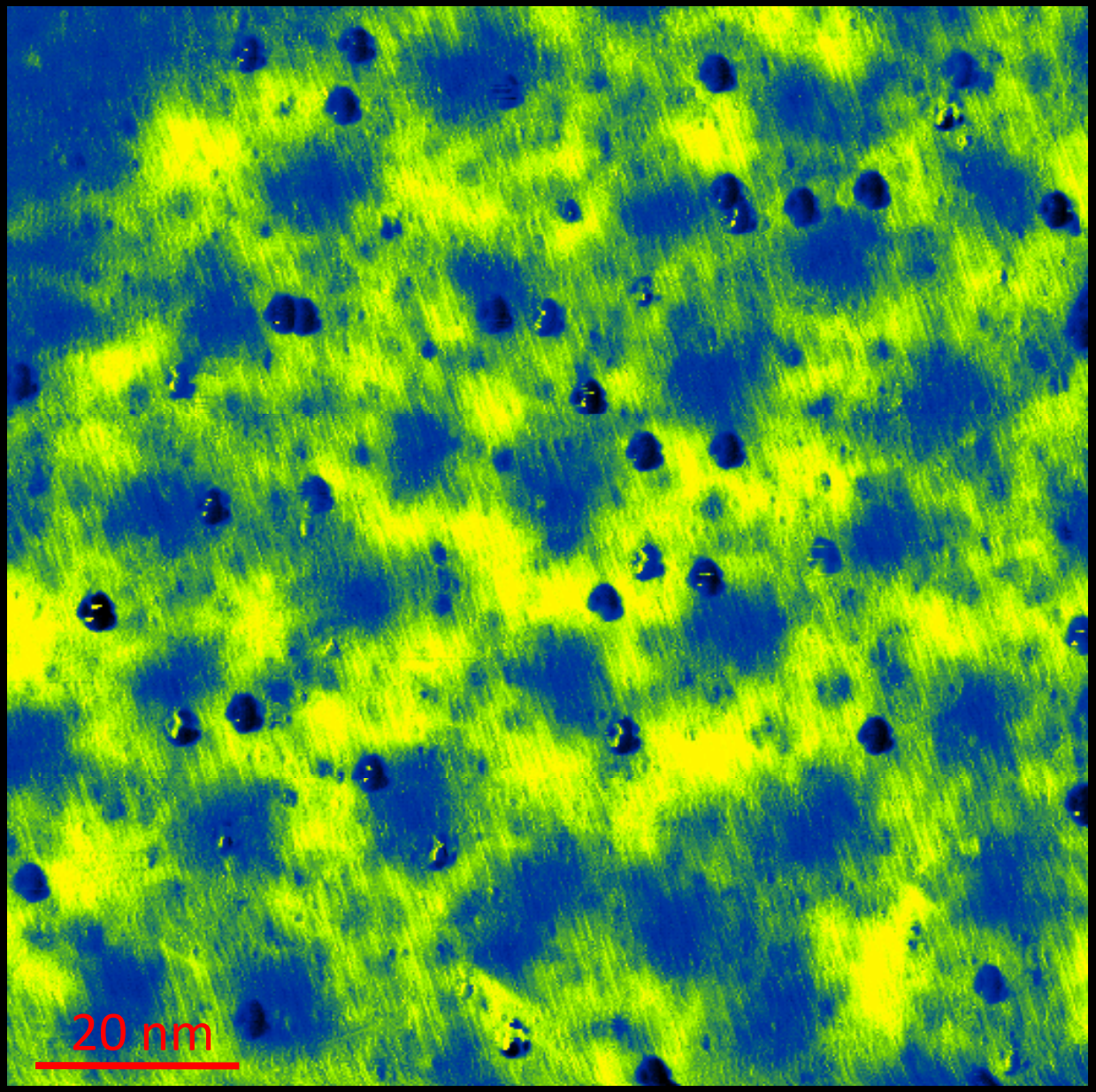
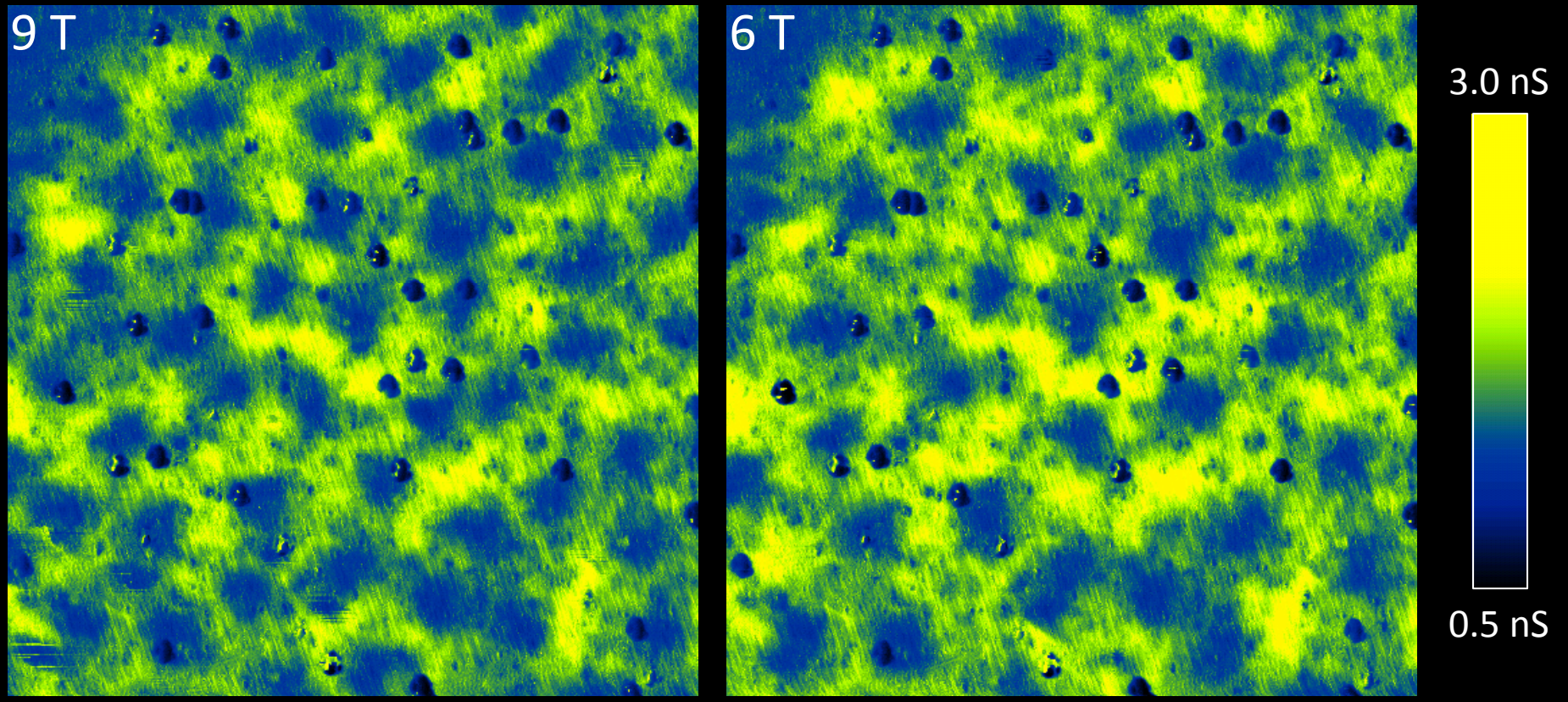


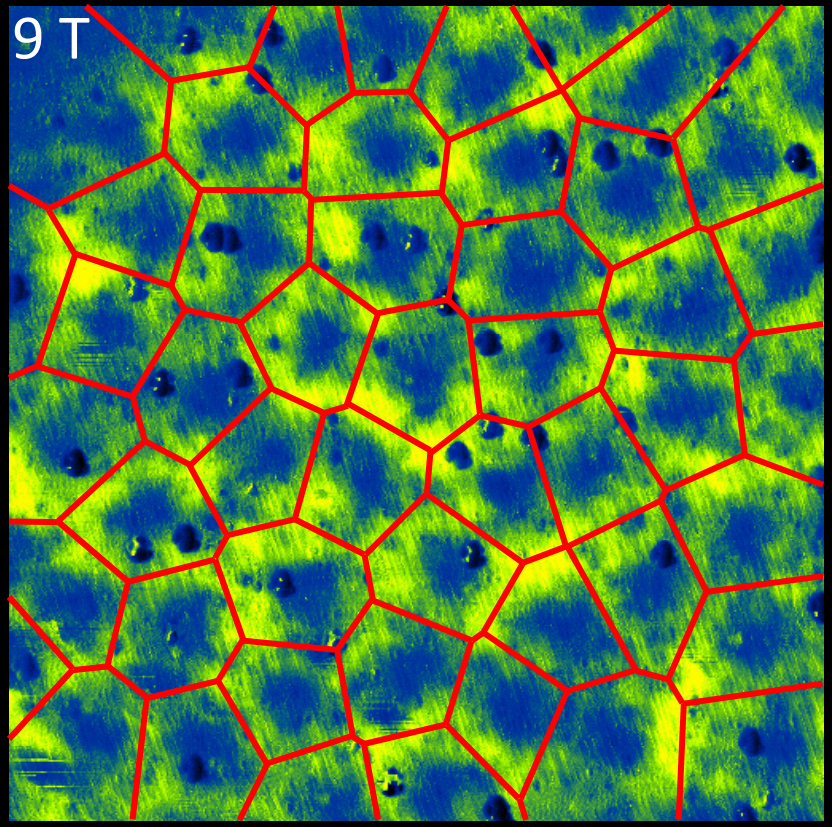
3.0 nS

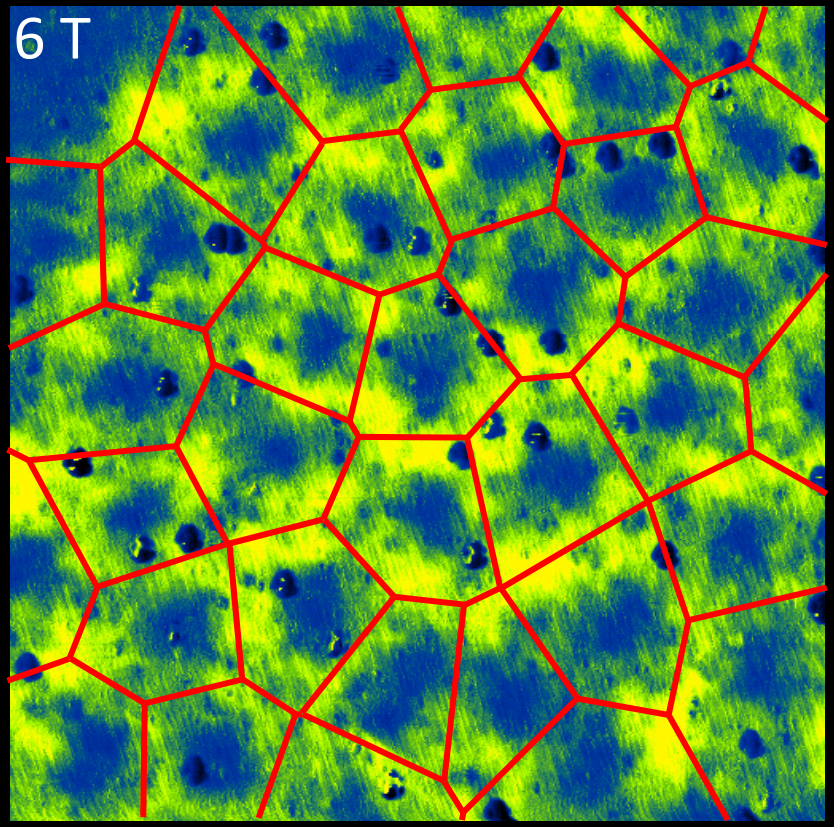
0.5 nS

Flux Measurement



Flux Measurement





average vortex area = 228 nm^2

→ $\phi(9T) = 2.05 \times 10^{-15}$ T·m^2

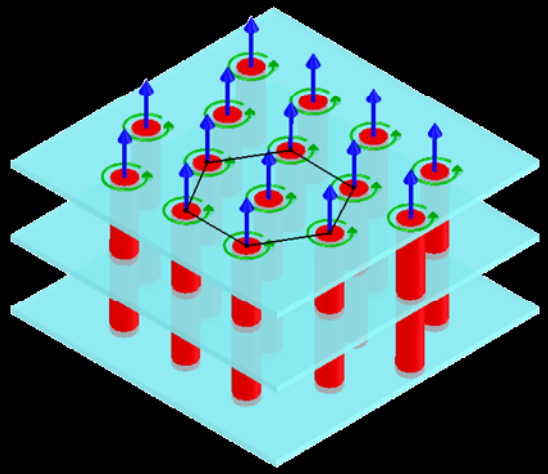
average vortex area = 362 nm^2

→ $\phi(6T) = 2.17 \times 10^{-15}$ T·m^2

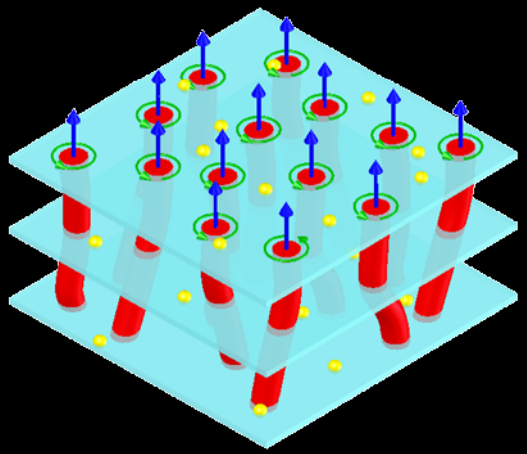
Single magnetic flux quantum: $\Phi_0 = 2.07 \times 10^{-15}$ T·m^2

Vortex pinning possibilities

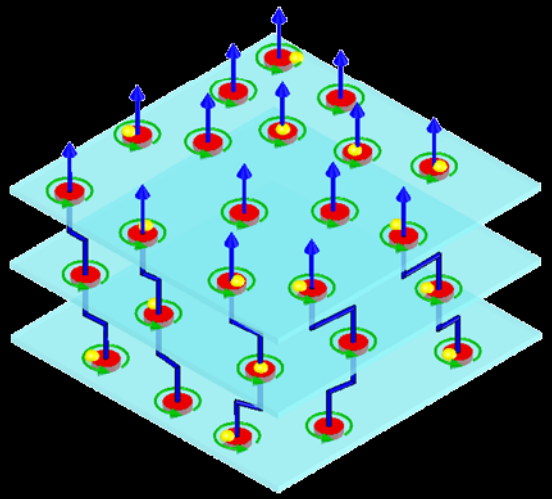
(1) no strong pinners
inter-vortex forces dominate
→ lattice formation



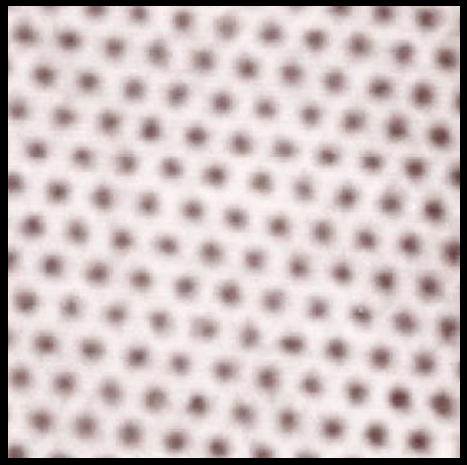
(2) strong pinners exist
low anisotropy
→ vortices bend slightly
to accommodate pinners



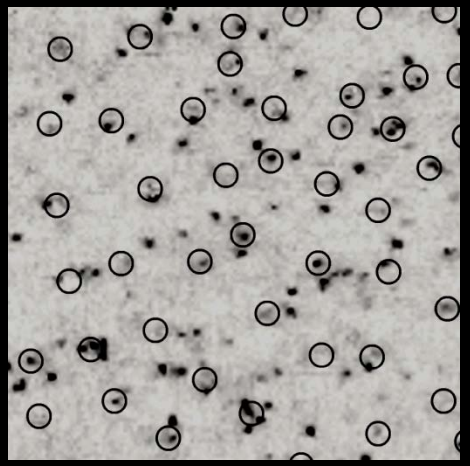
(3) strong pinners exist
high anisotropy
→ vortices pancake
each pancake pins independently



ideal case
for applications

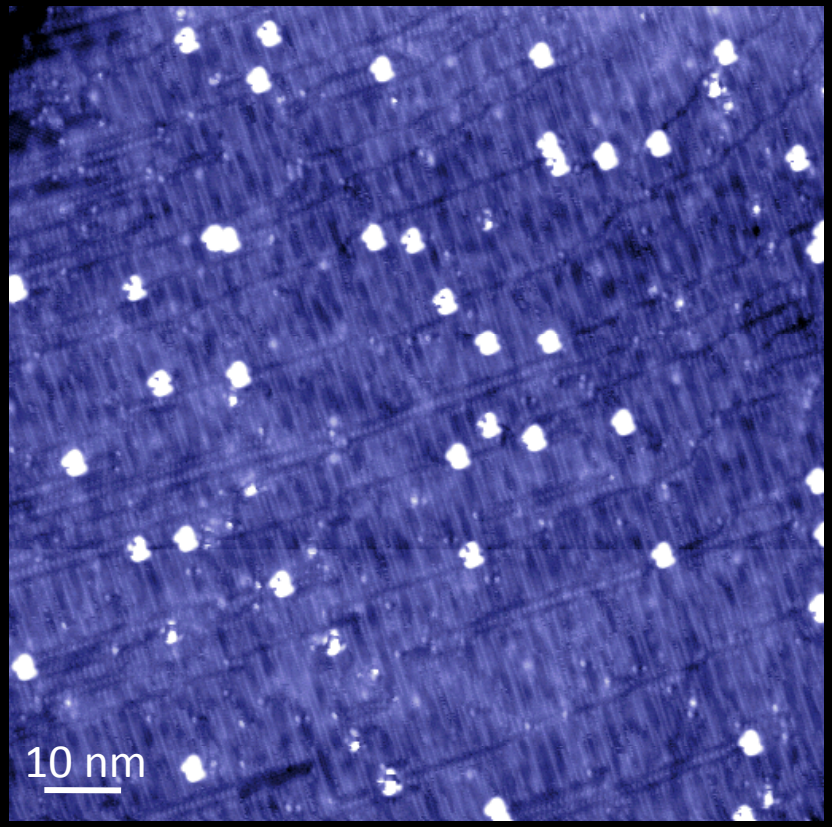


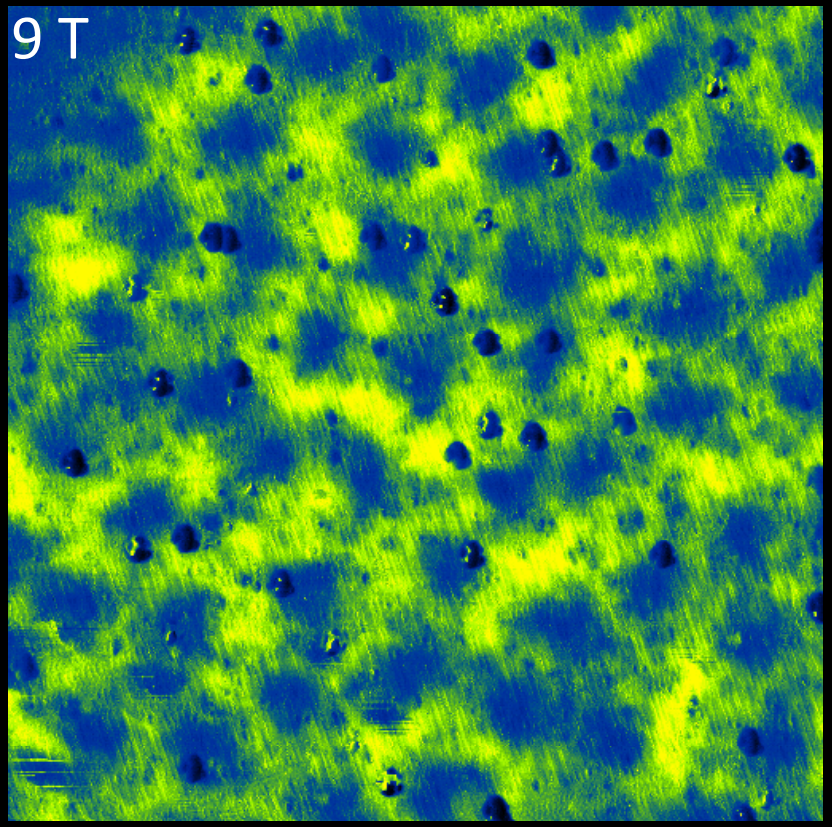
$NbSe_2$



$Bi_2Sr_2CaCu_2O_8$

Are Vortices Pinned to Surface Impurities?

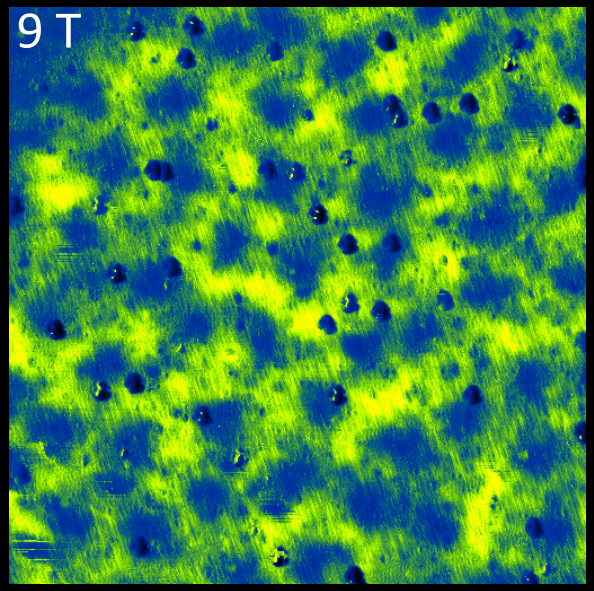


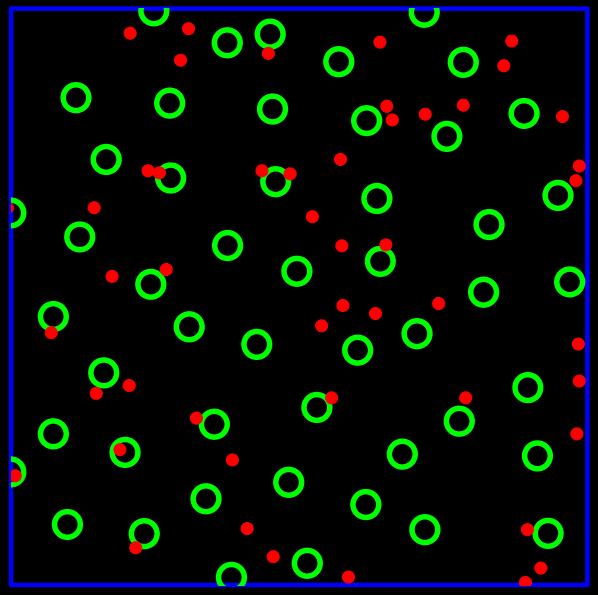


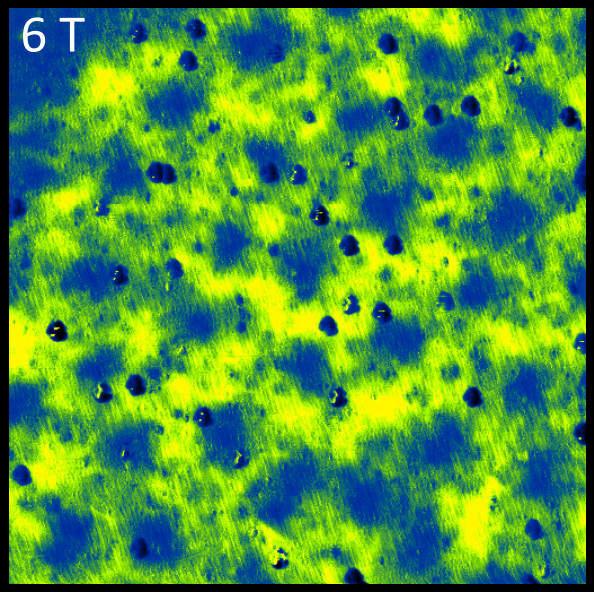
Are Vortices Pinned to Surface Impurities?

