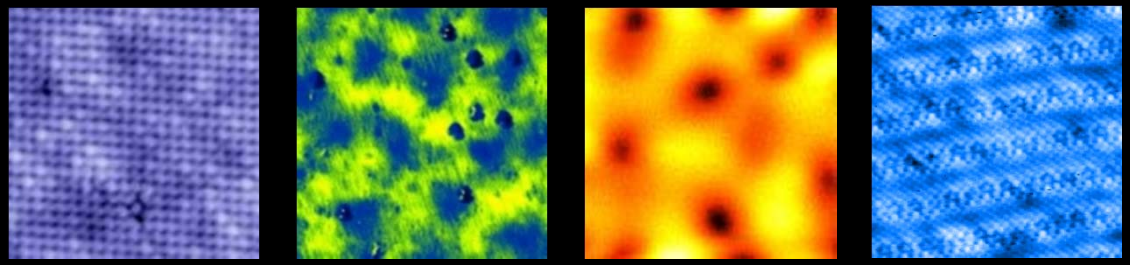
The Competitive Landscape of High-Tc Superconductivity

Jenny Hoffman



Experiments:

Magdalena Huefner
Jeehoon Kim
Liz Main
Tess Williams
Yi Yin
Martin Zech
Ilija Zeljkovic
Harvard Physics

Mike Boyer
Kamalesh Chatterjee
Doug Wise
Eric Hudson
MIT Physics

Samples:

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T. Takeuchi
Hiroshi Ikuta
Nagoya University

XiangFeng Wang
Gang Wu
Xianhui Chen
USTC

Genda Gu
Brookhaven

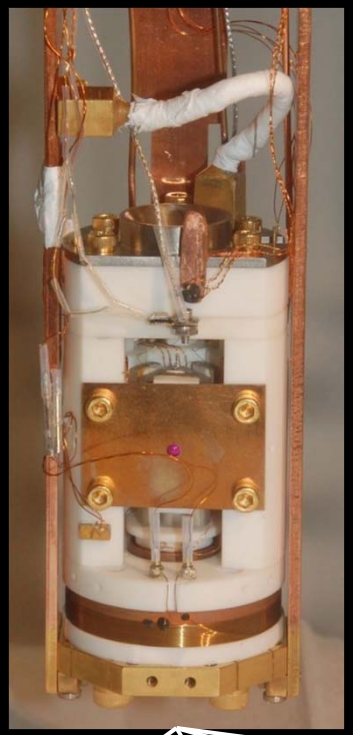
Paul Canfield
Ames Lab, Iowa

Thanks to:

NSEC

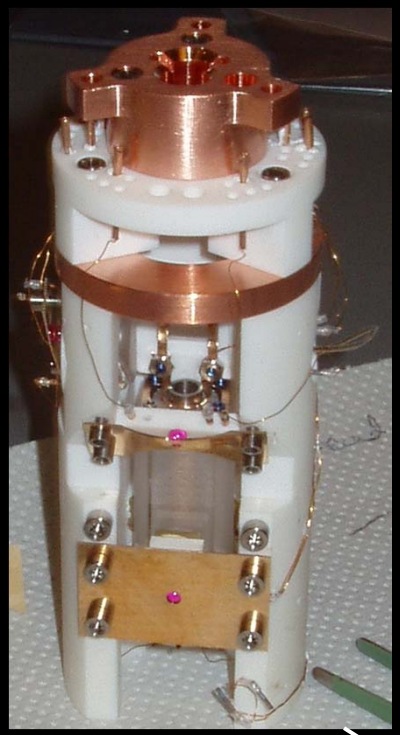
Hoffman Lab Local Probes

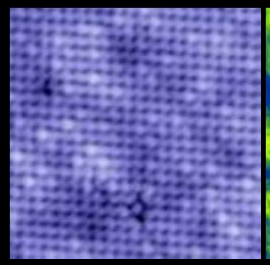
Scanning Tunneling Microscope



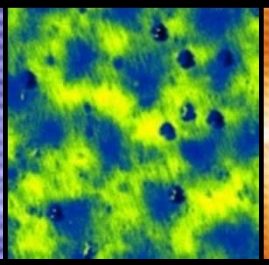
Force Microscope

Ultra-high vacuum STM

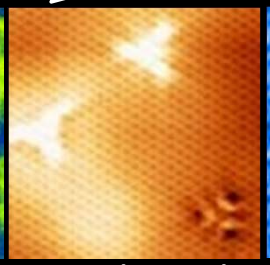




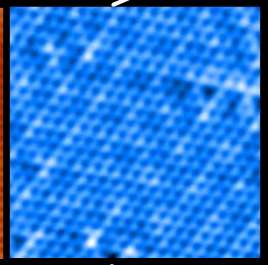
Bi-2201



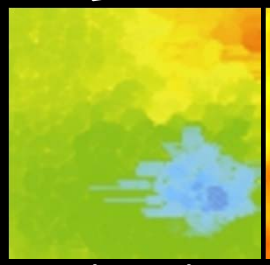
122 iron pnictide



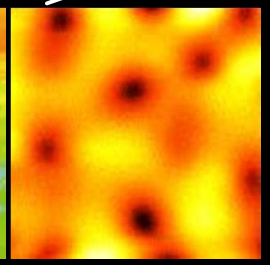
topological insulator



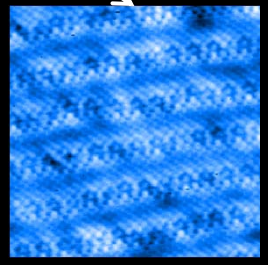
$NbSe_2$



metal-insulator transition in VO_2



1111 iron pnictide



Bi-2212

Outline

Superconductors: 100 Year History

Pseudogap in cuprates:

- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:

- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy

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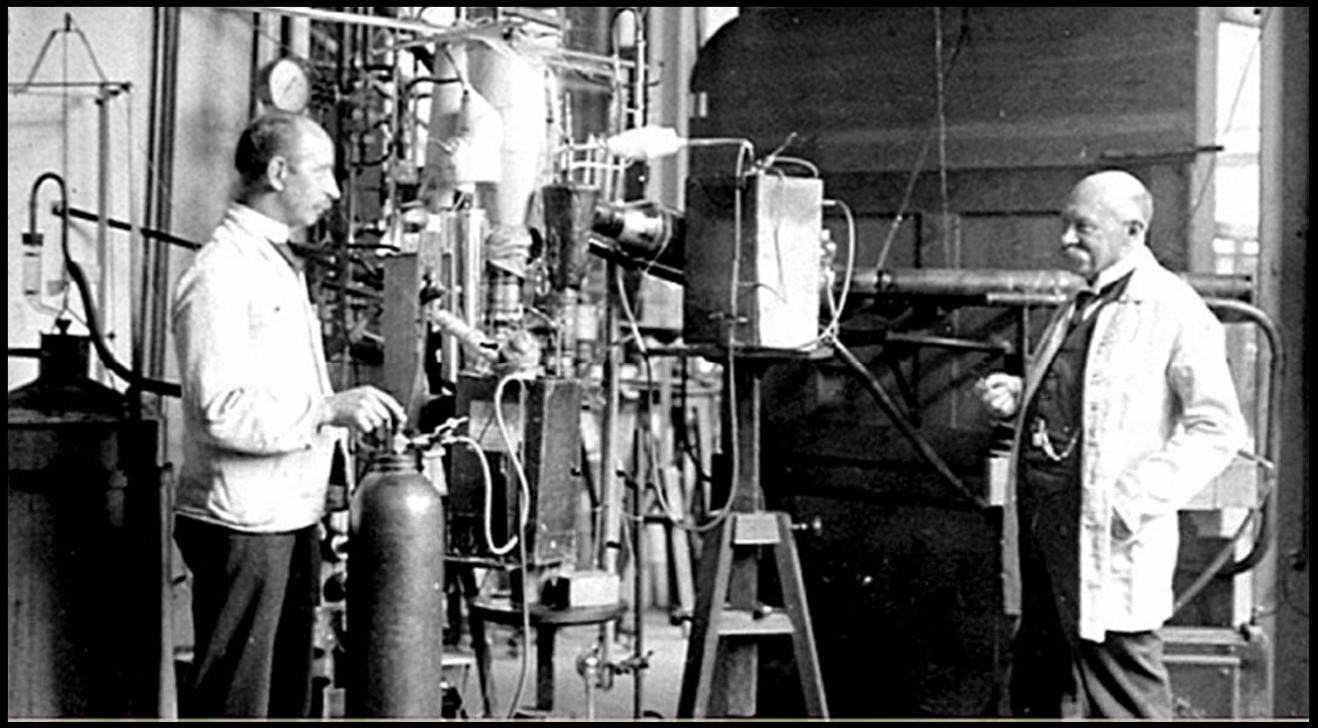
100 Year Anniversary of Discovery of Superconductors

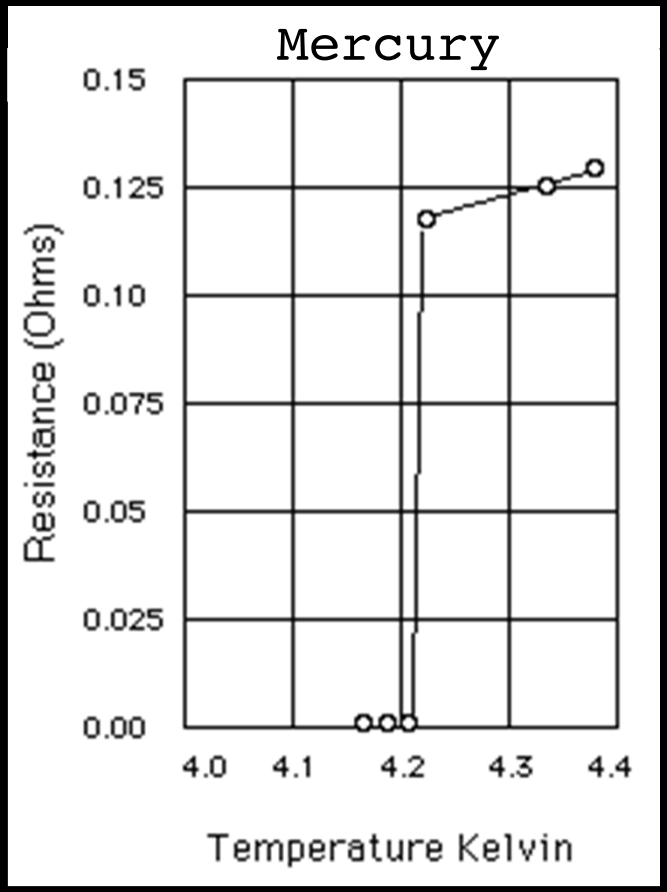


Heike Kamerlingh Onnes (right) and Gerrit Flim, his chief technician, at the helium liquefier in Kamerlingh Onnes's Leiden laboratory, circa 1911.

Physics Today, Sept 2010

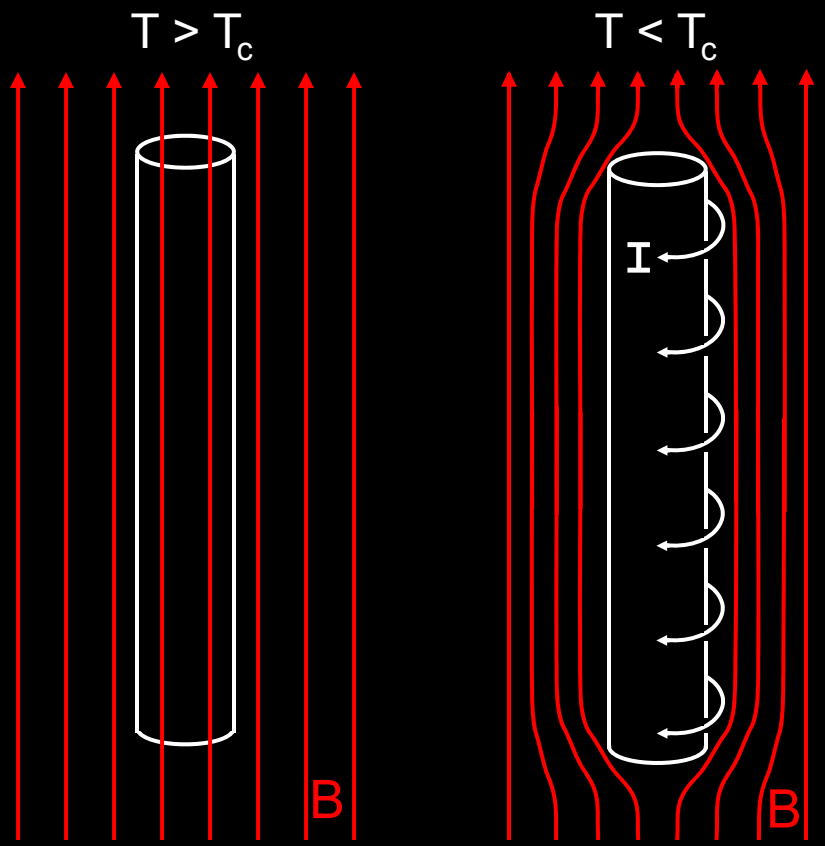
2 Properties of Superconductors

1. Vanishing of electrical resistivity (by Cooper pairing)



Kamerlingh-Onnes, 1911

2. Expulsion of magnetic field (by shielding currents)



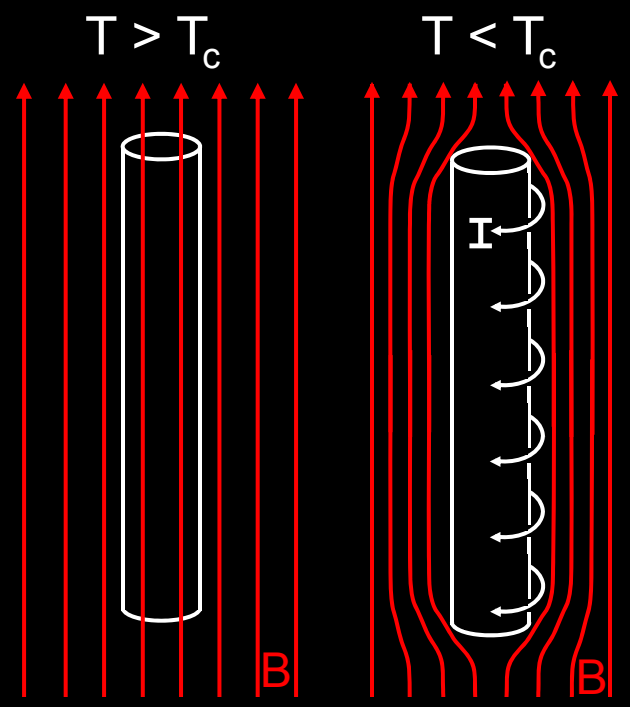
Meissner, 1933

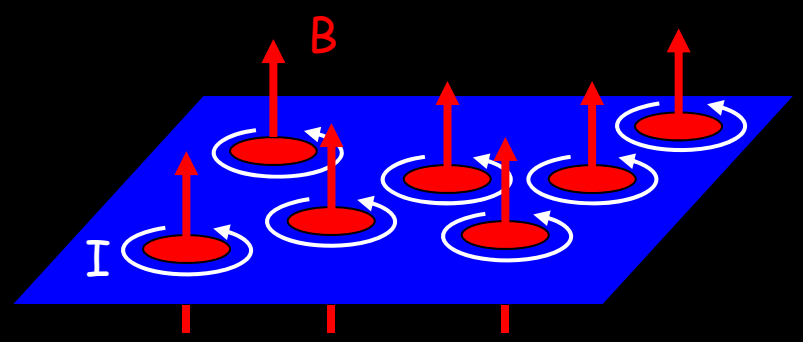
2 Types of Superconductors

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

Type I: Meissner

Type II: Vortices

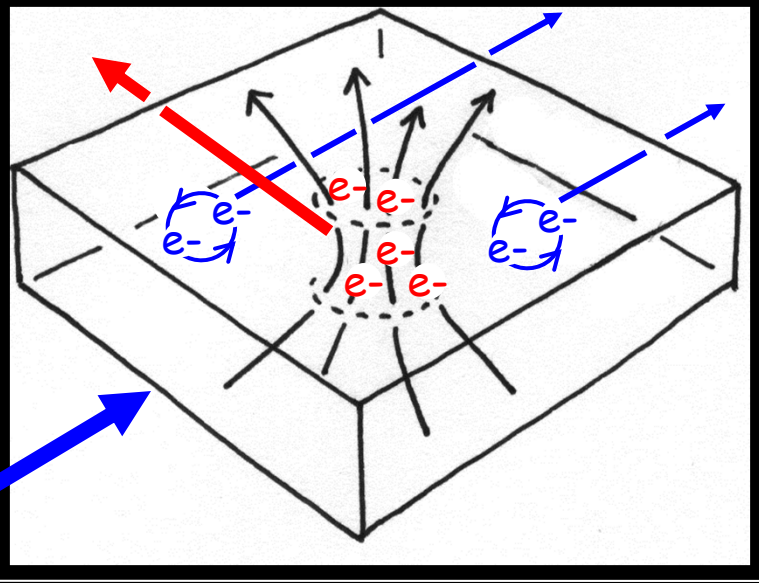




→ Type II Superconductors are generally more useful

Vortex Challenges

Normal electrons in vortex core cause dissipation when moved



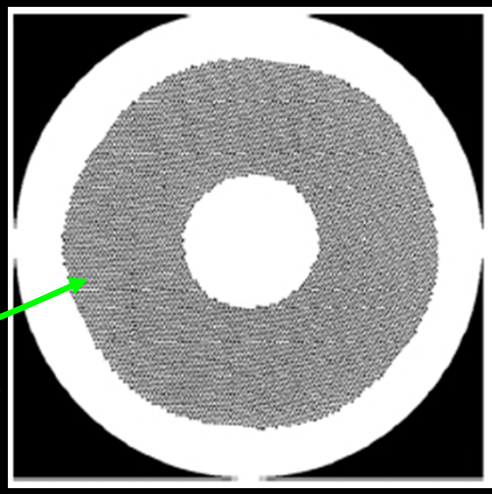
Apply current I: Cooper pairs flow without dissipation

→need some mechanism to *pin* vortices in place

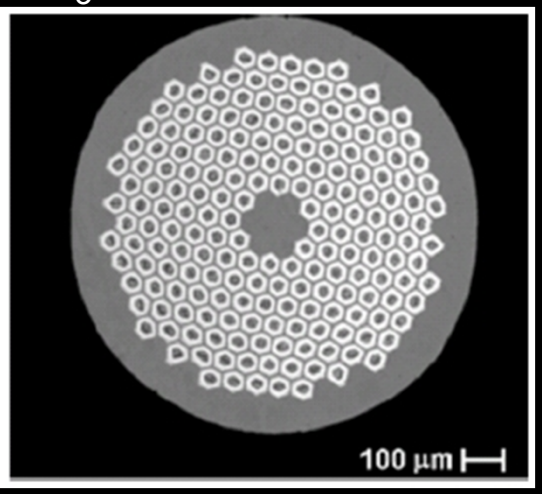
Center of vortex: superconductivity is destroyed → costs energy!

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

Nb47wt%Ti



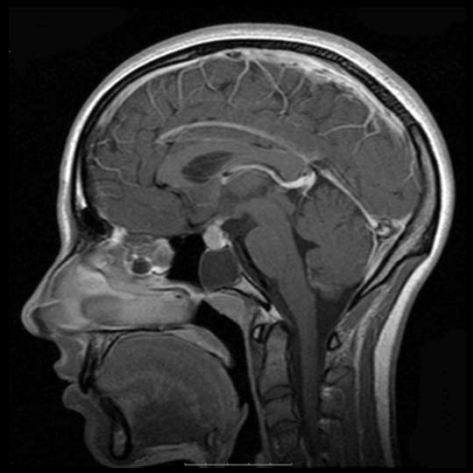
Nb_3Sn



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

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1933 – Meissner – superconductors screen B-field

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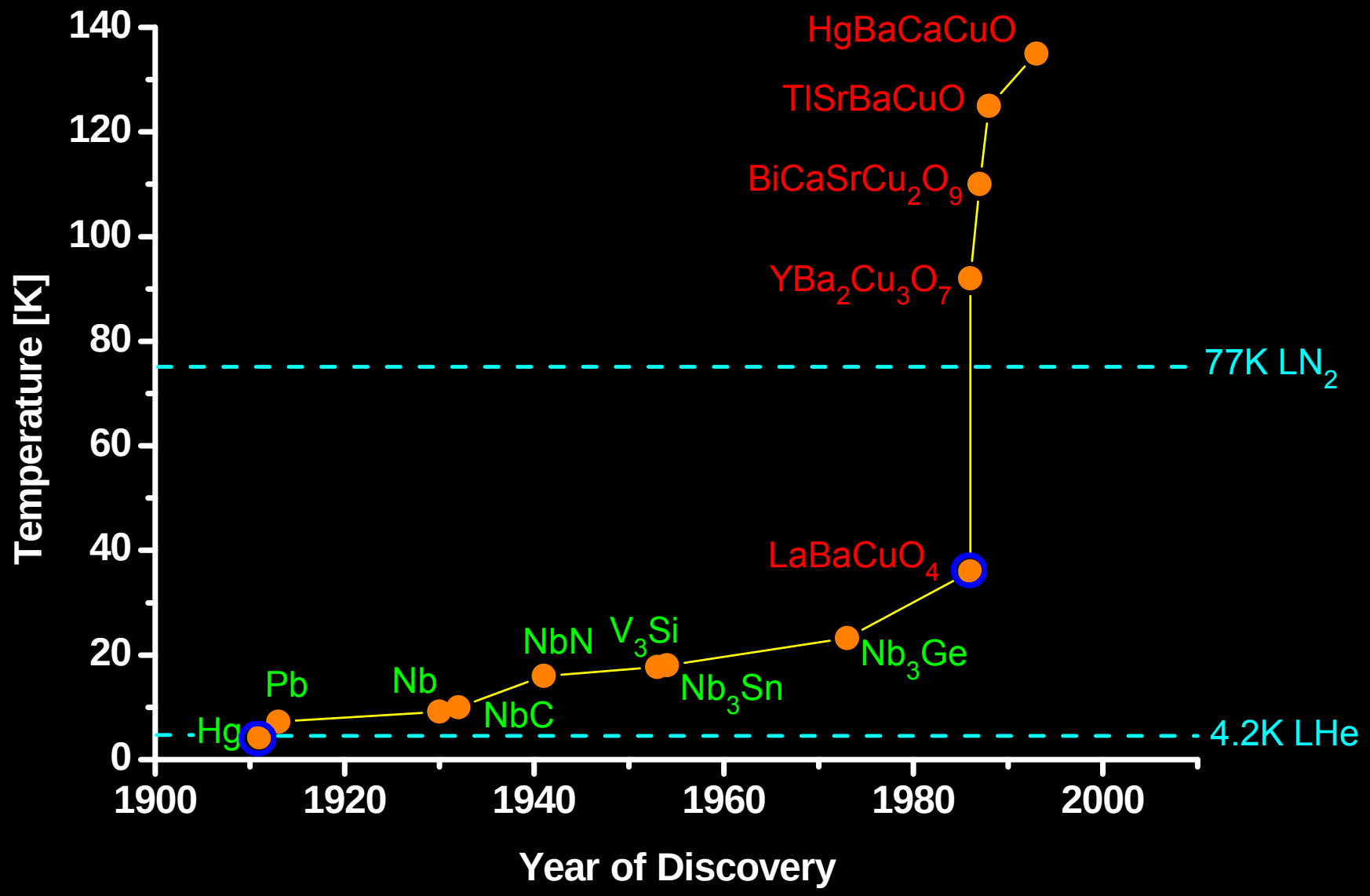
1962 – Josephson – field-dependent tunneling (SQUIDS) → 1973 Nobel Prize

Vortex pinning problem largely solved…
but still not so many practical applications because T requirements so severe…

History of Superconducting T_c



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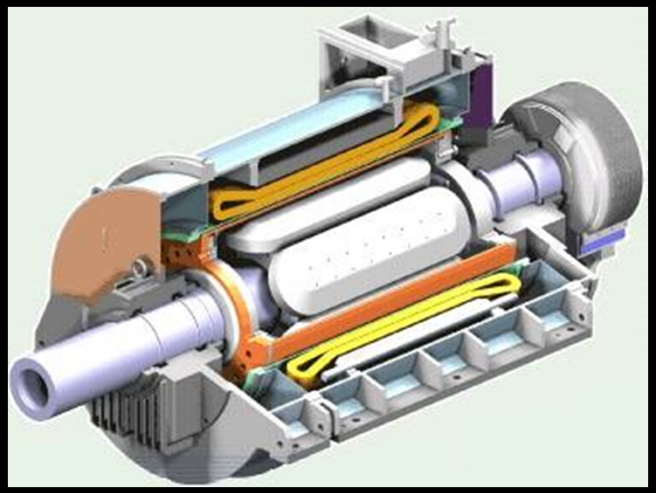
Applications of Cuprate Superconductors

Maglev Trains:
Southwest Jiaotong University, China

IEEE Transactions on Applied Superconductivity ***19****, 2142 (2009)*

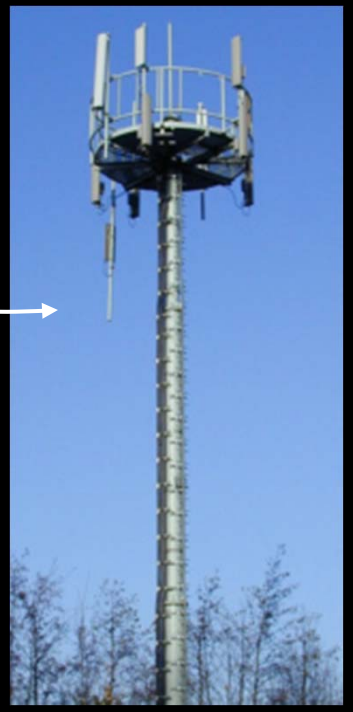


American Superconductor:
more efficient motors & generators
e.g. this 5 MegaWatt motor is
~30% weight, 50% size
of conventional motor
→ *great* for ships, airplanes!

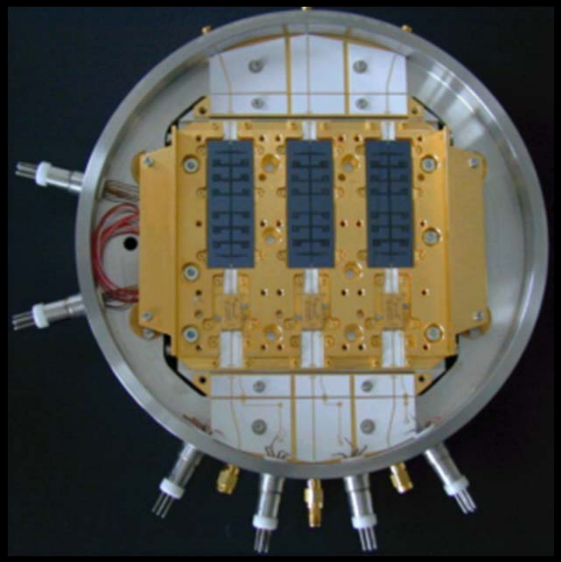
Applications of Cuprate Superconductors

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)

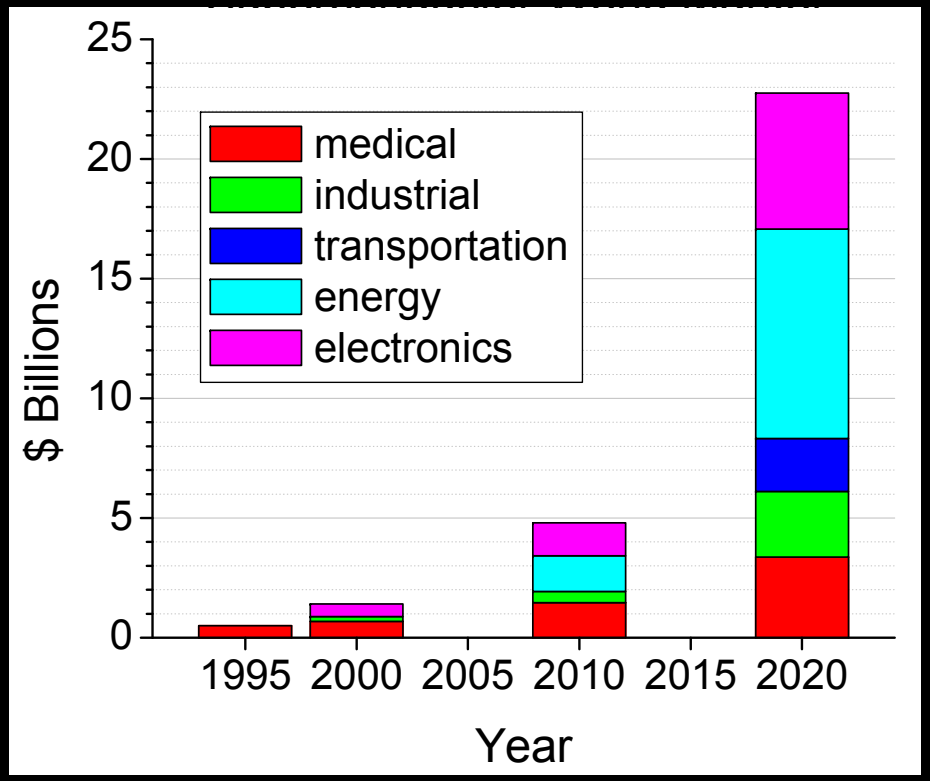


Superconductor Technologies



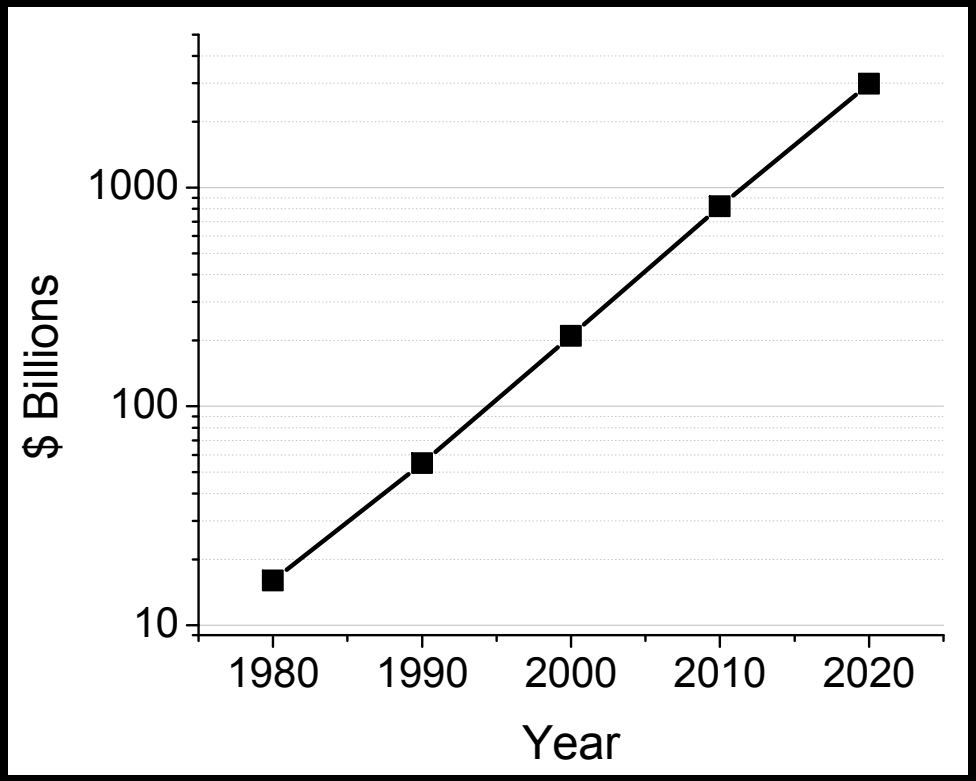
Projected World Markets

Superconductors:



(Conectus, 2004)

Semiconductors:



(Sakurai, 1999)

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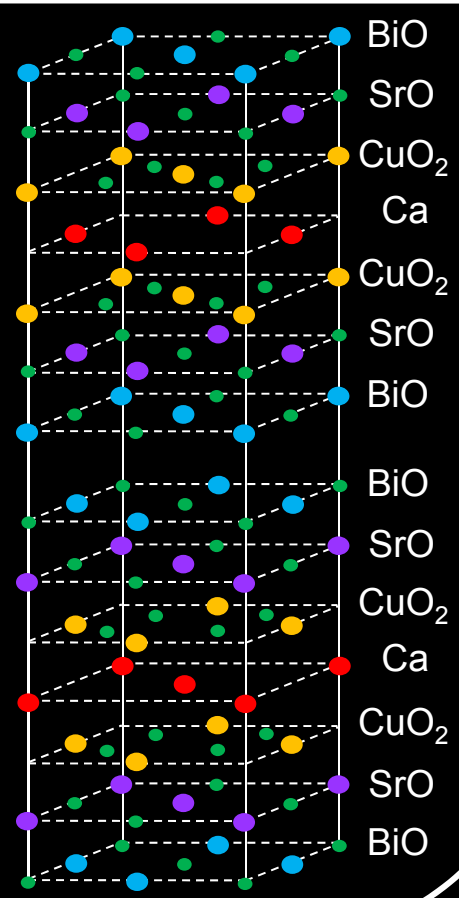
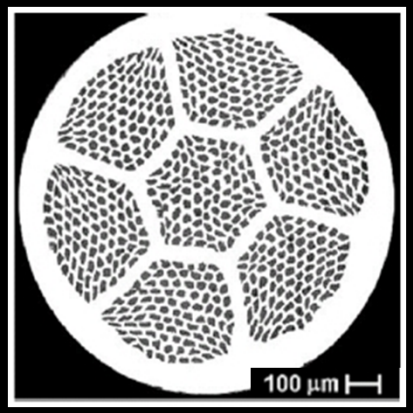
Still not so many practical applications…
severe vortex pinning problems in cuprates…
T requirements still non-trivial…

Material Considerations

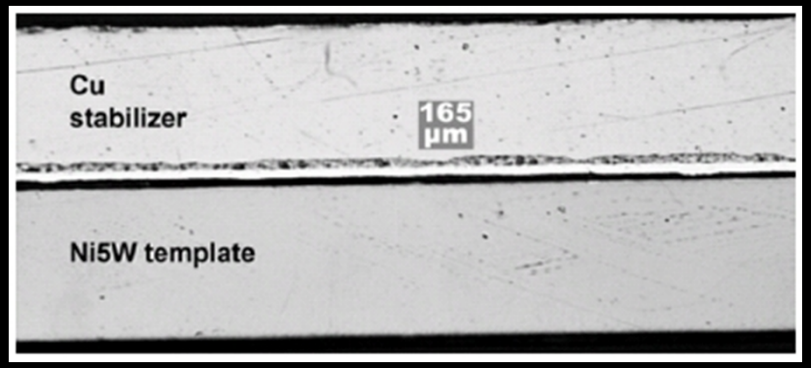


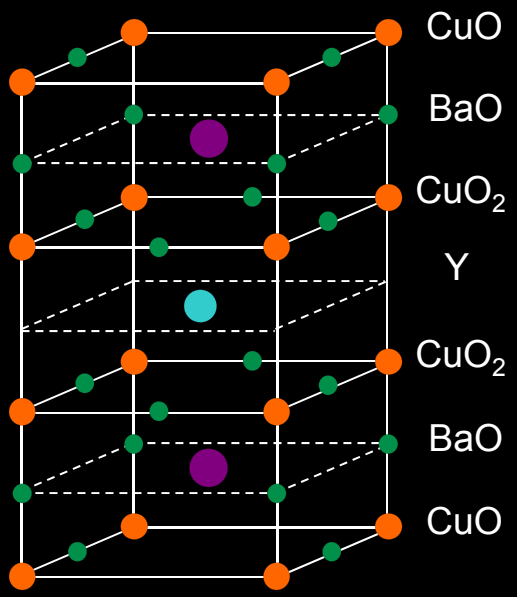
$Bi_2Sr_2CaCu_2O_{8+d}$/Ag wires



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

$YBa_2Cu_3O_{7-d}$ tapes

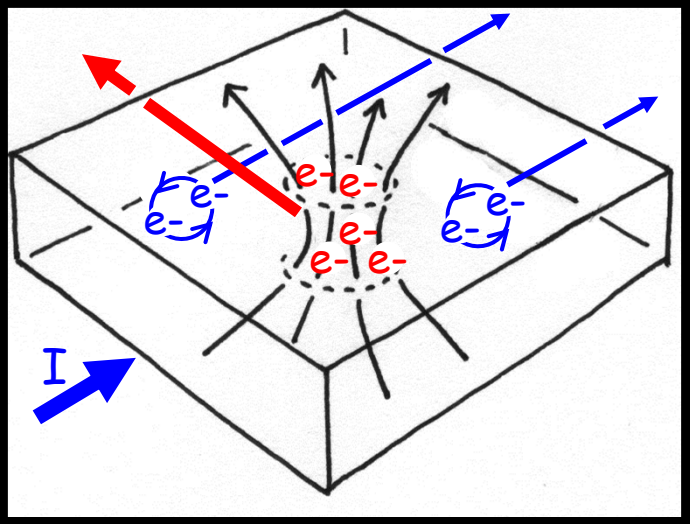


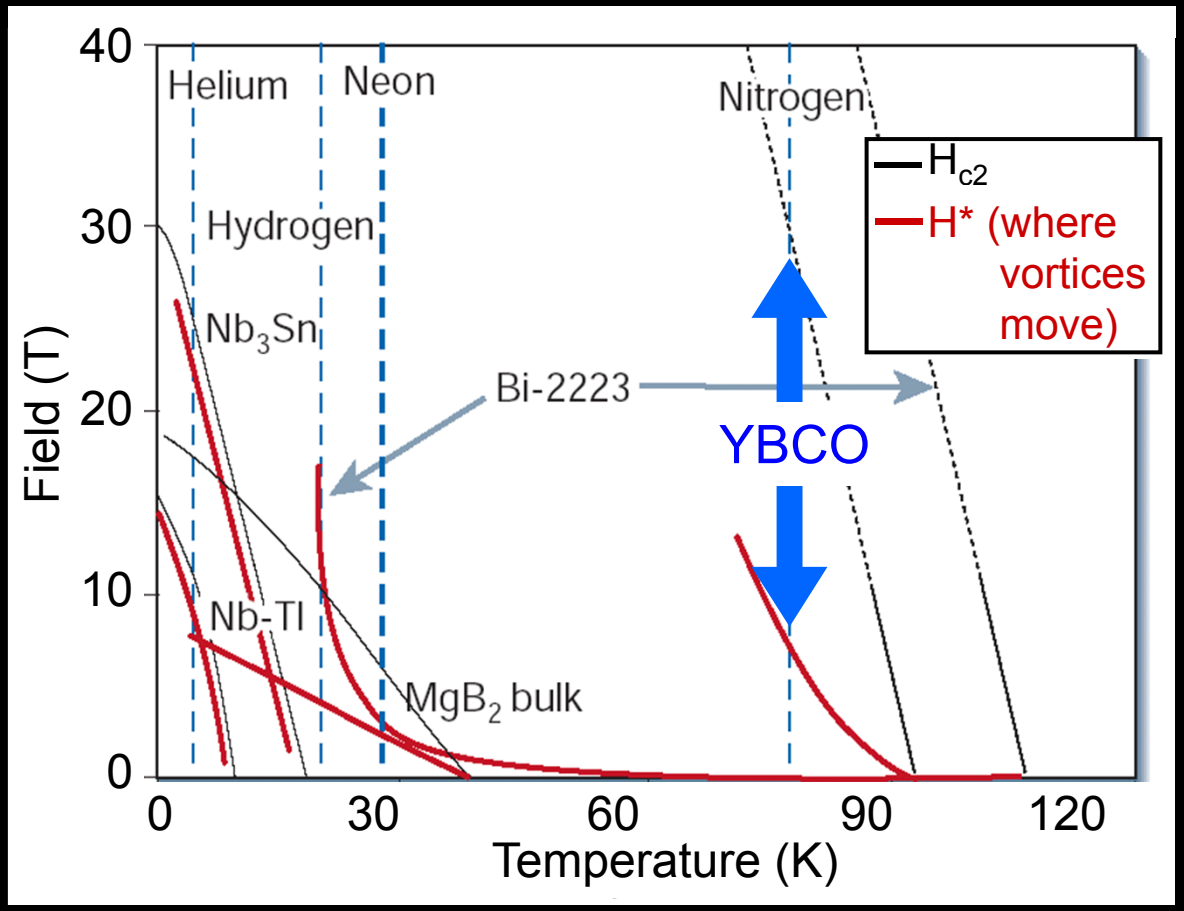


Advantages:
- cheaper materials
- tapes are aligned on 2 axes
  →cuts down on grain boundaries
- anisotropy is only ~7
- non-vacuum manufacture processes

review: Scanlan, IEEE 92, 1639 (2004)

Trouble With Vortices



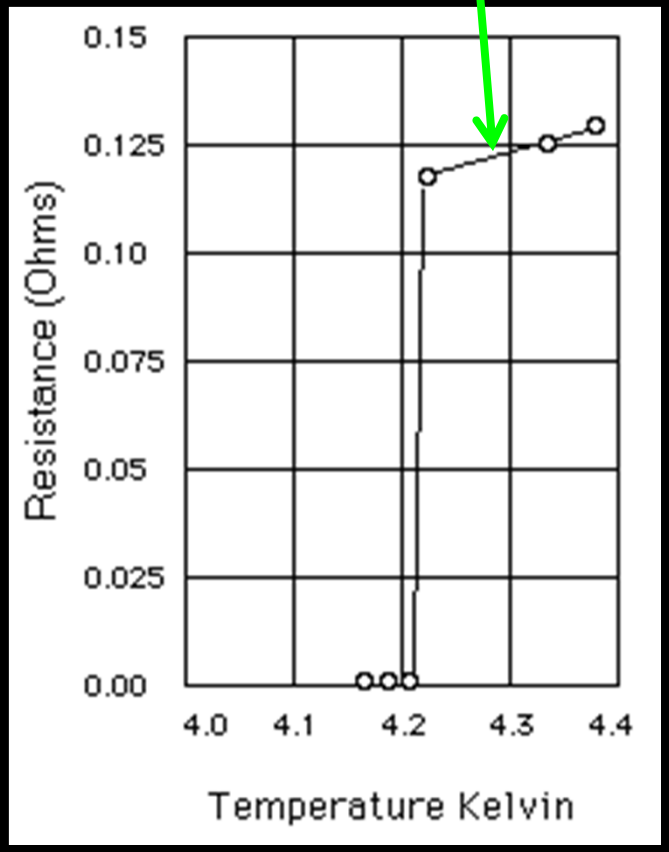


Larbalestier, Nature 414, 368 (2001)

Conventional – Cuprate Comparison

Conventional Superconductors

normal state is metallic



- materials are ductile, easy to make wires
- Fermi liquid ground state is a well-understood starting point for the theory of superconductivity

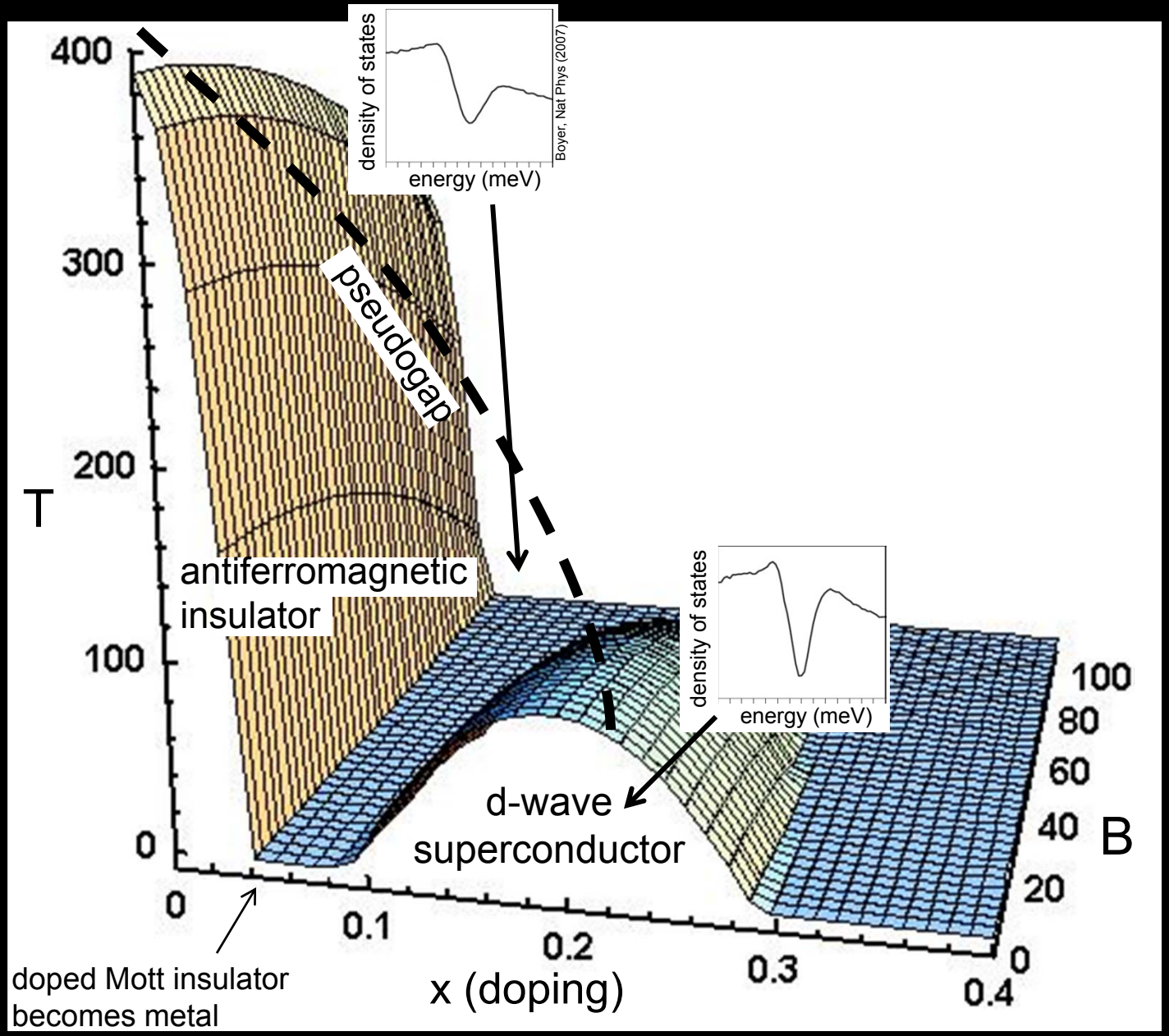
Cuprate Superconductors

"normal" state is insulating

?

- how can that be?
- how can we hope to understand superconductivity, if we don't even understand its precursor state?

Cuprate Phase Diagram



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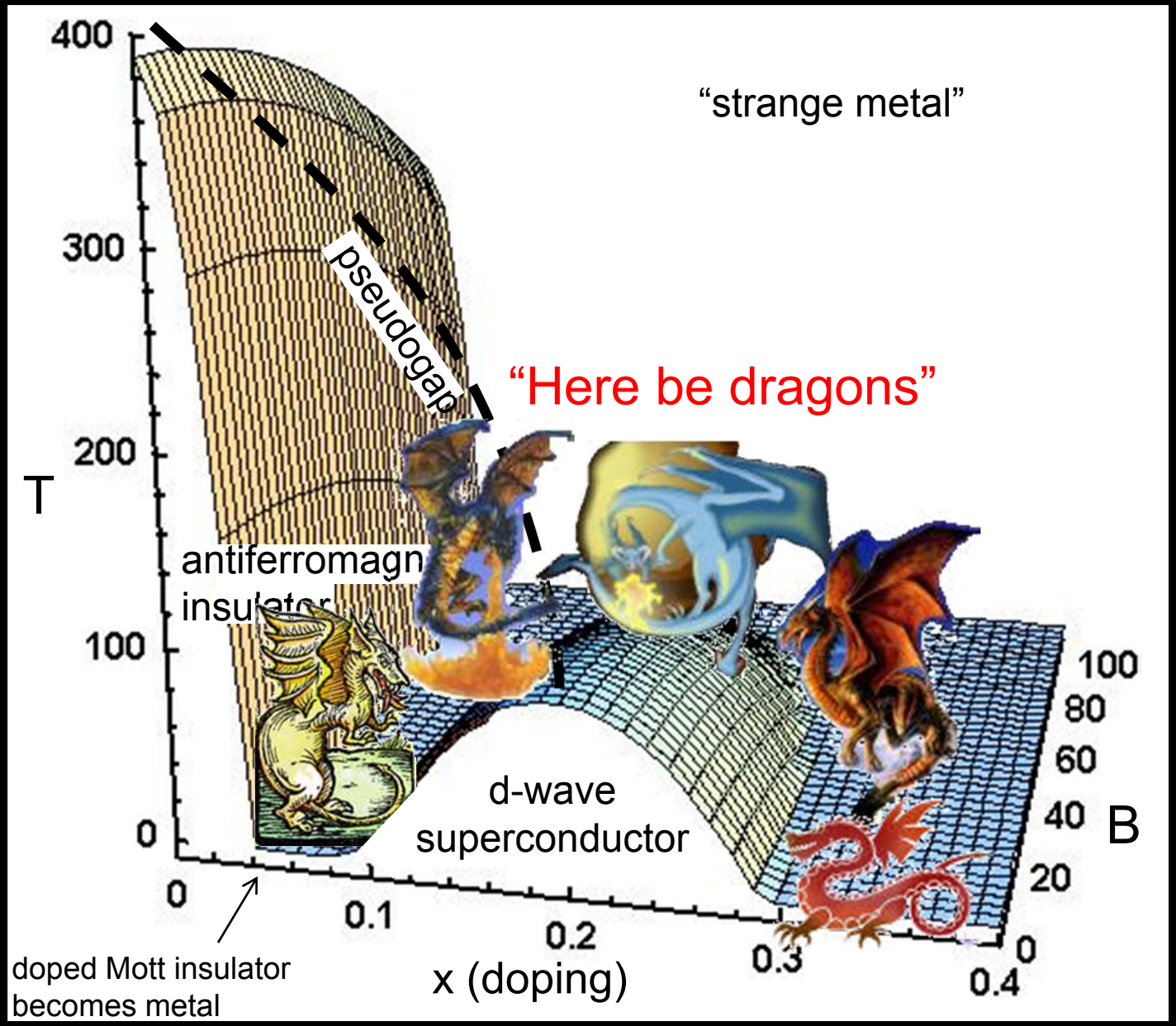

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severe vortex pinning problems in cuprates…
T requirements still non-trivial…

Today's frontiers:

1. discover higher-T_c materials → need to understand the ones we've got
2. improve vortex pinning in high-T_c materials

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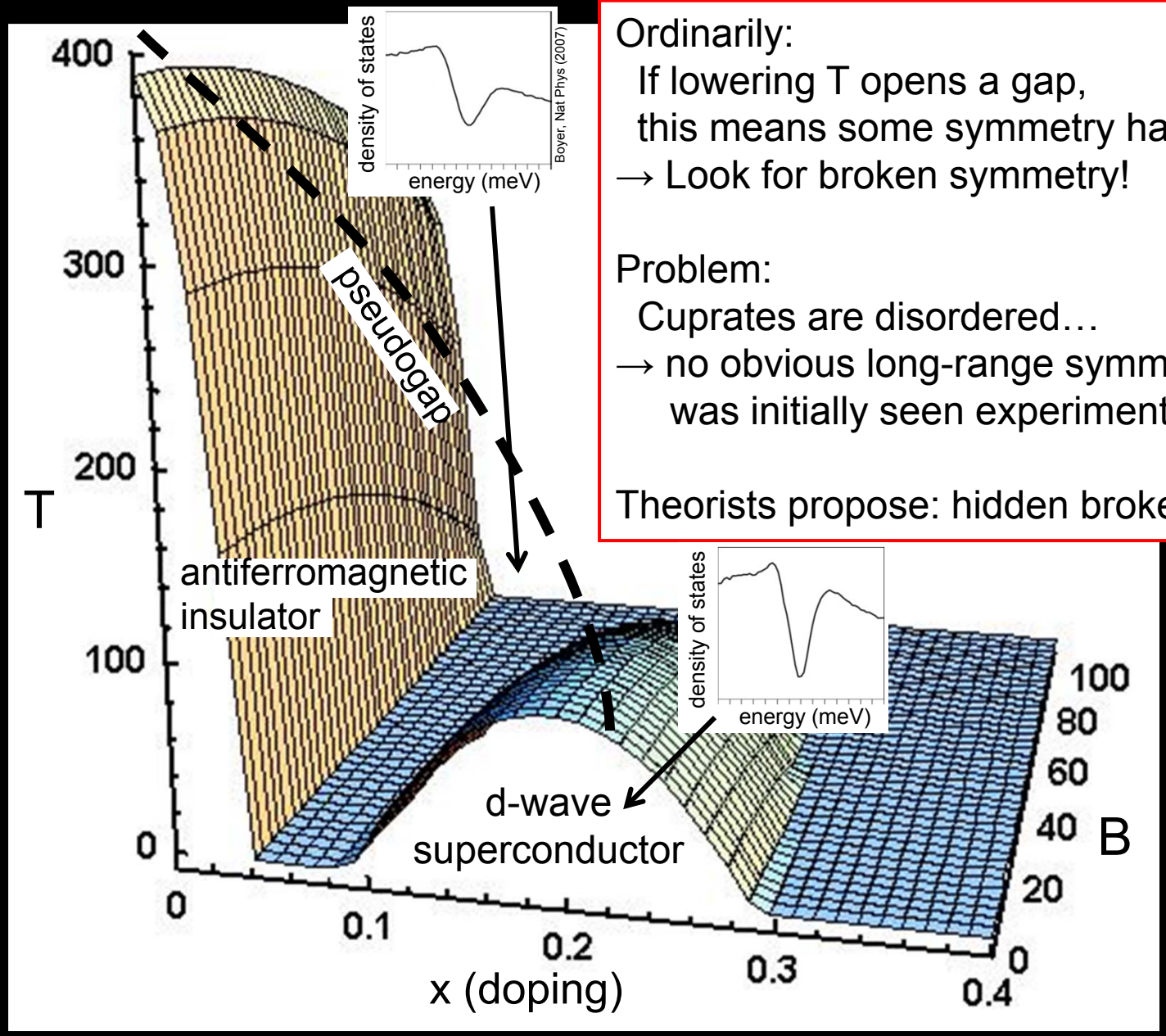


Ordinarily:
If lowering T opens a gap,
this means some symmetry has been broken.
→ Look for broken symmetry!

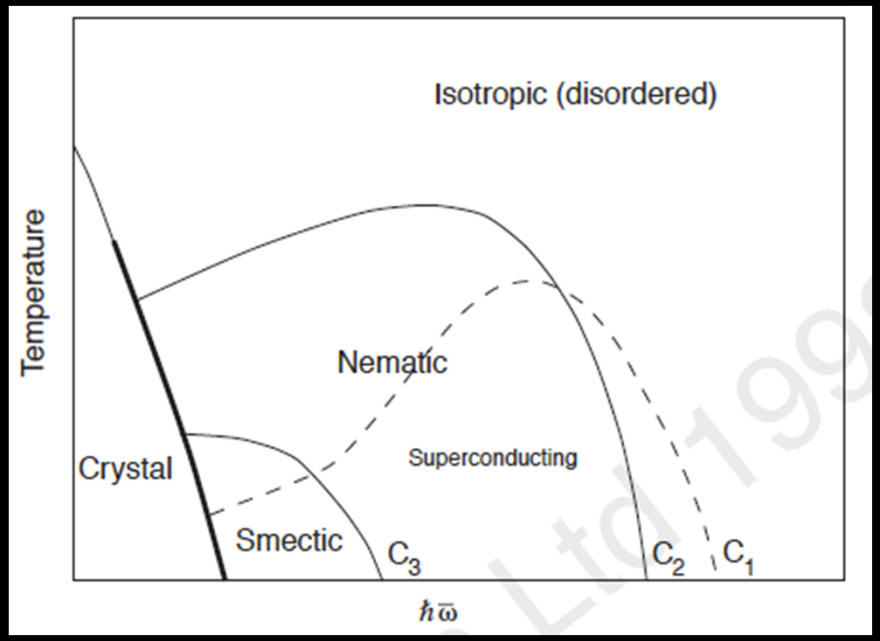
Problem:
Cuprates are disordered…
→ no obvious long-range symmetry breaking was initially seen experimentally

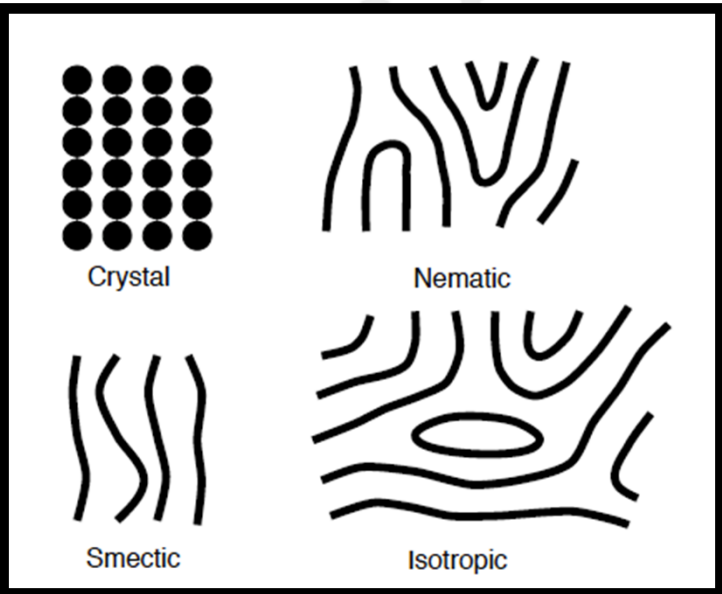
Theorists propose: hidden broken symmetries!

Kivelson: stripy liquid crystal phases

Fluctuating stripes play to role of the "nematogens" which allows for the formation of various "electronic liquid crystalline phases" in the pseudo-gap regime.

Local stripe order may enhance pairing, but stripe order certainly suppresses superfluid stiffness.





