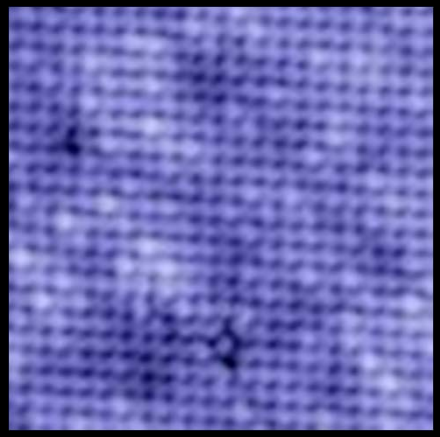
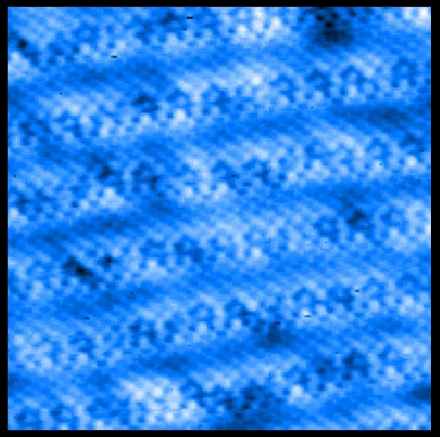
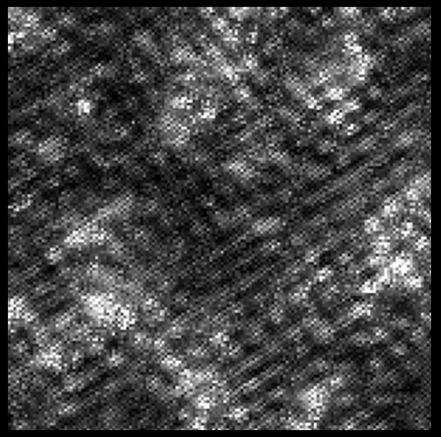
STM imaging of broken symmetry states in cuprate superconductors



STM Experiments:

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Harvard Physics

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Bi-2212 Samples:

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Brookhaven

Bi-2201 Samples:

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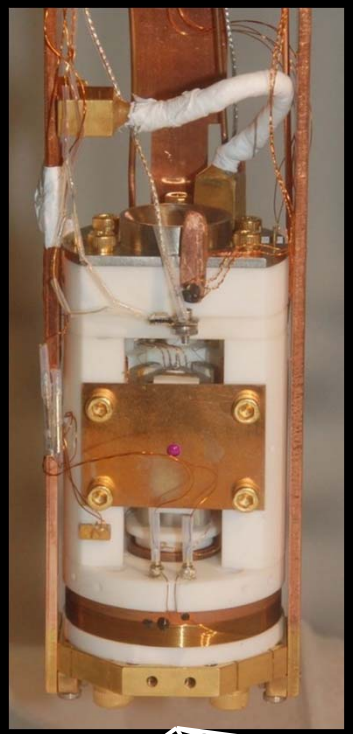
T. Takeuchi
Hiroshi Ikuta
Nagoya University

Thanks to:

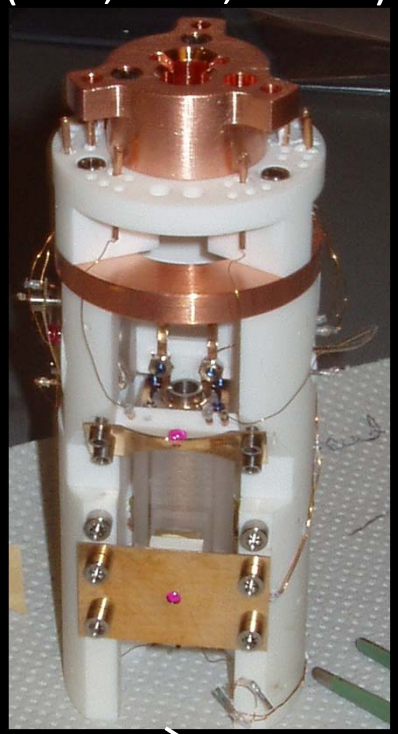
NSEC

Hoffman/Hudson Lab Local Probes

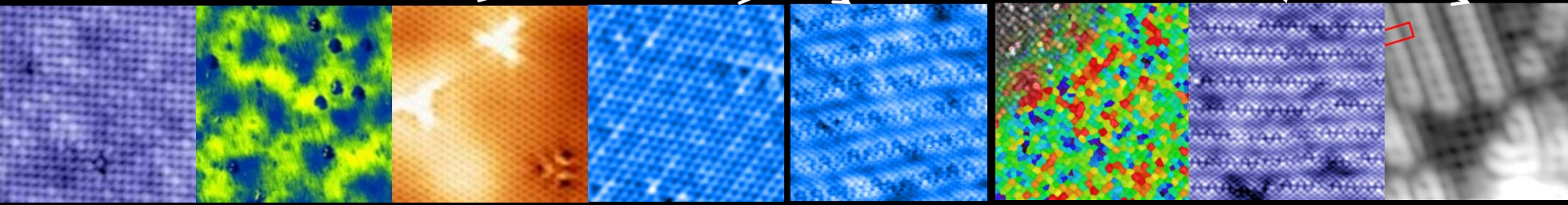
Hoffman Lab STM
(9T v, 3T h; 1-40K)