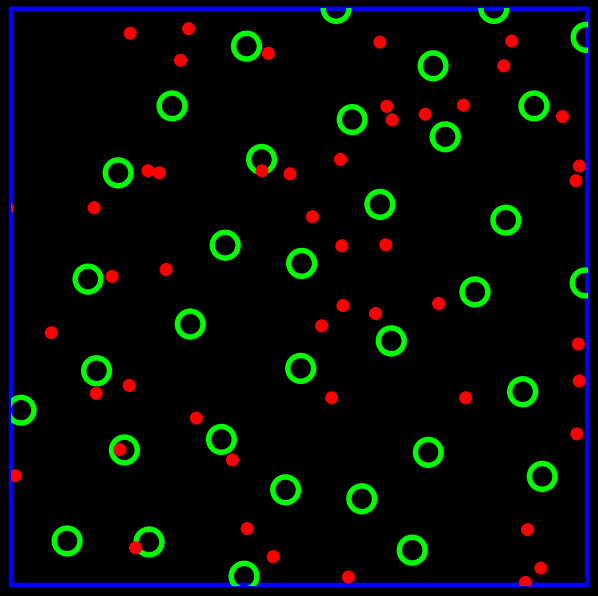
Raw Data

Idealized Data



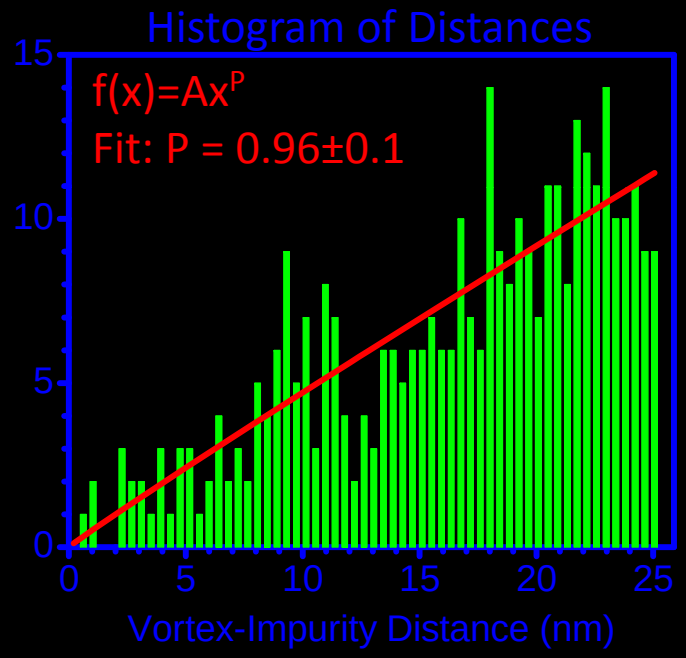






vortex, radius ξ_0 = 2.76 nm

impurity

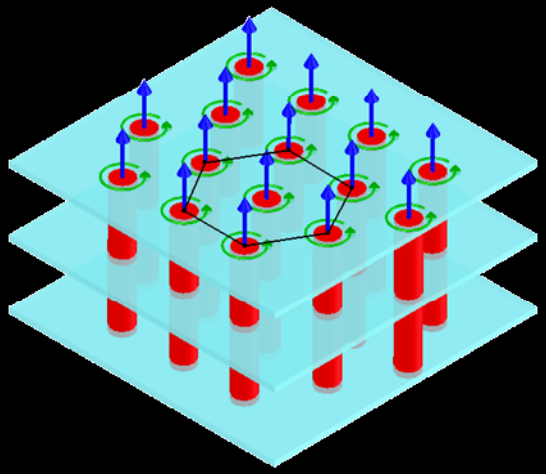


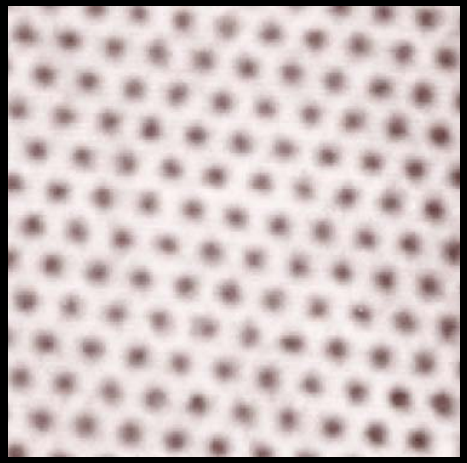
Linear fit!

→Vortices are <u>not</u> pinned to visible surface impurities

Vortex pinning possibilities

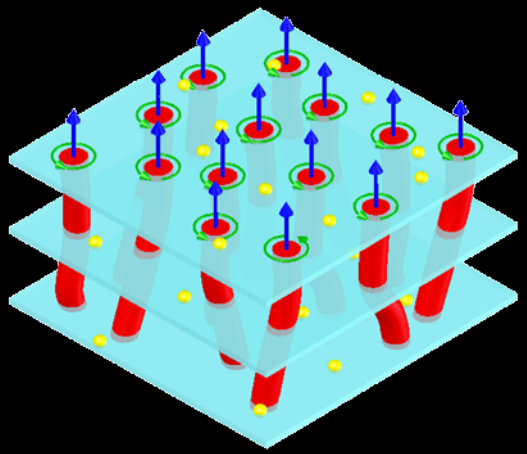
(1) no strong pinners
inter-vortex forces dominate
→ lattice formation

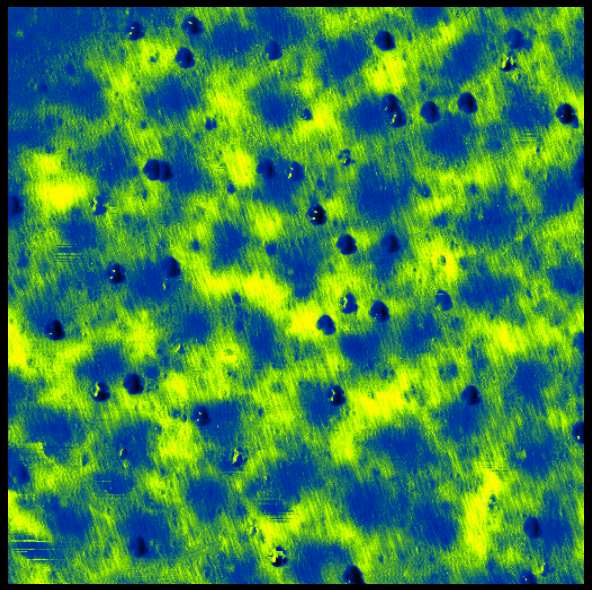




$NbSe_2$

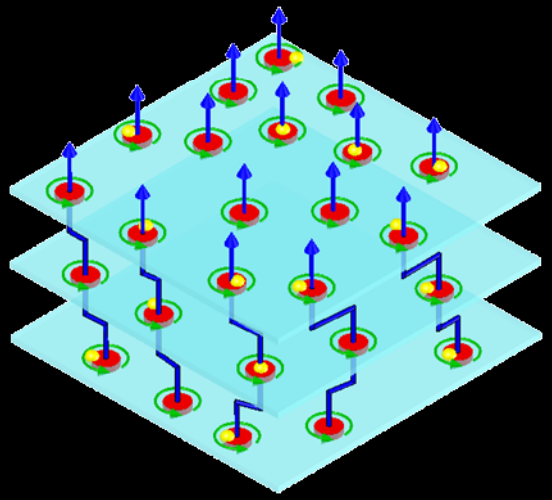
(2) strong pinners exist
low anisotropy
→ vortices bend slightly
to accommodate pinners

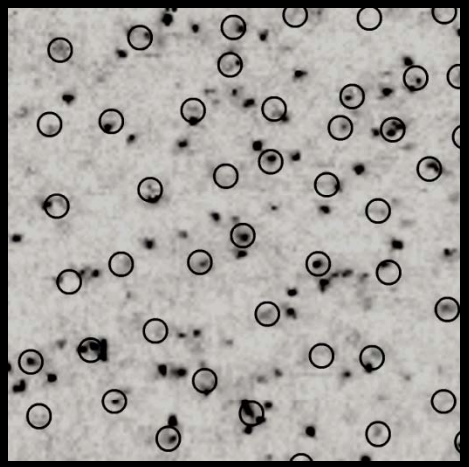




$Ba(Co_xFe_{1-x})_2As_2$

(3) strong pinners exist
high anisotropy
→ vortices pancake
each pancake pins independently

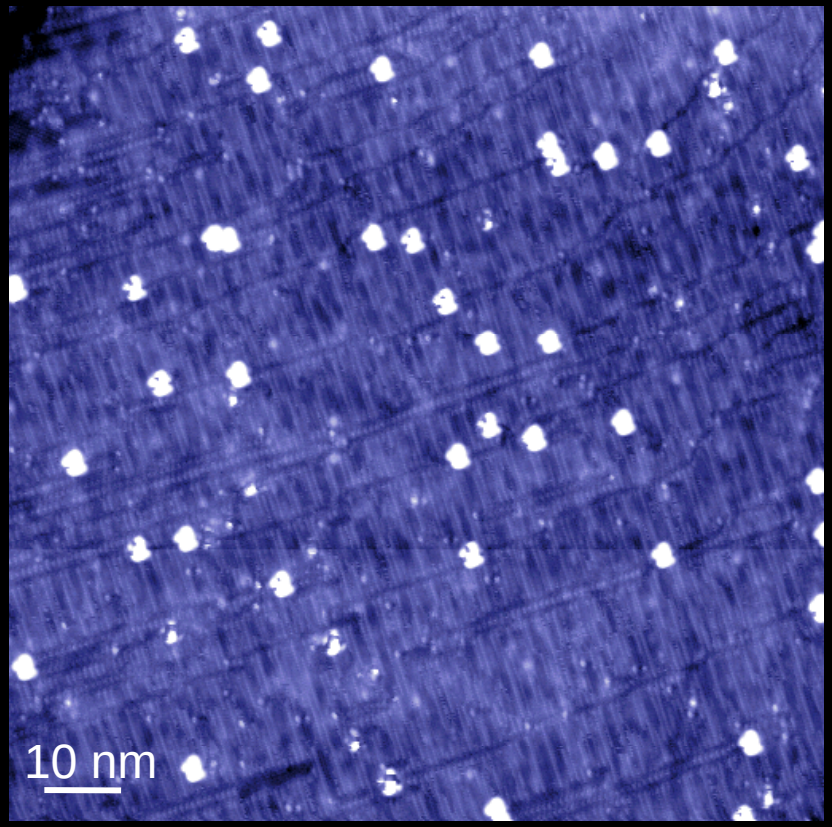




$Bi_2Sr_2CaCu_2O_8$

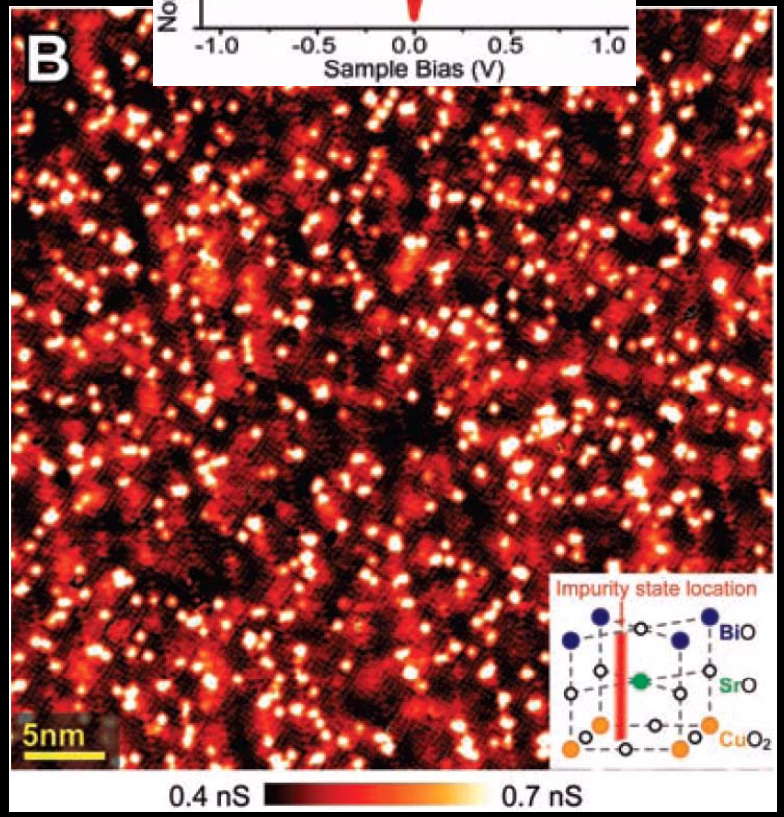
Where are the cobalt atoms?

Nowhere to be seen, yet…



Strong scatterers: 0.029% of Fe sites
Co dopants: 10% of Fe sites

Remember cuprates:
found oxygen at much higher energies



McElroy, Science 309, 1048 (2005)

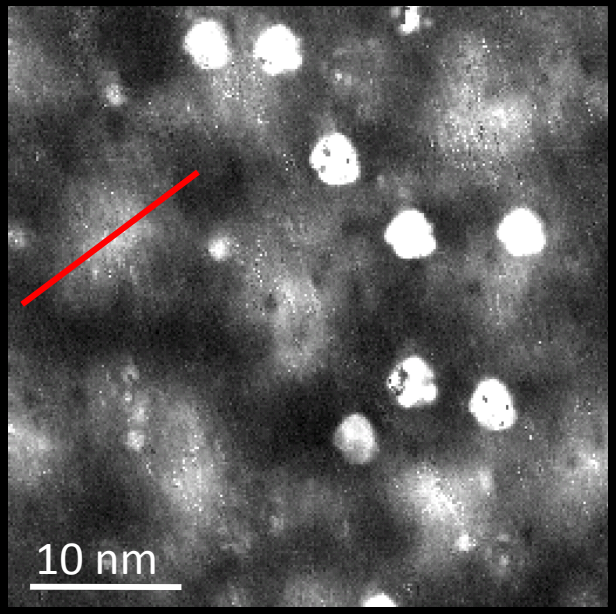
What we know so far…

- We have a superconducting gap, in agreement with ARPES
- We have vortices, which are strongly pinned in bulk

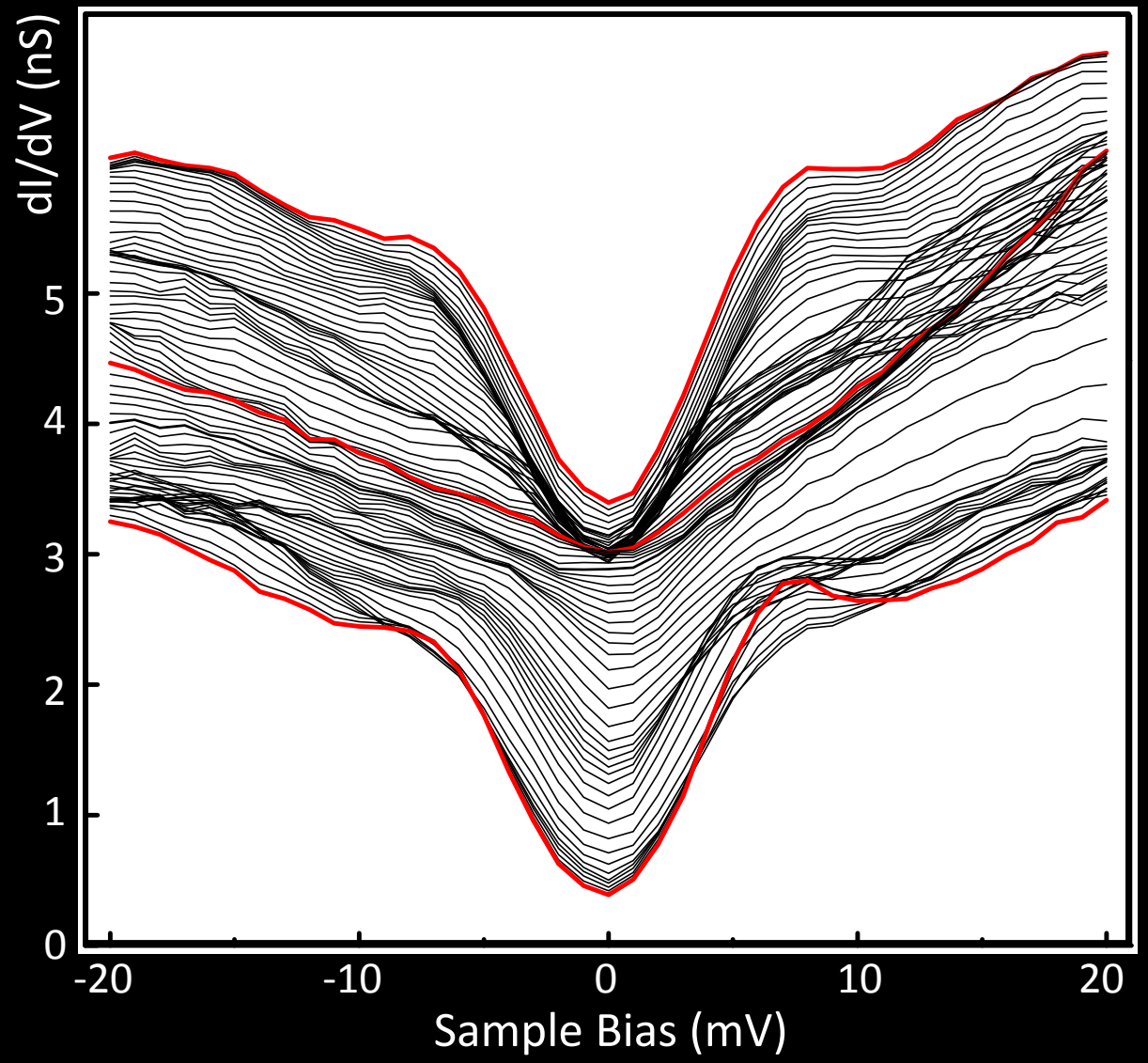
Vortex Spectroscopy

dI/dV map at 0 mV

(Fermi level)

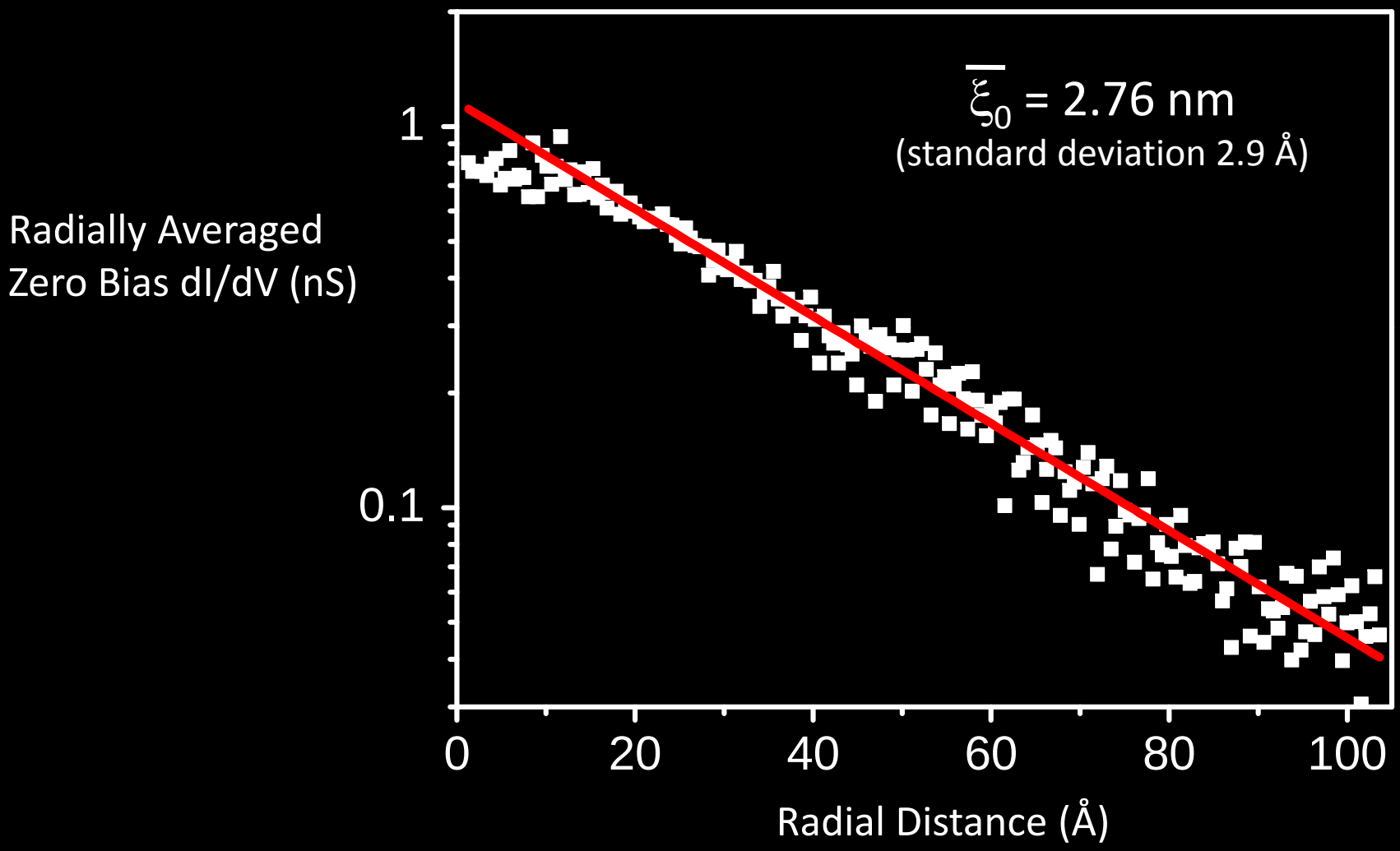


0 nS 1.5 nS



measurements at T=6K; k_BT = 0.5 meV
dV modulation = 1.5 meV

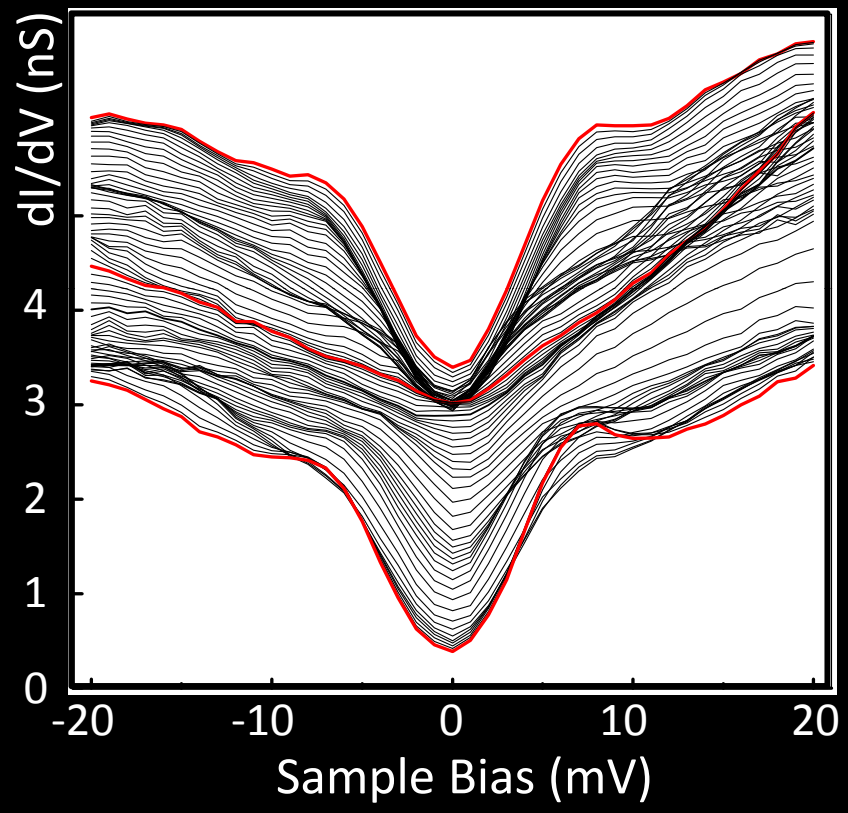
Coherence Length



Note: this ξ_0 translates to H_{c2}=43T
[close to 50T extrapolated, Yamamoto, APL 94, 062511 (2009)]