Nematic:
breaks long-range rotation
Smectic:
breaks long-range rotation & translation

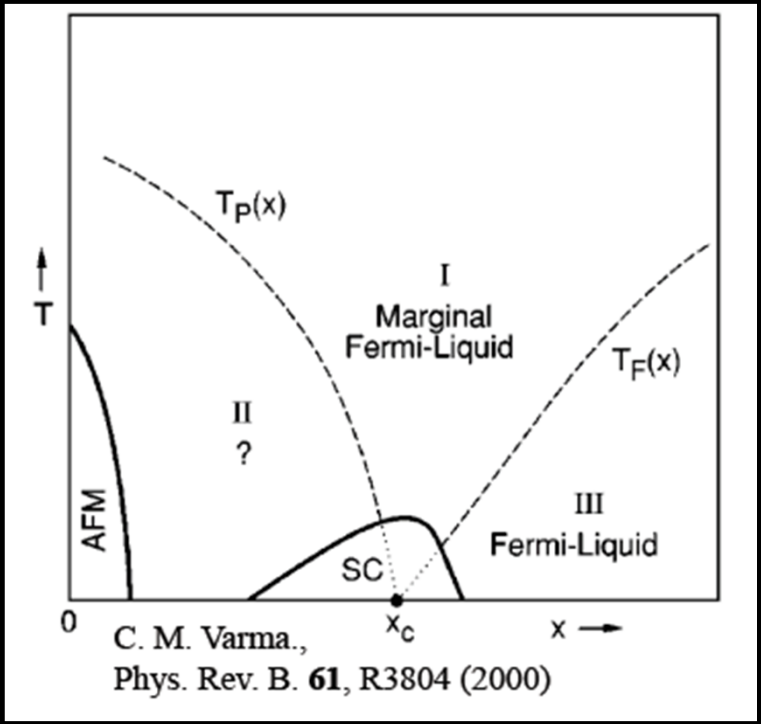
Kivelson, Fradkin, and Emery, Nature **393**, 550 (1998).

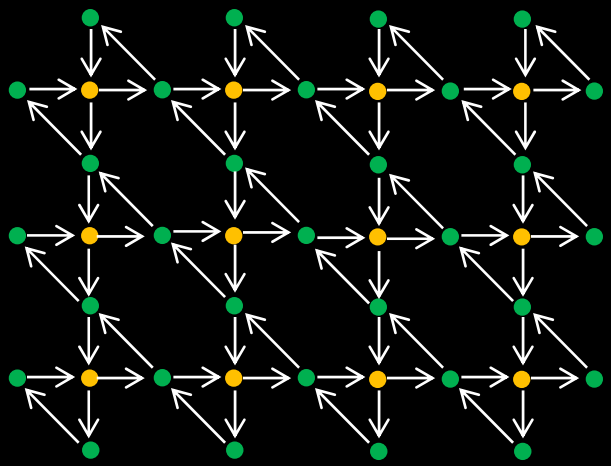
Varma: sub-unit-cell orbital ordering

Underdoped cuprates have
a hitherto undetected
broken symmetry phase
which does not break
translation symmetry.

The non-Fermi liquid "normal"
state is the **quantum**
critical regime, in which
order parameter fluctuations
strongly scatter the quasiparticles.

The critical fluctuations "mediate"
d-wave pairing.





Breaks time-reversal
and inversion
but not the produce of TI.

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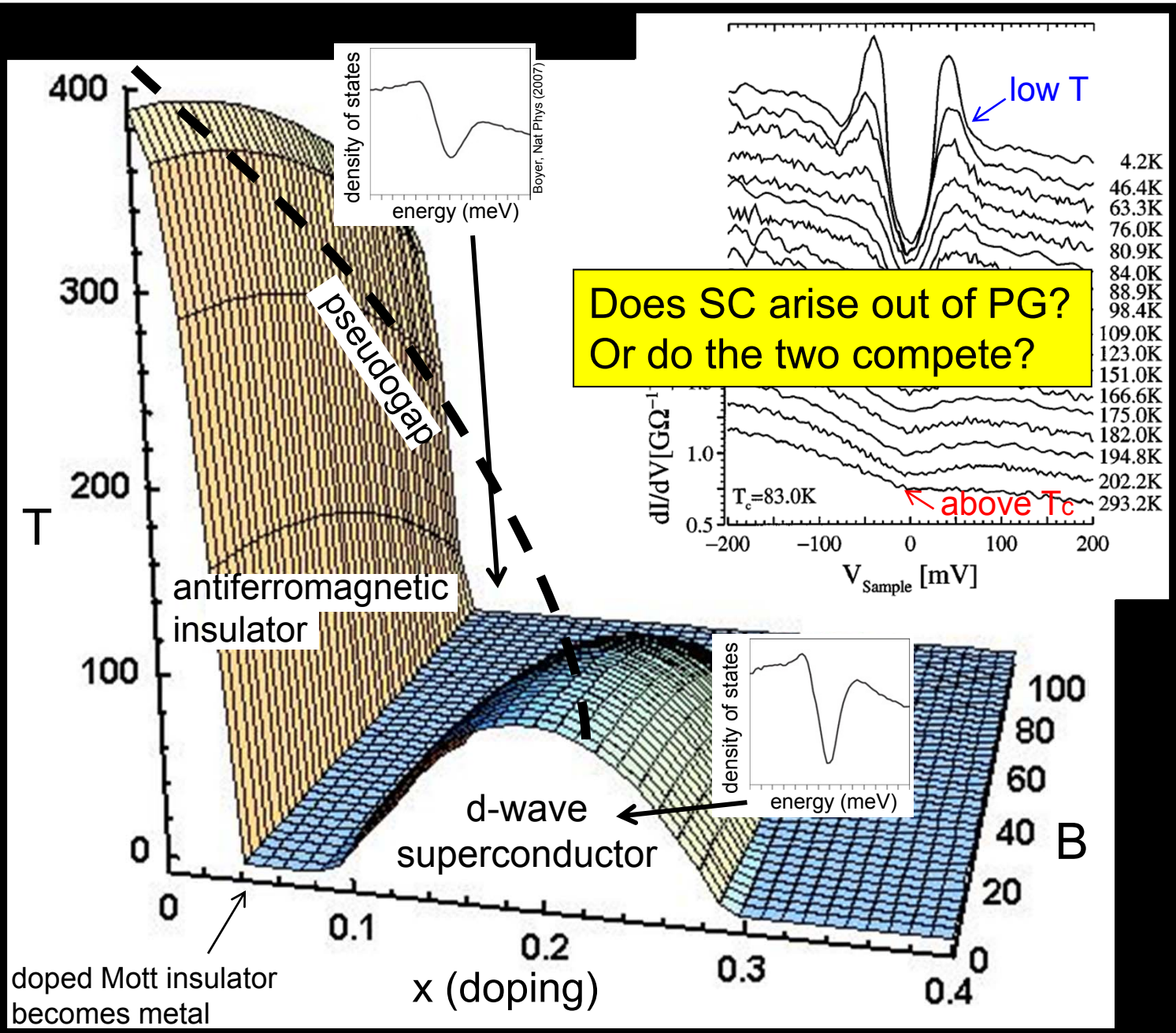
Relationship Between PG and SC ?



Crash Course in Solid State Physics

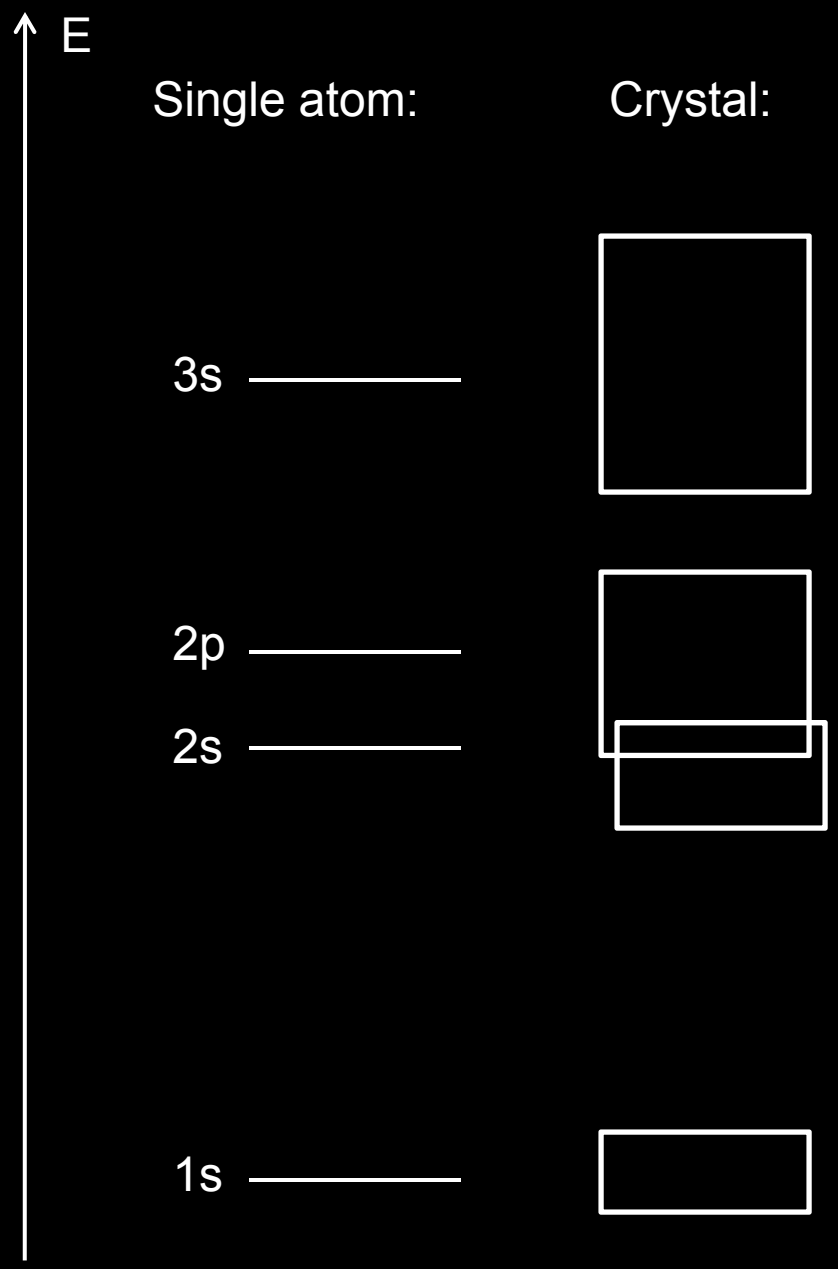
Brought to you by:

Brillouin zone

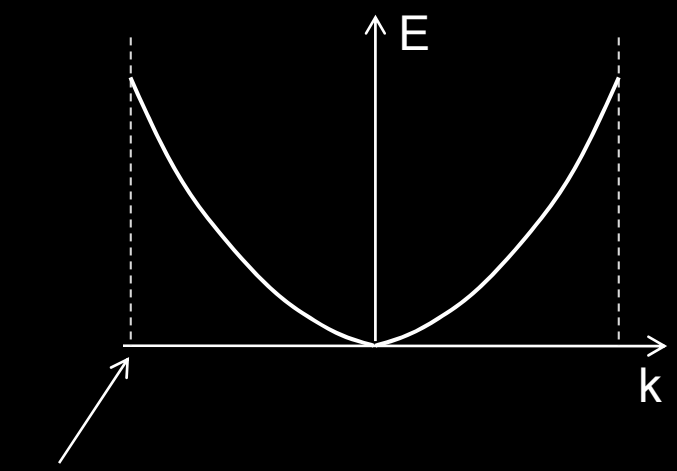
Me: “how do I explain a Brillouin zone?”

4-year-old who is stuck with 2 physicists for parents:
“Mommy, it’s a box that electrons live in!”

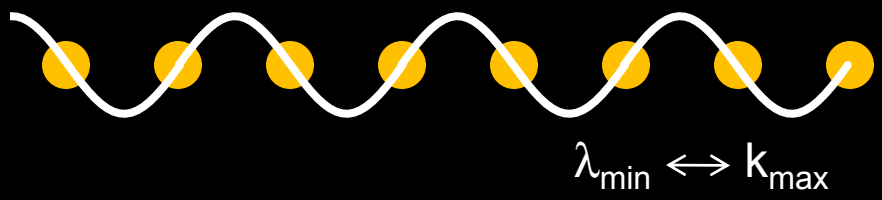
Band Theory



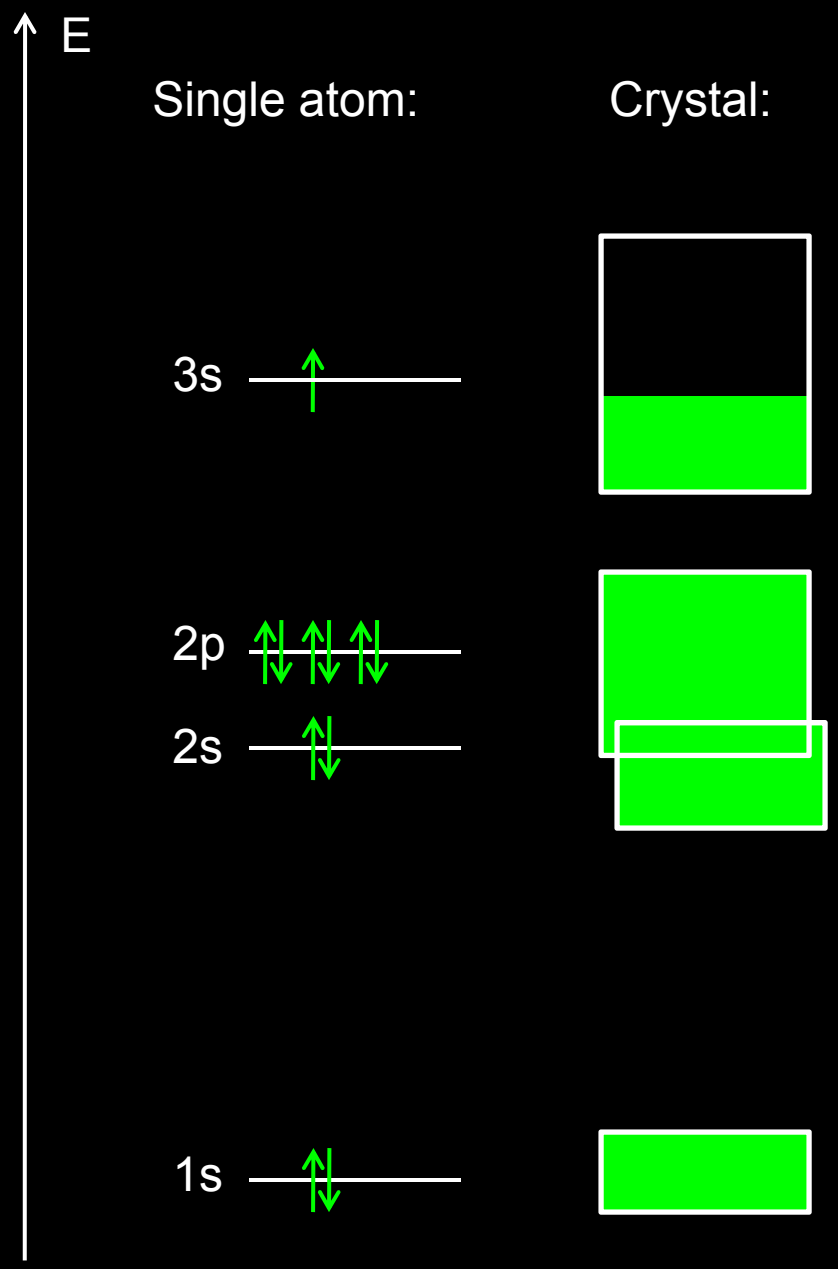
Add momentum information:



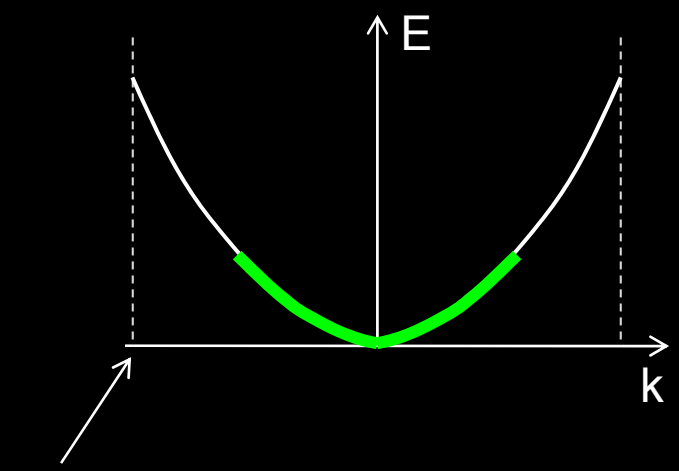
Brillouin zone edge:
highest unique wavevector k
(larger k's aren't sampled by the atoms so they are aliased back to smaller k's)



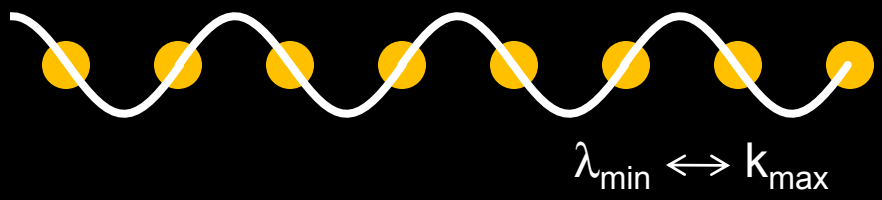
Band Theory: Metal



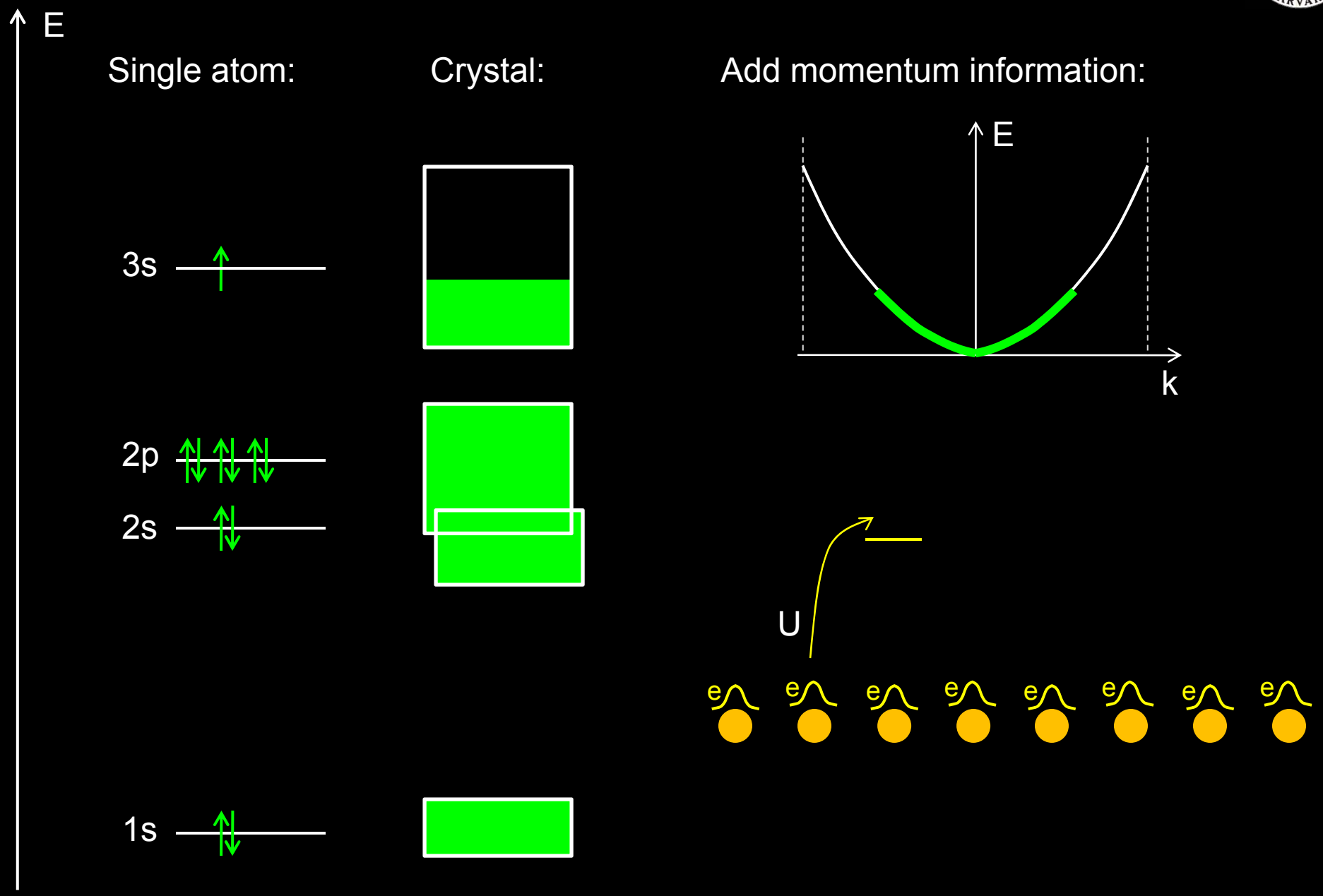
Add momentum information:



Brillouin zone edge:
highest unique wavevector k
(larger k's aren't sampled by the atoms so they are aliased back to smaller k's)



Add e-e correlations: Mott Insulator



Mott Transition

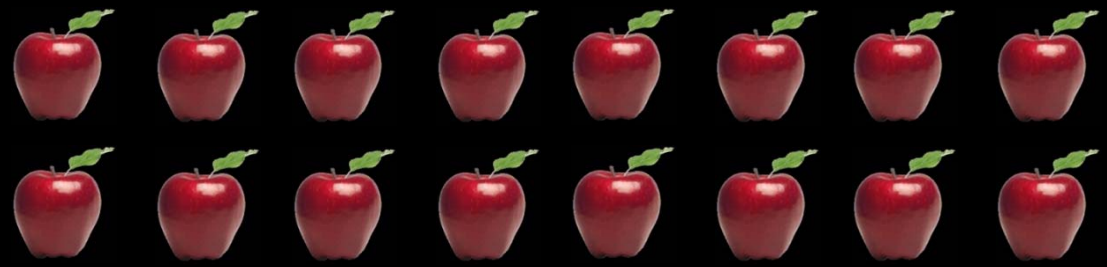
localized

↓

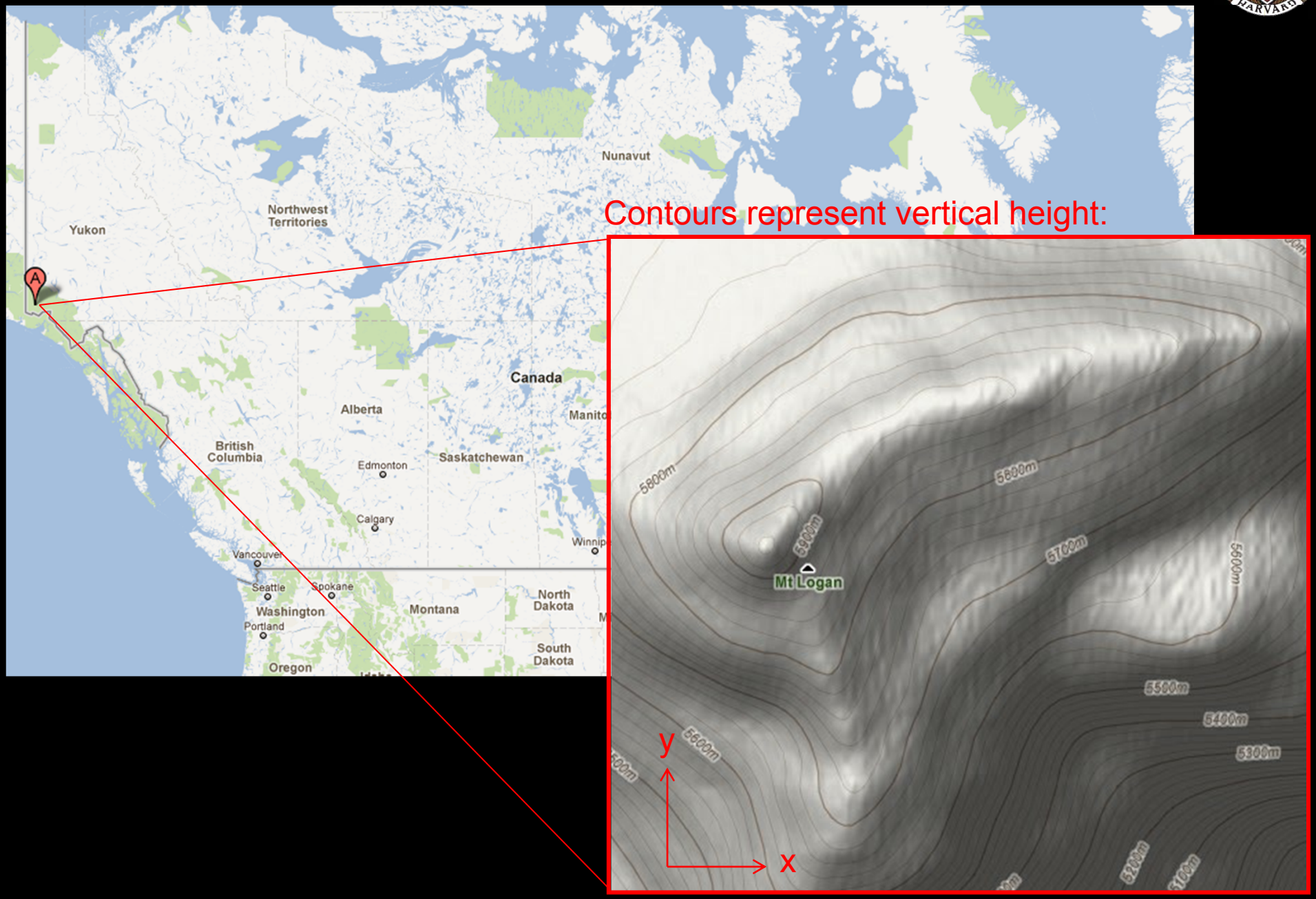
delocalized

↓

further delocalized



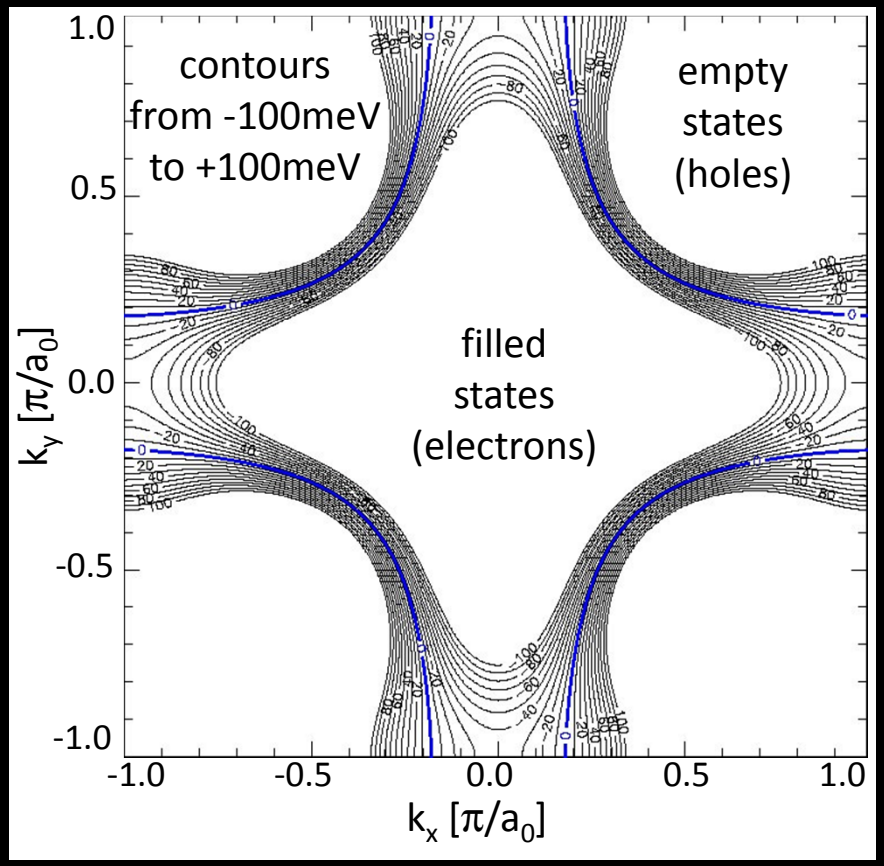
What is a Brillouin zone?



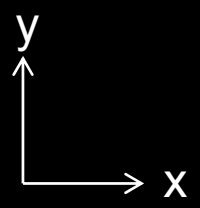
What is a Brillouin zone?

Topographic map:
contours represent physical height

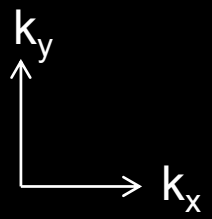
Brillouin zone:
contours represent electron energy



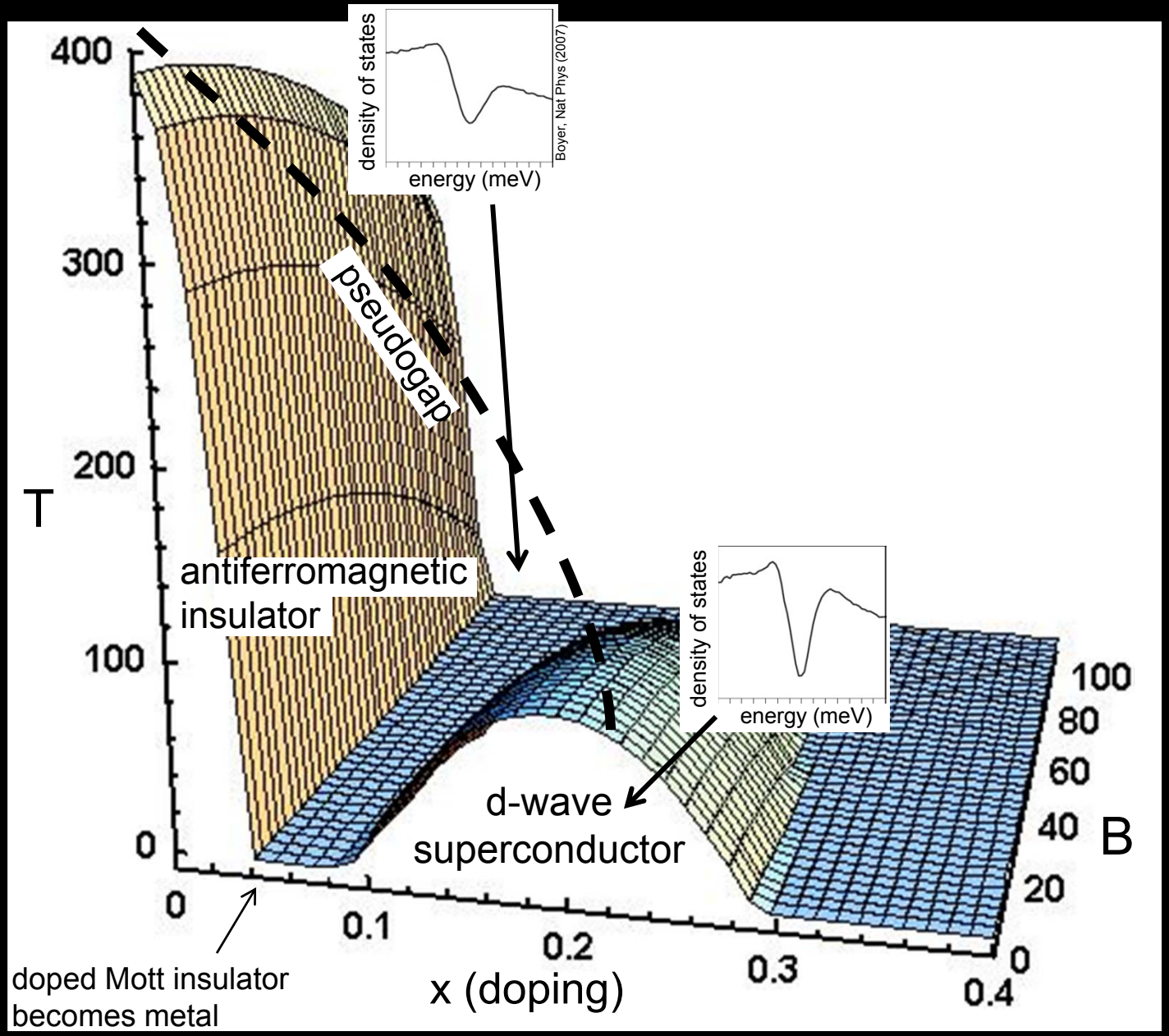
real space:



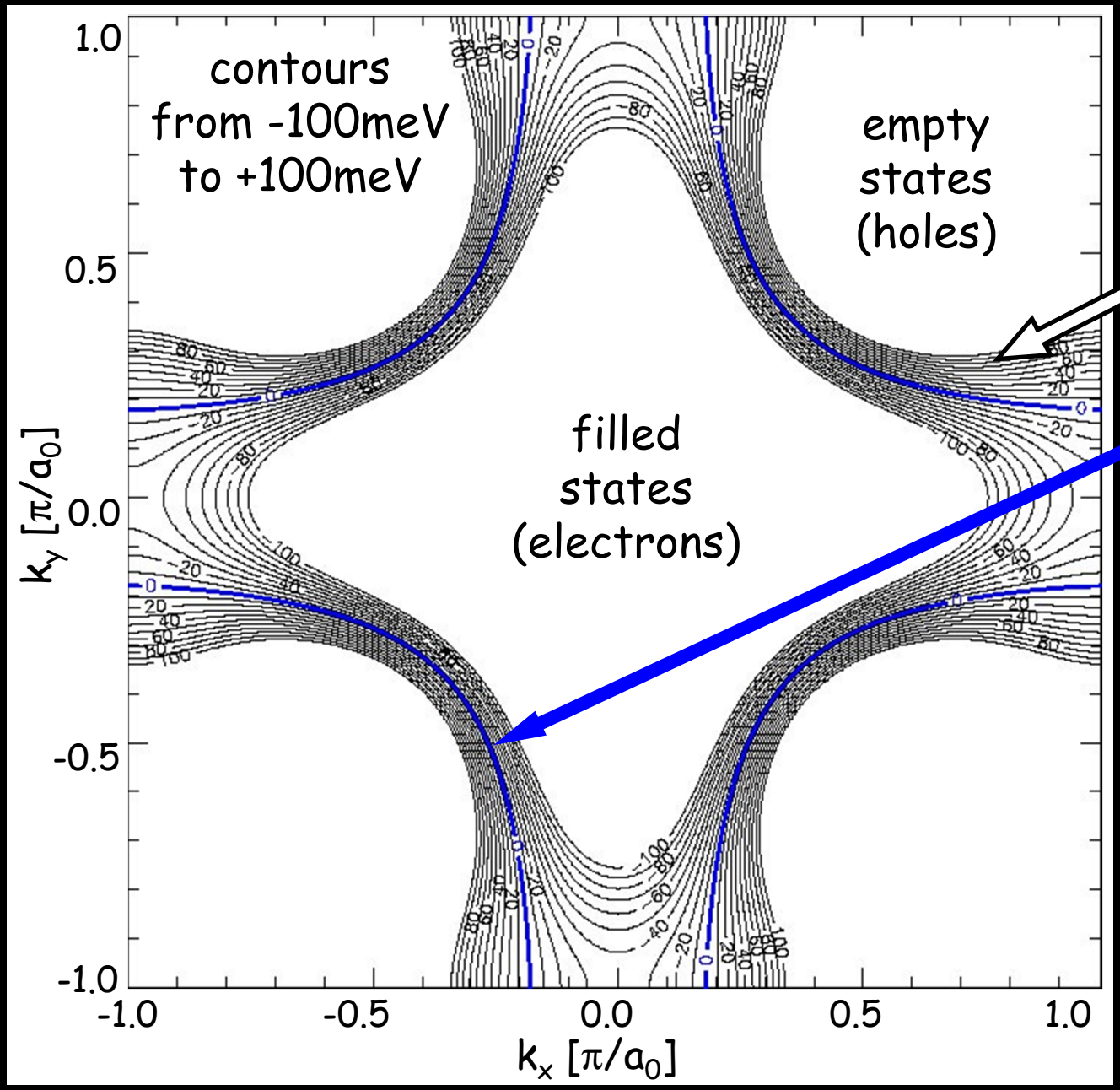
momentum space:



Cuprate Phase Diagram



Cuprate Brillouin Zone: "Normal" state



CCE (E): The location in k-space of states with energy E

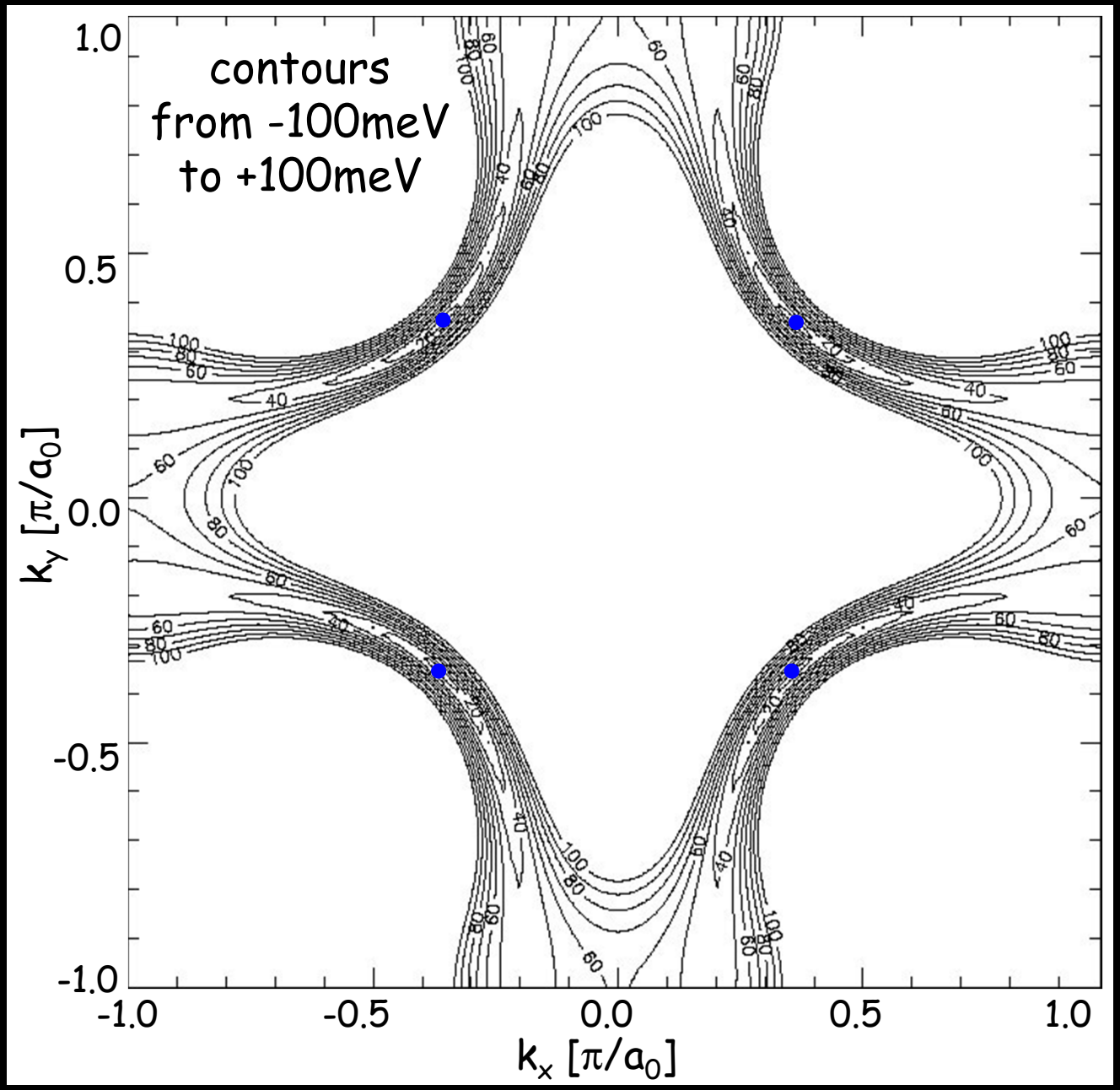
Fermi Surface

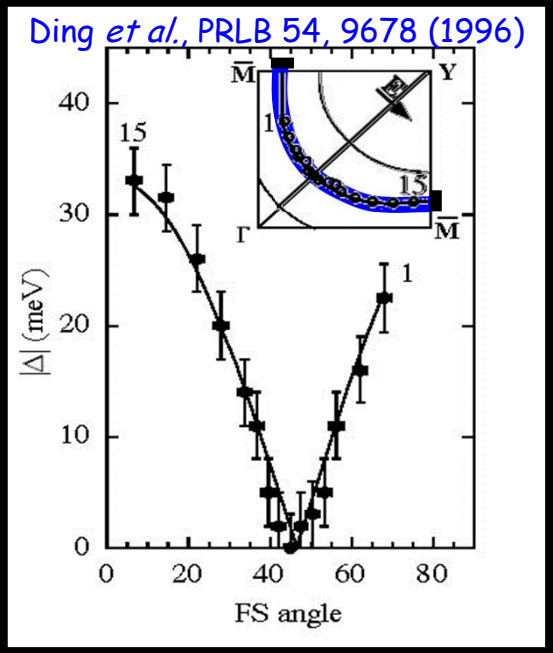
In a superconductor: e-e pairs form on FS.

Parameterization:
M. Norman
PRB 52, 615 (1995).

Based on data:
Ding *et al.*,
PRL 74, 2784 (1995).

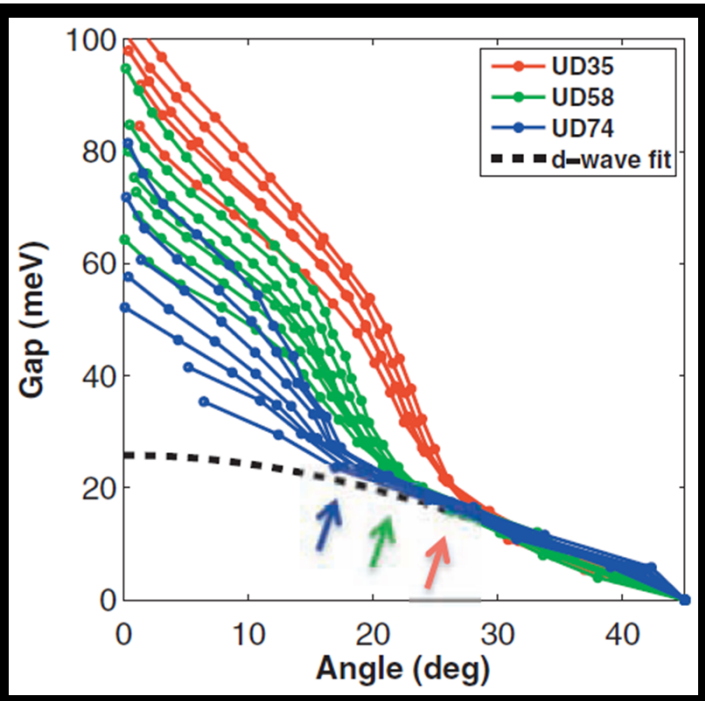
Cuprate Brillouin Zone: Gap vs. angle





Shen *et al*, PRL **70** 1553 (1993)
Ding *et al*, PRB **54** 9678 (1996)
Mesot *et al*, PRL **83** 840 (1999)

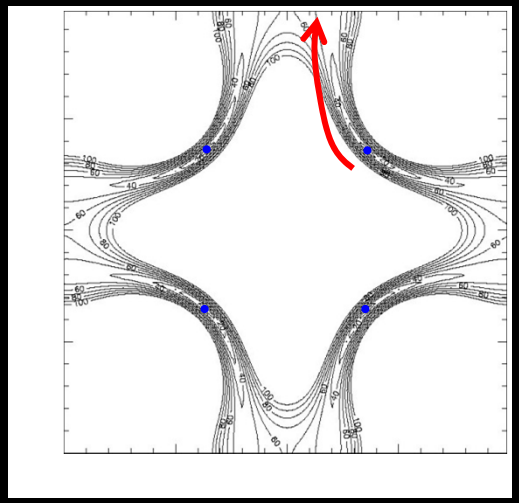
Relationship Between PG and SC ?

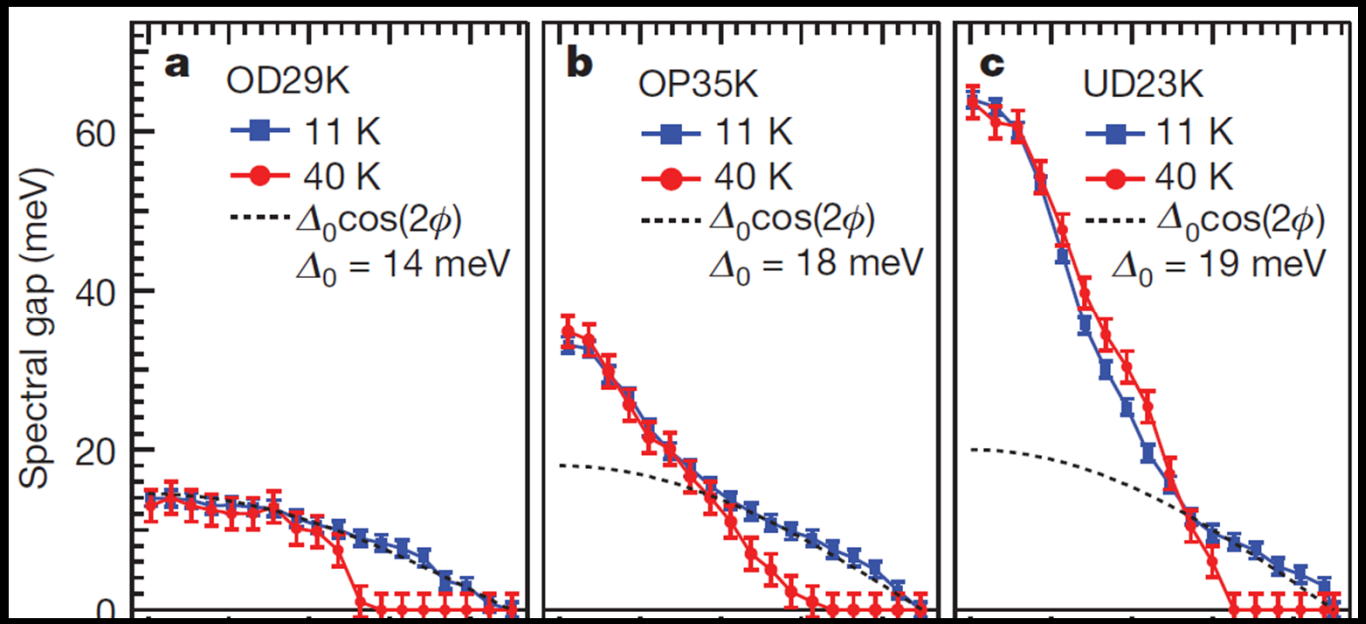


← STM
Pushp, Science 324, 1689 (2009)

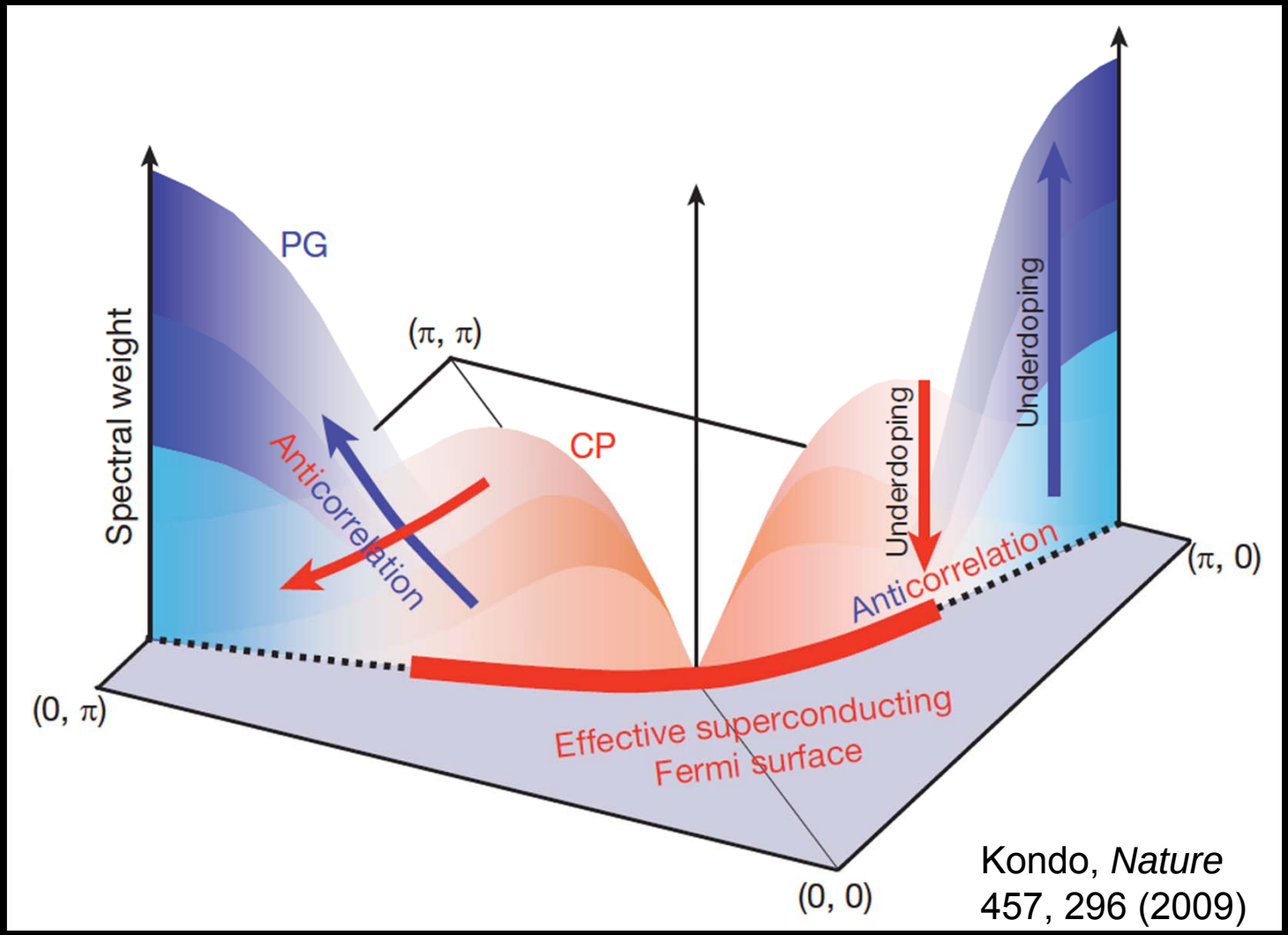
STM and ARPES both show competition between superconductivity (wins in nodal region) & pseudogap (wins in antinodal region)

↓ ARPES
Kondo, *Nature* 457, 296 (2009)





Competition Between PG and SC

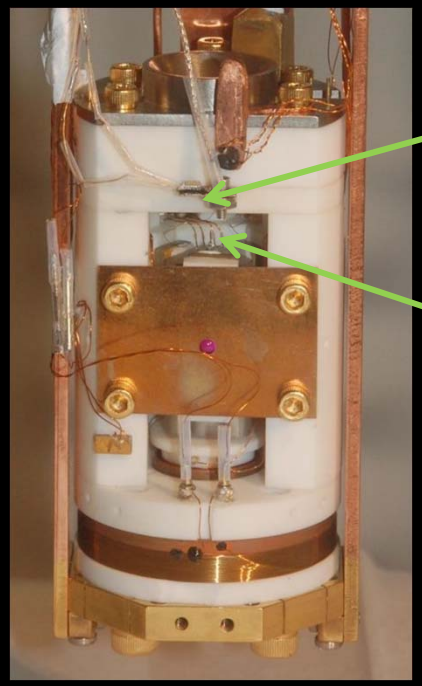


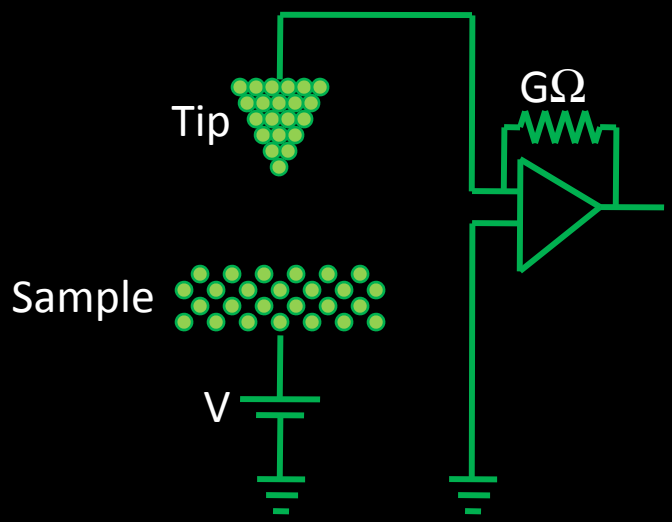
Kondo, *Nature* 457, 296 (2009)

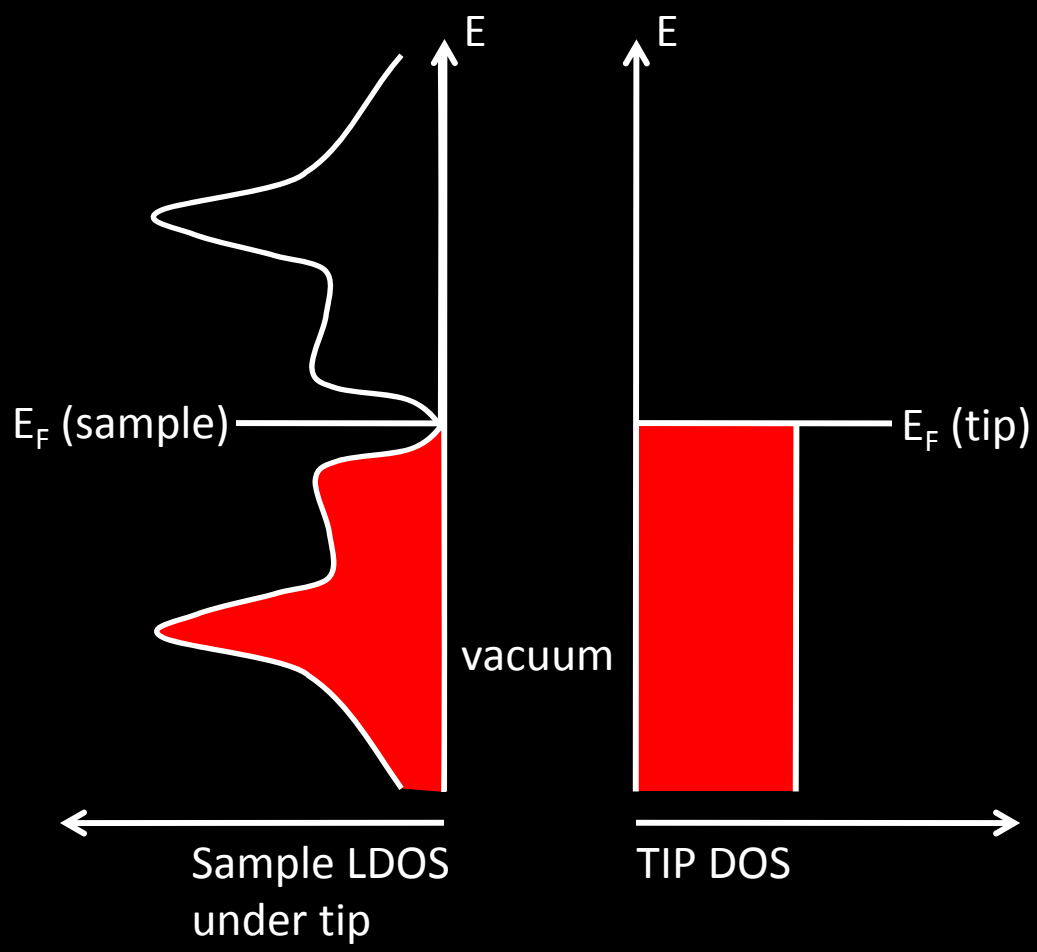
→ We want to know what the PG is (i.e. what symmetries it breaks) so we can control it & mitigate the competition!!

