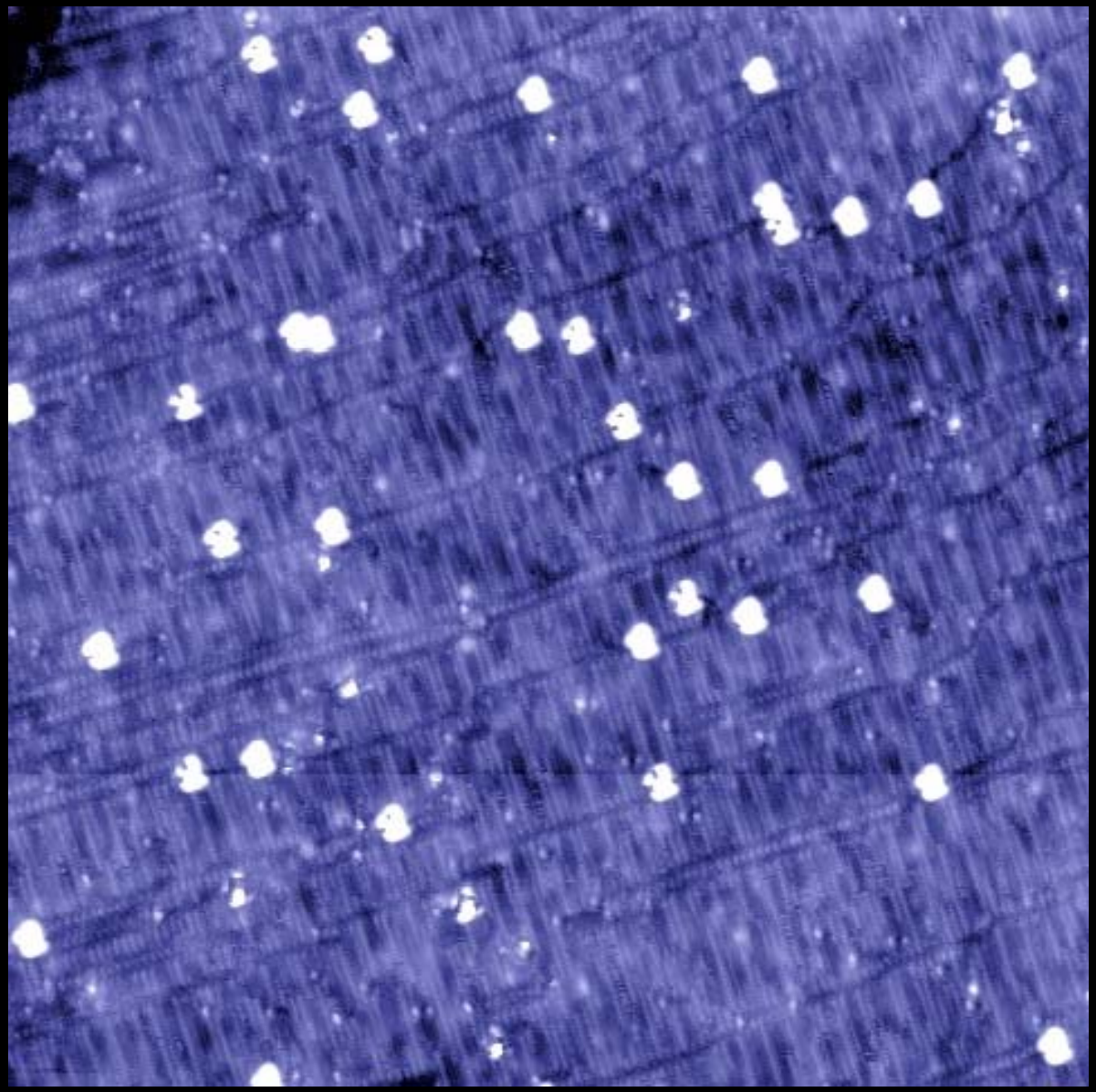
Imaging the New Iron-Arsenic High-T_c Superconductors



Yi Yin

Martin Zech

Tess Williams

XiangFeng Wang

Gang Wu

Xianhui Chen

Jenny Hoffman

Thanks to:

Outline

Superconductors: Brief History

Iron Pnictides: Revolution in Superconductivity!

→ What are the big outstanding questions?

→ Where do we stand in answering these questions?

STM applied to iron pnictides

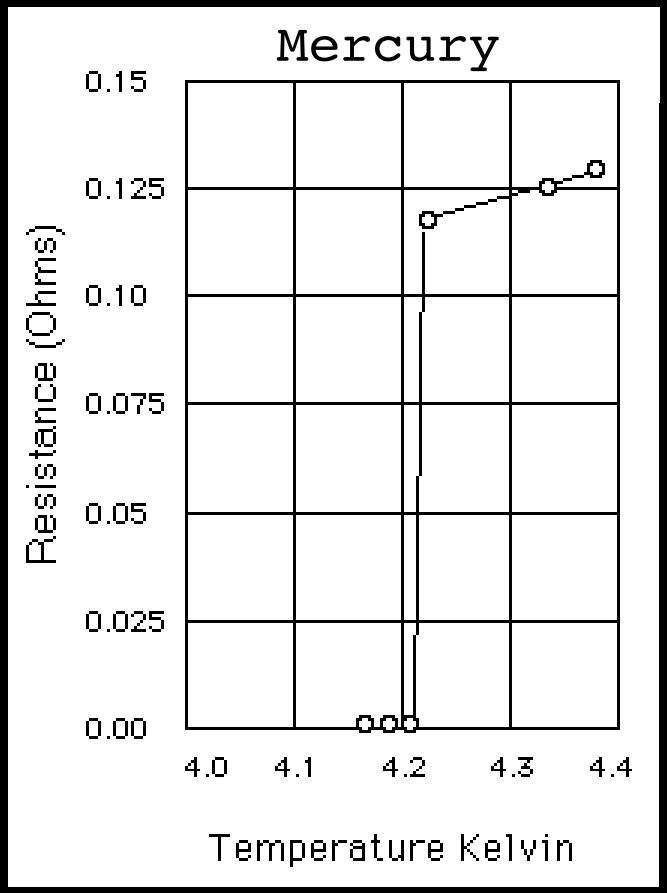
- surface considerations
- superconducting gap measurement
- vortex mapping

Direct comparison to cuprates

Outlook

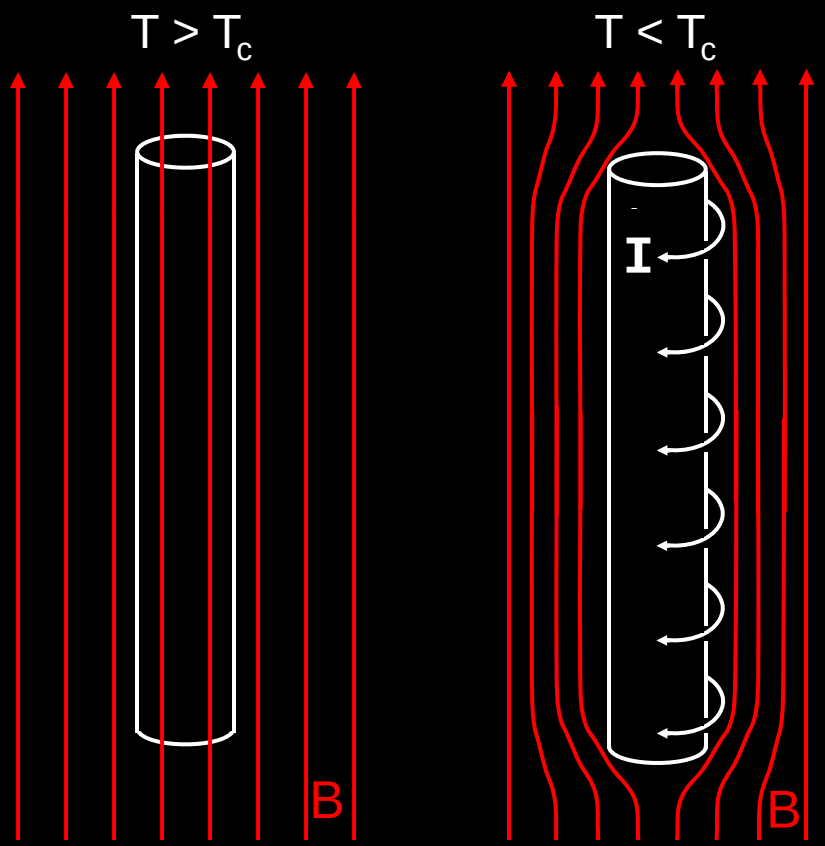
2 Properties of Superconductors

1. Vanishing of electrical resistivity (by Cooper pairing)



Kamerlingh-Onnes, 1911

2. Expulsion of magnetic field (by shielding currents)



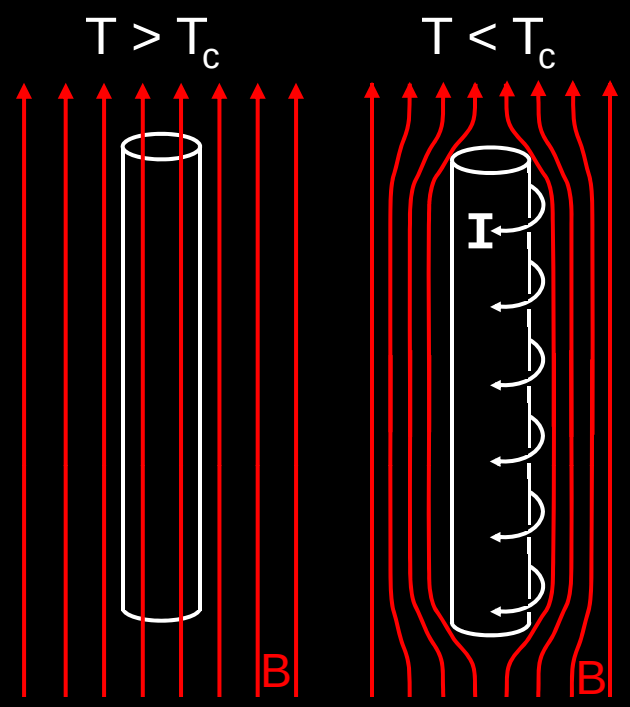
Meissner, 1933

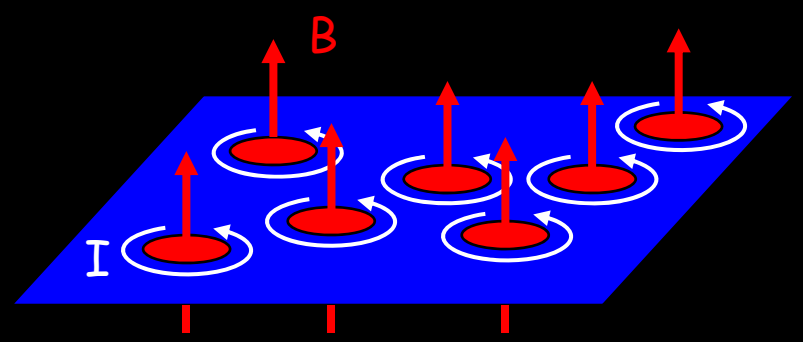
2 Types of Superconductors

Material	T_c (Kelvin)	H_c (Tesla)
Mercury	4.15	0.0411
Lead	7.2	0.0803
Niobium	9.2	0.1944
Aluminum	1.19	0.0099
Vanadium	5.3	0.1370
NbTi	10	15
$NbSn_3$	20	30

Type I: Meissner

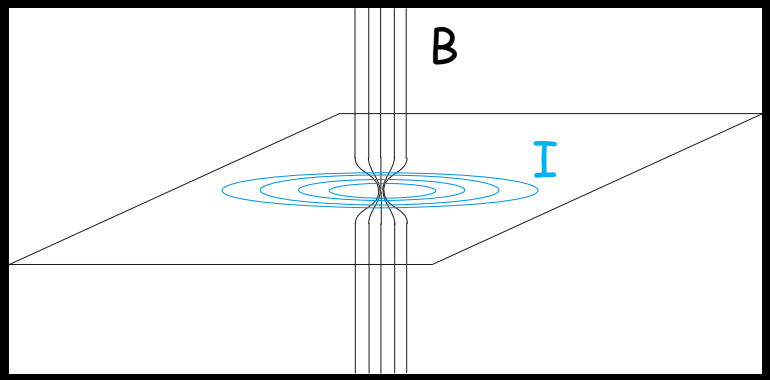
Type II: Vortices



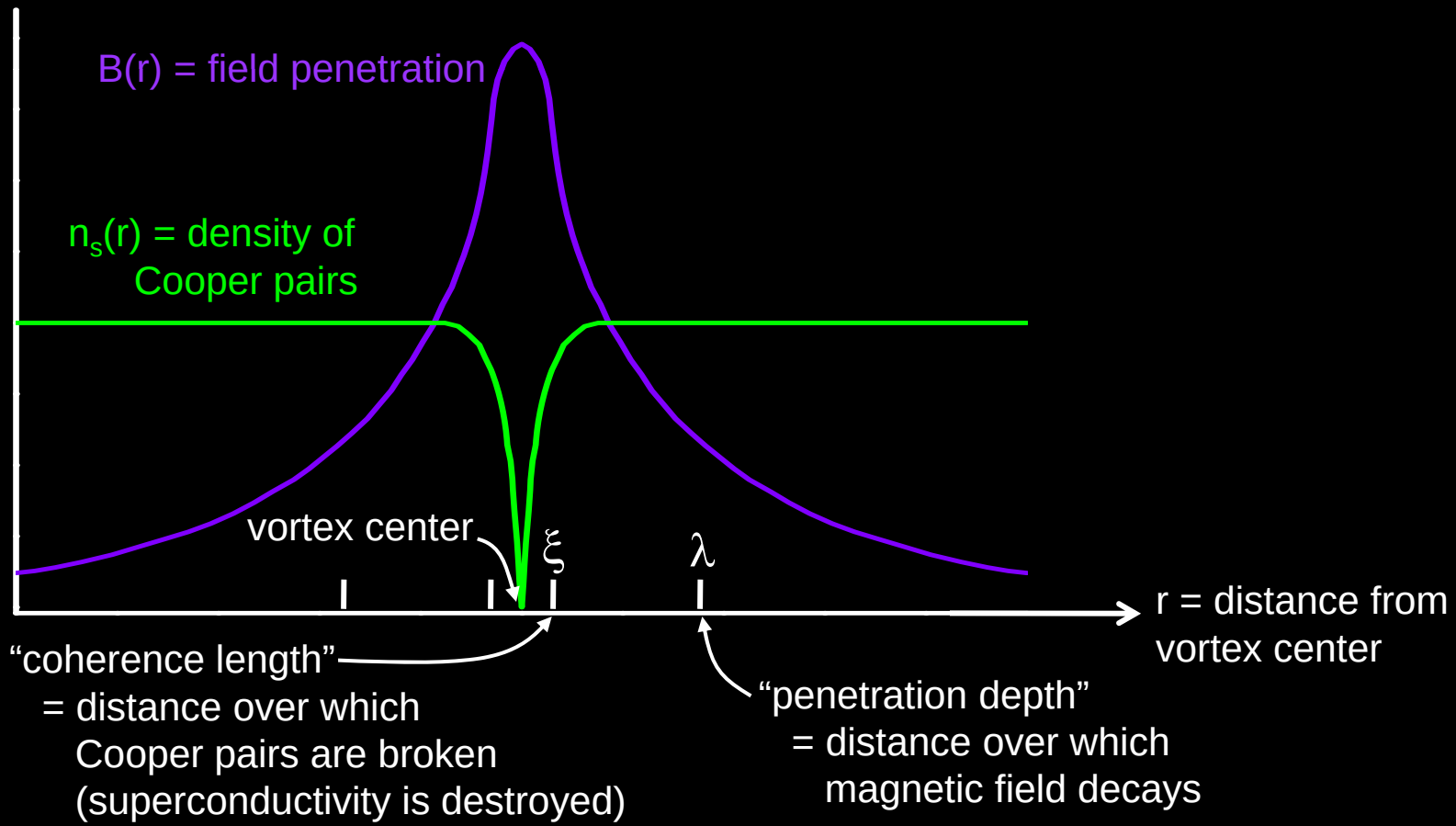


→ Type II Superconductors are generally more useful

Length Scales in Superconducting Vortices

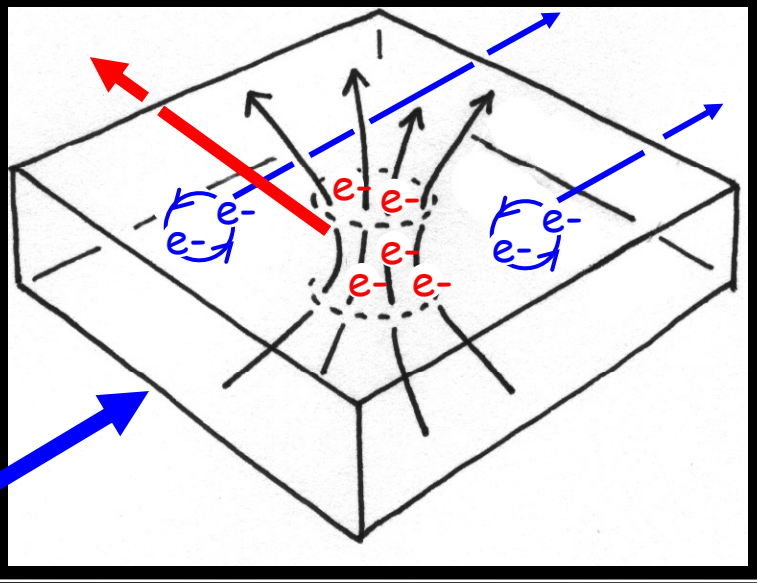


$\Phi = 2.07 \times 10^{-15}\ \mathrm{T \cdot m^2}$



Vortex Challenges

Normal electrons in vortex core cause dissipation when moved



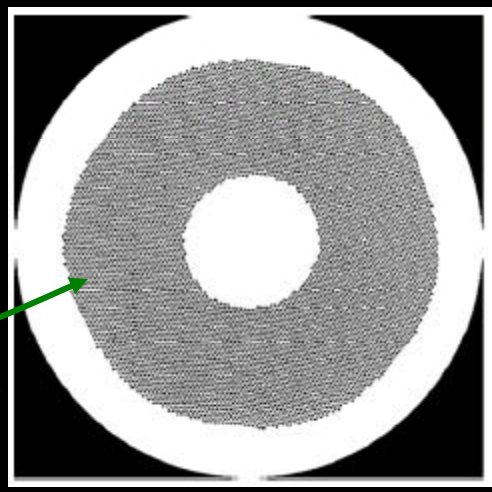
Apply current I: Cooper pairs flow without dissipation

→need some mechanism to *pin* vortices in place

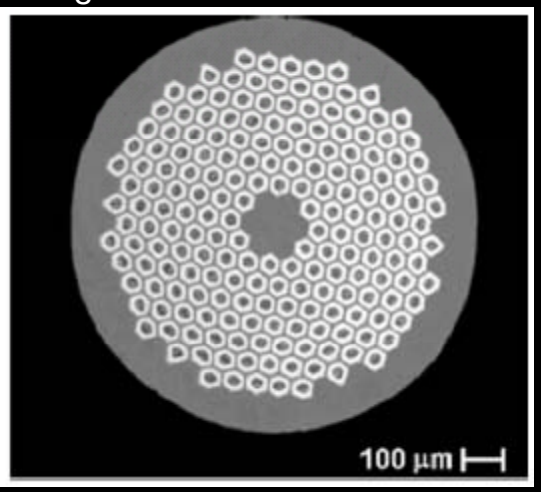
Center of vortex: superconductivity is destroyed → costs energy!

so introduce defects where superconductivity is already compromised → avoid paying energy cost twice!

Nb47wt%Ti



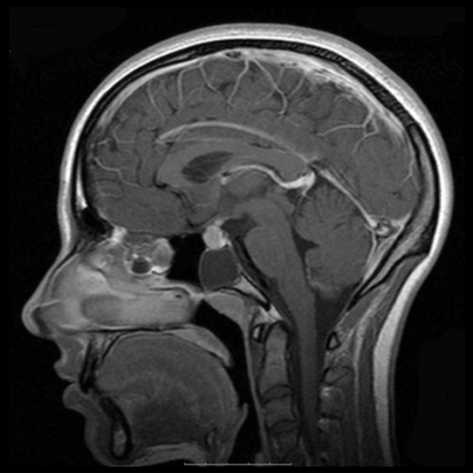
Nb_3Sn



review: Scanlan, IEEE 92, 1639 (2004)

Applications of Superconductors

Magnetic Resonance Imaging (MRI)



Large Hadron Collider (LHC) particle physics research: need large magnets to accelerate protons in 4.3-km ring

A Long History of Superconductivity

1911 – Kamerlingh Onnes – first superconductivity in Hg → 1913 Nobel Prize

1933 – Meissner – superconductors screen B-field

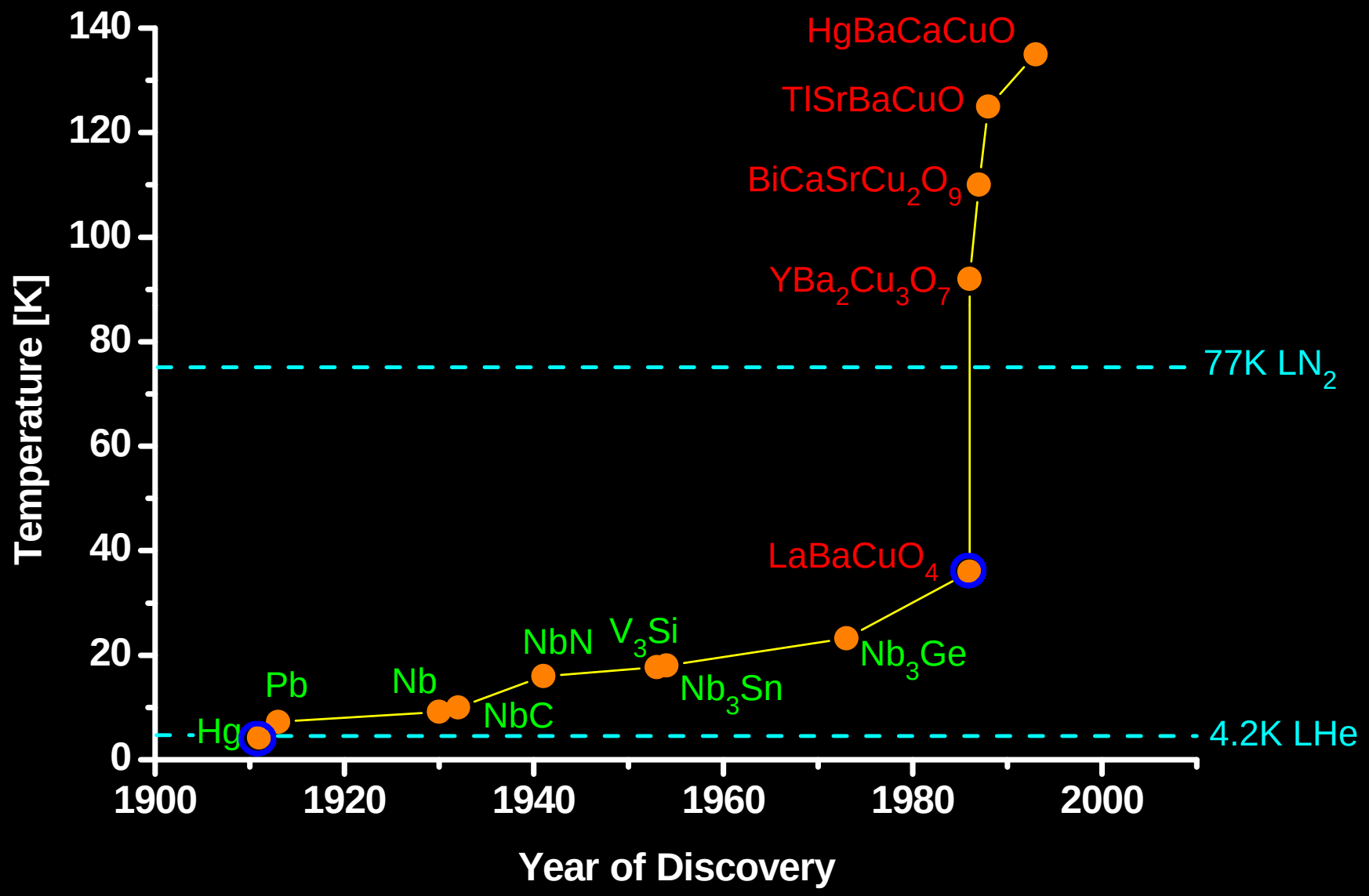
1952 – Abrikosov – predicted vortices → 2003 Nobel Prize

1957 – Cooper, Bardeen & Schriefer – theoretical understanding → 1972 Nobel Prize