Compare to Conventional *s*-wave Vortices

$BaCo_xFe_{2-x}As_2$

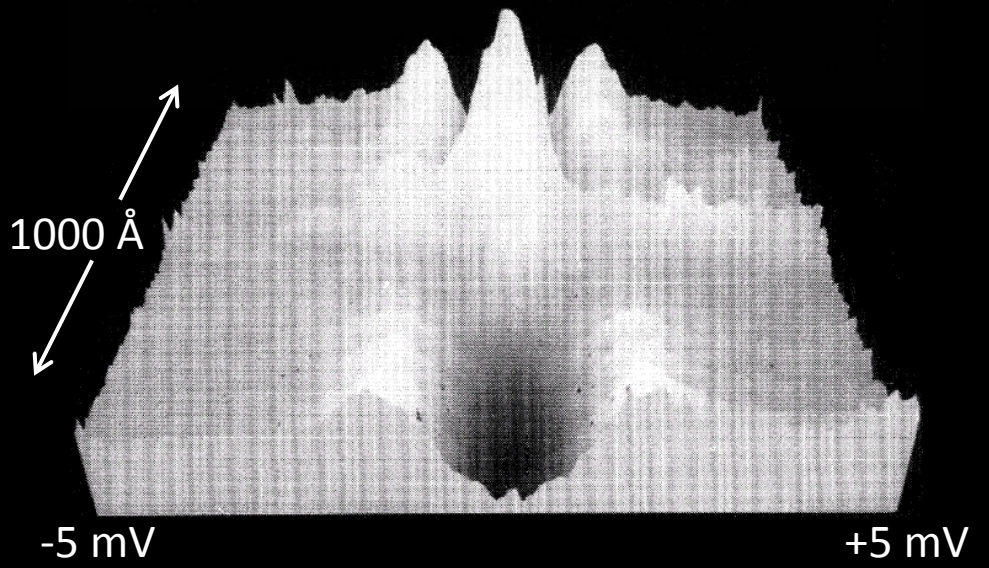


T_c = 25 K; measurement T = 6 K
→ T ~ T_c/4

Theory: $E = \frac{1}{2}\Delta^2/\varepsilon_F$

Caroli, deGennes, Matricon, PRL 9, 307 (1964)

STM experiments on $NbSe_2$



Hess, PRL 62, 214 (1989)

T_c = 7.2 K; measurement T = 1.45 K
→T ~ T_c/5

Clean Limit

Residual resistivity: $\rho_0 = 0.23\ m\Omega\cdot cm$

Hall coefficient: $R_H = 11 \times 10^{-9}\ m^3/C$

} bulk values, measured by Xianhui Chen

→ electronic mean free path:

$$\ell = \hbar\,(3\pi^2)^{1/3} / (e^2\, n^{2/3}\, \rho_0) \sim 81\ \text{Å}$$

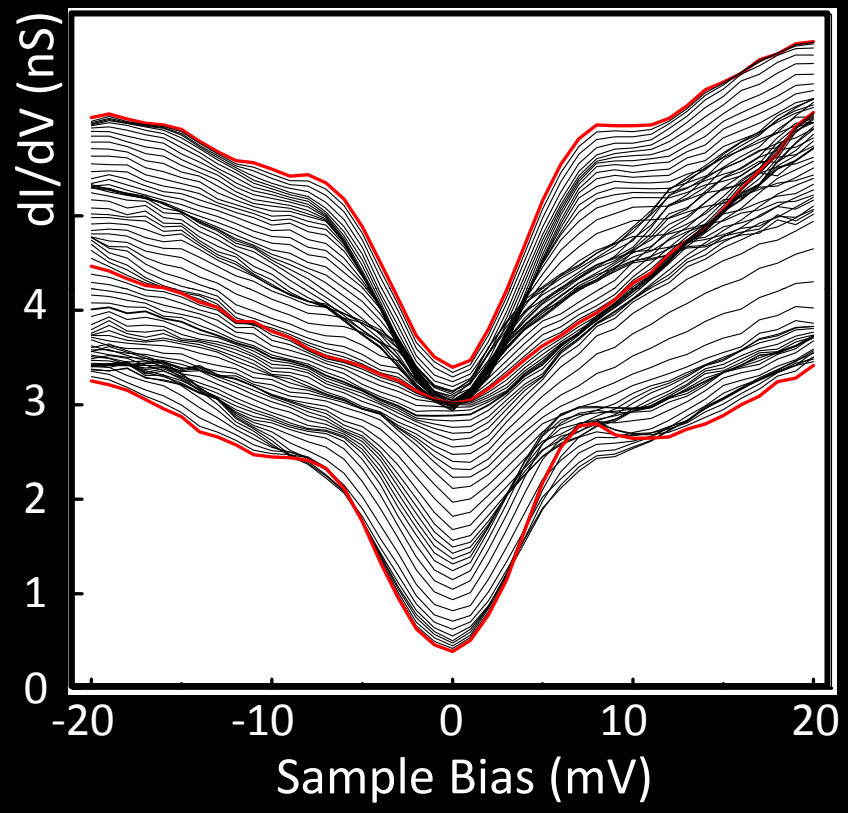
Compare to coherence length: $\xi_0 = 27.6$ Å

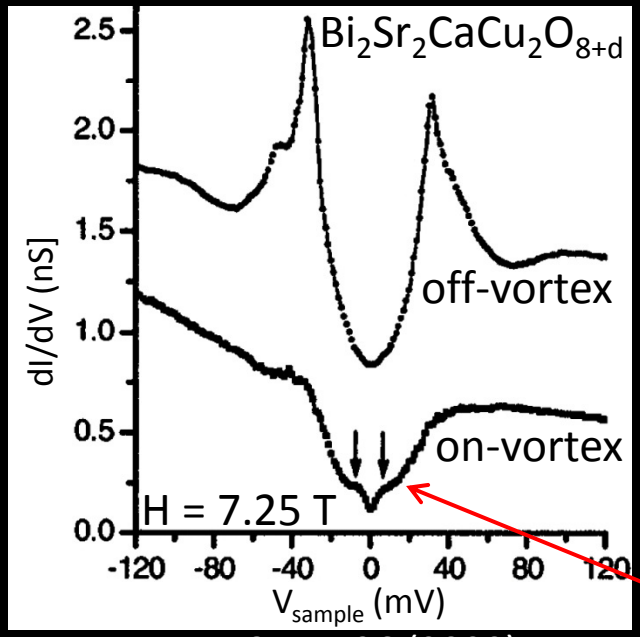
→ Clean limit

→ Wouldn't expect suppression of *s*-wave vortex core states

Compare to *d*-wave Vortex Spectroscopy

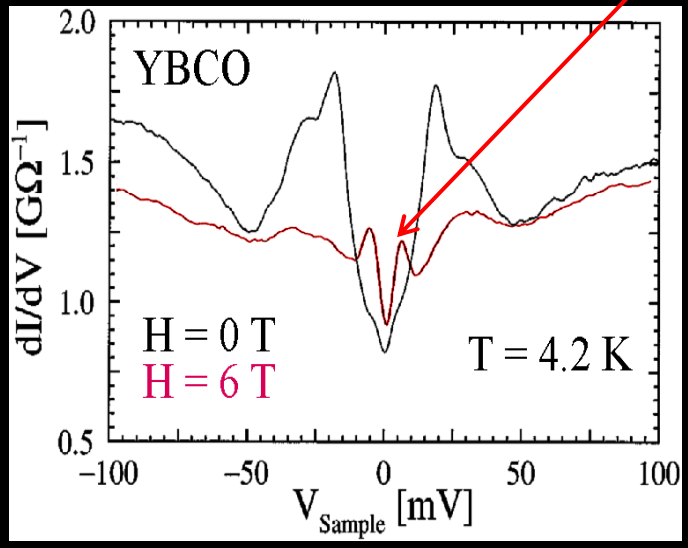
$BaCo_xFe_{2-x}As_2$





Pan, PRL 85, 1536 (2000)

$E \sim \Delta/4$

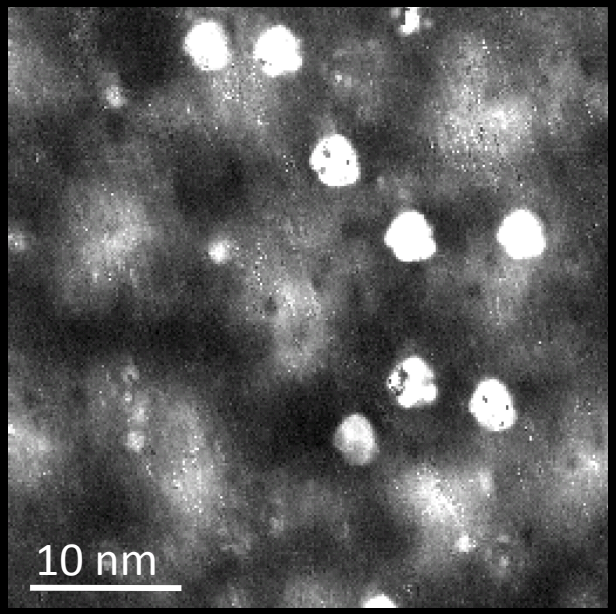


Maggio-Aprile, PRL 75, 2754 (1995)

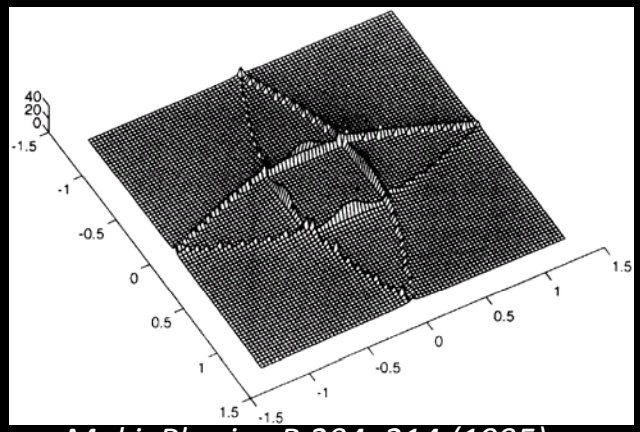
measurements at T=6K; k_BT = 0.5 meV
dV modulation = 1.5 meV

Compare to Theoretical *d*-wave Vortex Shape

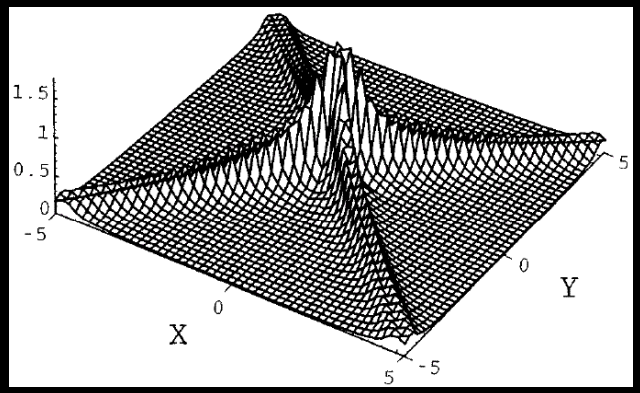
$BaCo_xFe_{2-x}As_2$



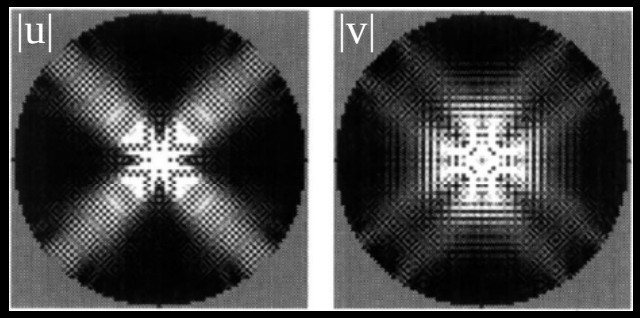
0 nS 1.5 nS



Maki, Physica B 204, 214 (1995)



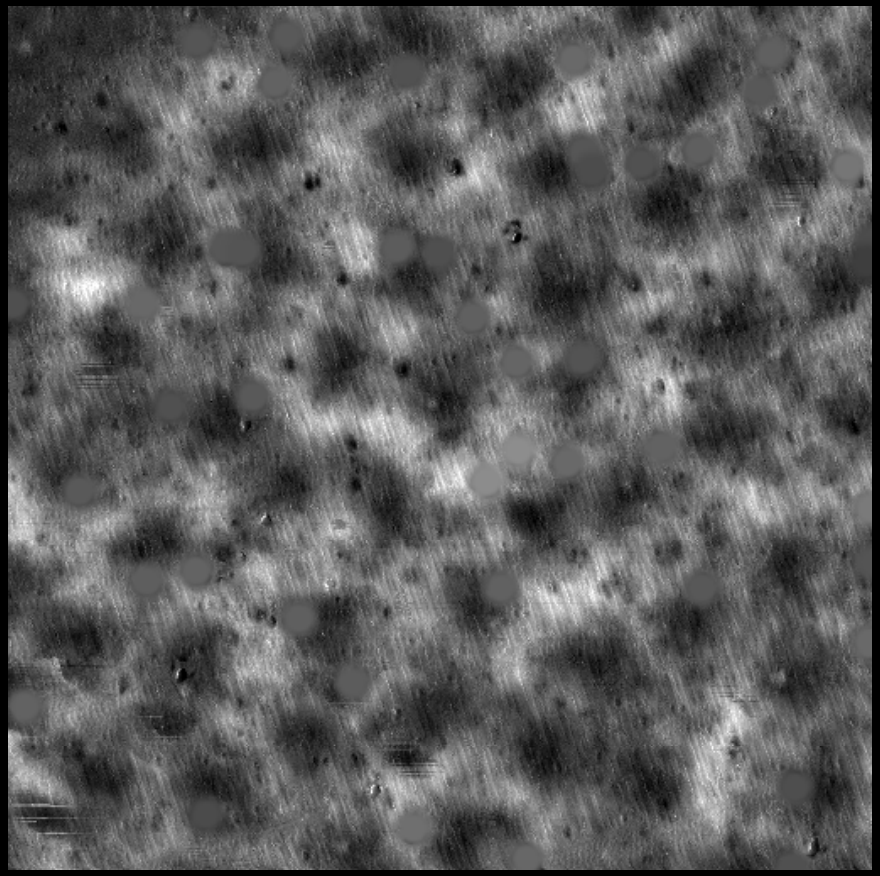
Ichioka, PRB 53, 15316 (1996)



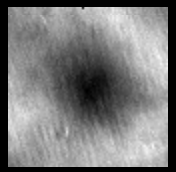
Franz & Tesanovic, PRB 53, 15316 (1996)

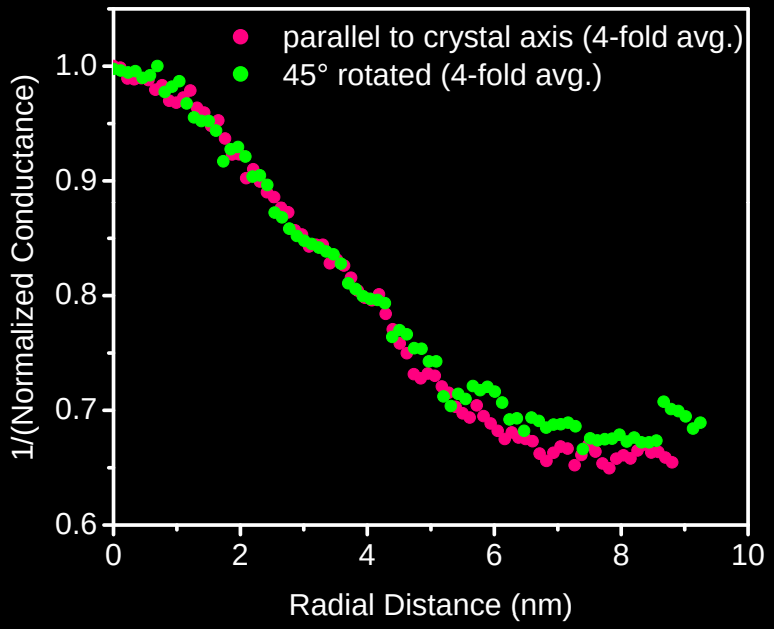
Are Vortices Isotropic?

Filter impurities



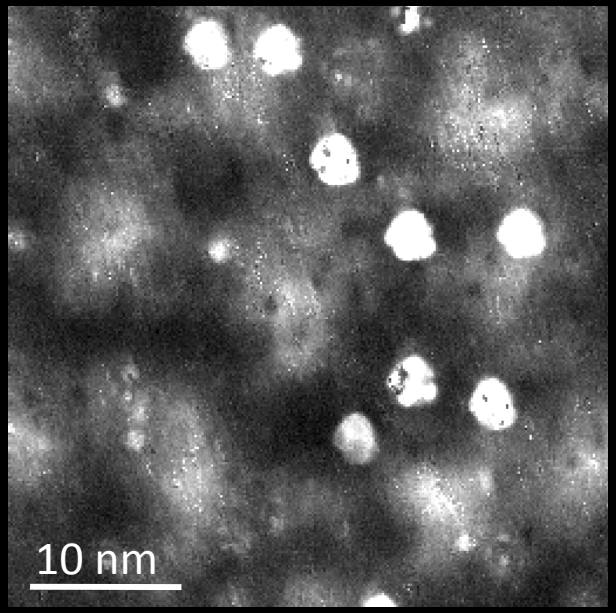
Average vortices





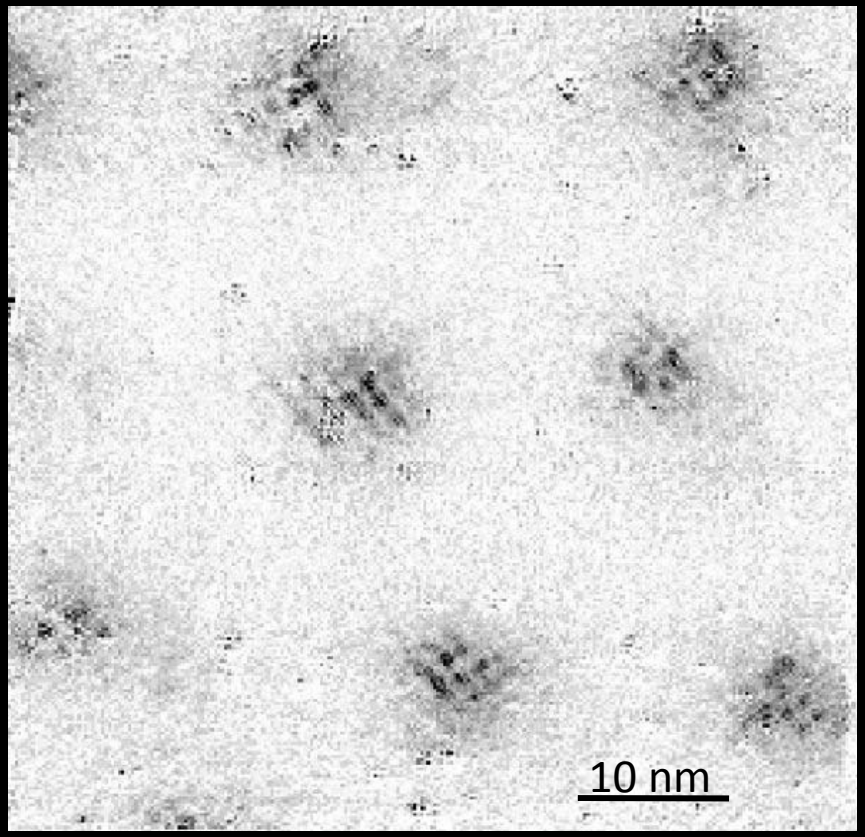
Compare to Experimental *d*-wave Vortex Shape

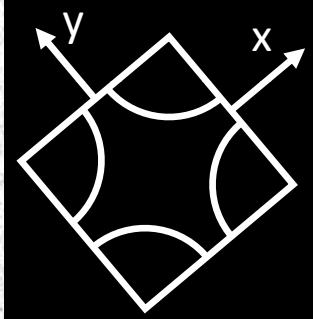
$BaCo_xFe_{2-x}As_2$



0 nS 1.5 nS

$Bi_2Sr_2CaCu_2O_{8+d}$





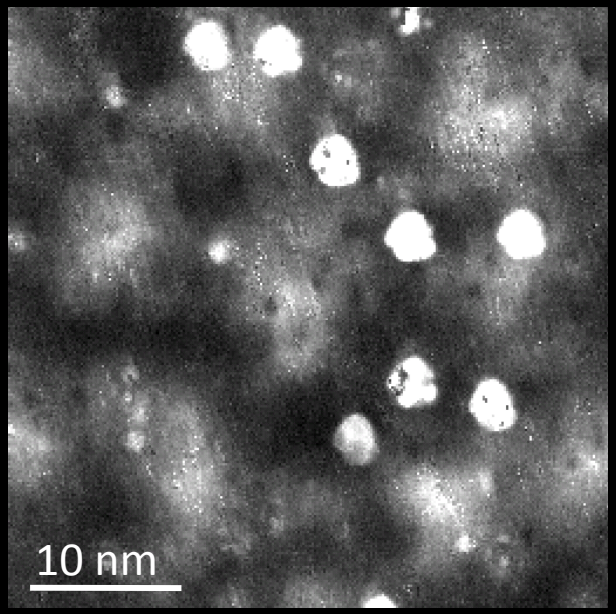
(integrated dI/dV from 0 meV to 12 meV)

0 pA 2 pA

Hoffman, Science 266, 455 (2002)

Compare to Experimental *d*-wave Vortex Shape

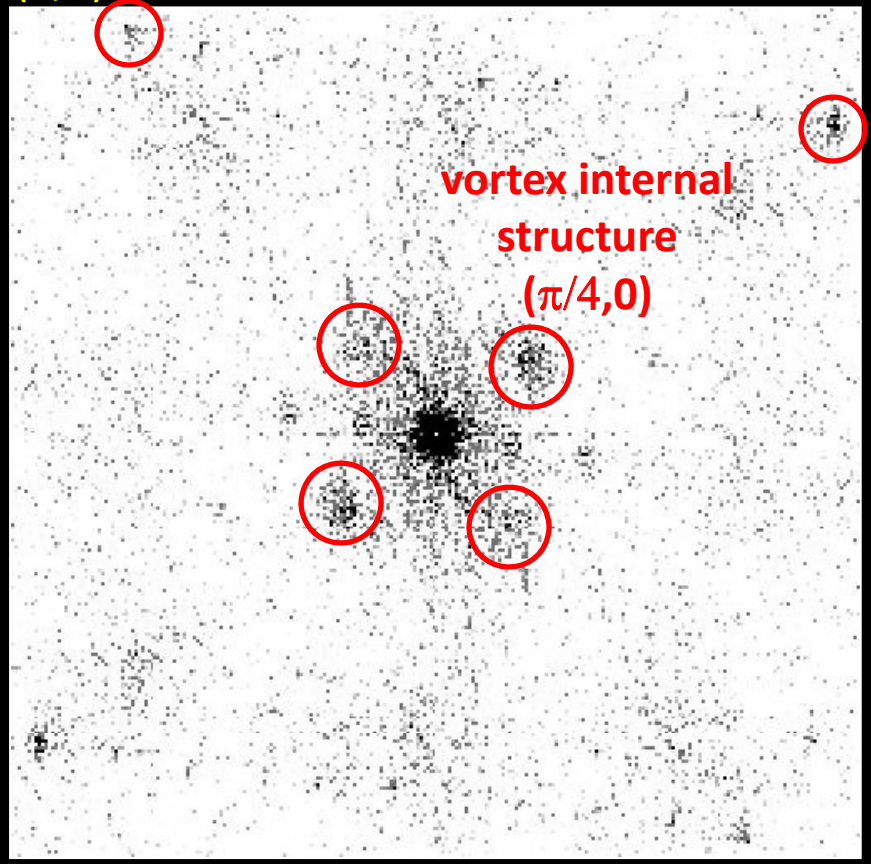
$BaCo_xFe_{2-x}As_2$



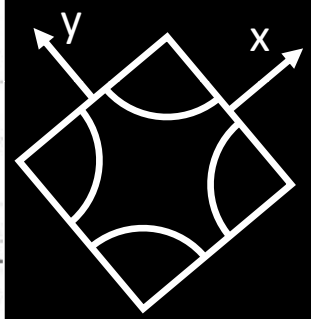
0 nS 1.5 nS

atoms
$(0,\pi)$

$Bi_2Sr_2CaCu_2O_{8+d}$



atoms
$(\pi,0)$

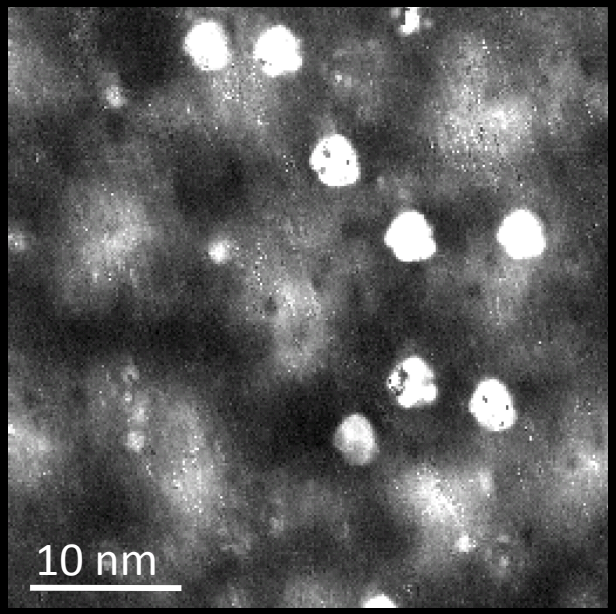


Fourier Transform

Hoffman, Science 266, 455 (2002)

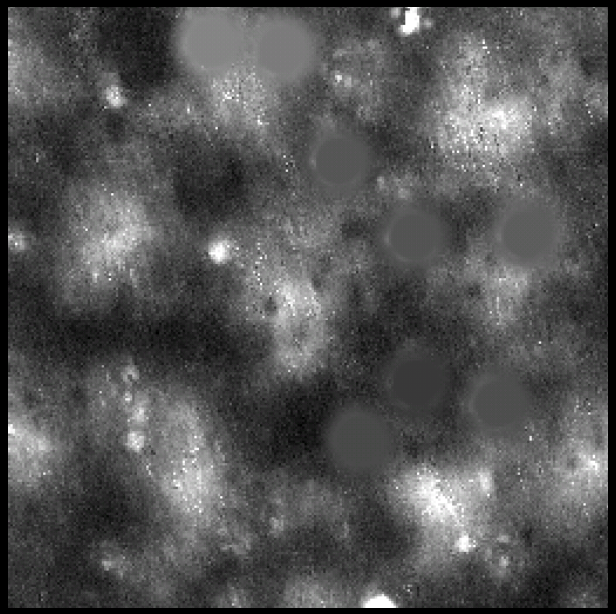
Internal structure in $BaCo_xFe_{2-x}As_2$ Vortices?