No obvious long-range order → use real space probe → STM

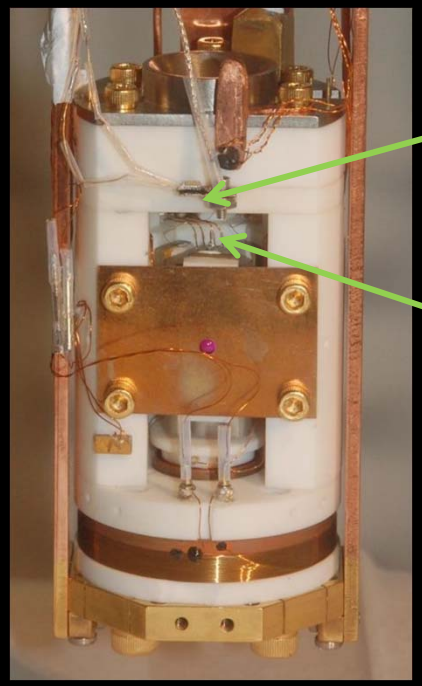
Introduction to STM

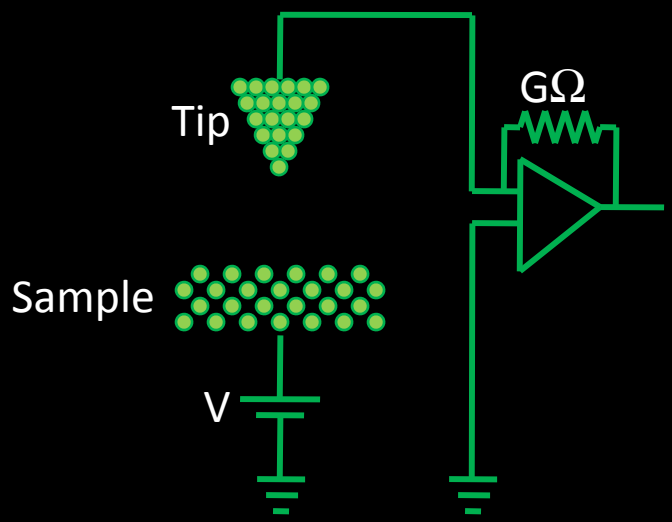




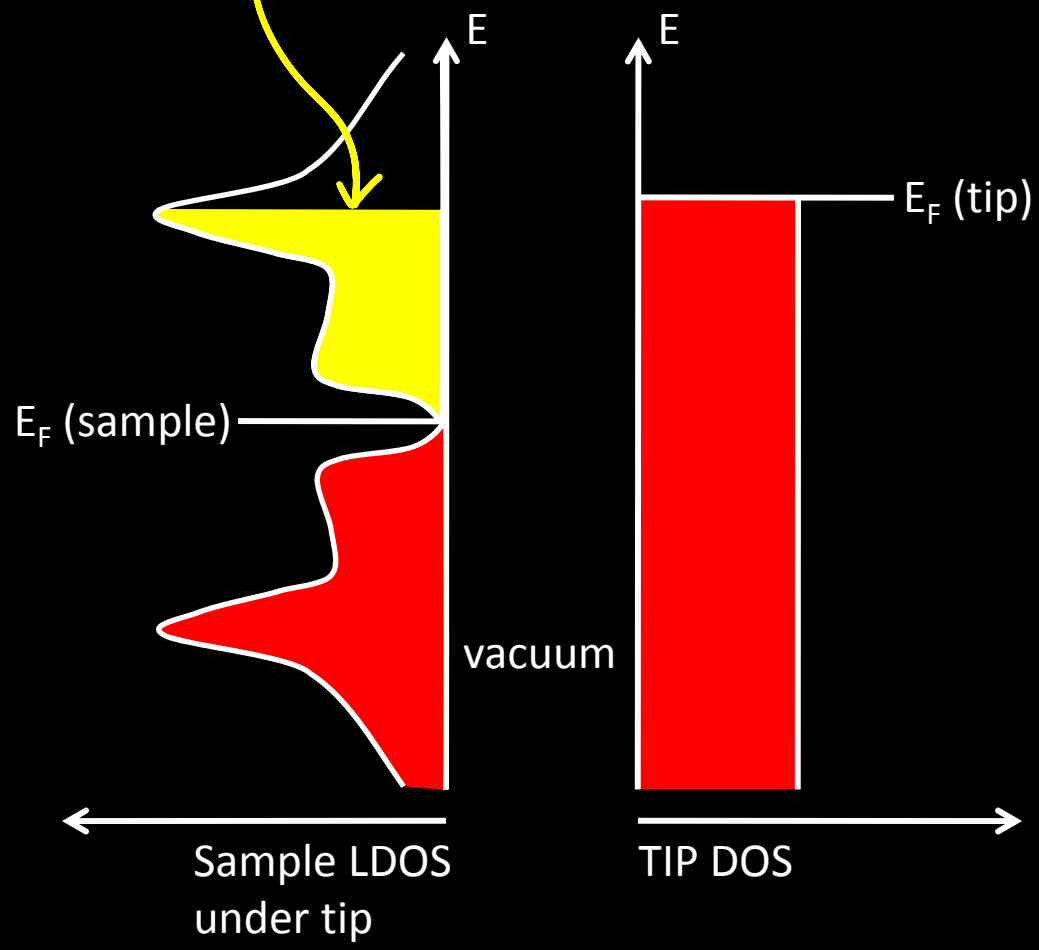


Introduction to STM

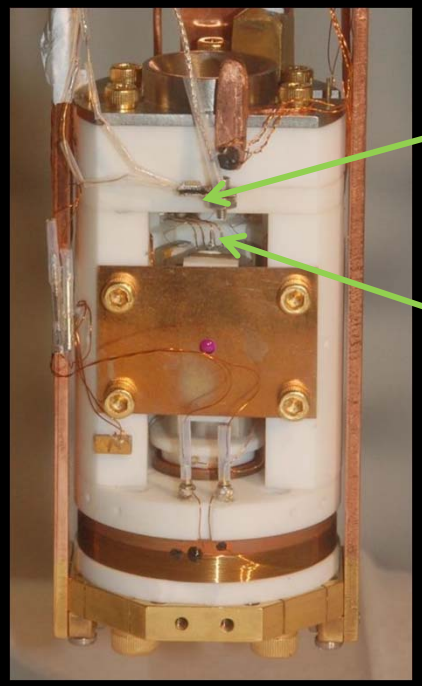


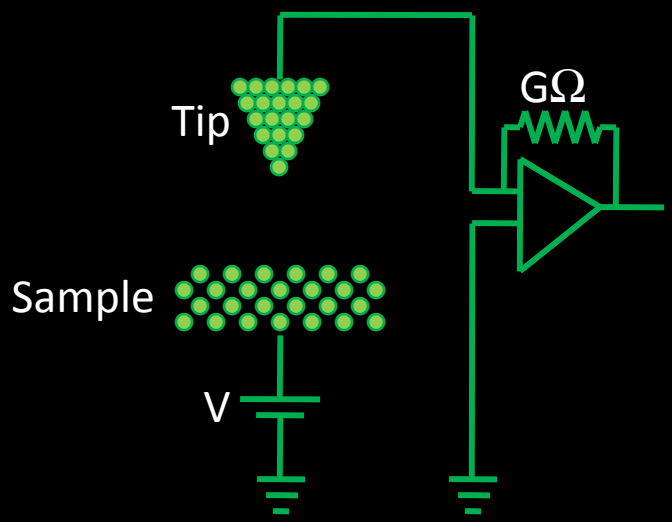


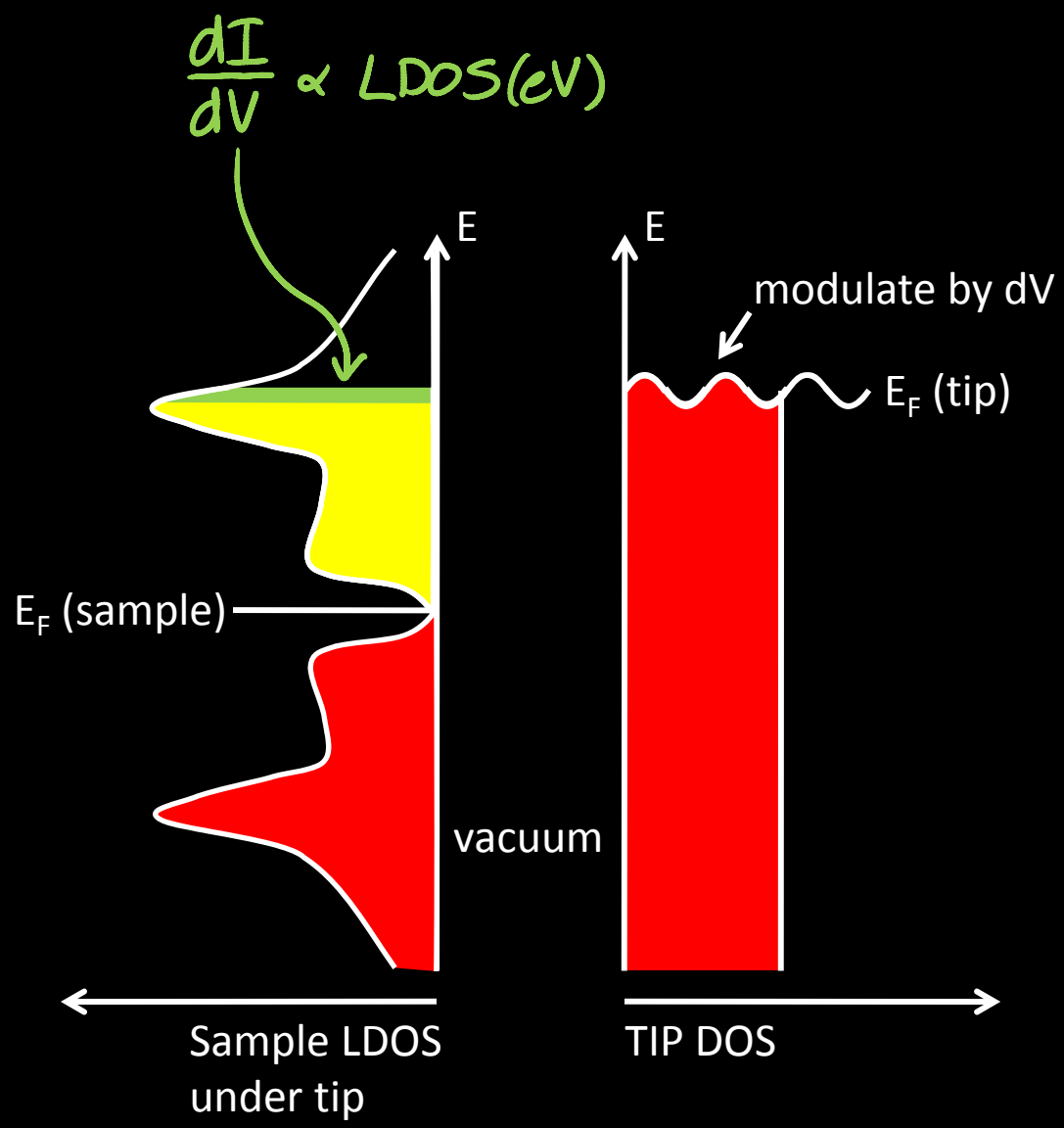
$$I(V) = \int_{E_F}^{eV} LDOS(E)\,dE$$



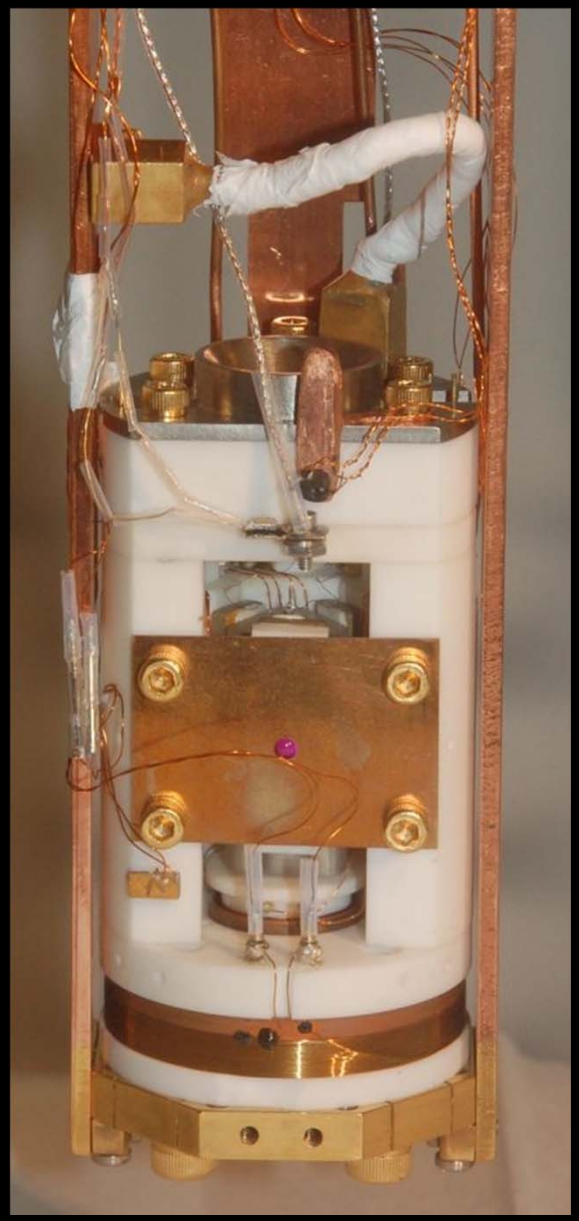
Introduction to STM



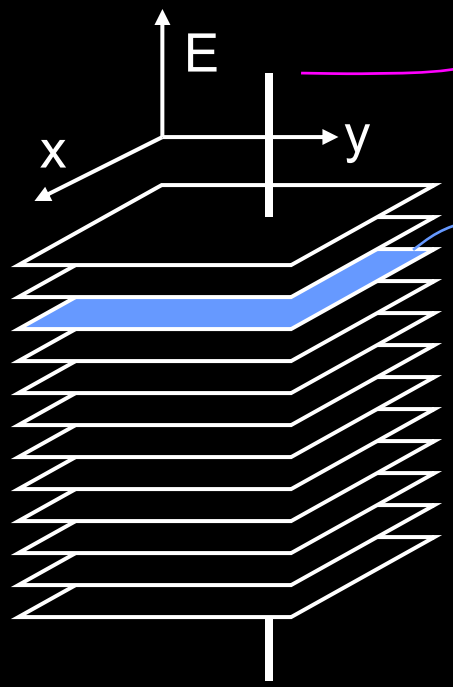




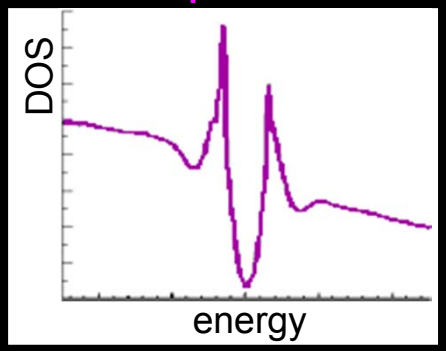
Types of STM Measurements



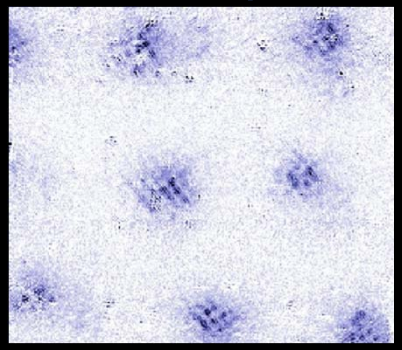
Local Density of States (x, y, E)



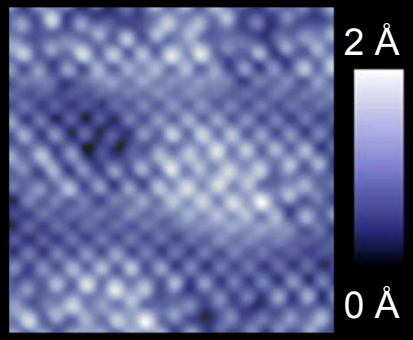
dI/dV Spectrum



dI/dV Map



Topography



Constant current mode:

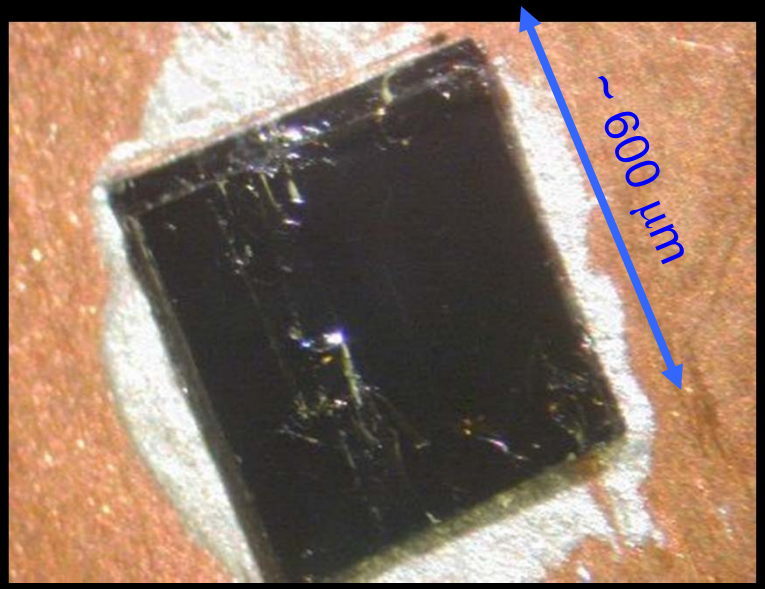
$$\int \frac{dI}{dV}$$

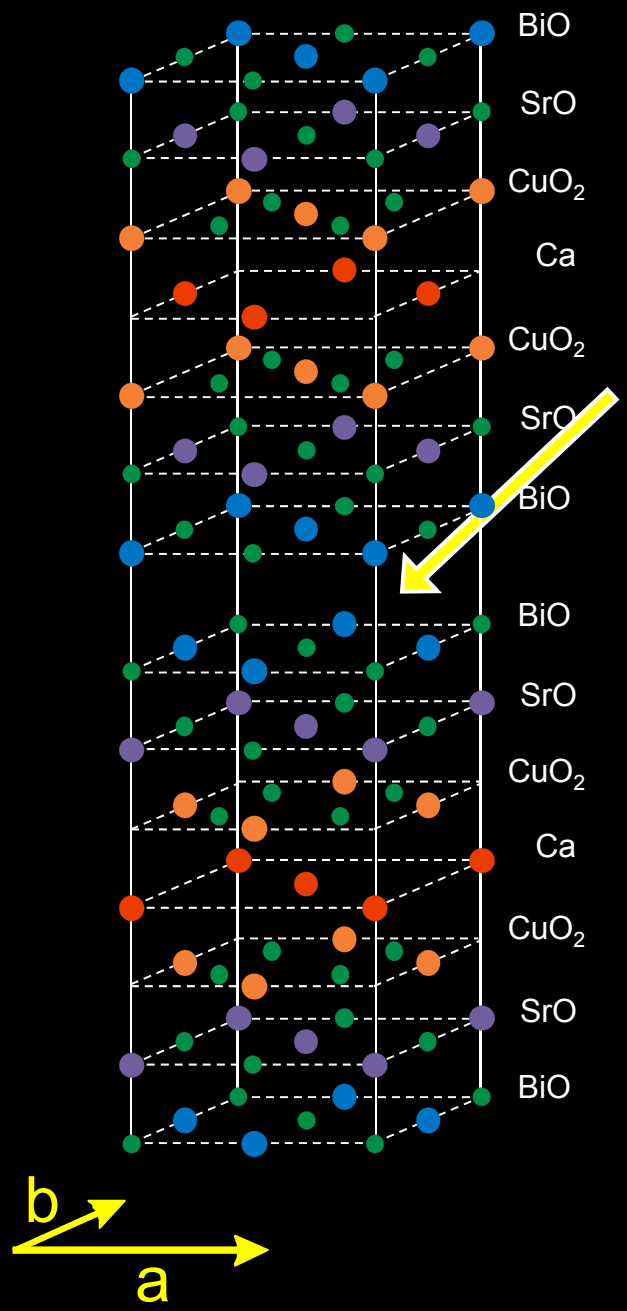
Structure of $Bi_2Sr_2CaCu_2O_{8+\delta}$

$a \approx b = 5.4$ Å

$c = 30.7$ Å

$T_c \sim 90$ K

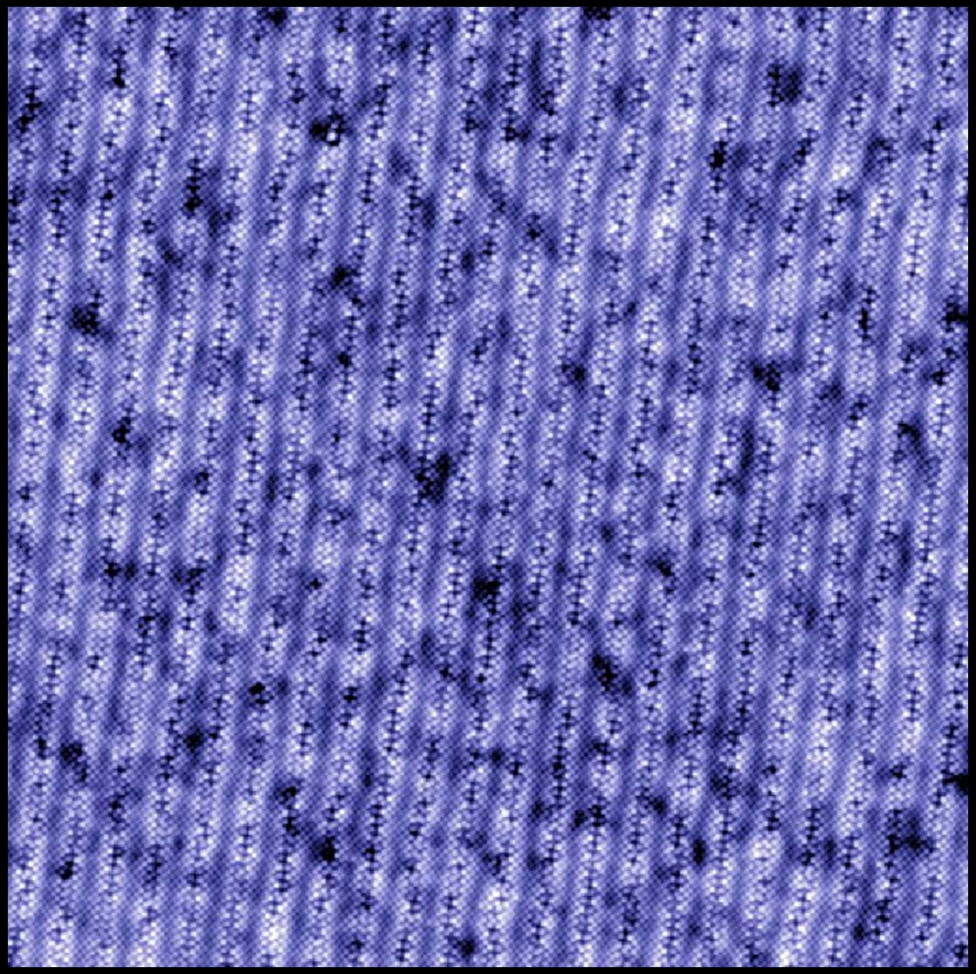




Cleave Here Reveals BiO Surface

$Bi_2Sr_2CaCu_2O_{8+\delta}$

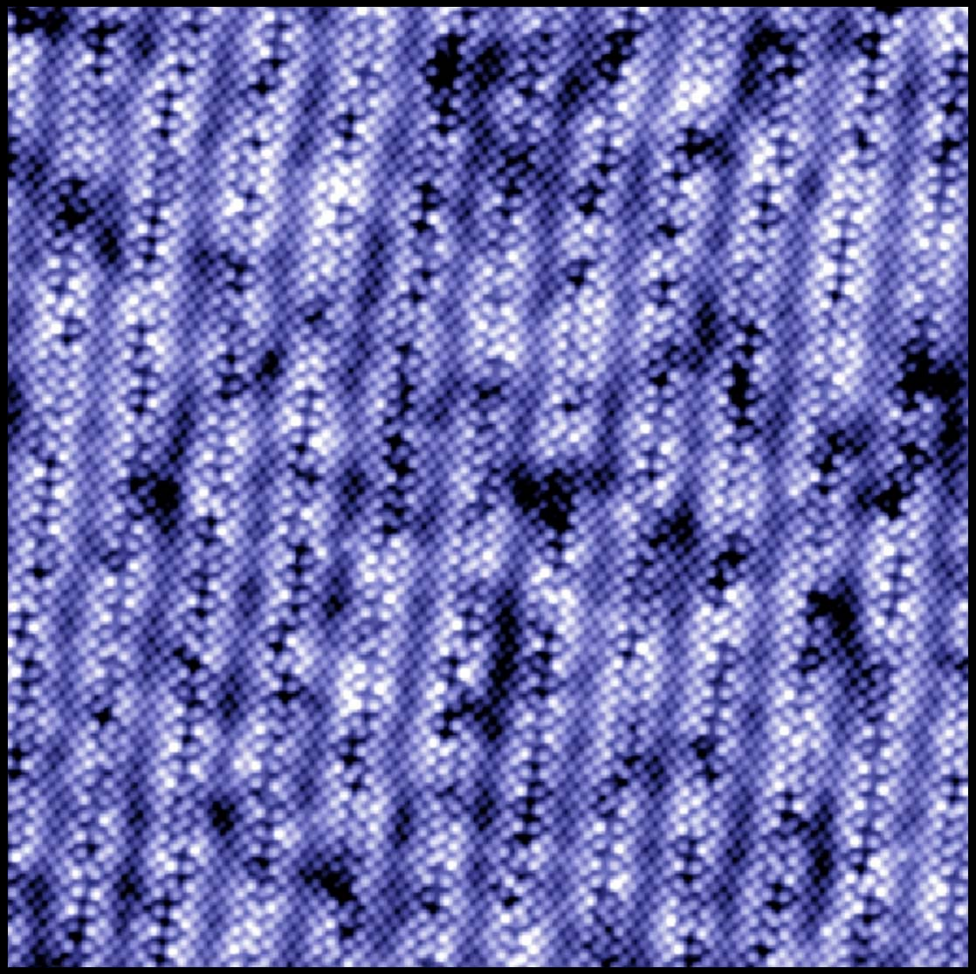
560 Å



T= 4.2K, B = 0T
100pA, -100mV

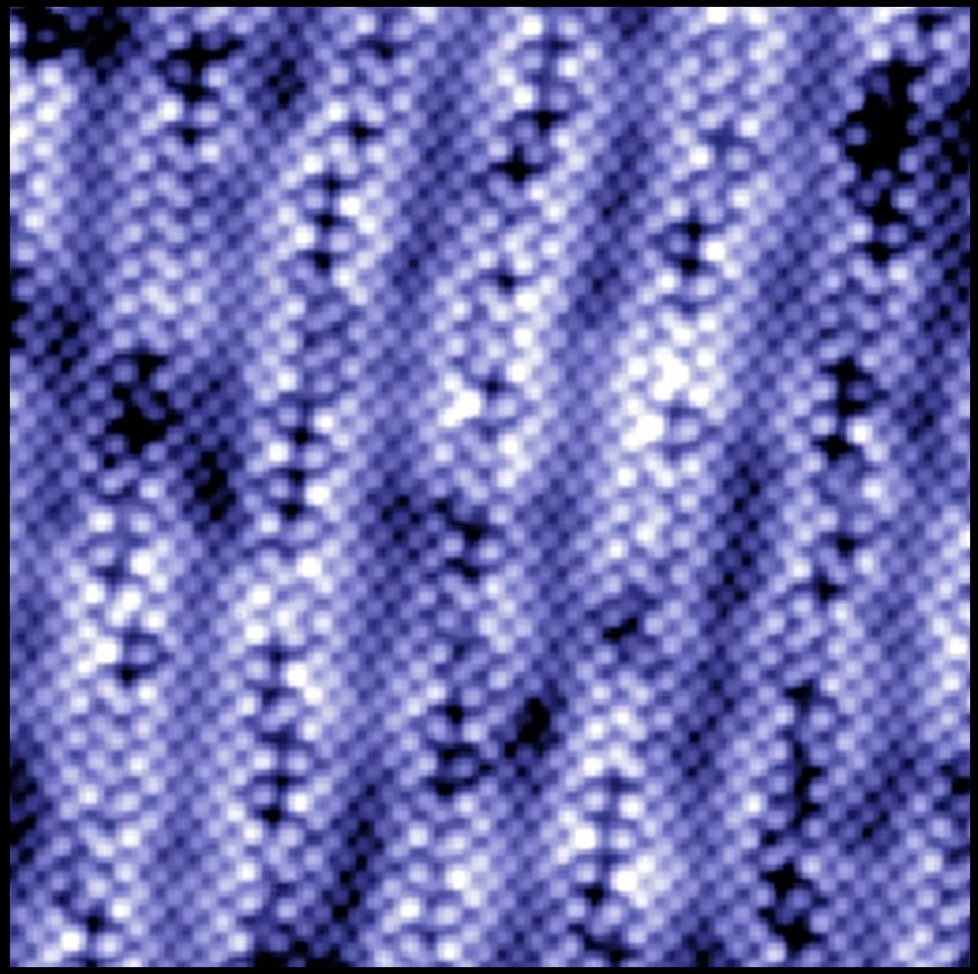
$Bi_2Sr_2CaCu_2O_{8+\delta}$

280 Å



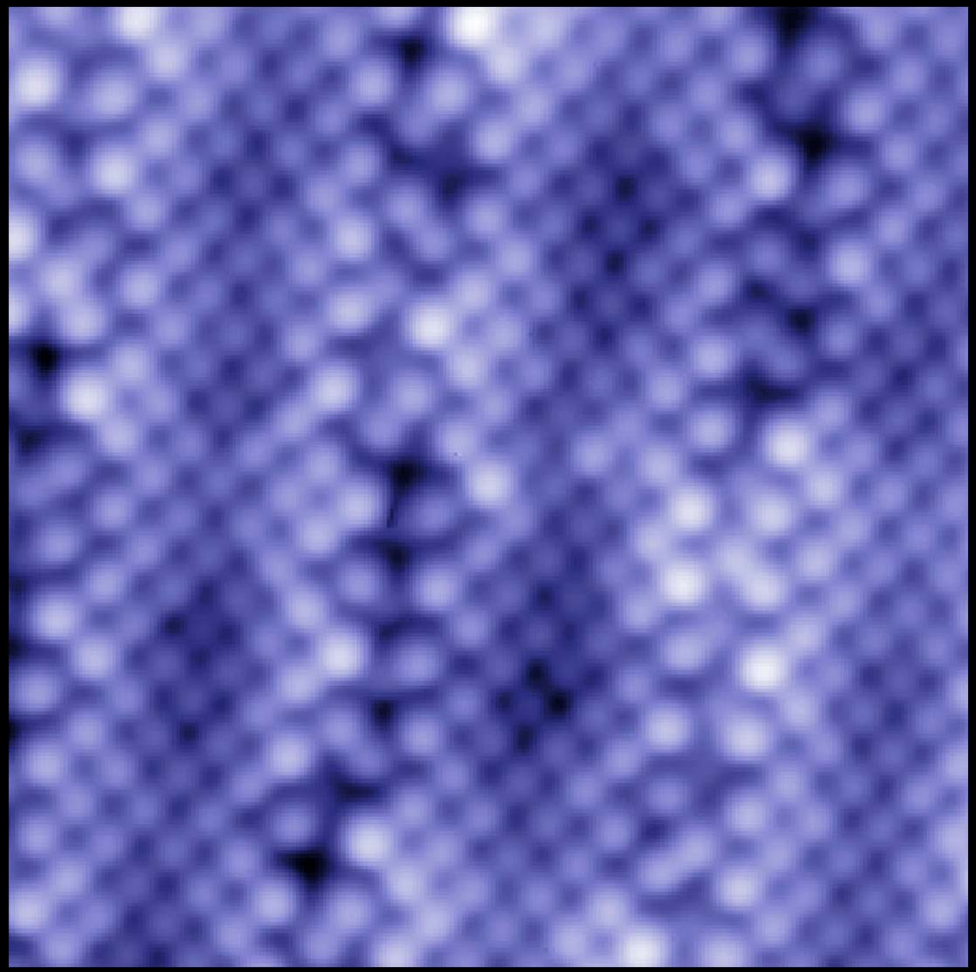
T= 4.2K, B = 0T
100pA, -100mV

$Bi_2Sr_2CaCu_2O_{8+\delta}$



T= 4.2K, B = 0T
100pA, -100mV

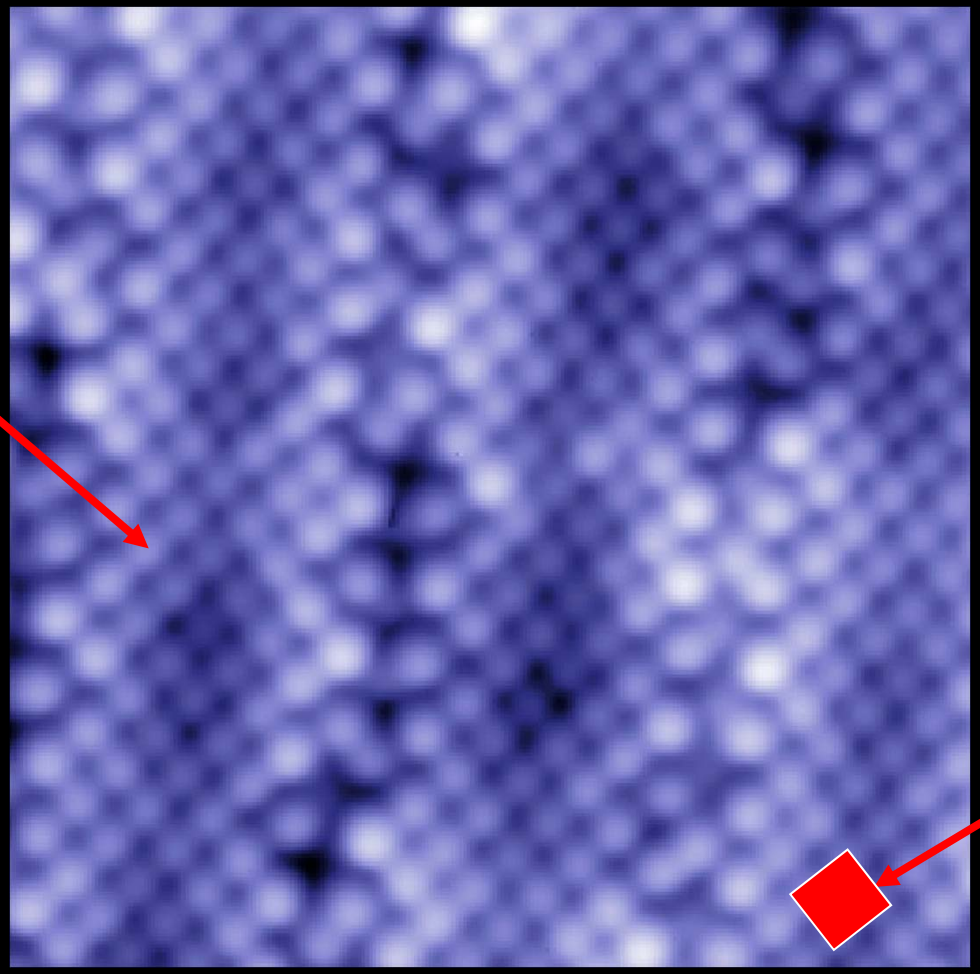
$Bi_2Sr_2CaCu_2O_{8+\delta}$



T= 4.2K, B = 0T
100pA, -100mV

$Bi_2Sr_2CaCu_2O_{8+\delta}$

Each bright spot is a Bi atom.



Size & orientation of CuO_2 unit cell (~ 5Å below surface).

T= 4.2K, B = 0T
100pA, -100mV

Outline

Superconductors: 100 Year History

Pseudogap in cuprates:

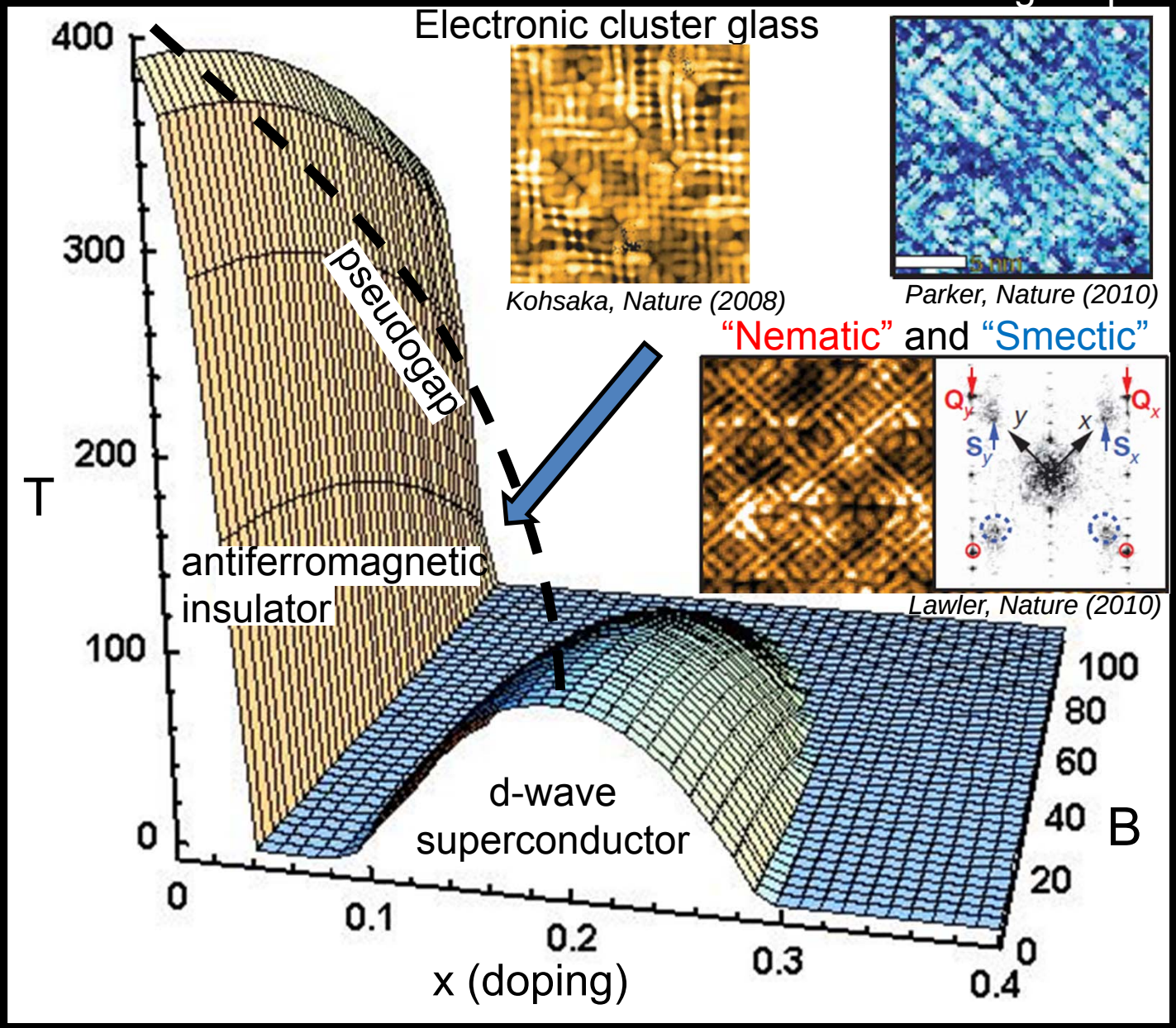
- Competing or collaborating?
- Inter-unit-cell order: smectics, checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:

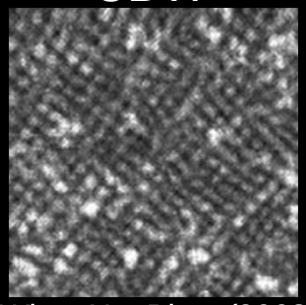
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy

Inter-unit-cell ordering: “checkers”

“Fluctuating Stripes”

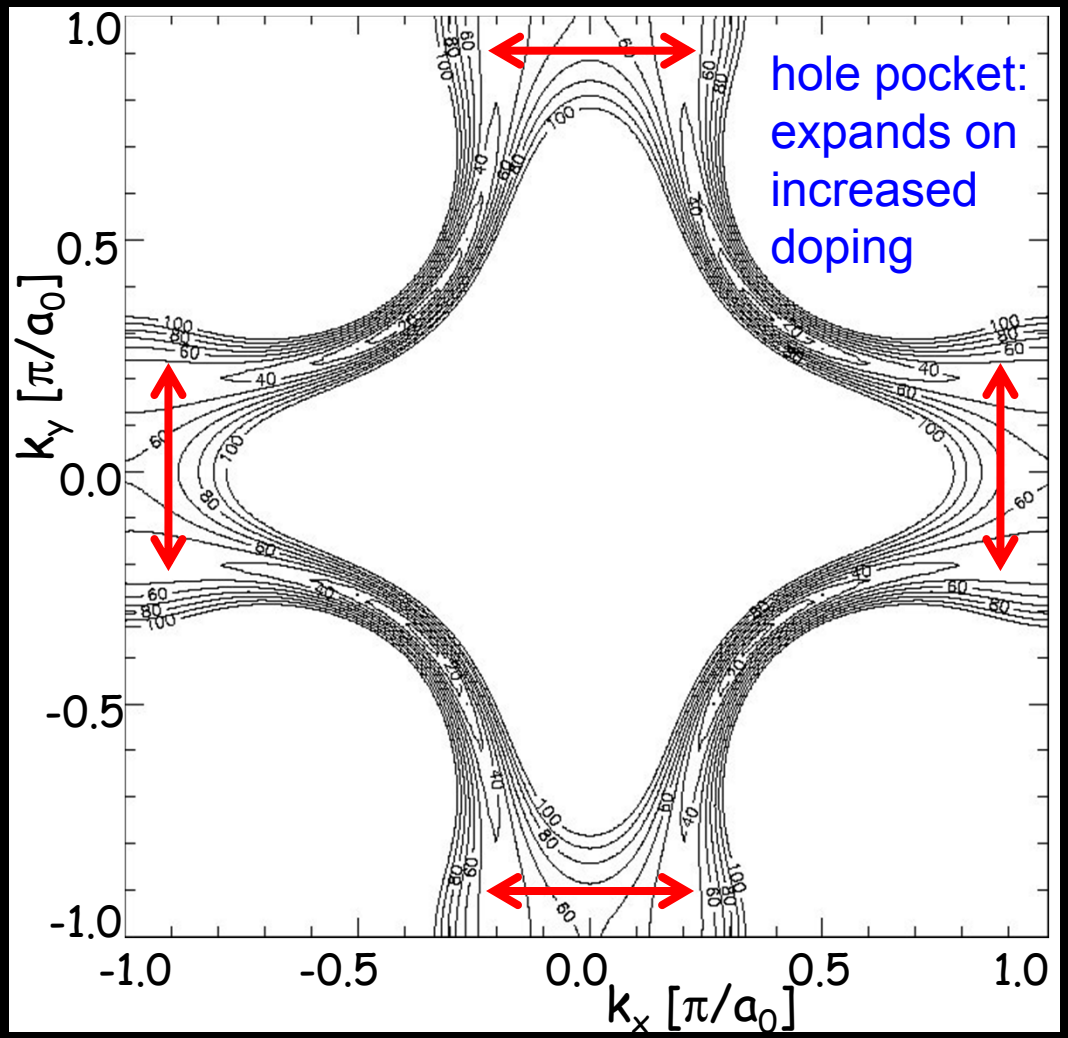


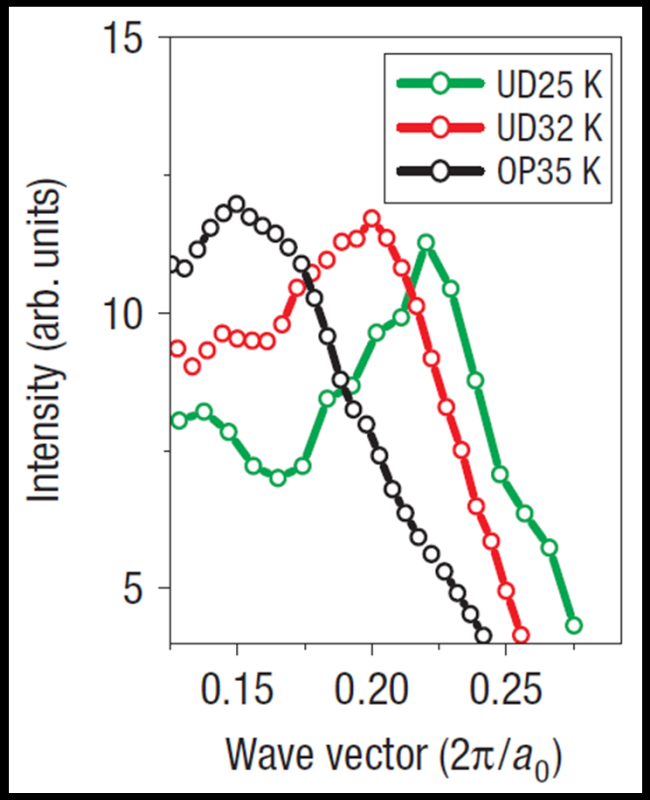
CDW



Wise, Nat Phys (2008)

"Checkers": CDW from Nesting

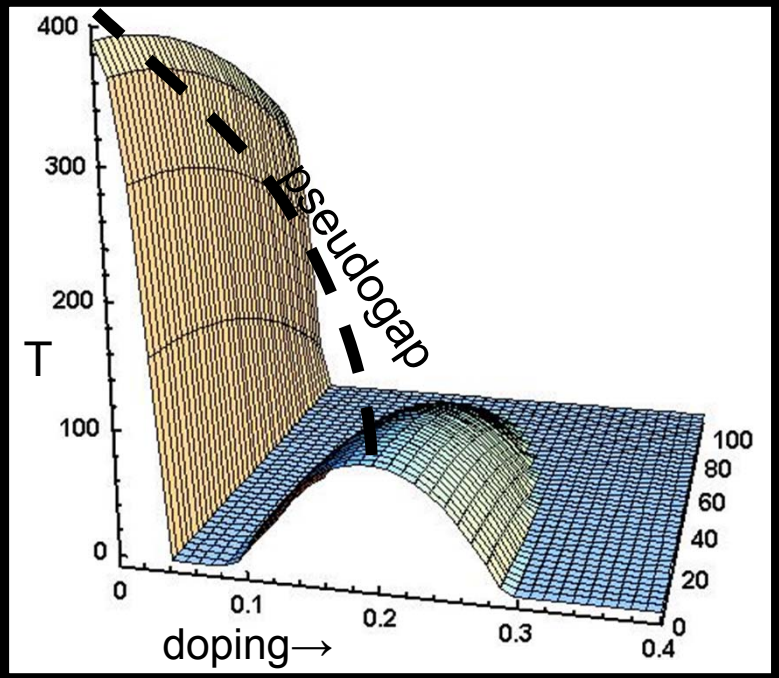


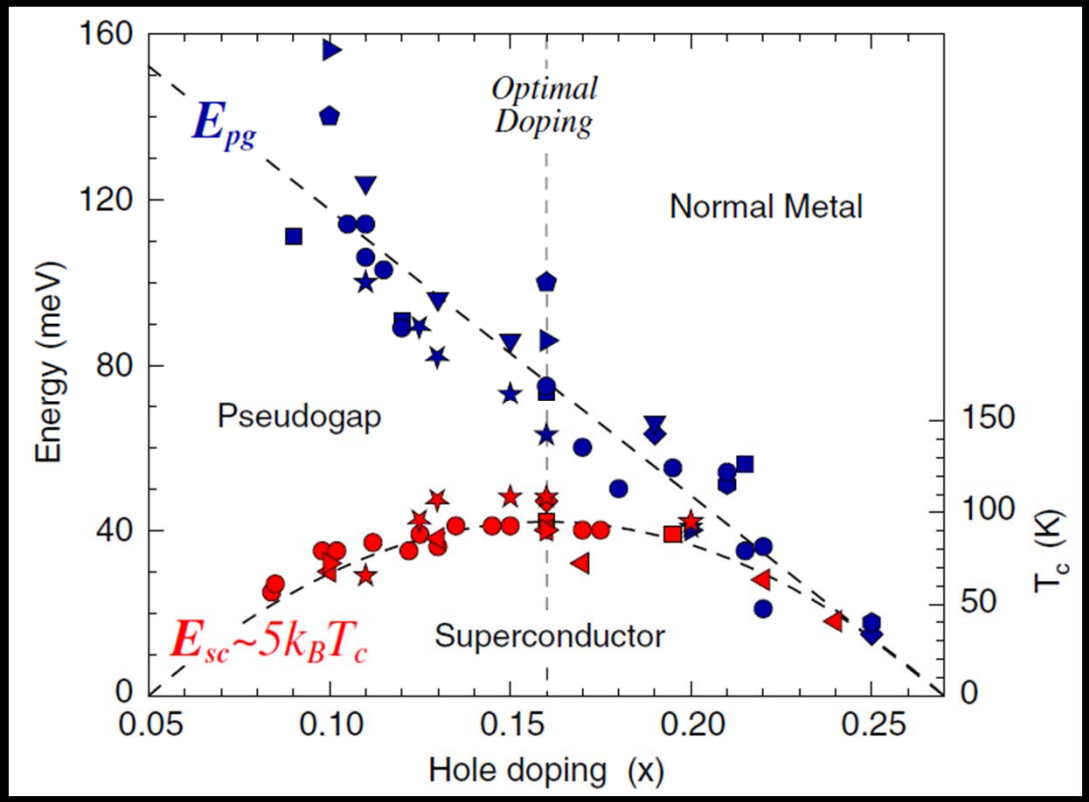


→ This state breaks translation symmetry but not rotation symmetry!

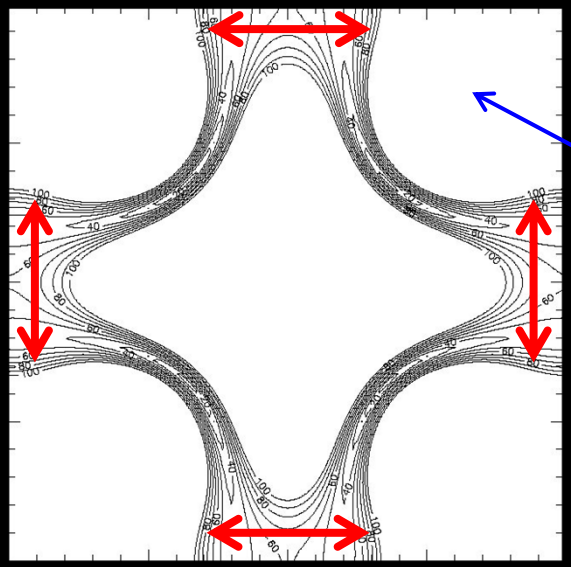
Wise, Hudson, Nat Phys (2008)

Pseudogap decreases with doping



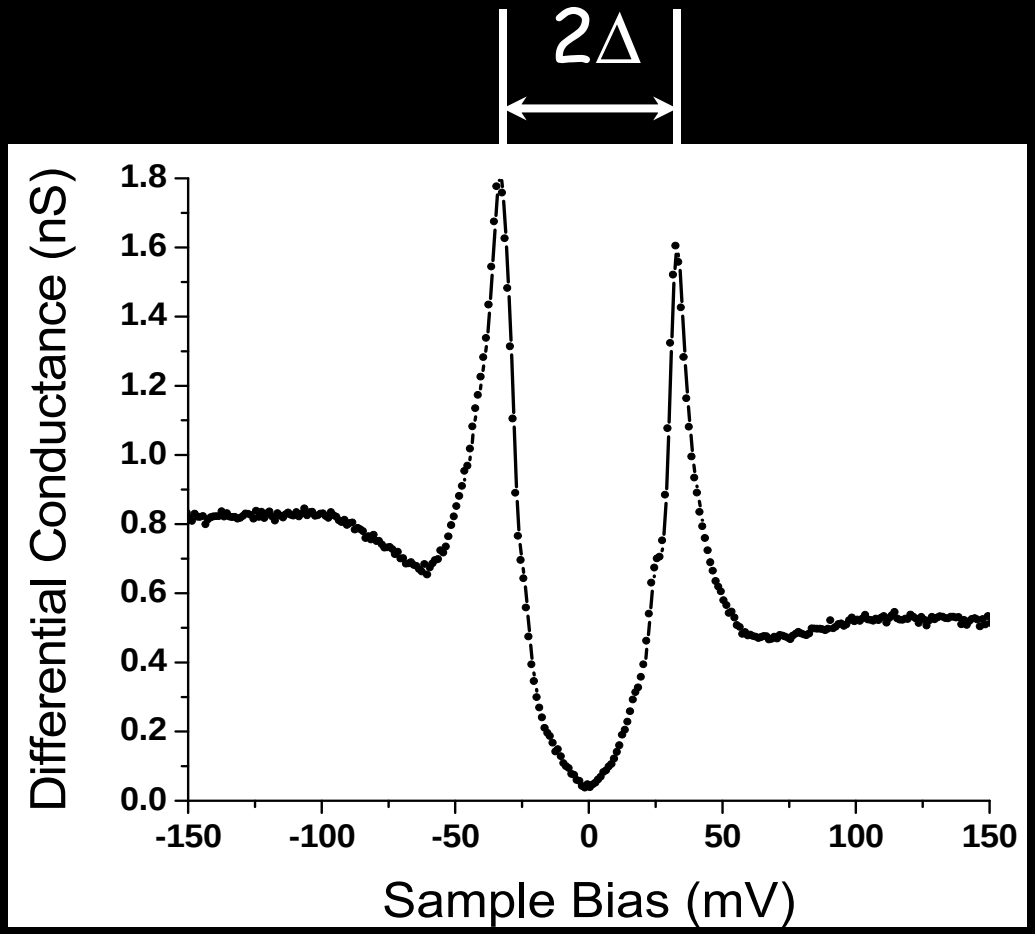


Also:

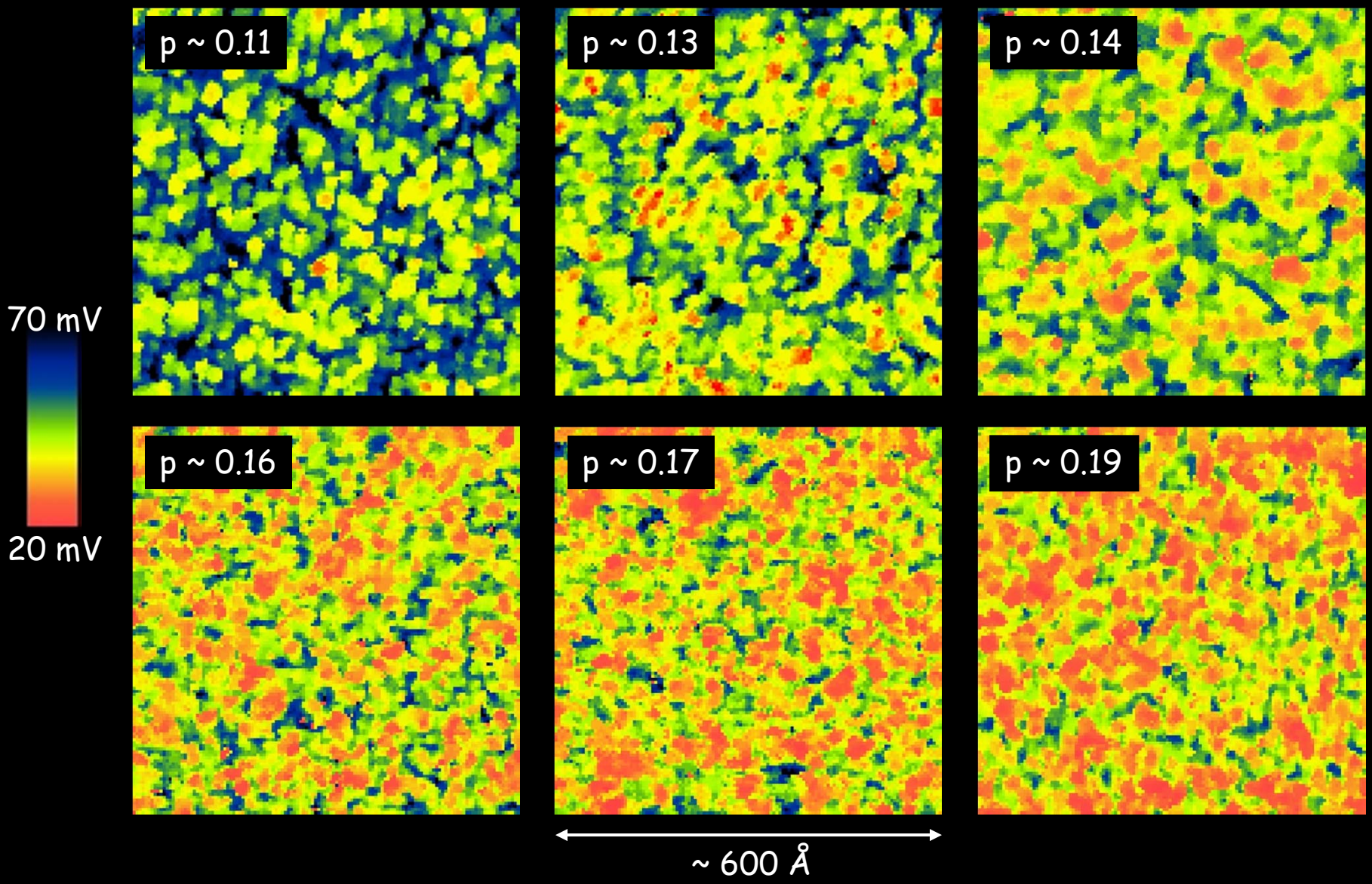


- hole pocket expands with doping
- nesting wavevector decreases with doping

Gapmap: map of Δ as a function of location

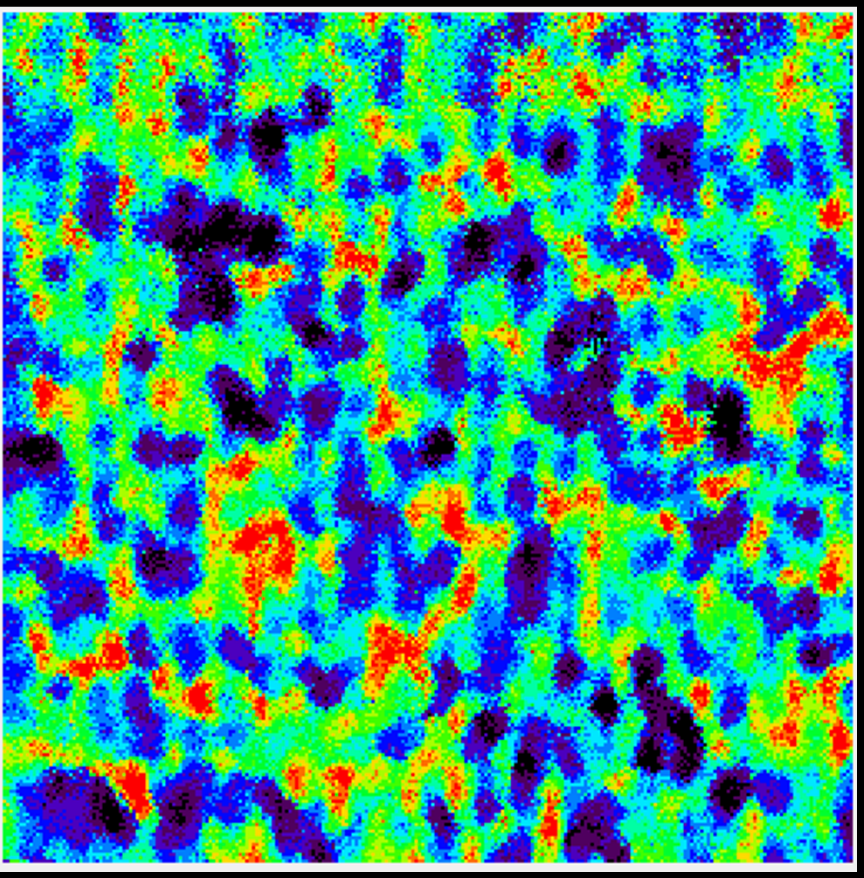


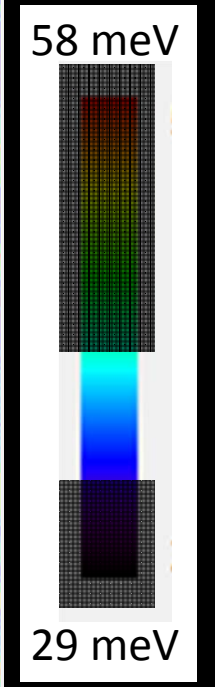
Gapmap: map of Δ as a function of location

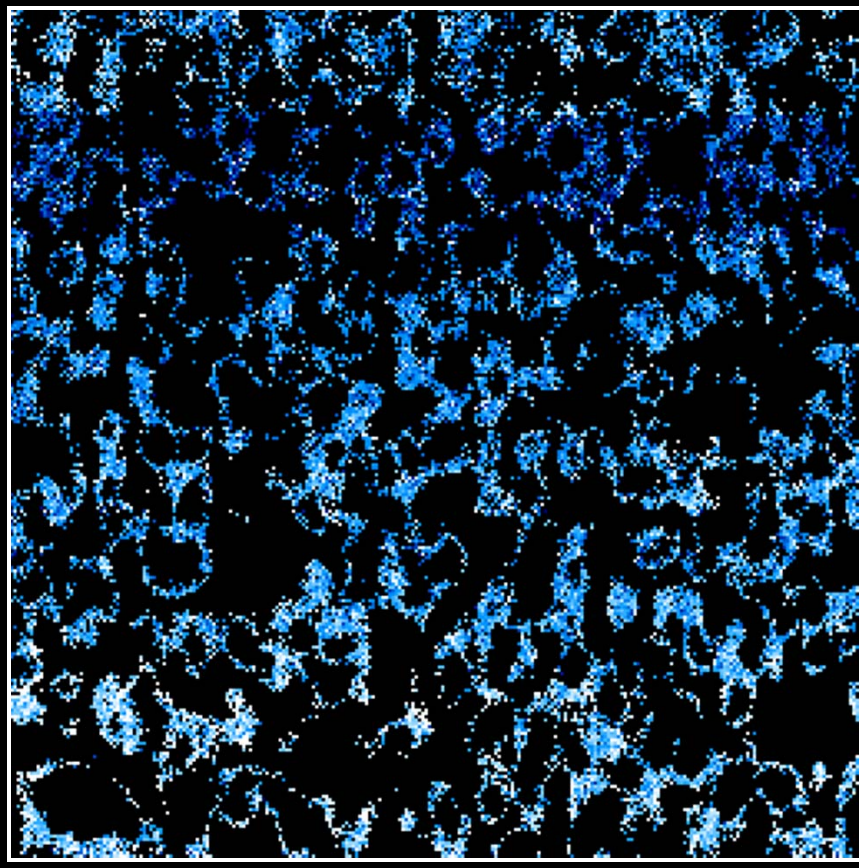


Lang, Nature (2002)
McElroy, PRL (2005)