1962 – Josephson – field-dependent tunneling (SQUIDS) → 1973 Nobel Prize

Still not so many practical applications…

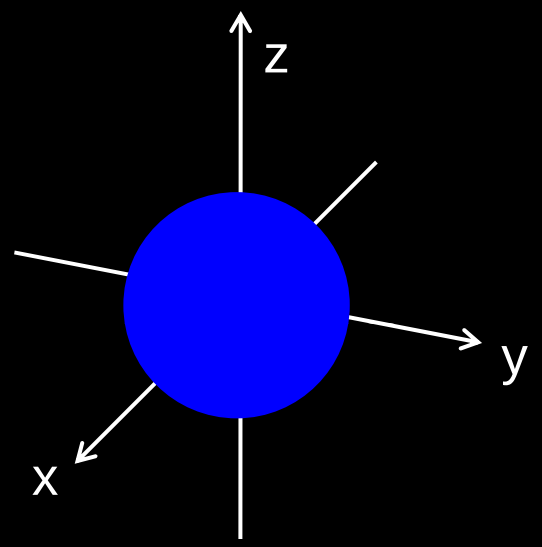
History of Superconducting T_c

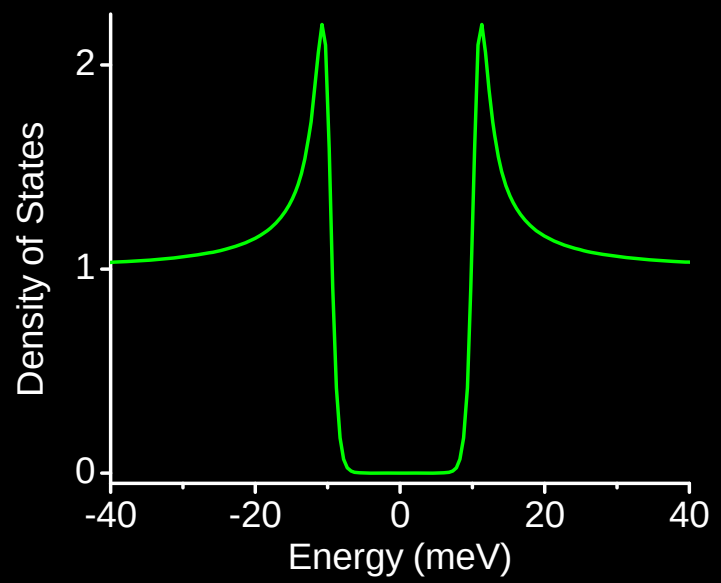


Pairing Symmetry

Conventional Superconductors

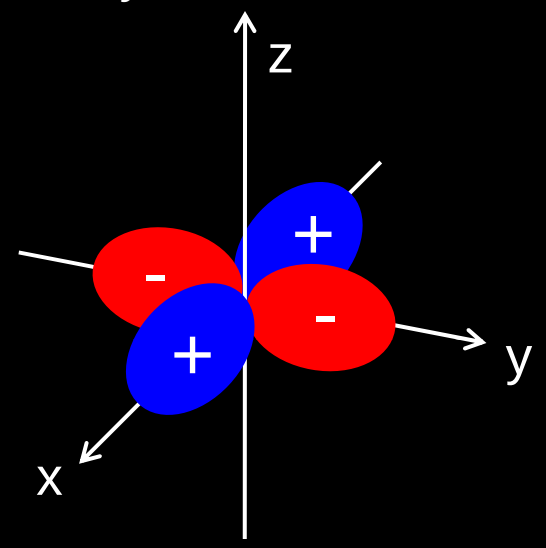
s wave pairing

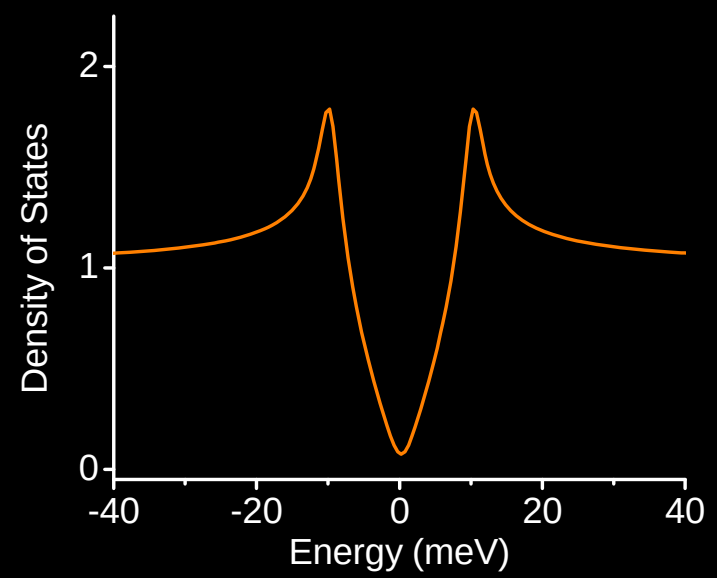




Cuprate Superconductors

$d_{x^2-y^2}$ wave pairing

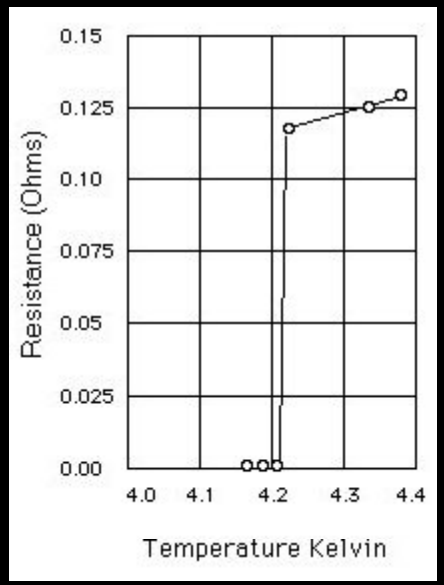




‘Normal’ State

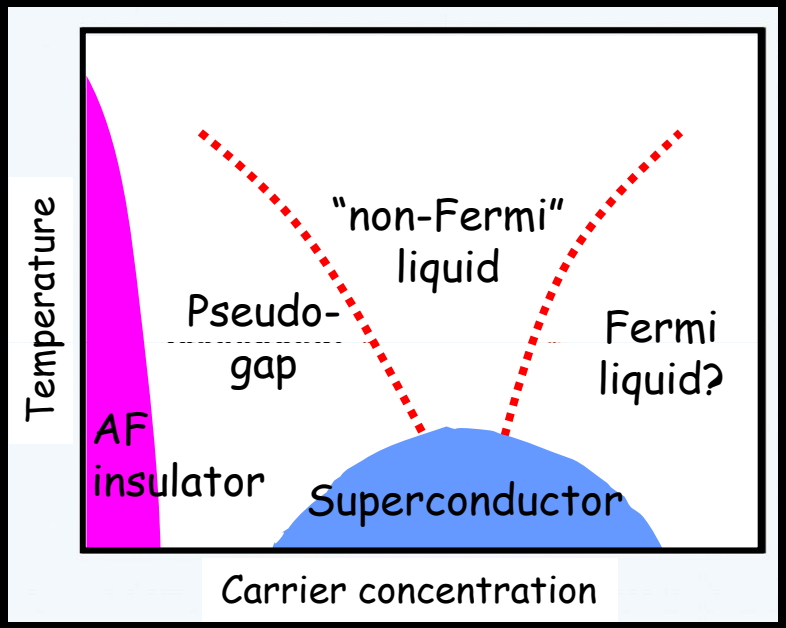
Conventional Superconductors

Normal state: metallic; Fermi liquid



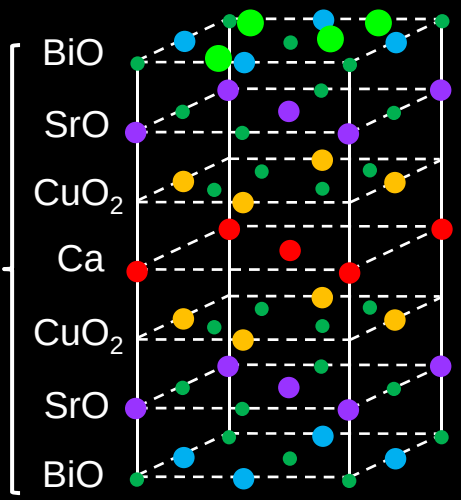
Cuprate Superconductors

Doped antiferromagnetic insulator



e.g.

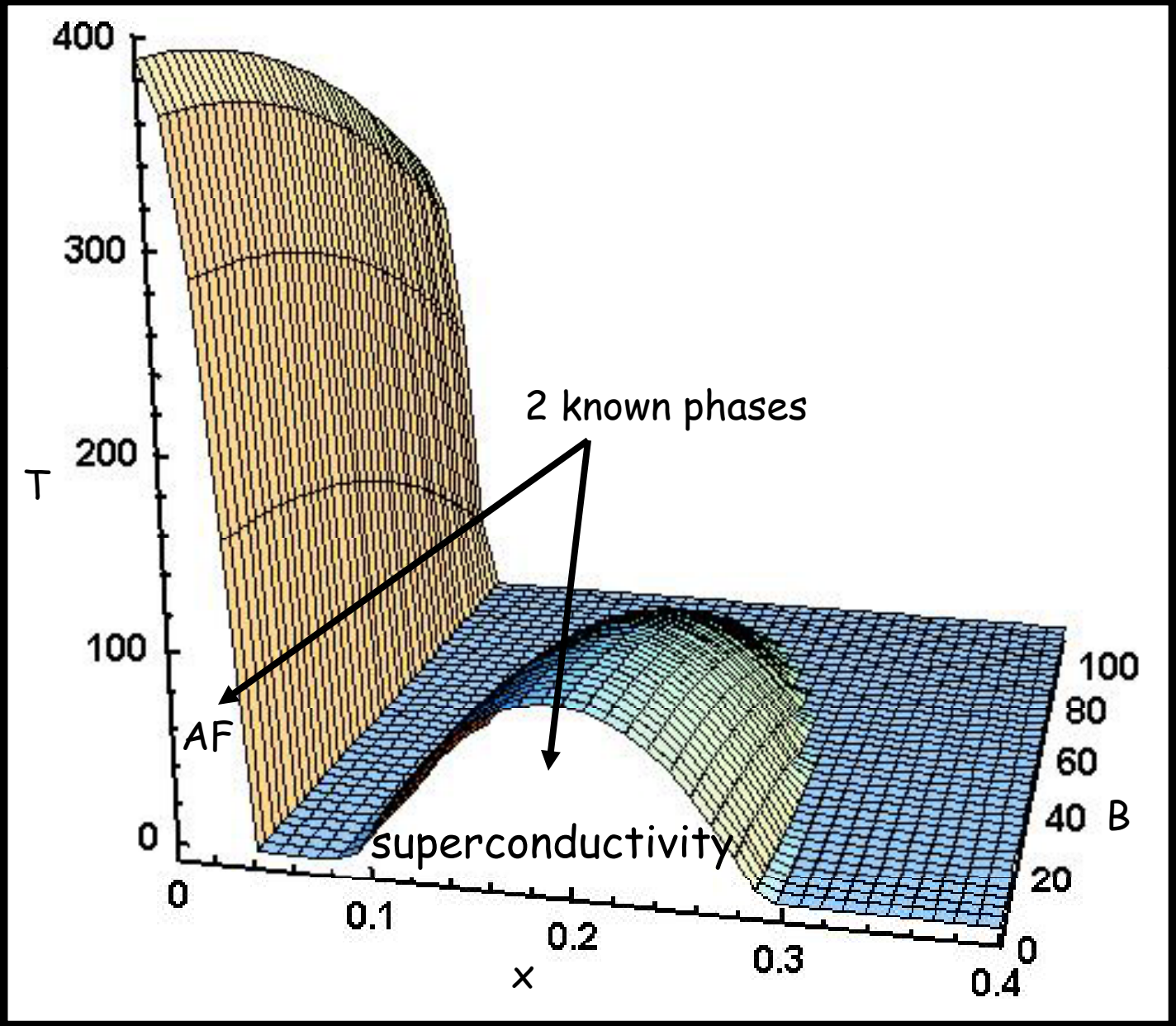
$Bi_2Sr_2CaCu_2O_8$



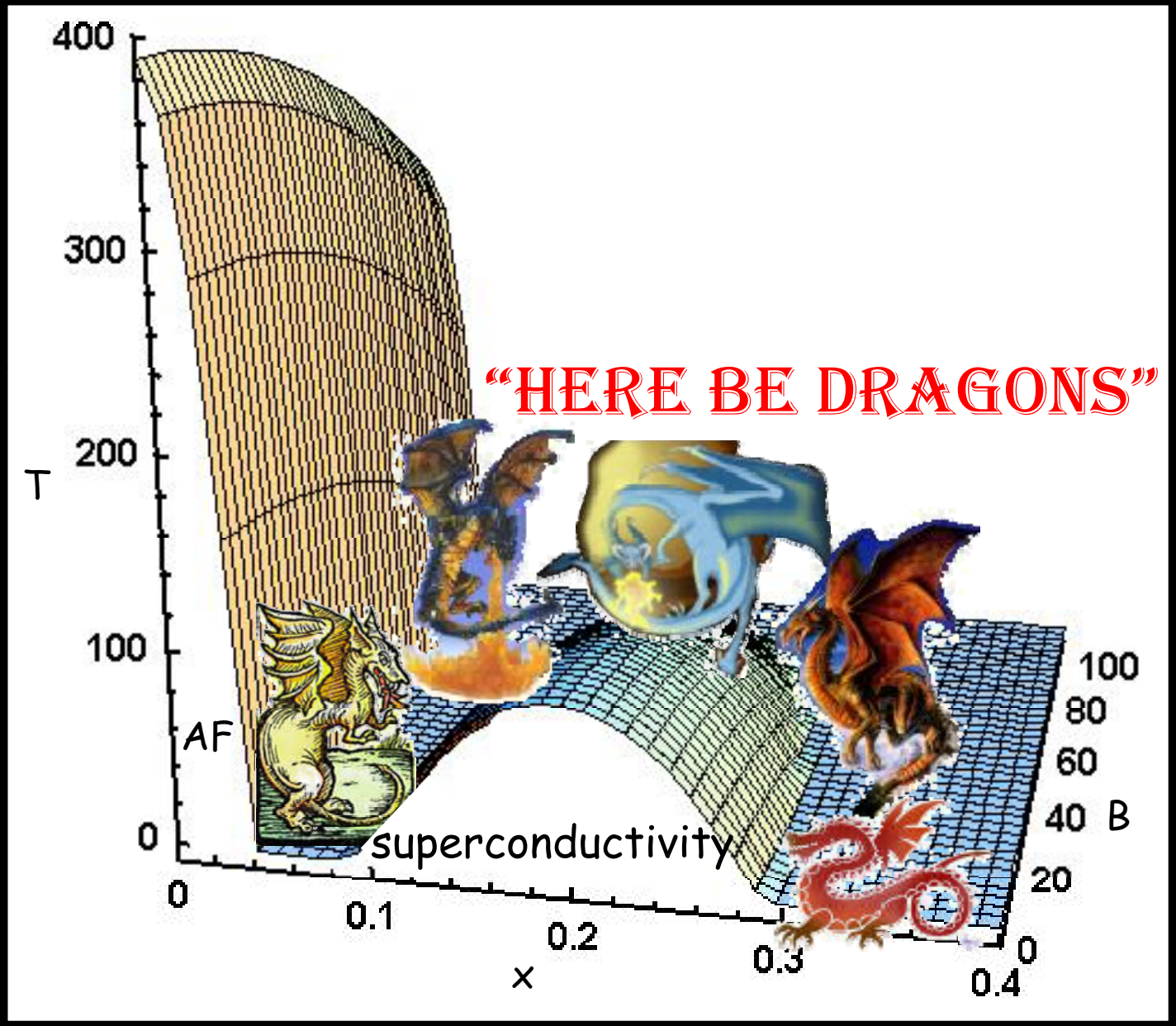
oxygen

(each Oxygen is thought to donate 2 holes)

3-Dimensional Cuprate Phase Diagram

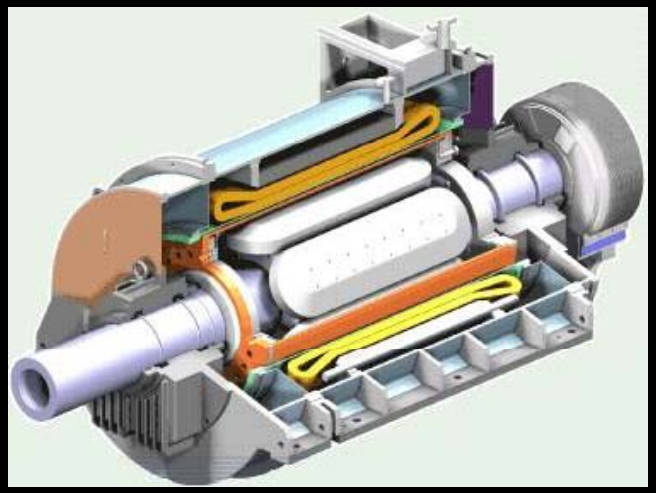


Too Much Phase Space



Applications of Cuprate Superconductors

Maglev Trains:
currently in operation at
Shanghai Pudong Airport



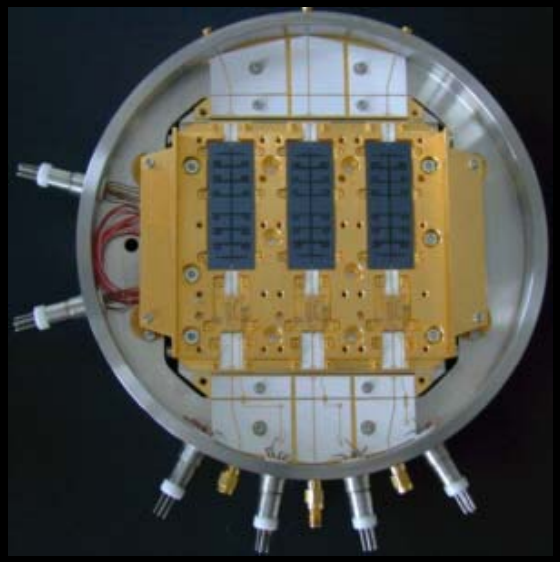
American Superconductor:
more efficient motors & generators
e.g. this 5 MegaWatt motor is
~30% weight, 50% size
of conventional motor
→ *great* for ships, airplanes!

Applications of Cuprate Superconductors

American Superconductor:
cooled cables for power transmission

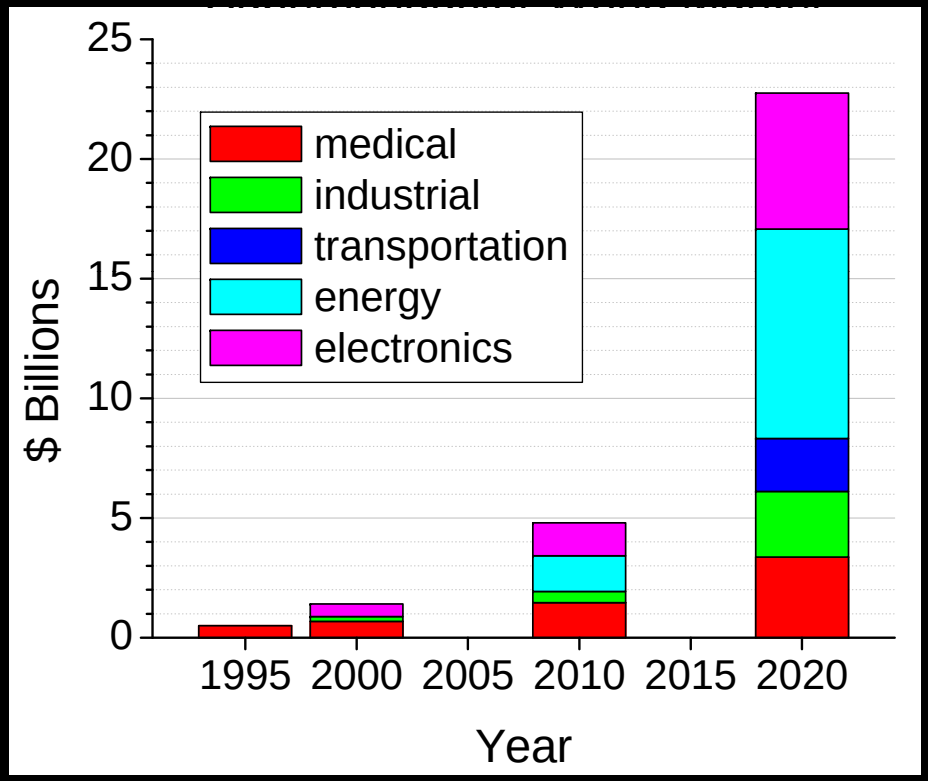
Filters in cell phone relay stations
→ make better use of bandwidth
→ put relay stations farther apart
→ reduce signal strength (safer cell phones)

Superconductor Technologies



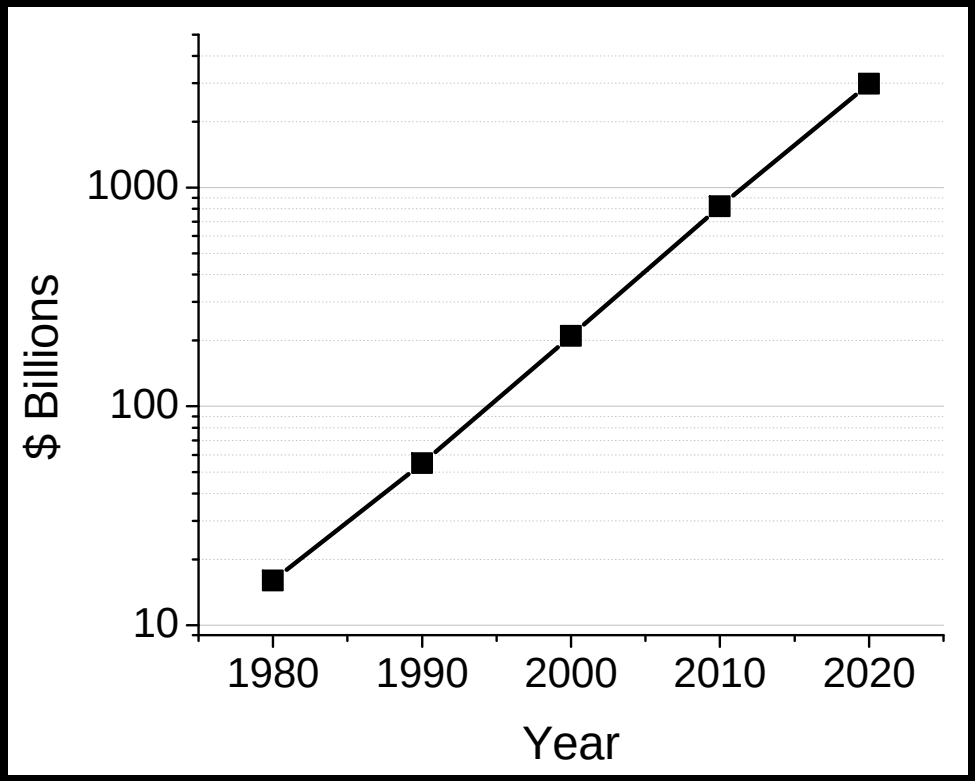
Projected World Markets

Superconductors:



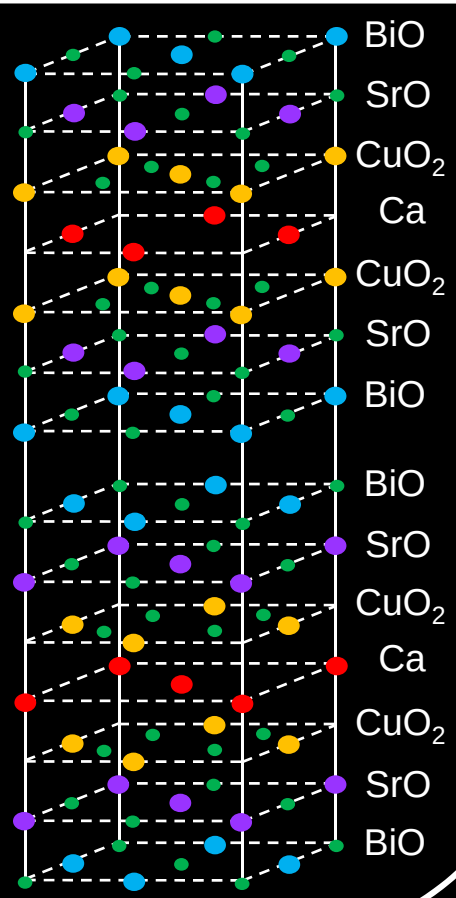
(Conectus, 2004)

Semiconductors:

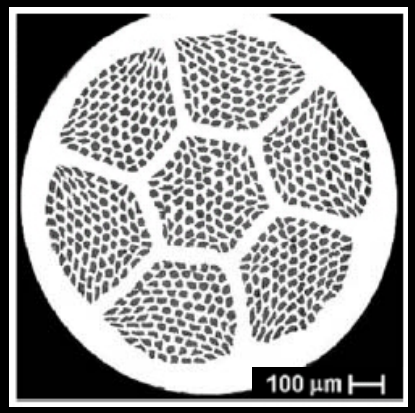


(Sakurai, 1999)

Material Considerations

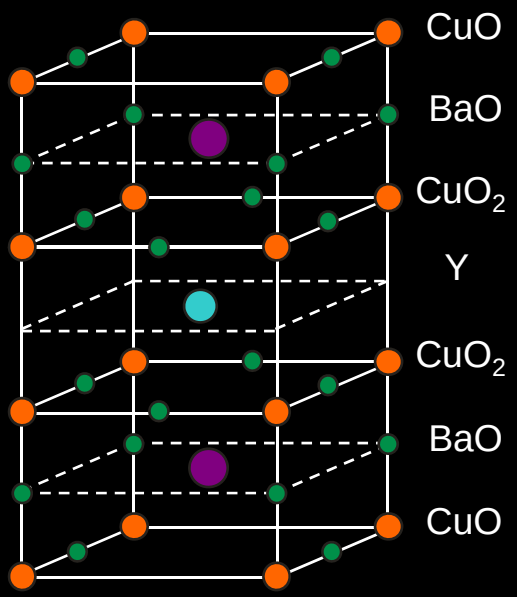


$Bi_2Sr_2CaCu_2O_{8+d}$/Ag wires



Problems:
- Ag matrix is expensive
- crystal grains poorly aligned
- poor conduction across grain boundaries
- anisotropy very high (~ 50 !)

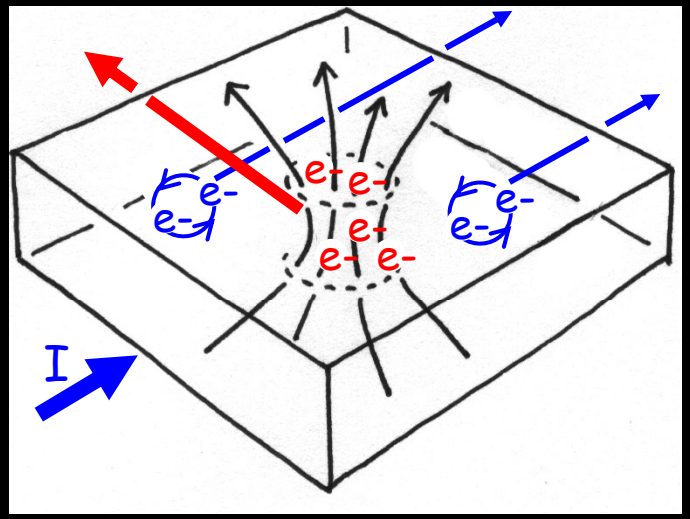
$YBa_2Cu_3O_{7-d}$ tapes

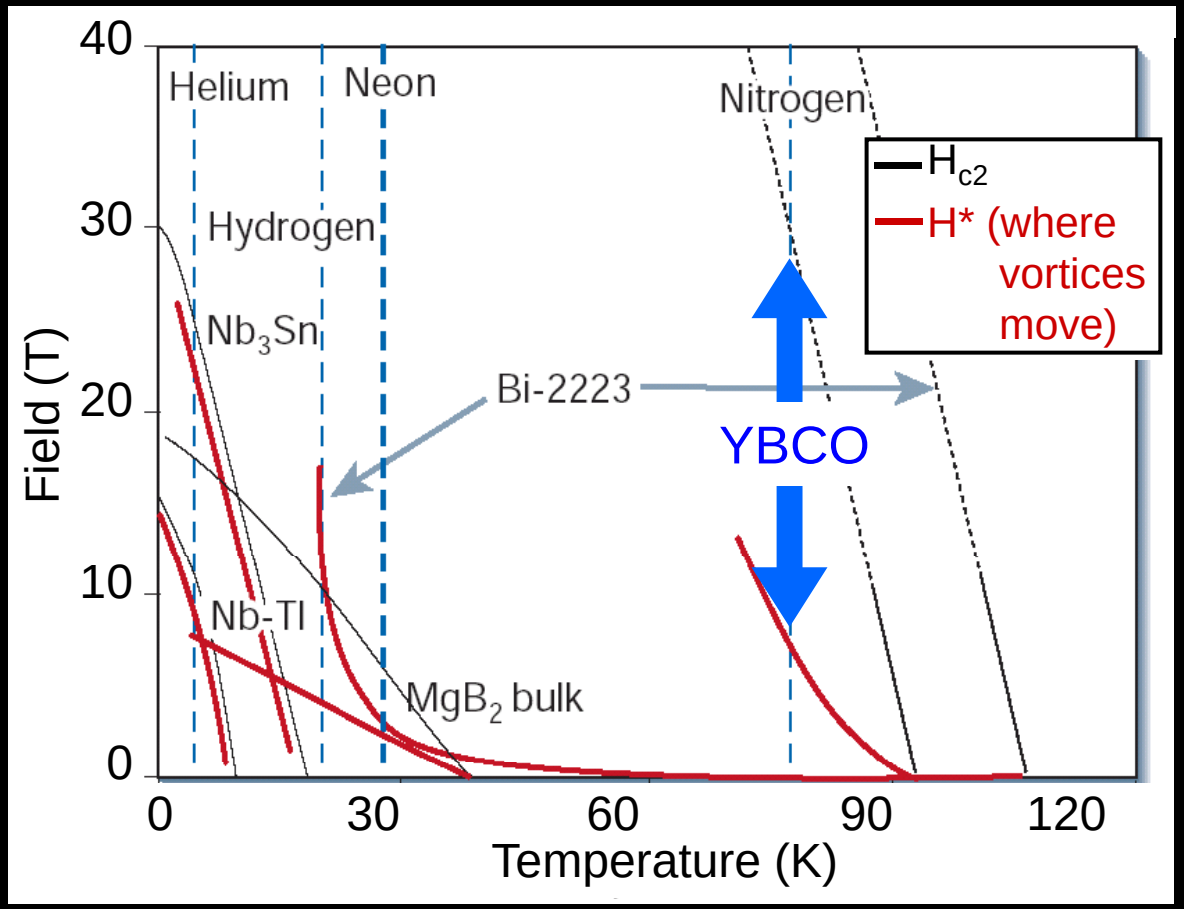


Advantages:
- cheaper materials
- tapes are aligned on 2 axes
  →cuts down on grain boundaries
- anisotropy is only ~7
- non-vacuum manufacture processes

review: Scanlan, IEEE 92, 1639 (2004)