$BaCo_xFe_{2-x}As_2$

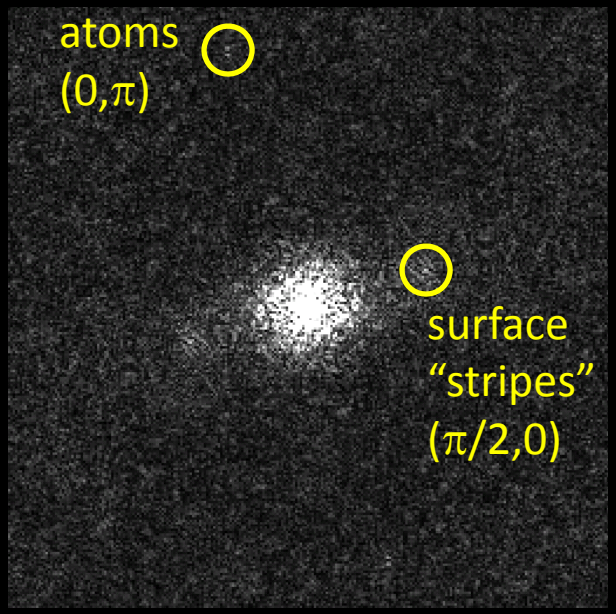


0 nS 1.5 nS

→ filter impurities

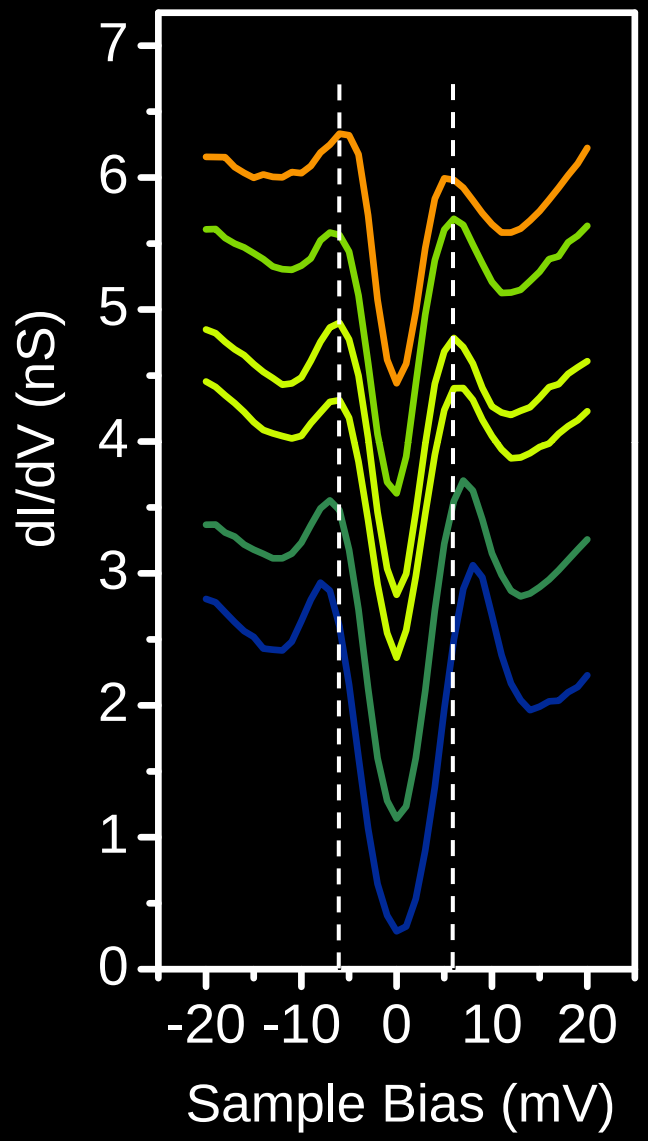


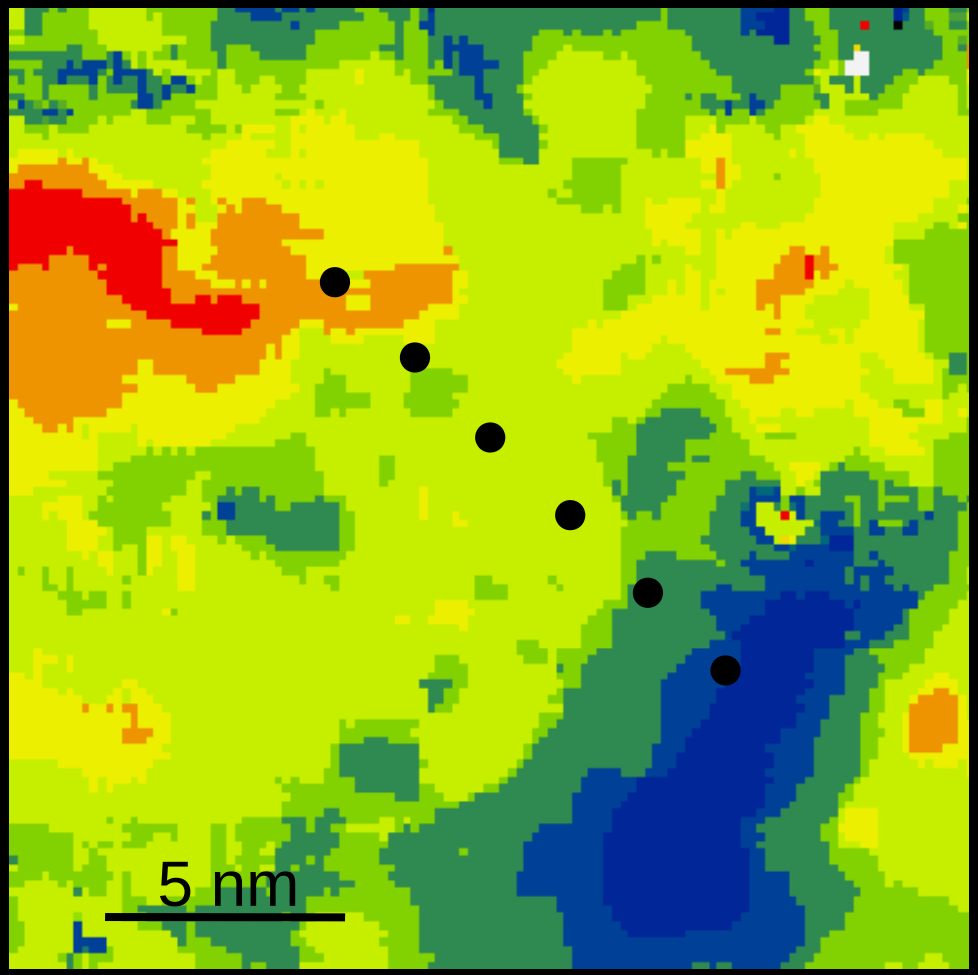
→ Fourier transform

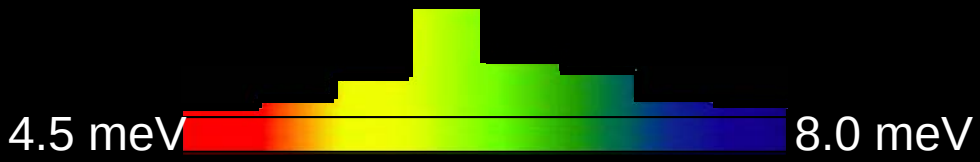


→ No internal structure observed.

Can we fit these superconducting gaps?

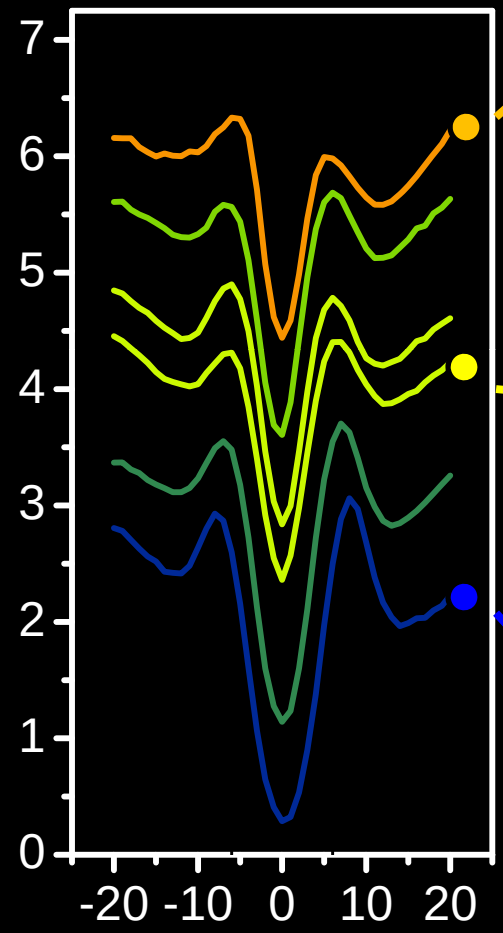


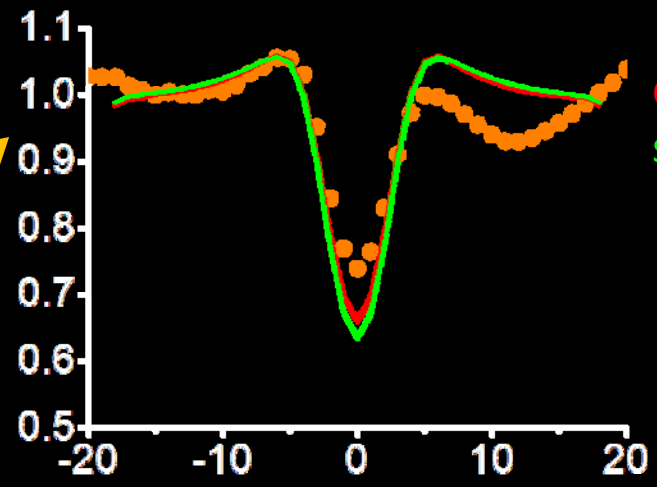




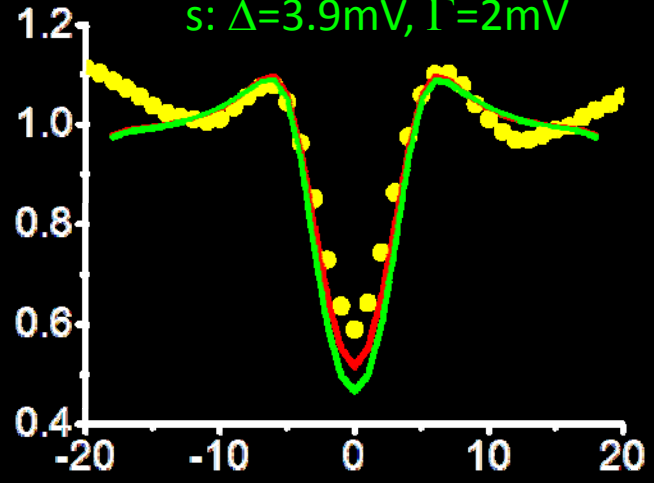
$\overline{\Delta}$ = 6.25 ± 0.73 meV (12% variation)

Can we fit these superconducting gaps?

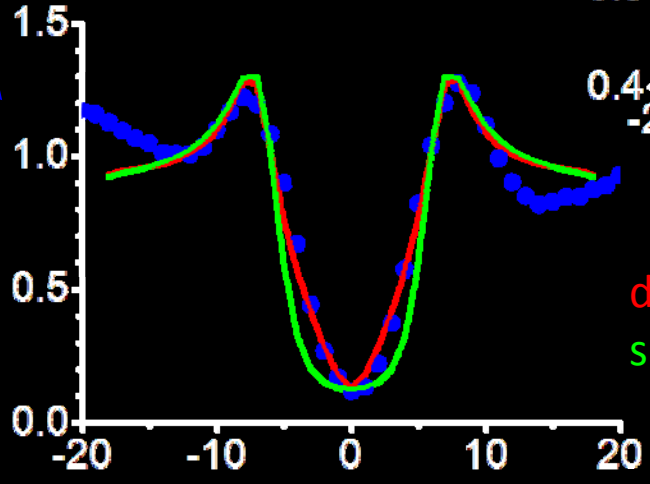




d: Δ=3.9mV, Γ=1.9mV
s: Δ=3.0mV, Γ=2.3mV



d: Δ=4.9mV, Γ=1.5mV
s: Δ=3.9mV, Γ=2mV

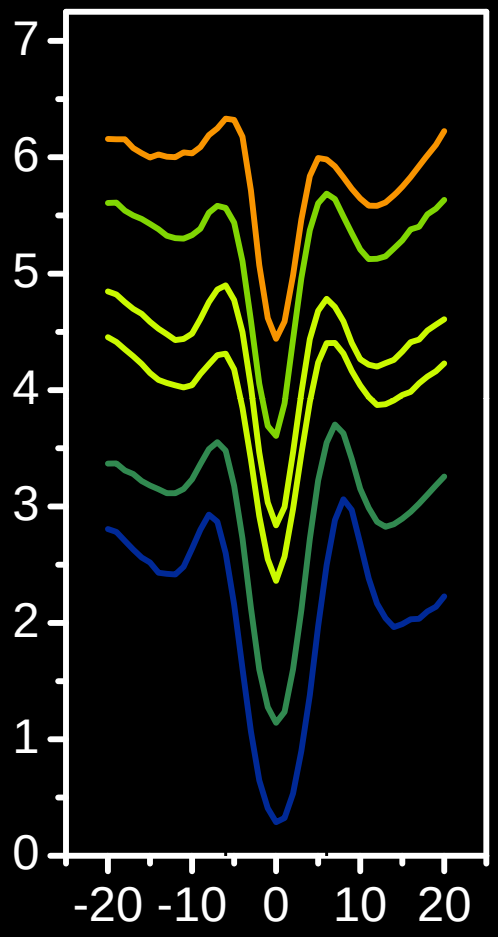


d: Δ=7.27mV, Γ=0.16mV
s: Δ=6.20mV, Γ=0.85mV

measurements at T=6K; k_BT = 0.5 meV
dV modulation = 1.5 meV

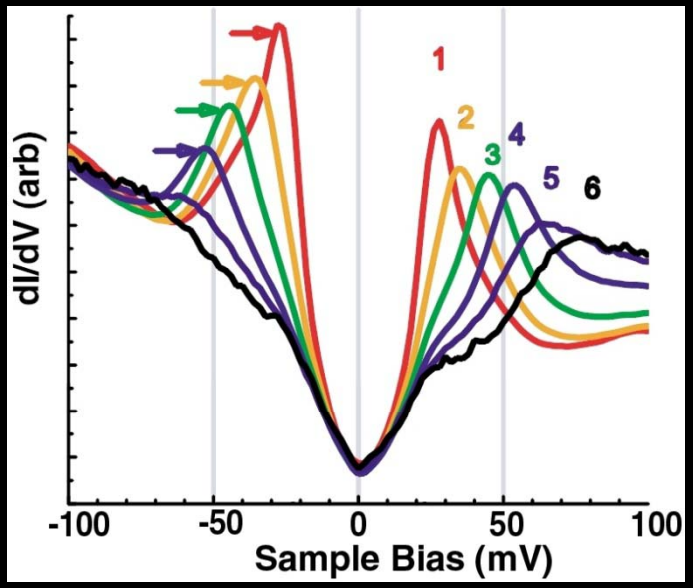
Comparison to Cuprates

$Ba(Co_xFe_{1-x})_2As_2$



wider gap (larger Δ) ↔ deeper gap sharper coherence peaks

$Bi_2Sr_2CaCu_2O_{8+d}$

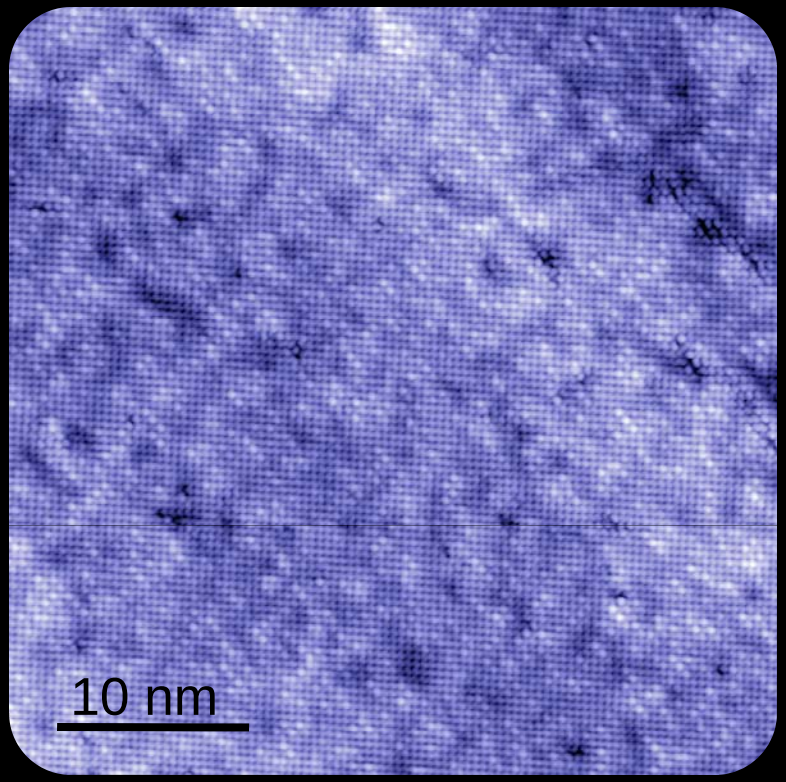


McElroy, PRL 94, 197005 (2005)

Apparent opposite relation?