Gap Masking

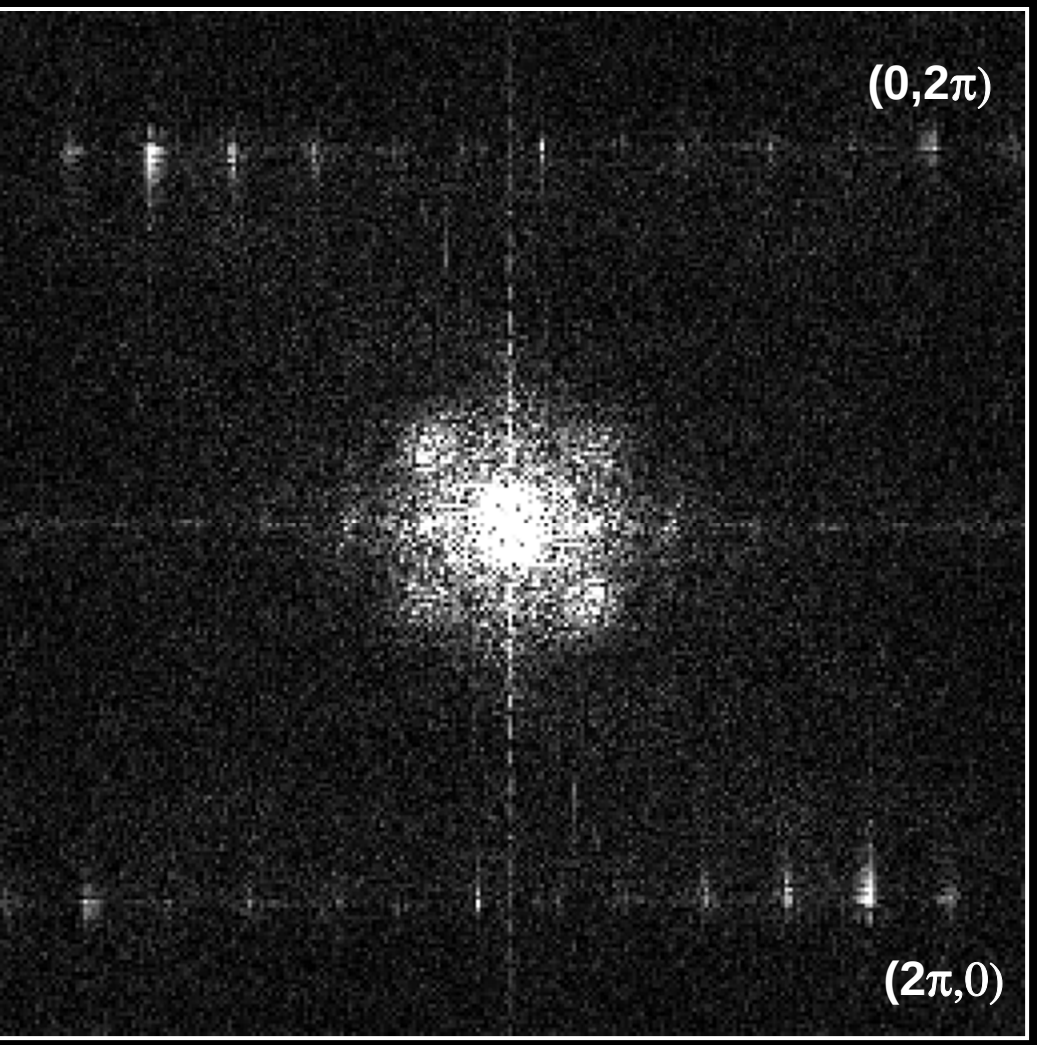


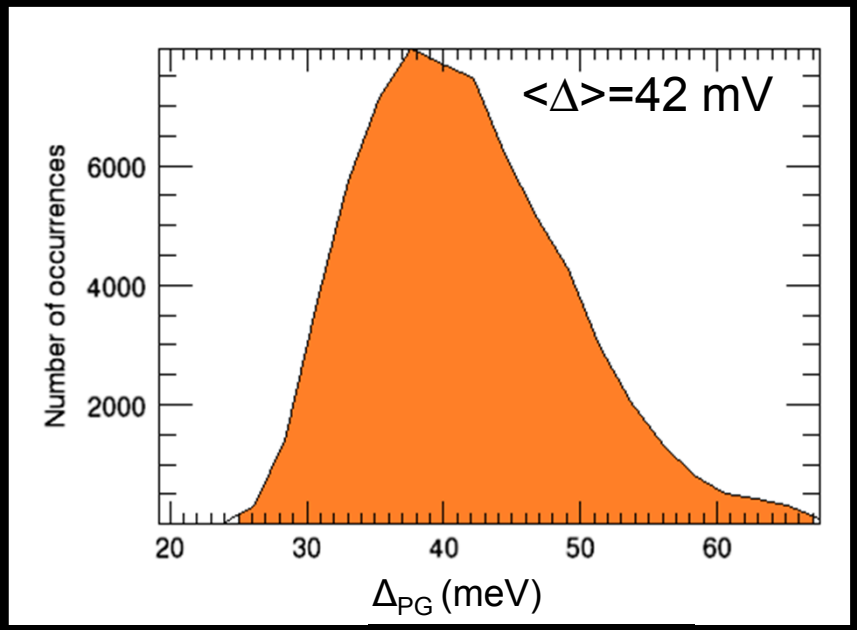


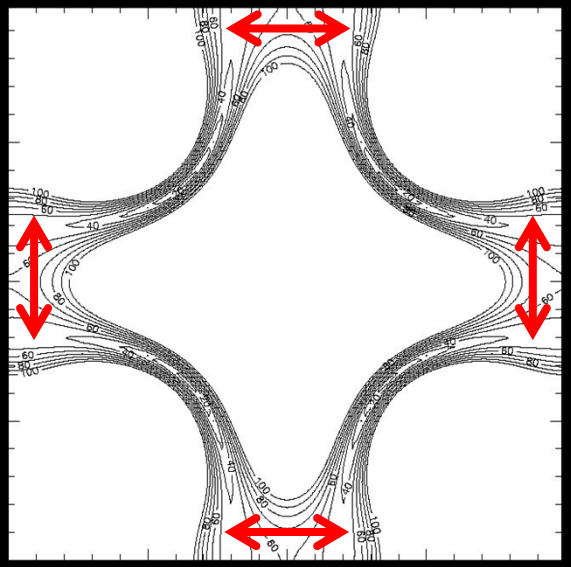


Look at just range of gap sizes:
e.g. Mask range: 37 to 42 meV

Gap-Based Checkerboard Evolution

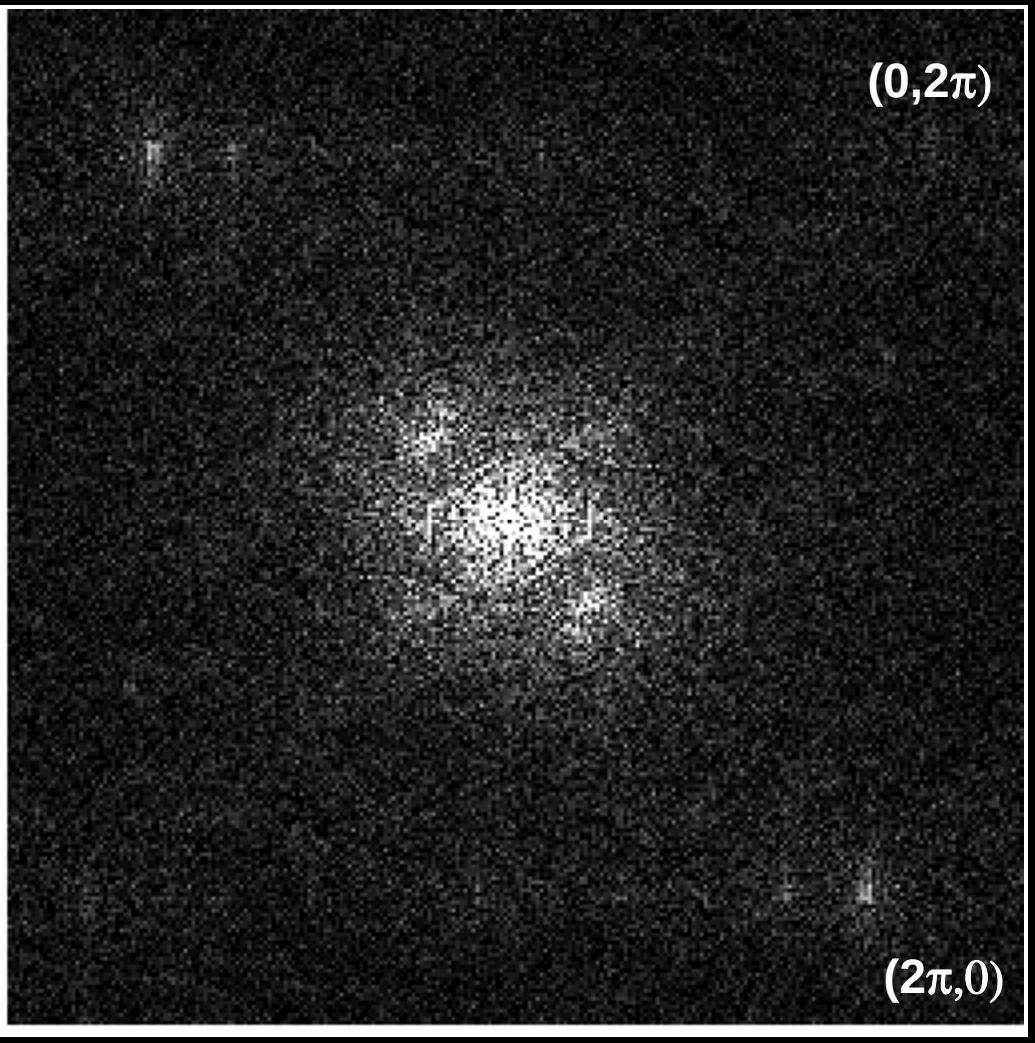


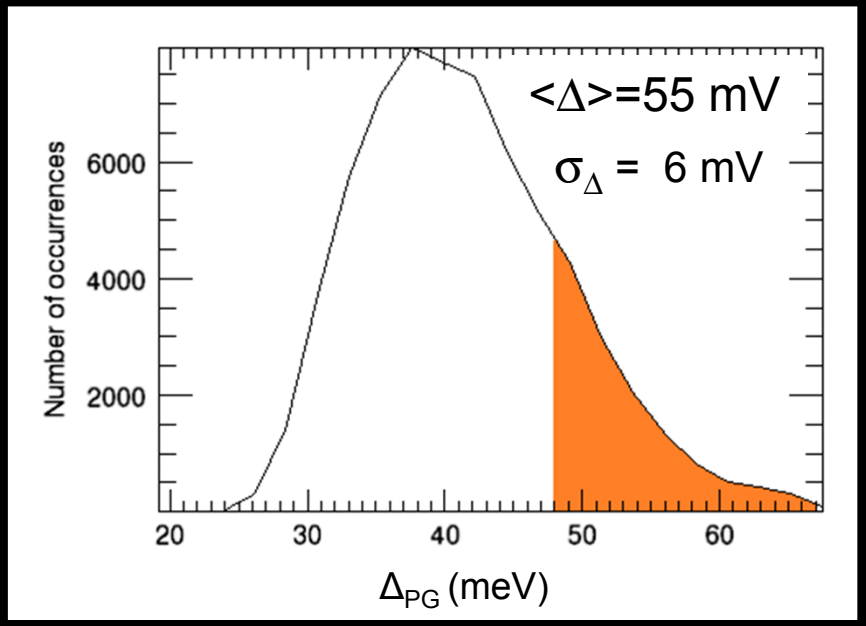


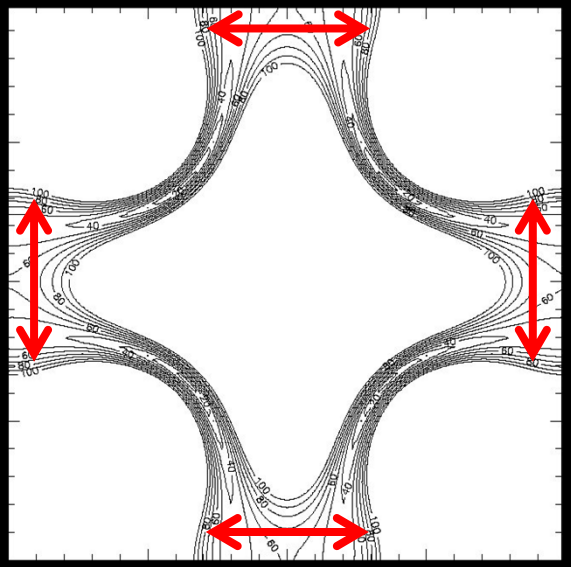


Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

Gap-Based Checkerboard Evolution

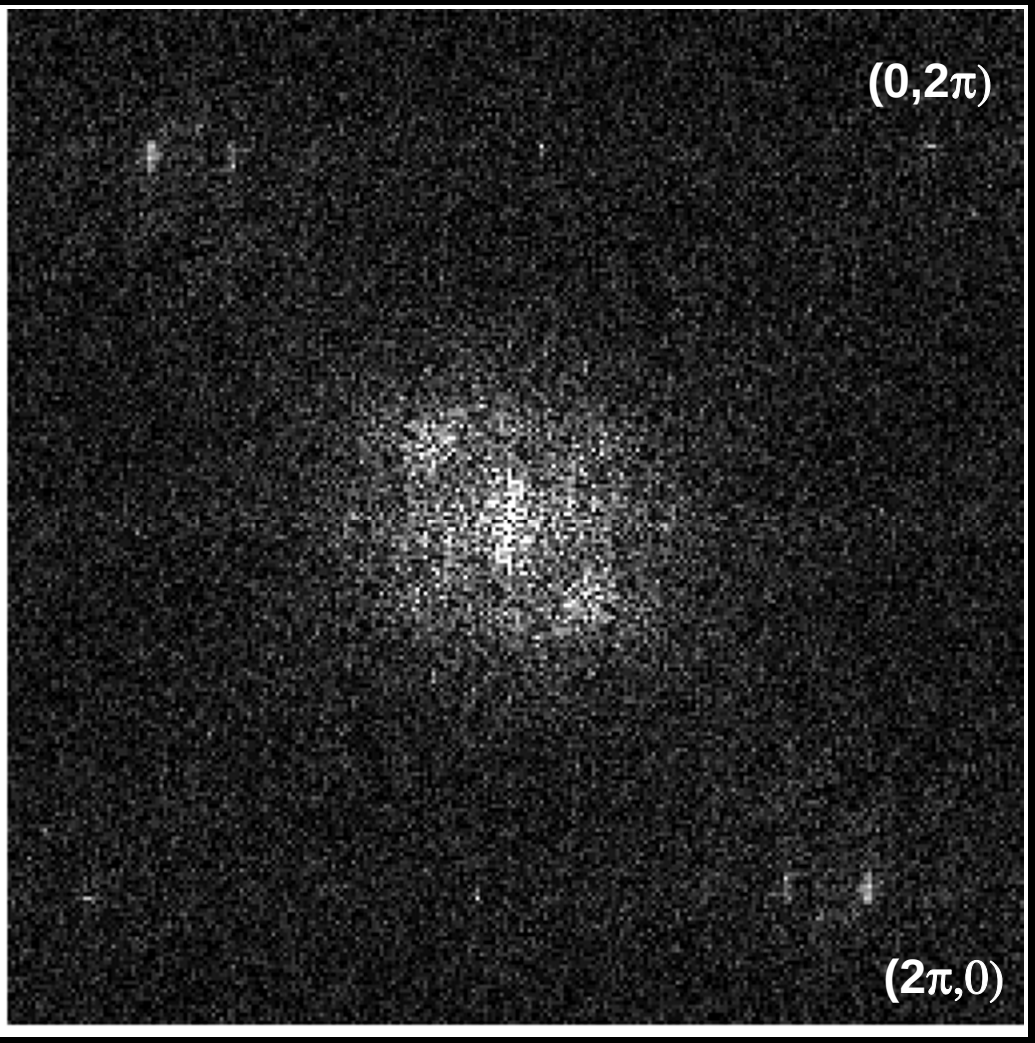


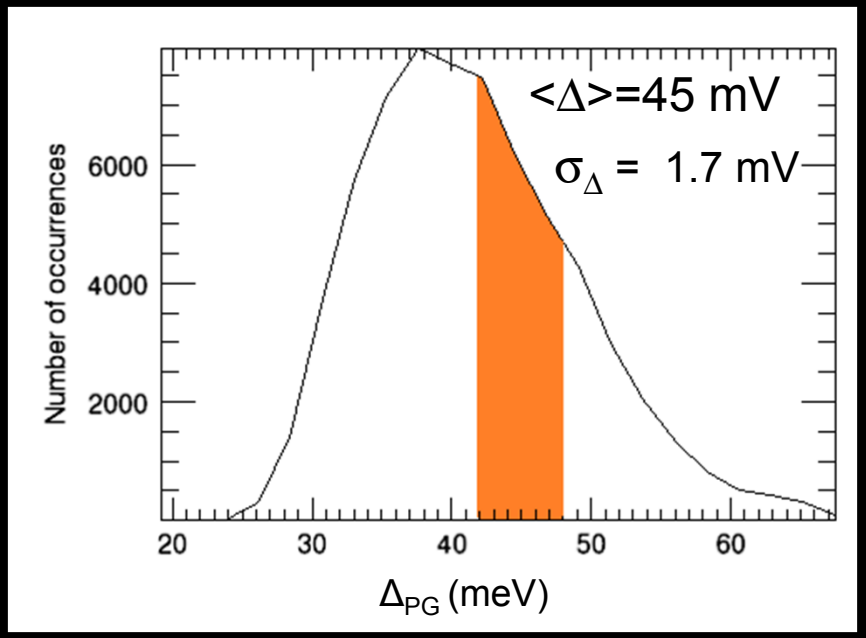


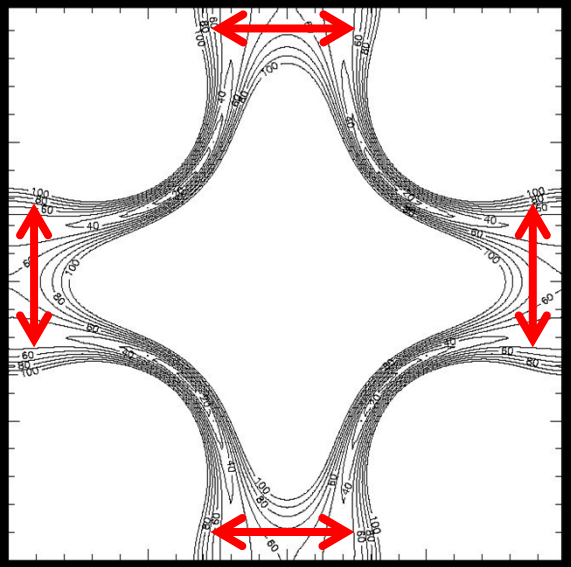


Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

Gap-Based Checkerboard Evolution

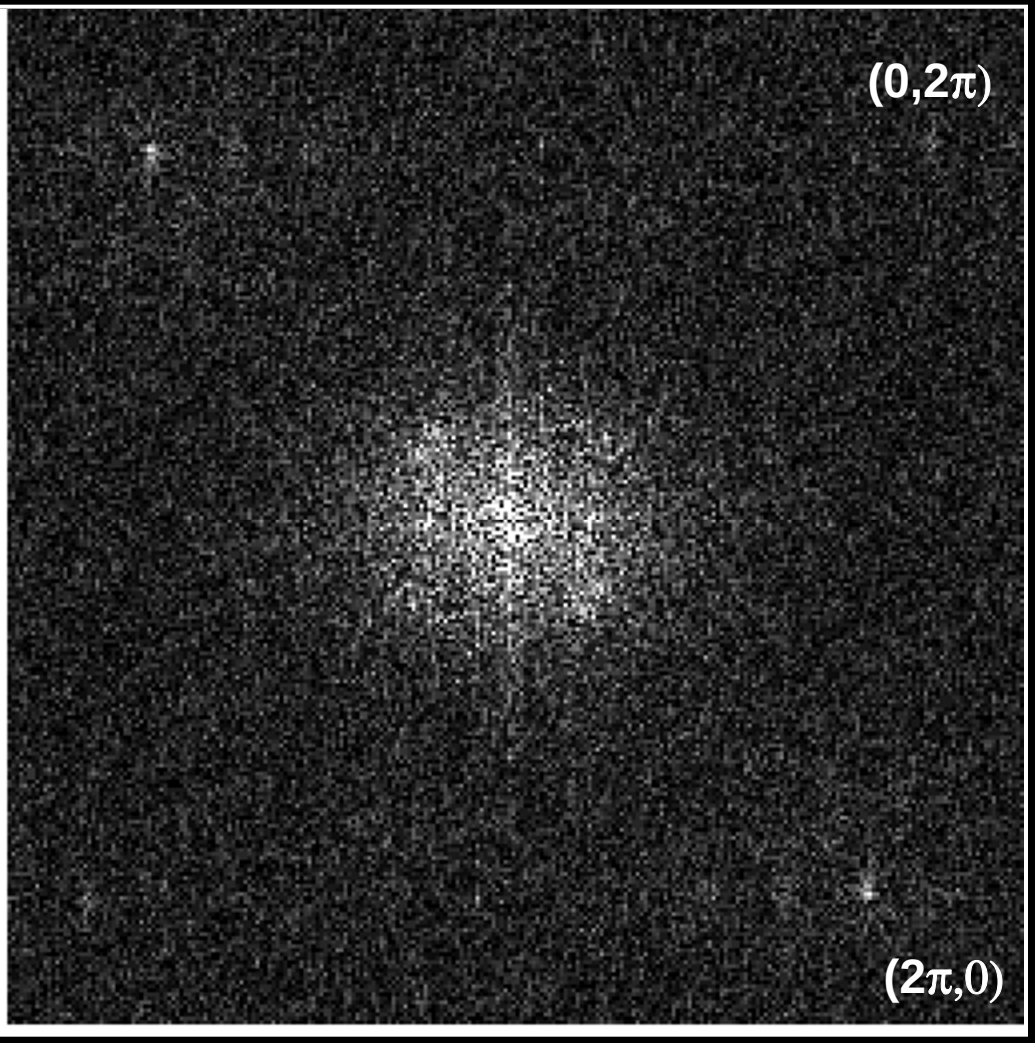


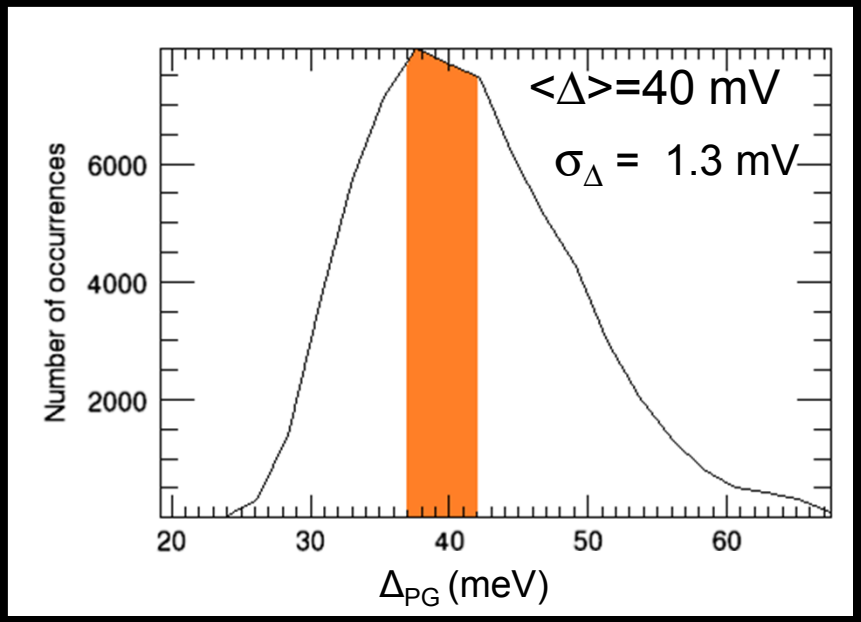


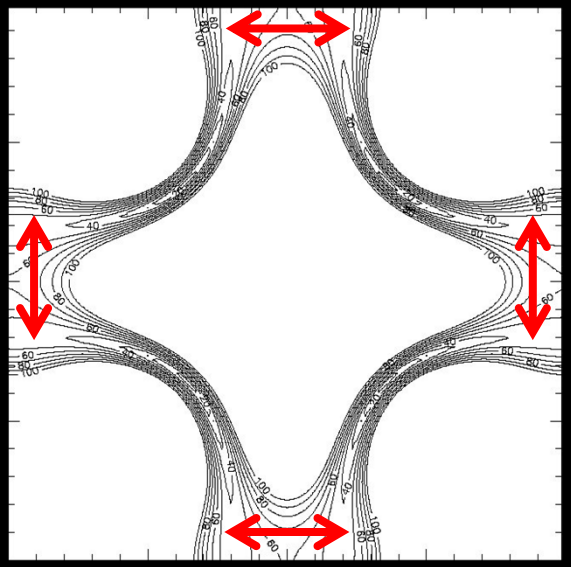


Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

Gap-Based Checkerboard Evolution

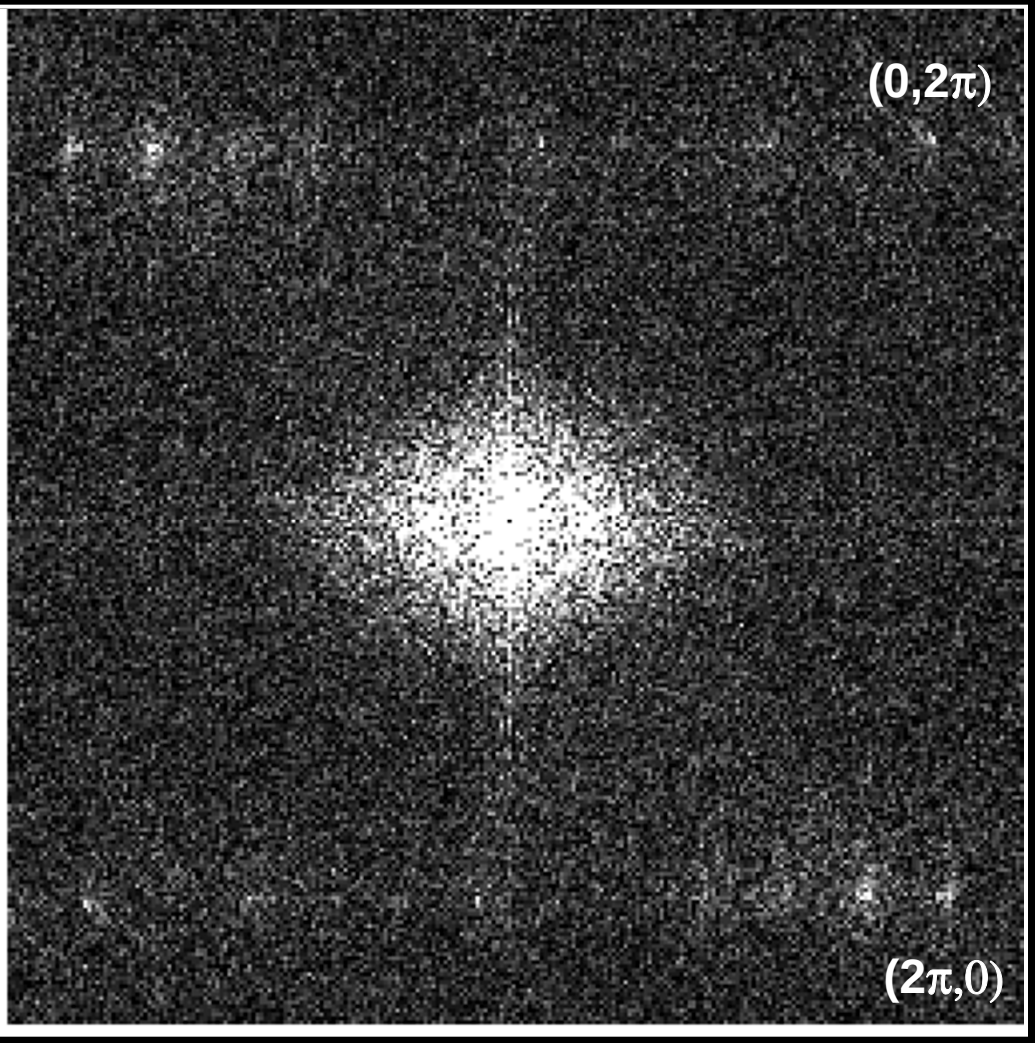


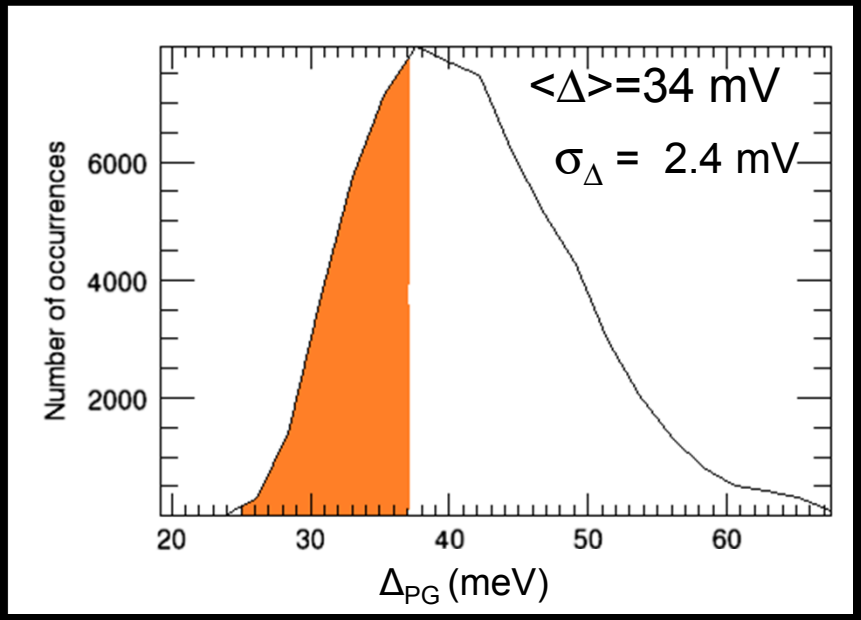


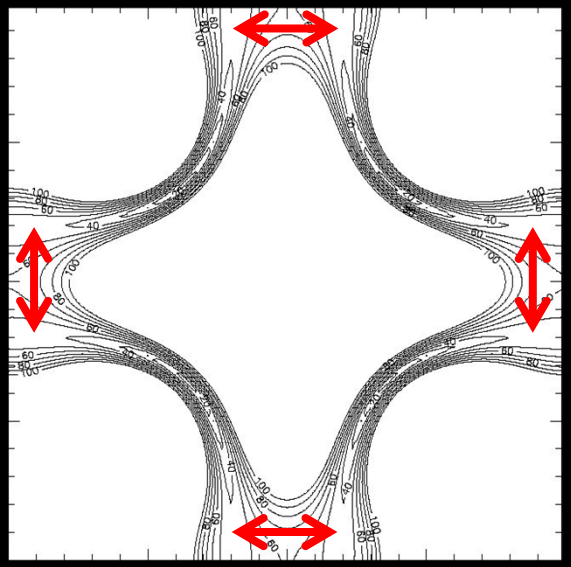


Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

Gap-Based Checkerboard Evolution





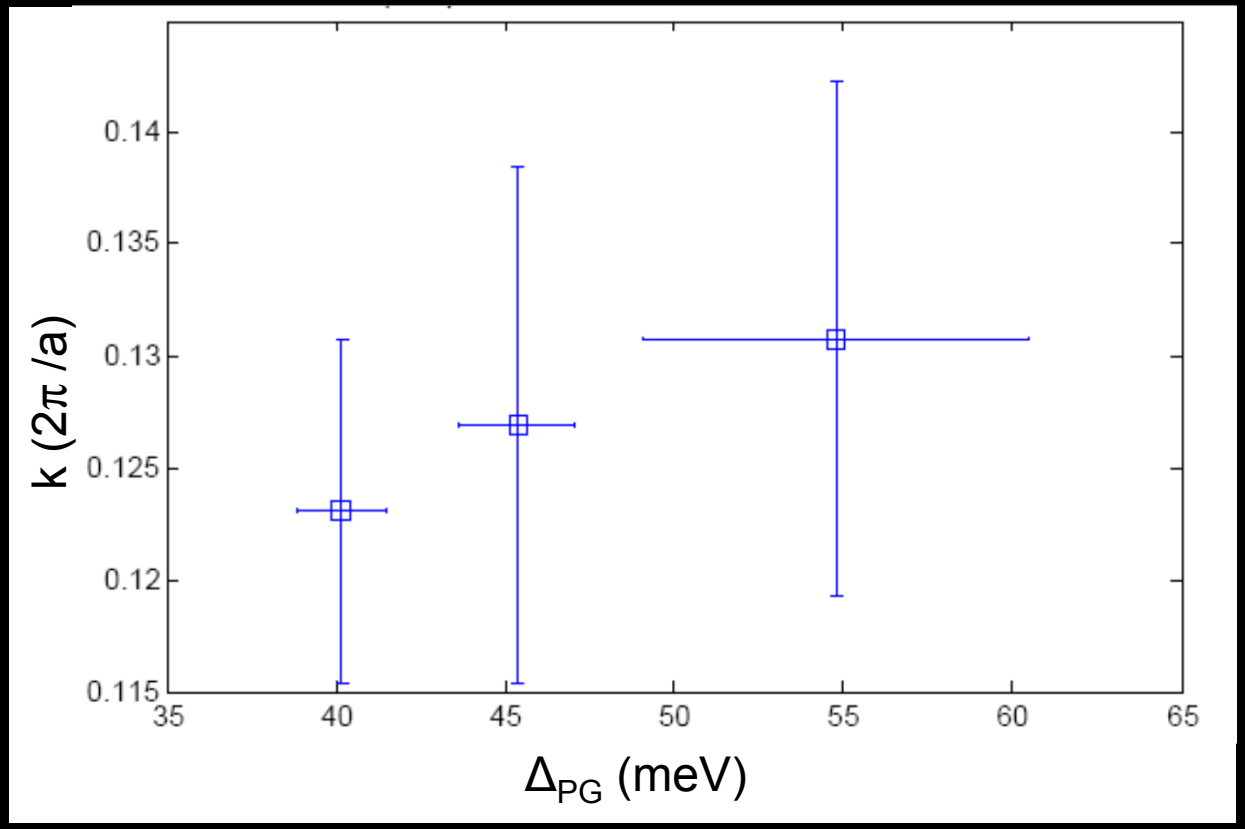


Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

Gap-Based Checkerboard Evolution

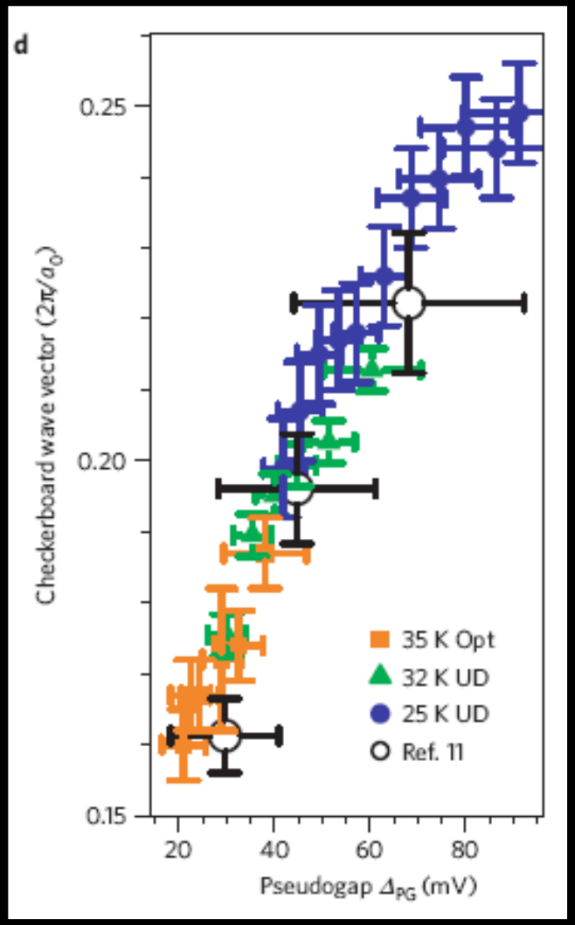
Our Data:

Bi-2212, from slightly OD sample, T=4K



Previous Data:

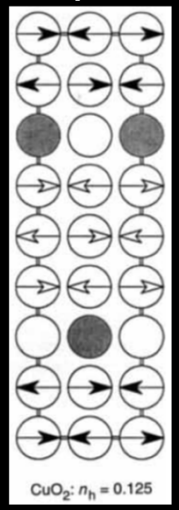
Bi-2201



Wise, Hudson, Nat Phys (2009)

Closer look: stripes or checkers?

stripes

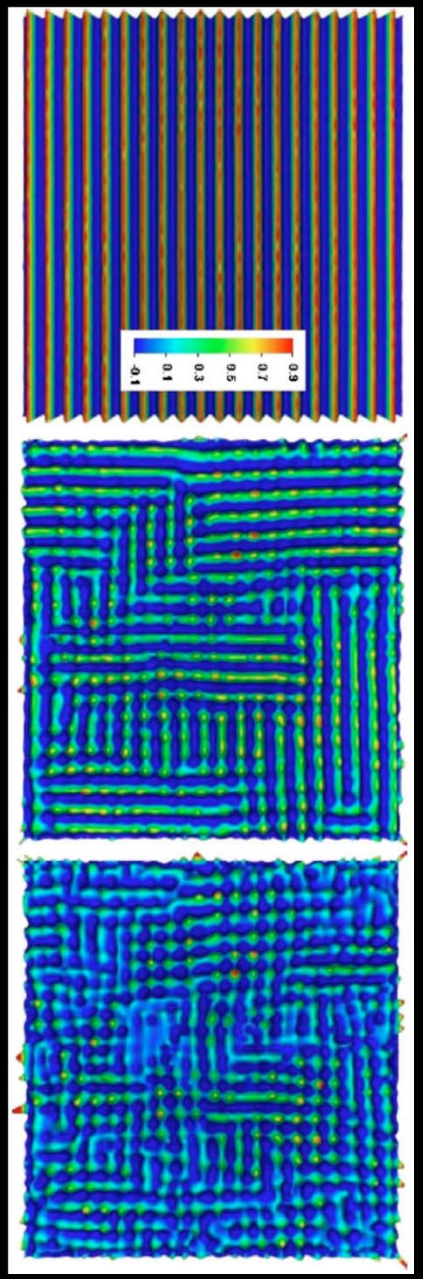


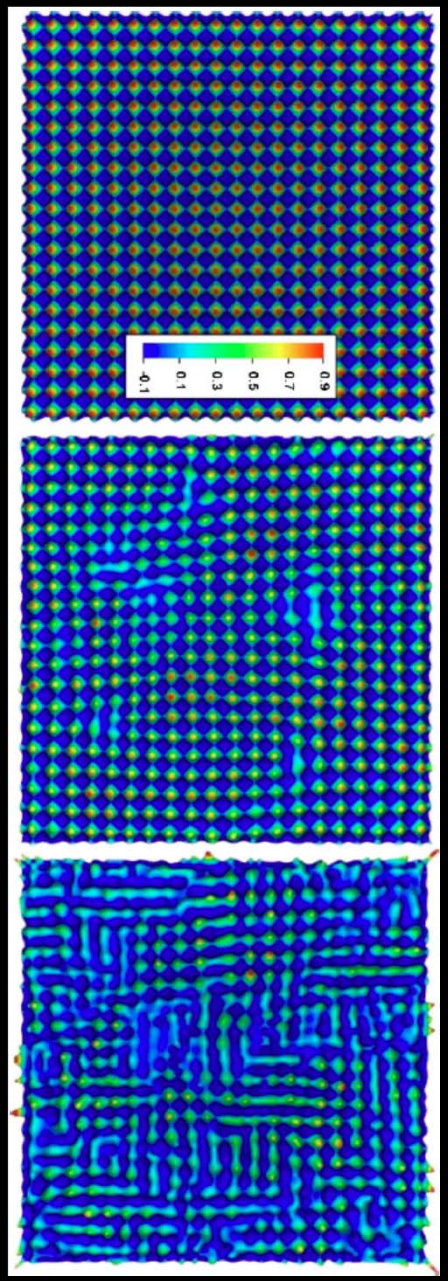
Static stripes. Weak disorder

Static stripes. Stronger disorder

Pinned fluctuating stripes.

Weak disorder





Static CB. Weak disorder

Static CB. Stronger disorder

Pinned fluctuating CB.

Weak disorder

Robertson, Kivelson, PRB 74, 134507 (2006)

ξ_{CDW} vs. ξ_{orient}

Charge modulation:

$$\rho(\mathbf{r}) = \bar{\rho} + [\varphi_1(\mathbf{r})e^{iQ_x x} + \varphi_2(\mathbf{r})e^{iQ_y y} + \text{c.c.}]$$

Hamiltonian:

$$H_{\text{eff}} = \frac{\kappa_L}{2}[|\partial_x\varphi_1|^2 + |\partial_y\varphi_2|^2] + \frac{\kappa_T}{2}[|\partial_y\varphi_1|^2 + |\partial_x\varphi_2|^2]$$

$$+ \frac{\alpha}{2}[|\varphi_1|^2 + |\varphi_2|^2] + \frac{u}{4}[|\varphi_1|^2 + |\varphi_2|^2]^2 + \gamma|\varphi_1|^2|\varphi_2|^2$$

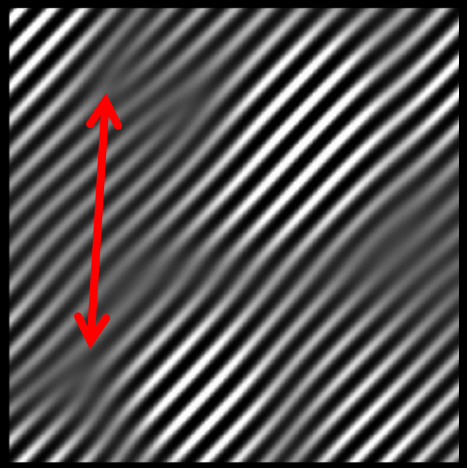
sign determines stripes vs. checkers

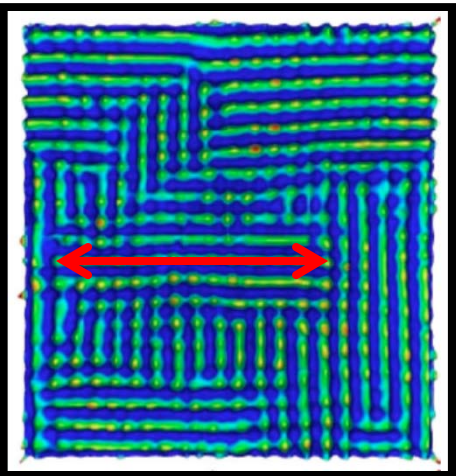
Correlation lengths:

A_1, A_2 = complex values of charge modulation in x, y directions

$$\xi^2_{\text{CDW}} \equiv \frac{|\int d\mathbf{r}\mathbf{A}|^2}{\int d\mathbf{r}|\mathbf{A}|^2}$$

$$\xi^2_{\text{orient}} \equiv \frac{|\int d\mathbf{r}[|A_1|^2 - |A_2|^2]|^2}{\int d\mathbf{r}||A_1|^2 - |A_2|^2|^2}$$





Robertson, Kivelson, PRB 74, 134507 (2006)

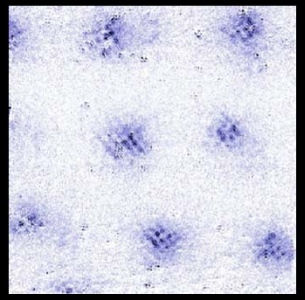
Stripe domains?

unpublished data

Inter-unit-cell checkerboard: Conclusions

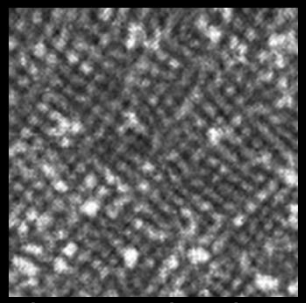
1. Checkerboard seen for 10 years → many names

Checkerboard



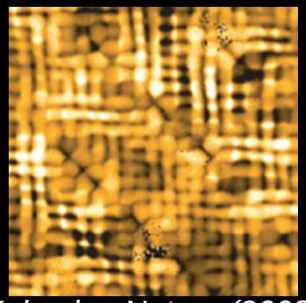
Hoffman, *Science* (2002)

Charge Density Wave



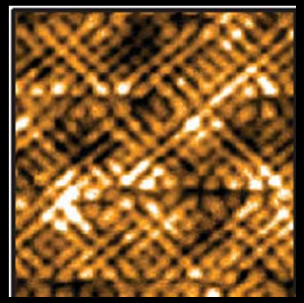
Wise, Nat Phys (2008)

Electronic Cluster Glass



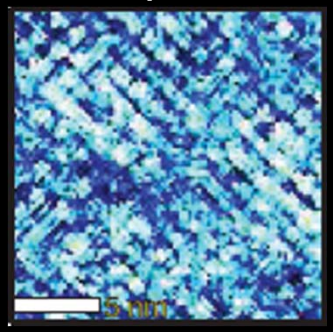
Kohsaka, Nature (2008)

"Smectic"



Lawler, Nature (2010)

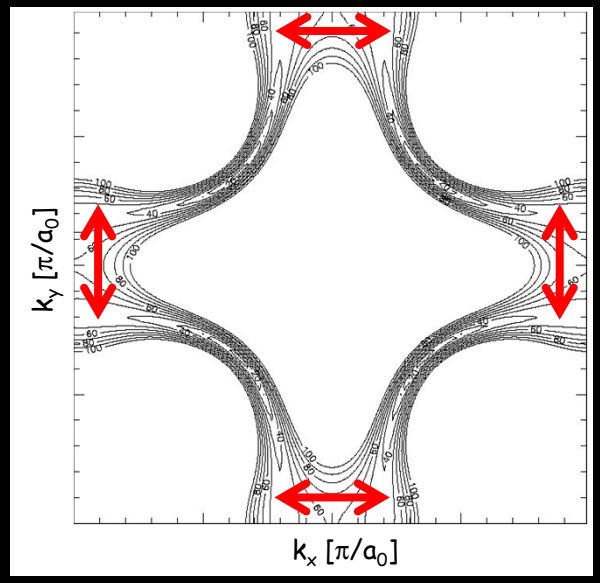
"Fluctuating Stripes"



Parker, Nature (2010)

2. Checkerboard wavelength correlates with antinodal nesting wavevector in Brillouin zone

3. Checkerboard=pseudogap, competes with superconductivity



Next step: is it really a checkerboard?
or small, disordered domains of stripes?

Outline

Superconductors: 100 Year History

Pseudogap in cuprates:

- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:

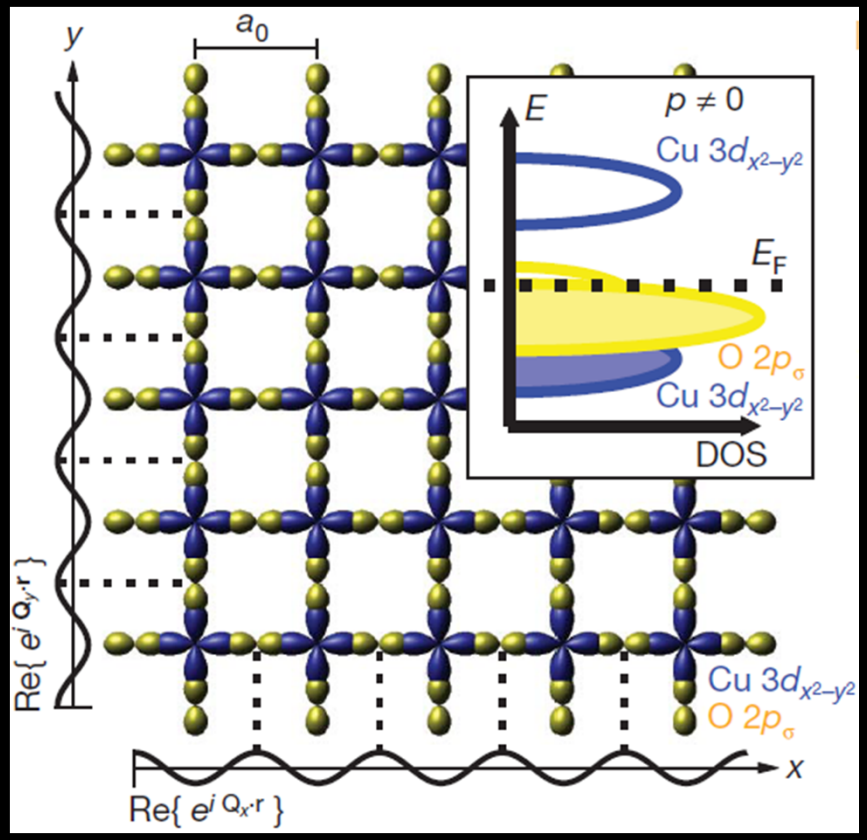
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy

Intra-unit-cell ordering: nematicity? inversion?

("nematic" = fluid state which breaks rotation symmetry, but not translation)

Goals:

1. detect "nematic" orbital ordering = difference between 2 inequivalent O sites
2. detect "inversion symmetry breaking" at Cu sites



Lawler, Nature (2010)

Implementation:

1. nematic: is there difference between x & y real parts of FT?
1. inversion: is there imaginary part of FT?

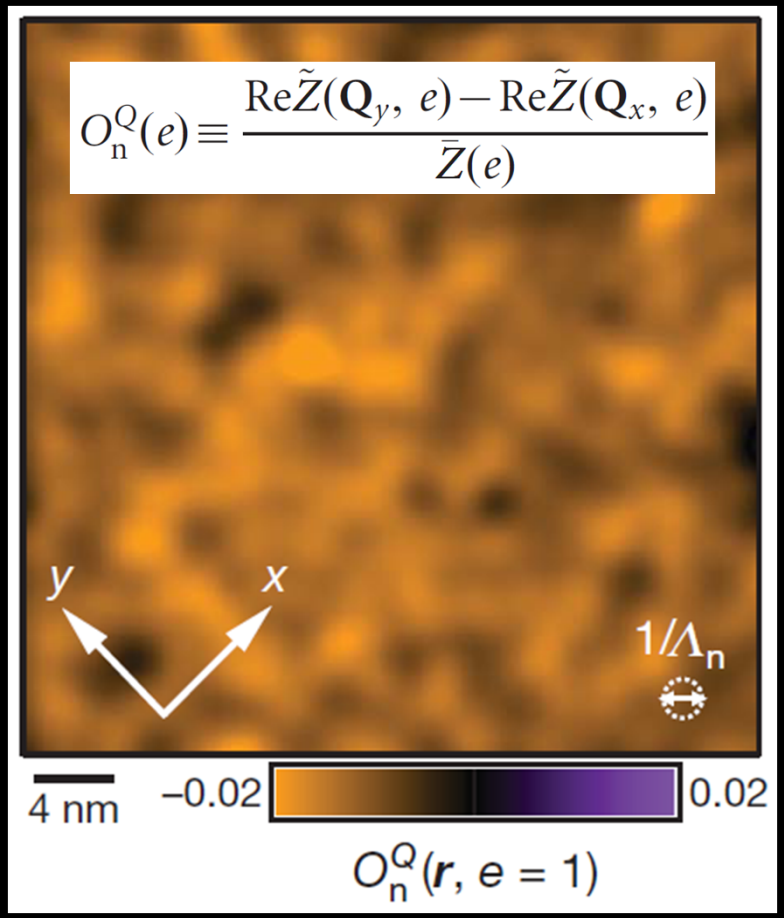
Lawler, Davis, Kim invented drift correction algorithm to line up atoms onto perfect grid!