Trouble With Vortices



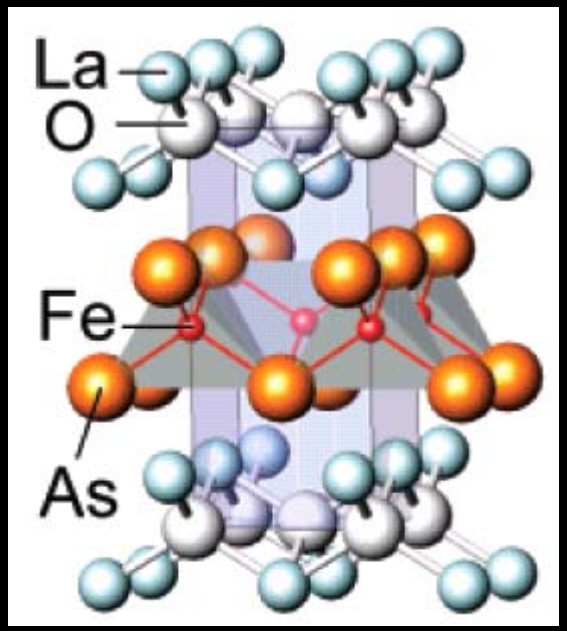


Larbalestier, Nature 414, 368 (2001)

2008: A New Revolution in Superconductivity

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

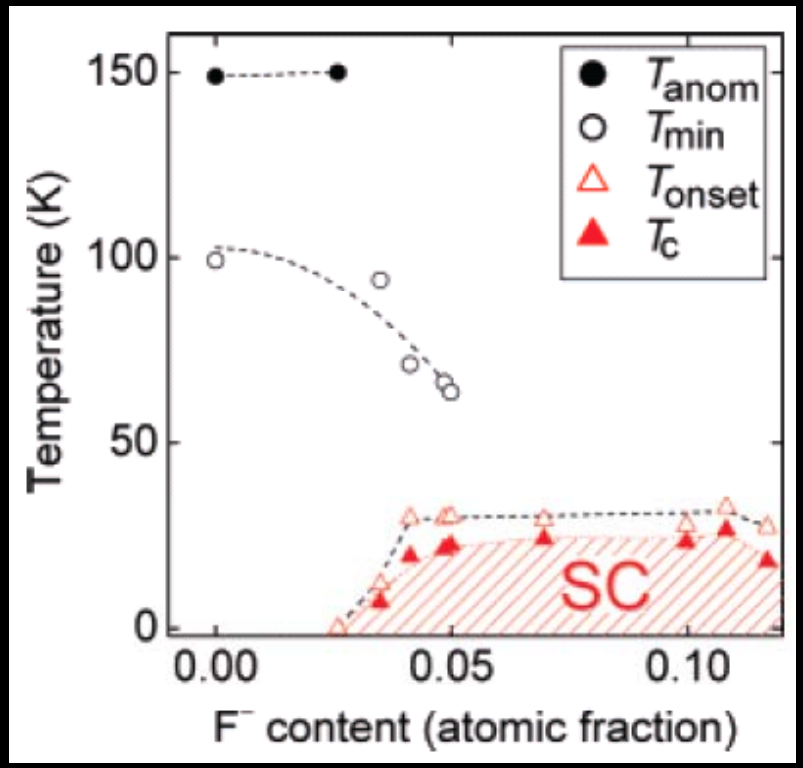
$LaFeAsO_{1-x}F_x$



insulating layer

conducting layer

T_c=26K

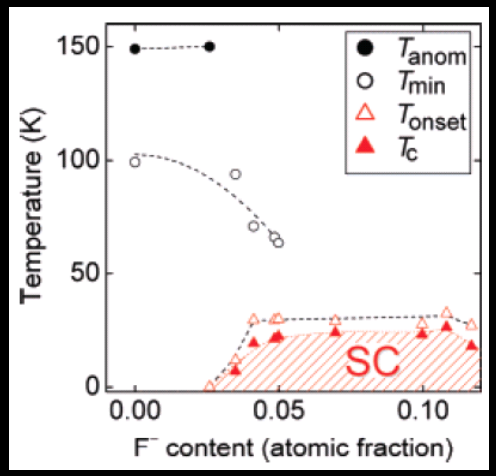


Why the excitement?

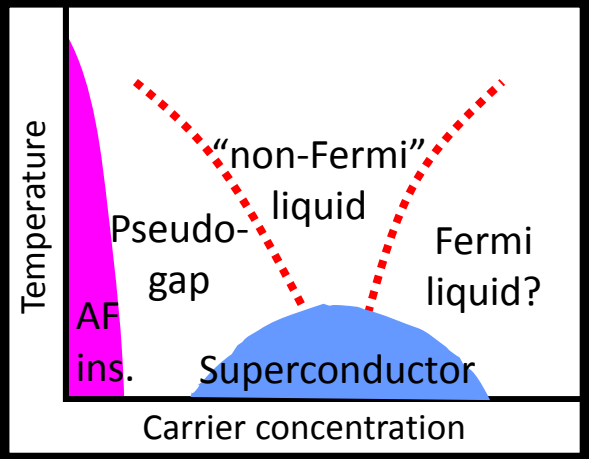
1) Physics
   - A second chance to get it right!
   - A foil for cuprates

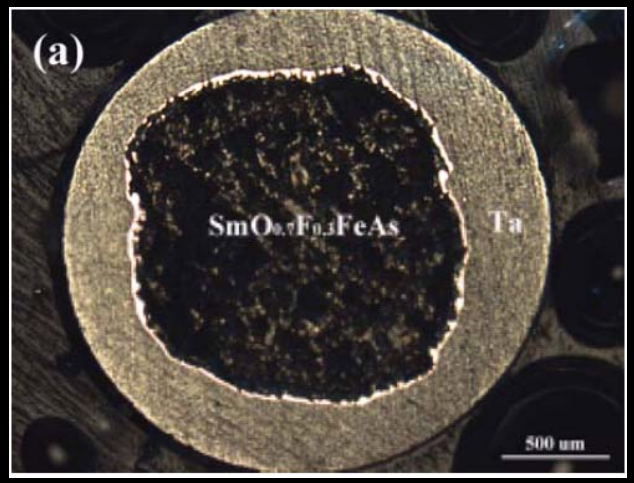
2) Applications
   - Low anisotropy
   - High H_{c2}
   - Strong pinning

$LaFeAsO_{1-x}F_x$



Cuprates



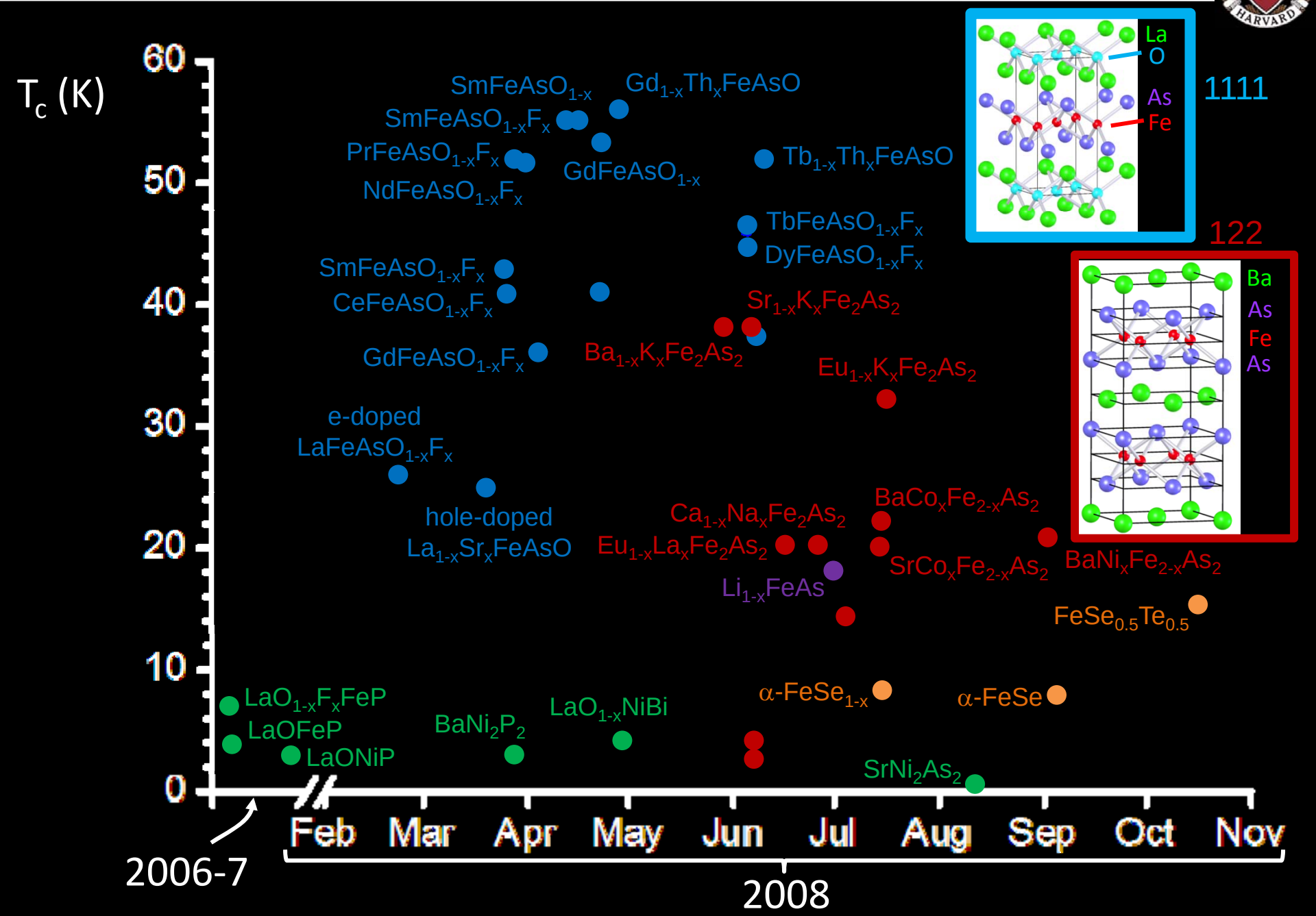


$SmO_{0.7}F_{0.3}FeAs$ wires fabricated by powder-in-tube method

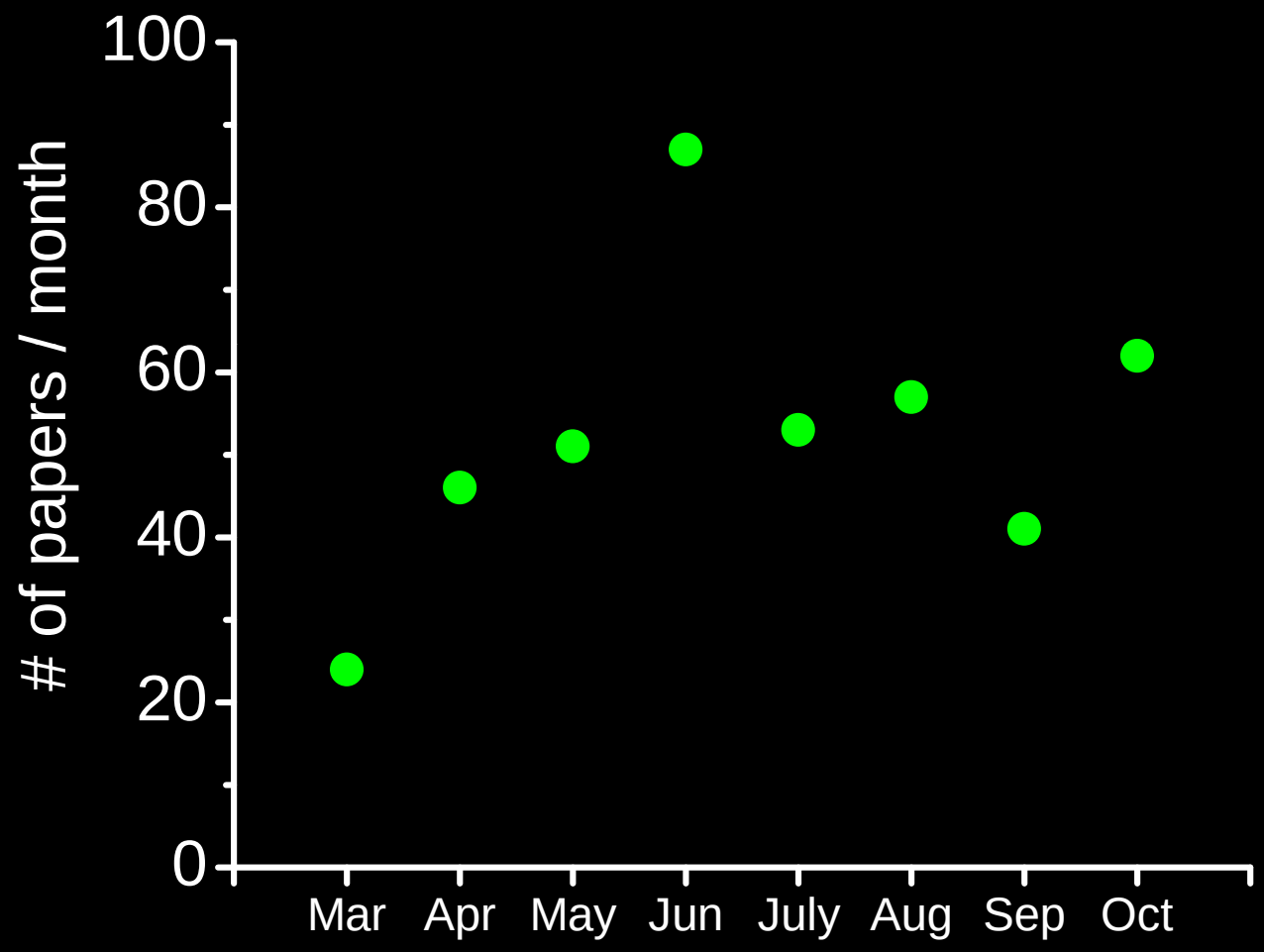
T_c=52K, J_c up to 3900 A/cm^2, extrapolated H_{c2} up to 120T
(J_c within grains ~ 2x10^5 A/cm^2)

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

A Short History of Iron-Pnictide Superconductivity



“Tsunami of Papers”



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?

(2) What is the role of spin?

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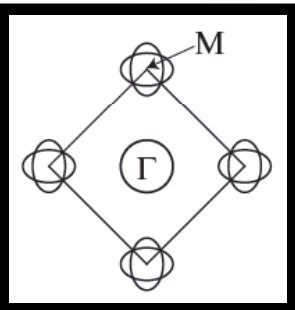
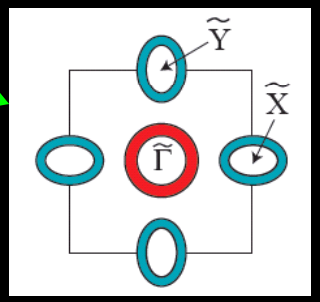
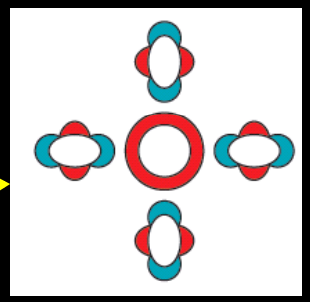
Theory: What is the pairing symmetry?



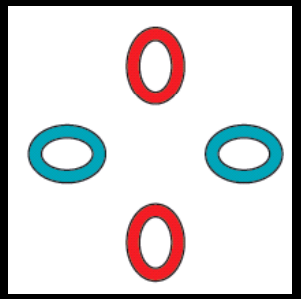
(1) nodeless extended s-wave (s±)
- Mazin, PRL 101, 057003 (2008)
- Wang, PRL 102, 047005 (2009)
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)



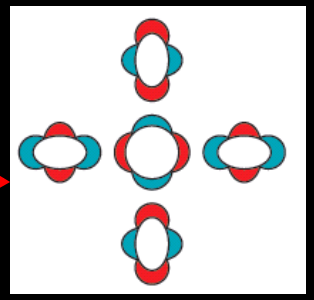
(2) nodal s-wave
- Kuroki, PRL 101, 087004 (2008)



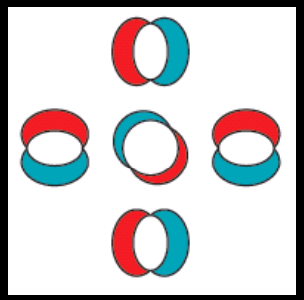
(3) nodeless d
- Kuroki, PRL 101, 087004 (2008)



(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)

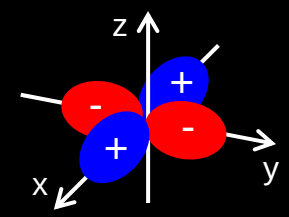


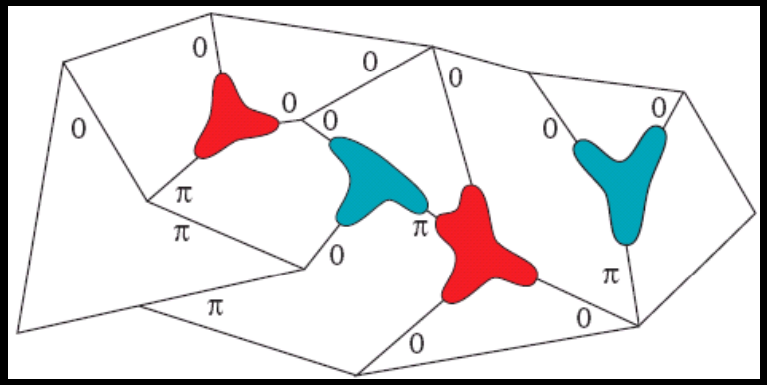
(6) interband p order
- Dai, PRL 101, 057008 (2008)

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

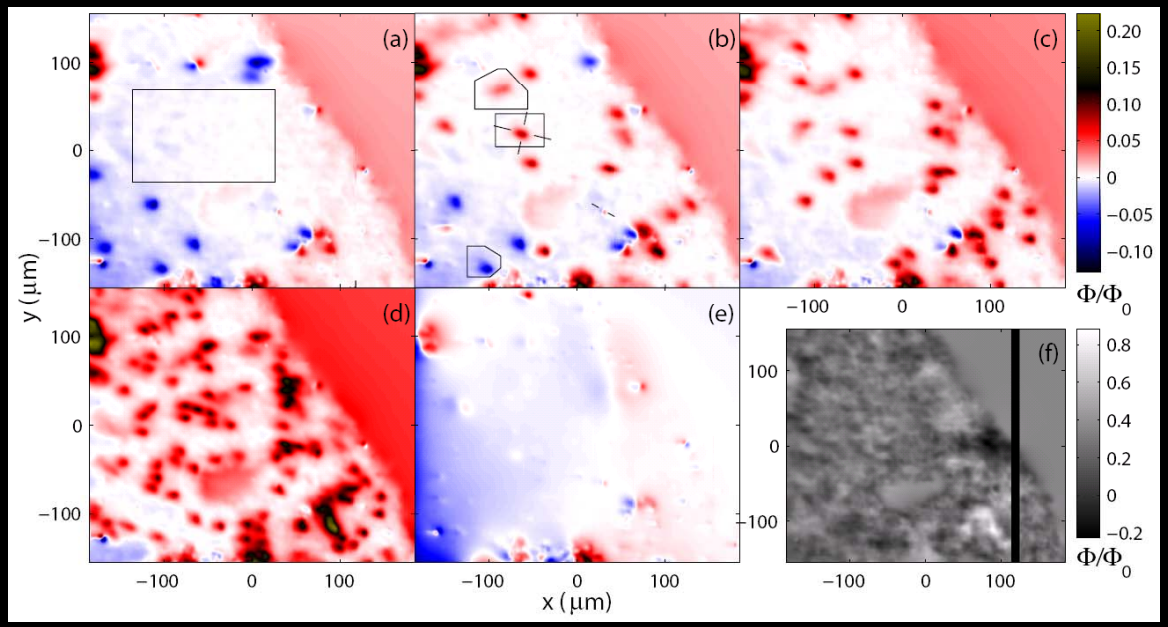
Scanning SQUID: what is the pairing symmetry?

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!



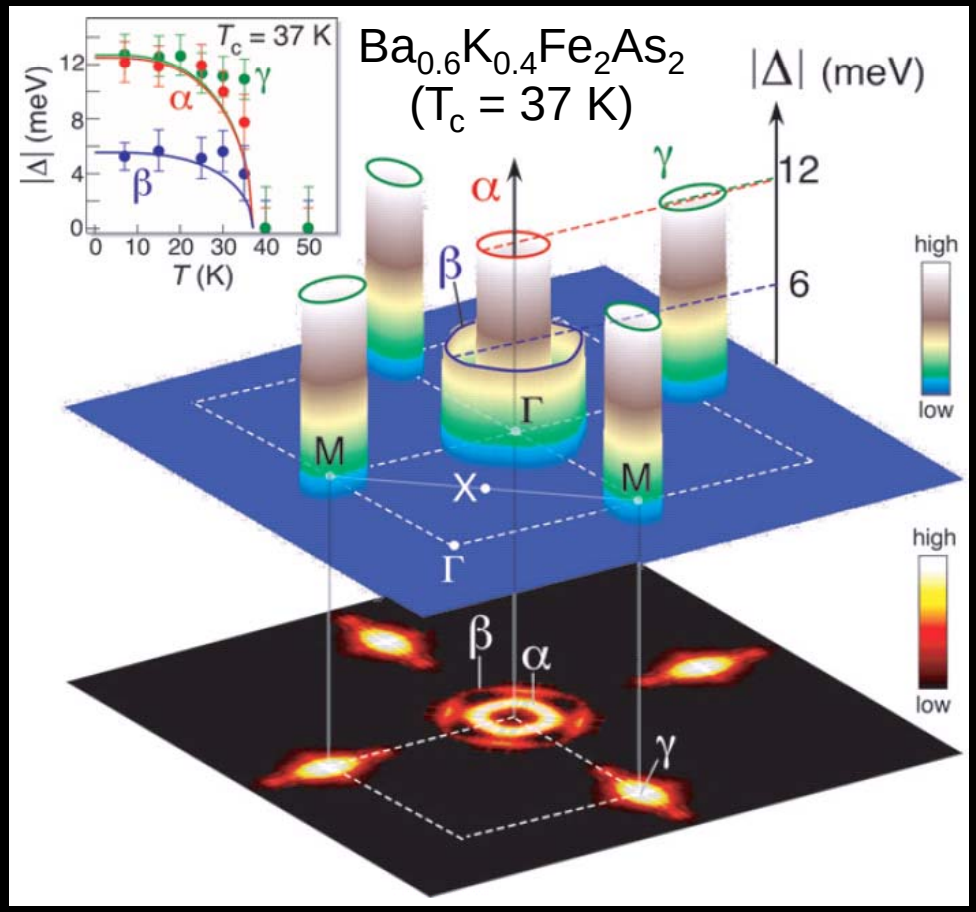


$NdFeAsO_{0.94}F_{0.06}$ (T_c = 48 K)
No Fractional Vortices Observed!

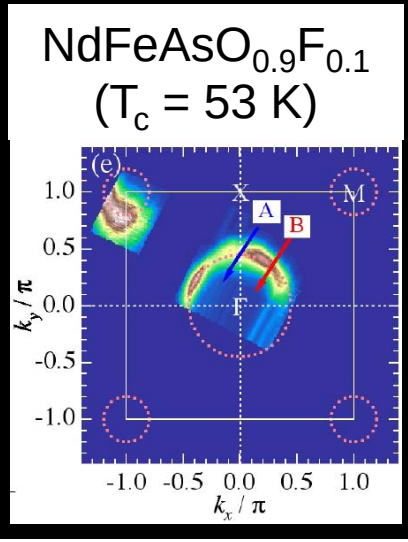


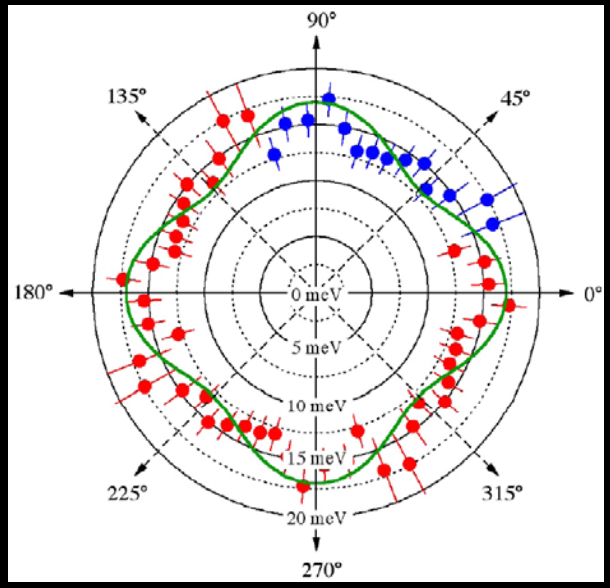
Hicks, … Moler, JPSJ 78, 013708 (2009)

ARPES: What is the pairing symmetry?



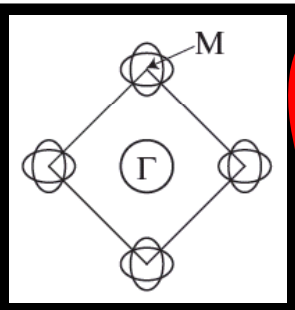
Ding, EPL 83, 47001 (2008)



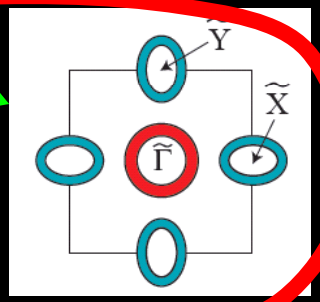


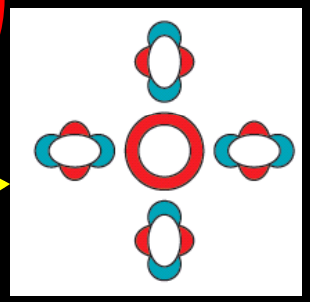
Kondo, PRL 101, 147003 (2008)

Converging on s± symmetry?

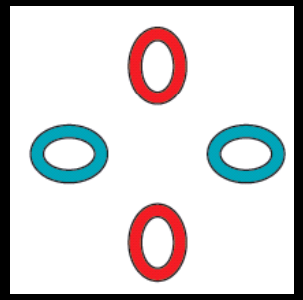


(1) nodeless extended s-wave (s±)
- Mazin, PRL 101, 057003 (2008)
- Wang, PRL 102, 047005 (2009)
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)

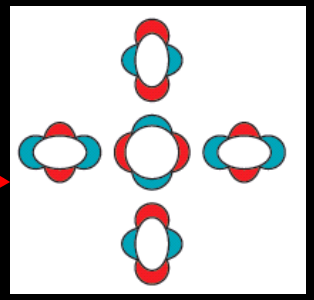




(2) nodal s-wave
- Kuroki, PRL 101, 087004 (2008)

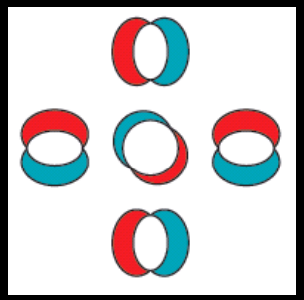


(3) nodeless d
- Kuroki, PRL 101, 087004 (2008)



(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)

BUT… Plenty of 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 $Ba(Co_{0.07}Fe_{0.93})_2As_2$
  [Gordon *et al*, arXiv: 0810.2295]
- Penetration depth λ in LaFePO
  [Fletcher *et al*, arXiv: 0812.3858]

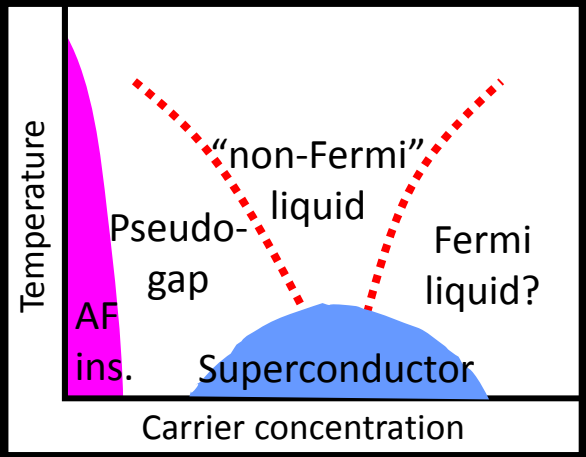
Big Unanswered Questions

(1) What is the pairing symmetry?