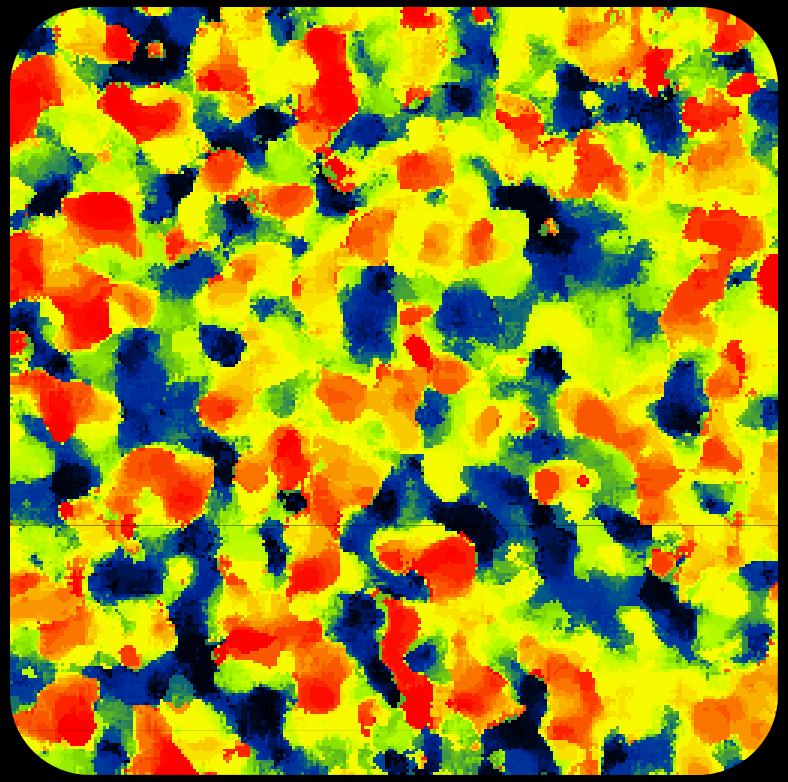
Switch Gears: $Bi_2Sr_2CuO_{6+d}$ work in progress

Topography



0 120 pm

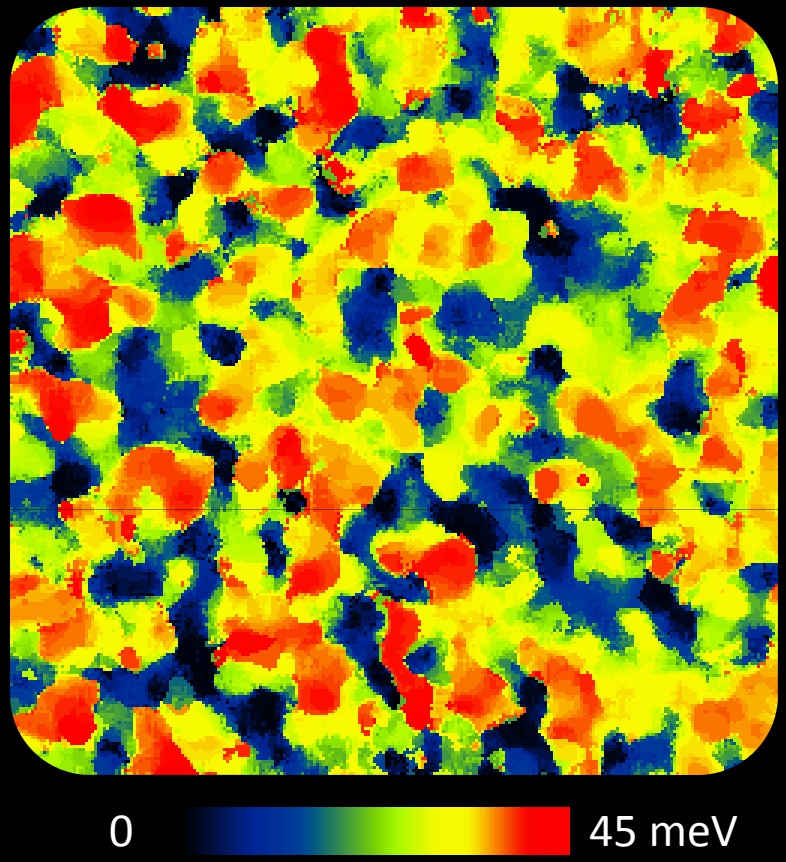
Δ map



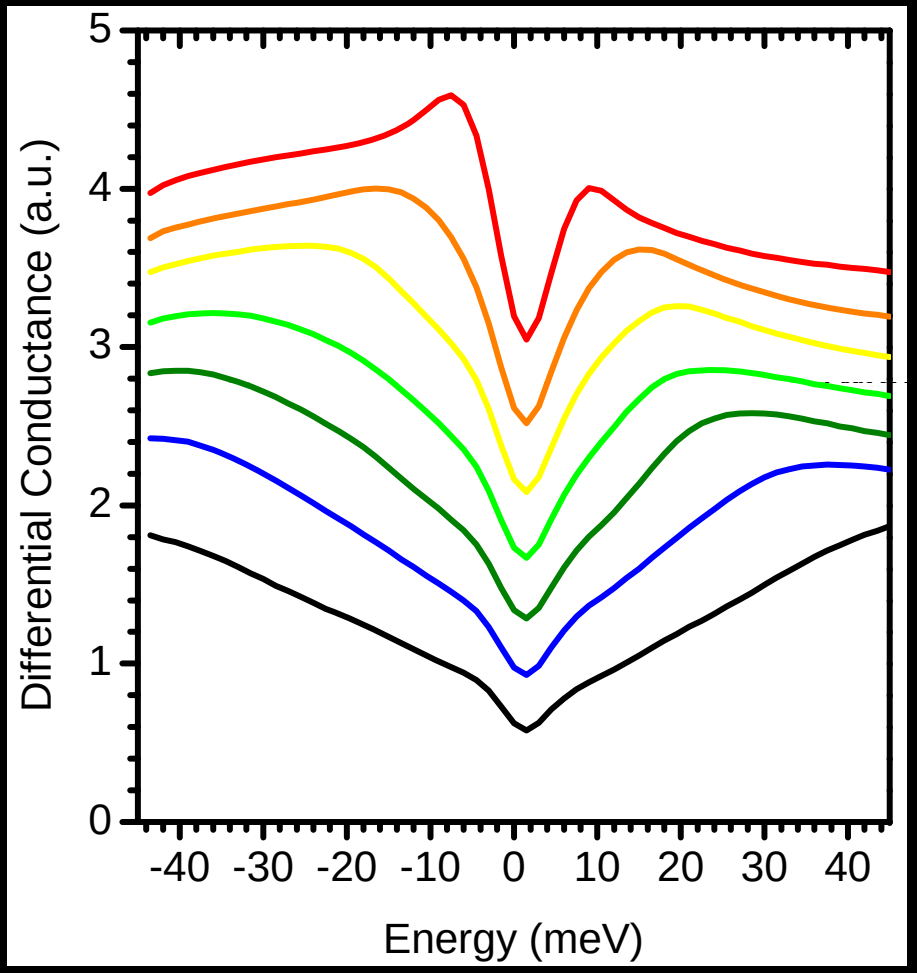
0 45 meV

Sort Spectra by Δ

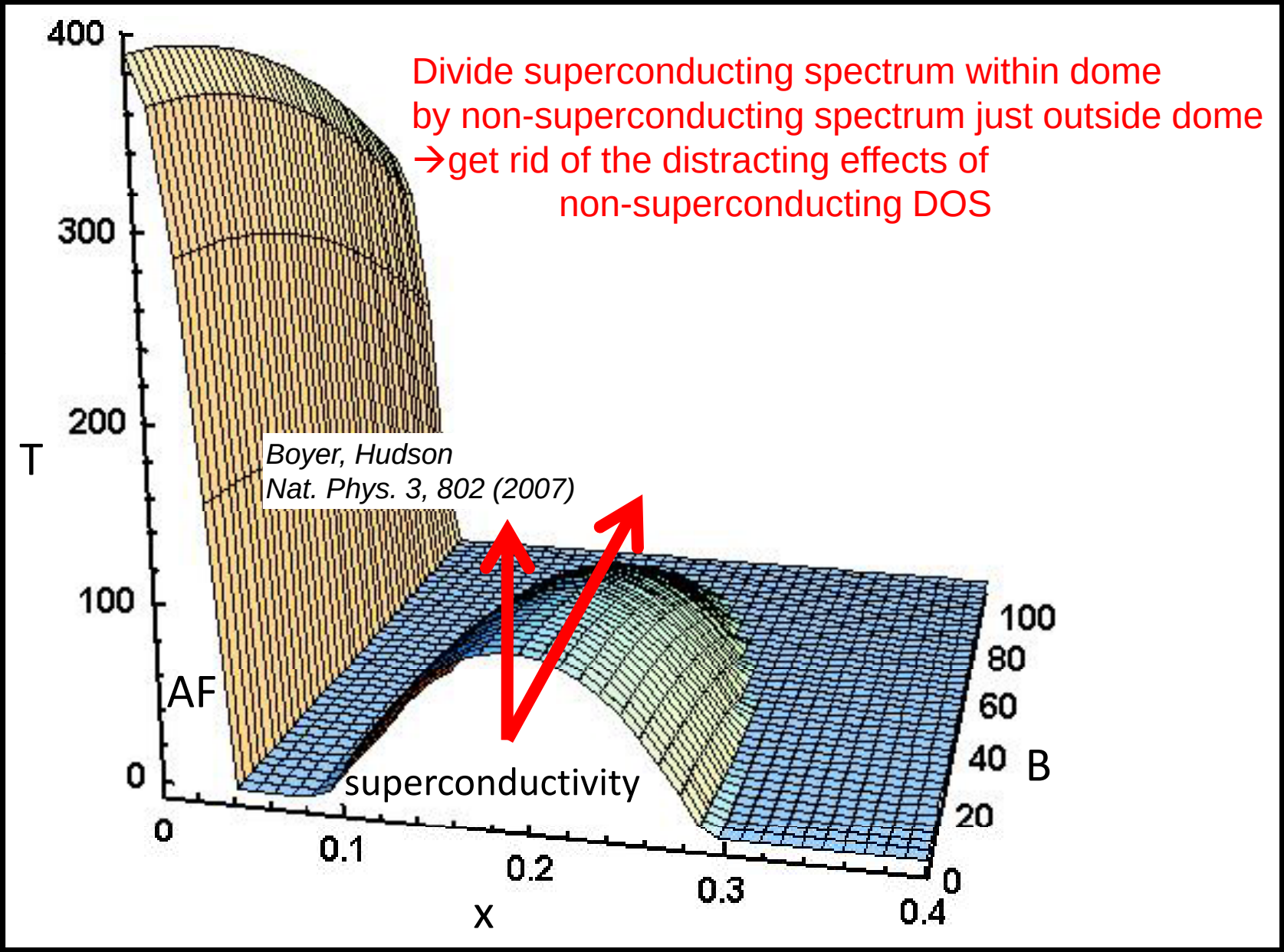
Δ map



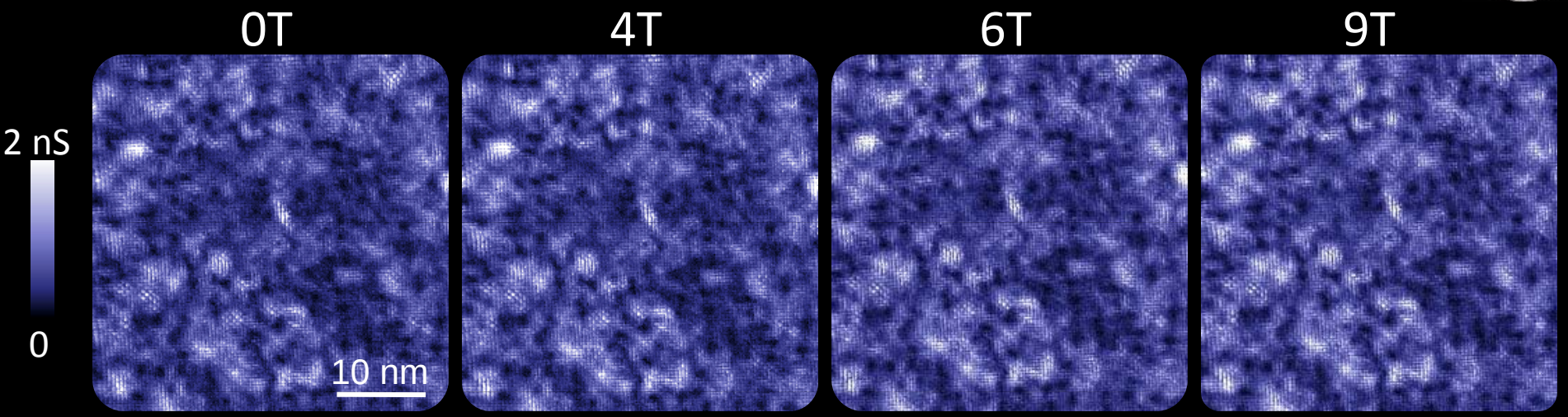
0 45 meV



Spectra Normalization Procedure



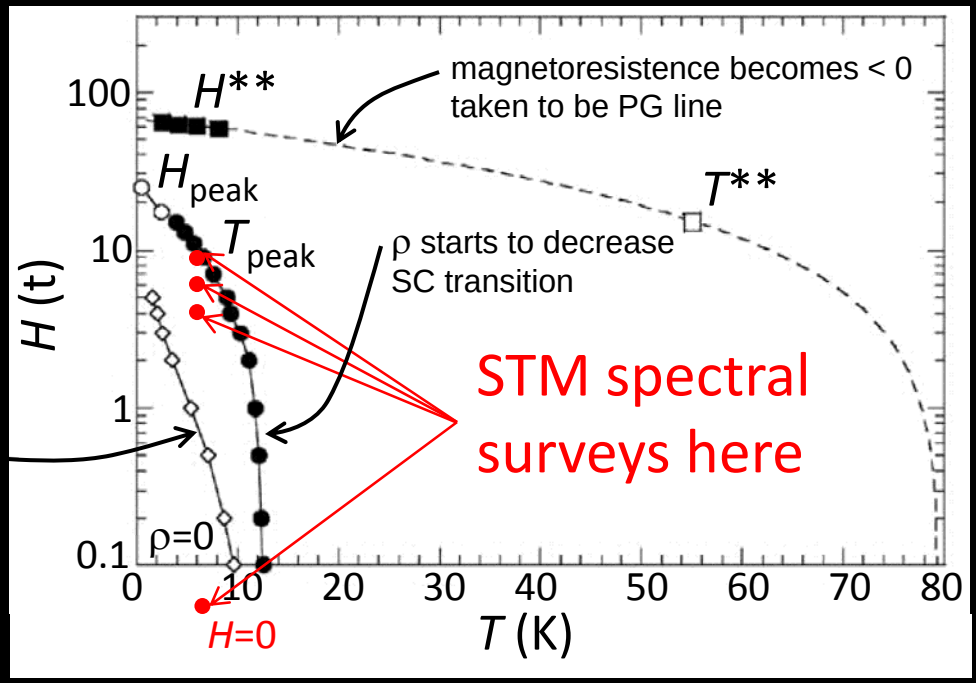
Increase B field: Where are the vortices?



0 meV Density of States

No obvious change

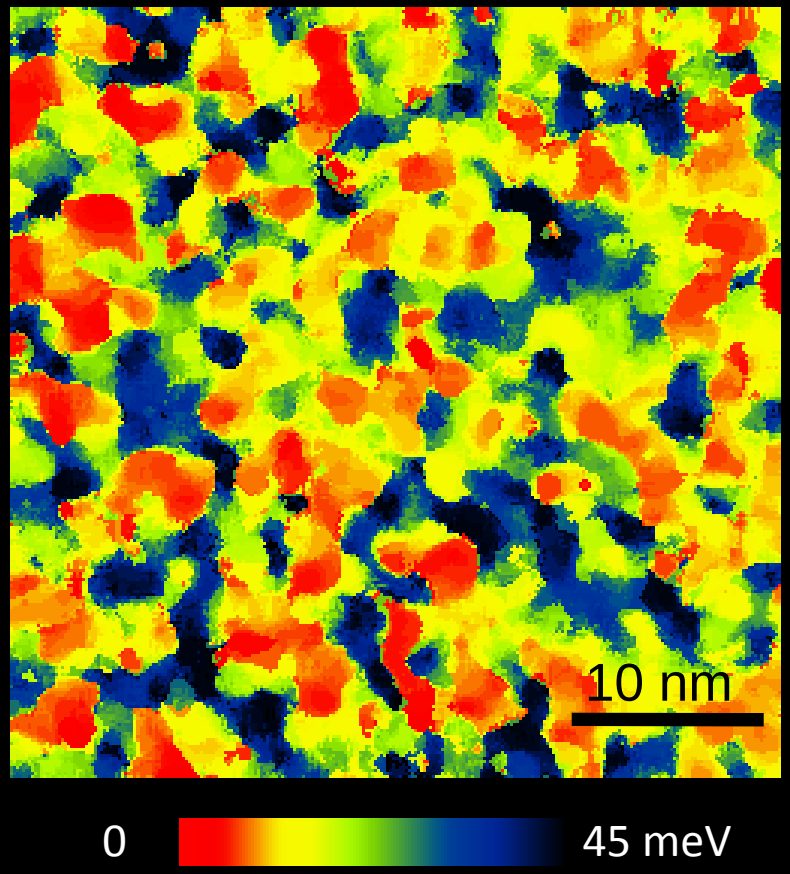
→ must be vortex liquid!

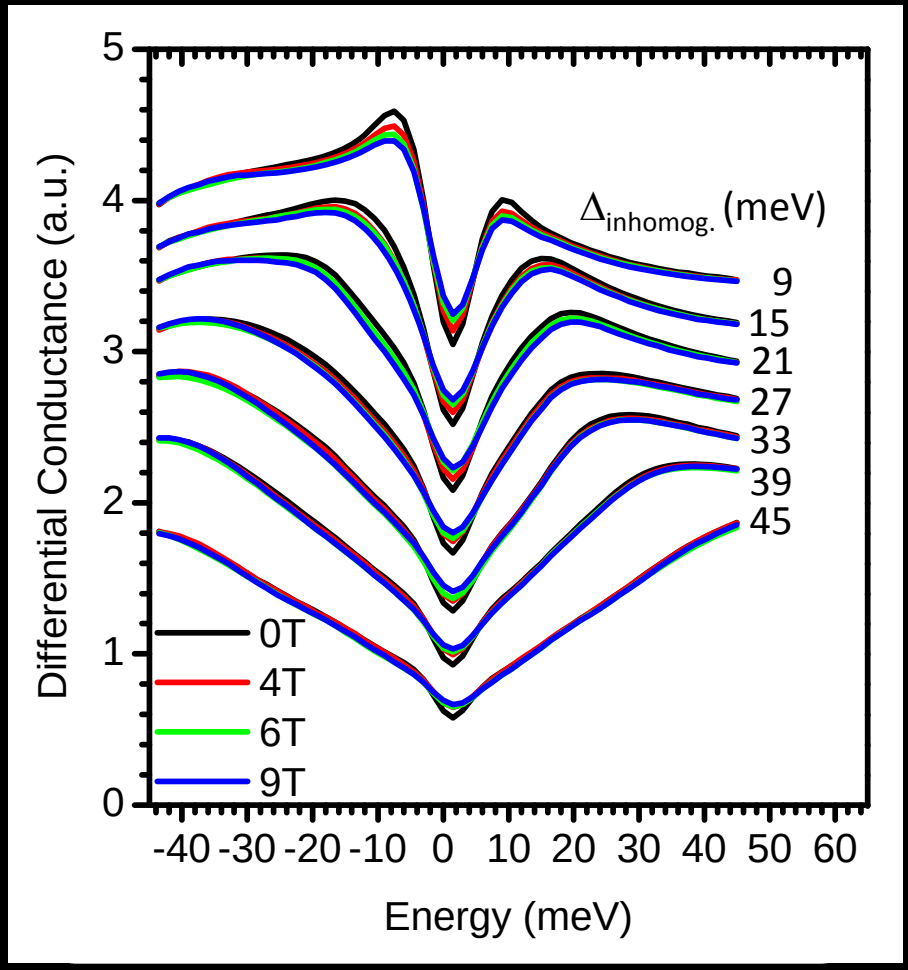


Kudo *et al*, Physica C 426, 251 (2005)

Sort Spectra by Δ

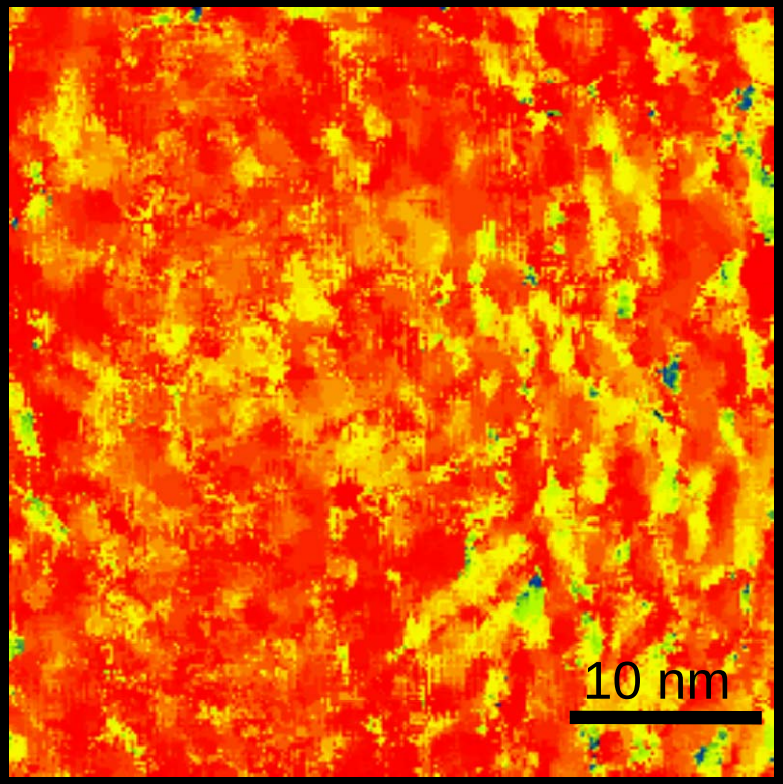
Δ map





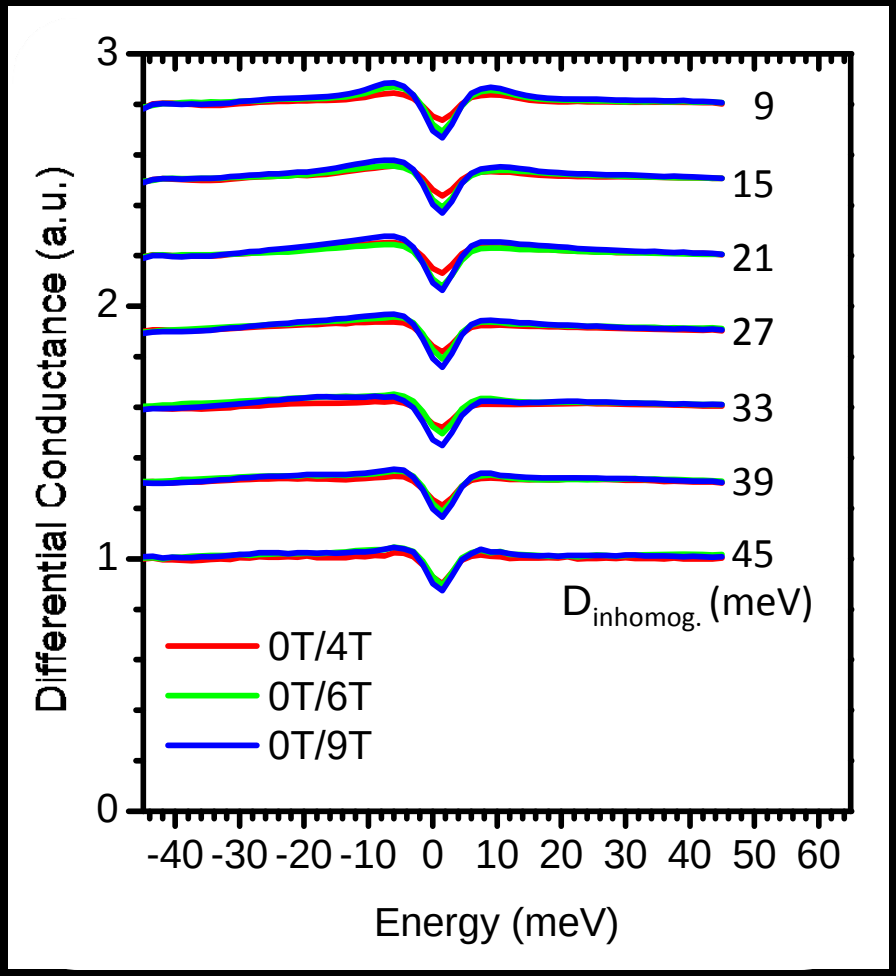
Divide Low-Field by High-Field

New Δ map



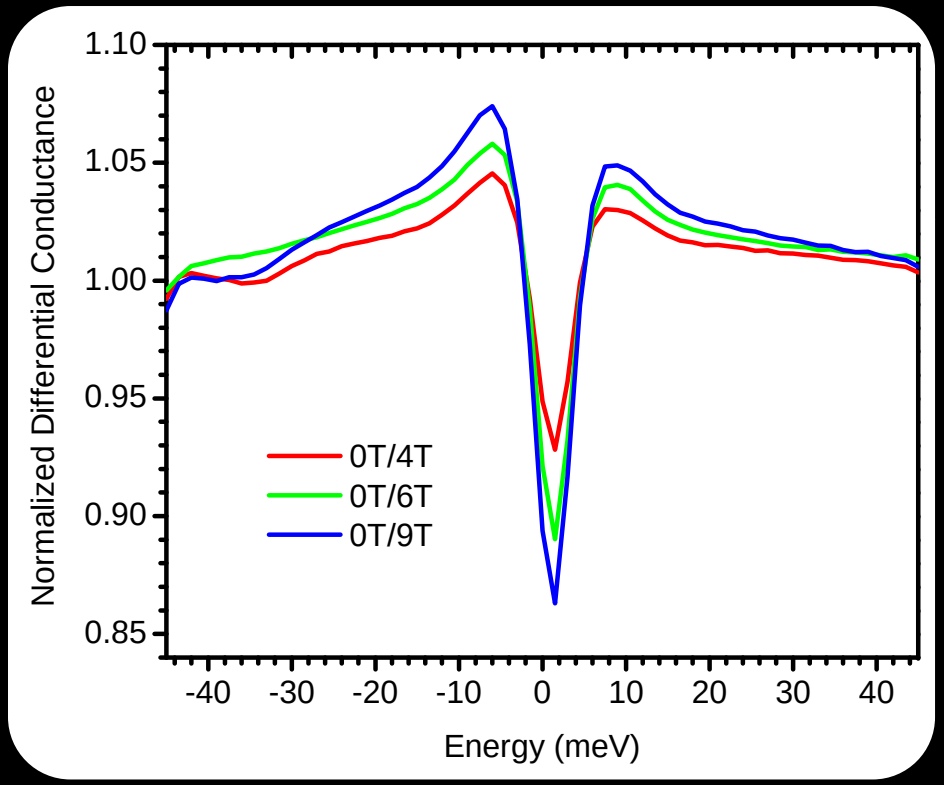
0 45 meV

→ Homogenous!