Hoffman Lab UHV STM
(9T v, 3T h; 2-80K)

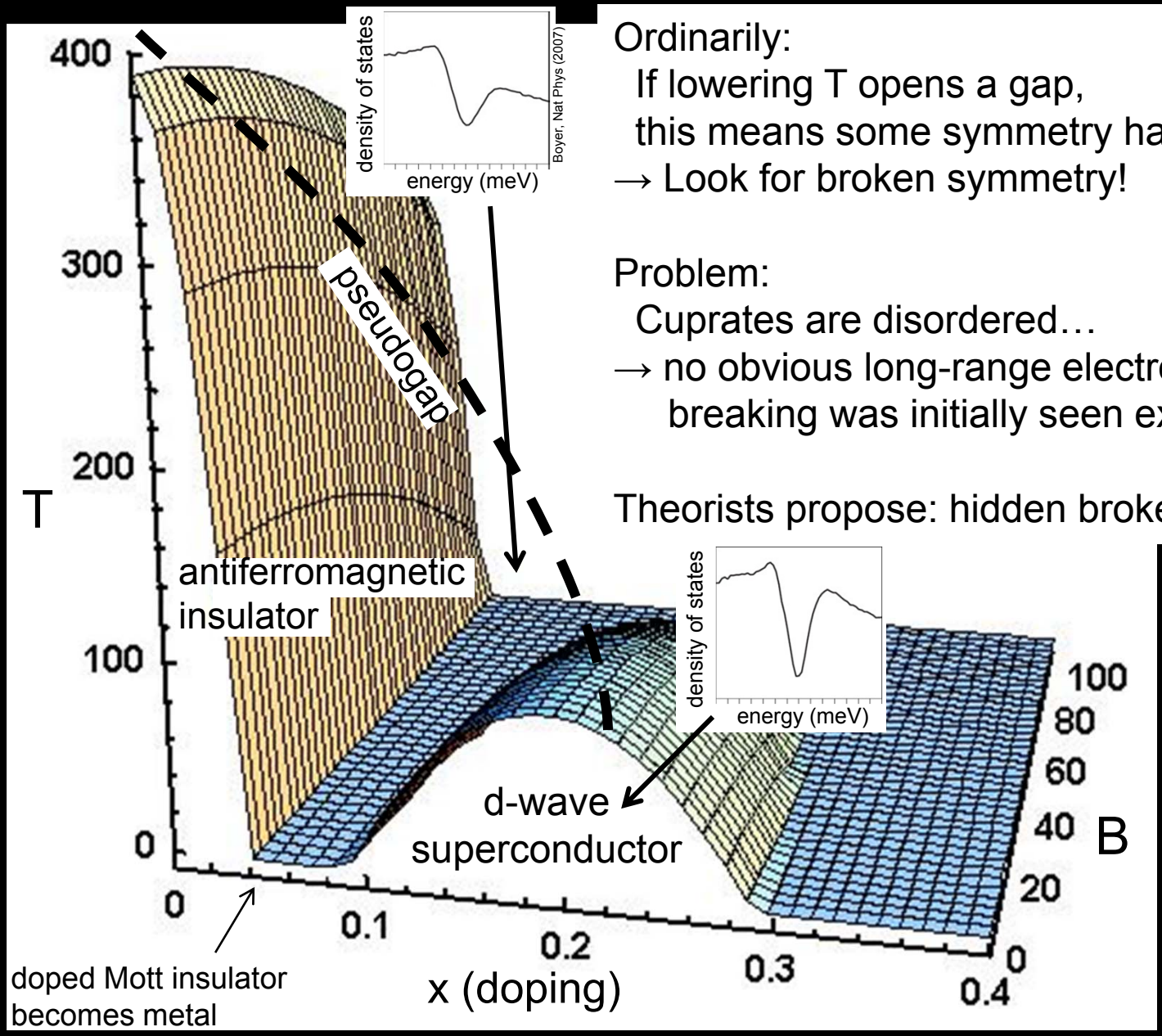


Hudson Lab UHV STM
(4-120K)



Bi-2201 | Ba-122 iron pnictide | topological insulator | $NbSe_2$ | Bi-2212 | Bi-2201 | Bi-2212 | Sr-122 iron pnictide