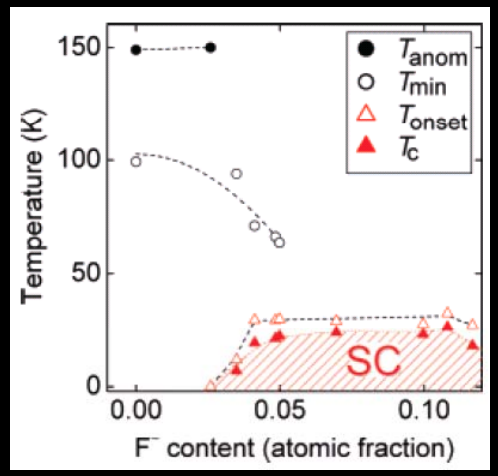
(2) What is the role of spin?

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

Cuprates



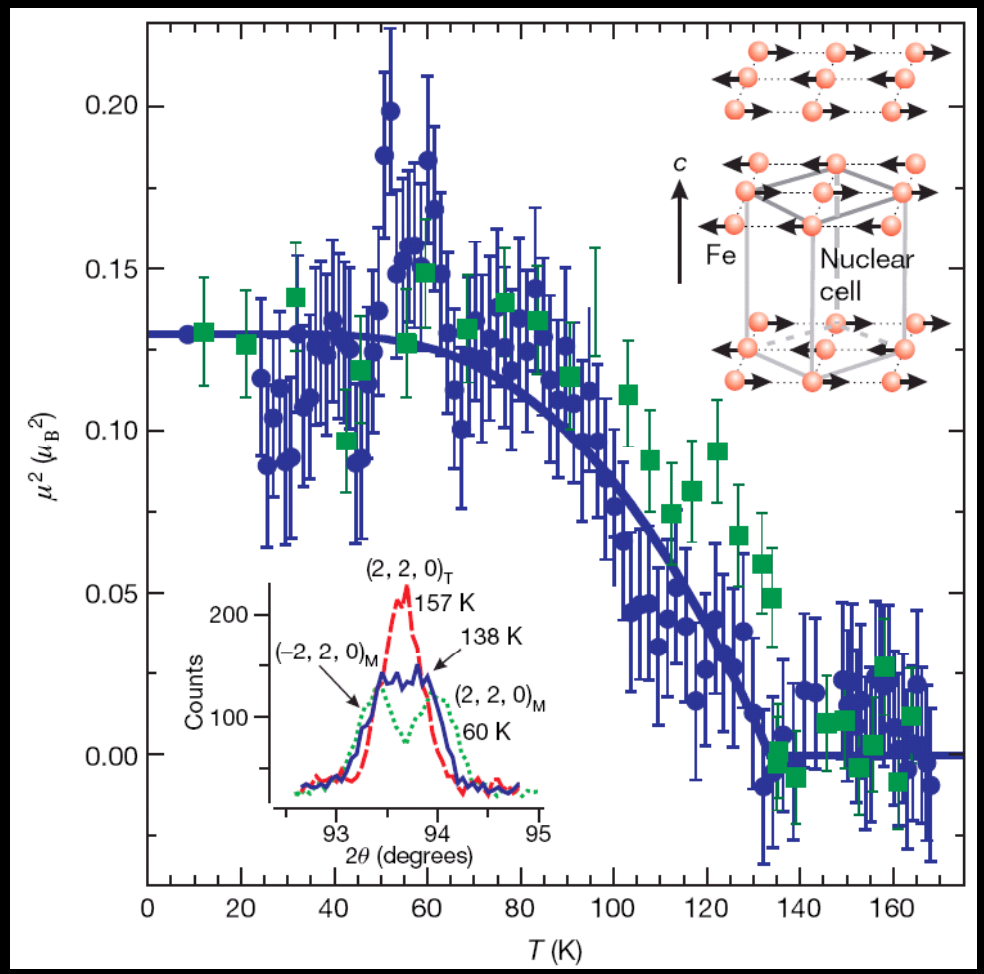
$LaFeAsO_{1-x}F_x$



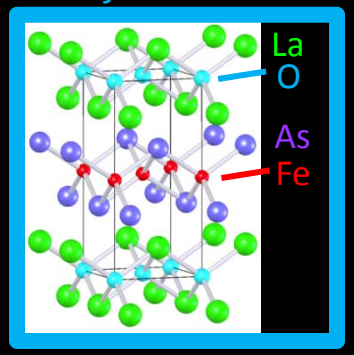
Neutron Scattering: What is the role of spin?

$LaO_{1-x}F_xFeAs$

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

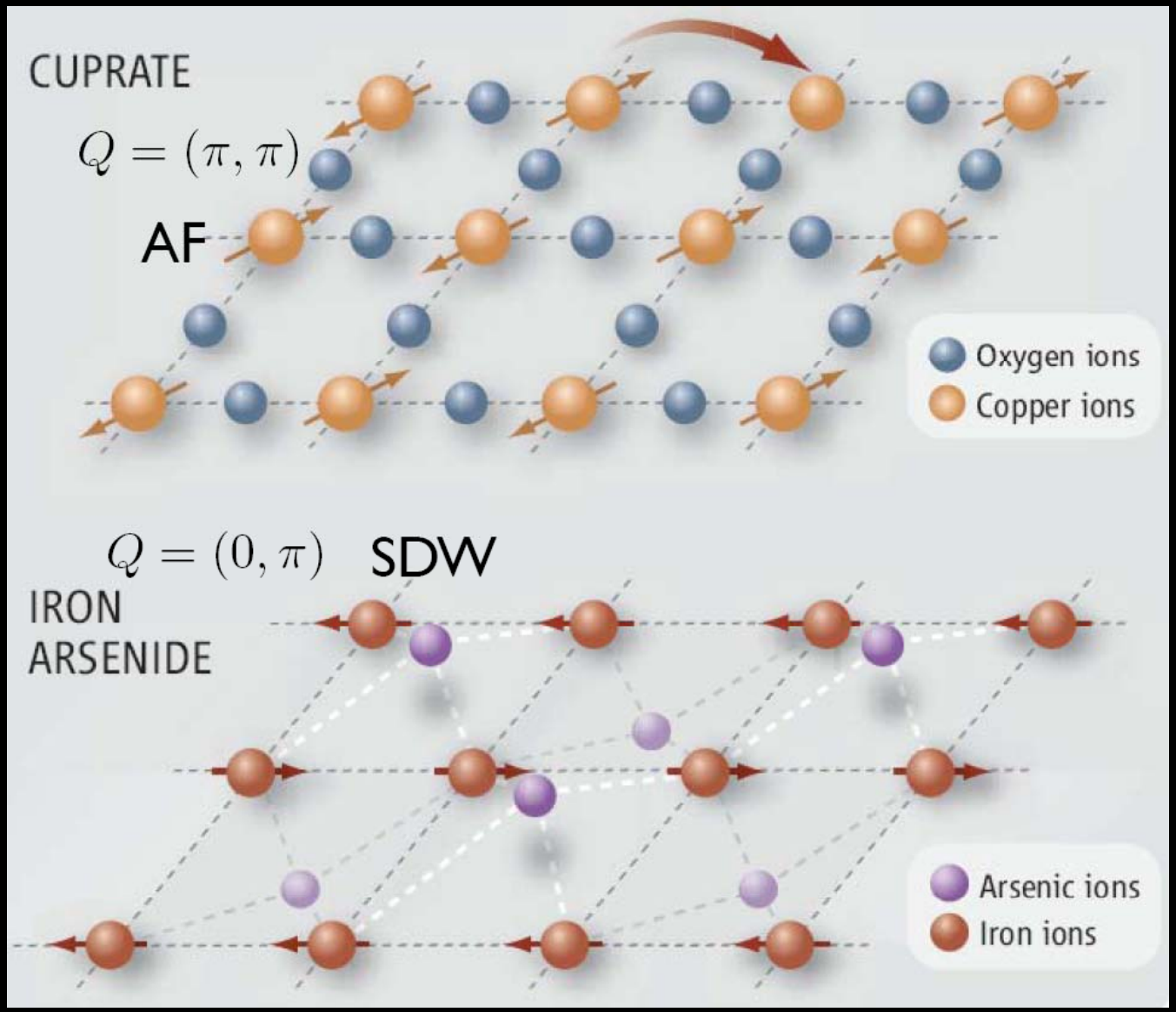


full crystal structure

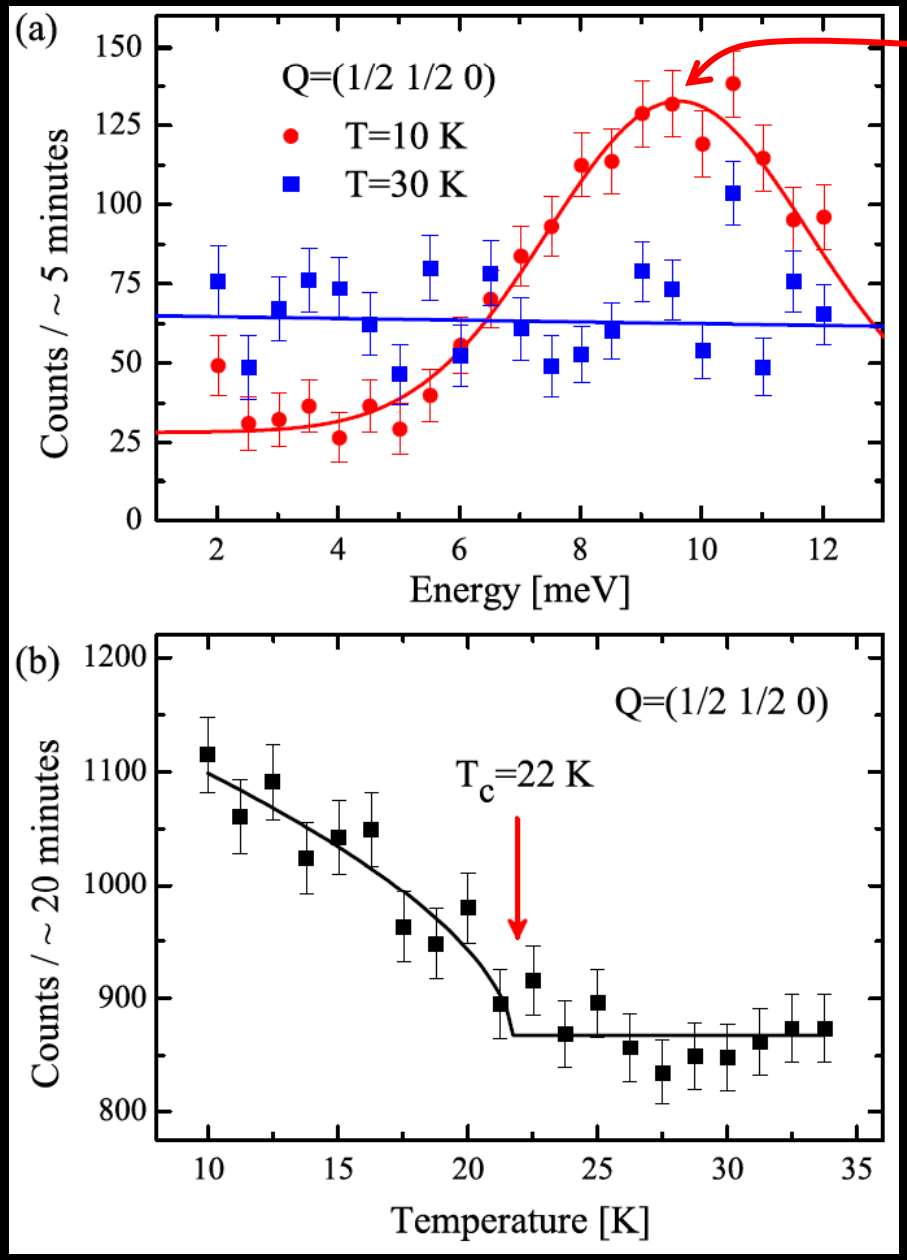


de la Cruz *et al*, Nature 453, 899 (2008)

Cuprate vs. Pnictide Spin Comparison

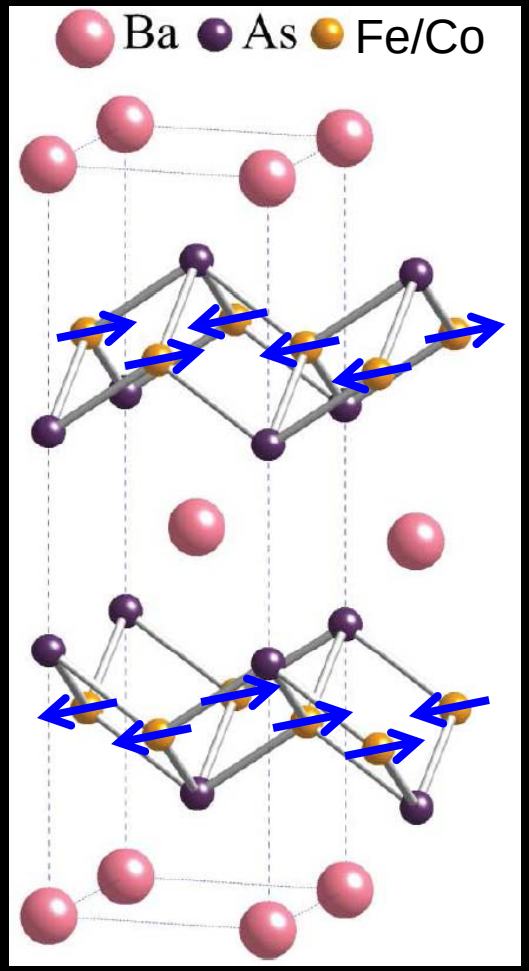


Inelastic Neutron Scattering



magnetic resonance energy ~ $5k_BT_c$

$BaFe_{1.84}Co_{0.16}As_2$



Lumsden, arXiv:0811:4755

Big Unanswered Questions

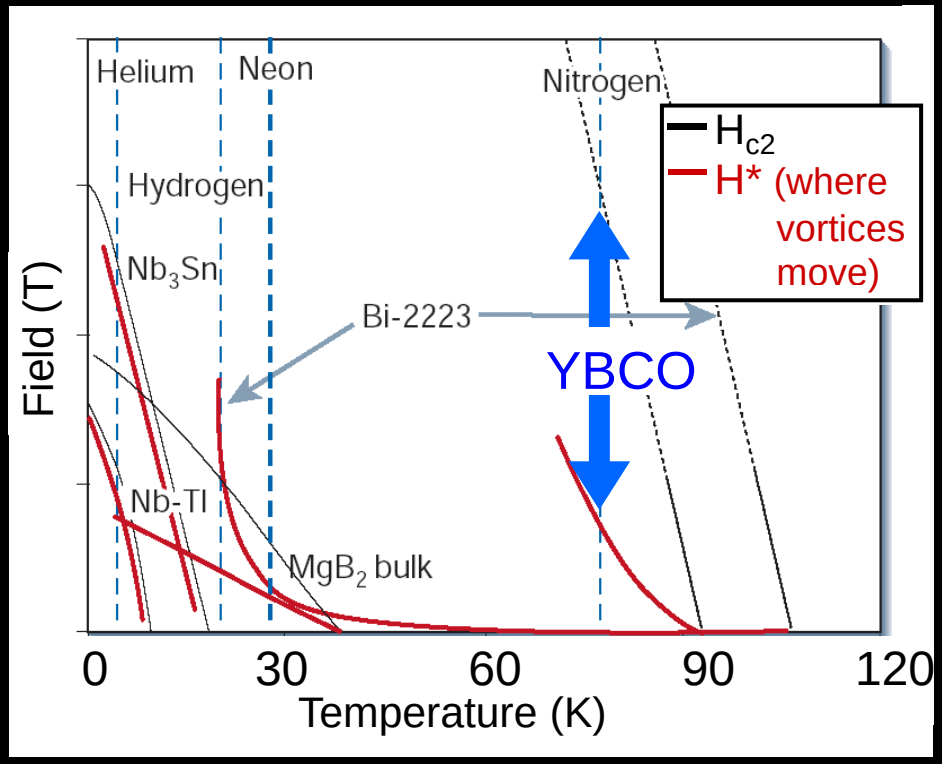
(1) What is the pairing symmetry?

(2) What is the role of spin?

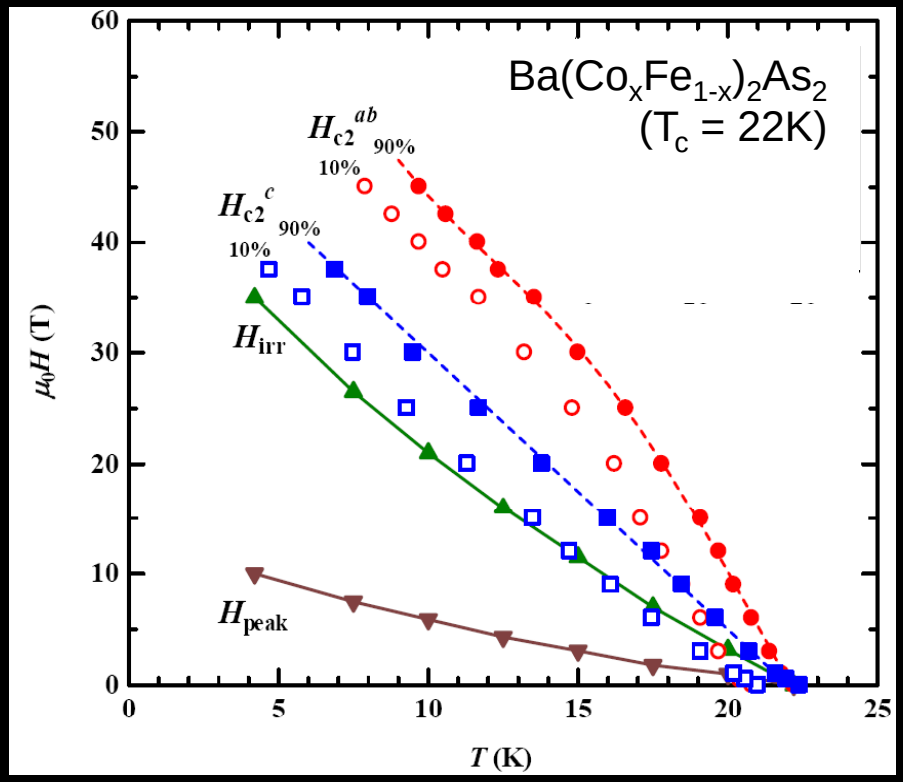
(3) Quantify & understand H_{c2} and vortex pinning?

Vortex pinning: low anisotropy, high H_{c2}

Cuprate Superconductors



Pnictide Superconductors



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)

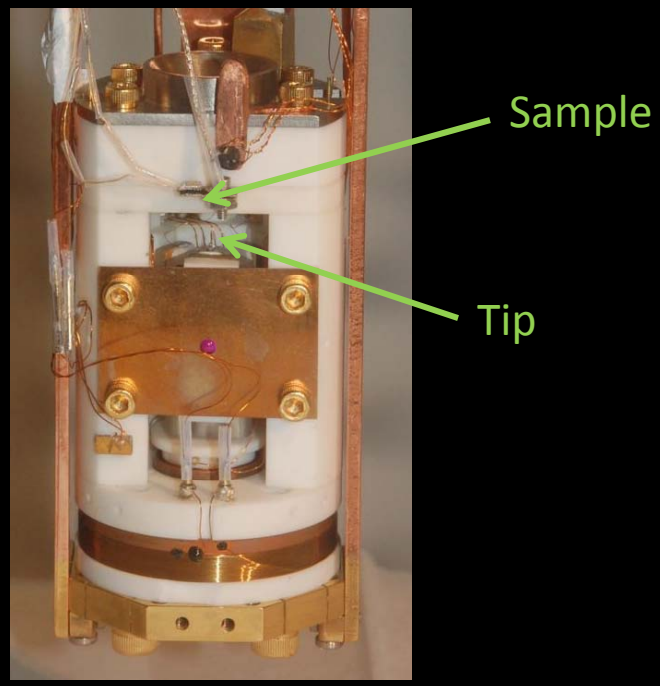
Big Unanswered Questions – Our Contributions

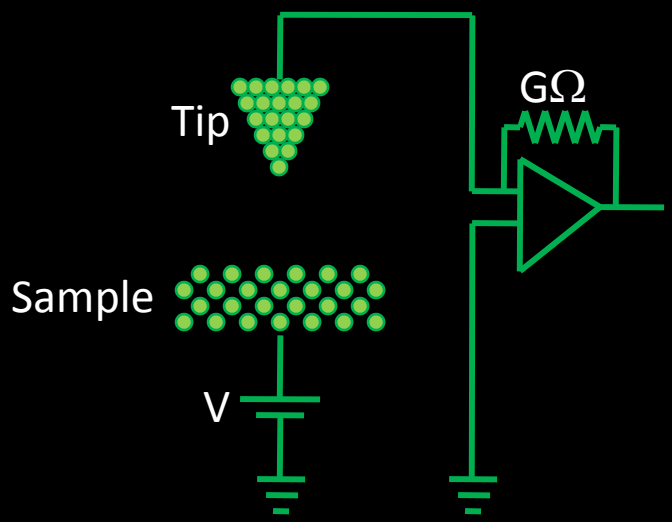
(1) What is the pairing symmetry?

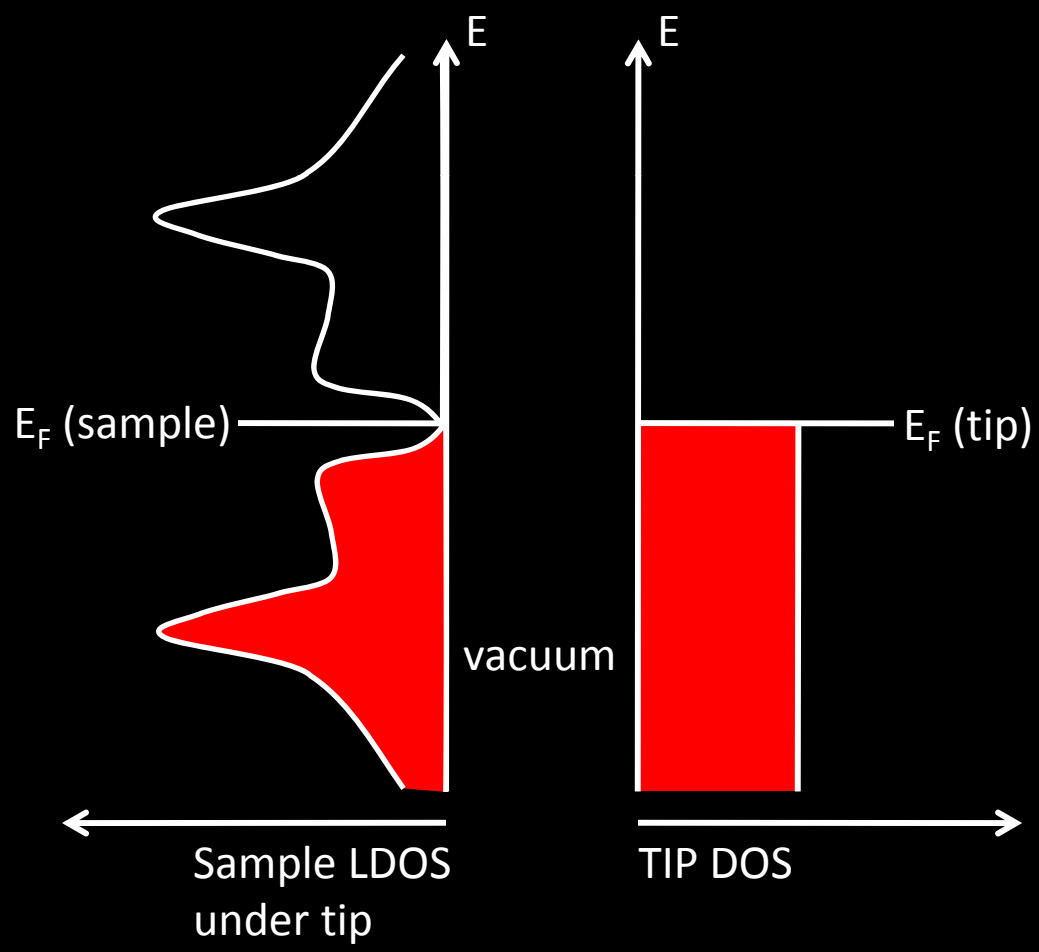
(2) What is the role of spin? → will have to wait…