Gap Depth vs. Field

Spectra divided point-by-point,
then averaged over whole field of view.



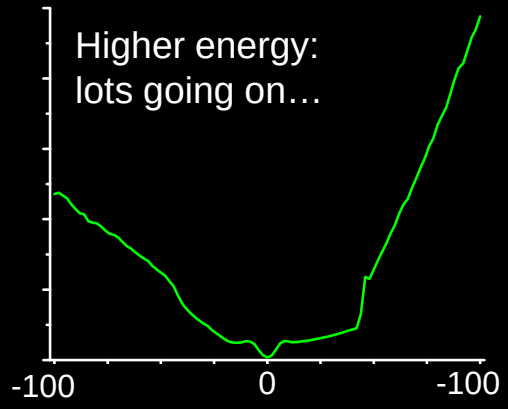
Applied magnetic field allows separation of two energy scales:

- one is inhomogeneous and obvious to the naked eye
- second is apparently much more homogeneous, becomes obvious after division
- division wouldn't necessarily preserve gap shape but would expose existence and size of second energy scale
- next: look more closely at smaller inhomogeneity of second energy scale, compare to pnictides

STM To-Do List

- Better surface characterization:
  cleave temperature dependence, a la Pennec *et al*, PRL 101, 216103 (2008)

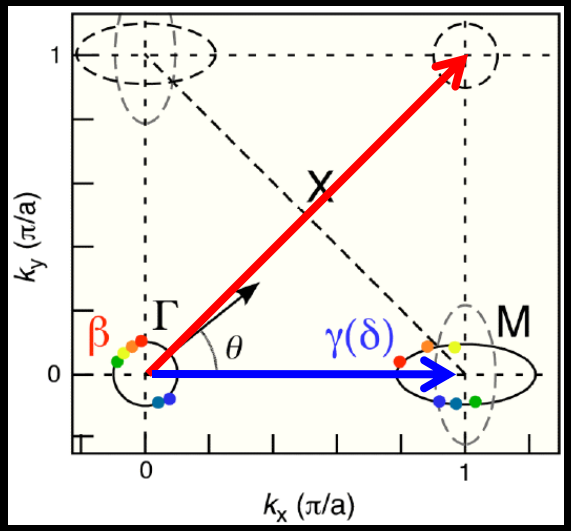
- Normalize to higher T



- Data at lower T, to resolve multiple gaps,
  see how each behaves in field
  → STM currently off-line for upgrade to ^{3}He fridge

STM To-Do List

- Quasiparticle interference



s± symmetry scenario:
predicted scattering from magnetic impurities

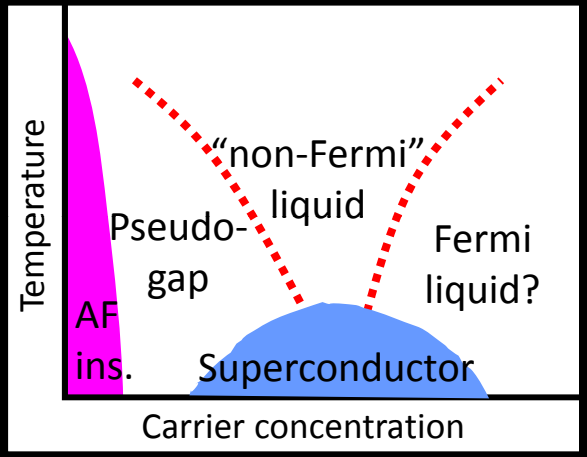
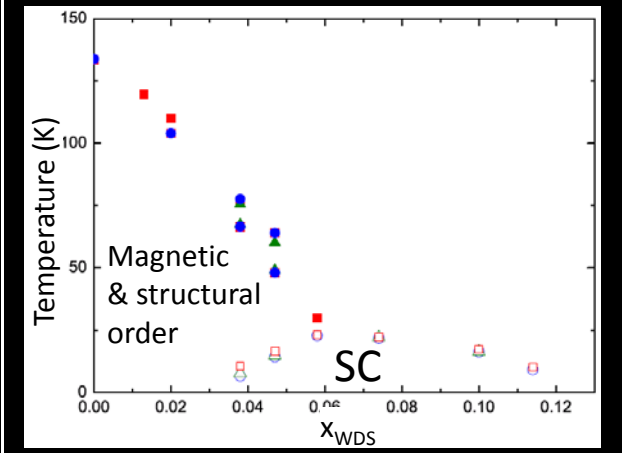
- q=(2π,0) scattering → STRONG
- q=(π,π) scattering → weak

[Wang, Zhai, D. H. Lee, EPL, 85, 37005 (2009)]

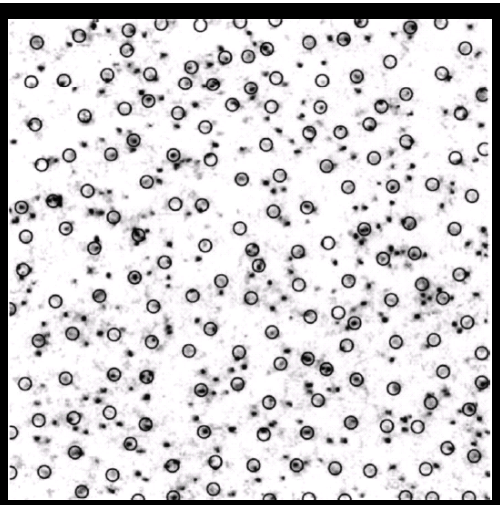
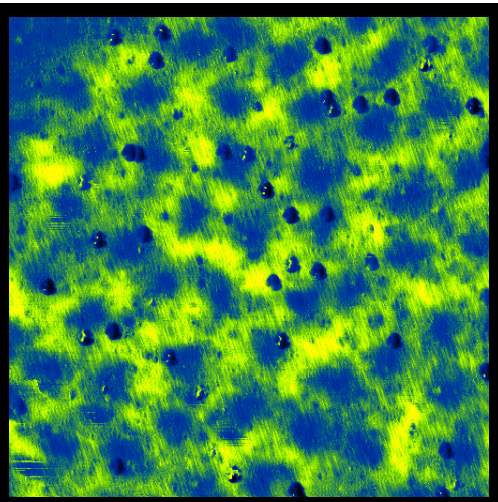
- Repeat impurity measurements, compare to preliminary theory
  [Michael Lawler, Eun-Ah Kim]

- Compare vortex core state measurements to theory
  [J.X. Zhu, C.S. Ting]

Cuprate-Pnictide Comparison

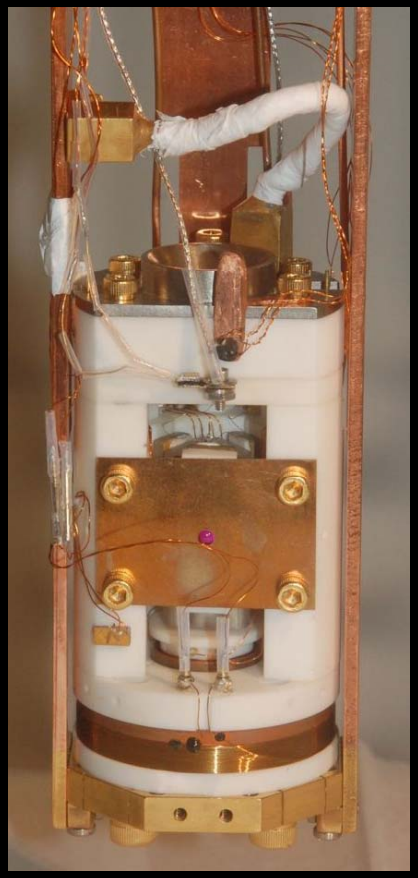
	Cuprate: $Bi_2Sr_2CaCu_2O_{8+d}$	Pnictide: $BaCo_xFe_{2-x}As_2$
phase diagram		 Ni, Canfield, *et al*, arXiv:0811.1767
ground state	antiferromagnetic Mott insulator	itinerant antiferromagnet semimetal
gap symmetry	*d*-wave	*s*± ??
anisotropy, γ	~ 50	~ 1-3
optimal T_c	91 K	25.3 K

Cuprate-Pnictide Comparison

	Cuprate: $Bi_2Sr_2CaCu_2O_{8+d}$	Pnictide: $BaCo_xFe_{2-x}As_2$
superconducting gap, Δ	Δ ~ 33 meV $2\Delta/k_BT_c$ ~ 6-10	Δ = 6.25 meV $2\Delta/k_BT_c$ = 5.73
gap inhomogeneity	σ ~ 7 meV σ/Δ ~ 21%	σ = 0.73 meV σ/Δ = 12%
coherence length, ξ_0	2.2 nm	2.7 nm
vortex pinning	 vortices pinned to surface impurities	 vortices NOT pinned to surface impurities

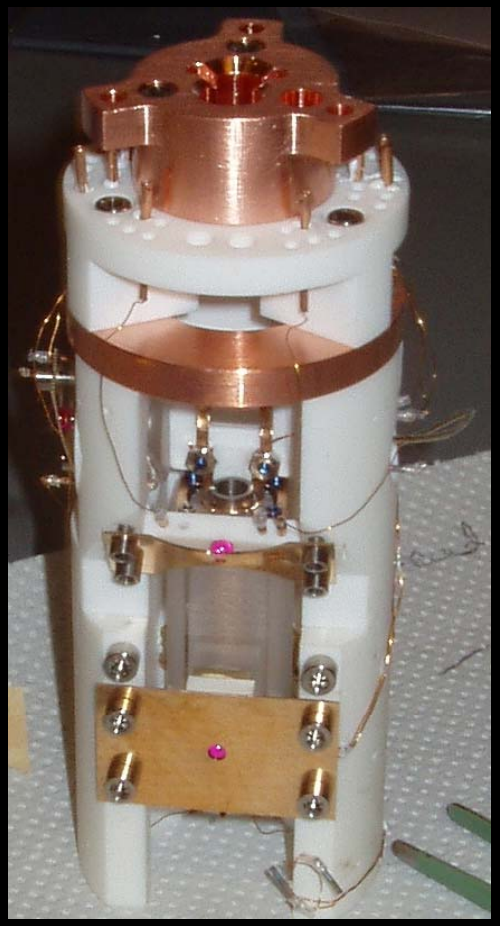
Scanning Probe Microscopy

STM



all of the data
in this talk

Spin-Polarized
STM



Magnetic Force
Microscope

coming on line in the next 6 months - year

Conclusion: What can we learn from SPM?

What is the gap symmetry?

- shape/energy structure of vortices DONE!
- shape/energy structure of impurities in progress…
- fit single spectra (need high-T or high-H data to normalize background, need lower-T data to separate multiple gaps) in progress…
- quasiparticle interference will tell us Brillouin Zone info in progress…

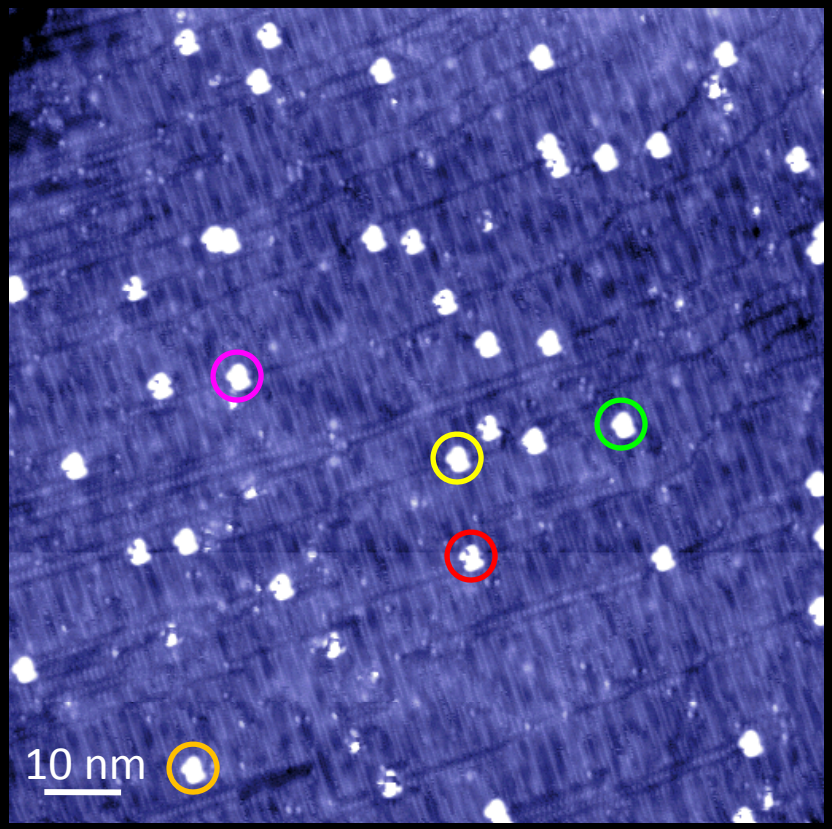
How do spin waves relate to SC?

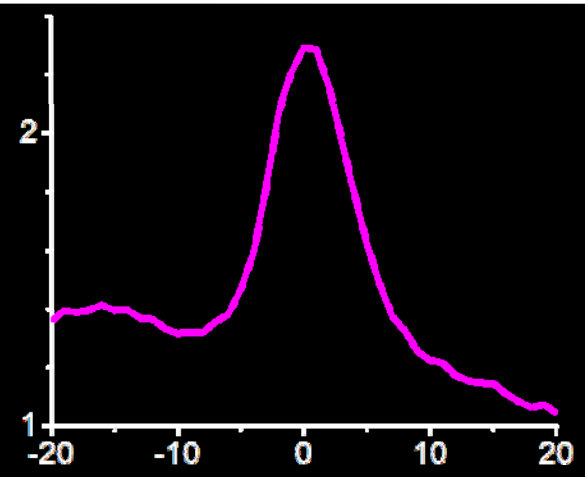
- inelastic tunneling can tell us energy of inelastic modes, but not whether they're spin/phonons
- best tool may be spin-polarized STM… stay tuned!

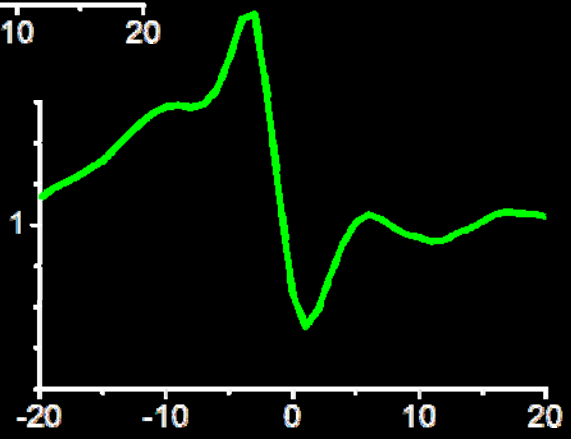
Vortex pinning?

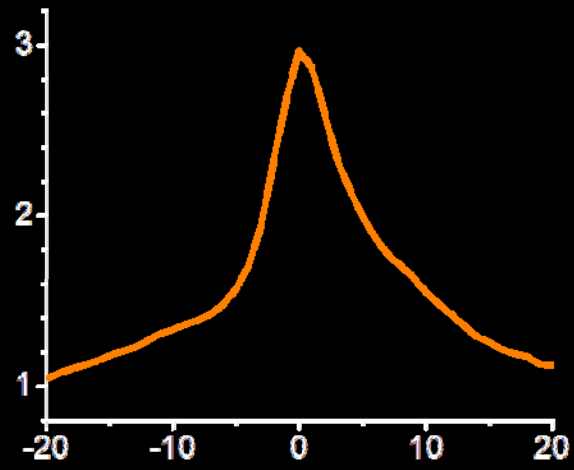
- directly measure coherence length from vortex core size DONE!
- correlate impurity locations with surface defects DONE!
- can change field, run current, or simply quantify the disorder in vortex lattice to put bounds on vortex pinning forces
- best tool is magnetic force microscopy… stay tuned!

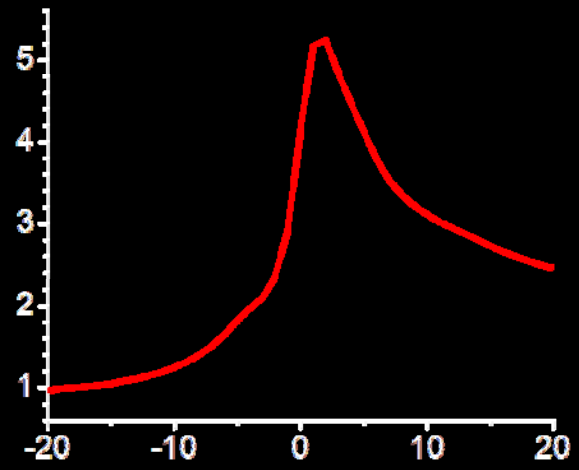
Strong Scatterers (9 Tesla)

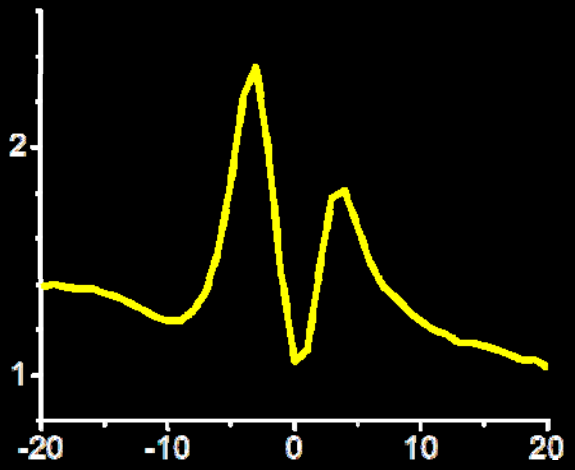




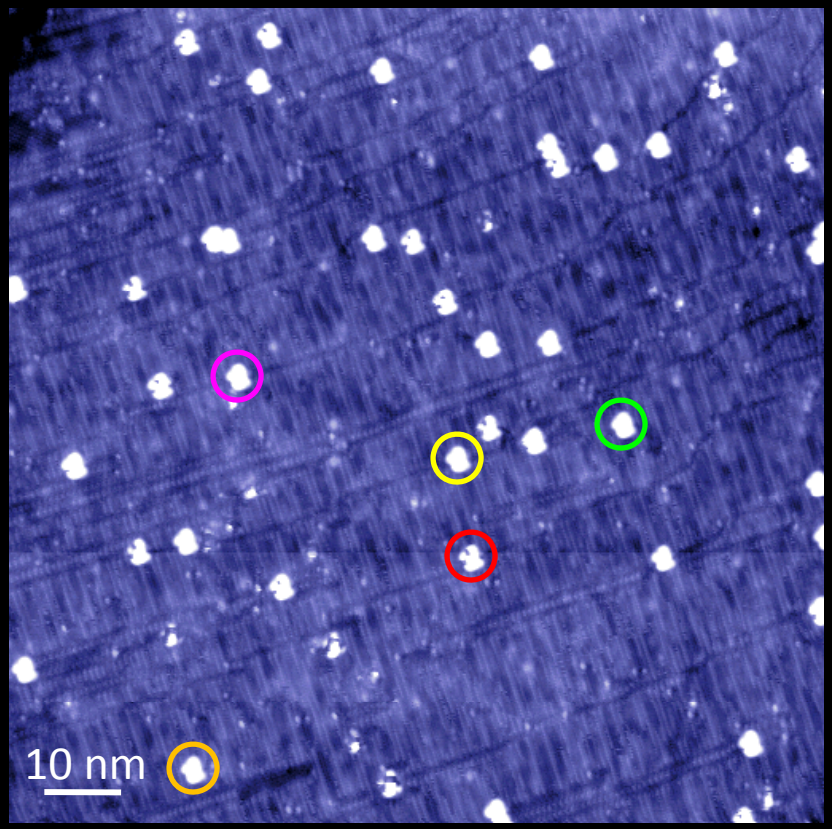


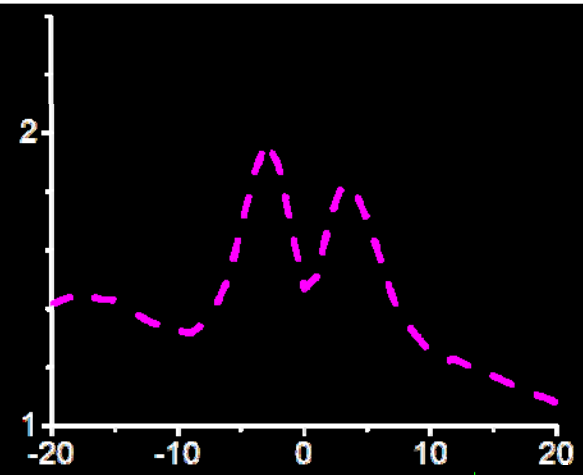


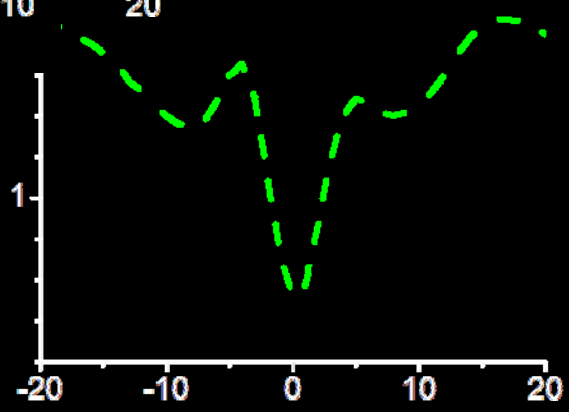


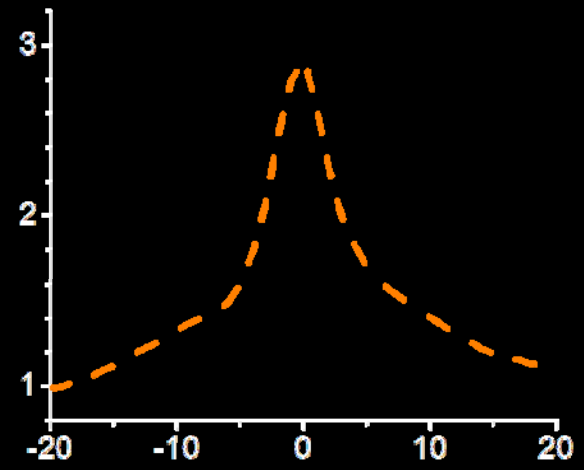


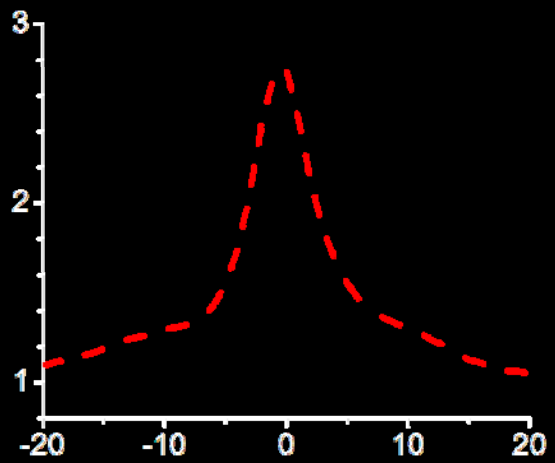
Strong Scatterers (6 Tesla)