Lawler's "Nematic"

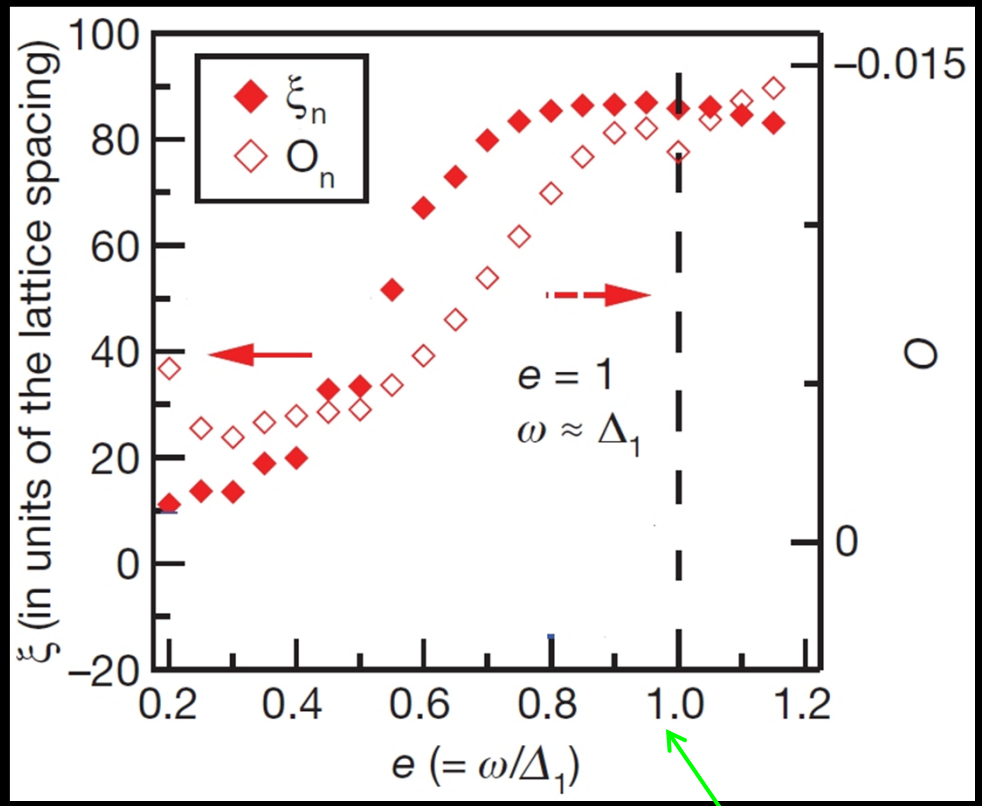
Lawler:

1. use the topography to get the drift-correction field
2. apply the same drift-correction field to the density of states at the pseudogap energy
3. compare the single-pixel Re(Qx) and Re(Qy) to look for nematicity

"Long range" order in 40nm sq



Order is strongest at Pseudogap energy

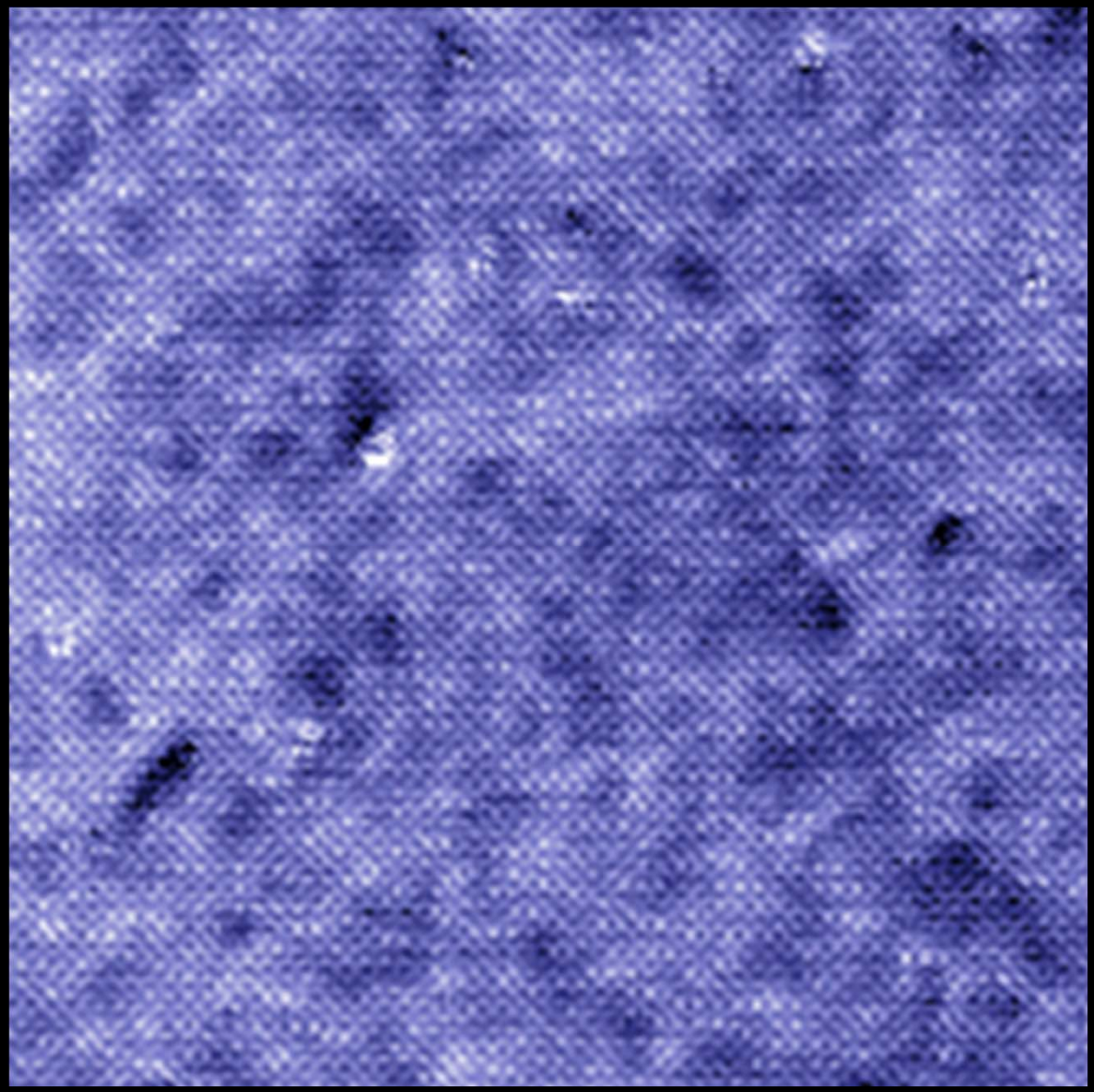


pseudogap

Lawler, Nature (2010)

Our data: Bi-2201 without supermodulation

Topography:
30 nm x 30 nm



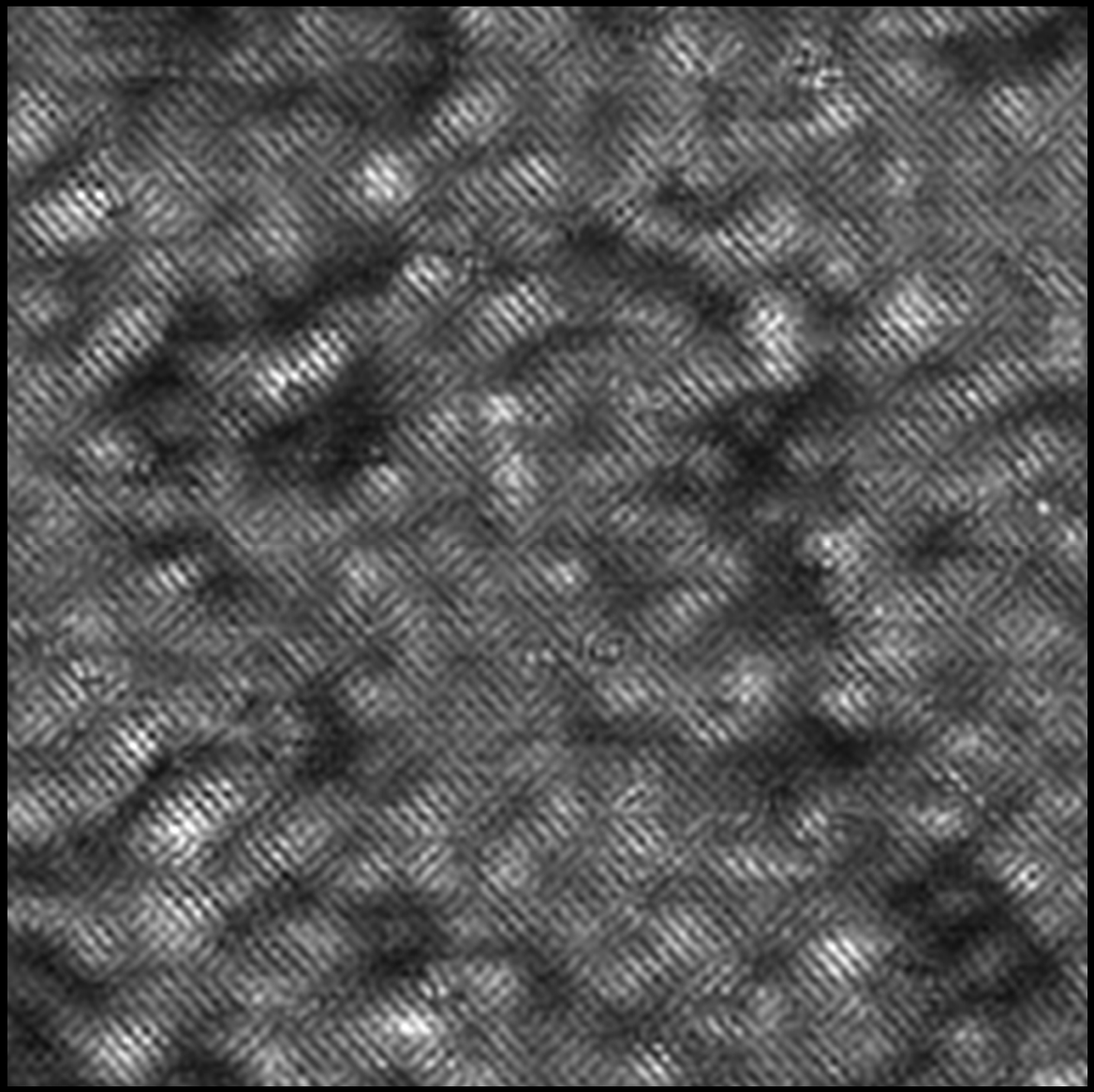
Optimally doped Bi-2201
(Tc = 35K)

Pb-doped to remove supermodulation

Hudson/Hoffman lab, combined Bi-2201 datasets

Our data: Bi-2201 without supermodulation

Density of states at E=30 meV: 30 nm x 30 nm

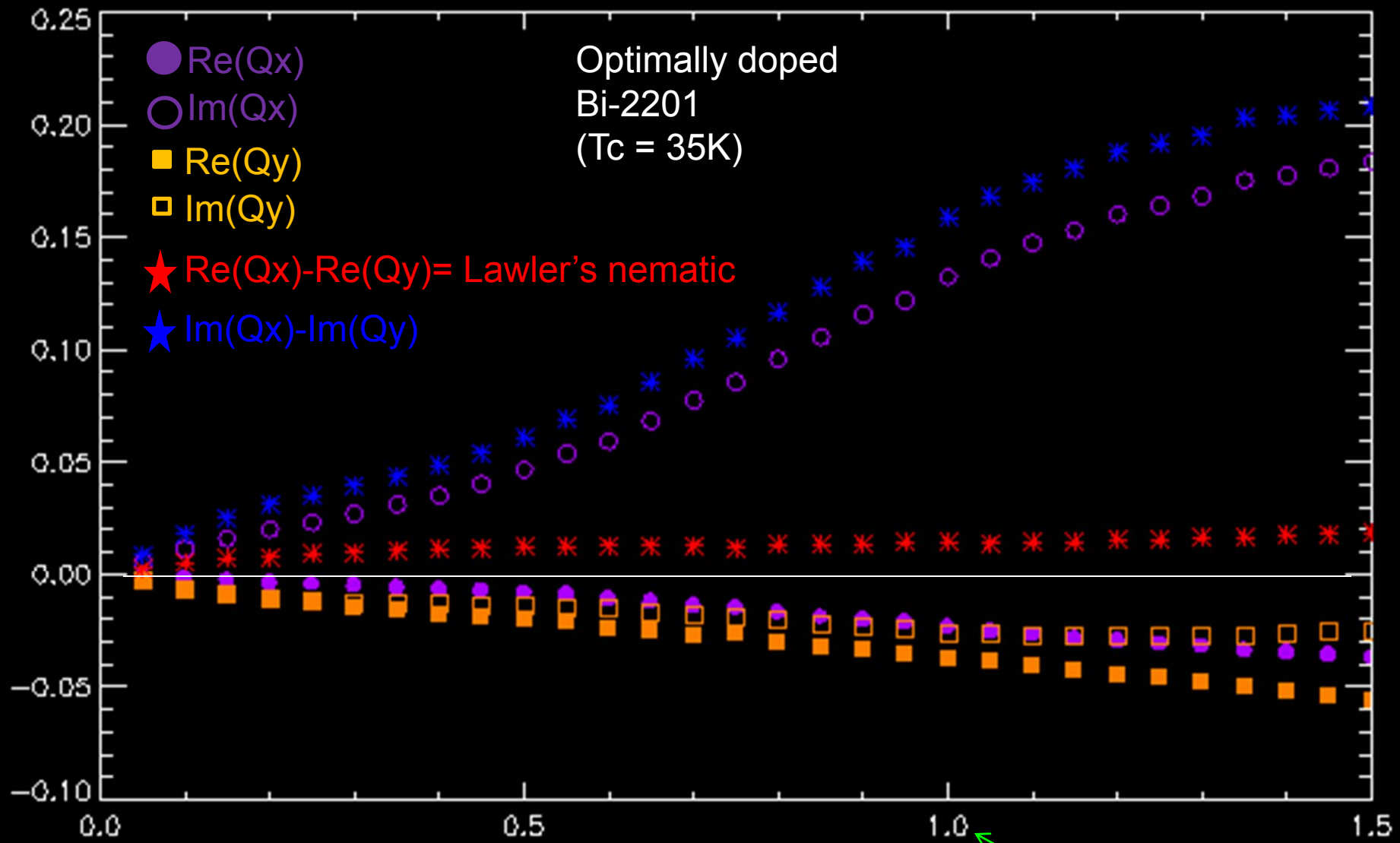


Optimally doped Bi-2201 (Tc = 35K)

Pb-doped to remove supermodulation

Hudson/Hoffman lab, combined Bi-2201 datasets

Imaginary Complications

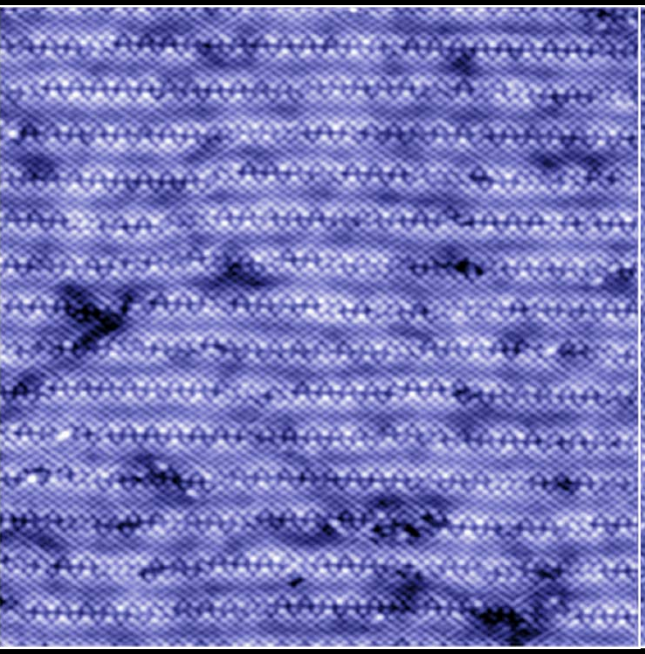


Δ_{PG} ~ 30 meV

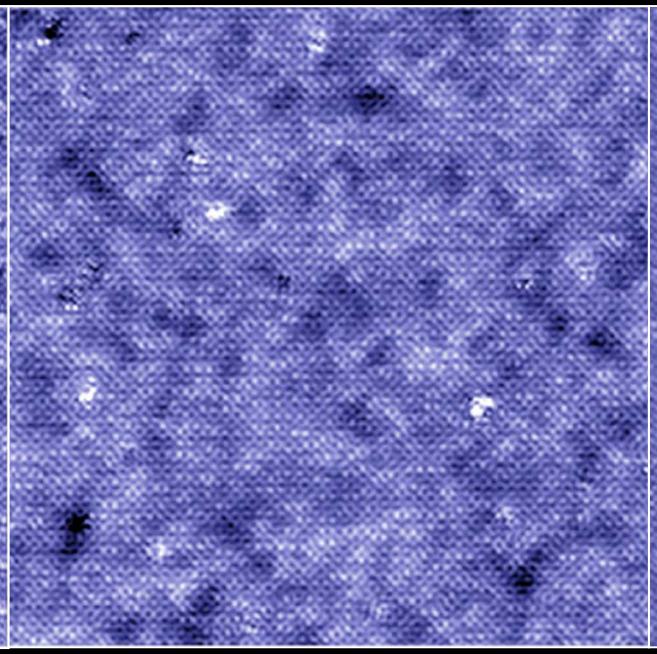
Hudson/Hoffman lab, combined Bi-2201 datasets

? Structural ↔ Electronic ?

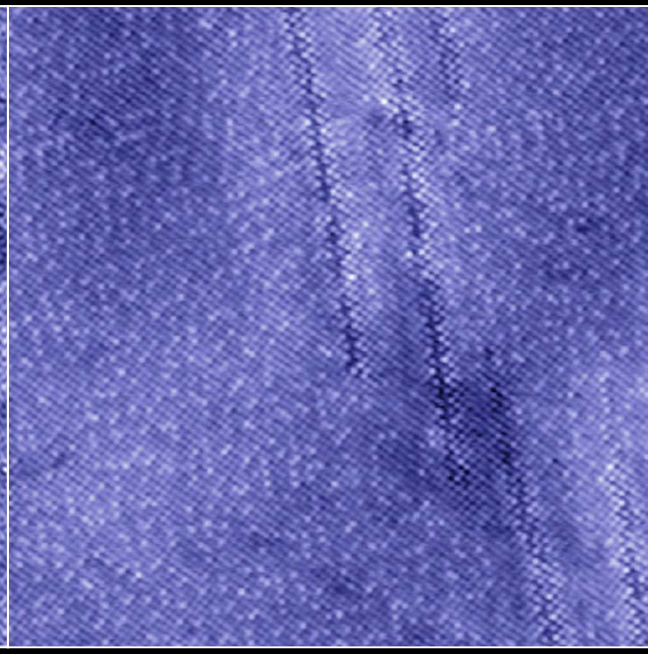
Bi-2212



Bi-2201, Pb-doped

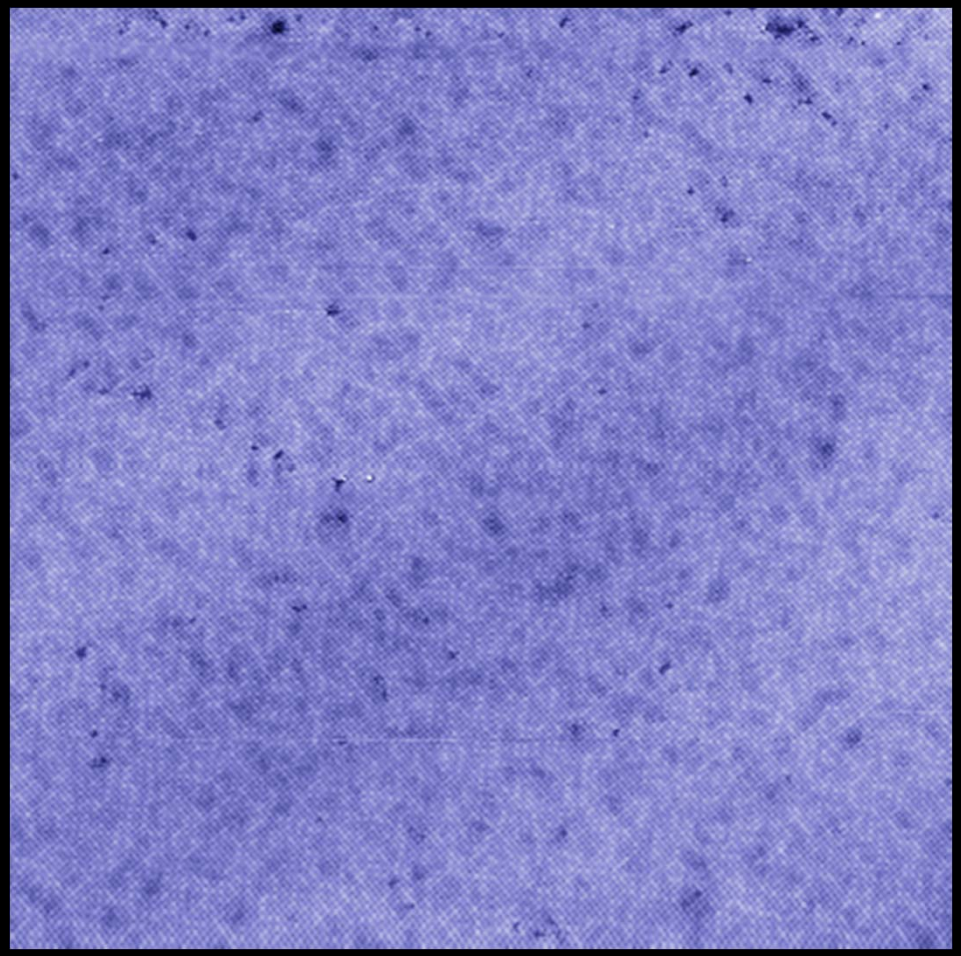


another Bi-2201, Pb-doped

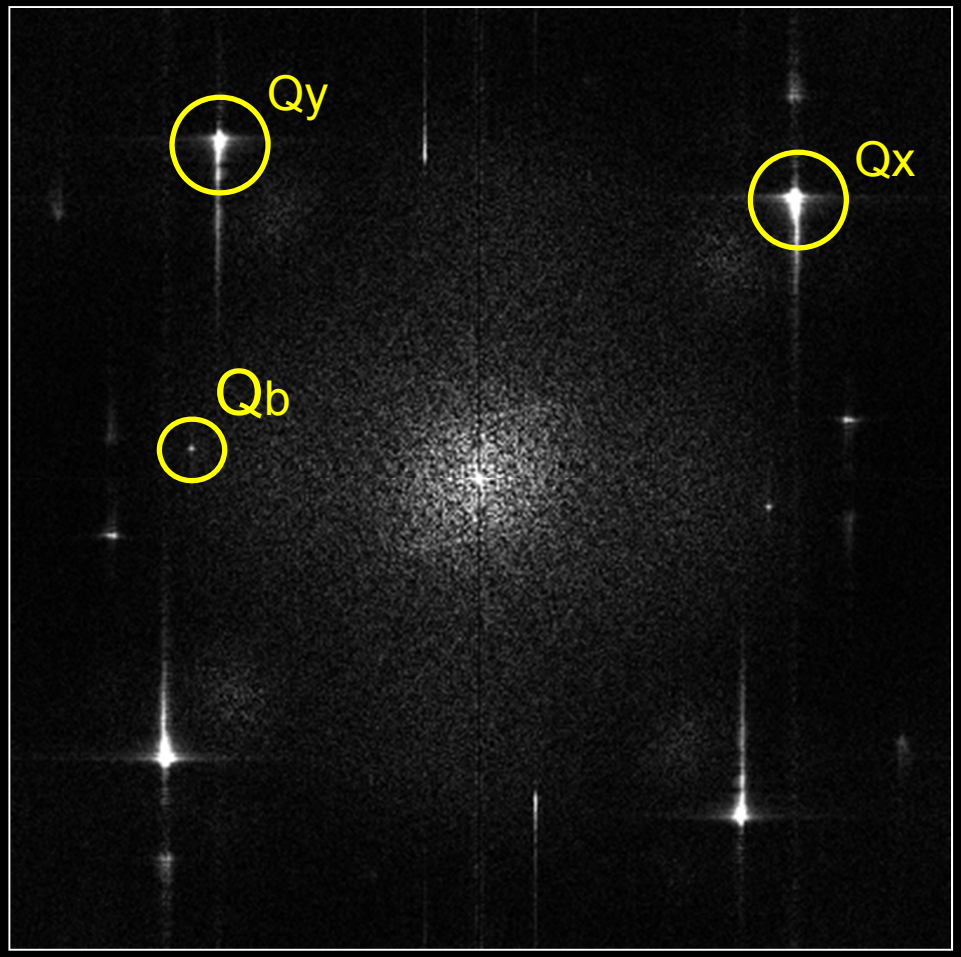


Raw data

(Bi-2201, Tc=32K, slightly underdoped)



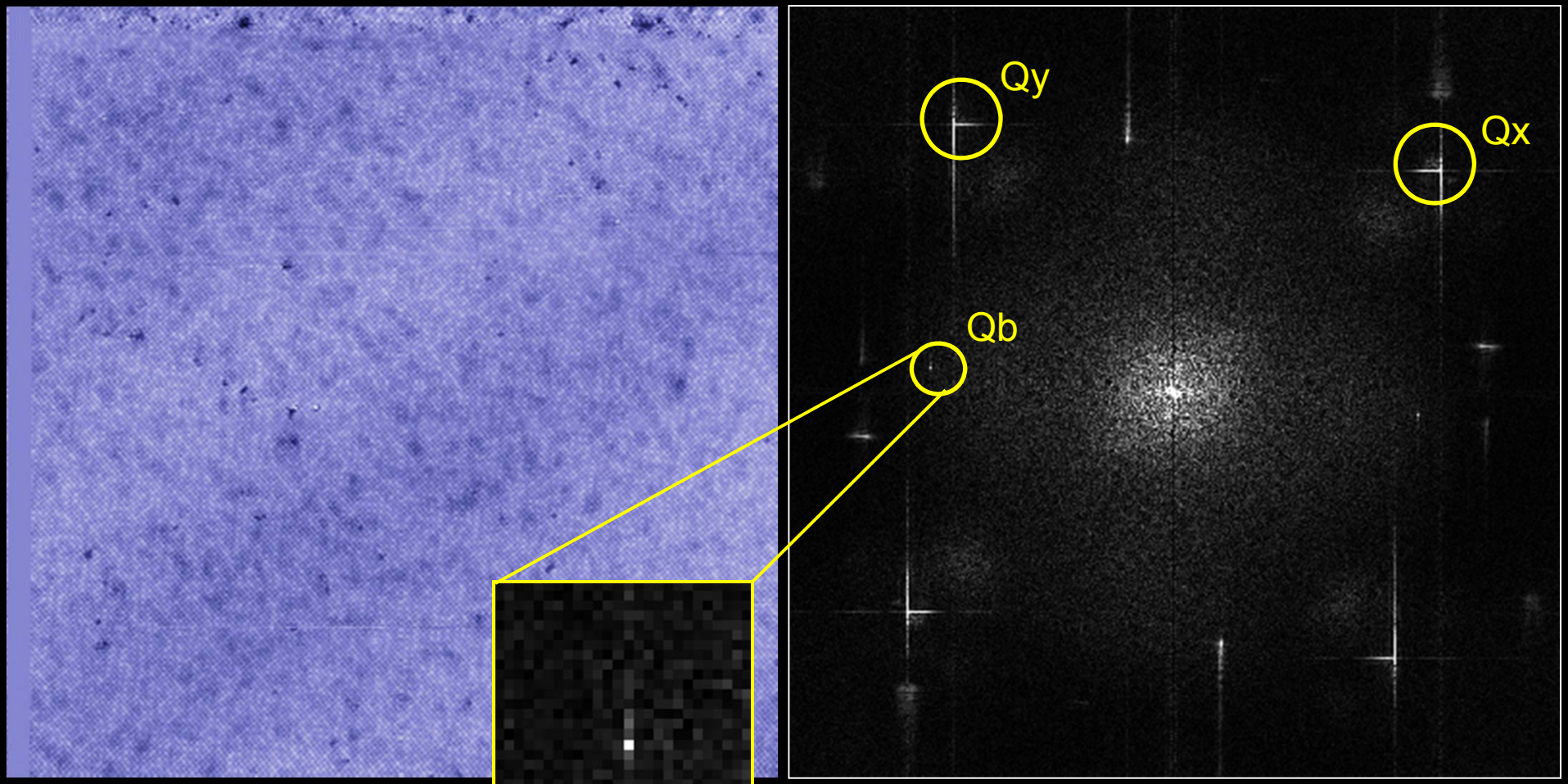
66x66 nm^2



Bragg peaks are blurred → need to apply Lawler algorithm to drift-correct!

Drift-corrected data

(Bi-2201, Tc=32K, slightly underdoped)



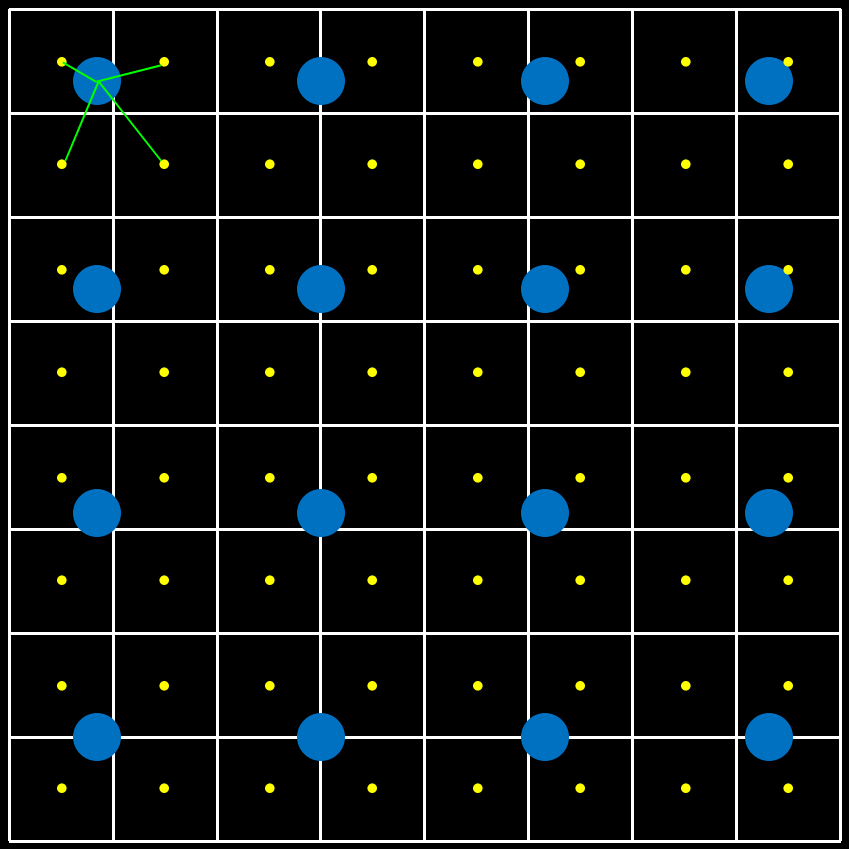
center pix > 5x brighter than nearest neighbors

Make Average Unit Cell

— Pixel grid

• exact tip location when data acquired

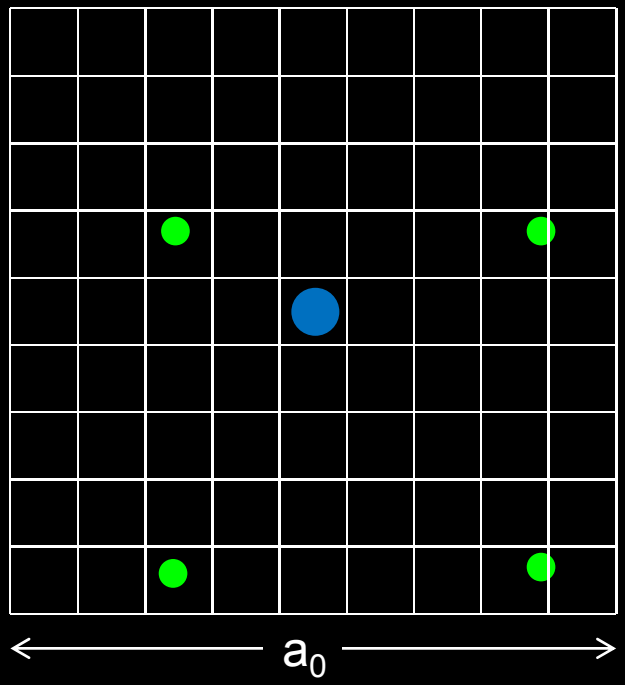
● Bi atom



Make a new grid, one unit cell,
but with more pixels than in raw data.

Center Bi in center of this unit cell.

Build up a histogram of weight at each sub-unit-cell-resolved location.

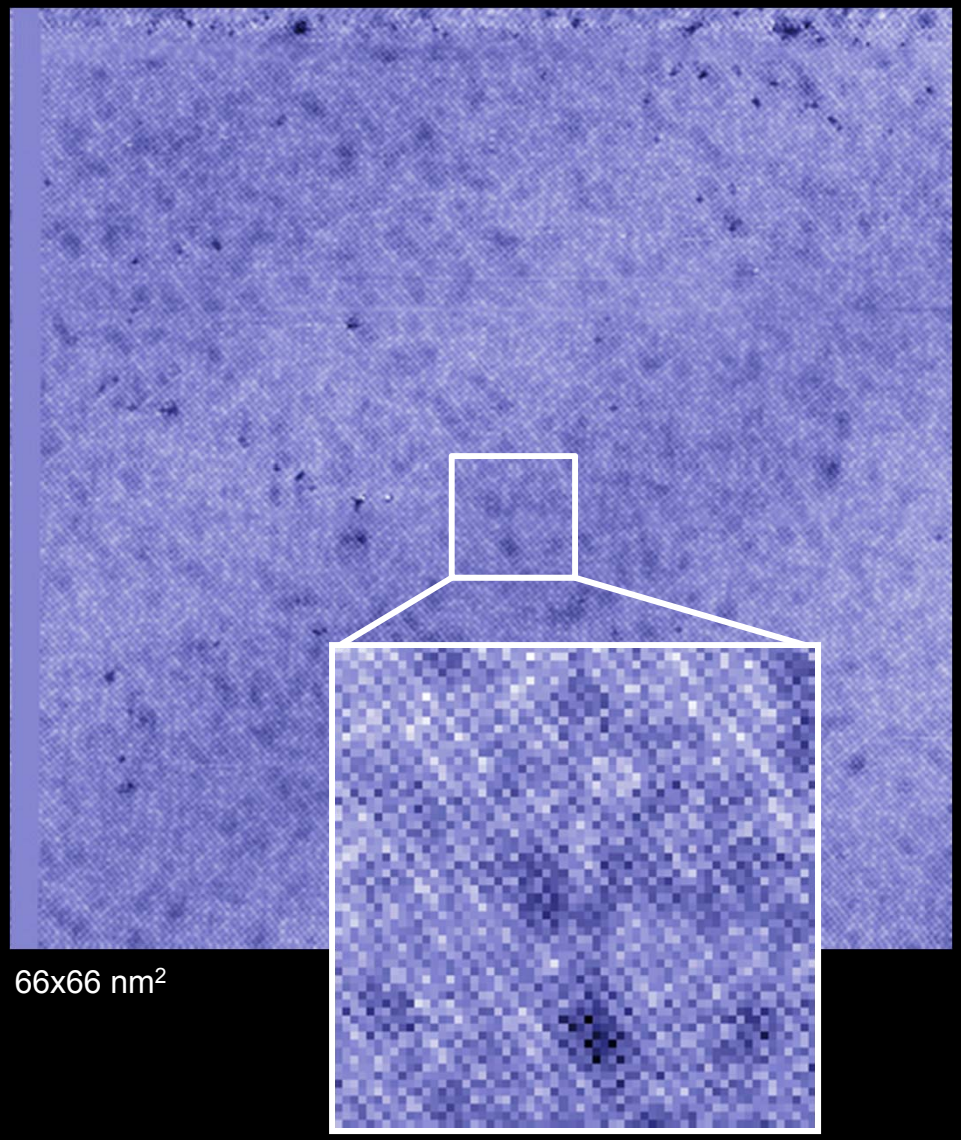


Note: data acquisition only slightly better than Nyquist frequency for atoms!

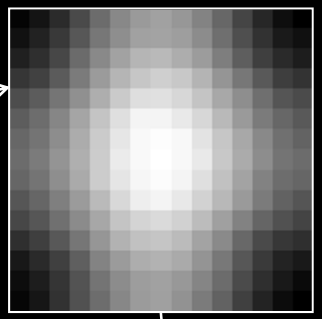
Perfect registry allows sub-unit-cell resolution!

Make Average Unit Cell

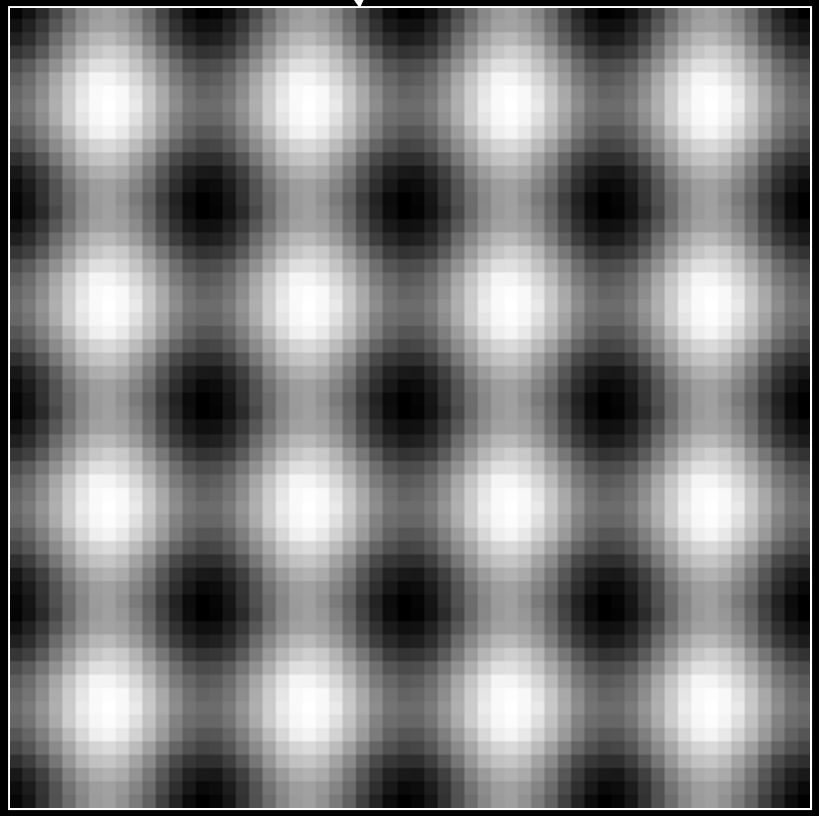
(Bi-2201, Tc=32K, slightly underdoped)



make average unit cell

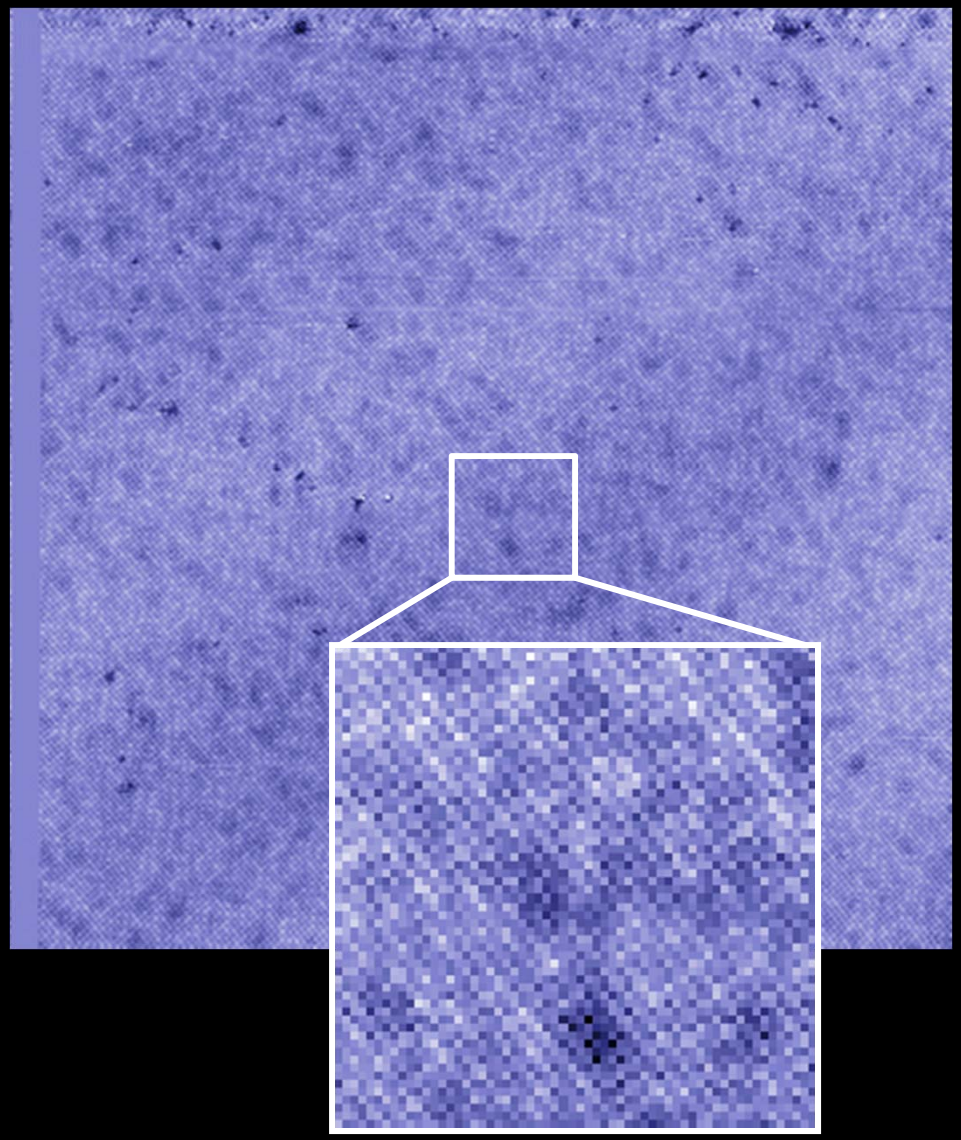


tile 4x4

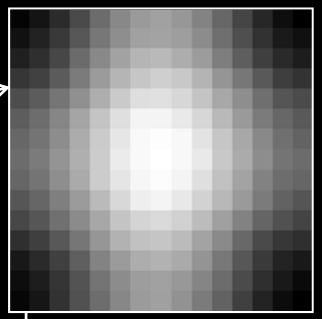


Make Average Unit Cell

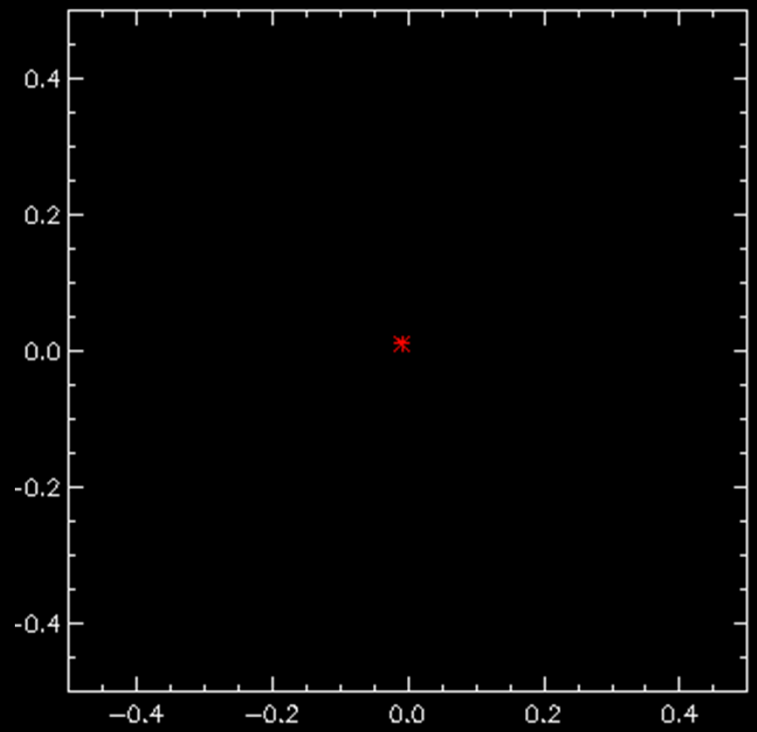
(Bi-2201, Tc=32K, slightly underdoped)



make average unit cell

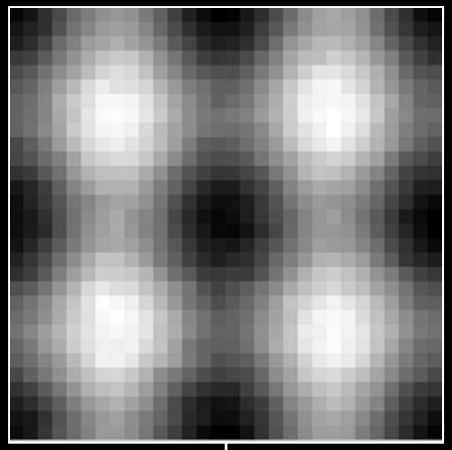


fit to make sure Bi is at center, where we think it should be

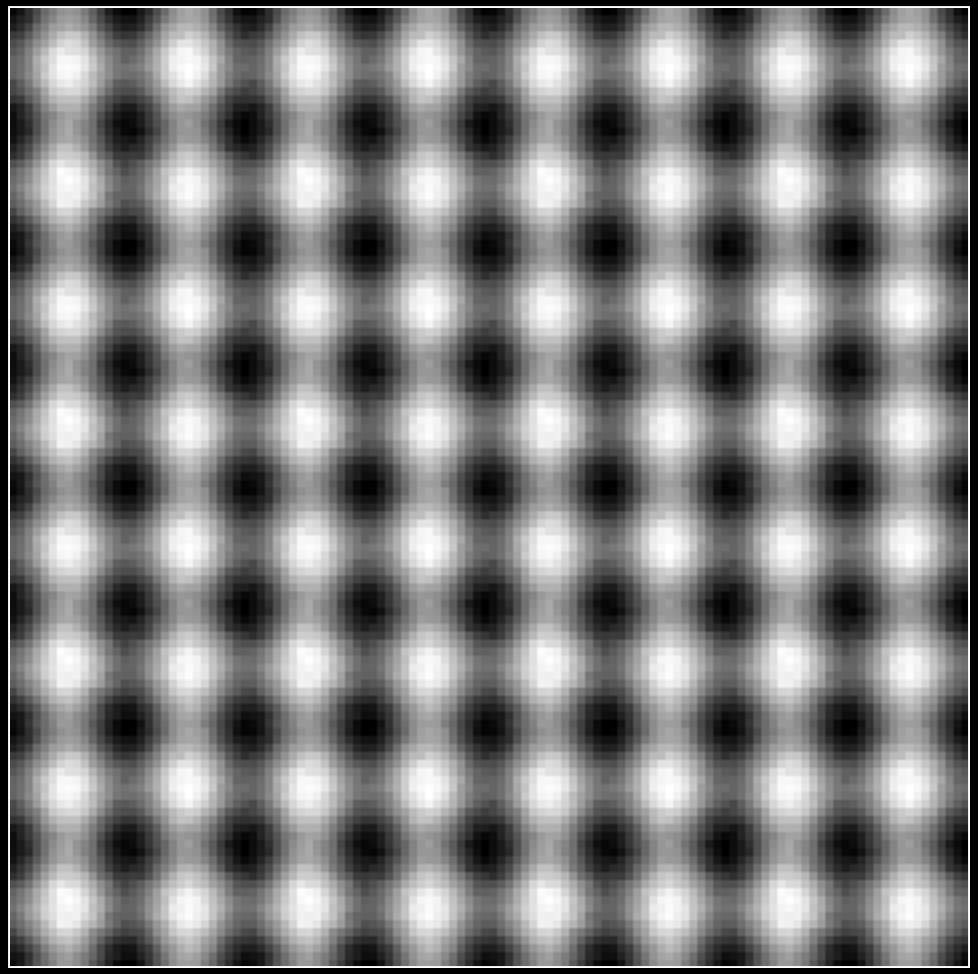


Make Average Supercell: 2x2

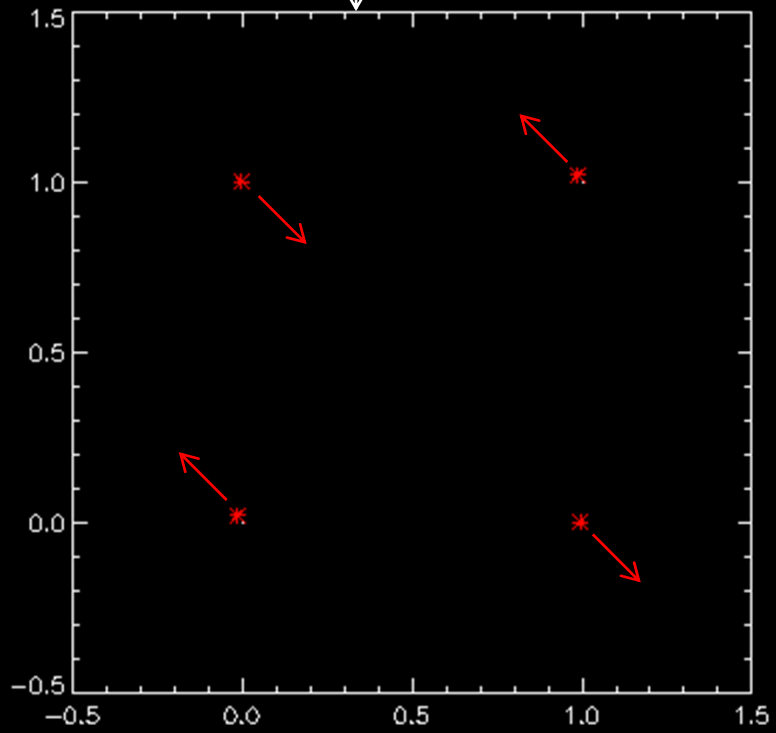
(Bi-2201, Tc=32K, slightly underdoped)



tiled →



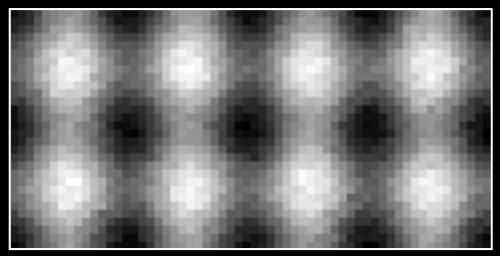
fit ↓



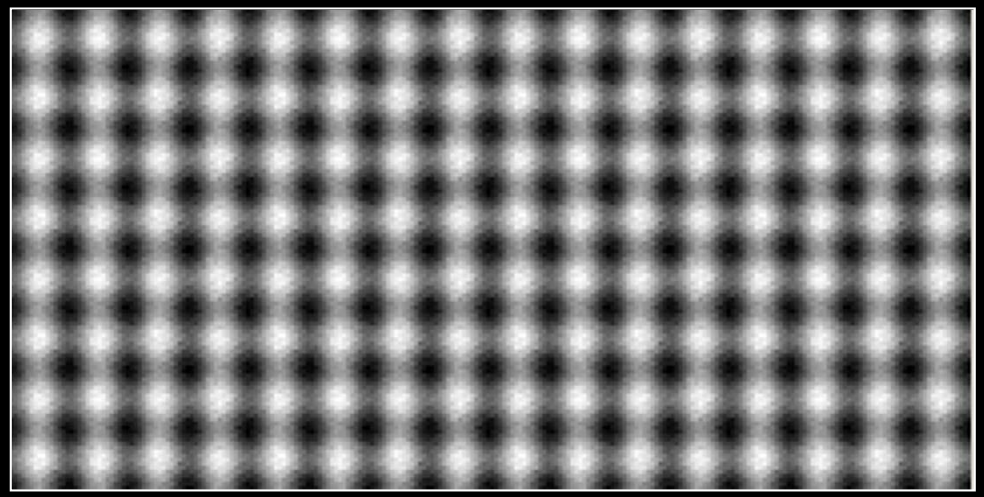
shift by ~1% of unit cell

Make Average Supercell: 4x2

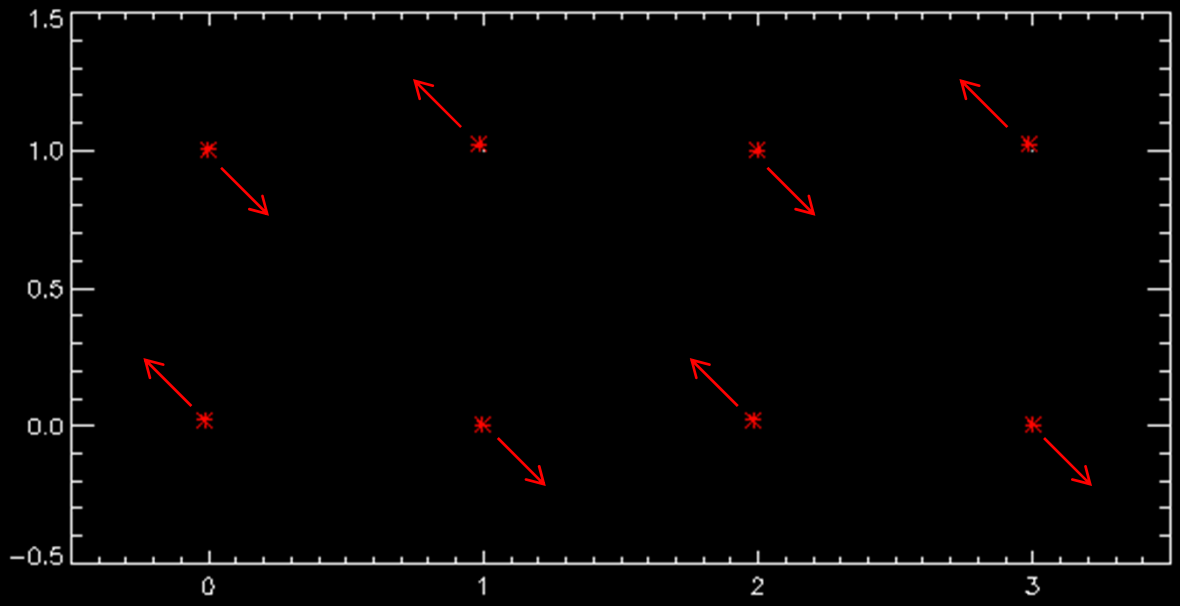
(Bi-2201, Tc=32K, slightly underdoped)



tiled →

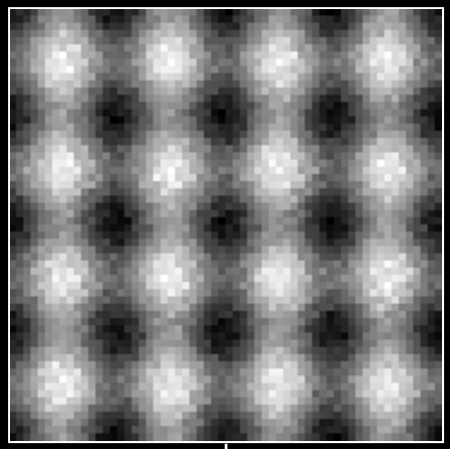


↓ fit

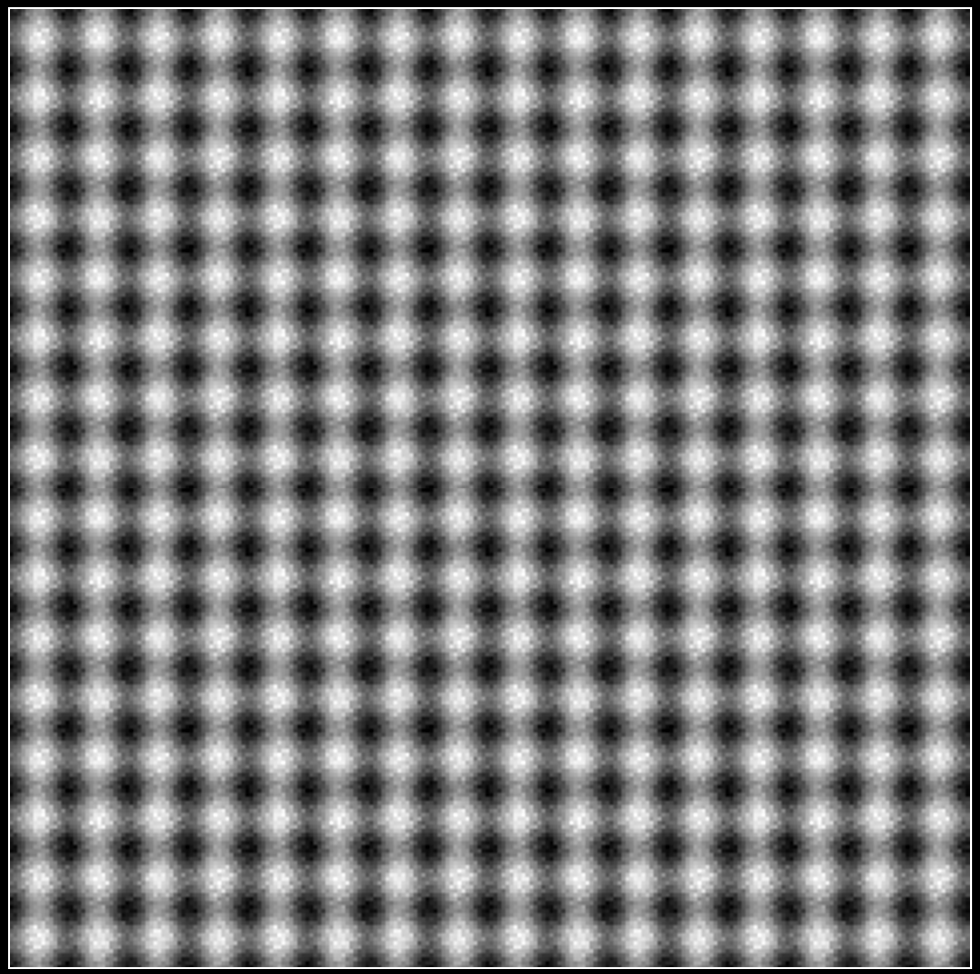


Make Average Supercell: 4x4

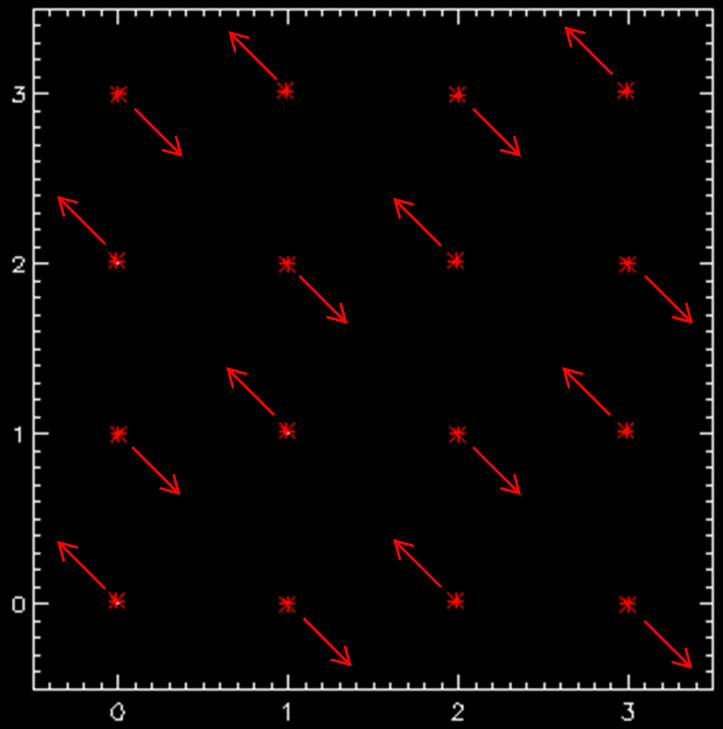
(Bi-2201, Tc=32K, slightly underdoped)



tiled →



↓ fit



16 inequivalent sites:

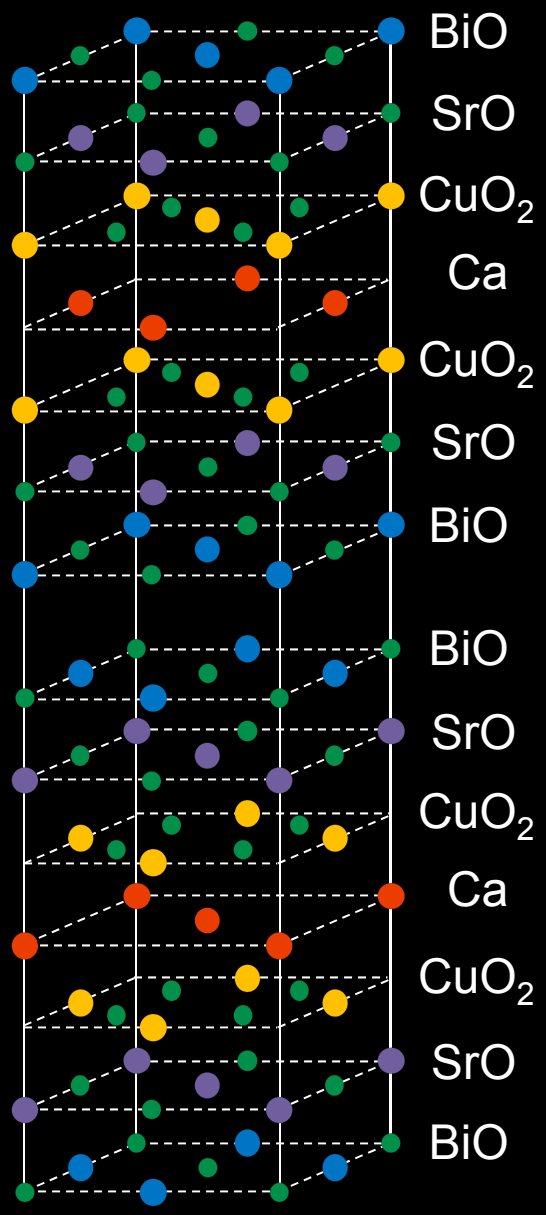
average displacement: 1.1%

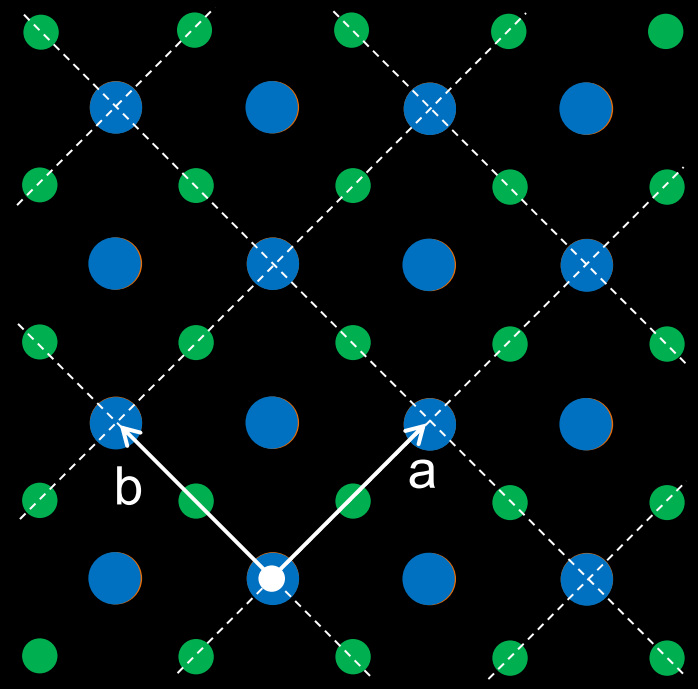
standard deviation: 0.36%

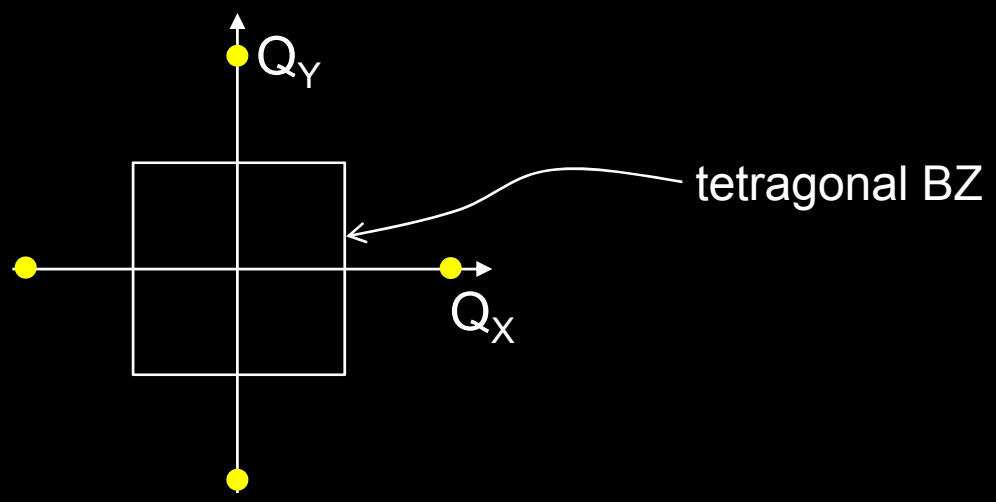
(error bar ~1/3 of effect → inconsistent with zero)