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

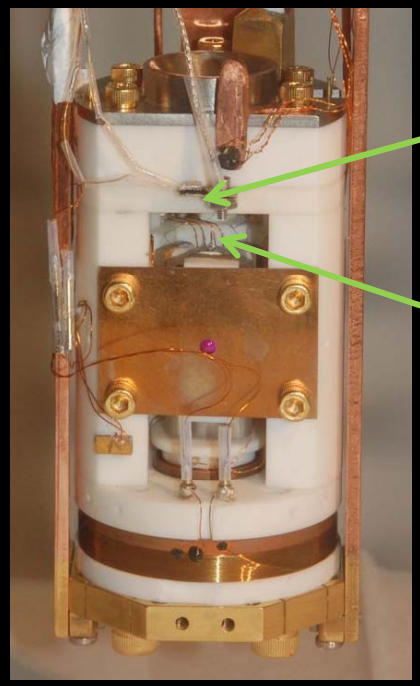
Introduction to STM

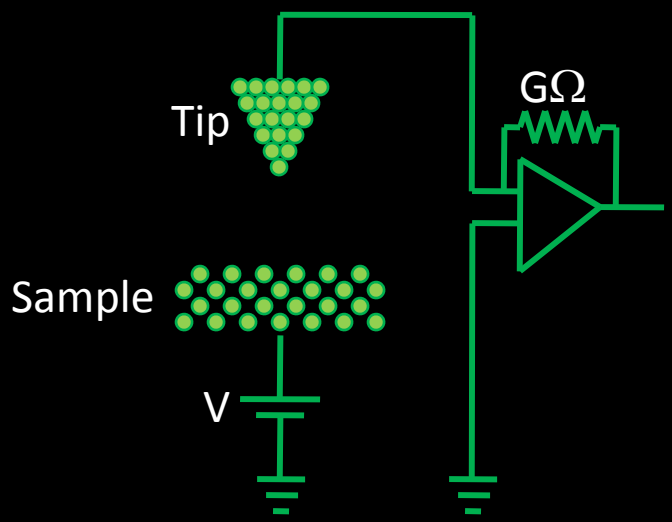




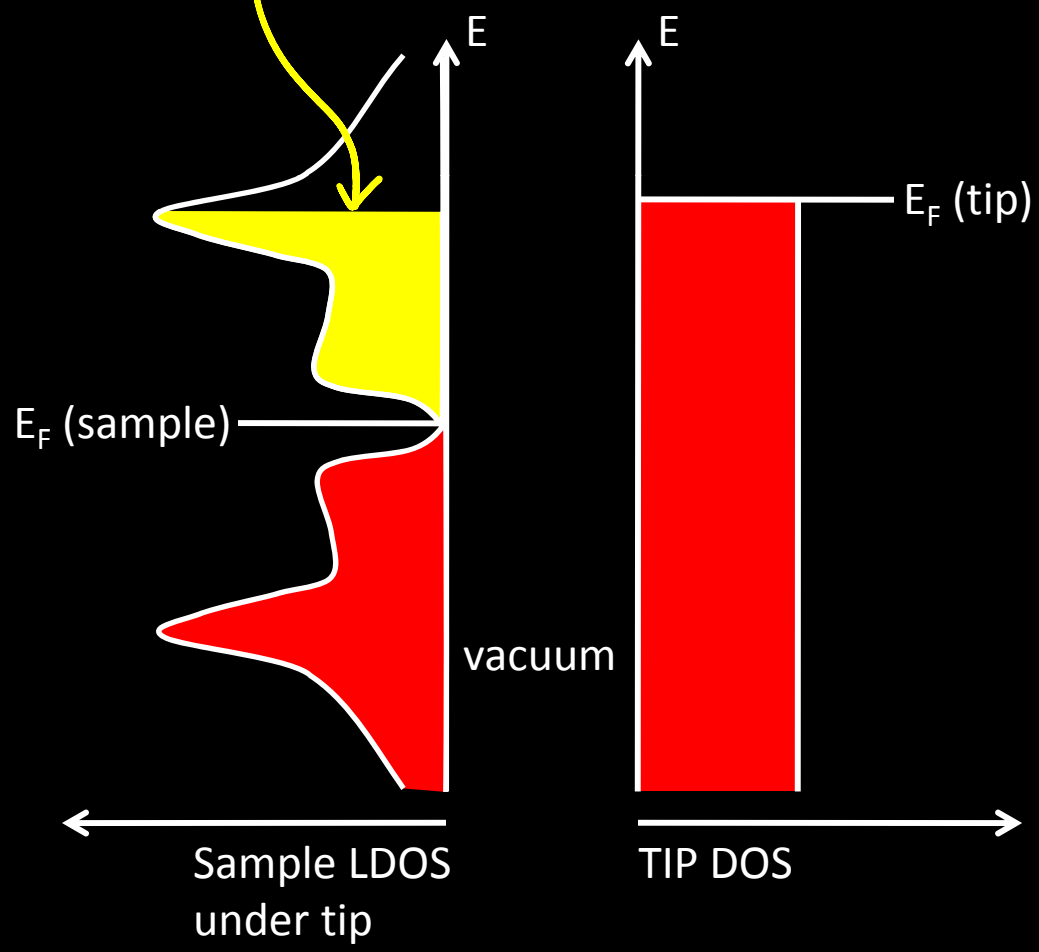


Introduction to STM

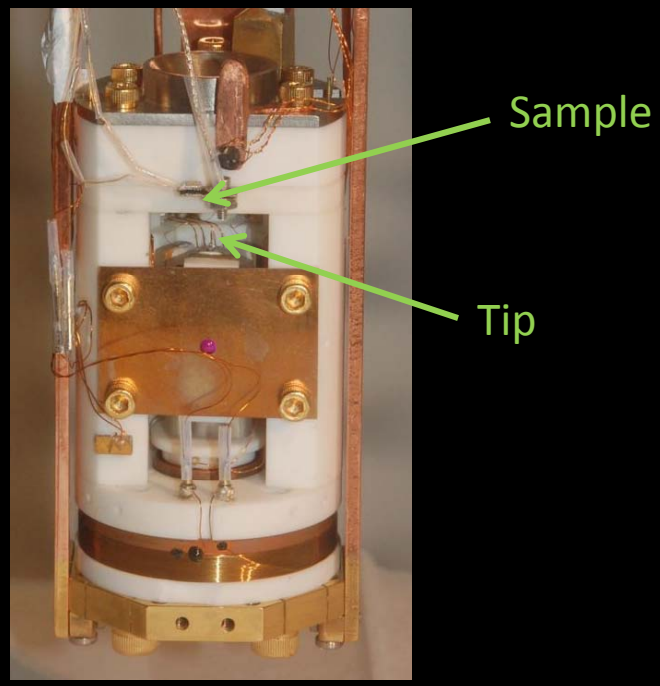


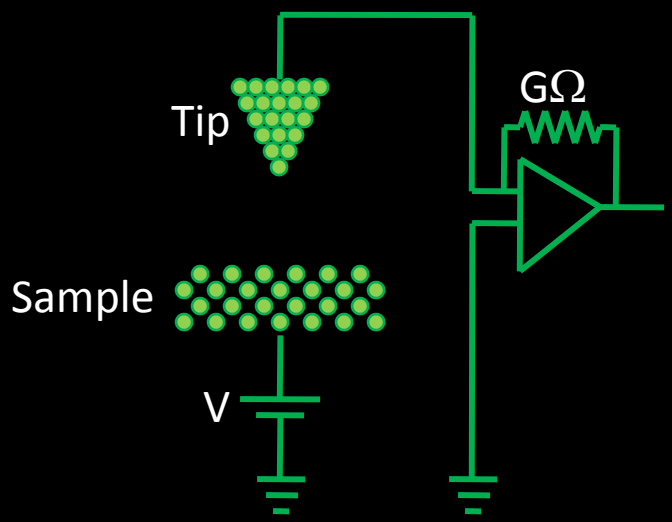


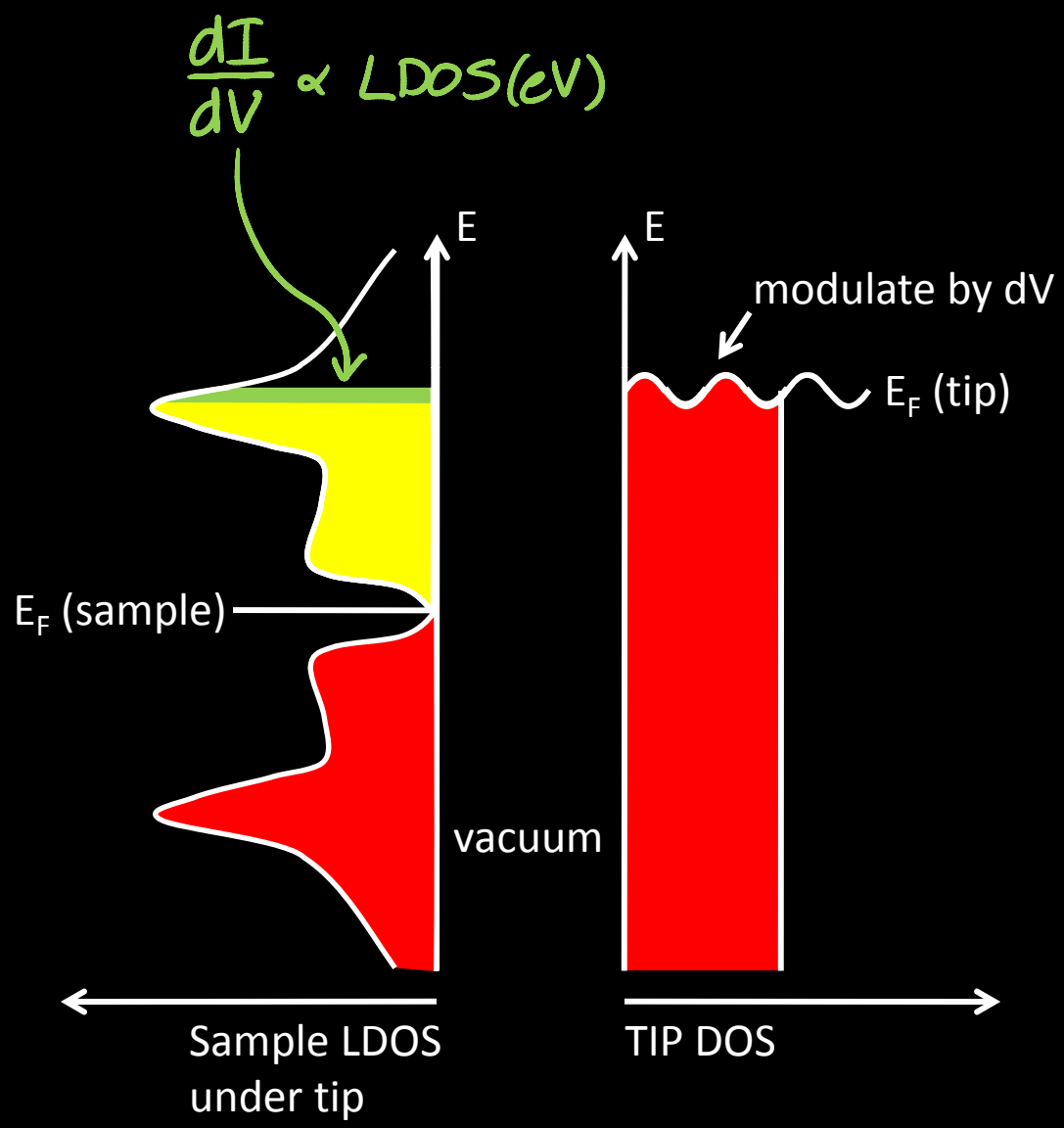
$$I(V) = \int_{E_F}^{eV} LDOS(E)\,dE$$



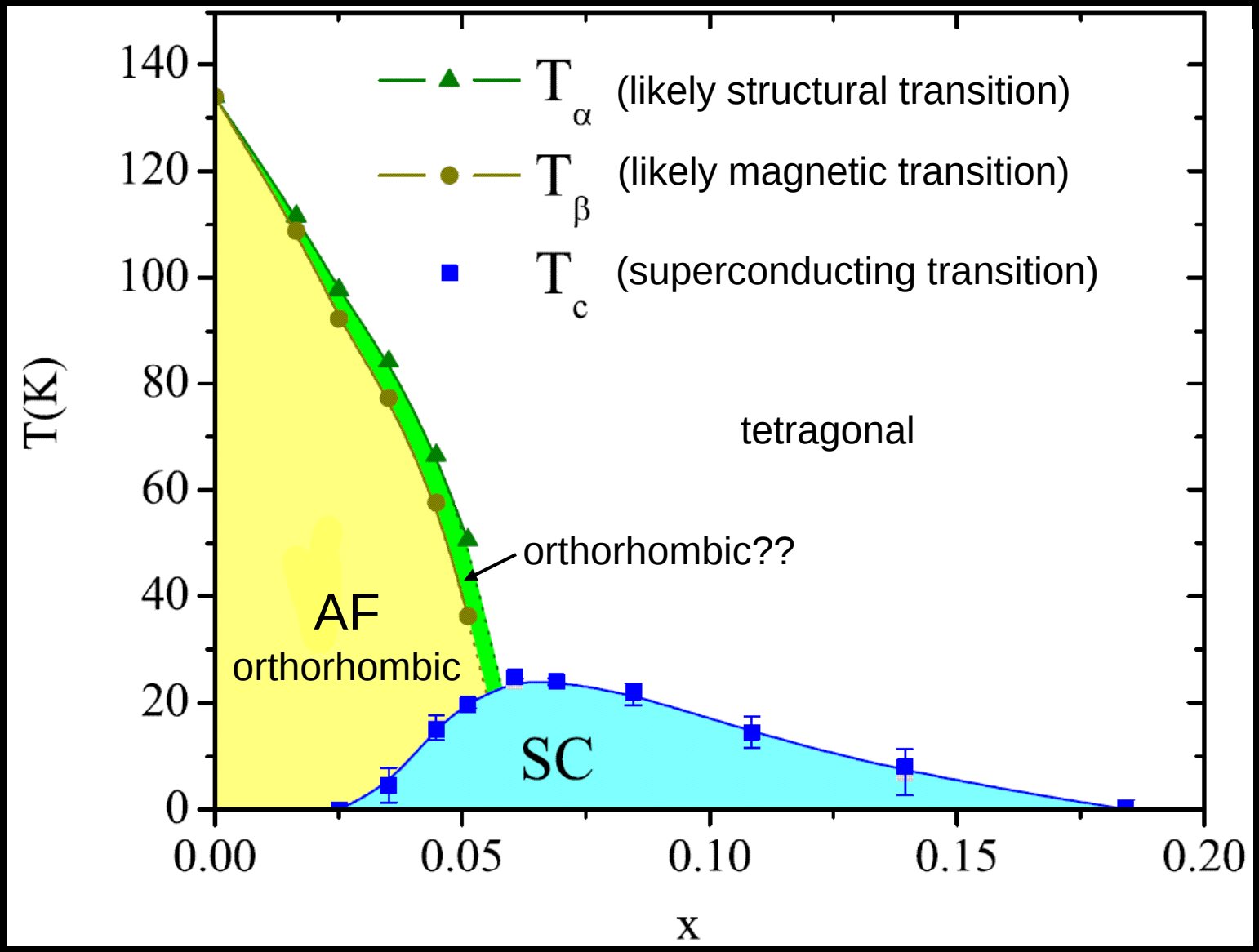
Introduction to STM







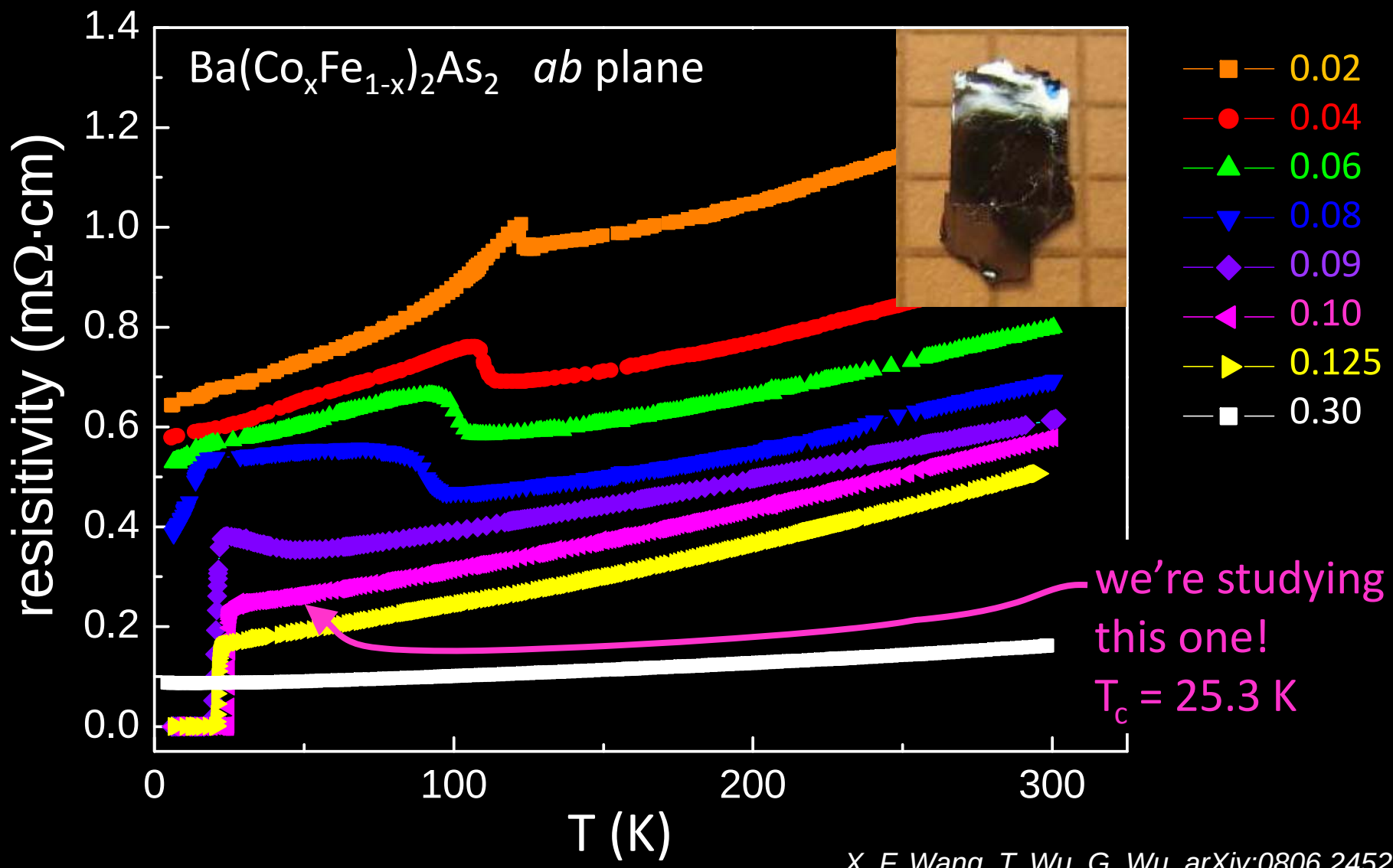
$Ba(Co_xFe_{1-x})_2As_2$ Phase Diagram



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

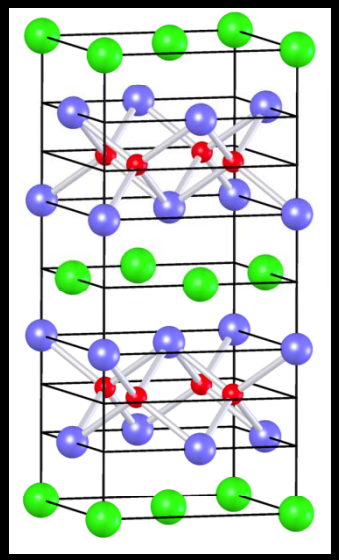
Resistivity of our $Ba(Co_xFe_{1-x})_2As_2$

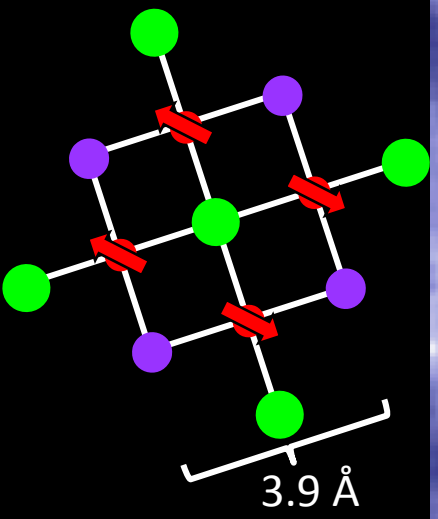
single crystals grown by Prof. XianHui Chen



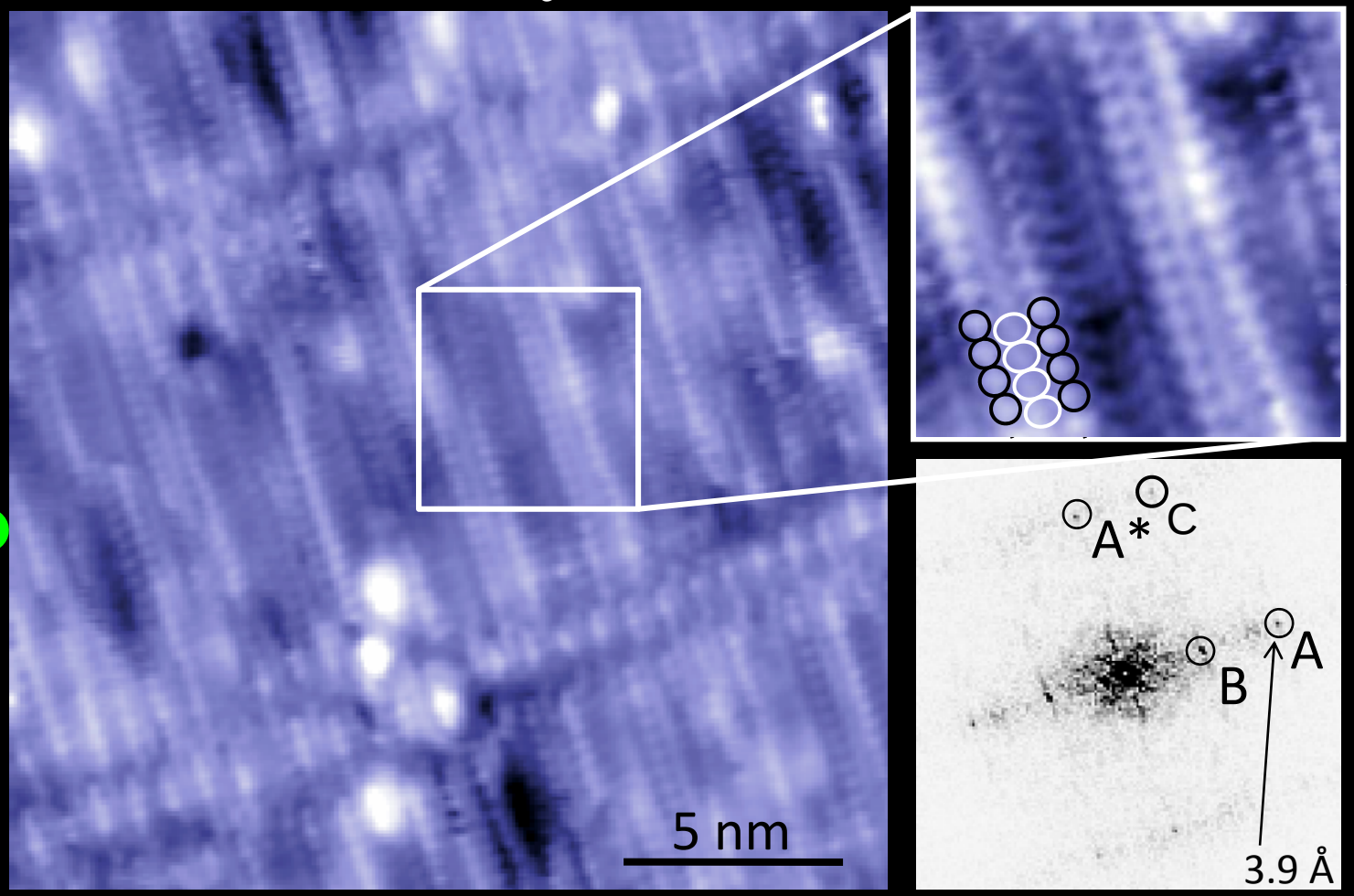
X. F. Wang, T. Wu, G. Wu, arXiv:0806.2452
to be published in Phys. Rev. Lett.

Atomic Resolution Topography





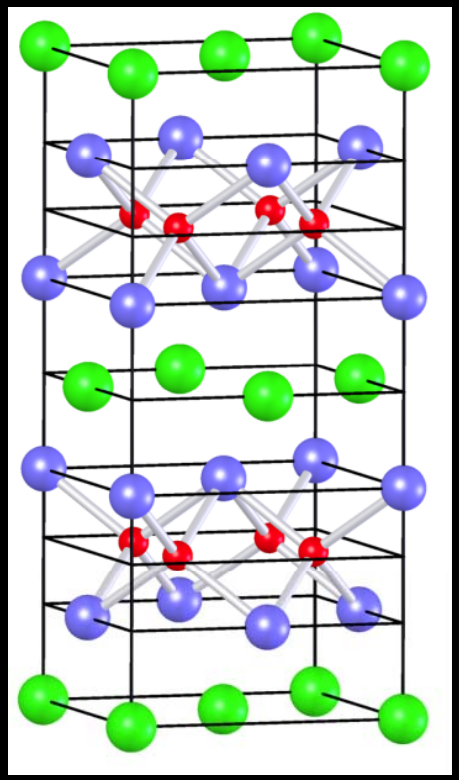
$Ba(Co_xFe_{1-x})_2As_2$
(x=0.1 nominal, T_c=25.3K)



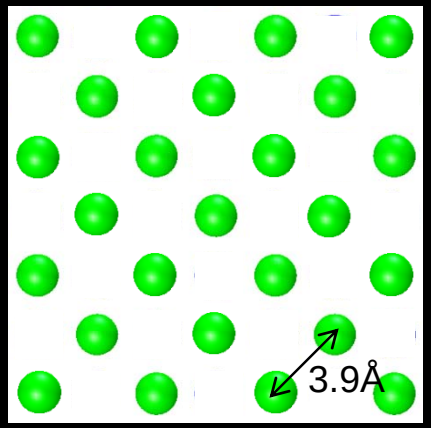
$Ba(Co_xFe_{1-x})_2As_2$ cleavage plane?

Ba (2+)

As, Fe (1-)

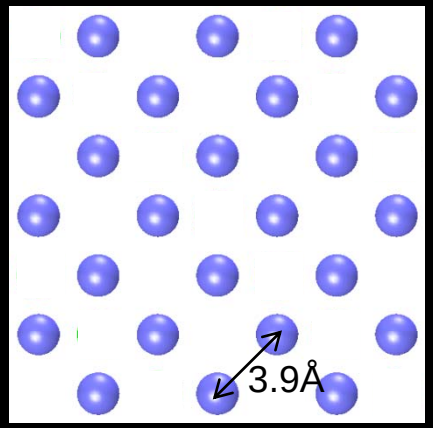


all Ba remain?



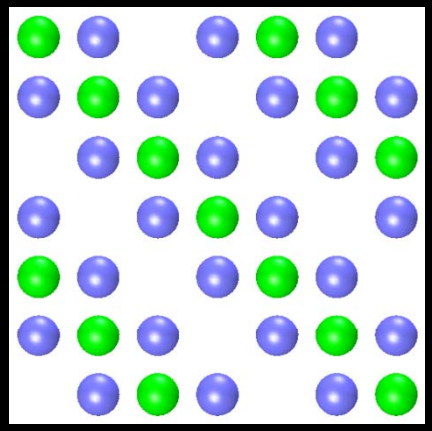
→ top Ba layer has charge 1+

all Ba removed?



→ top As layer has charge 1-

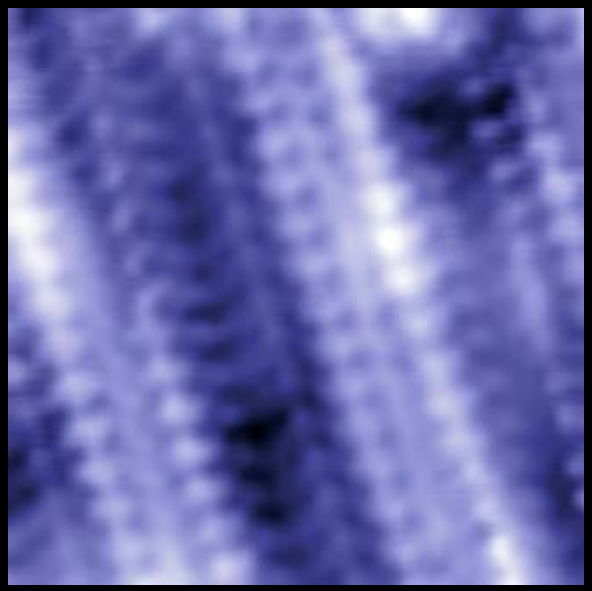
½ Ba removed, ½ Ba remain?