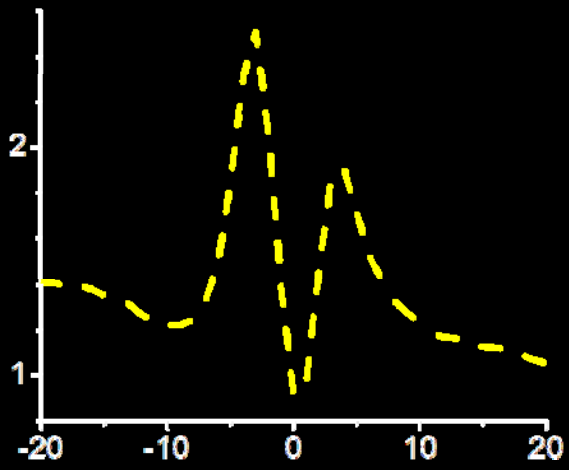




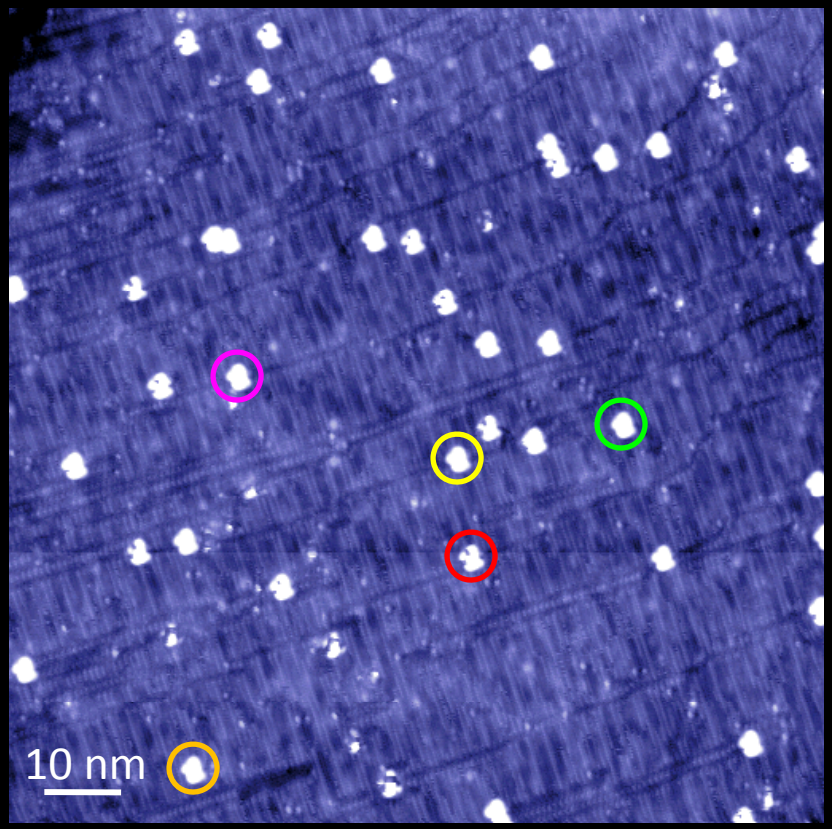


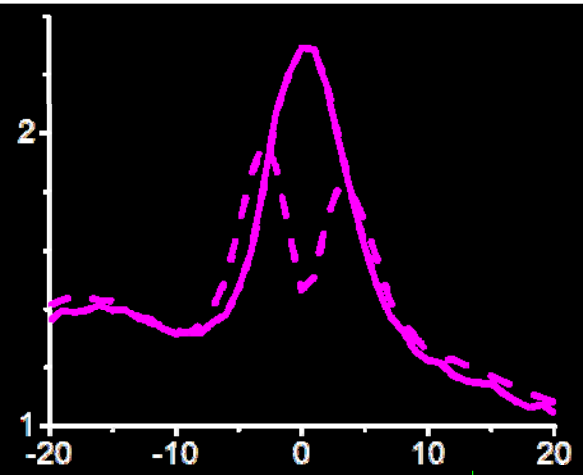


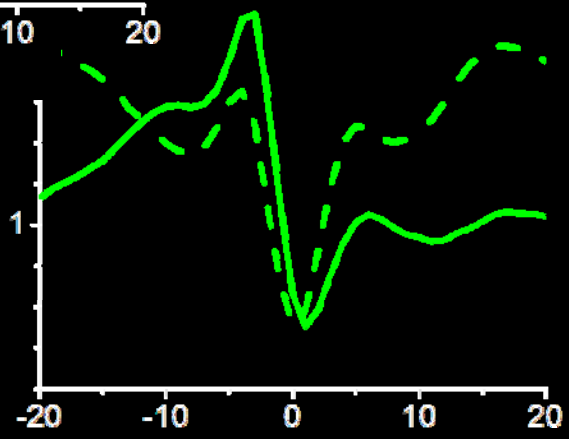


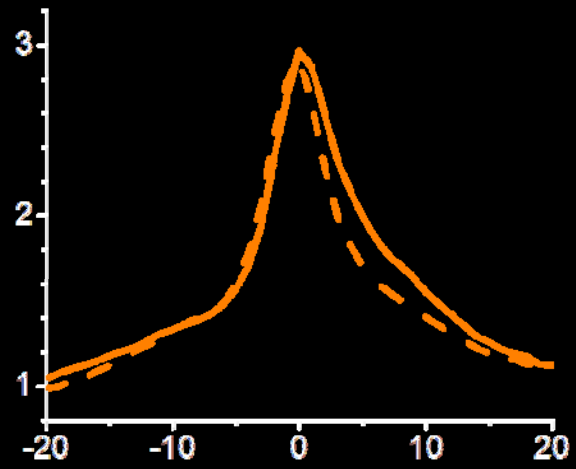


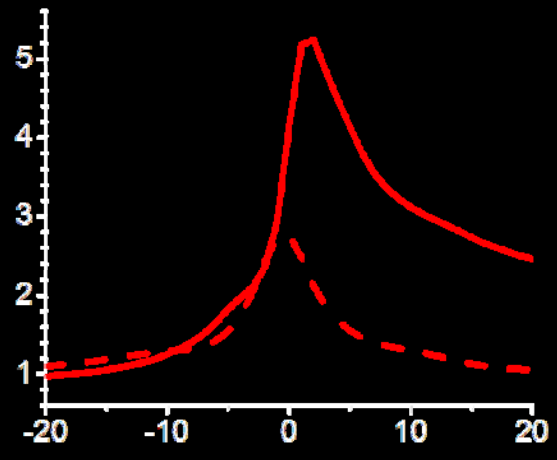
Strong Scatterers (6 and 9 Tesla)

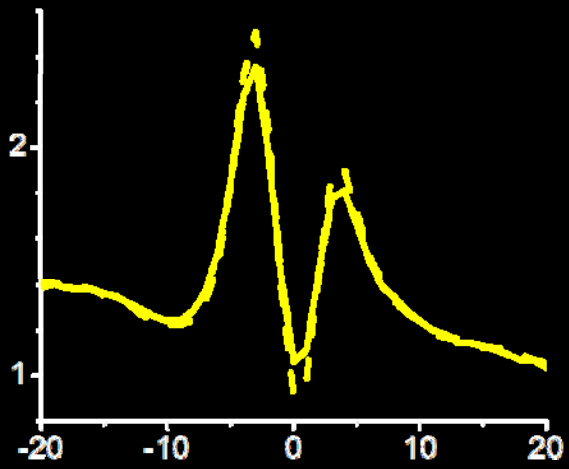






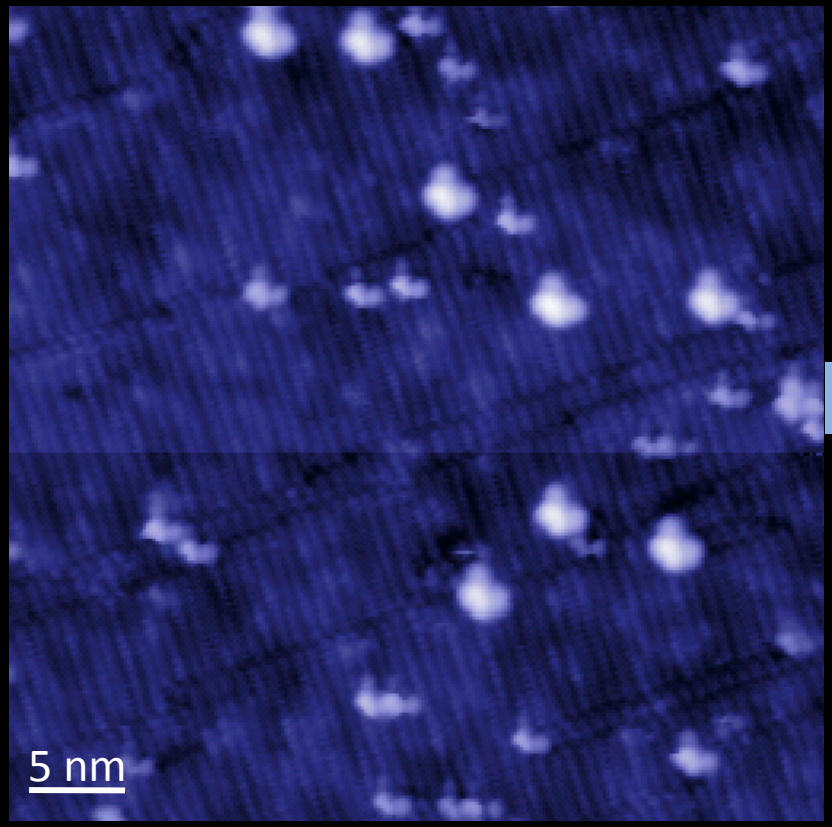






dI/dV → Catastrophic surface reconstruction

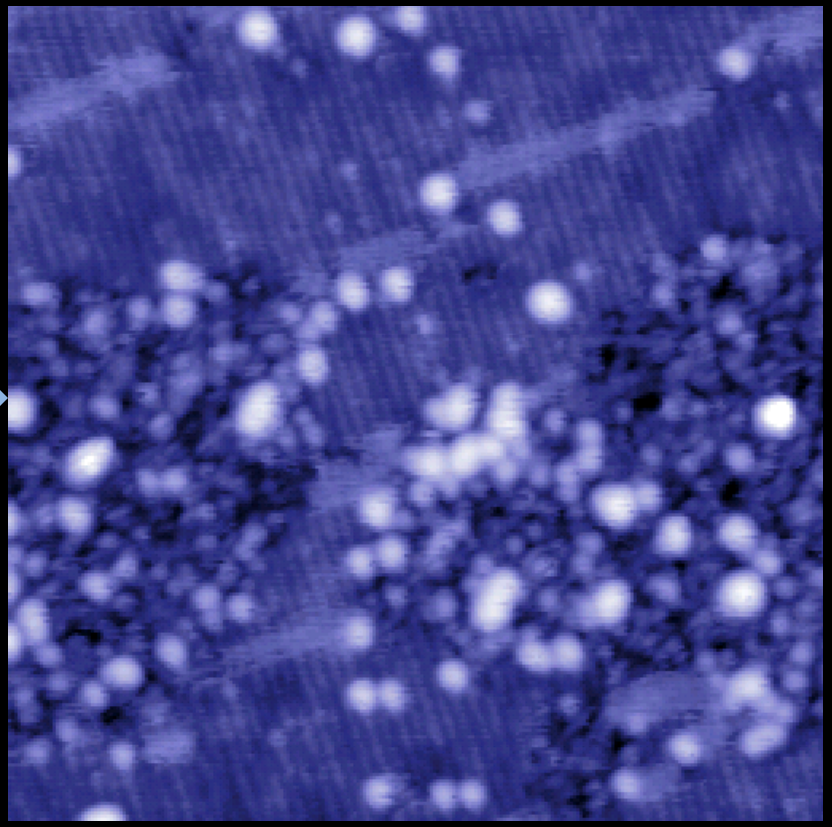
Before



0 Å 3 Å

dI/dV map

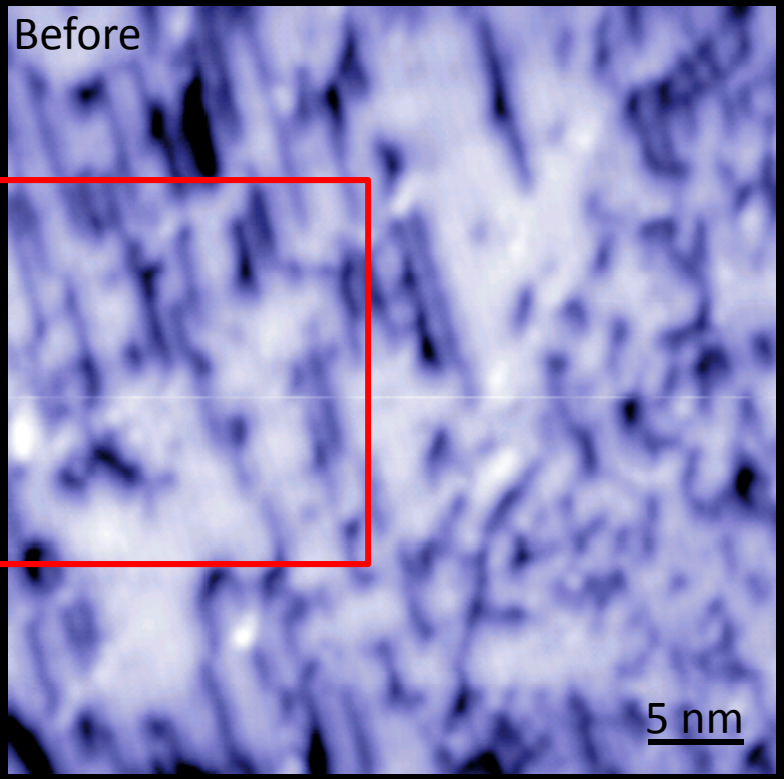
After

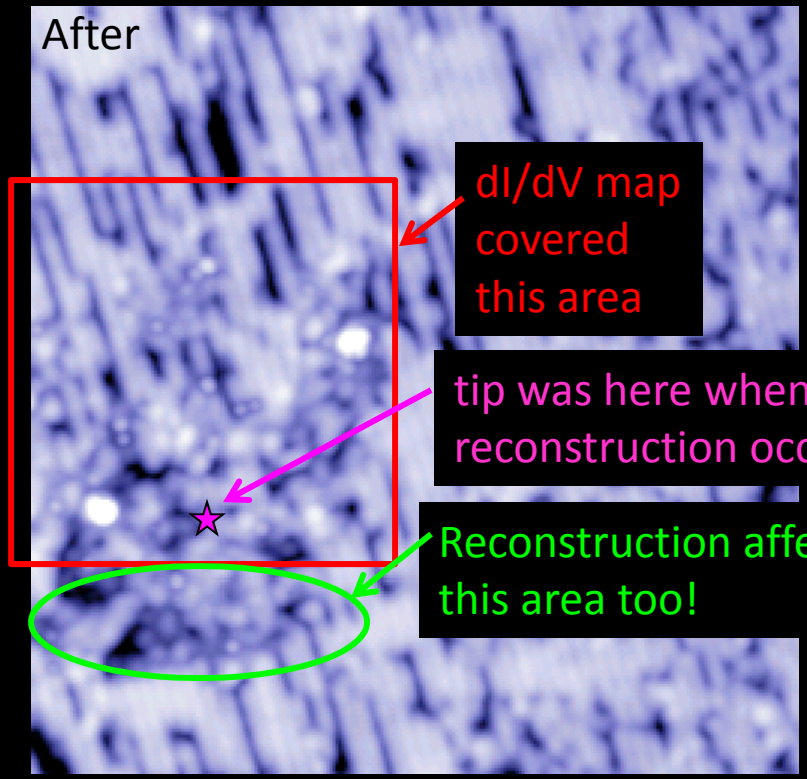


0 Å 4 Å

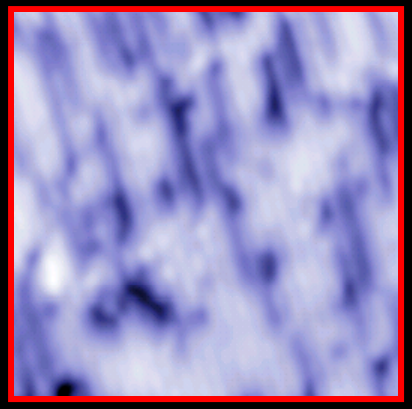
Can measure topography forever, no changes.
But dI/dV map triggers catastrophic surface reaction!

Surface reconstruction is non-local!

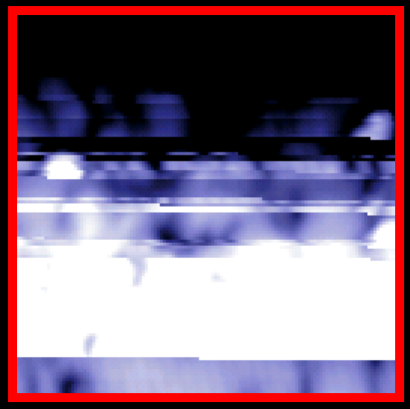




Immediately before dI/dV map:



Topography simultaneous with dI/dV map:



Scans start identically (no reconstruction yet)

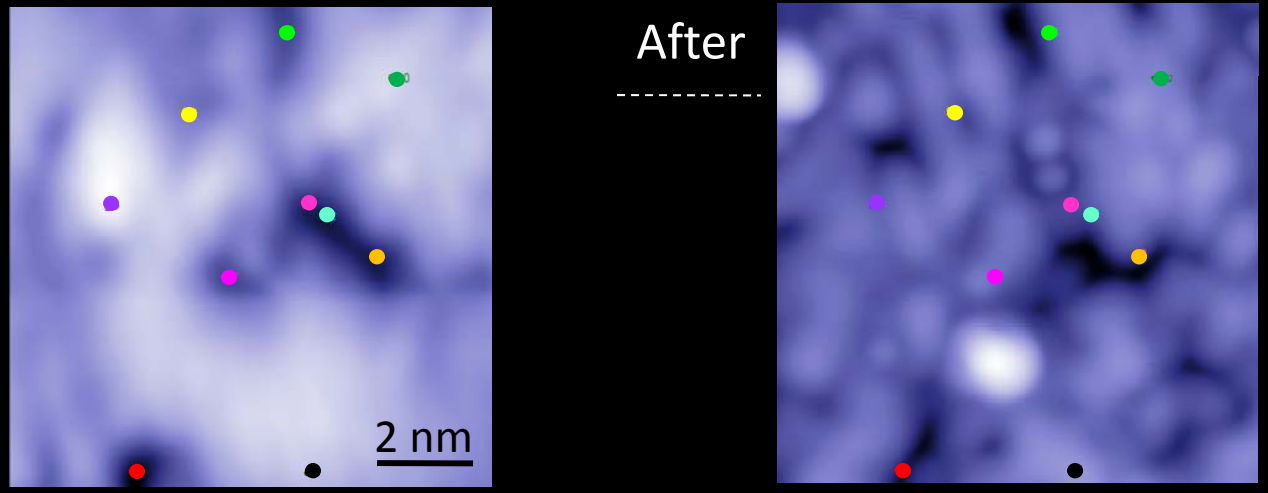
Scan from bottom to top

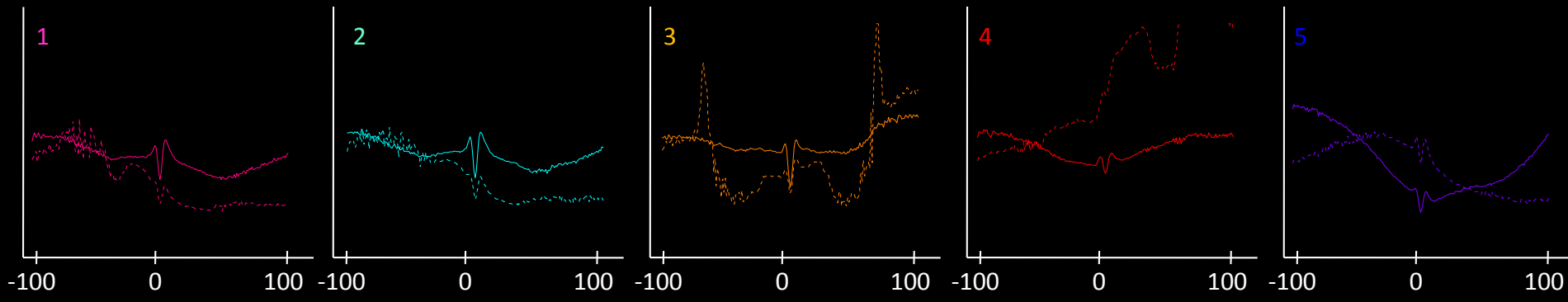
Note: this is an example from a superconducting $Sr_{1-x}K_xFe_2As_2$ sample

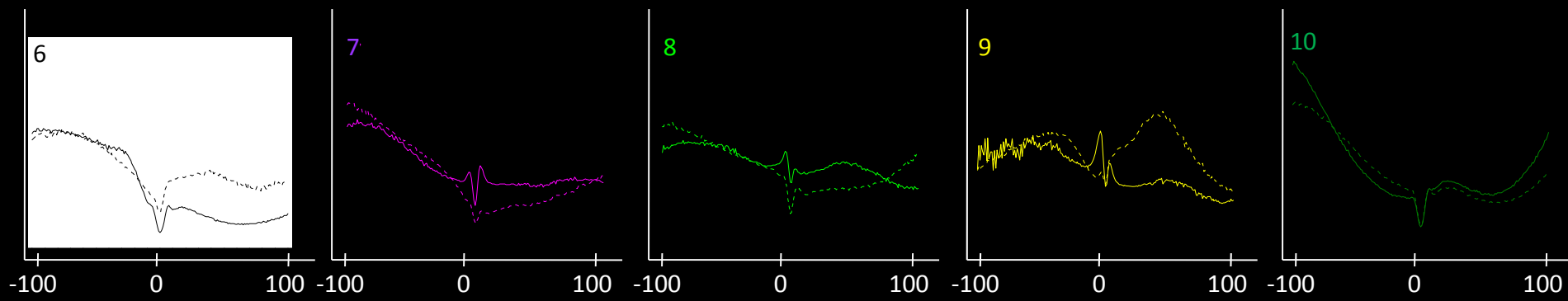
Spectroscopy Before & After Reconstruction

Before

After



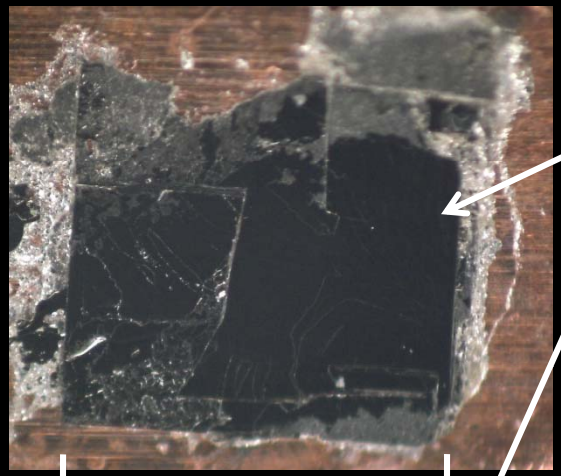




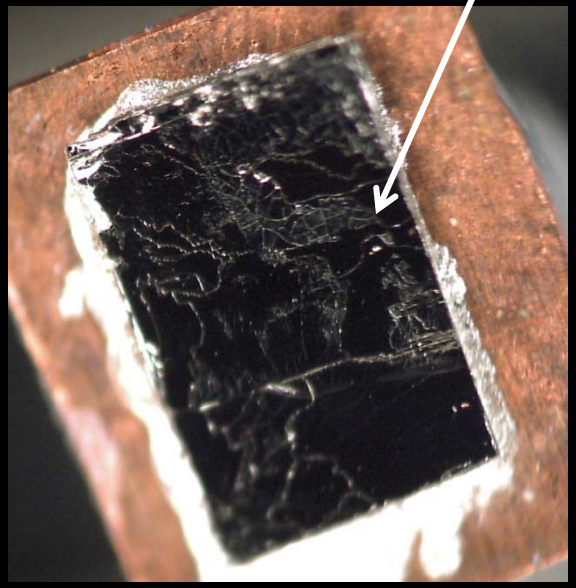
Note: this is an example from a superconducting $Sr_{1-x}K_xFe_2As_2$ sample