Crystal Structure

$Bi_2Sr_2CaCu_2O_8$







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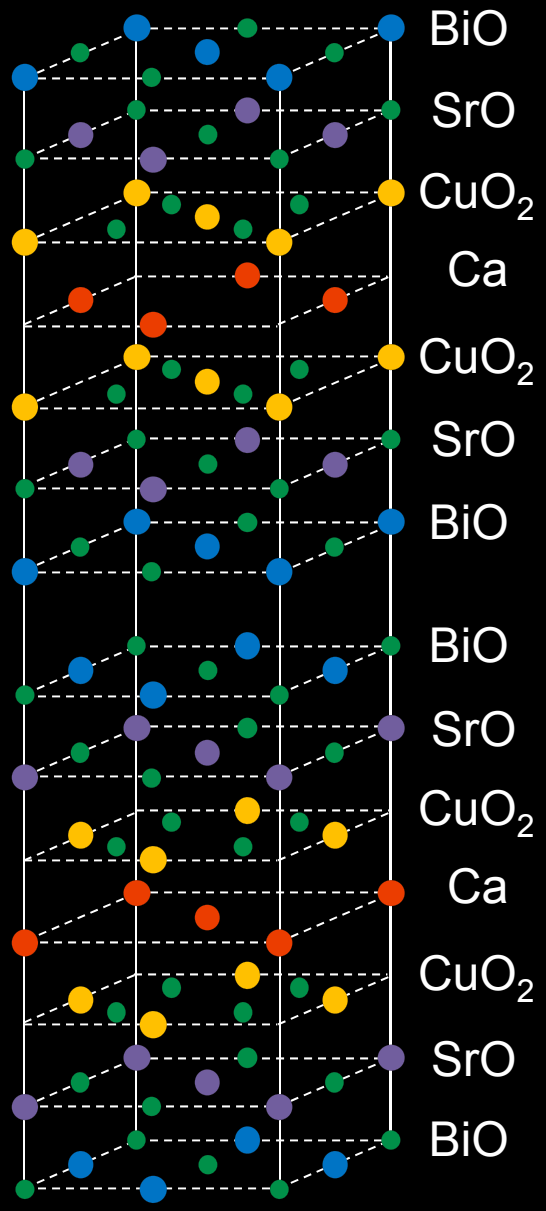

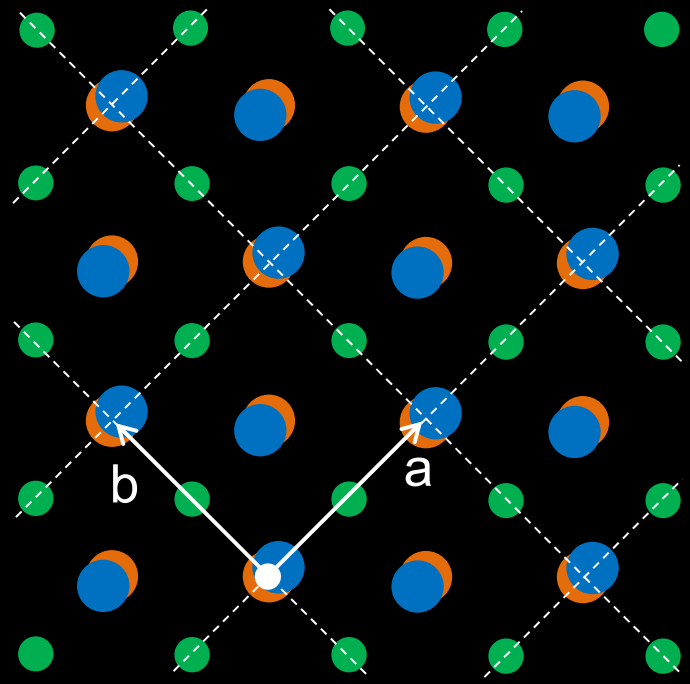

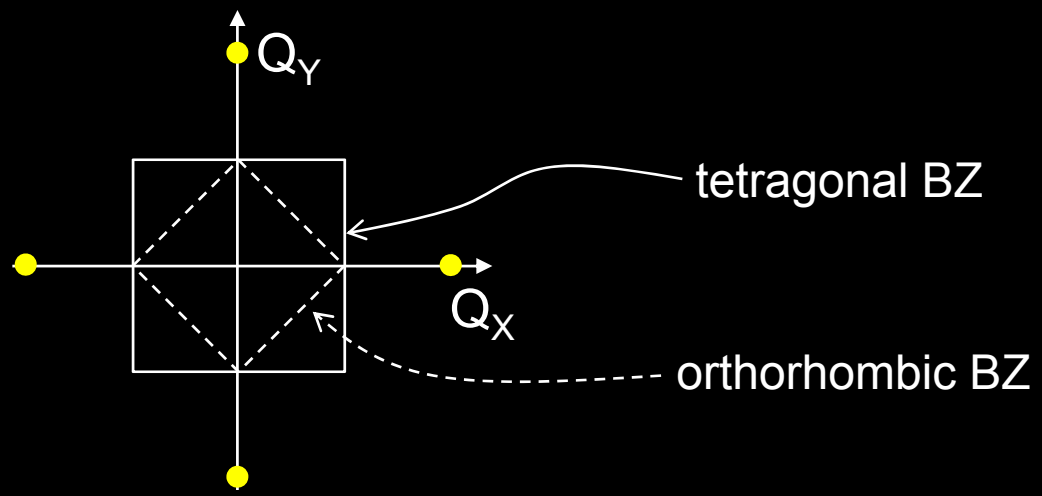

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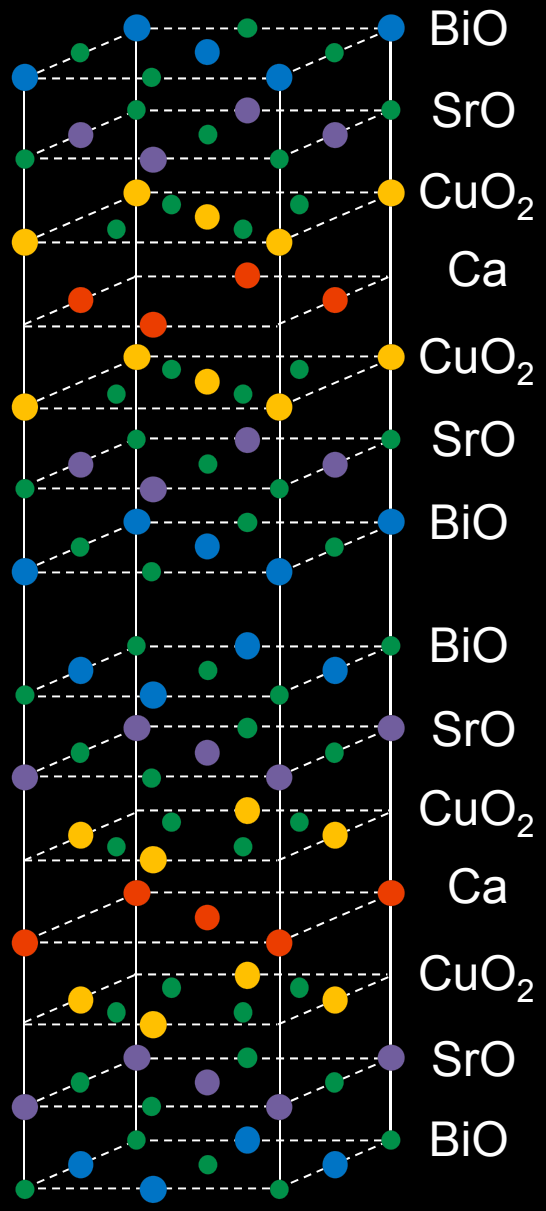
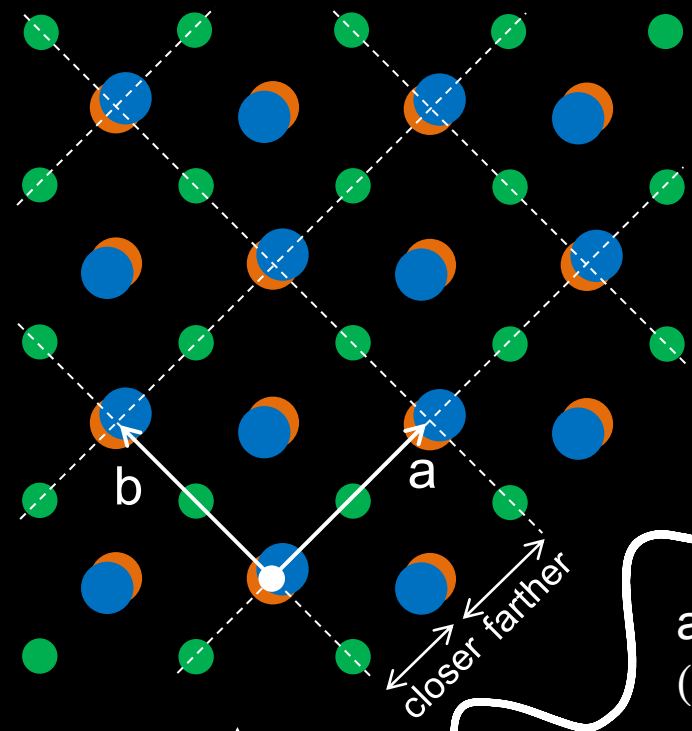
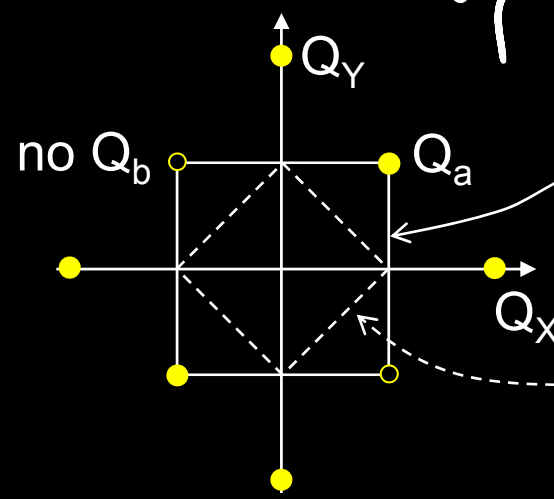
$Bi_2Sr_2CaCu_2O_8$





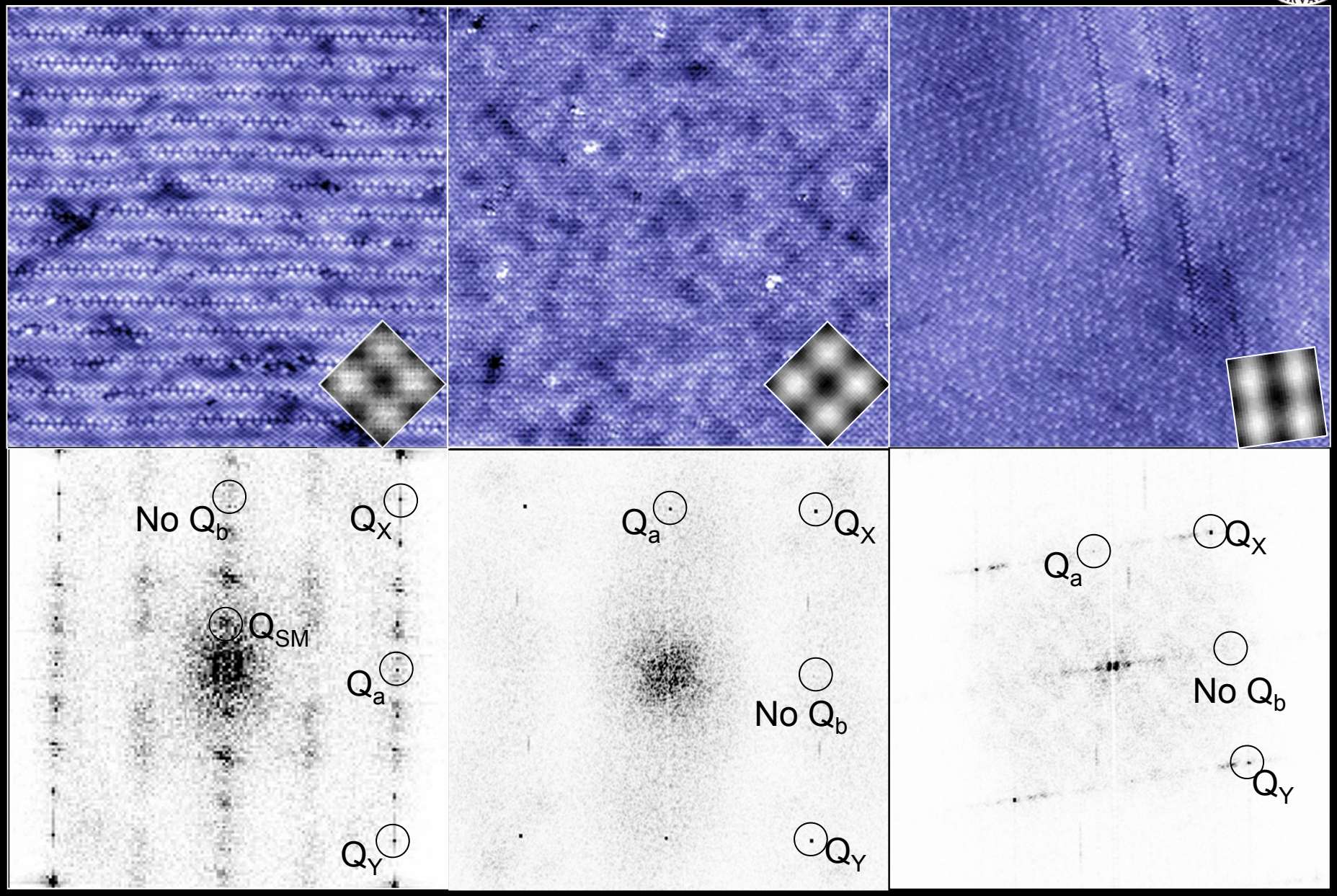
a-axis modulation
($\pi/2$ phase)



tetragonal BZ

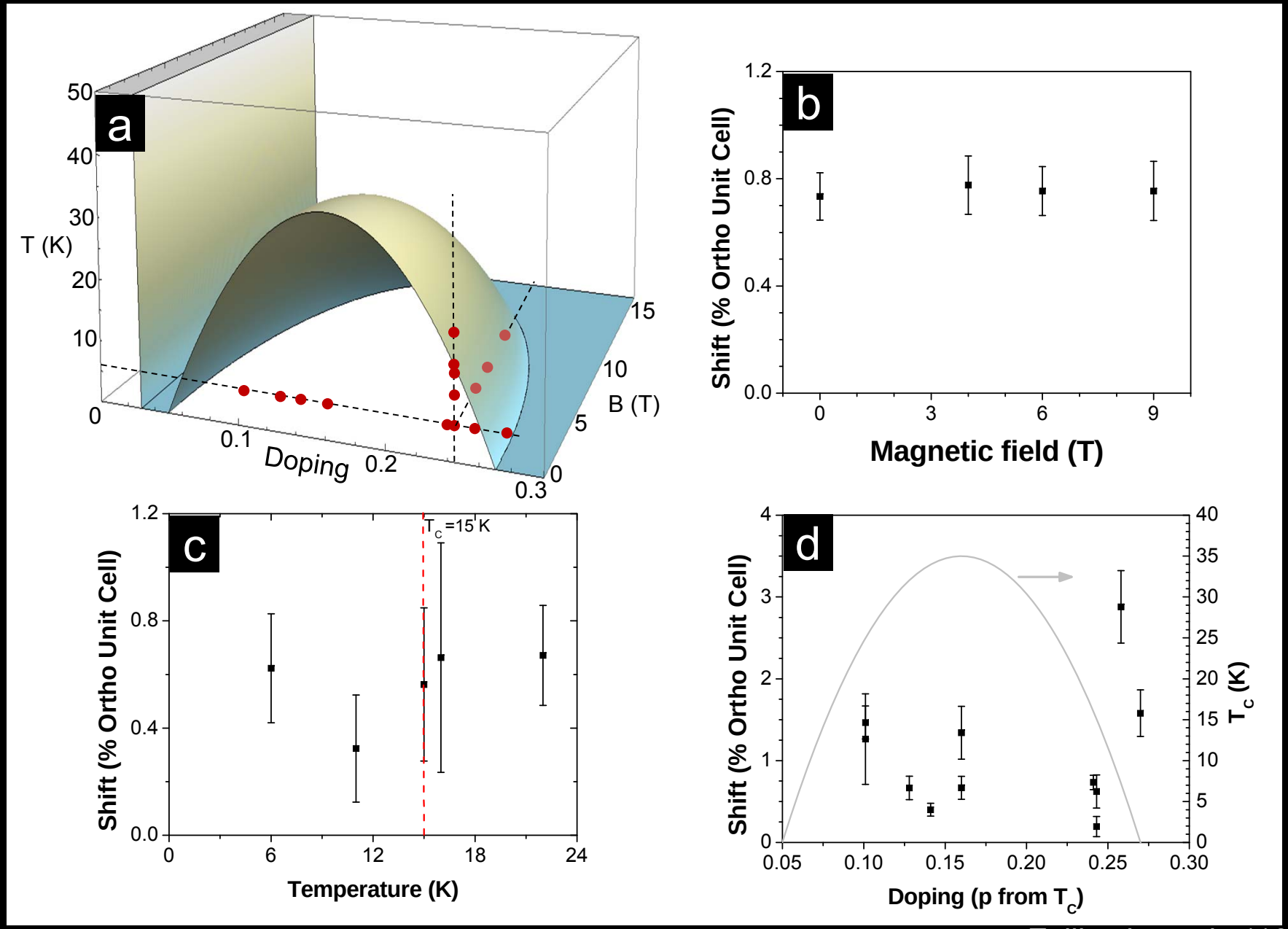
orthorhombic BZ

Apply avg unit cell methods to many samples



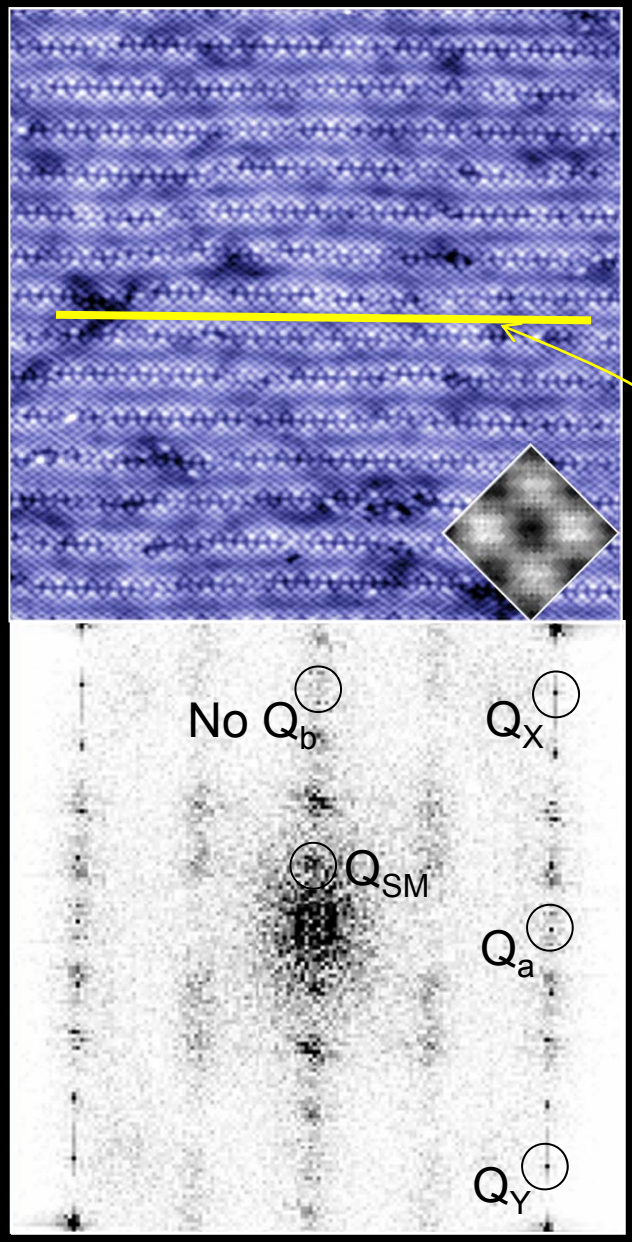
Zeljkovic, arxiv:1104.4342

Bi-2201 throughout the SC dome



Zeljkovic, arxiv:1104.4342

8 different Bi-2212 samples



$Q_{SM} \equiv$ crystalline b axis

10 samples: ortho distortion along a axis

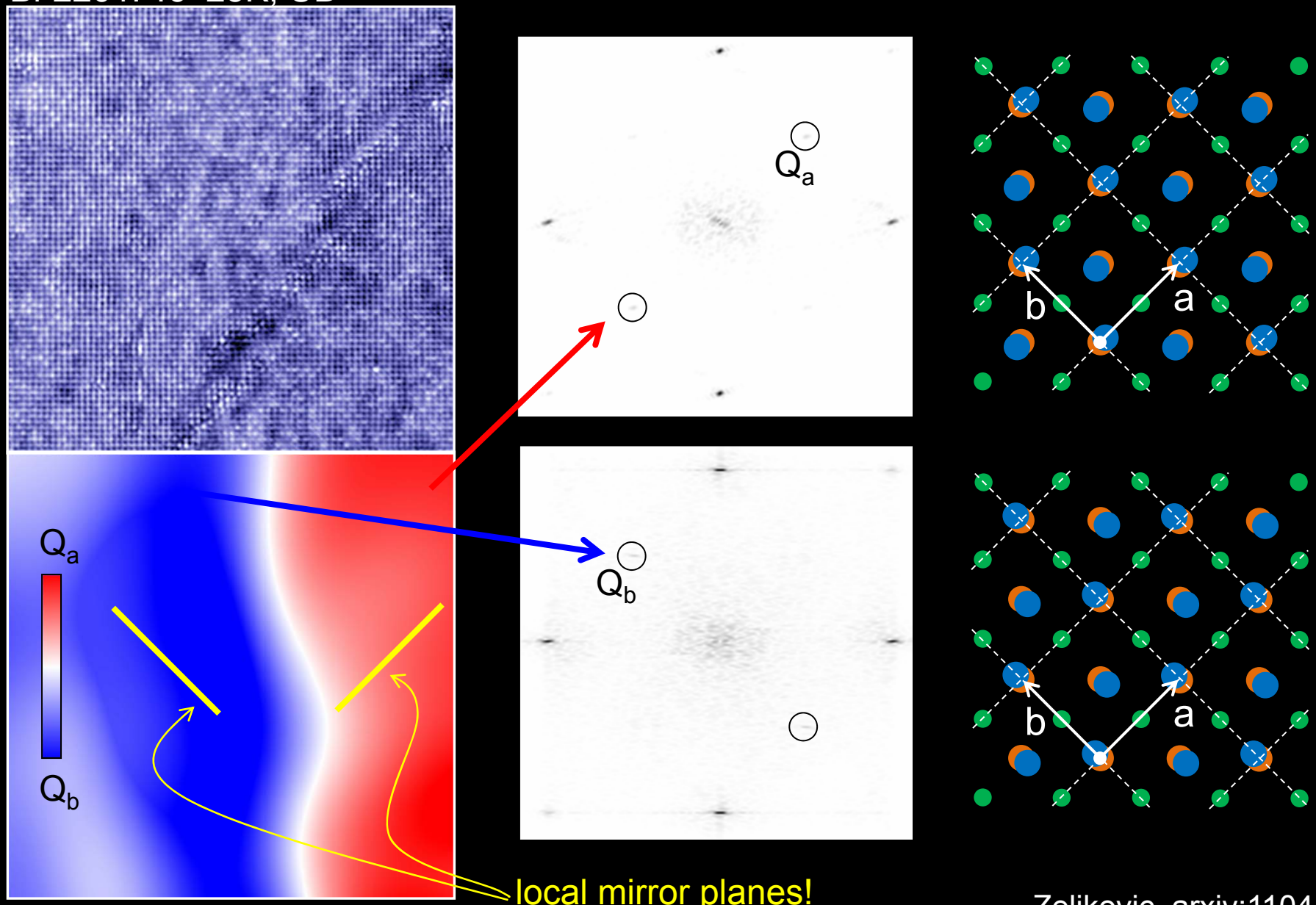
mirror plane always chooses this axis

Historical: Structure from Scattering

Material	Pb?	Technique	Bi distortion	Cu distortion	Ref
Bi-2223	no	XRD	2.22% (b axis)	-0.01% (b axis)	Subramanian, Science (1988)
Bi-2201	no	XRD	2.58% (b axis)	none	Torardi, PRB (1998)
Bi-2212	no	neutrons	2.55% (a axis)	-0.07% (a axis)	Miles, Physica C (1998)
Bi-2201	yes	XRD	1.82% (a axis) 6.34% (b axis)	none	Ito, PRB (1998)
Bi-2212	yes	XRD	1% (a axis) 1.65% (b axis)	2.57% (a axis) -0.02% (b axis)	Calestani, Physica C (1998)
Bi-2212	yes	XRD	1.1% (a axis) 1.53% (b axis)	0.08% (b axis)	Gladyshevskii, PBR (2004)
Bi-2201	yes and no	LEED, ARPES	one axis only	can't determine	Mans, PRL (2006)

STM adds: *LOCAL* symmetry determination

Bi-2201: Tc=25K, UD



Zeljkovic, arxiv:1104.4342

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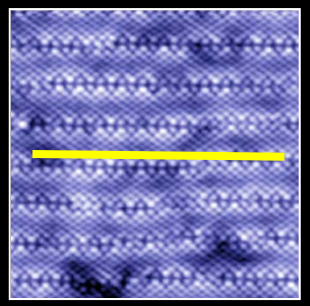
Bi-2201	yes and no	LEED, ARPES	one axis only	can't determine	Mans, PRL (2006)

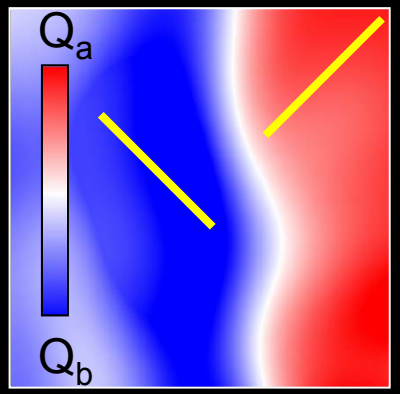
In the absence of supermodulation, there can be twin boundaries
→ leads to the appearance of shifts along 2 axes

Intra-unit-cell structure: Conclusions

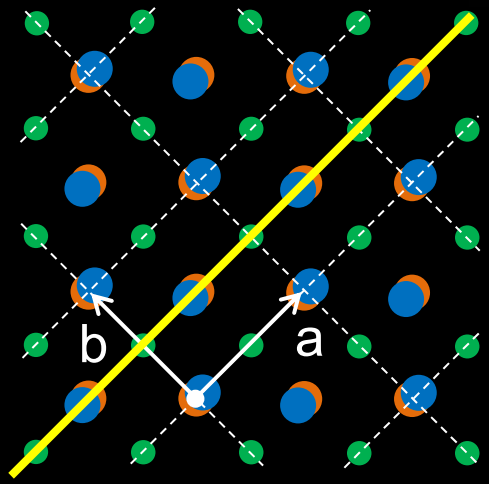
1. structural distortion in BiO plane breaks inversion symmetry at the Bi site, but preserves mirror plane



2. mirror plane is always aligned with supermodulation

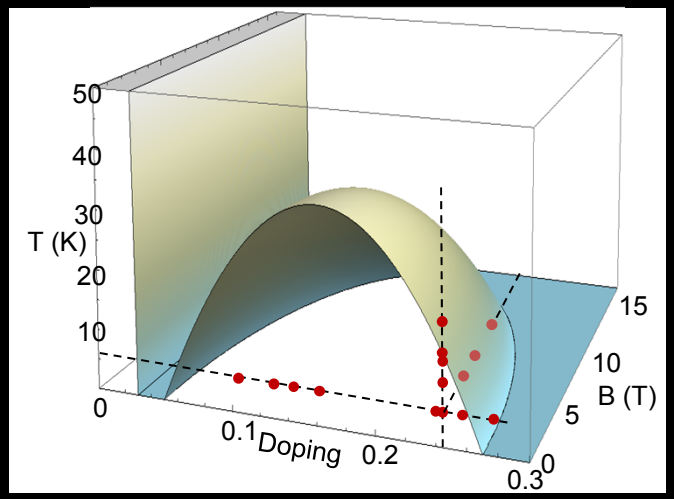


3. can image the local mirror plane



4. resolve long discrepancies in the bulk scattering literature:
   - supermodulated samples → no ortho twinning;
   - Pb-doped samples → can have ortho twinning

5. orthorhombic distortion present across large regions of Bi-2201 phase diagram



Next step: is apparent electronic inversion sym breaking fully explained by this structural effect?

Outline

Superconductors: 100 Year History

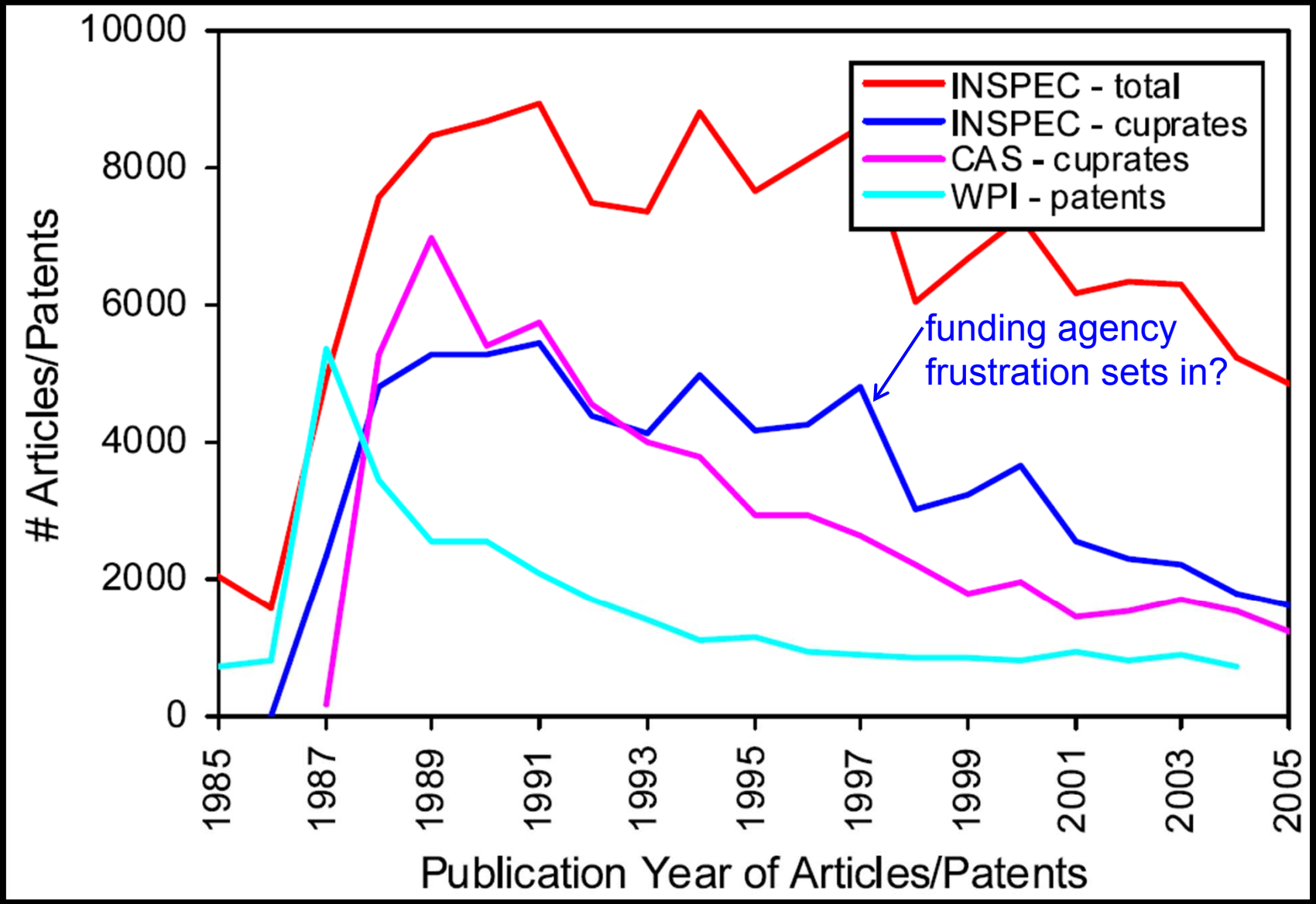
Pseudogap in cuprates:

- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:

- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy

Interest in High-T_c Cuprates

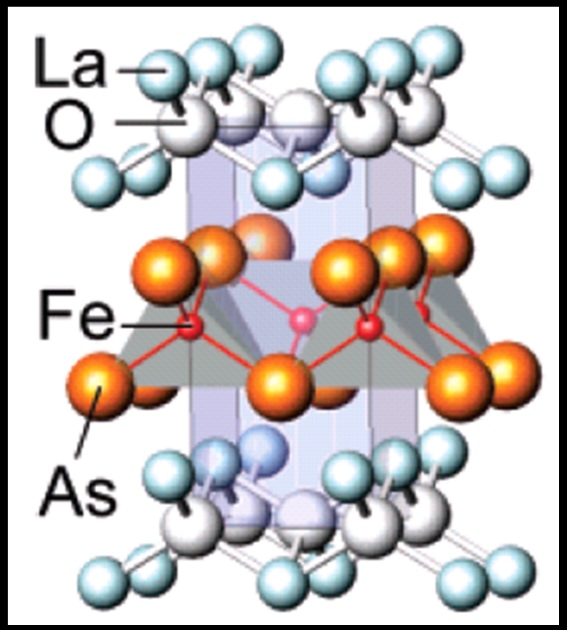


J Supercond Nov Magn 21, 113 (2008)

2008: A New Revolution in Superconductivity

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

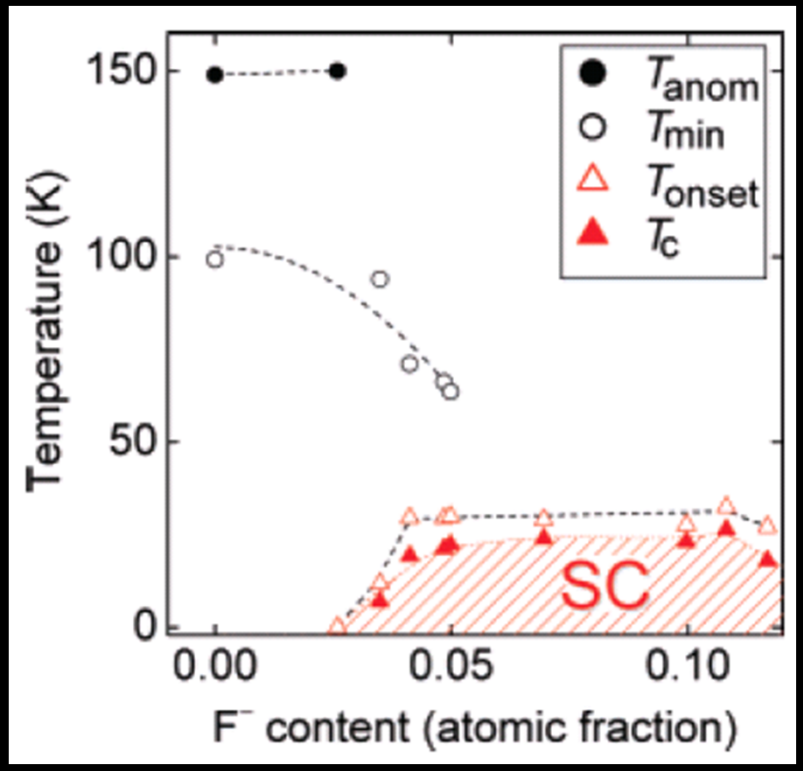
$LaFeAsO_{1-x}F_x$



insulating layer

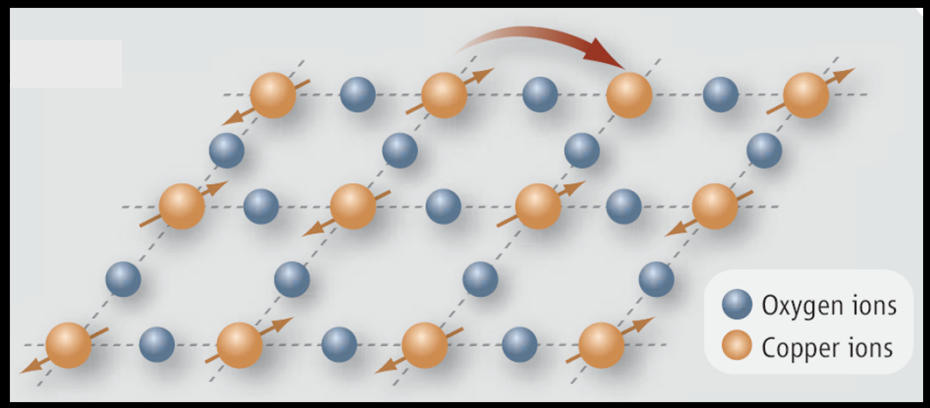
conducting layer

T_c=26K

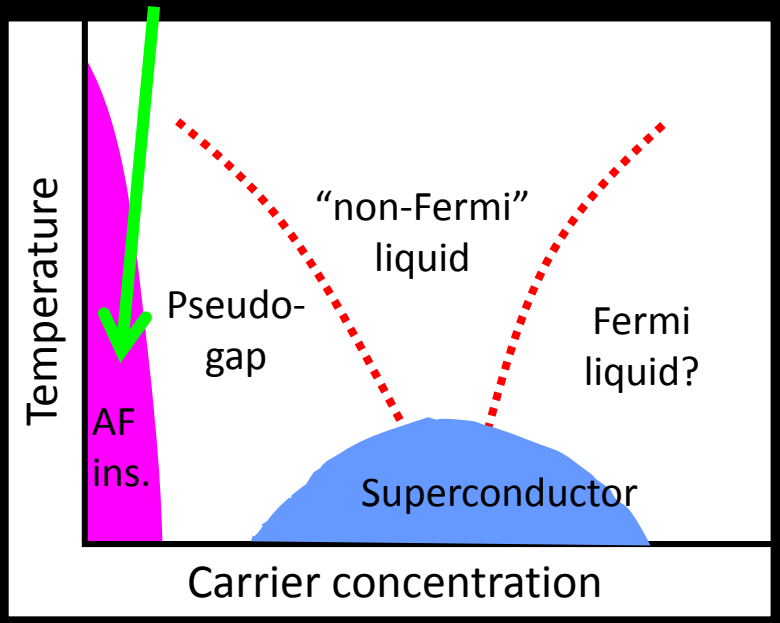


Cuprate-Pnictide Comparison

Cuprate Superconductors

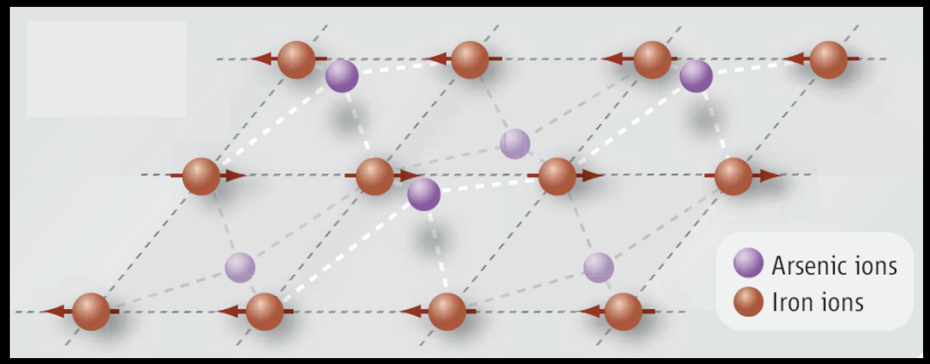


antiferromagnetic Mott insulator

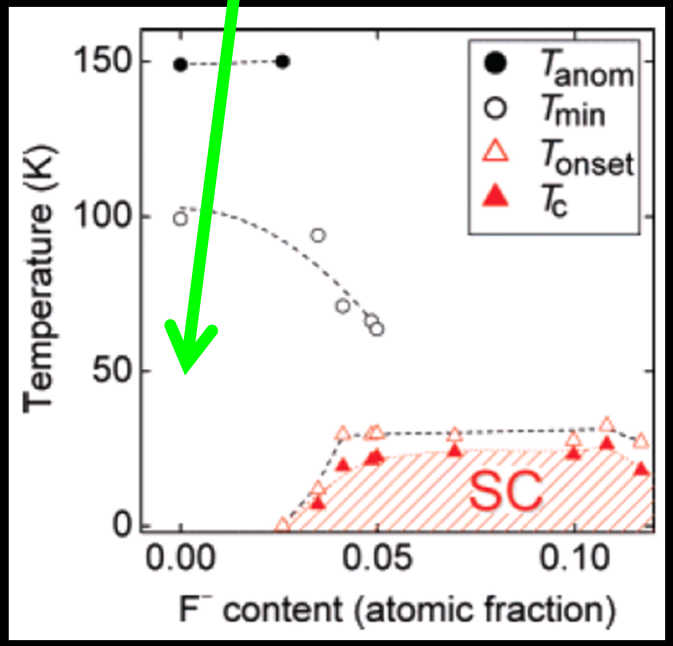


$T_c^{max} \sim 135$ K

Iron-Pnictide Superconductors



collinear antiferromagnet semimetal



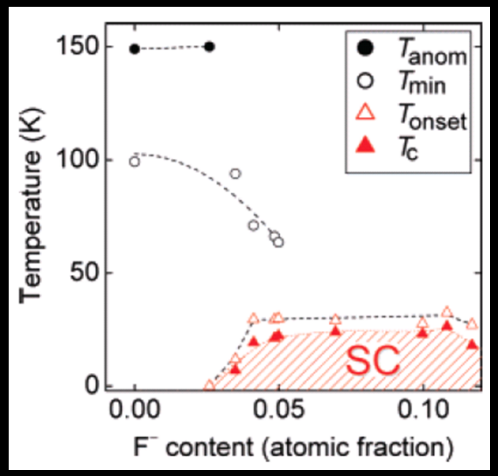
$T_c^{max} \sim 57$ K

Why the excitement?

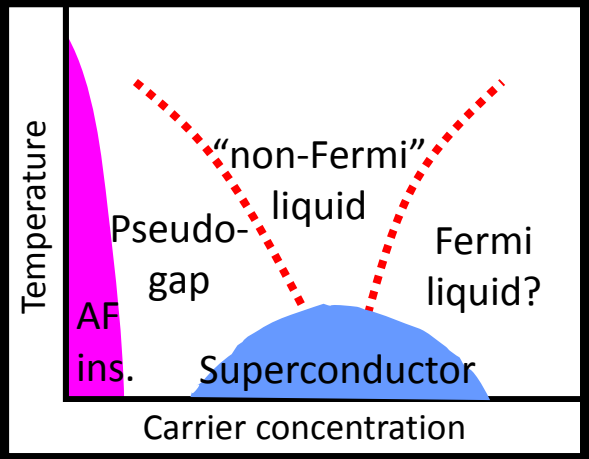
1) Physics
   - A second chance to get it right!
   - A foil for cuprates

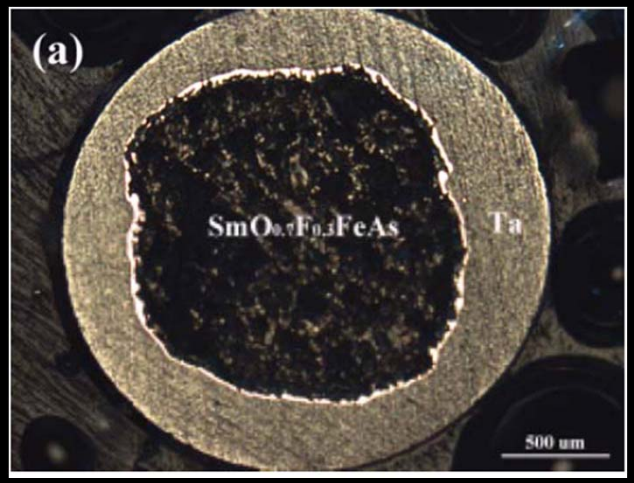
2) Applications
   - Low anisotropy
   - High H_{c2}
   - Strong pinning

$LaFeAsO_{1-x}F_x$



Cuprates



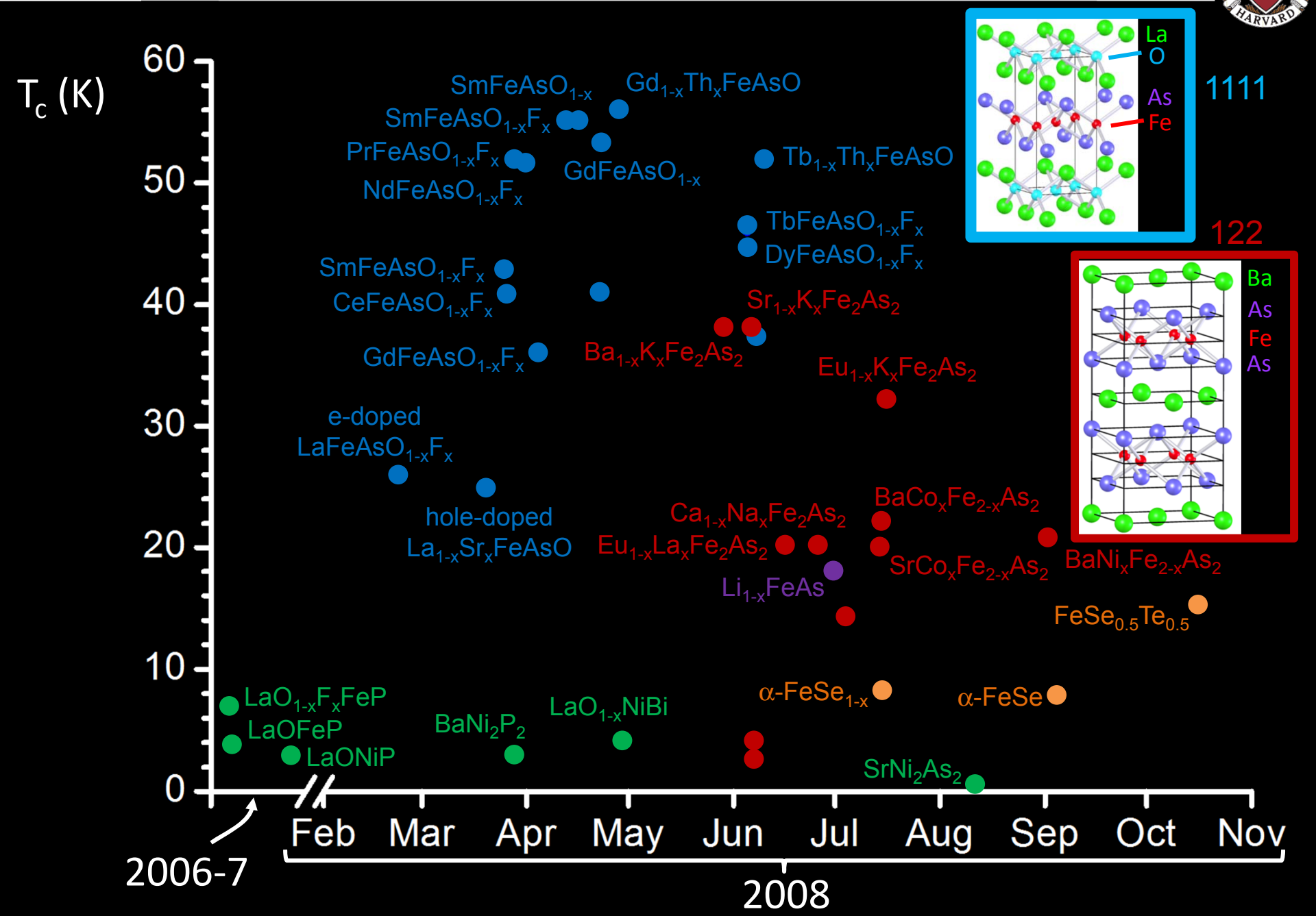


$SmO_{0.7}F_{0.3}FeAs$ wires fabricated by powder-in-tube method

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



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

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

Vortex pinning problem largely solved…
but still not so many practical applications because T requirements so severe…

1986 – Bednorz & Mueller – high-Tc superconductors → 1987 Nobel Prize

Still not so many practical applications…
severe vortex pinning problems in cuprates…
T requirements still non-trivial…

2008 – Hosono – Fe-based high-Tc superconductors

Today's frontiers:

1. discover higher-Tc materials → need to understand the ones we've got
2. improve vortex pinning in high-Tc materials

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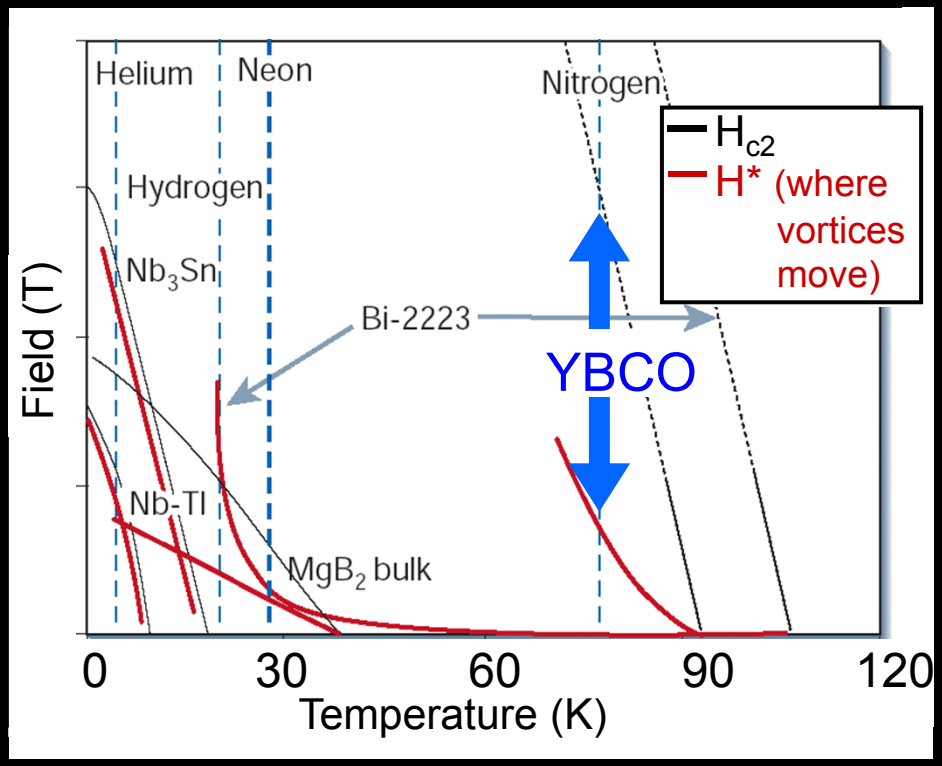
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy

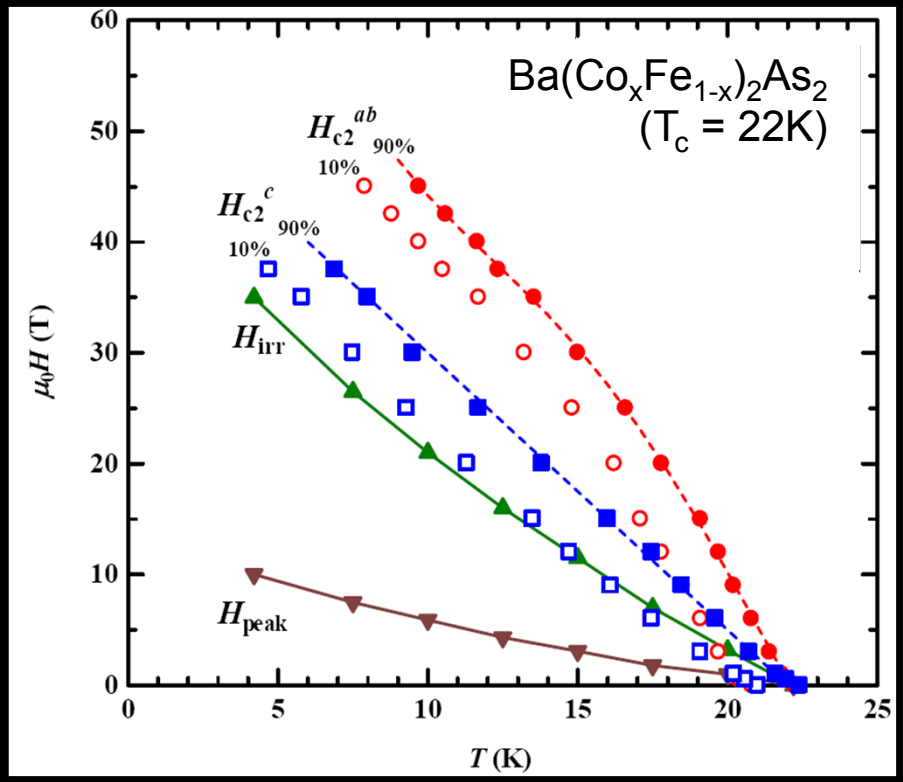
Vortex pinning: low anisotropy, high H_{c2}

Conventional Superconductors

Cuprate Superconductors

Pnictide Superconductors



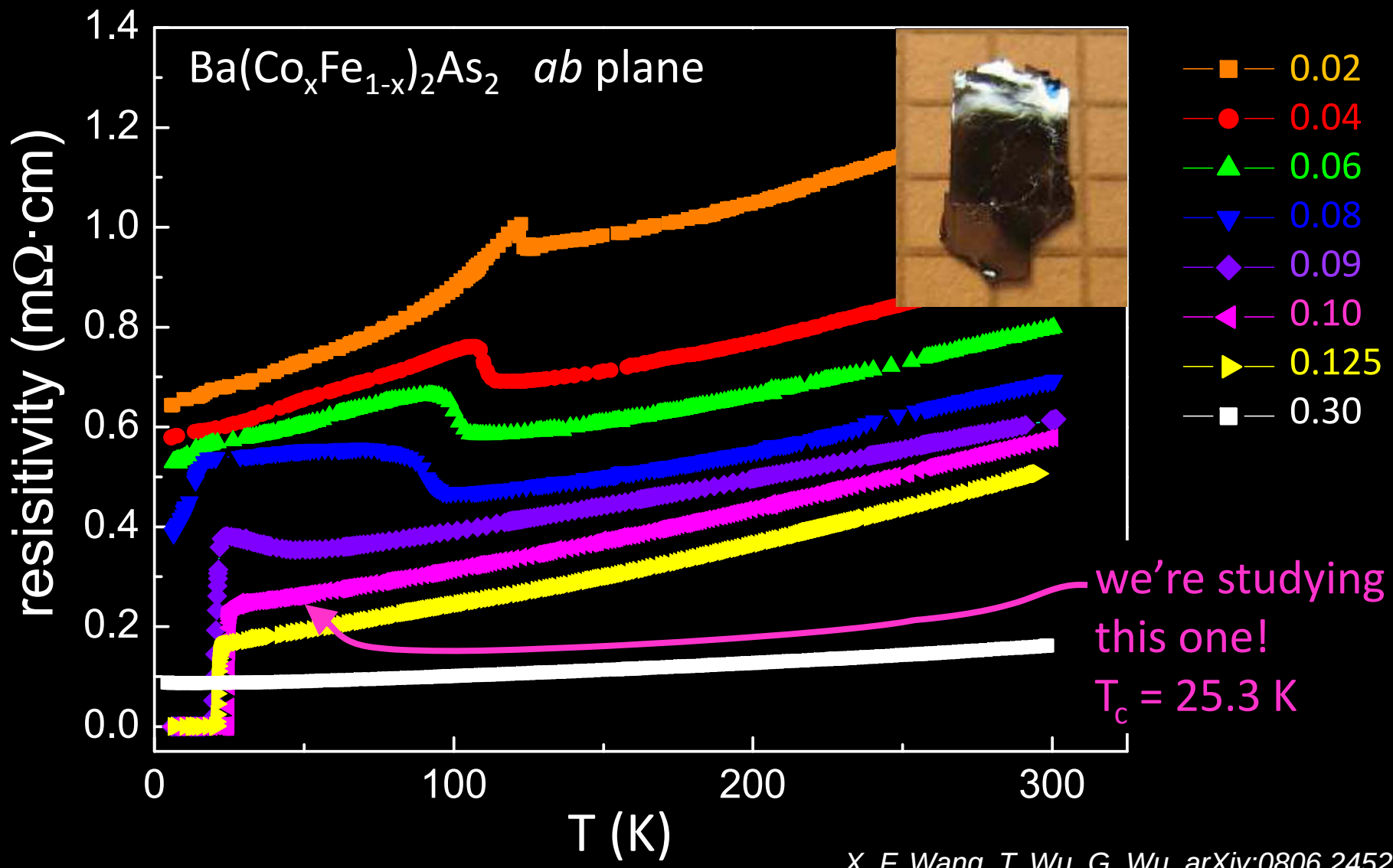


strong pinning, speculation that it comes from nanoscale pinning sites, e.g. Co dopant inhomogeneities → need a local tool to study these materials!