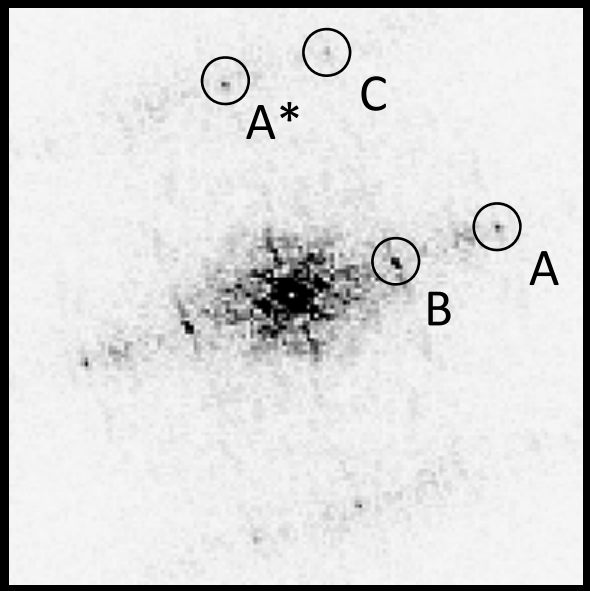
→ top layer is charge neutral

Fourier Transform Analysis

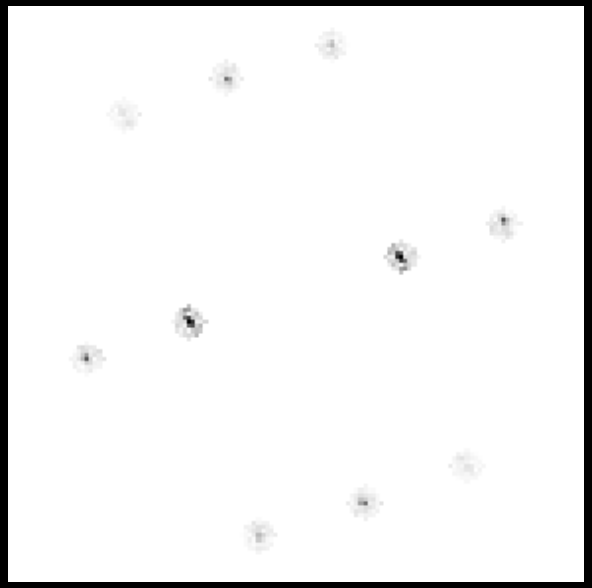
Raw data:



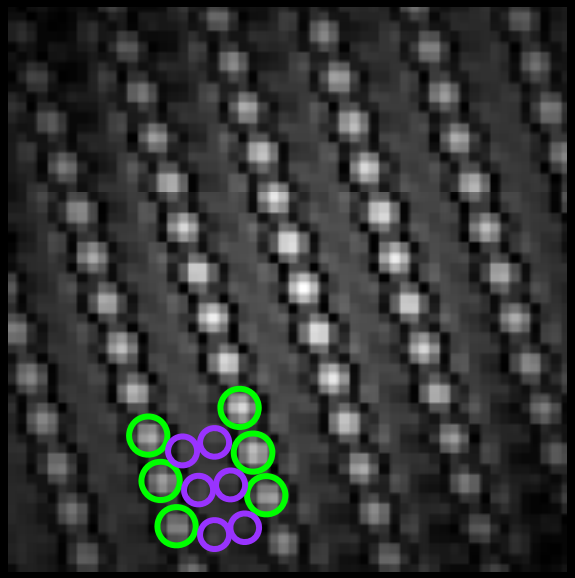
Fourier transform →



↓ filter

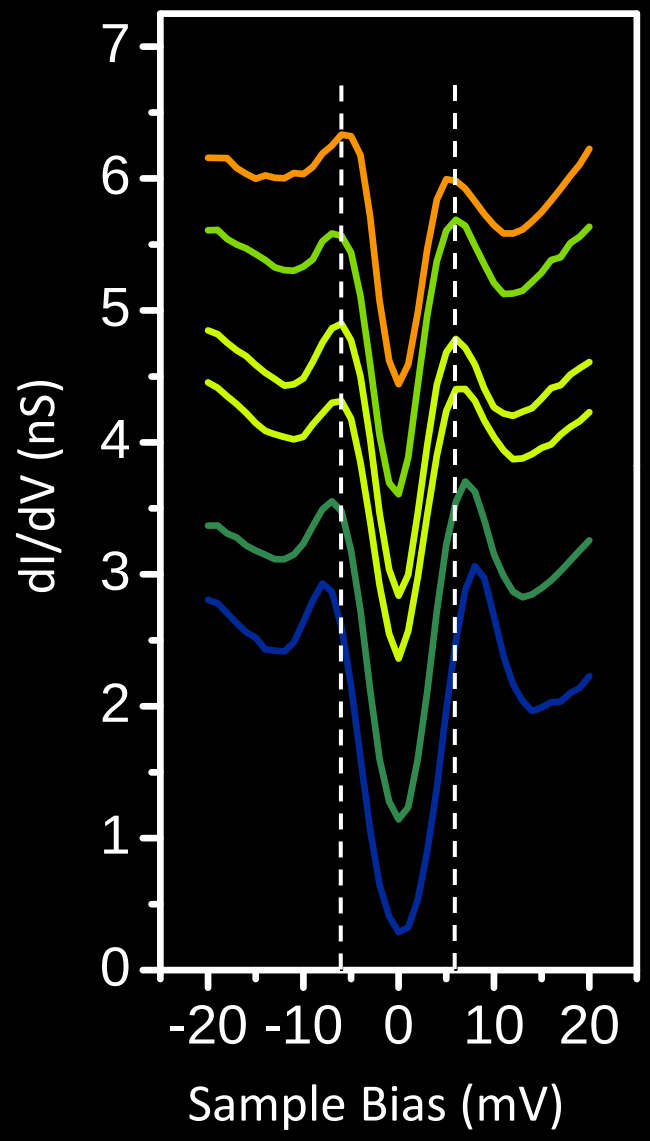


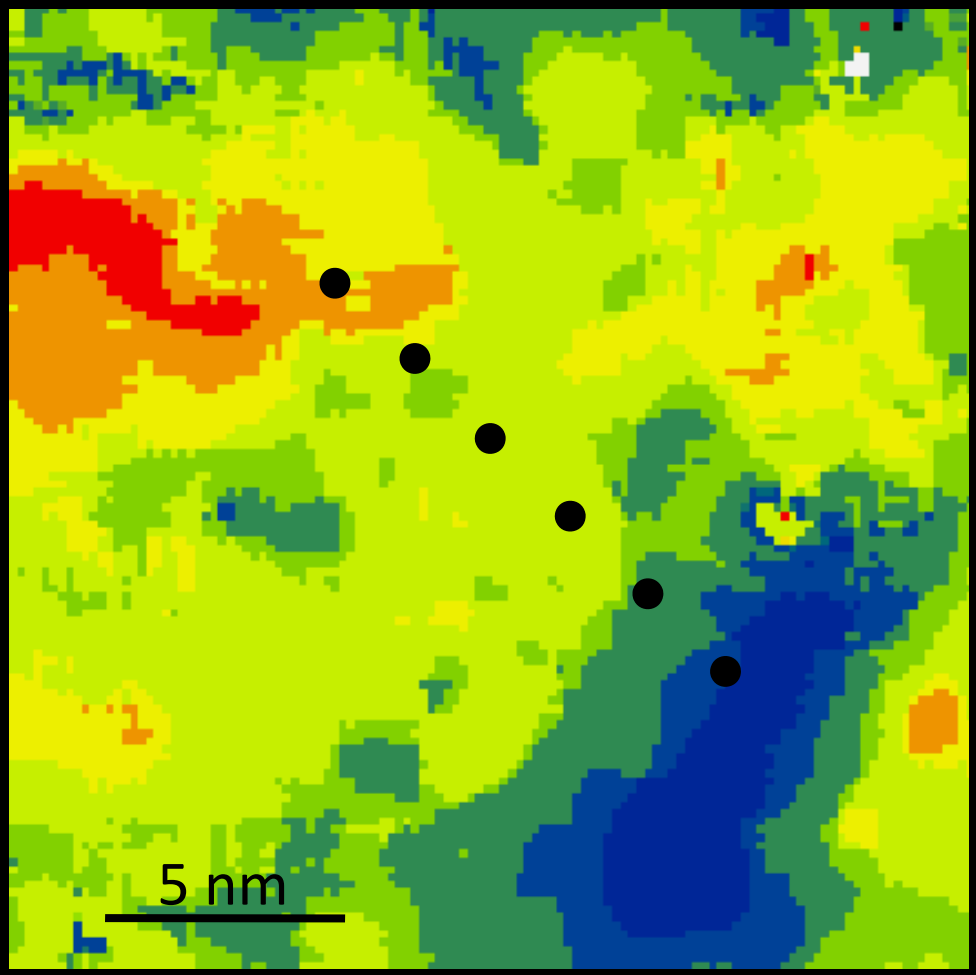
← inverse Fourier transform

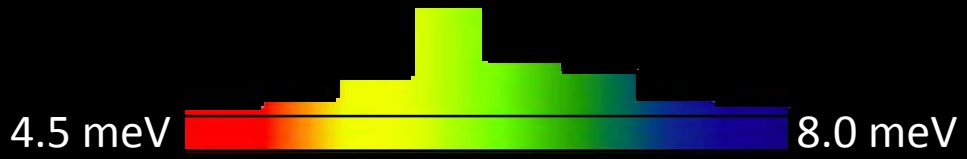


Ba
As

Gap Mapping



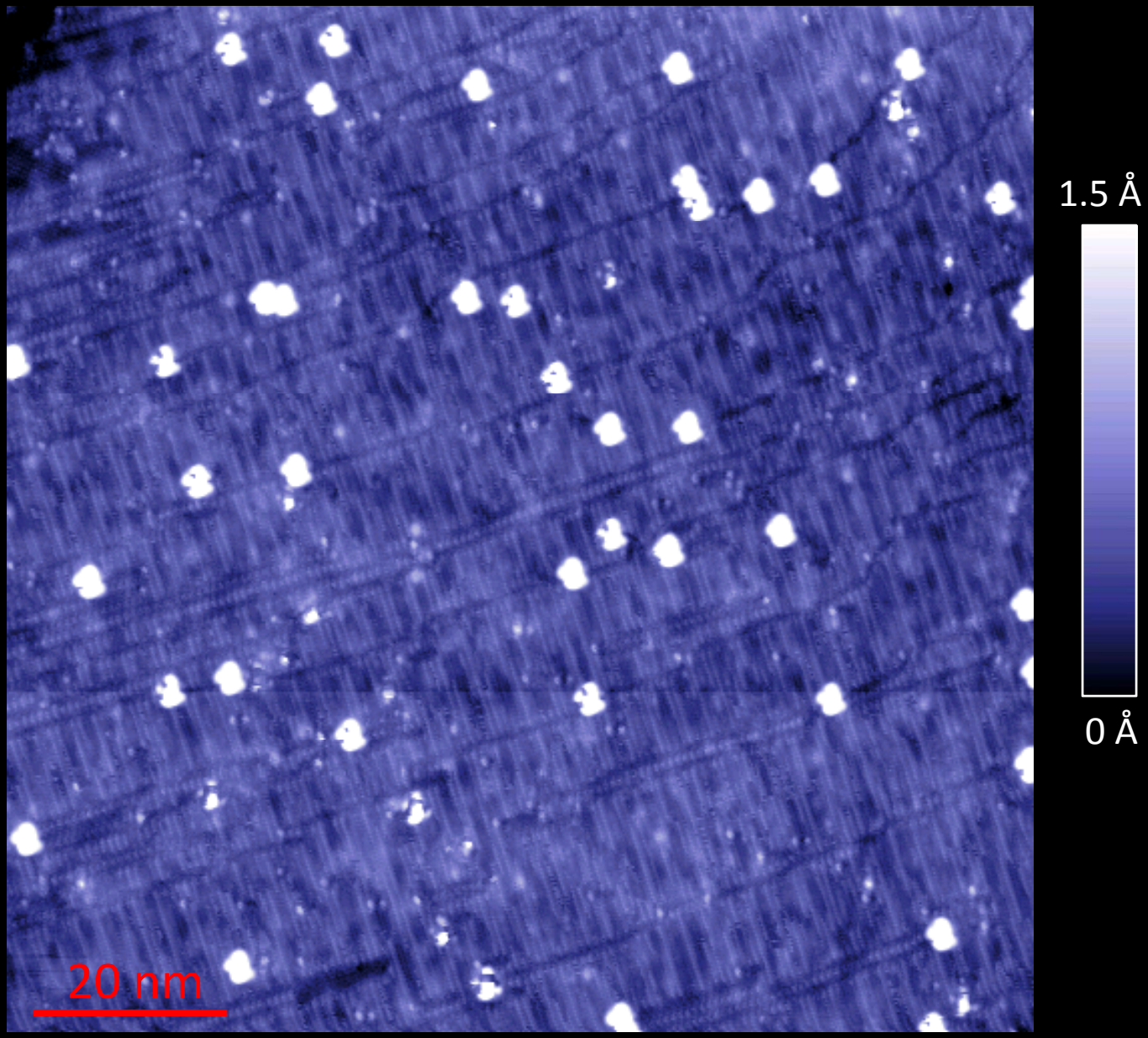




$\overline{\Delta}$ = 6.25 ± 0.73 meV (12% variation)

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

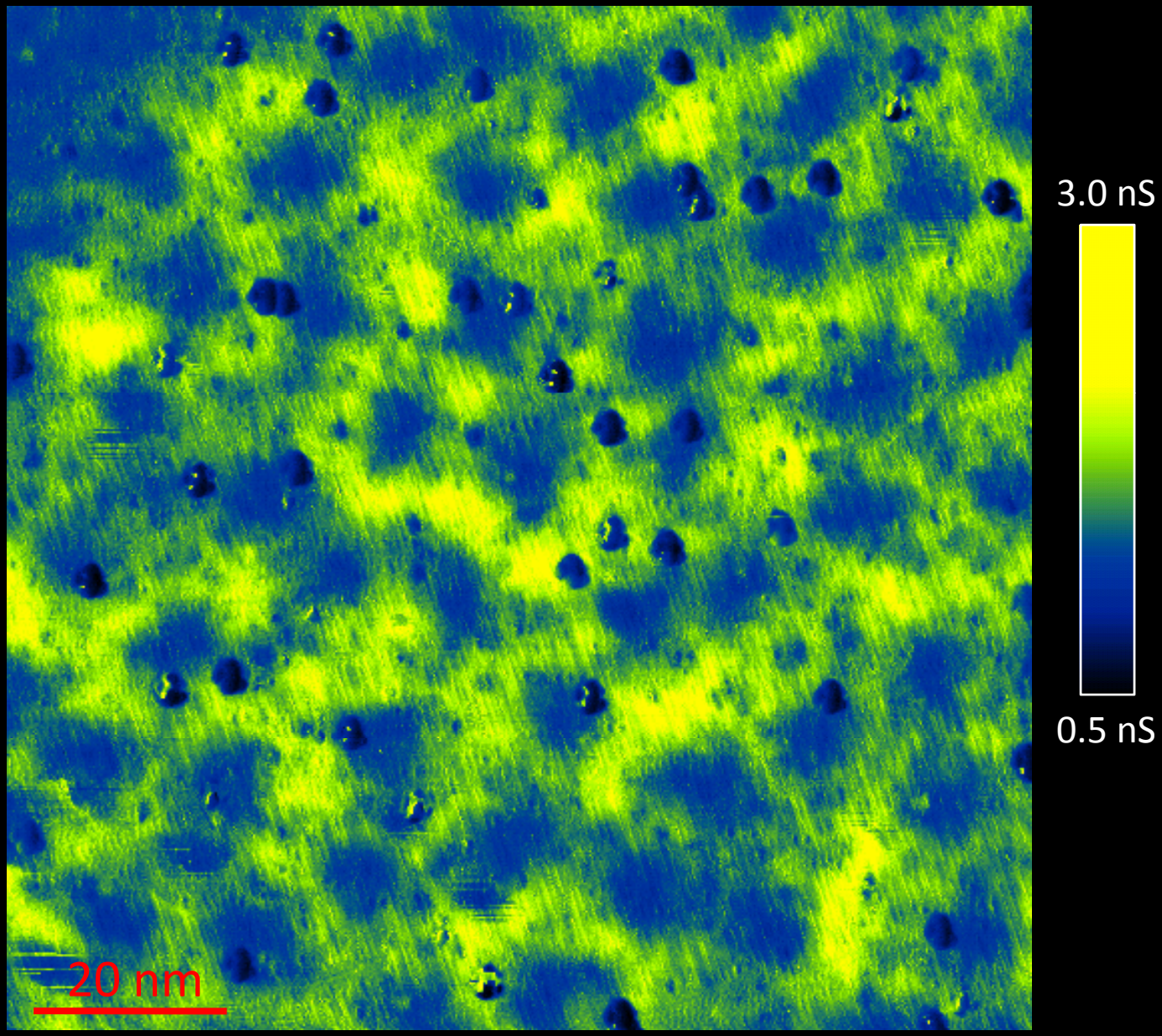
Topography



Vortices at 9T

dI/dV at 5 mV

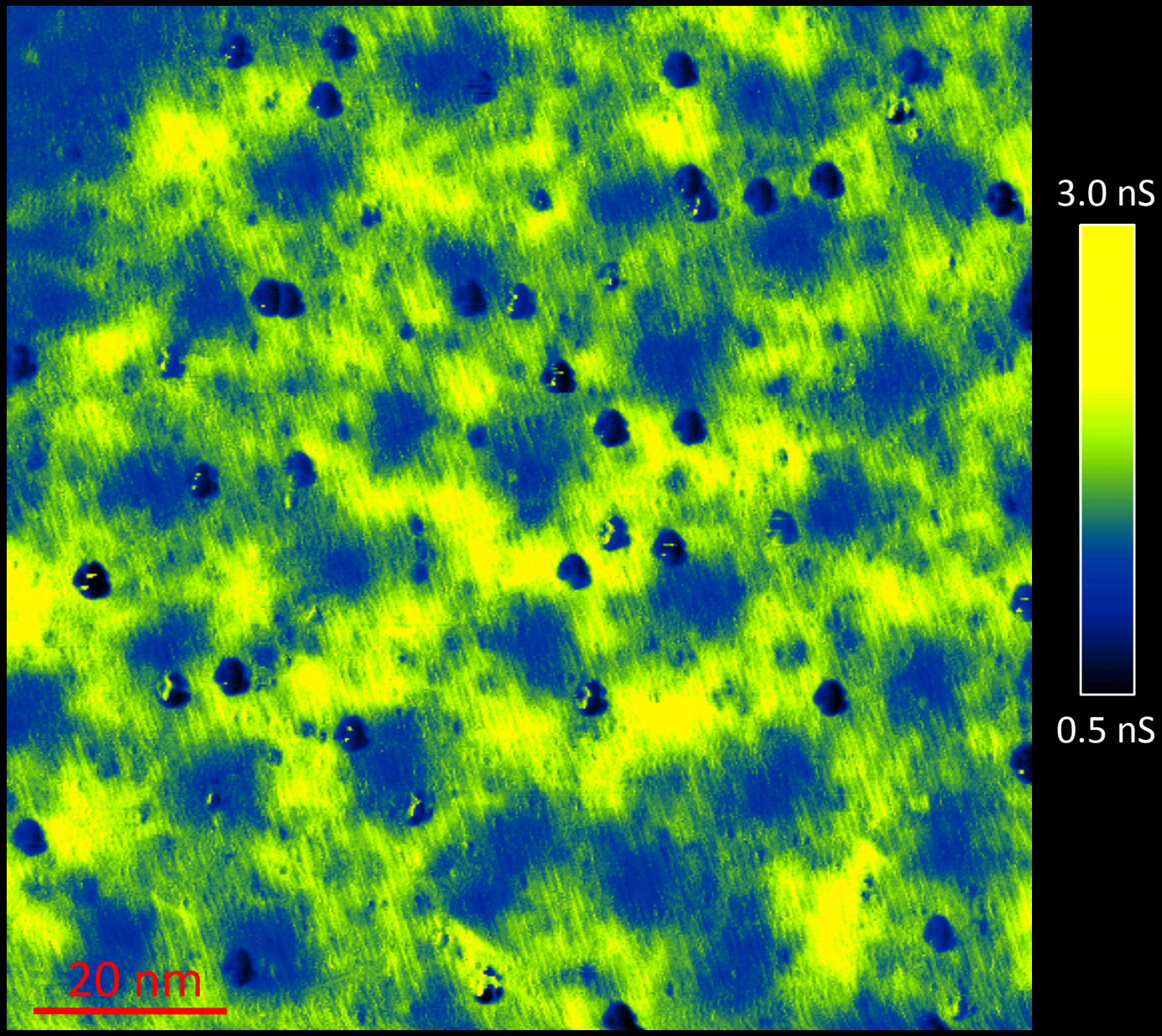
(approximate coherence peak energy)



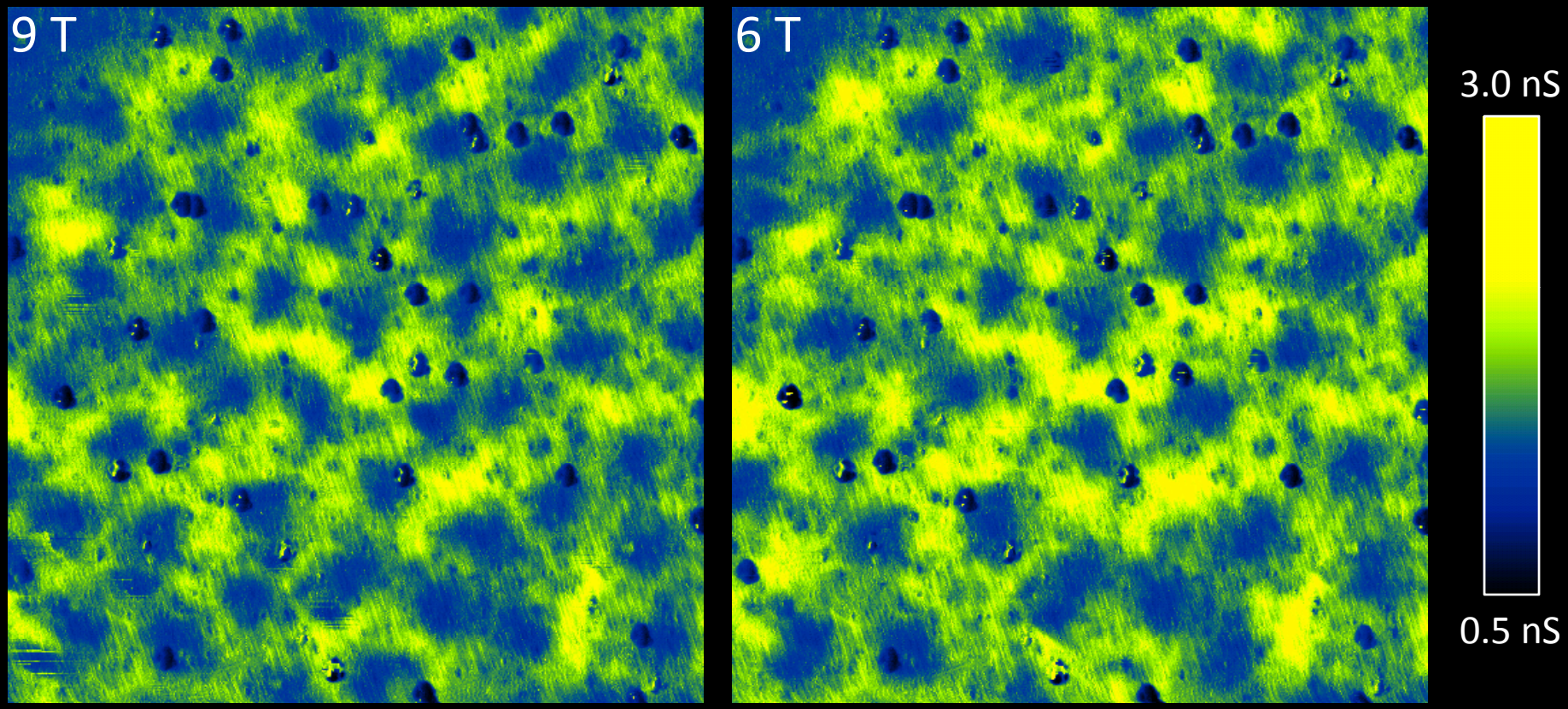
Vortices at 6T

dI/dV at 5 mV

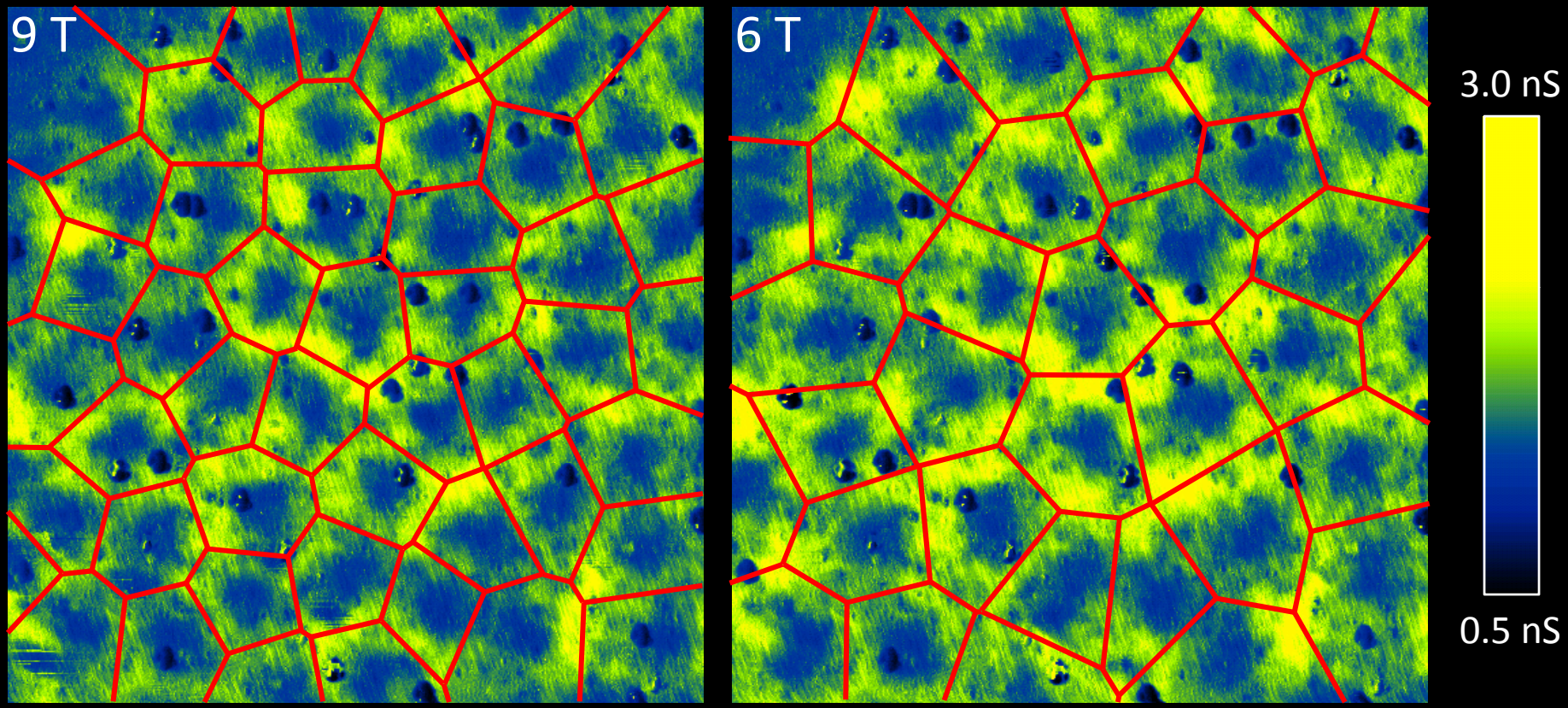
(approximate coherence peak energy)