Optical Photos of Cleaved Samples

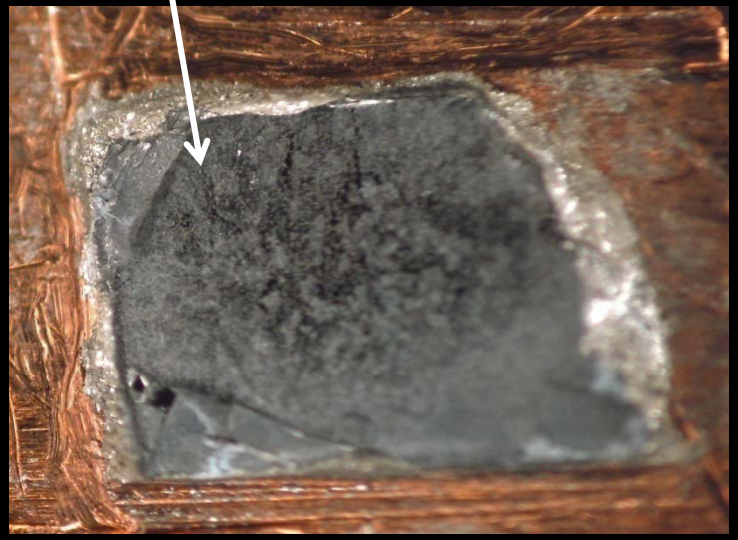
(all cleaved at T~25K in cryogenic UHV)



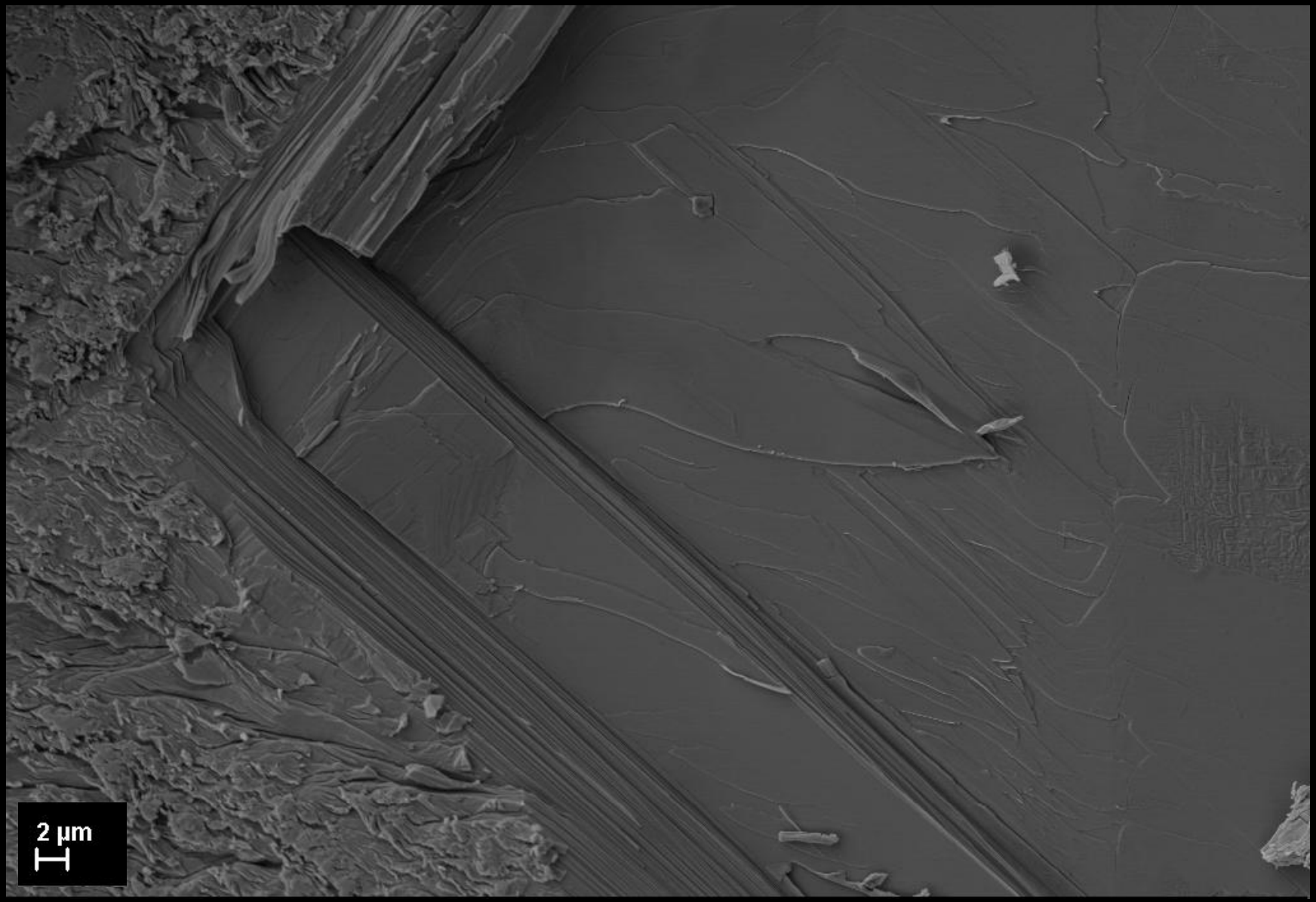
shiny cleaves



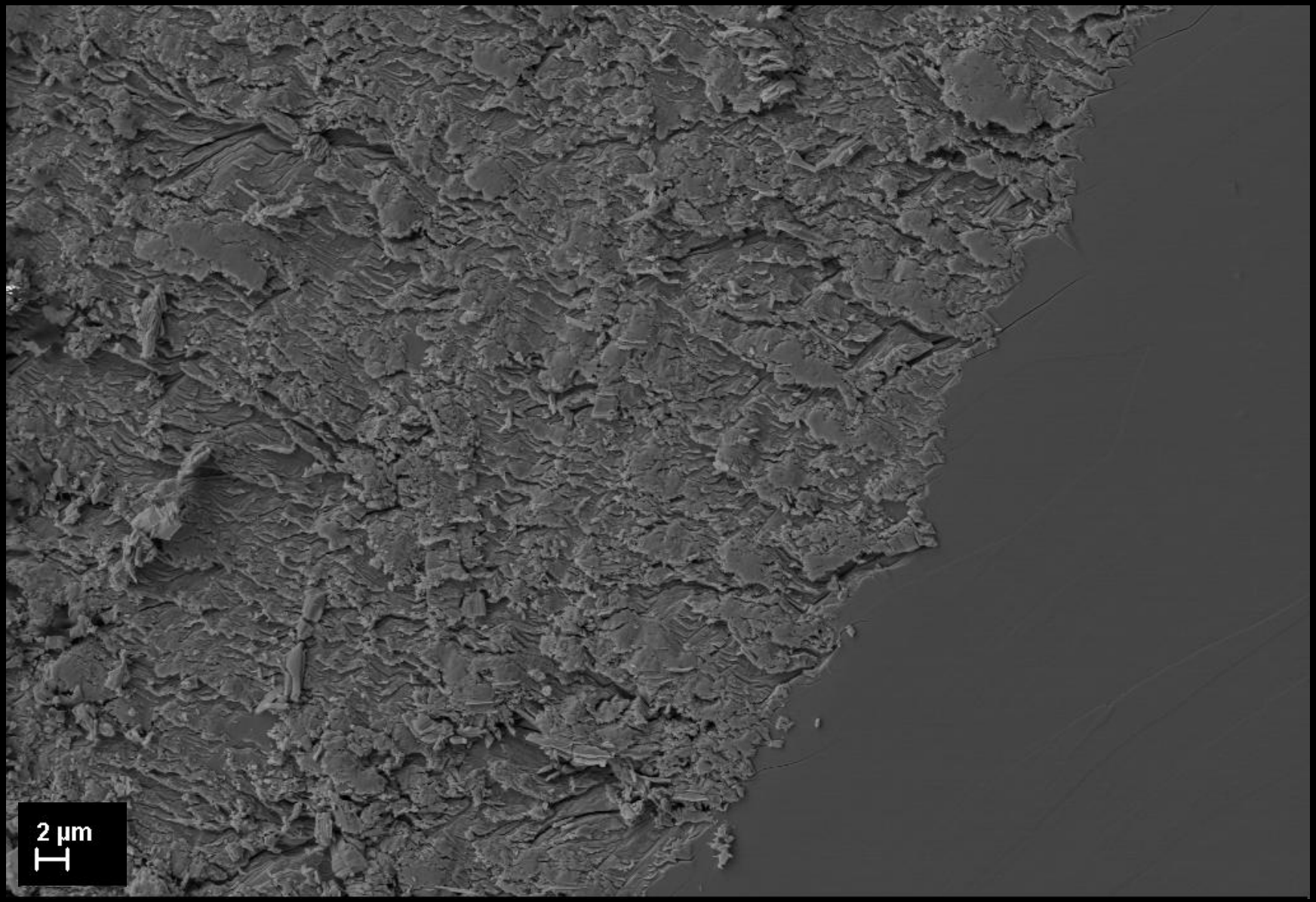
dull cleave



SEM: Boundary of a nice cleave

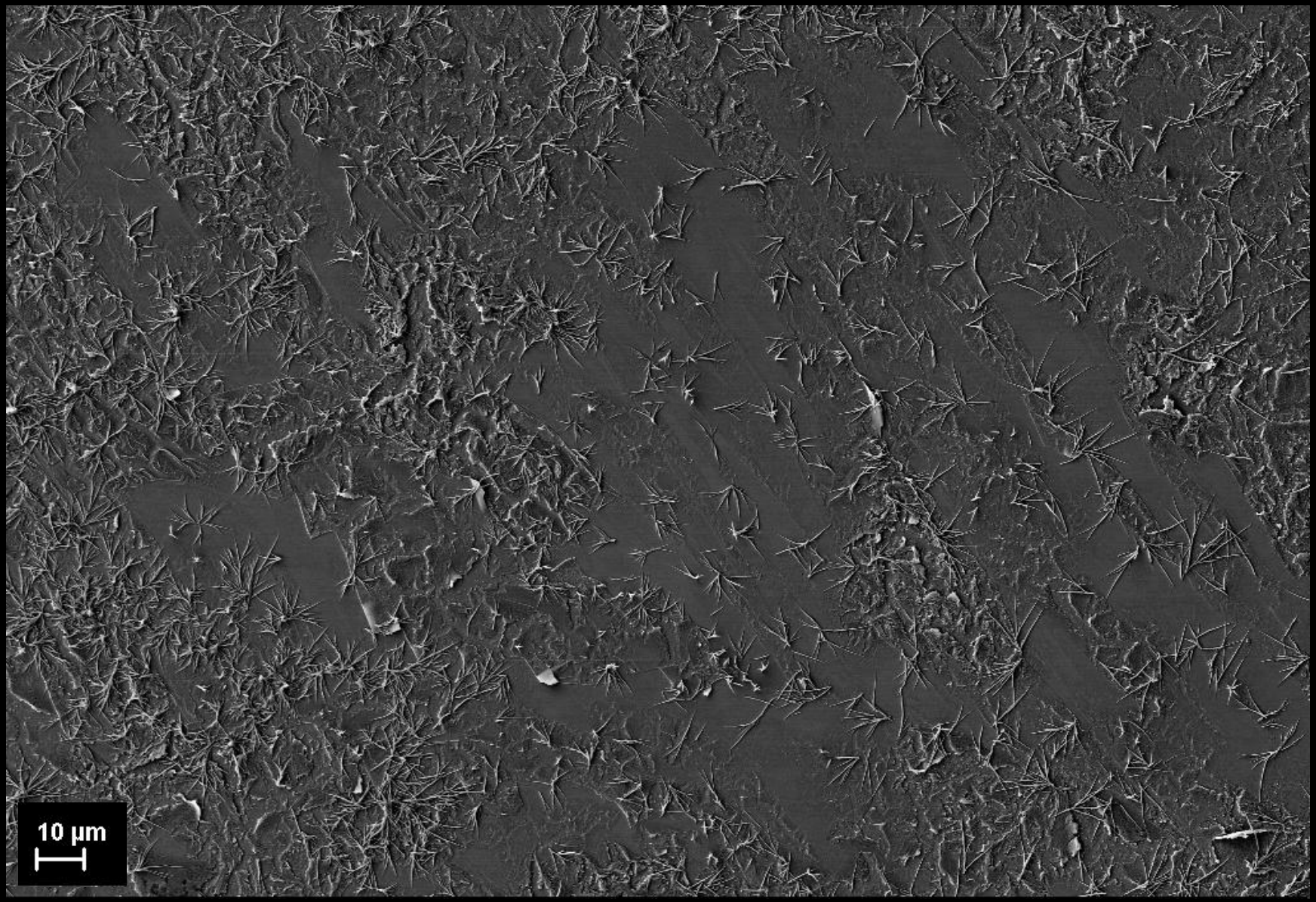


SEM: Boundary of a nice cleave

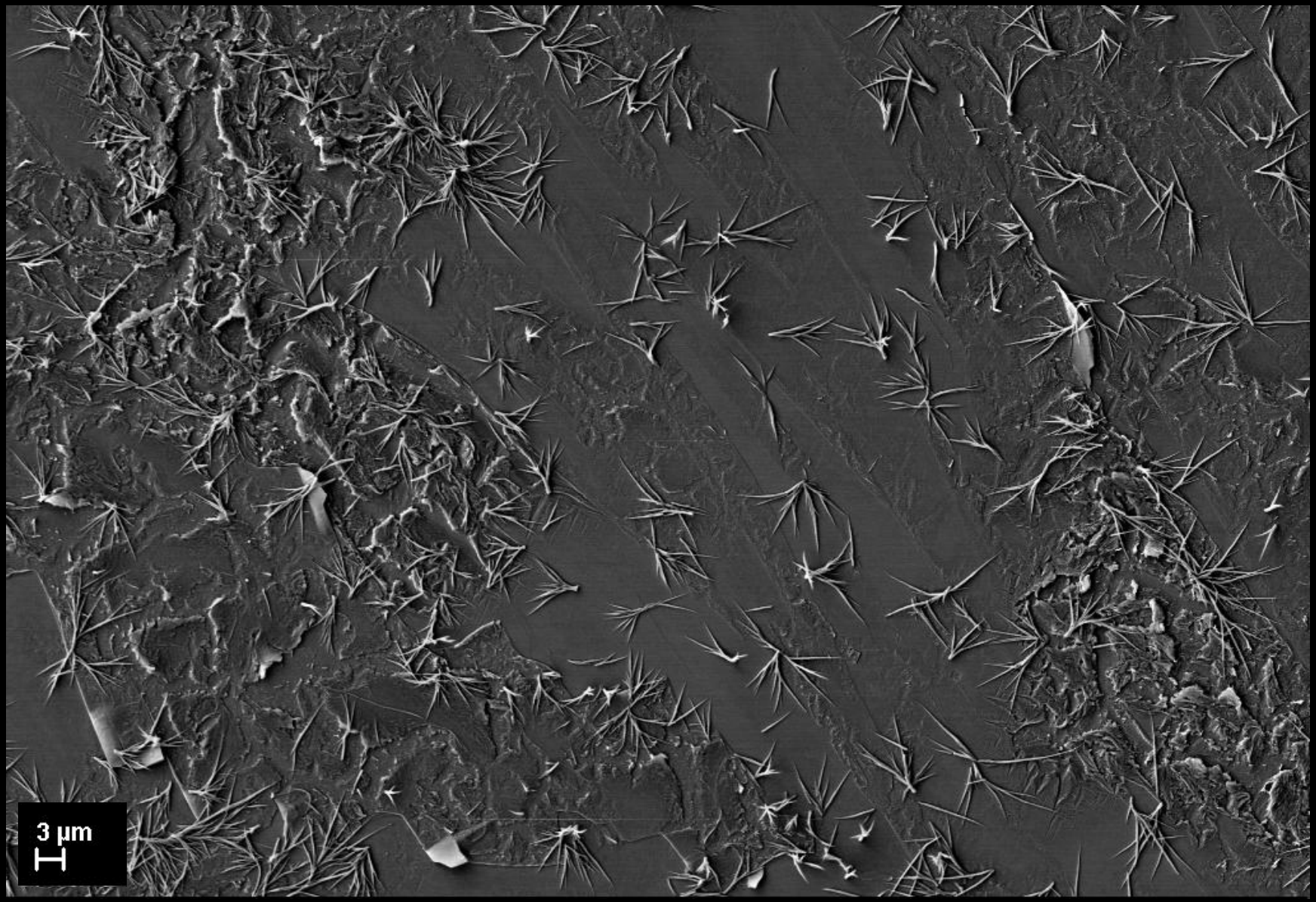


SEM: Beautiful flat cleave

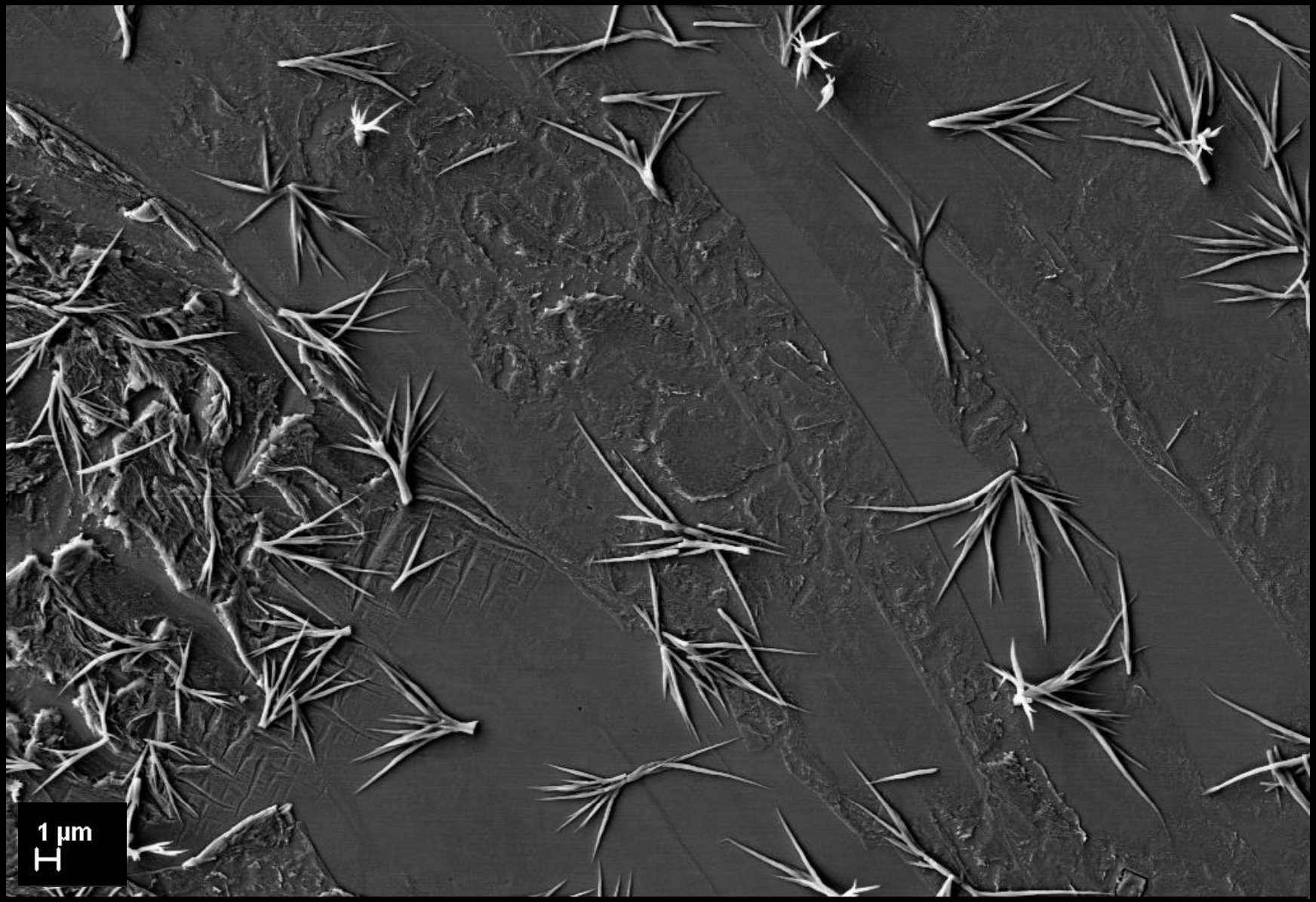
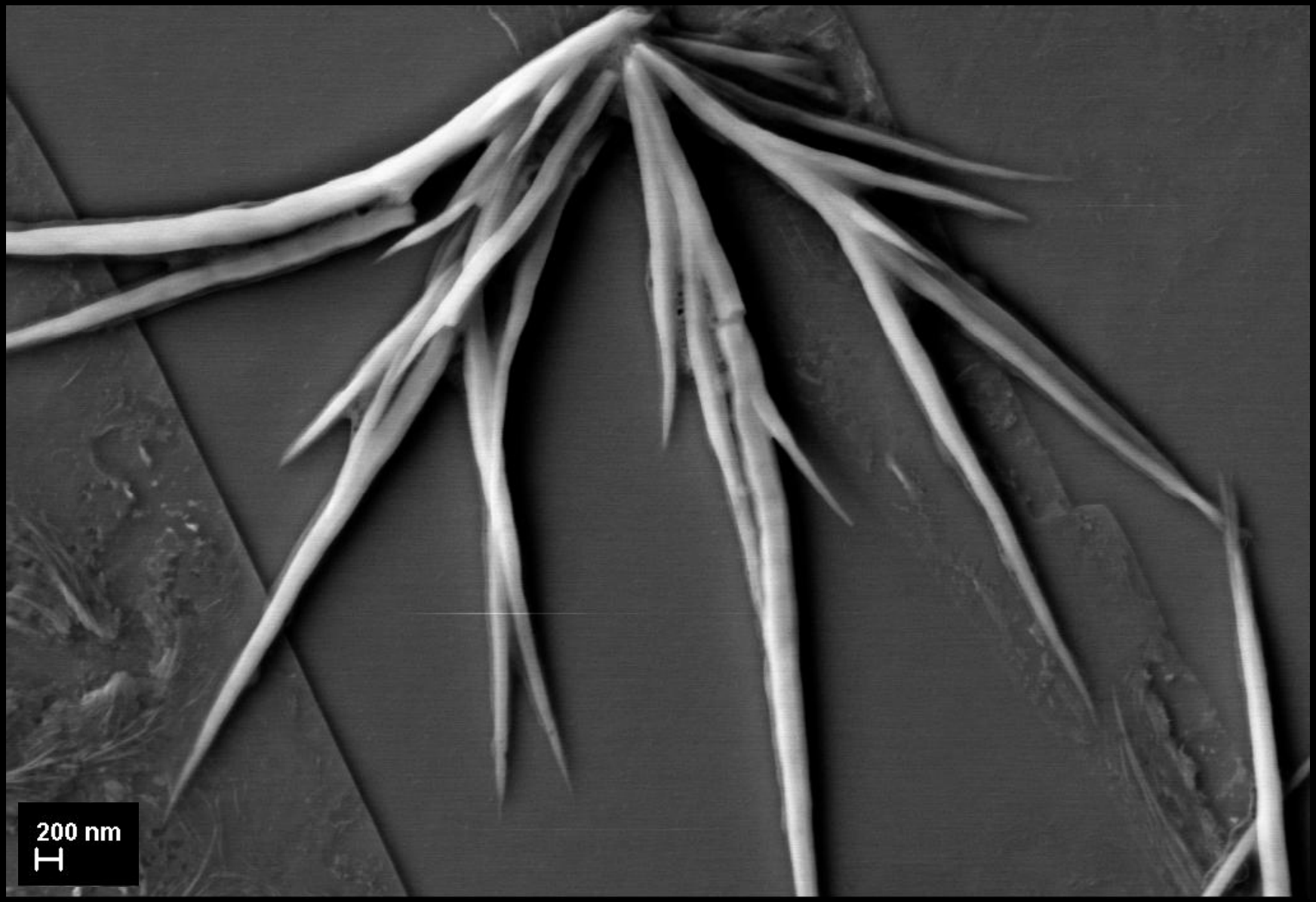
Weird Surface Stuff



Weird Surface Stuff



Weird Surface Stuff



Weird Surface Stuff