Yamamoto, APL 94, 062511 (2009)

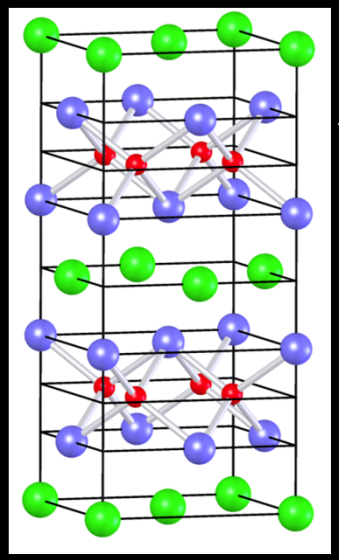
Resistivity of our $Ba(Co_xFe_{1-x})_2As_2$

single crystals grown by Prof. XianHui Chen

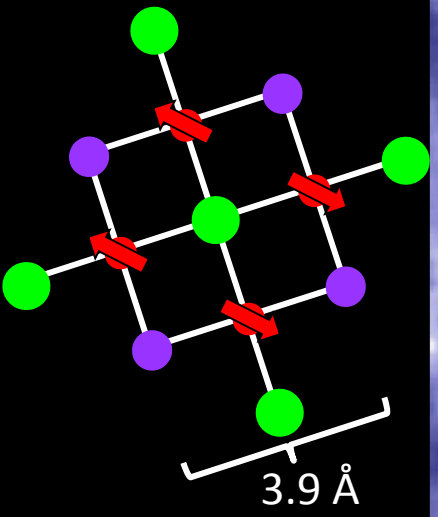


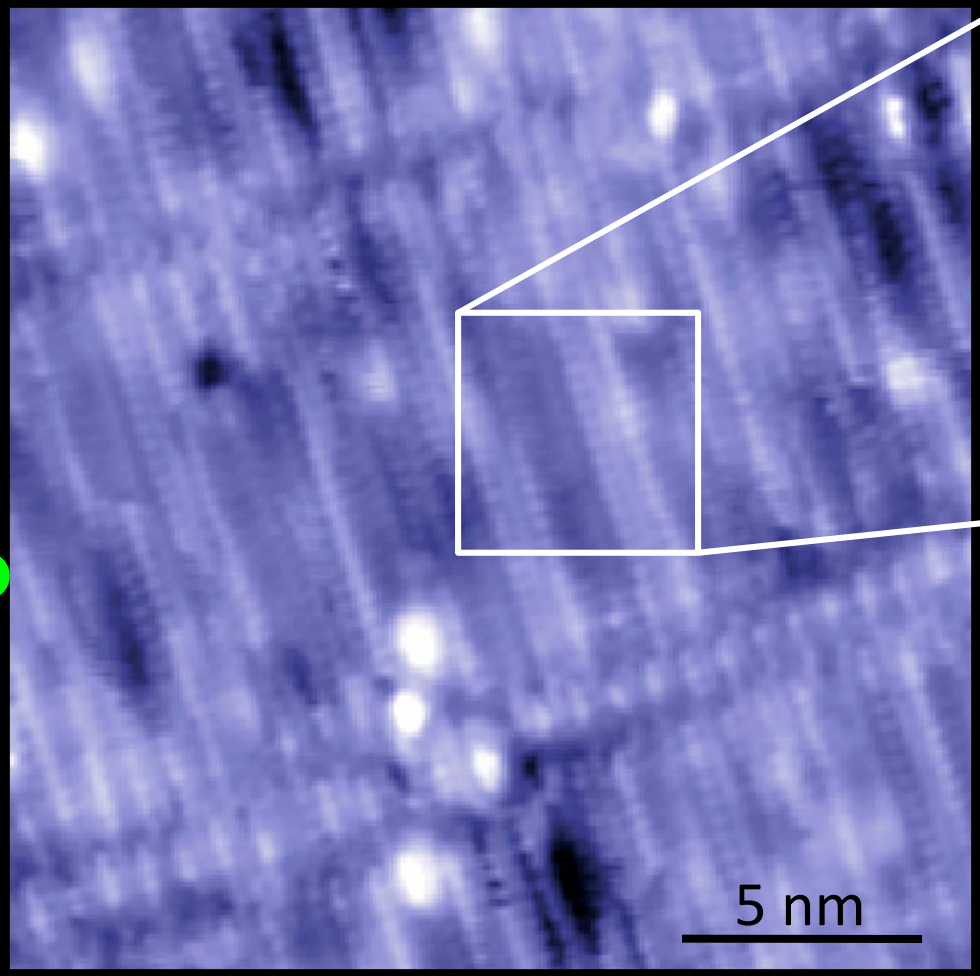
X. F. Wang, T. Wu, G. Wu, arXiv:0806.2452
to be published in Phys. Rev. Lett.

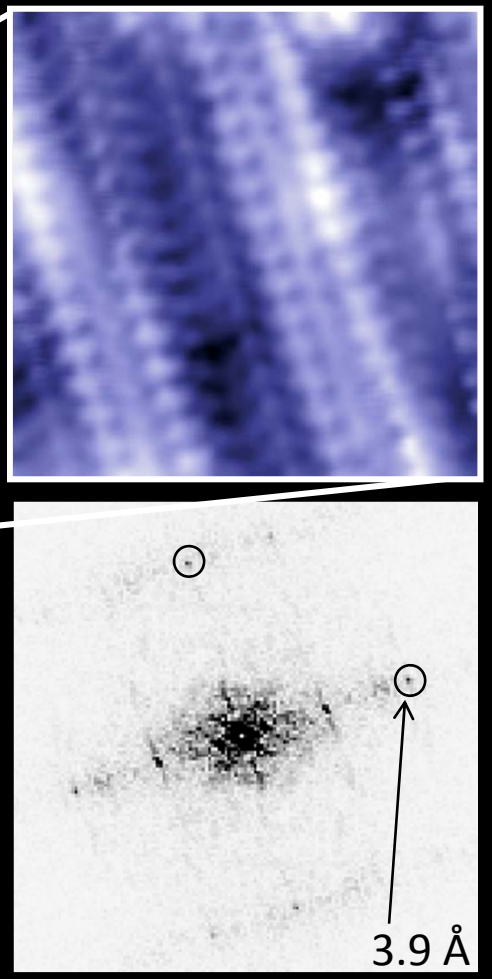
Atomic Resolution Topography



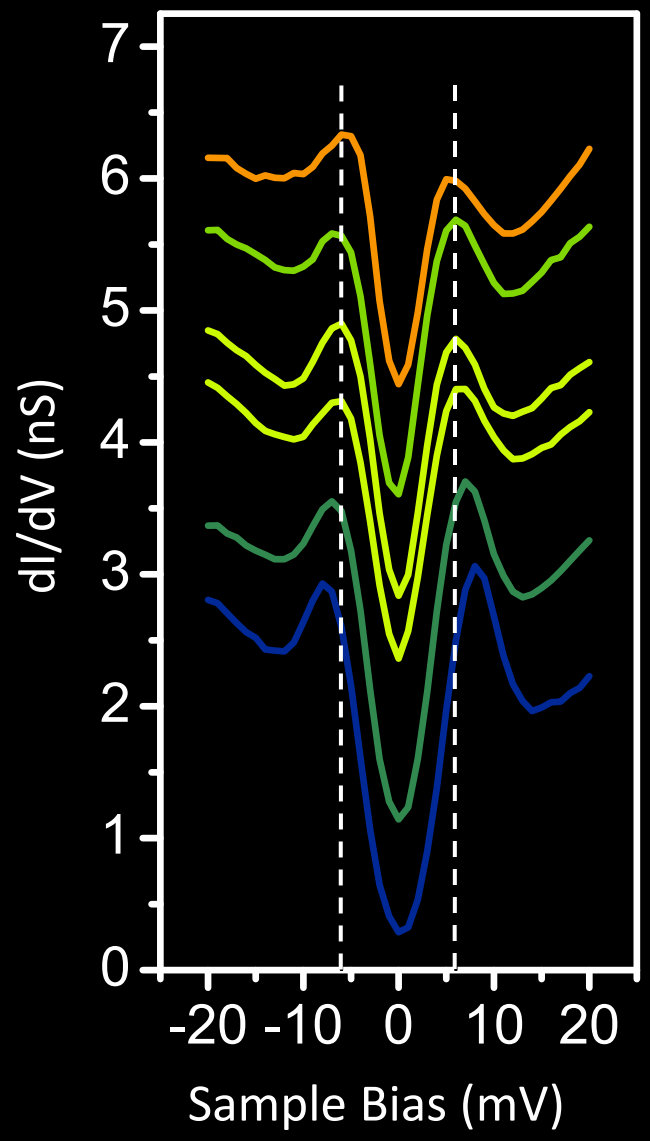
$Ba(Co_xFe_{1-x})_2As_2$
(x=0.1 nominal, T_c=25.3K)

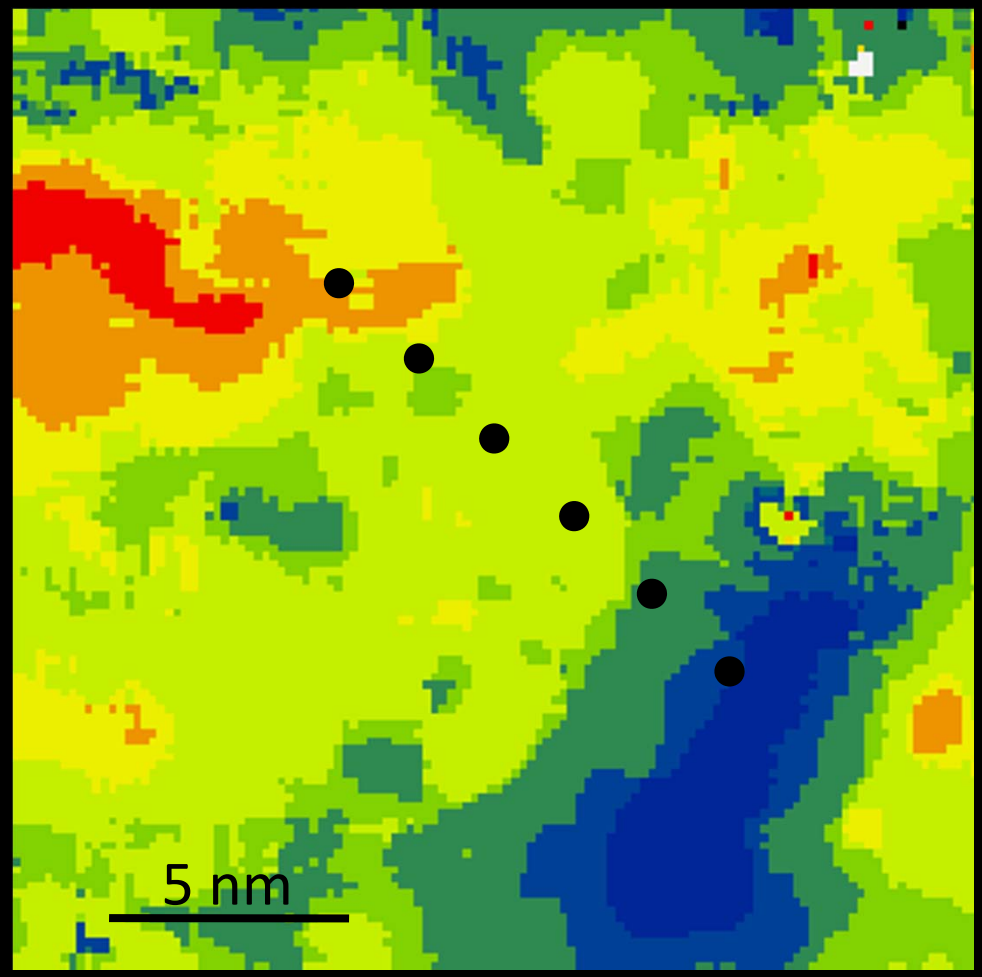


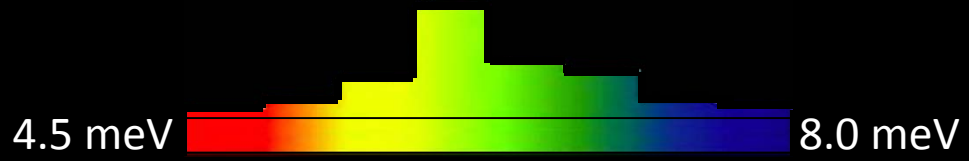




Gap Mapping



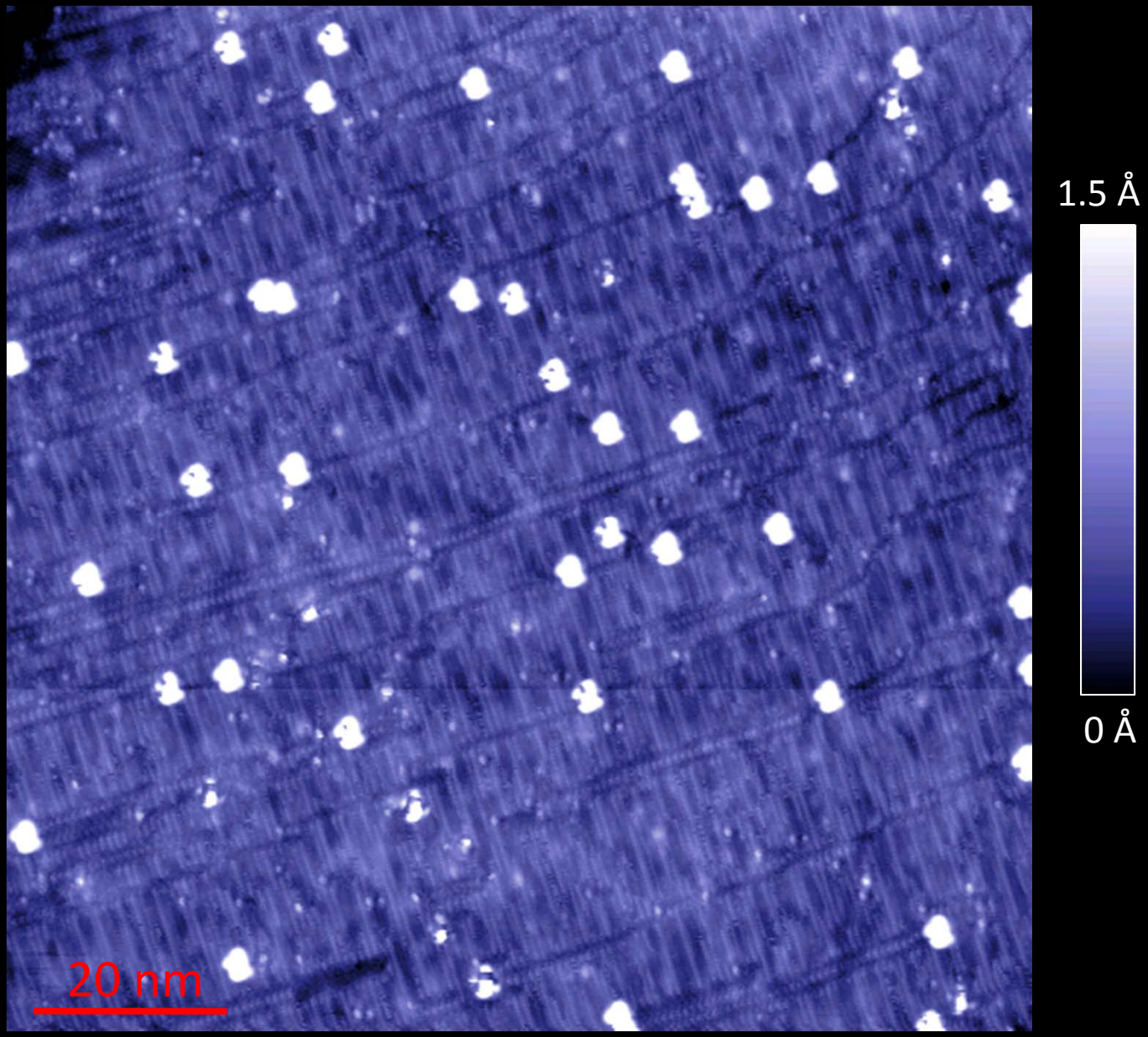




$\overline{\Delta}$ = 6.25 ± 0.73 meV (12% variation)

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

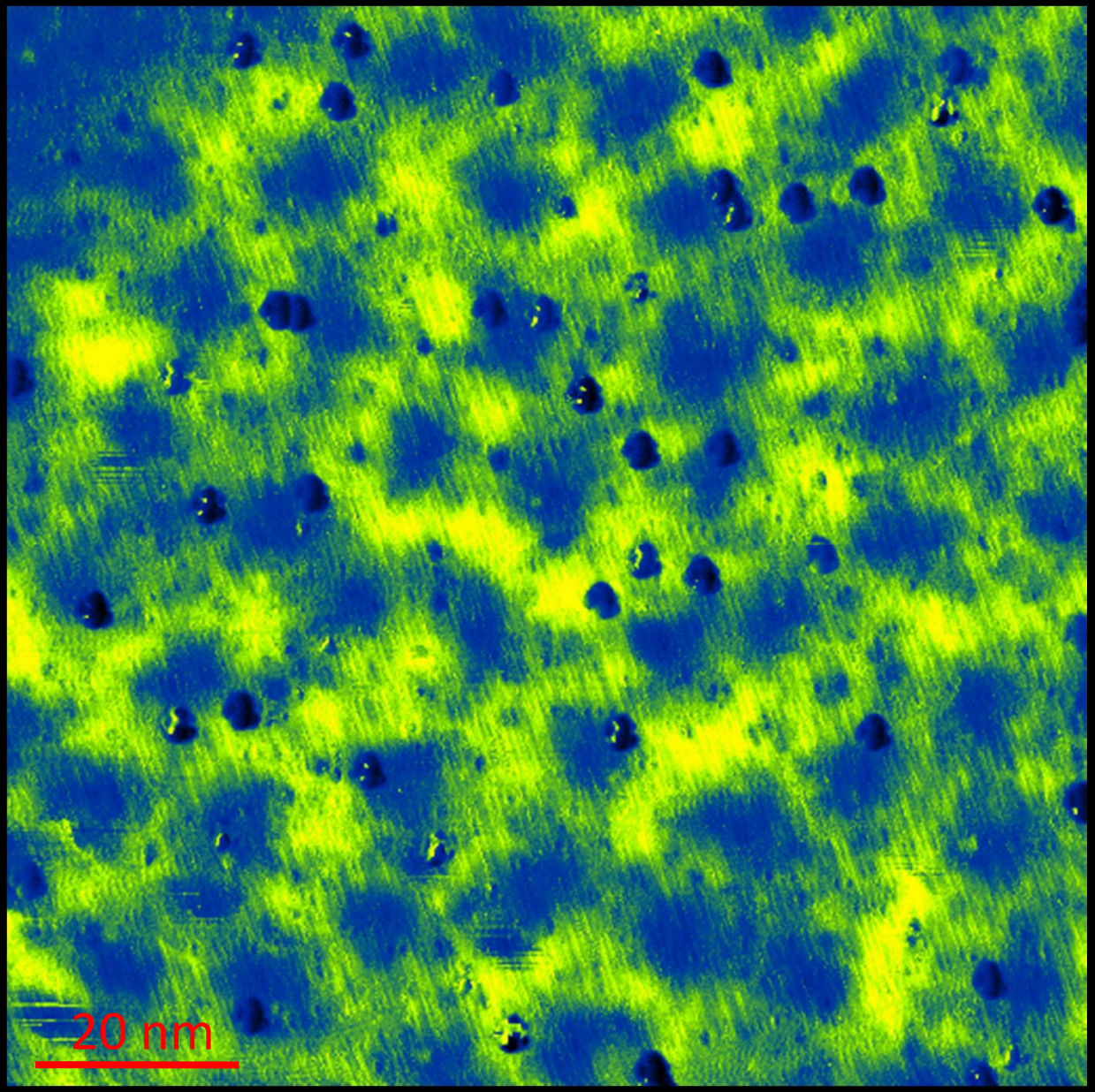
Topography



Vortices at 9T

dI/dV at 5 mV

(approximate coherence peak energy)



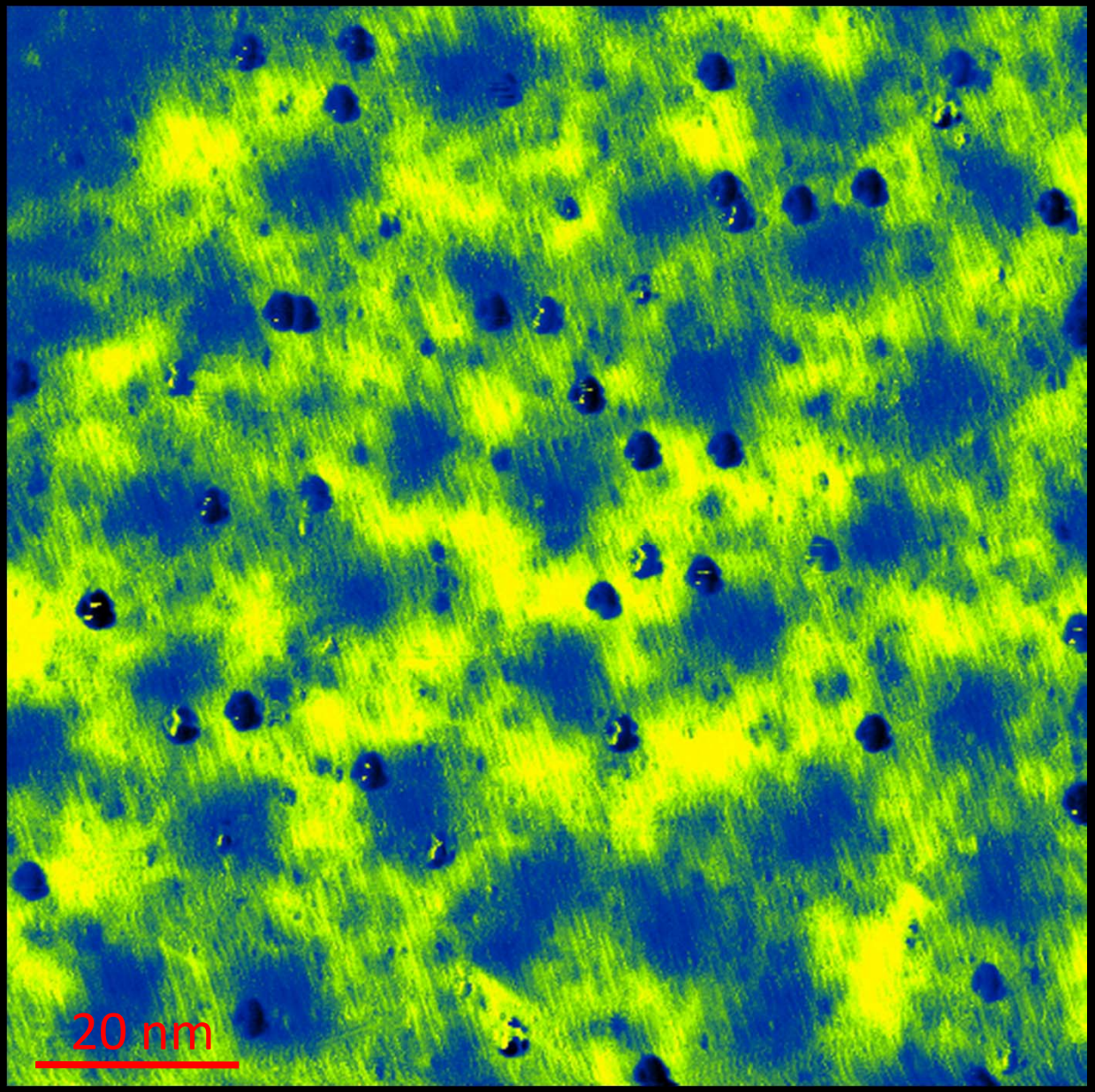
3.0 nS

0.5 nS

Vortices at 6T

dI/dV at 5 mV

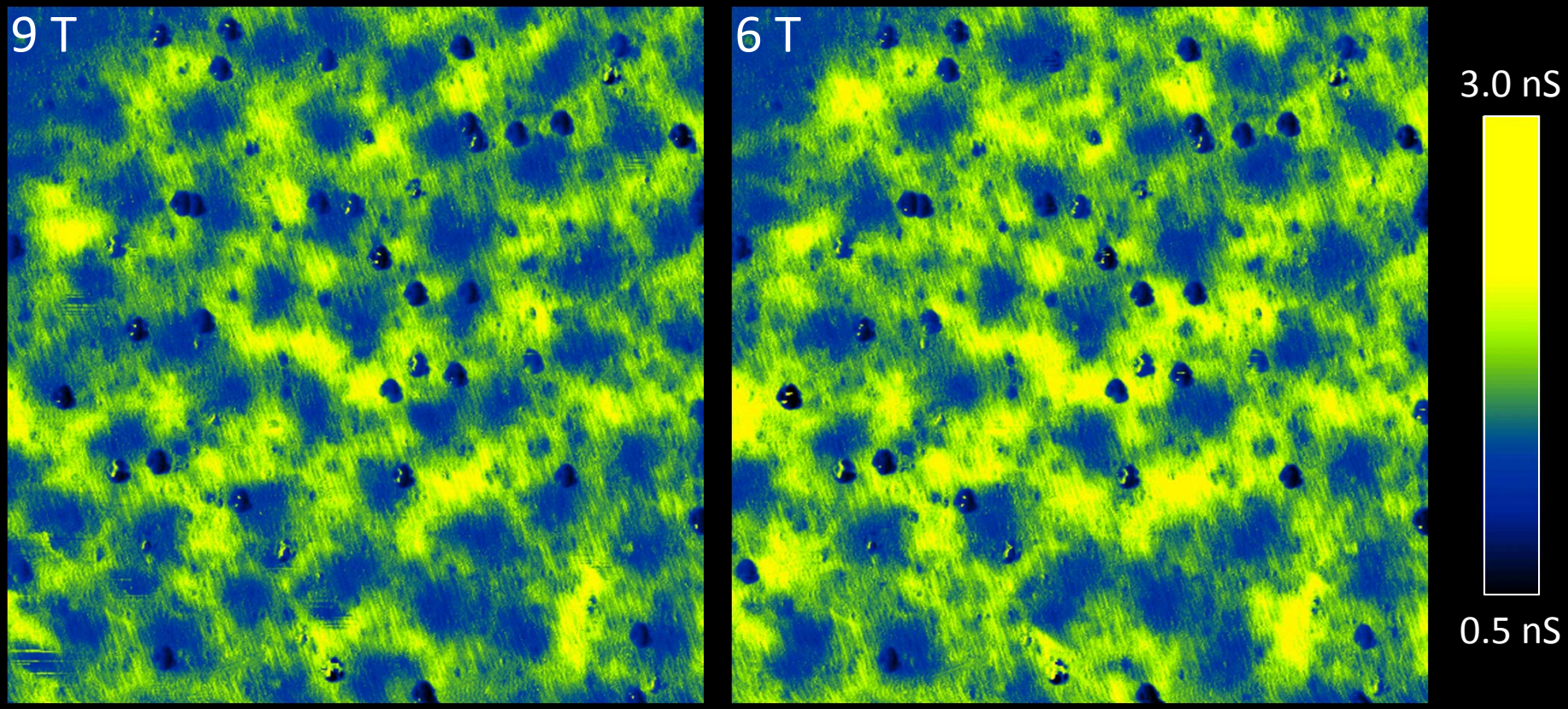
(approximate coherence peak energy)



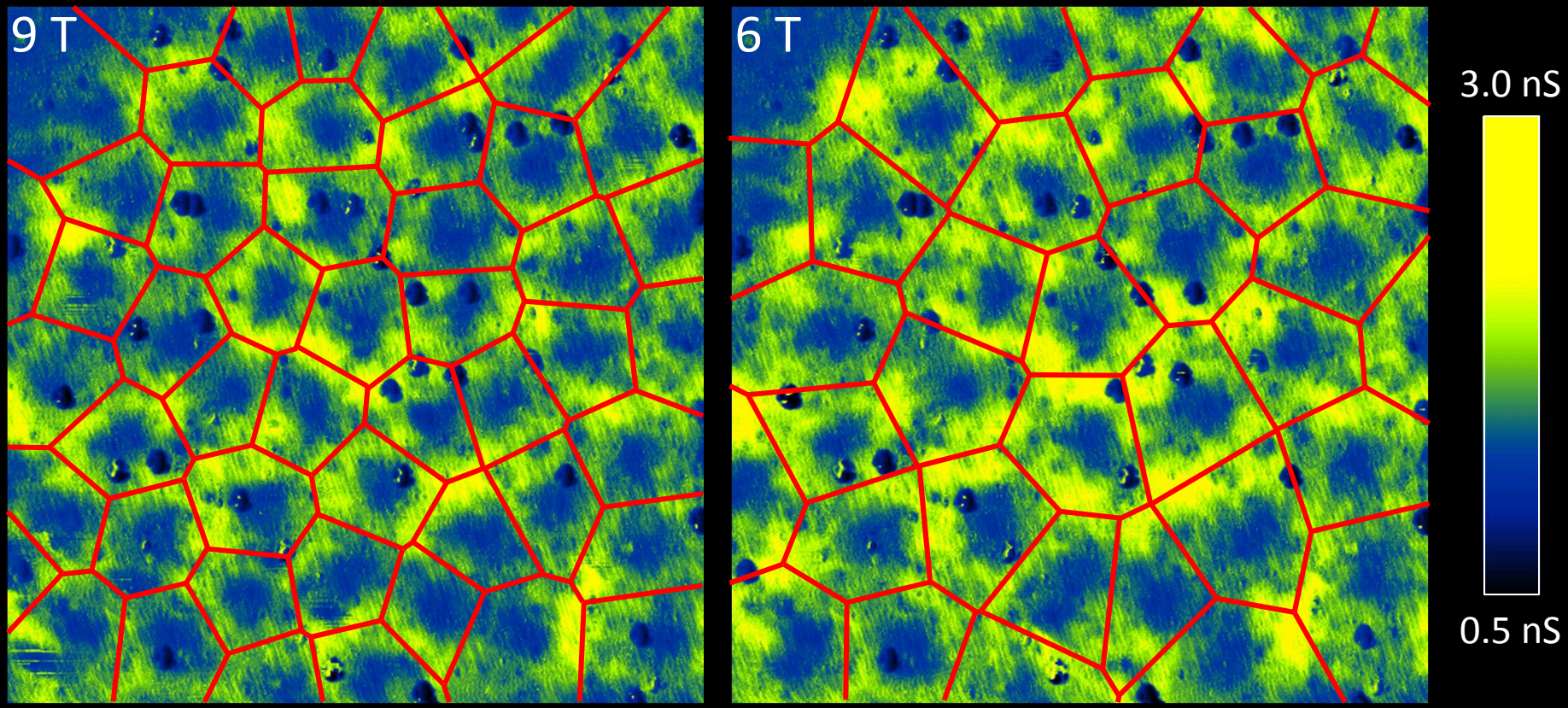
3.0 nS

0.5 nS

Flux Measurement



Flux Measurement



average vortex area = 228 nm^2

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

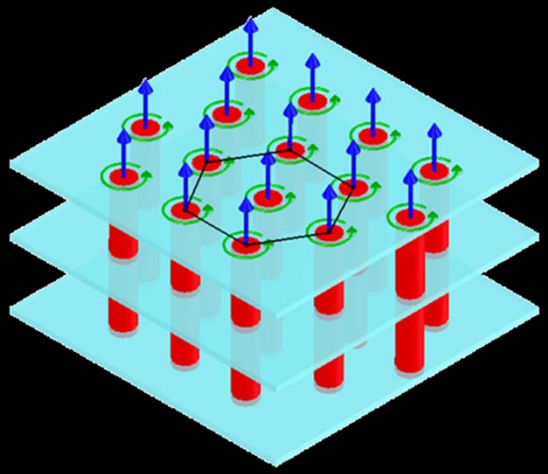
average vortex area = 362 nm^2

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

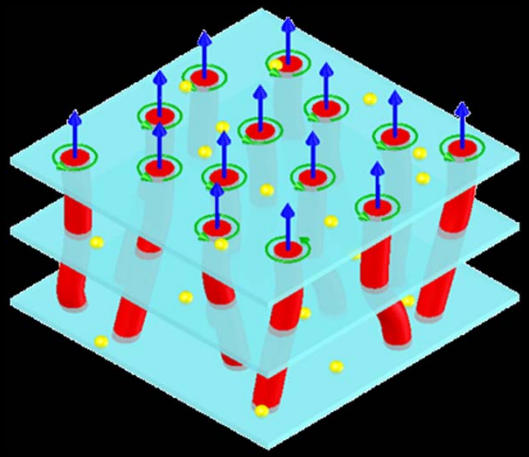
Single magnetic flux quantum: $\Phi_0 = 2.07 \times 10^{-15}$ T·m^2

Vortex pinning possibilities

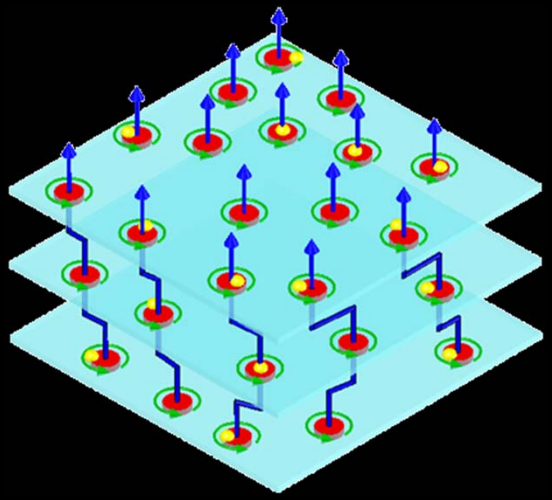
(1) no strong pinners
inter-vortex forces dominate
→ lattice formation

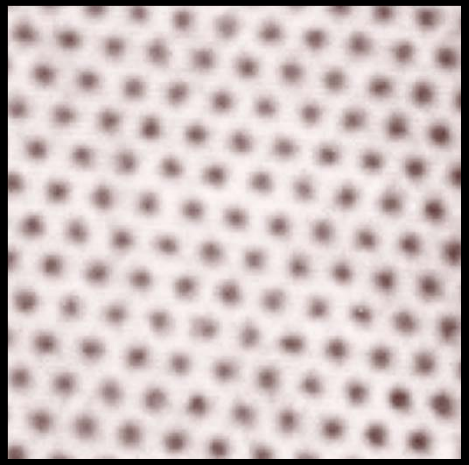


(2) strong pinners exist
low anisotropy
→ vortices bend slightly
to accommodate pinners



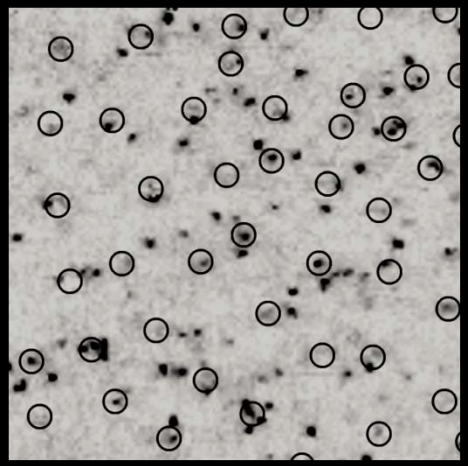
(3) strong pinners exist
high anisotropy
→ vortices pancake
each pancake pins independently





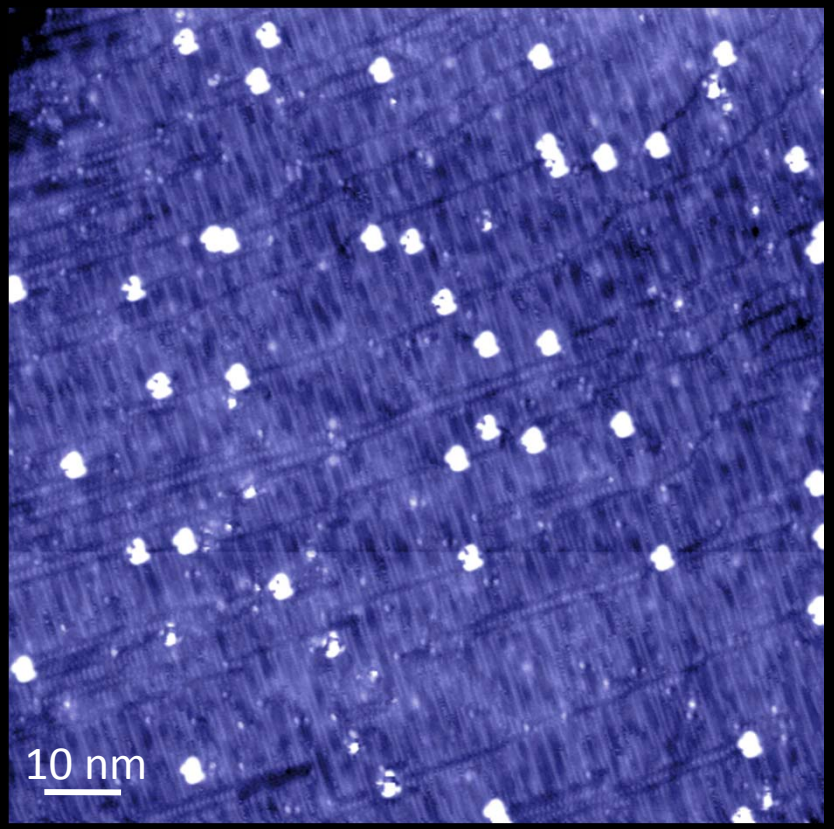
$NbSe_2$

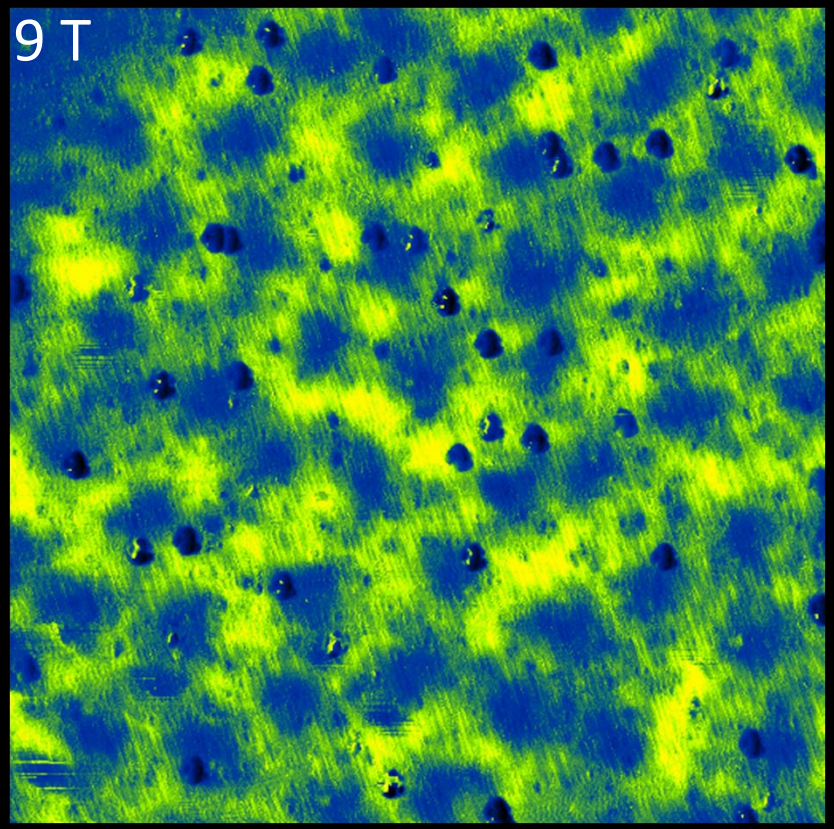
ideal case
for applications

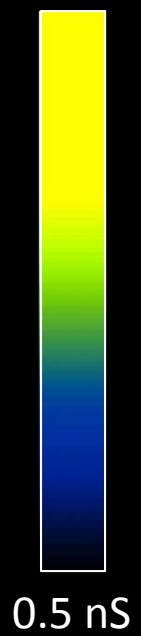


$Bi_2Sr_2CaCu_2O_8$

Are Vortices Pinned to Surface Impurities?



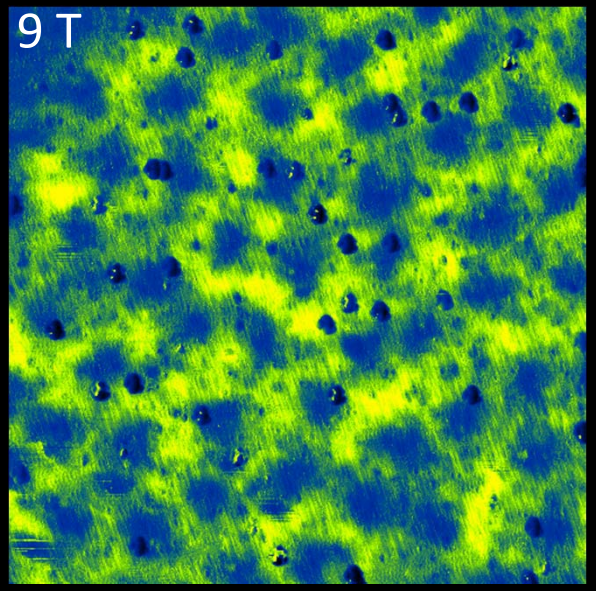


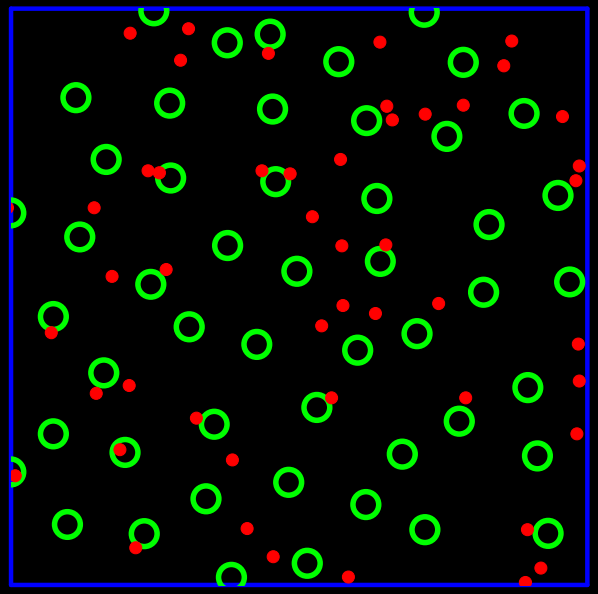


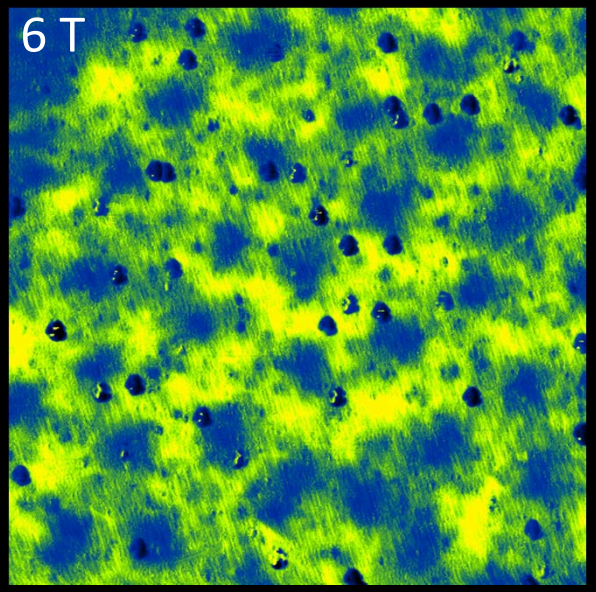
Are Vortices Pinned to Surface Impurities?

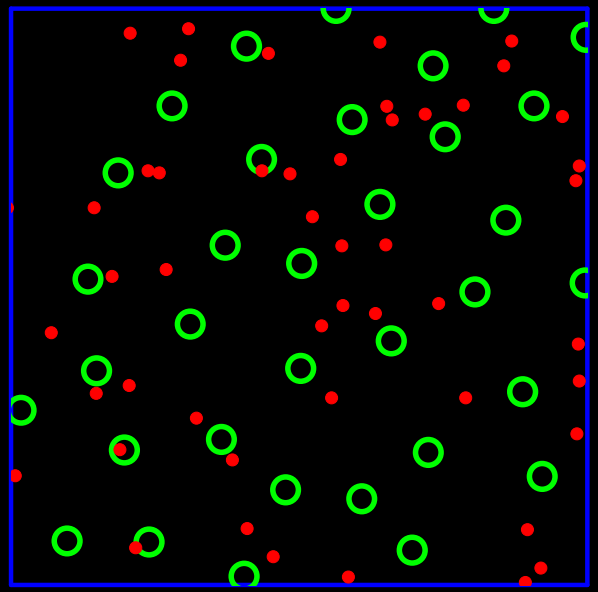
Raw Data

Idealized Data



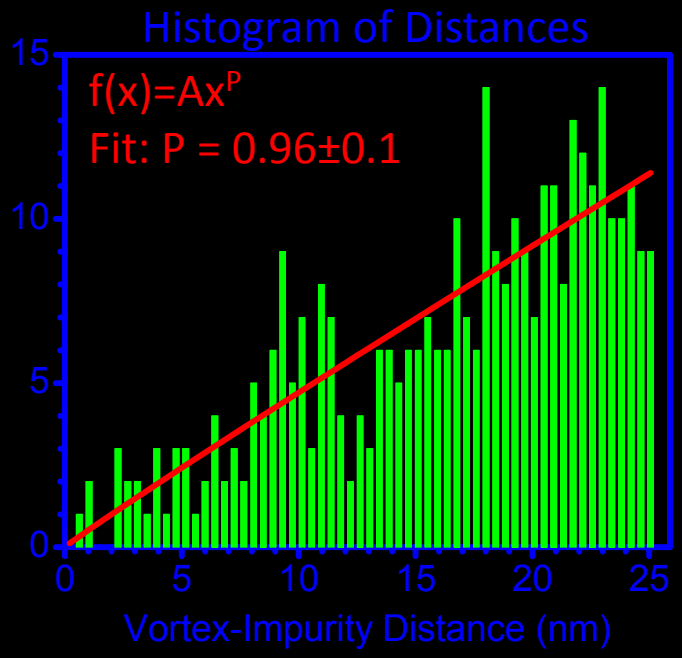






○ vortex, radius ξ_0 = 2.76 nm

• impurity

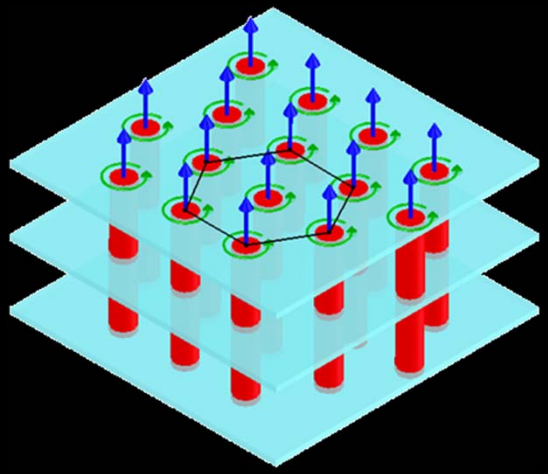


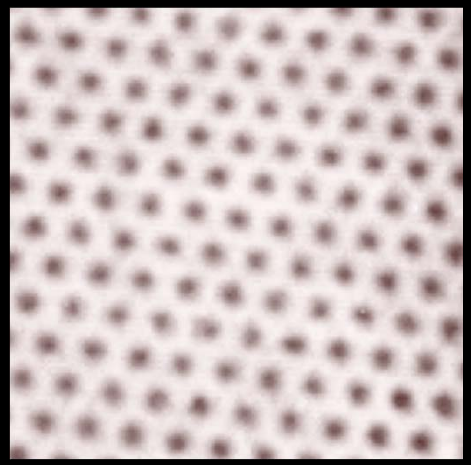
Linear fit!

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

Vortex pinning possibilities

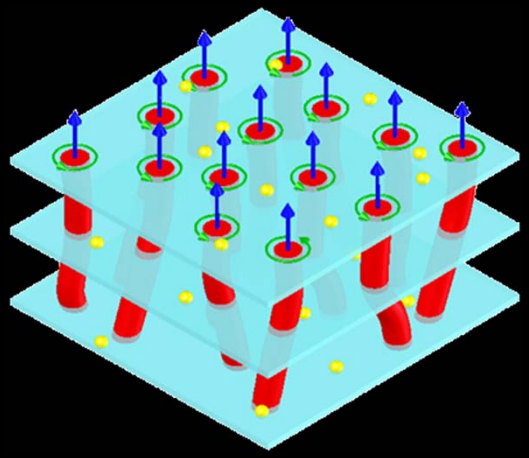
(1) no strong pinners
inter-vortex forces dominate
→ lattice formation

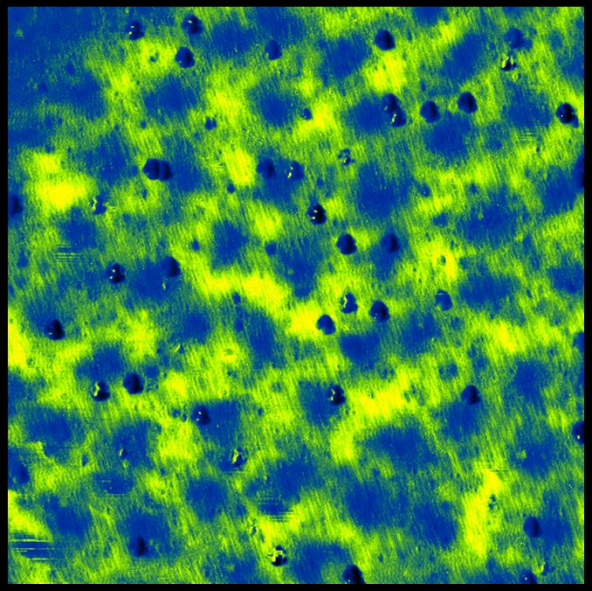




$NbSe_2$

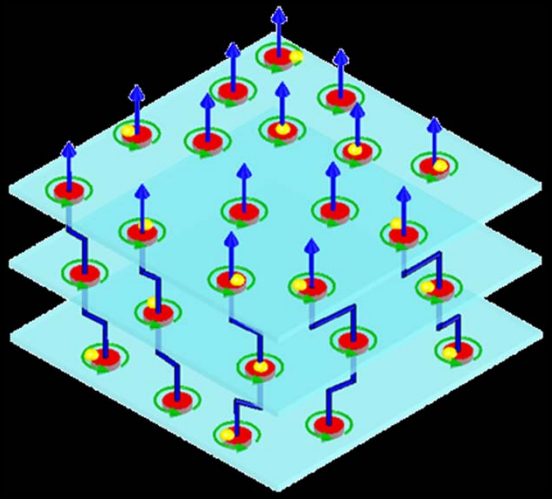
(2) strong pinners exist
low anisotropy
→ vortices bend slightly
to accommodate pinners

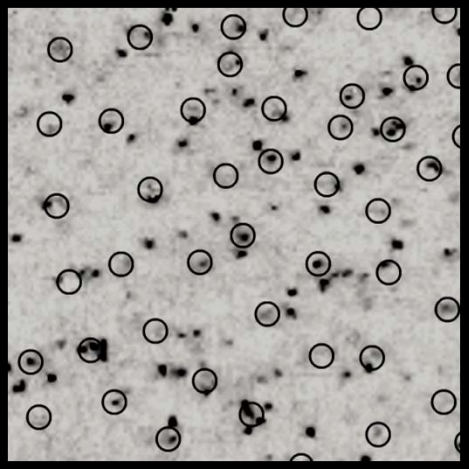




$Ba(Co_xFe_{1-x})_2As_2$

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



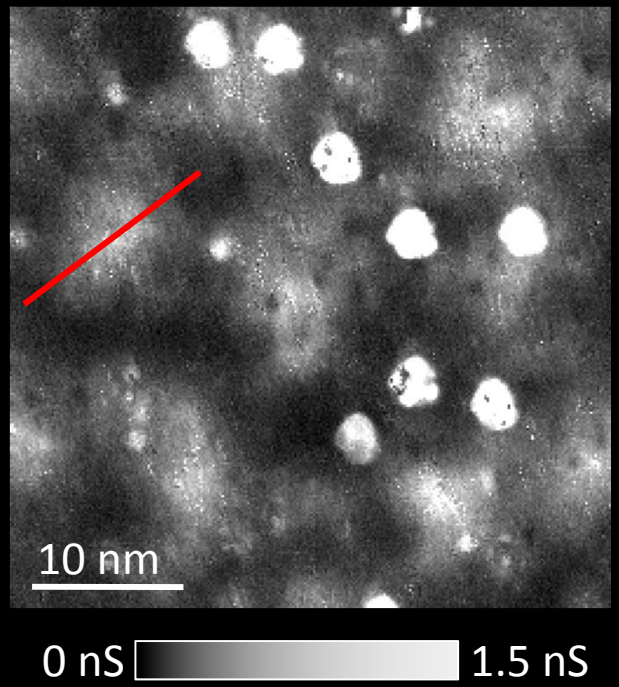


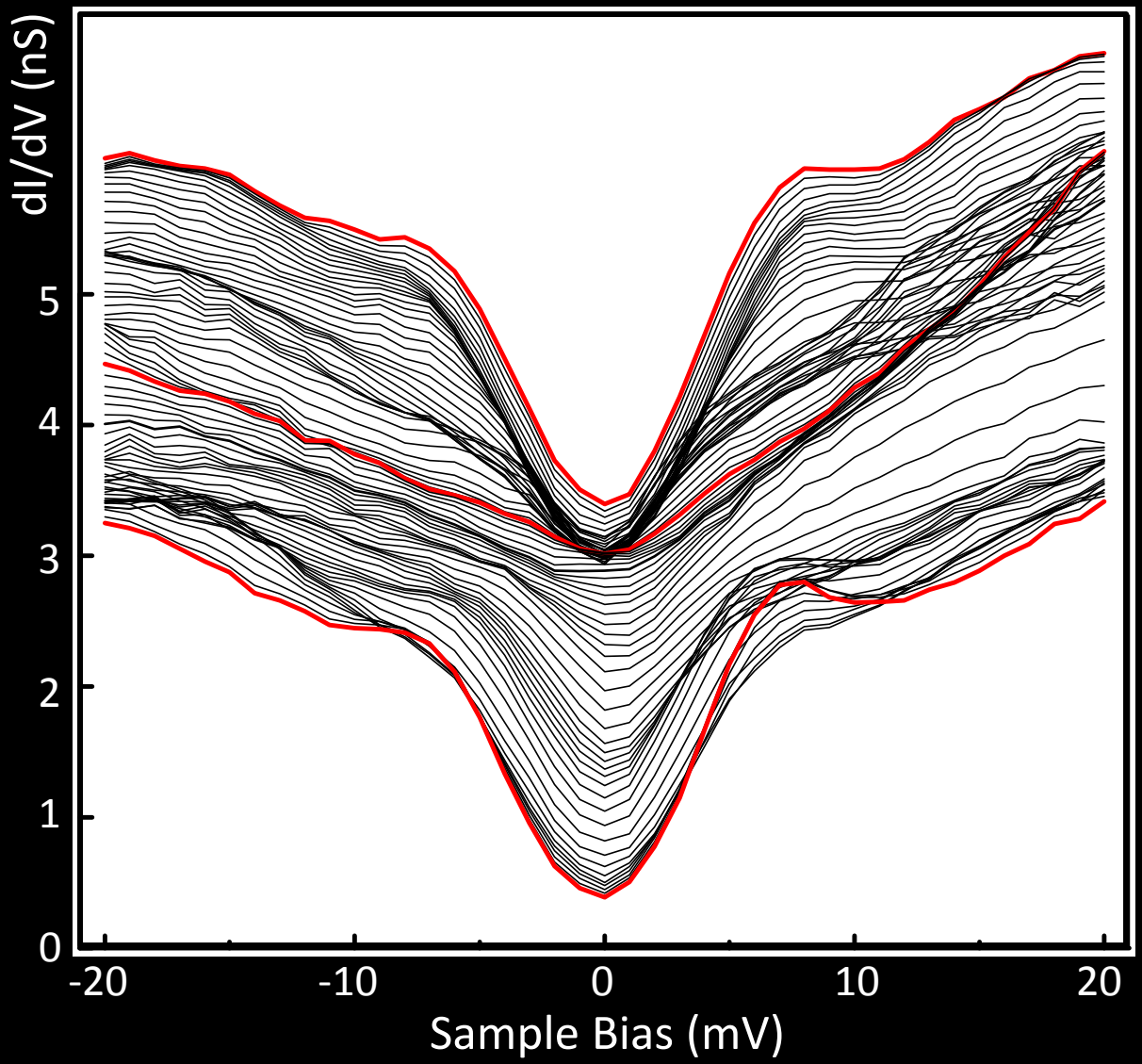
$Bi_2Sr_2CaCu_2O_8$

Vortex Spectroscopy

dI/dV map at 0 mV

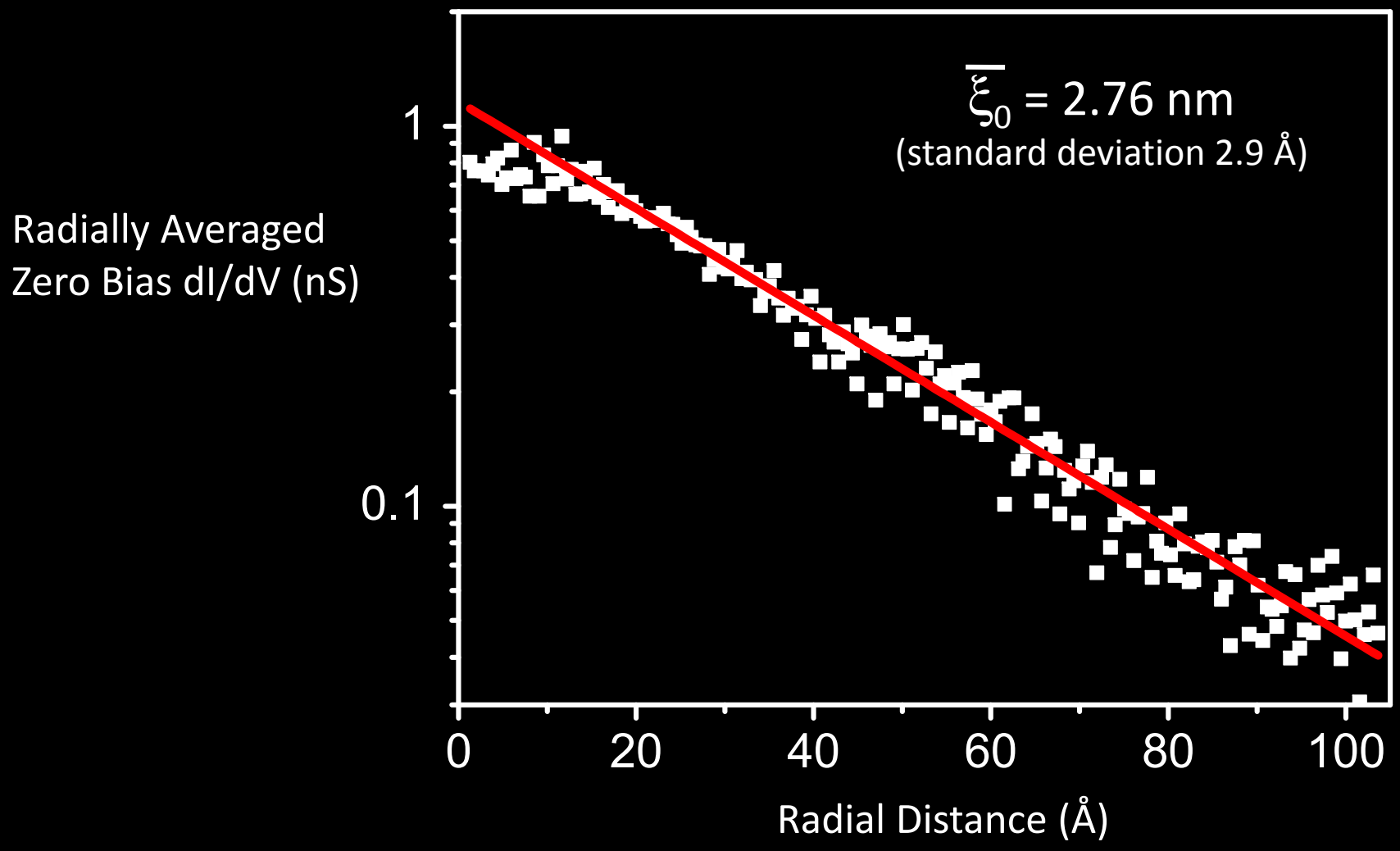
(Fermi level)