Flux Measurement



Flux Measurement



average vortex area = 228 nm^2

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

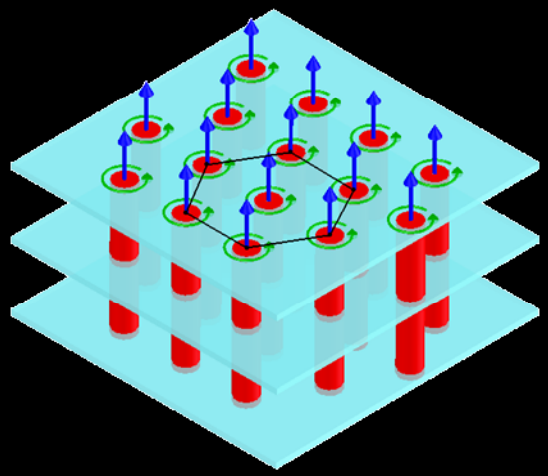
average vortex area = 362 nm^2

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

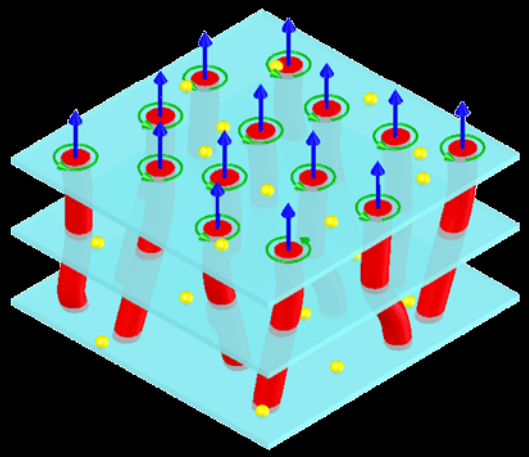
Single magnetic flux quantum: $\Phi_0 = 2.07 \times 10^{-15}$ T·m^2

Vortex pinning possibilities

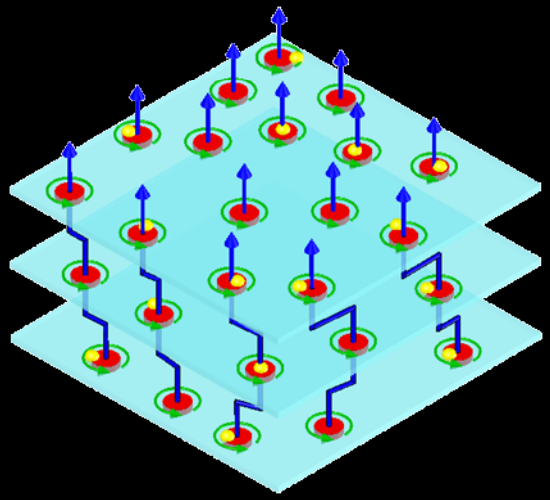
(1) no strong pinners
inter-vortex forces dominate
→ lattice formation

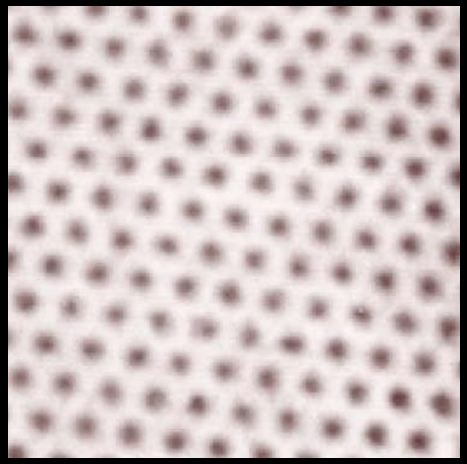


(2) strong pinners exist
low anisotropy
→ vortices bend slightly
to accommodate pinners



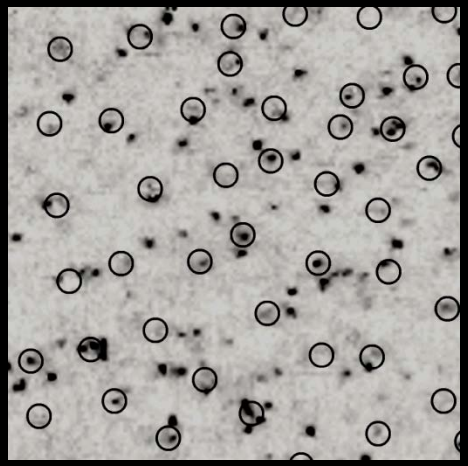
(3) strong pinners exist
high anisotropy
→ vortices pancake
each pancake pins independently





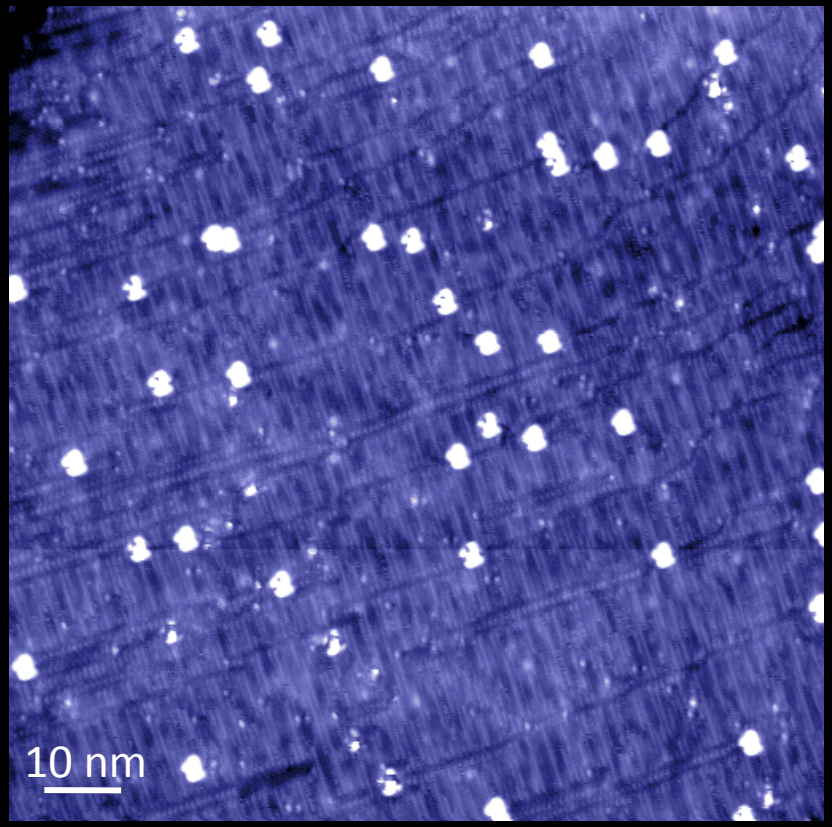
$NbSe_2$

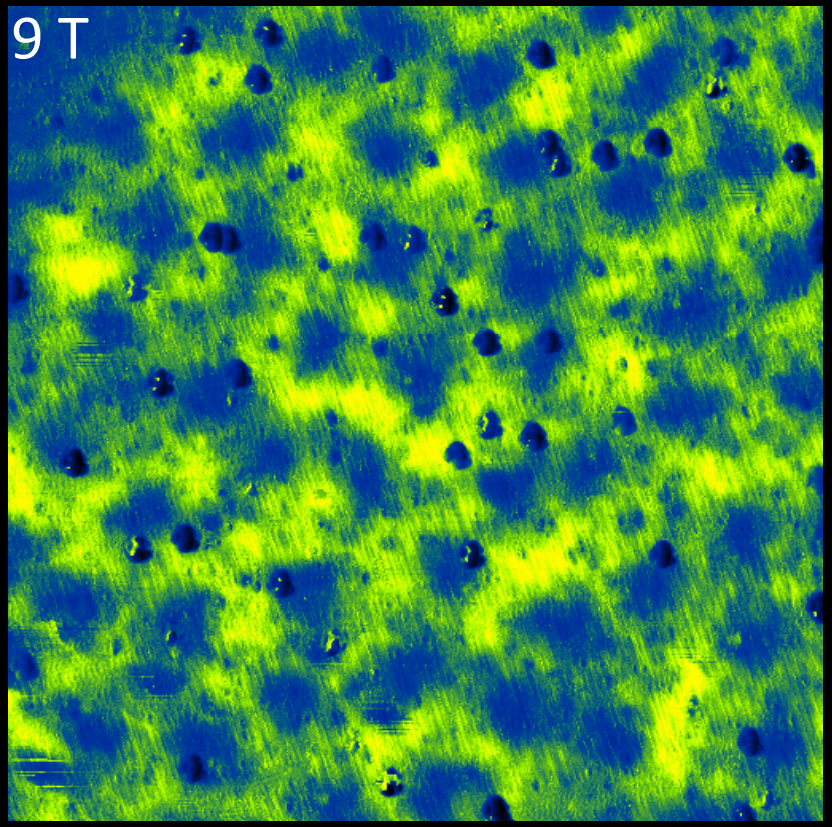
ideal case
for applications



$Bi_2Sr_2CaCu_2O_8$

Are Vortices Pinned to Surface Impurities?

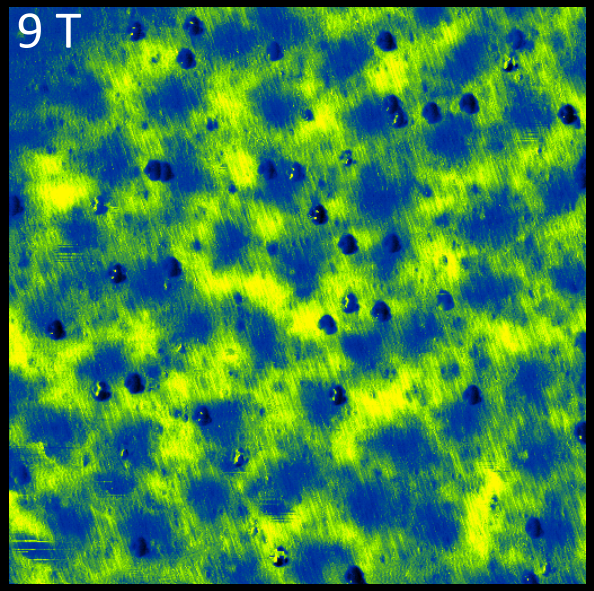


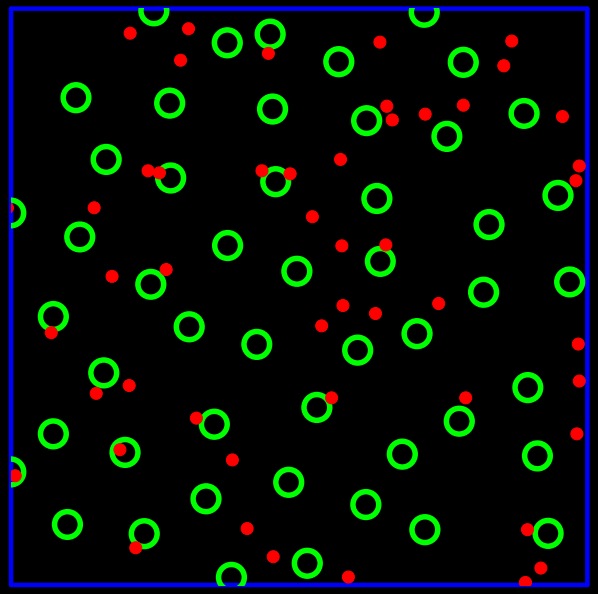


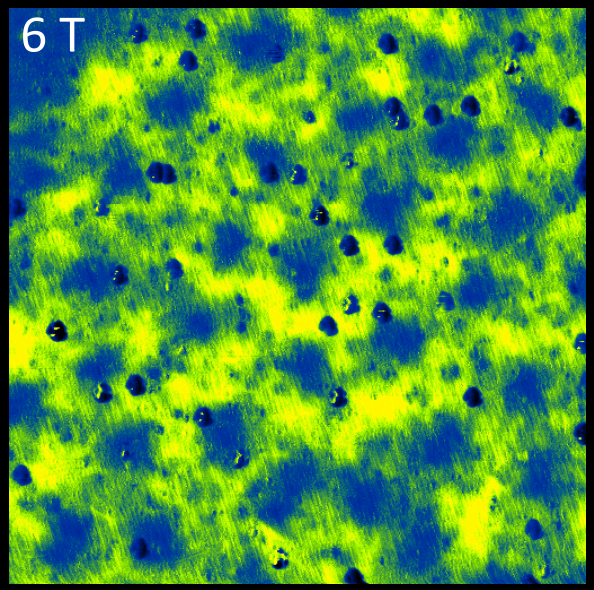
Are Vortices Pinned to Surface Impurities?

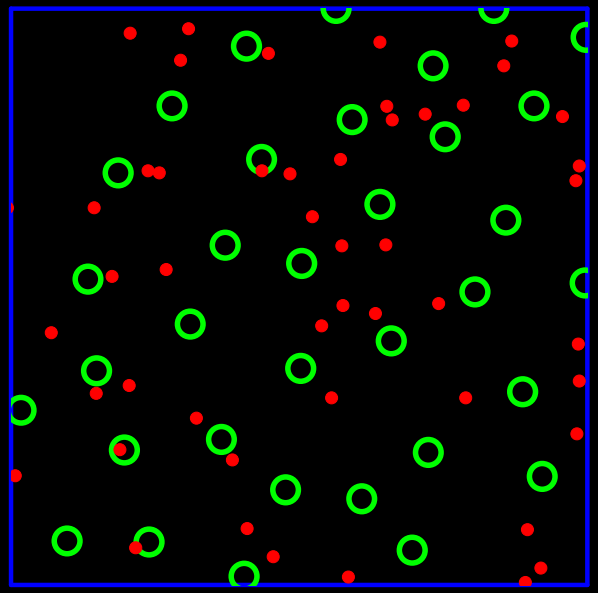
Raw Data

Idealized Data



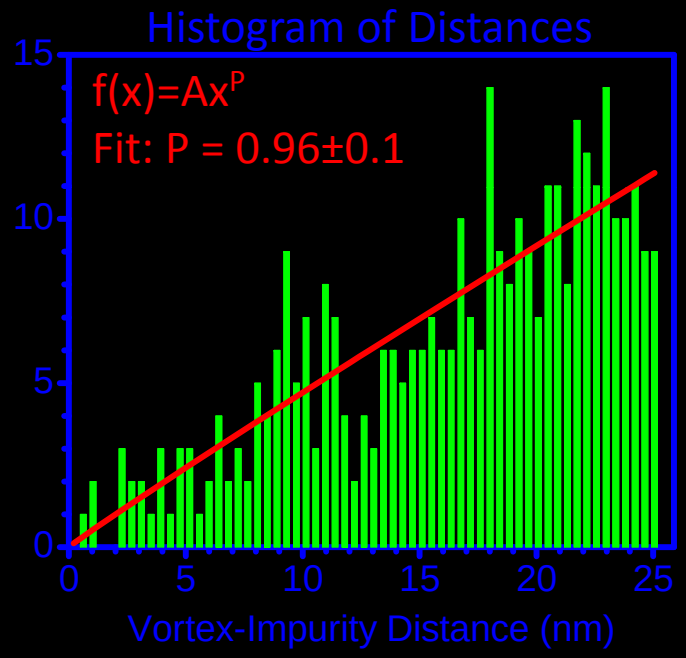






vortex, radius ξ_0 = 2.76 nm

impurity

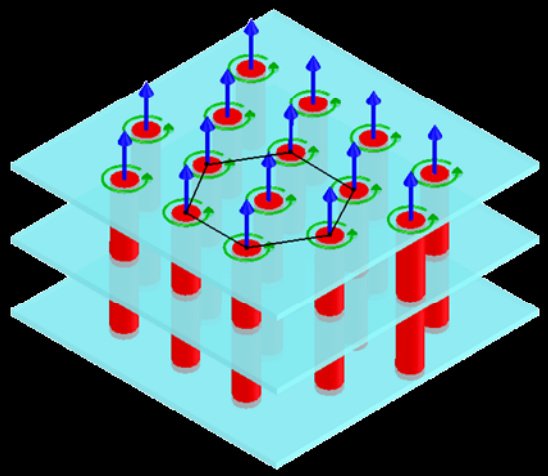


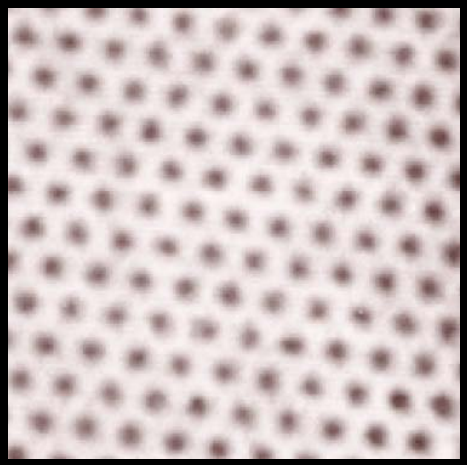
Linear fit!

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

Vortex pinning possibilities

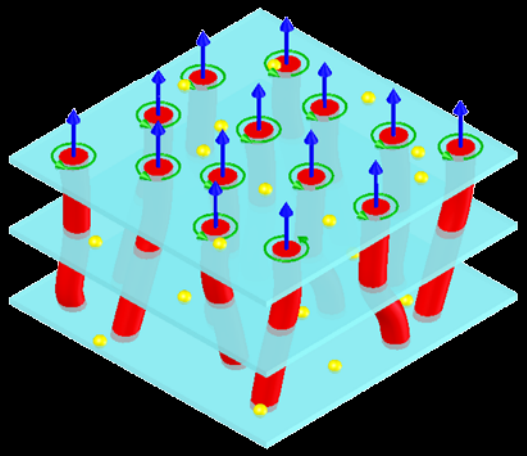
(1) no strong pinners
inter-vortex forces dominate
→ lattice formation

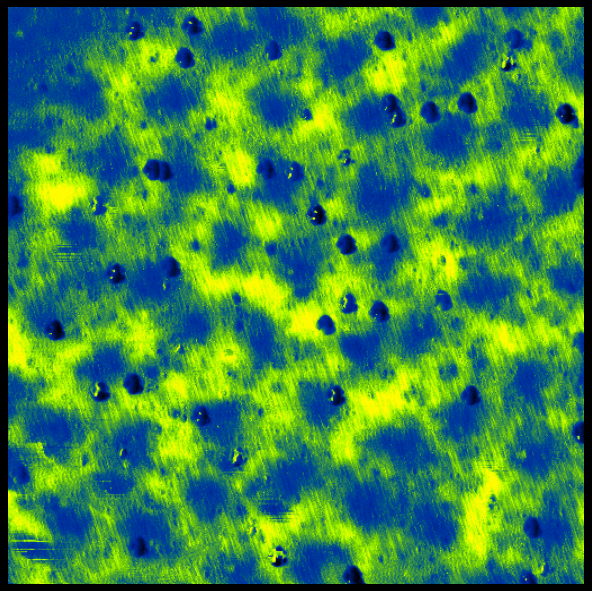




$NbSe_2$

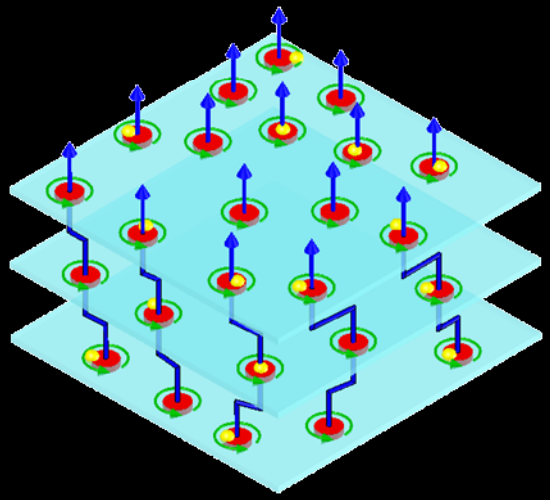
(2) strong pinners exist
low anisotropy
→ vortices bend slightly
to accommodate pinners

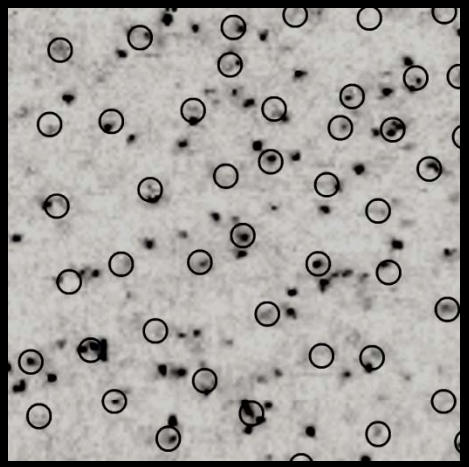




$Ba(Co_xFe_{1-x})_2As_2$

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





$Bi_2Sr_2CaCu_2O_8$

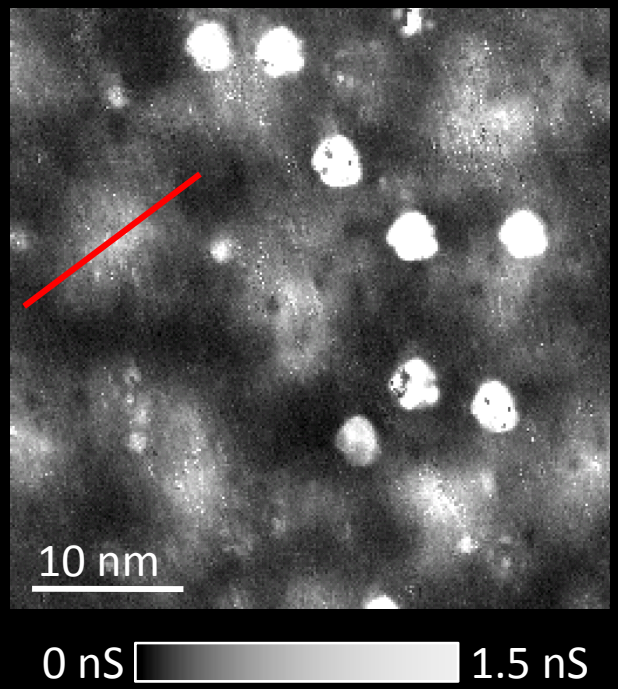
What we know so far…

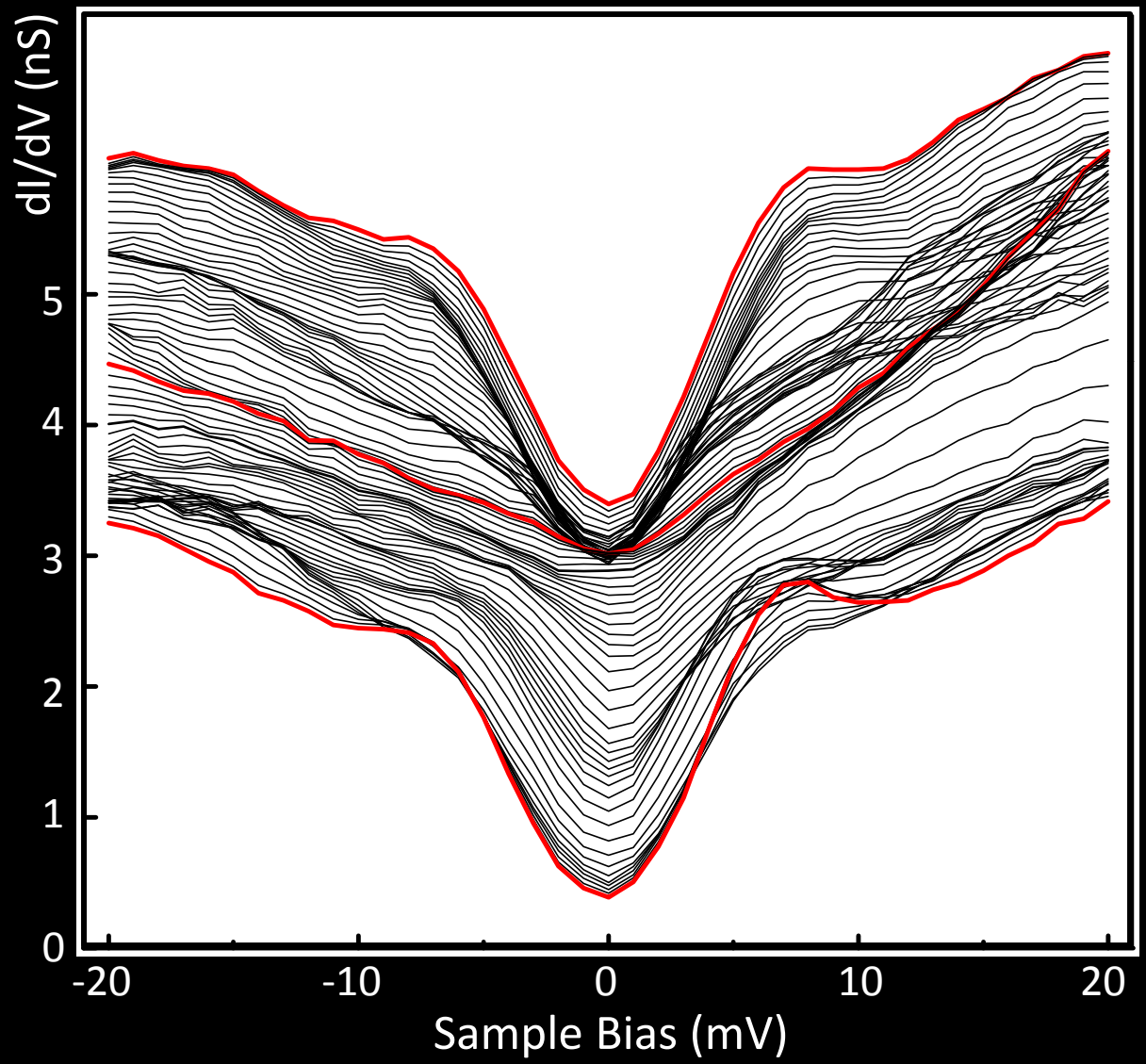
- We have a superconducting gap, in agreement with ARPES
- We have vortices, which are strongly pinned in bulk

Vortex Spectroscopy

dI/dV map at 0 mV

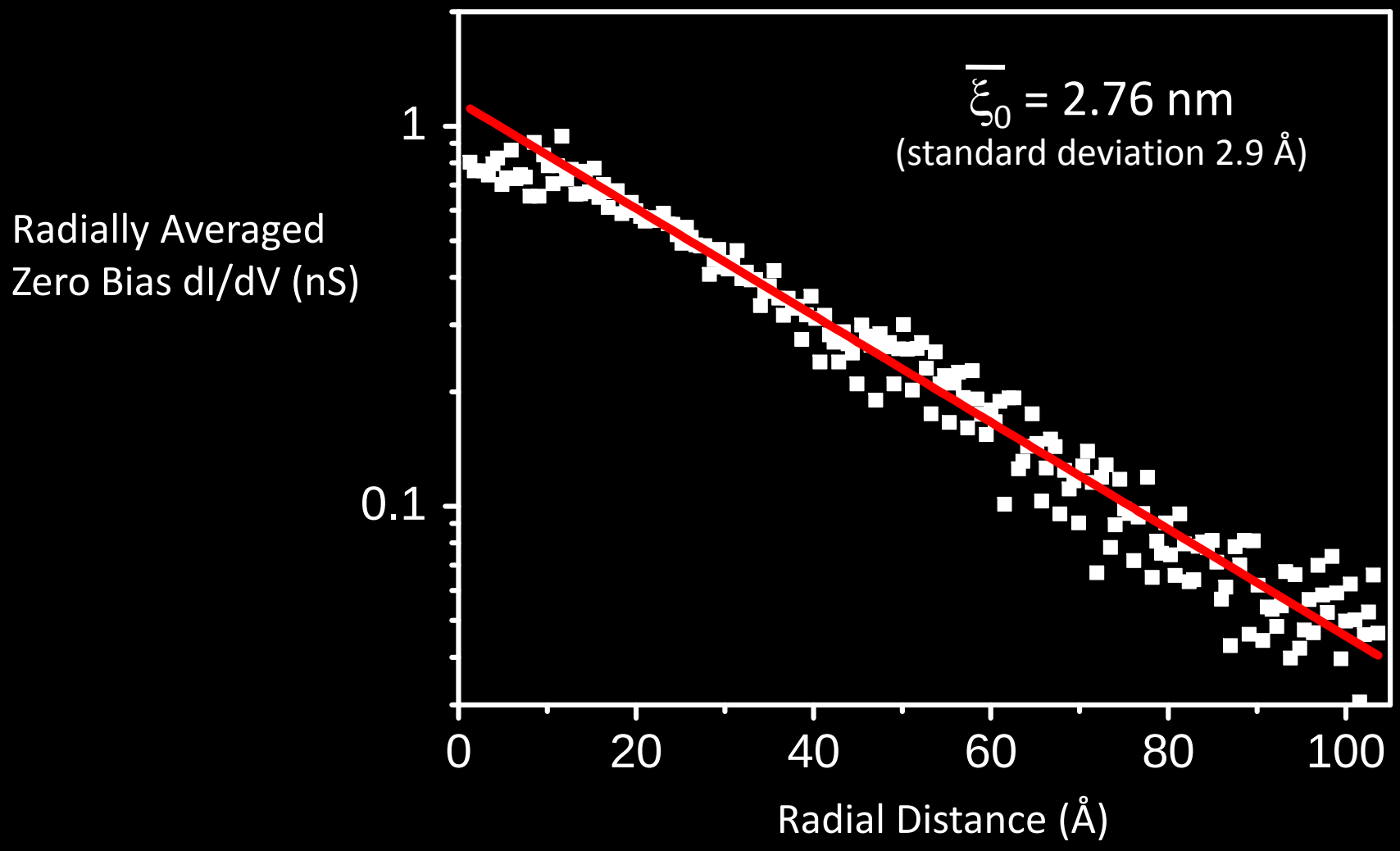
(Fermi level)





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

Coherence Length



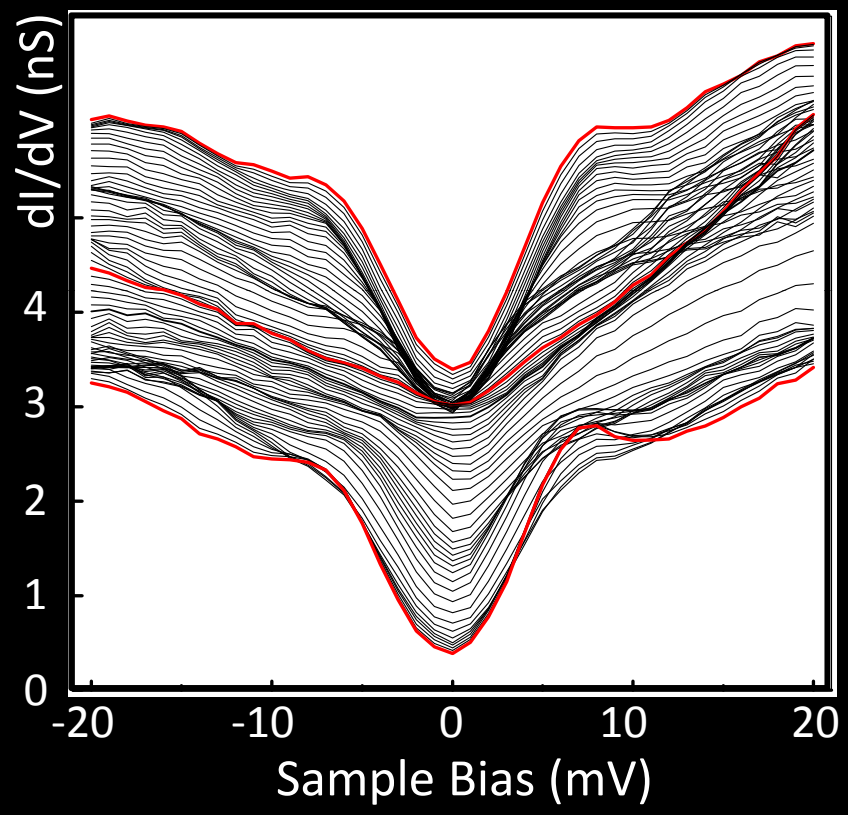
Note: this ξ_0 translates to H_{c2}=43T
[close to 50T extrapolated, Yamamoto, APL 94, 062511 (2009)]

Compare to Conventional *s*-wave Vortices

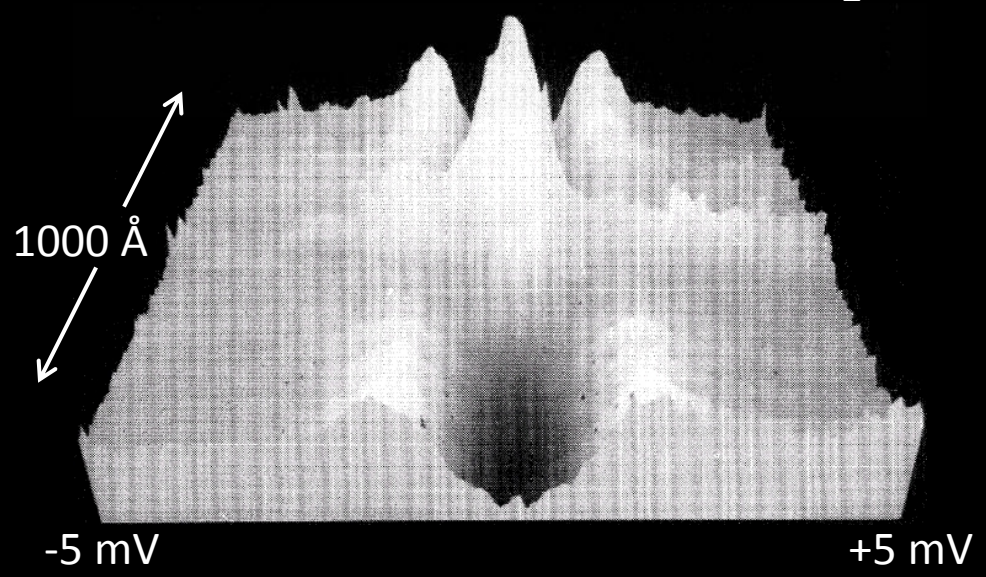
Theory: $E = \frac{1}{2}\Delta^2/\varepsilon_F$

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

$BaCo_xFe_{2-x}As_2$



STM experiments on $NbSe_2$



Hess, PRL 62, 214 (1989)

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

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

Clean Limit

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

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

bulk values,
measured by Xianhui Chen

→ electronic mean free path:

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

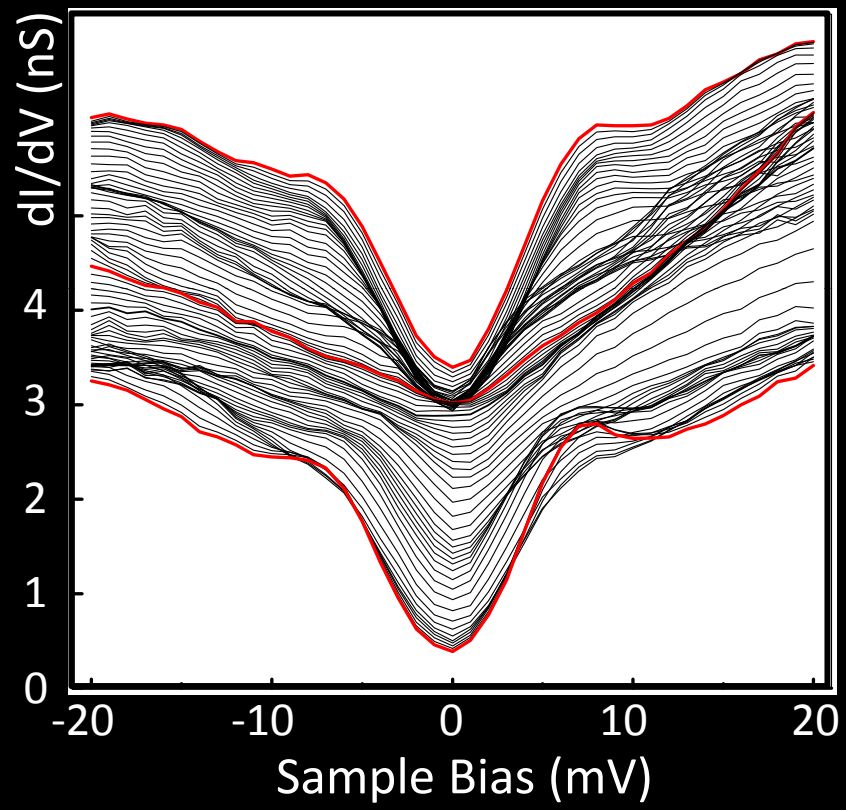
Compare to coherence length: $\xi_0 = 27.6$ Å

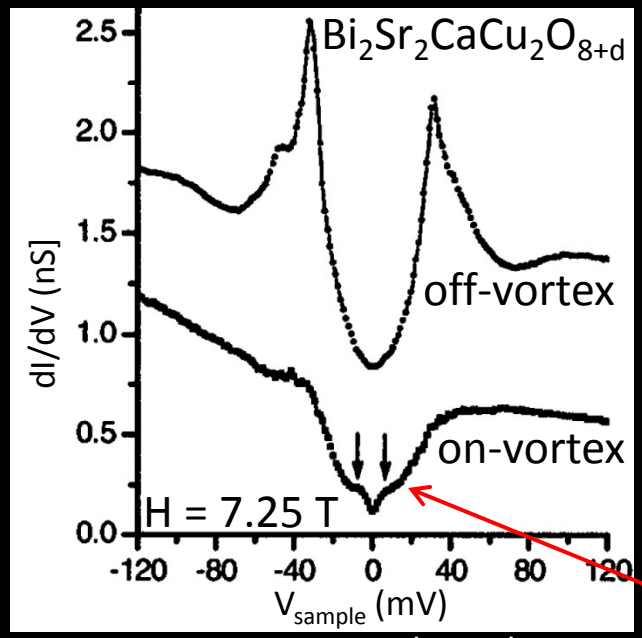
→ Clean limit

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

Compare to *d*-wave Vortex Spectroscopy

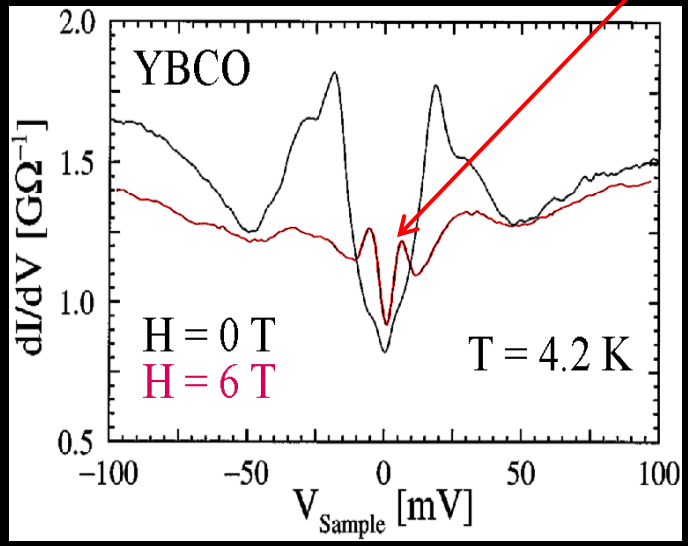
$BaCo_xFe_{2-x}As_2$





Pan, PRL 85, 1536 (2000)

E ~ Δ/4

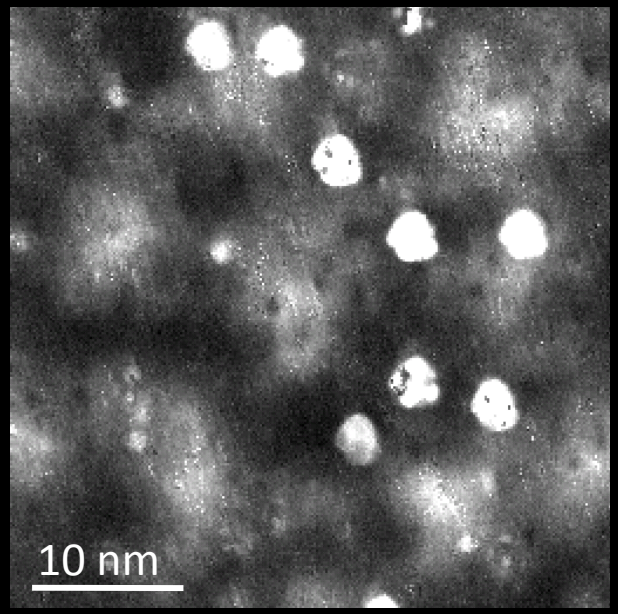


Maggio-Aprile, PRL 75, 2754 (1995)

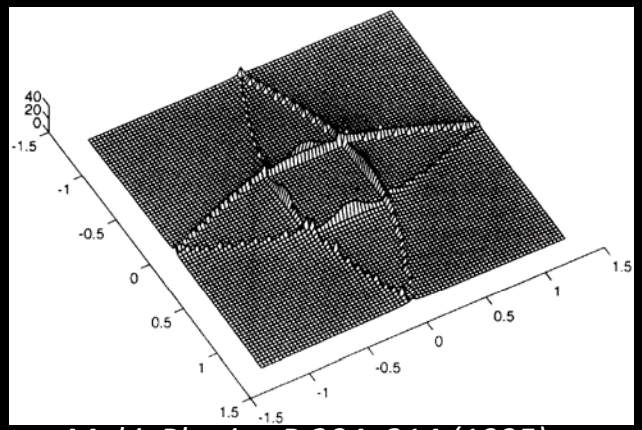
measurements at T=6K; k_BT = 0.5 meV
dV modulation = 1.5 meV

Compare to Theoretical *d*-wave Vortex Shape

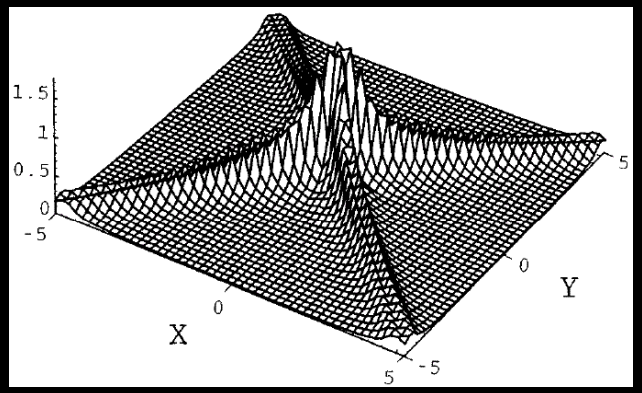
$BaCo_xFe_{2-x}As_2$



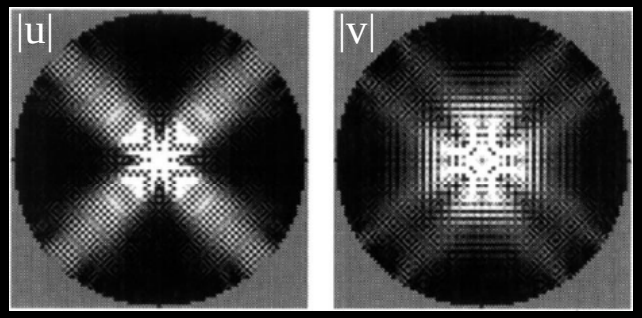
0 nS 1.5 nS



Maki, Physica B 204, 214 (1995)



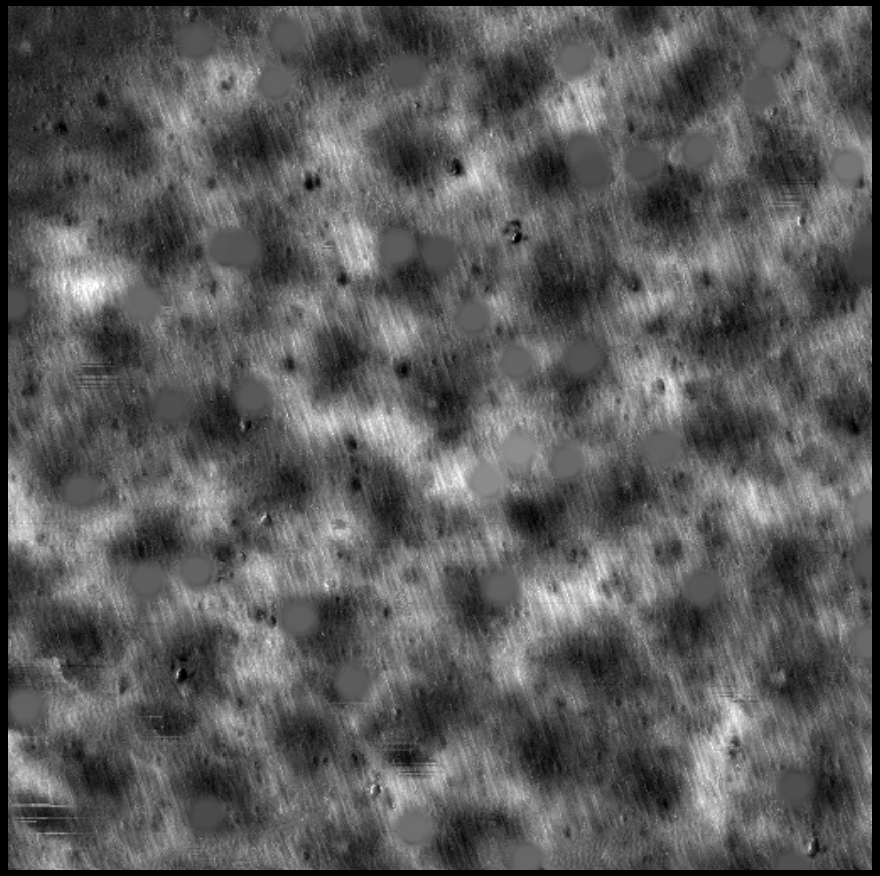
Ichioka, PRB 53, 15316 (1996)



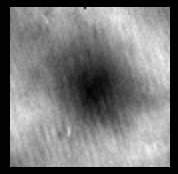
Franz & Tesanovic, PRB 53, 15316 (1996)

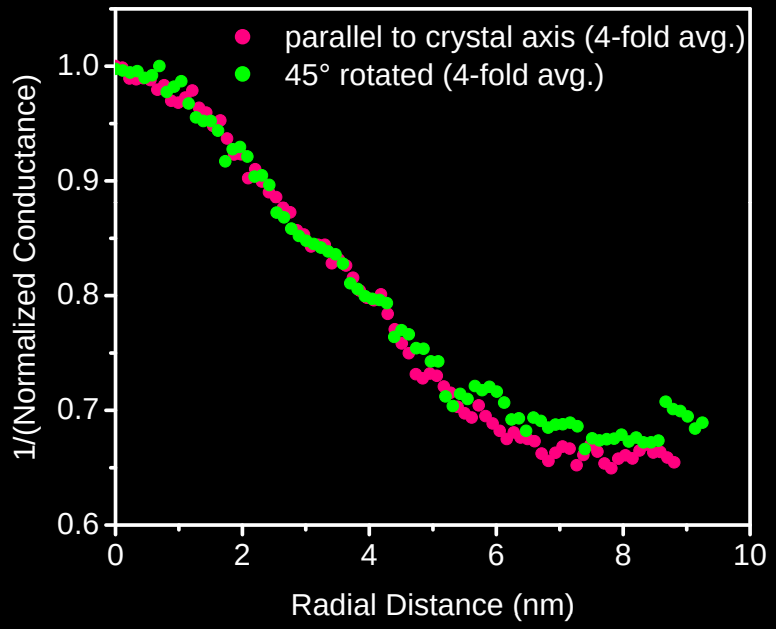
Are Vortices Isotropic?

Filter impurities



Average vortices

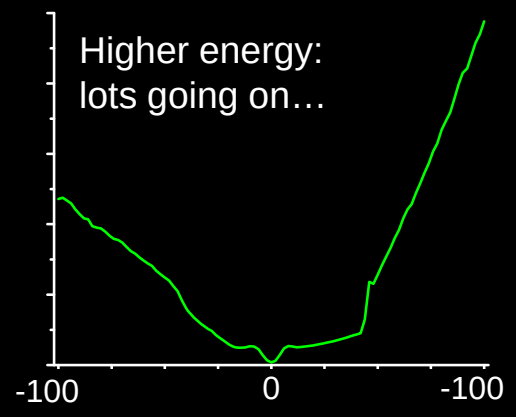




STM To-Do List

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

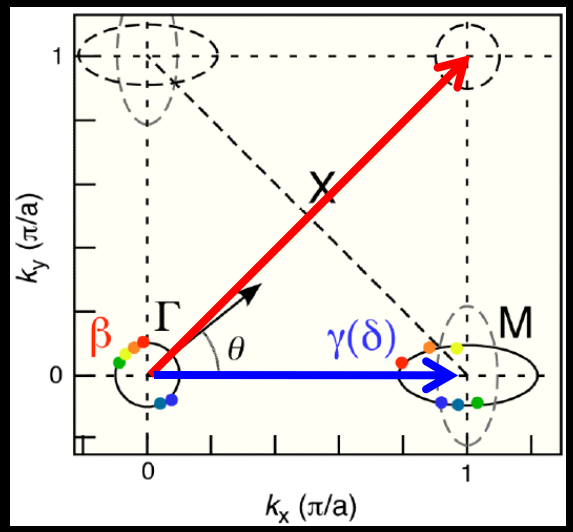
- Normalize to higher T



- 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

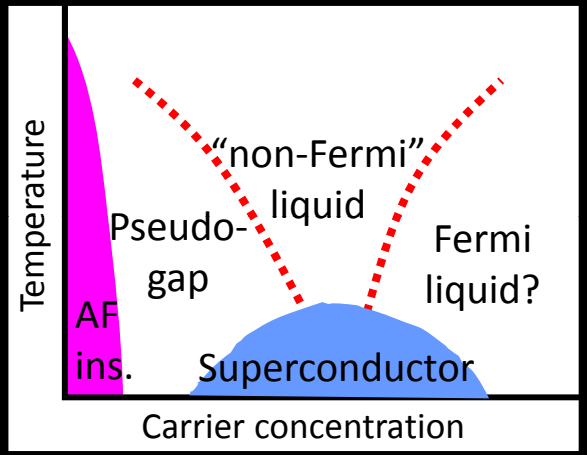
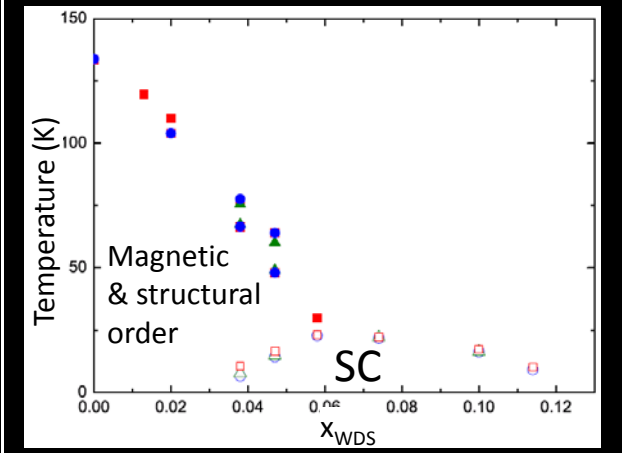
[Wang, Zhai, D. H. Lee, EPL, 85, 37005 (2009)]

[Note: Pereg-Barnea & Franz similarly predicted for d-wave scenario,
+/+ scattering enhanced in B, +/- scattering unaffected by B
PRB 78, 020509 (2008).]

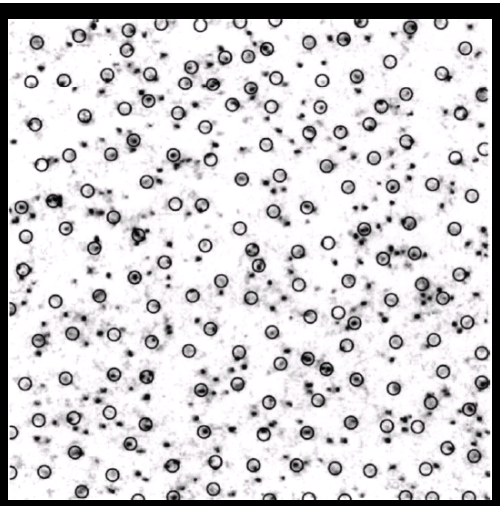
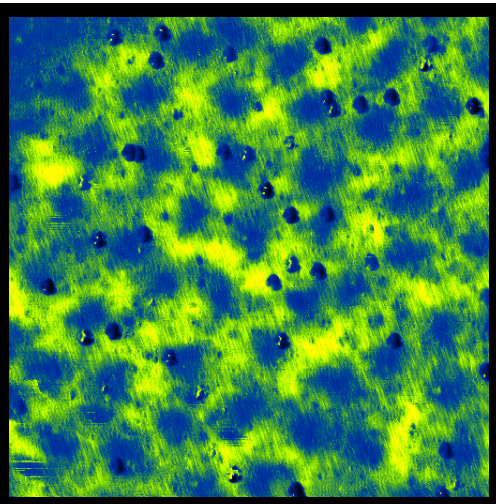
- Repeat impurity measurements, compare to preliminary theory
  [Michael Lawler, Eun-Ah Kim]

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

Cuprate-Pnictide Comparison

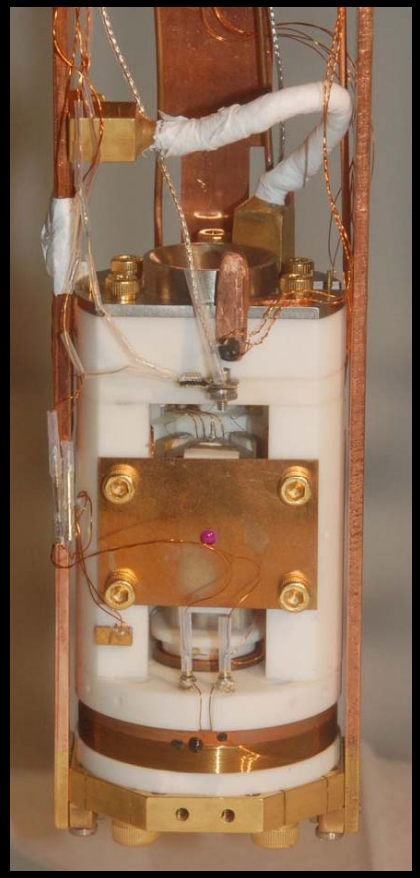
	Cuprate: $Bi_2Sr_2CaCu_2O_{8+d}$	Pnictide: $BaCo_xFe_{2-x}As_2$
phase diagram		 Ni, Canfield, *et al*, arXiv:0811.1767
ground state	antiferromagnetic Mott insulator	itinerant antiferromagnet semimetal
gap symmetry	*d*-wave	*s*± ??
anisotropy, γ	~ 50	~ 1-3
optimal T_c	91 K	25.3 K

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

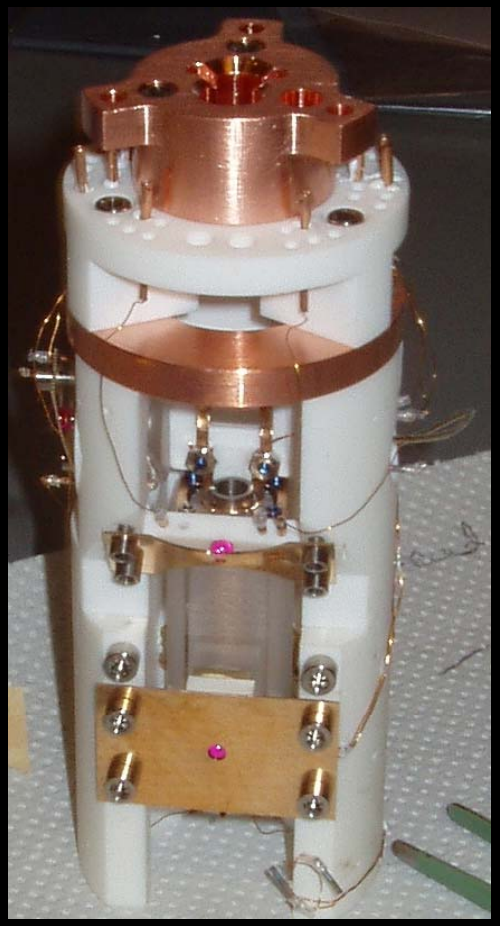
Scanning Probe Microscopy

STM



all of the data
in this talk

Spin-Polarized
STM



Magnetic Force
Microscope

coming on line in the next 6 months - year