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)]

Outline

Superconductors: 100 Year History

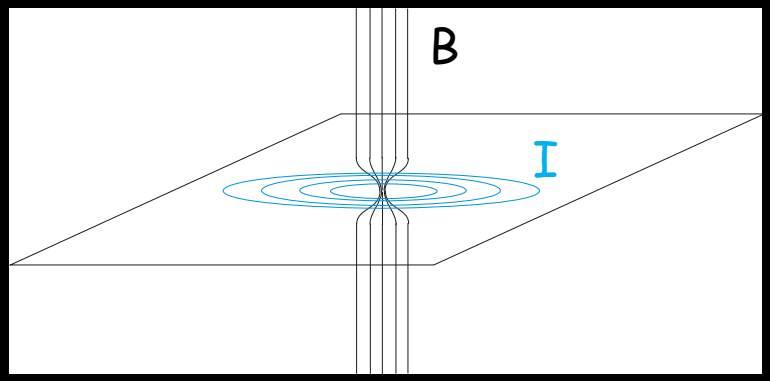
Pseudogap in cuprates:

- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

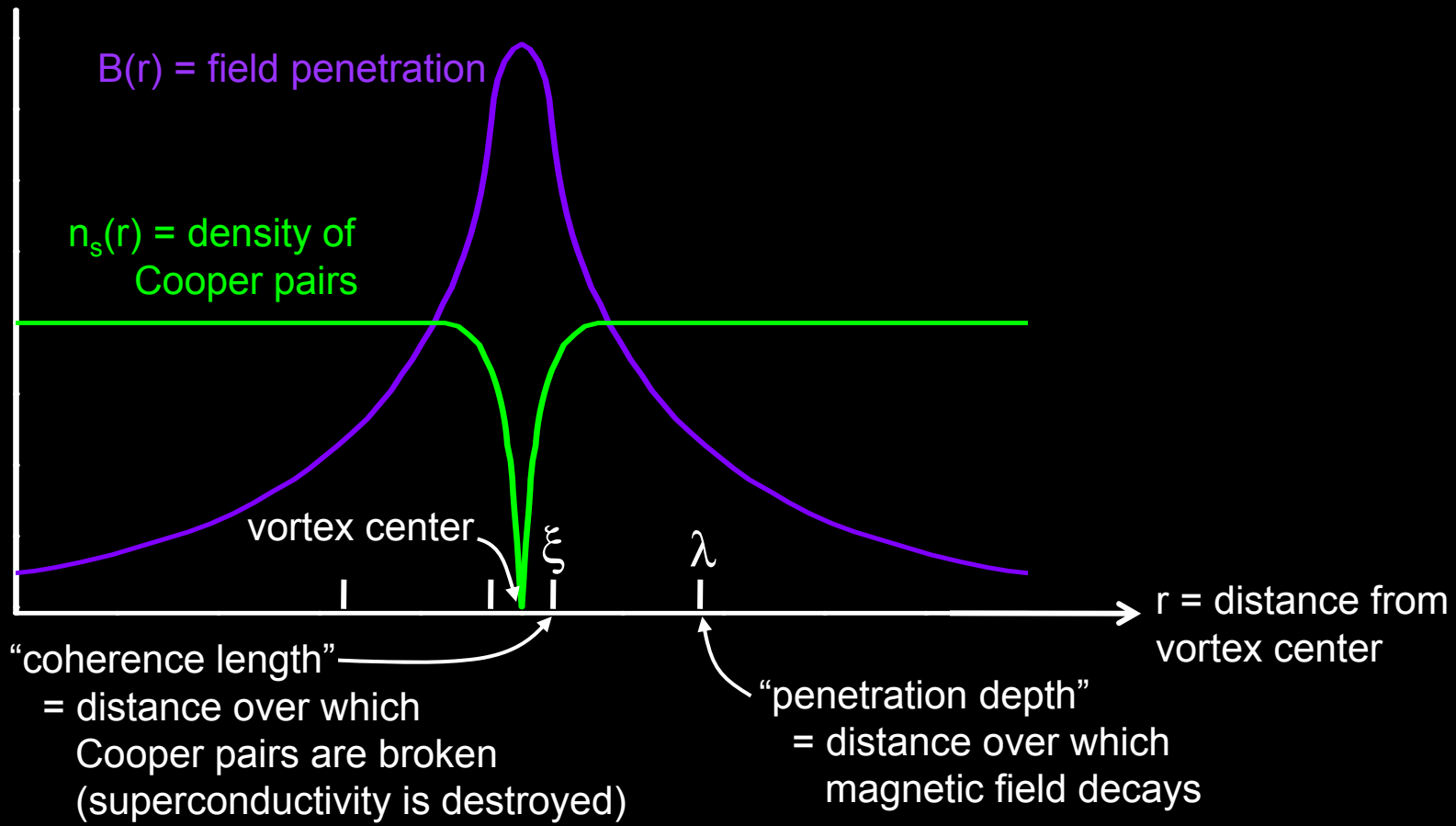
Vortex pinning in cuprates & pnictides:

- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy

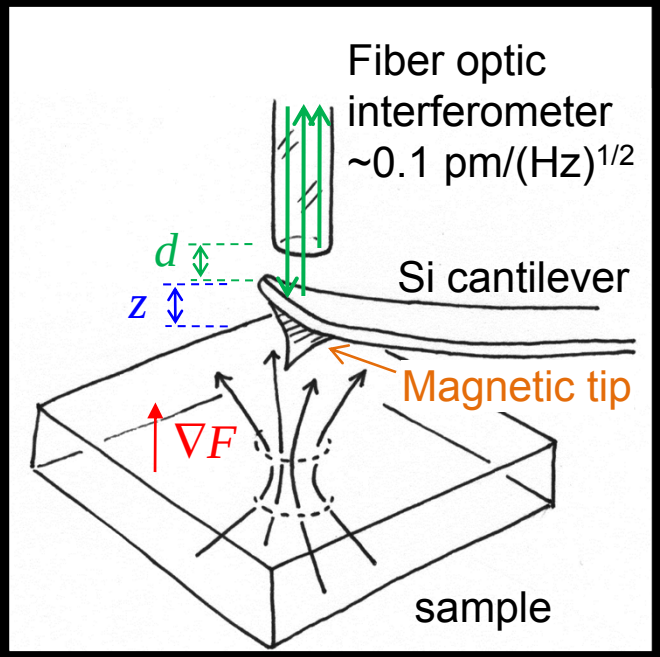
Length Scales in Superconducting Vortices



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



Magnetic Force Microscope



Force between tip and sample:

$$\mathbf{F} = \nabla(\mathbf{m} \cdot \mathbf{B})$$

Frequency modulation imaging

(directly measures force gradient):

$$\frac{\Delta\omega}{\omega_0} = \frac{-1}{2k}\frac{dF_{ts}}{dz}$$

Pros and Cons of MFM

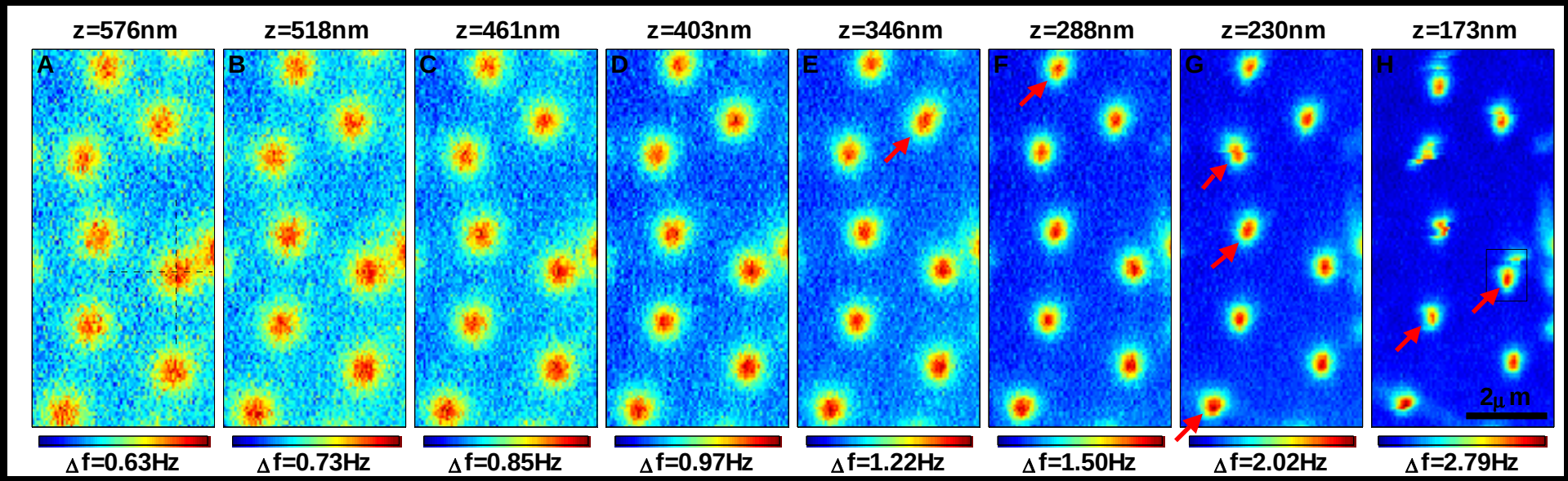
Tip Geometry
Con: Imperfectly known
Pro: Up to 20 nm spatial resolution

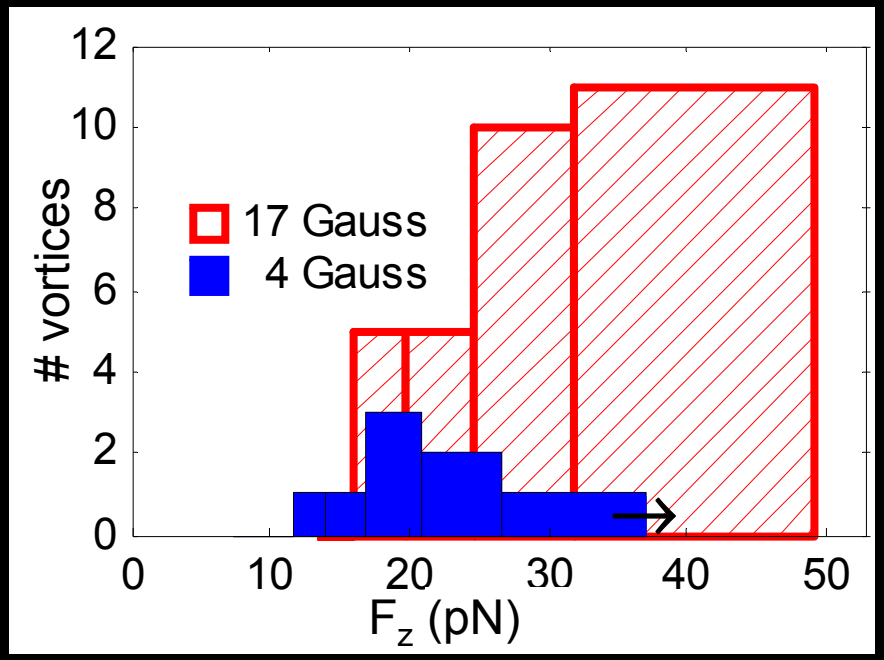
Other signals
Con: See atomic forces too
Pro: Simultaneous topography

Invasiveness
Con: Tip exerts force on vortex
Pro: Tip exerts force on vortex

Vertical force gradient → imaging
Horizontal force → manipulation

Nb vortices: Pinning Force Histogram



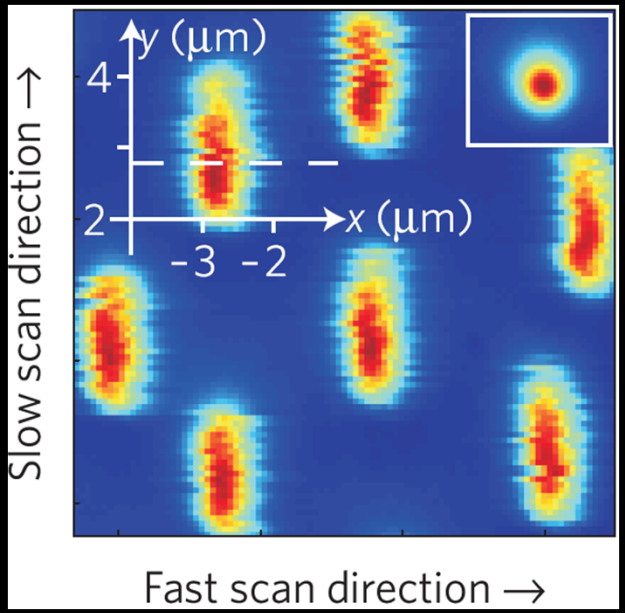


F_{depin} ranges from
4 to 12 pN
at 5.5 K

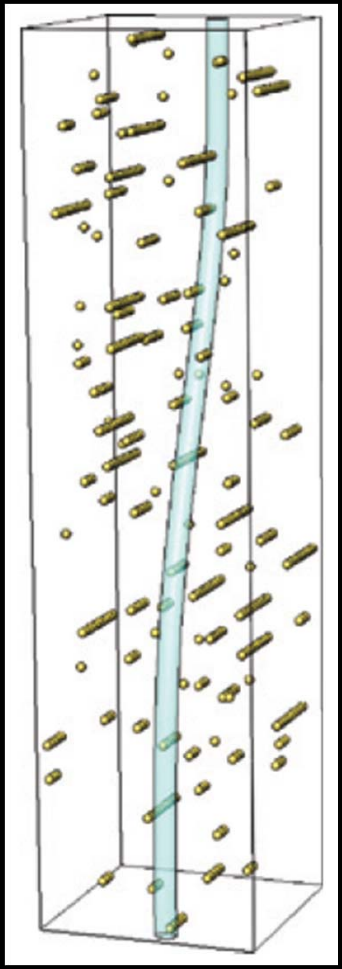
E. W. J. Straver, J. E. Hoffman,
O. M. Auslaender, D. Rugar, K. A. Moler,
Appl. Phys. Lett. 93, 172514 (2008).

$YBa_2Cu_3O_{7-d}$ vortices: Probe Bulk Pinning

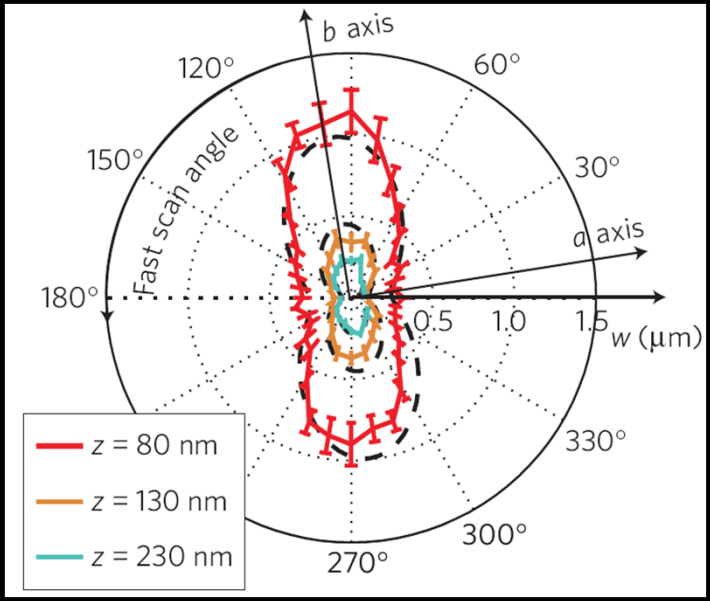
map anisotropy



deduce anisotropy of bulk pinning

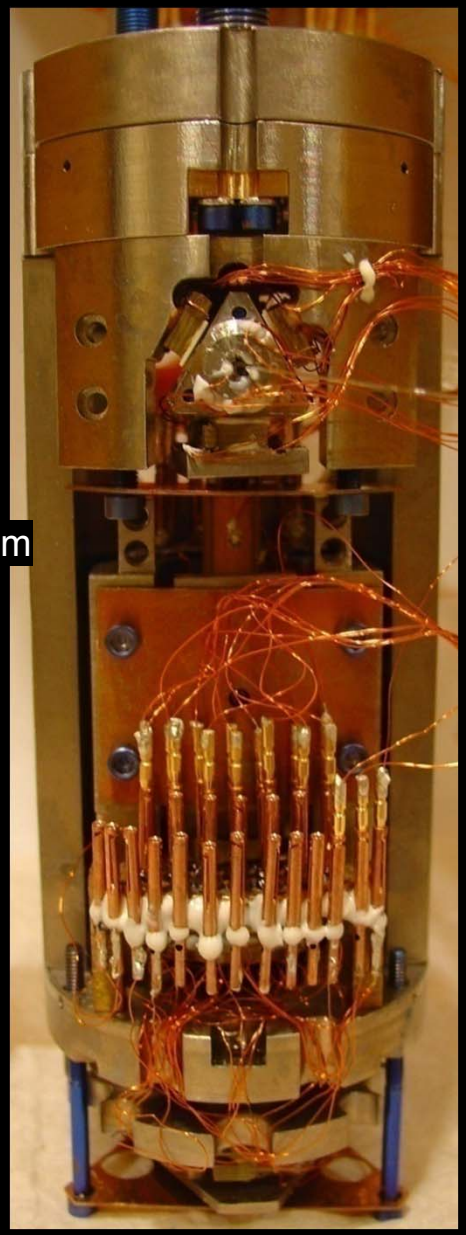


fit anisotropy



O. M. Auslaender, L. Luan, E. W. J. Straver, J. E. Hoffman, N. C. Koshnick, E. Zeldov, D. A. Bonn, R. Liang, W. N. Hardy, K. A. Moler, ***Nature Physics*** 5, 35 (2009).

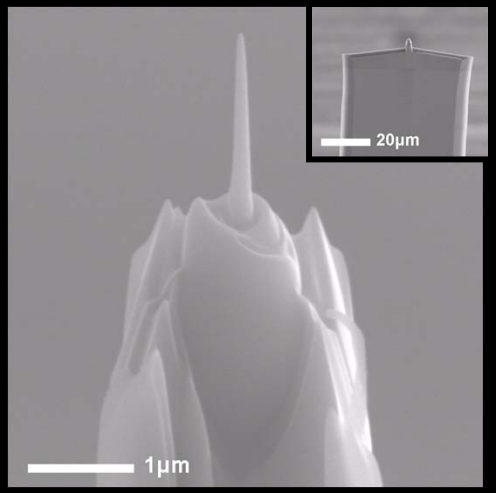
Hoffman Lab Force Microscope



built by Dr. Jeehoon Kim

- 2 K to above 340 K
- 5 T vertical field
- lateral coarse motion (3 mm x 3 mm) allows imaging of isolated features in addition to bulk materials
- high-resolution, easily modelable tips fabricated in house via focused ion beam

Radius of curvature : 15-25 nm
Cone half-angles : 1-3°
Aspect ratios : 12-18



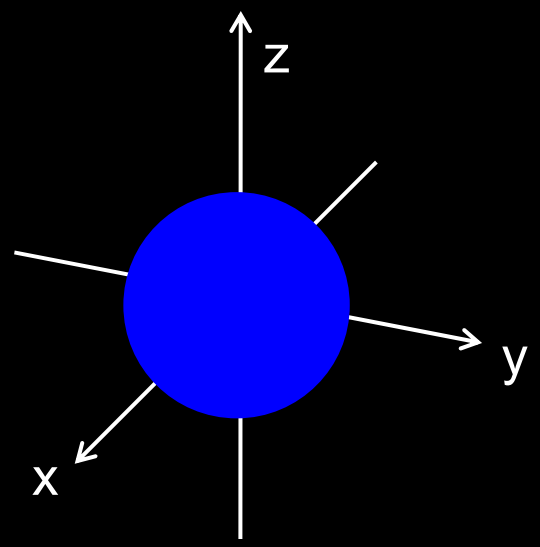
Versatility:

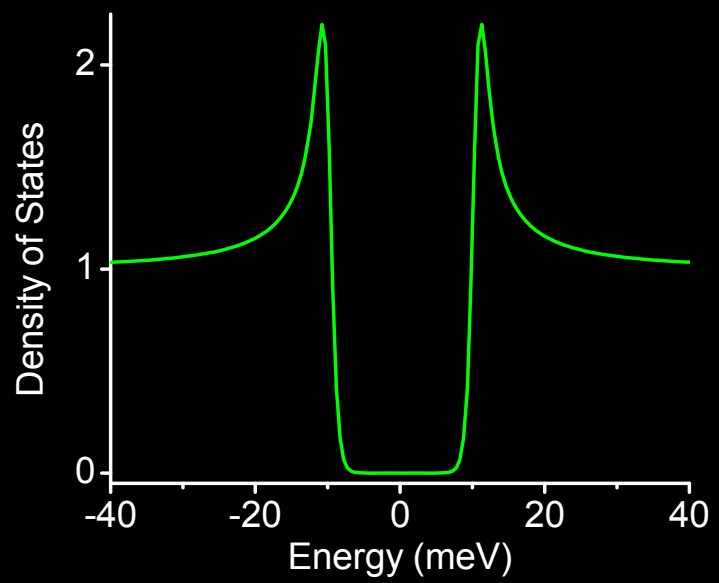
- vertical or lateral force measurement
- magnetic tips for magnetic imaging and manipulation
- conducting tips for local conductivity imaging and switching
- vertical cantilevers for friction imaging

Pairing Symmetry

Conventional Superconductors

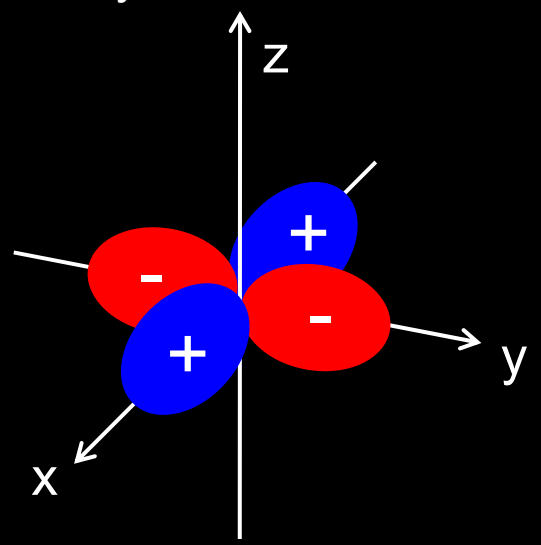
s wave pairing

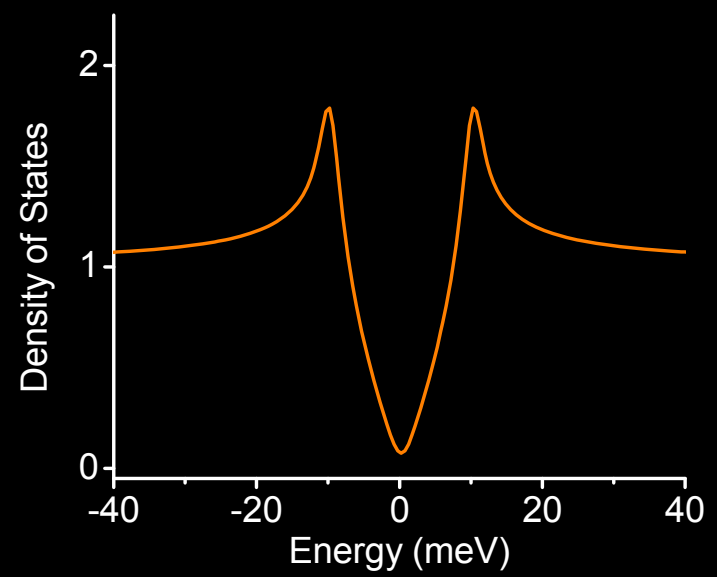




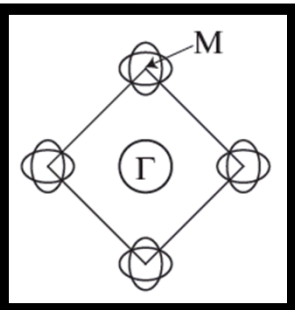
Cuprate Superconductors

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

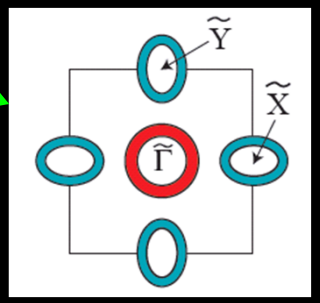


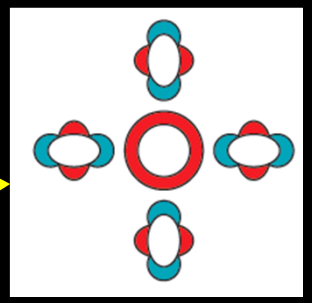


Iron-pnictides: What is the pairing symmetry?



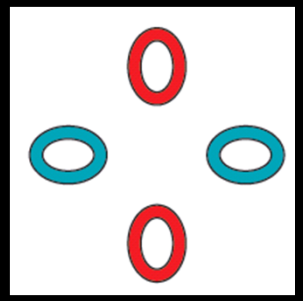
(1) nodeless extended s-wave (s±)
- Mazin, PRL 101, 057003 (2008)
- Wang, PRL 102, 047005 (2009)
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)



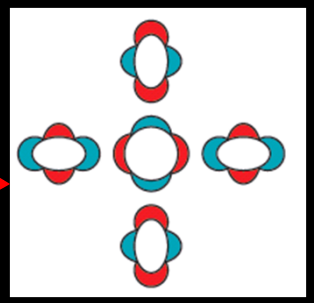


(2) nodal s-wave
- Kuroki, PRL 101, 087004 (2008)

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

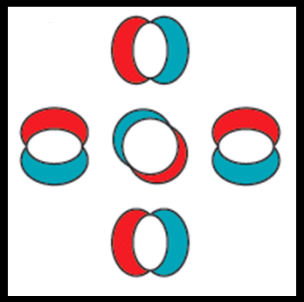


(4) d_{x2-y2} order
- Yao, Li & Wang, New J. Phys. 11, 025009 (2009)



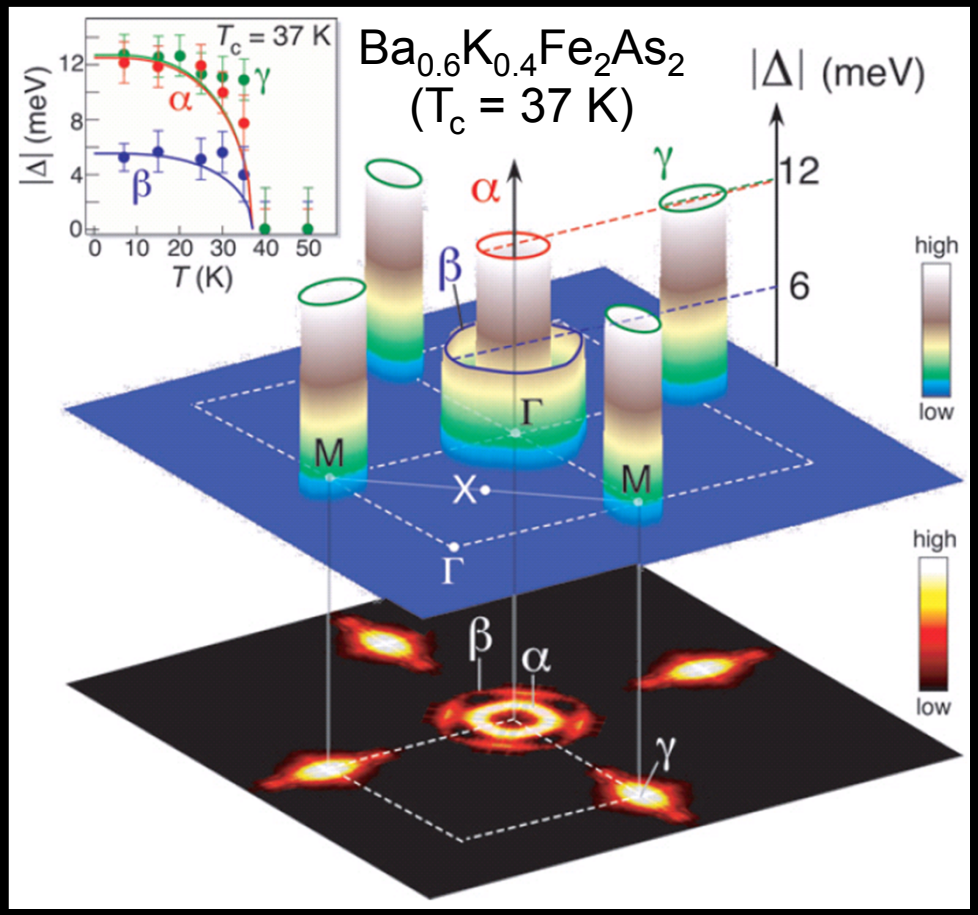
(5) nodal intraband p order
- Lee & Wen, PRB 78, 144517 (2008)

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



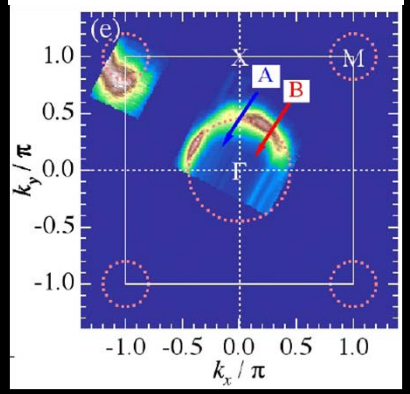
figures borrowed from from Hicks, … Moler, JPSJ 78, 013708 (2009)

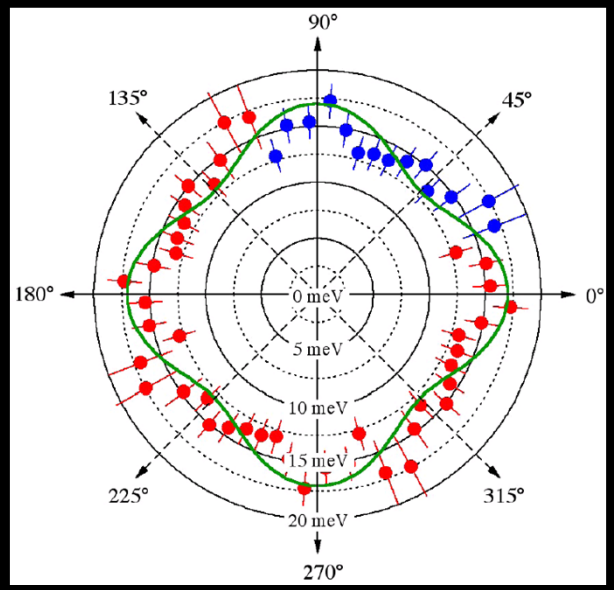
ARPES: What is the pairing symmetry?



Ding, EPL 83, 47001 (2008)

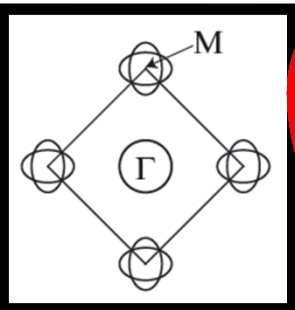
$NdFeAsO_{0.9}F_{0.1}$
(T_c = 53 K)





Kondo, PRL 101, 147003 (2008)

Converging on s± symmetry?



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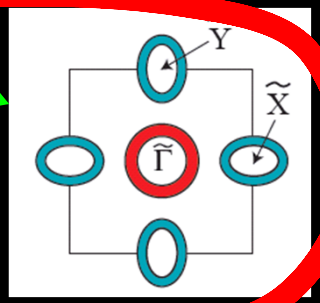
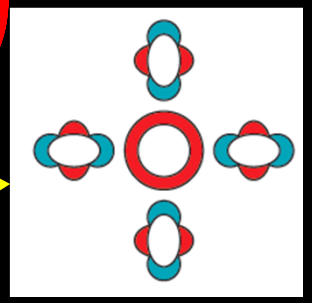
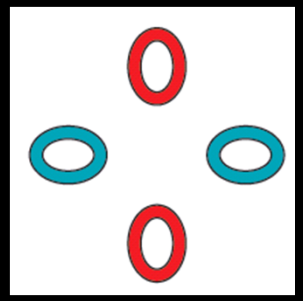
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)

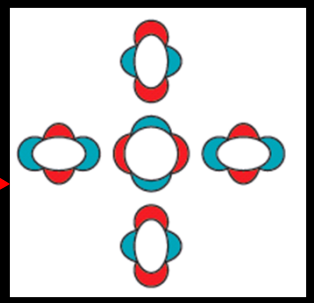




(2) nodal s-wave
- Kuroki, PRL 101, 087004 (2008)

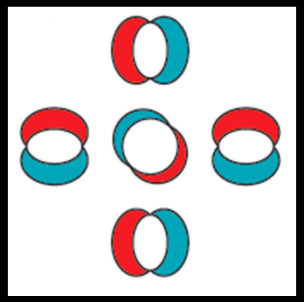


(3) nodeless d
- Kuroki, PRL 101, 087004 (2008)



(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)

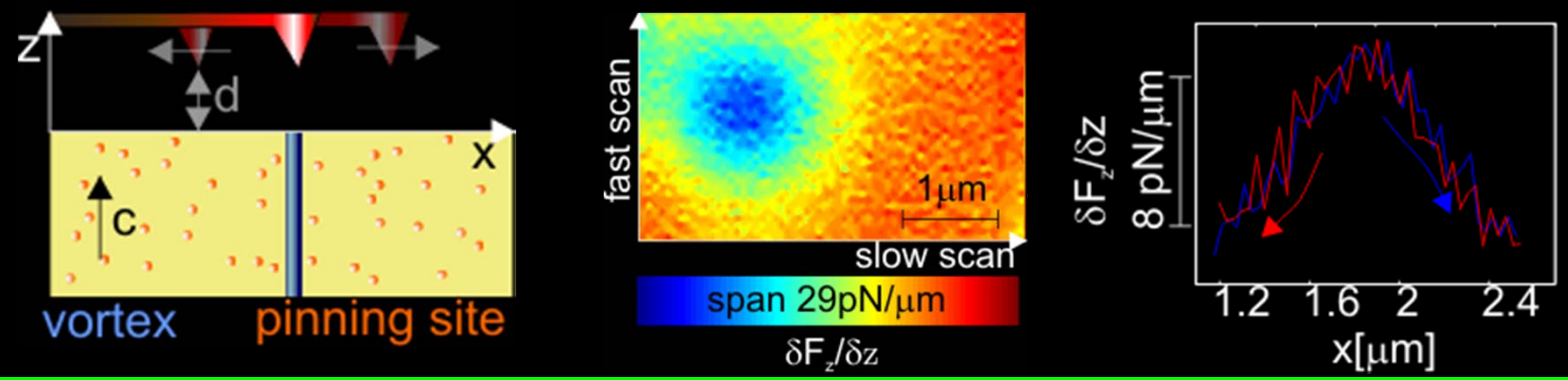
BUT… Plenty of Evidence For Gap Nodes

- 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]

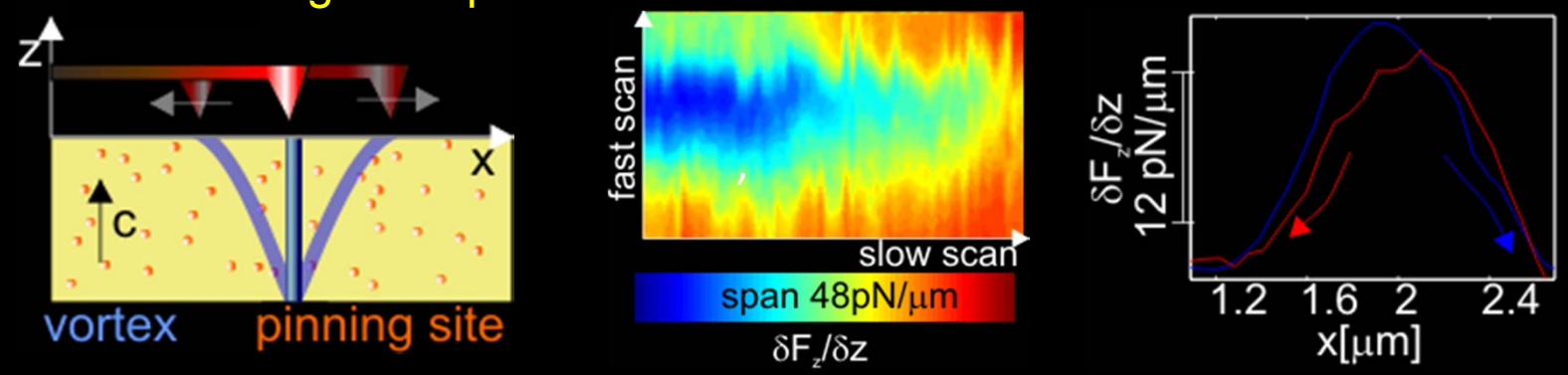
→ What can we contribute?

Vortex Manipulation in $NdO_{1-x}F_xFeAs$

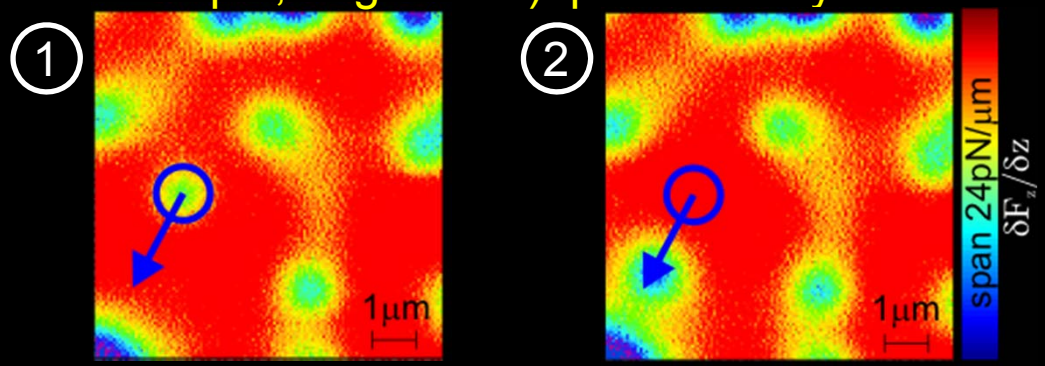
d large (tip far from sample, small force): image without disturbing vortex



d intermediate: drag the top of the vortex

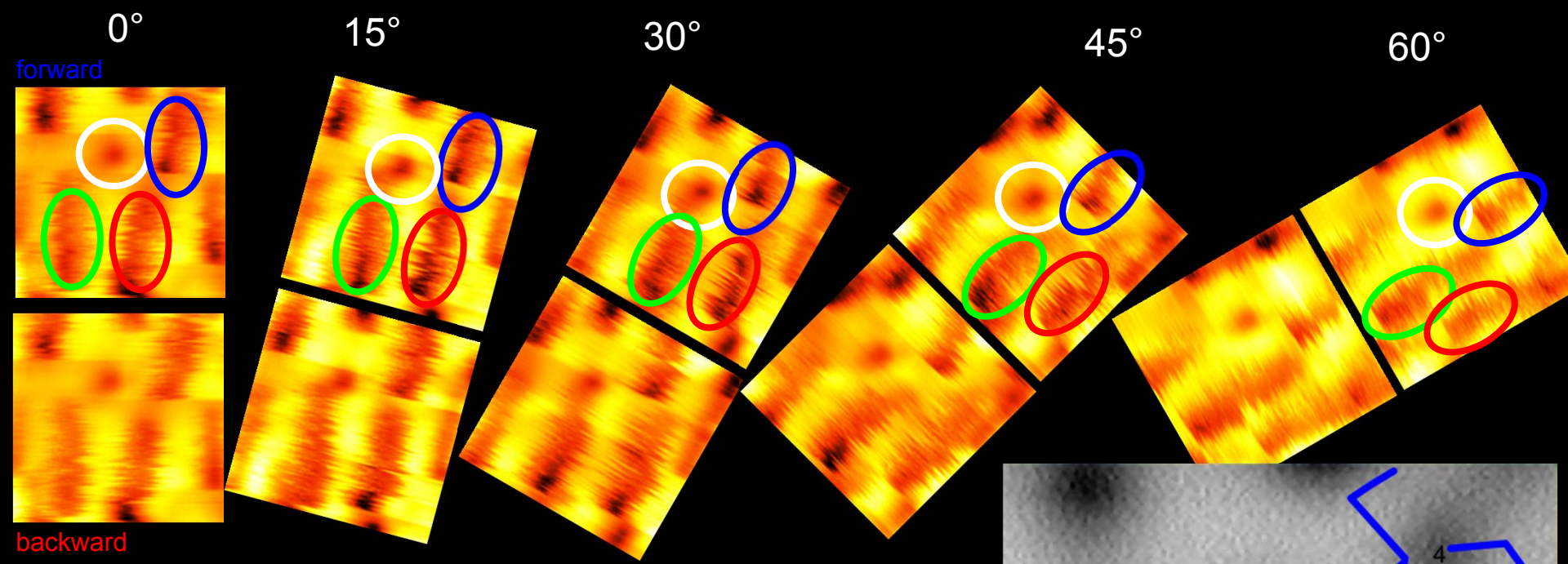


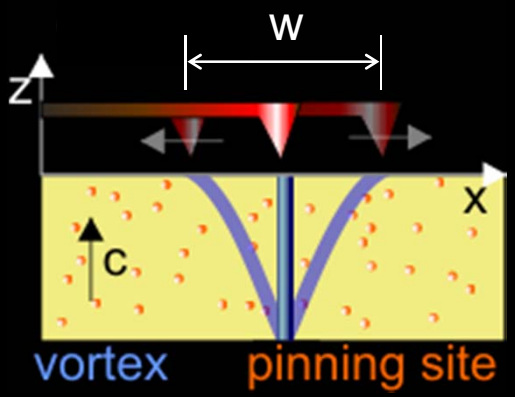
d small (tip close to sample, large force): permanently move the entire vortex



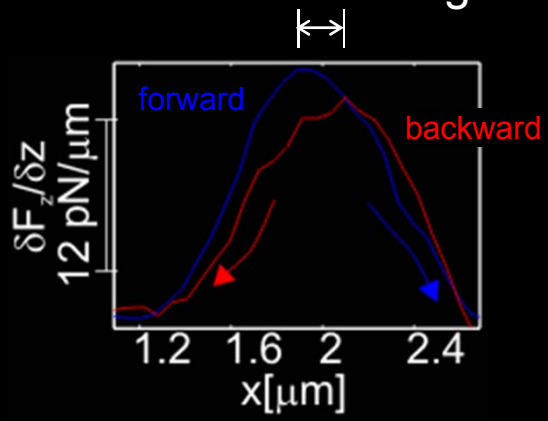
Angular dependence in $NdO_{1-x}F_xFeAs$

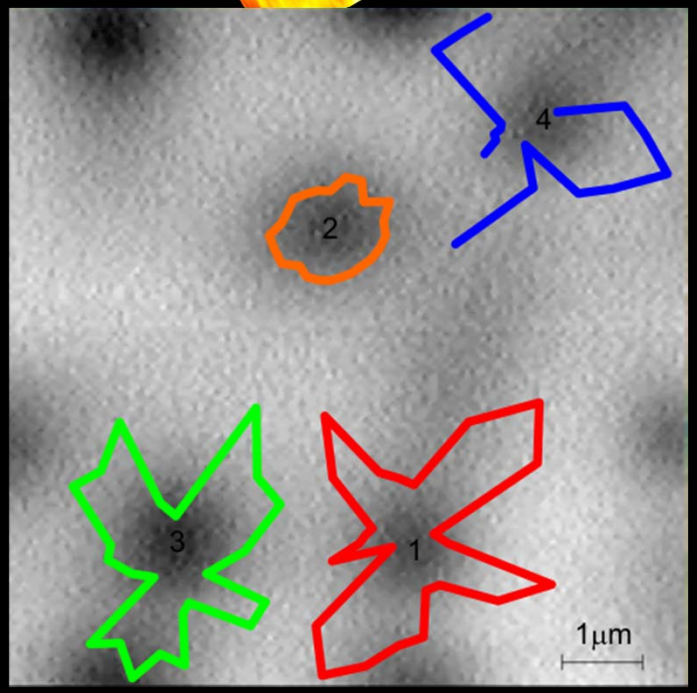
d intermediate: drag the top of the vortex



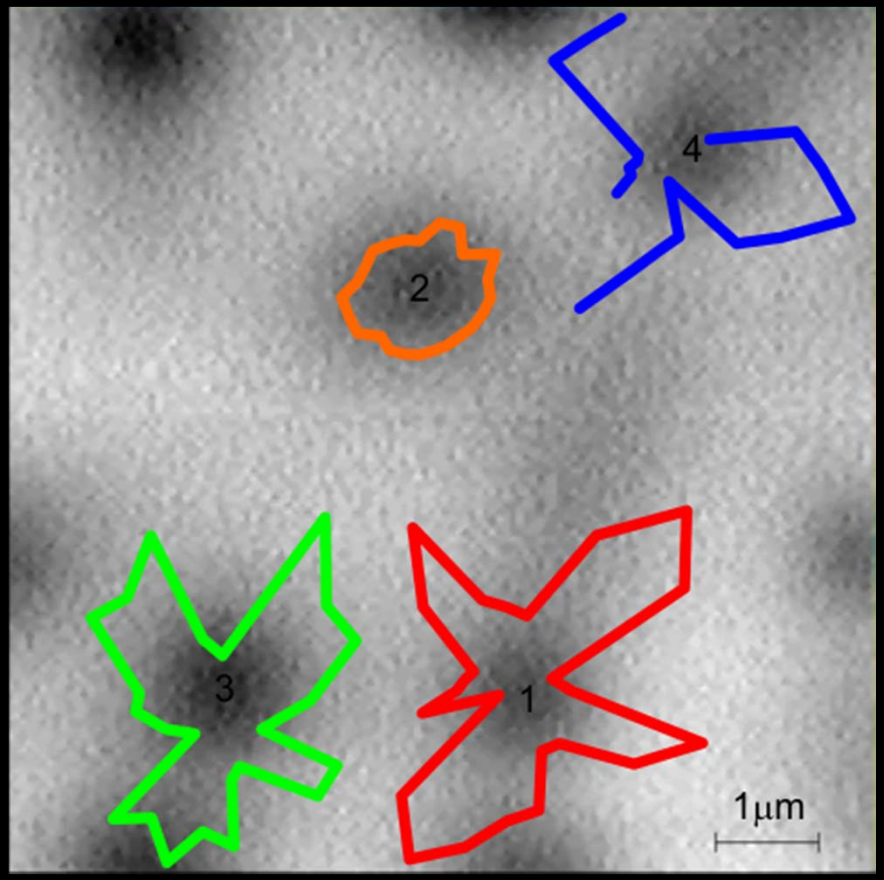


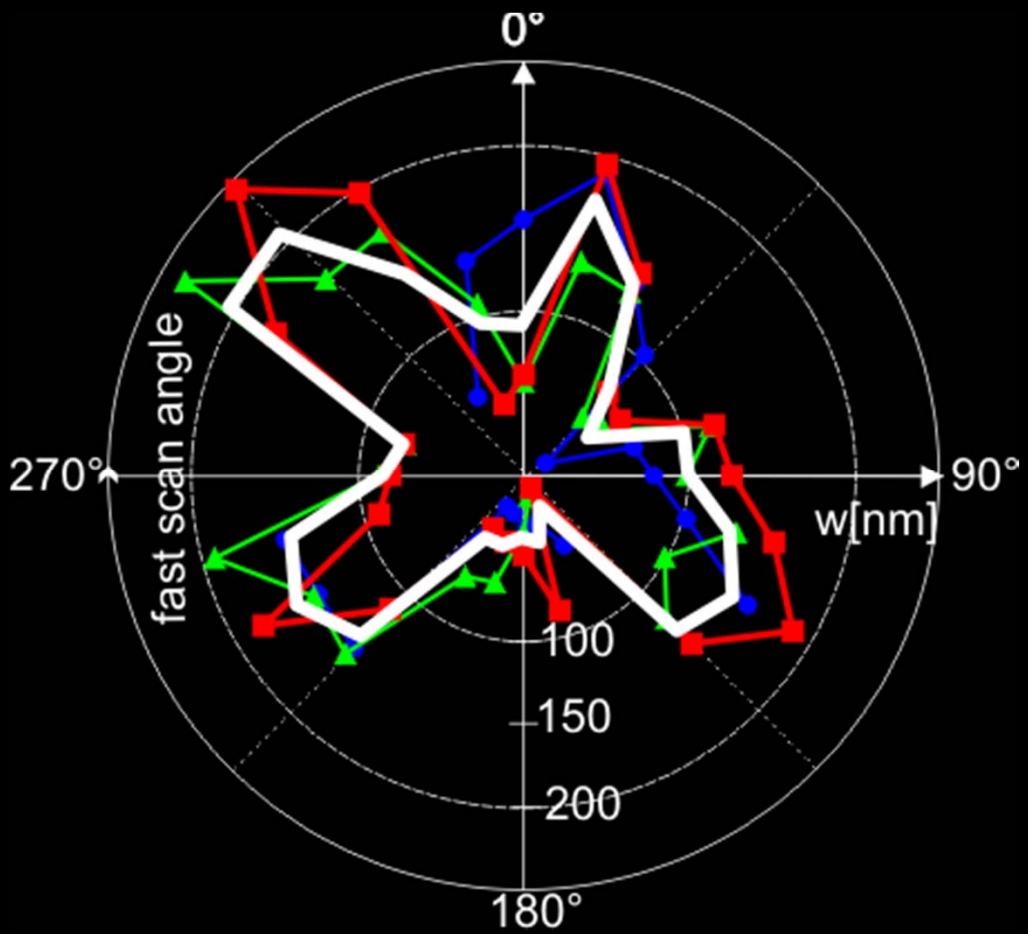
w = fast scan drag width





Angular dependence in $NdO_{1-x}F_xFeAs$

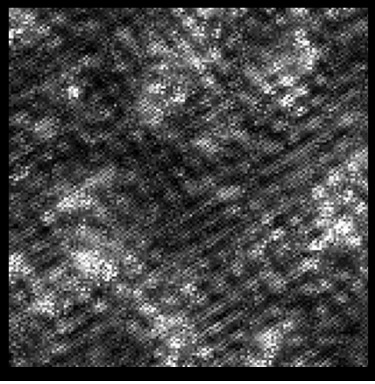
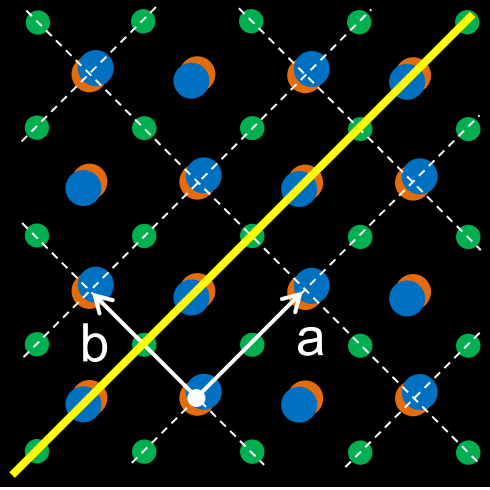




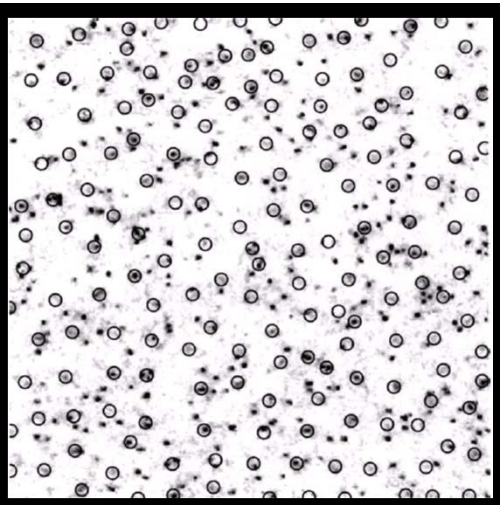
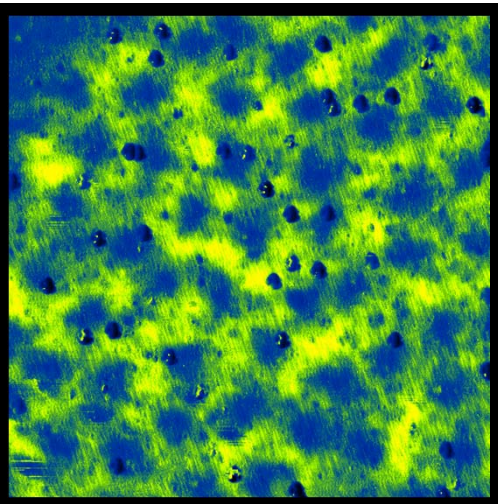
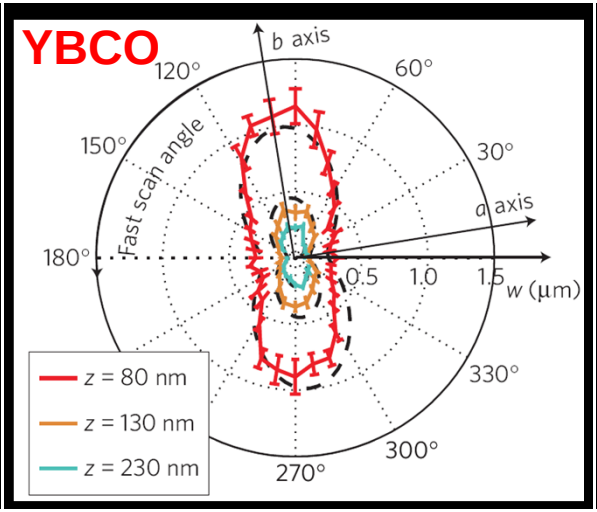
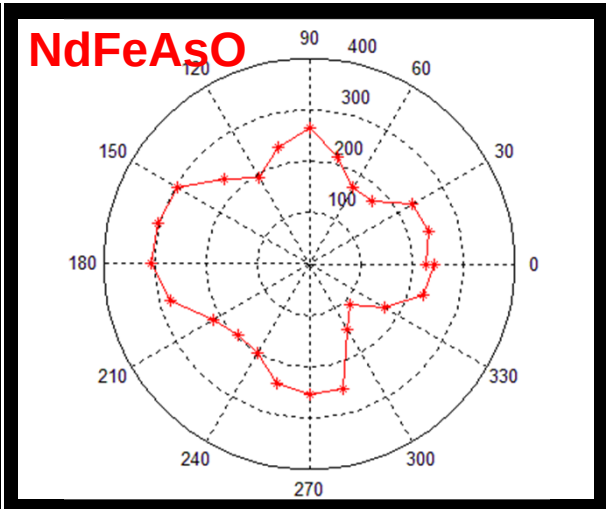
Burning question:

→ does 4-fold symmetry come from anisotropic defects or from intrinsic pairing property of Fe-based superconductor?

Cuprate-Pnictide Comparison

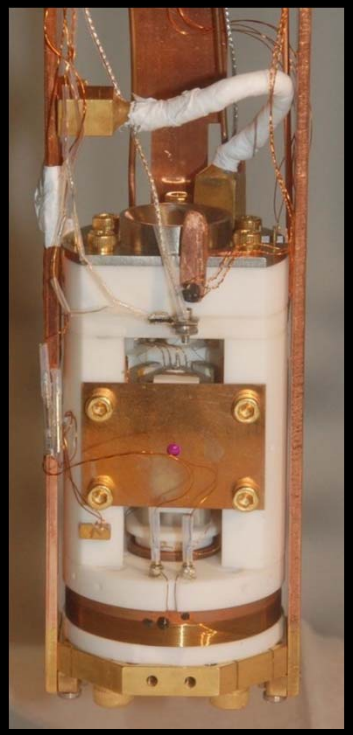
	Cuprate: $Bi_2Sr_2CaCu_2O_{8+d}$	Pnictide: $BaCo_xFe_{2-x}As_2$
Pseudogap Short range order	Broken translational symmetry: “checkers” 	Pseudogap not consistently observed.
Structural Long range order	Structure: breaks inversion symmetry 	Structure: orthorhombic, but no evidence of inversion symmetry breaking

Cuprate-Pnictide Comparison

	Cuprate: $Bi_2Sr_2CaCu_2O_{8+d}$	Pnictide: $BaCo_xFe_{2-x}As_2$
Vortex pinning	 vortices pinned to surface impurities	 vortices NOT pinned to surface impurities
Preliminary: vortex pinning anisotropy		

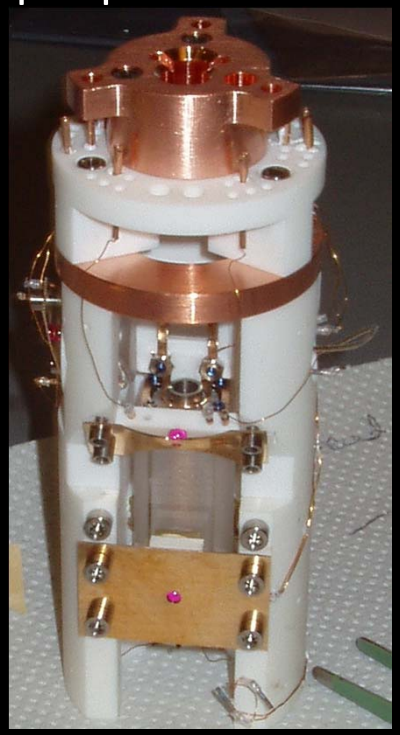
Future Directions

STM

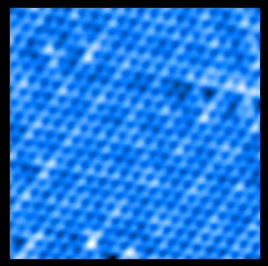


Force Microscope

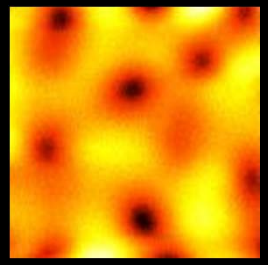
Spin-polarized STM



- $NbSe_2$: understand interplay of SC and CDW in a "simpler" system



- Quantify pinning forces and anisotropies on single vortices



NdFeAsO

- Search for real space evidence of spin density waves & relation to SC
- Quantify local relationship between broken symmetries & superconductivity