Cuprate Phase Diagram



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 electronic symmetry breaking was initially seen experimentally

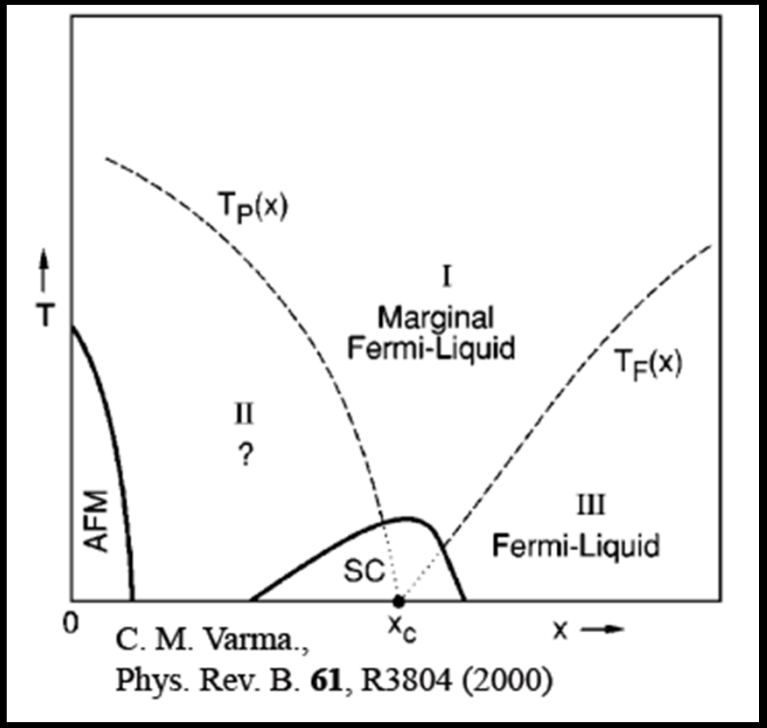
Theorists propose: hidden broken symmetries!

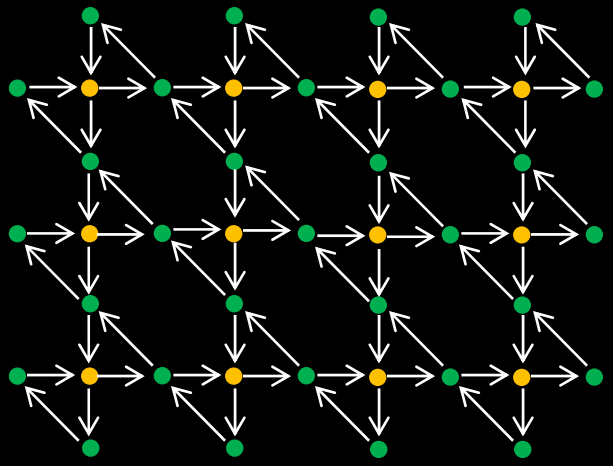
Varma: sub-unit-cell orbital ordering

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.



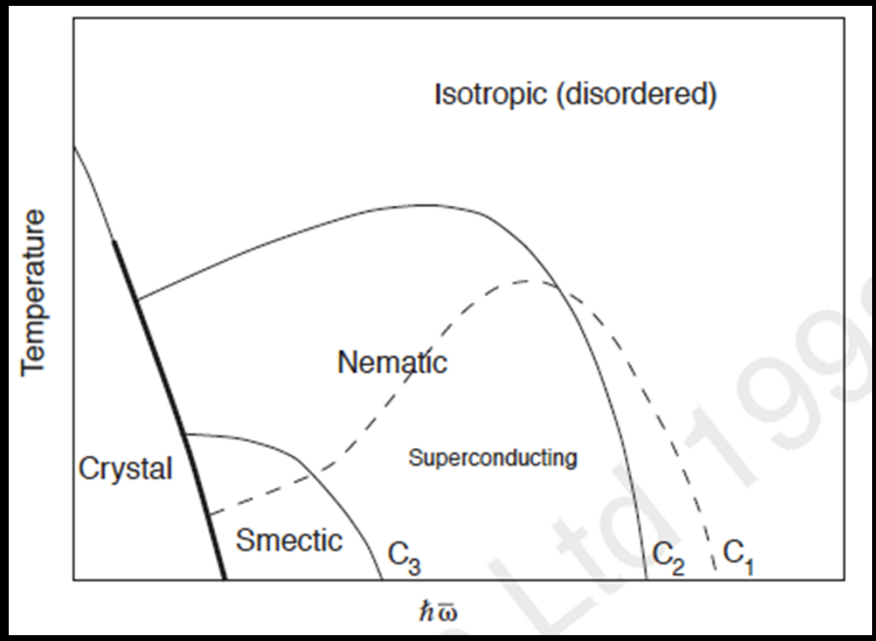


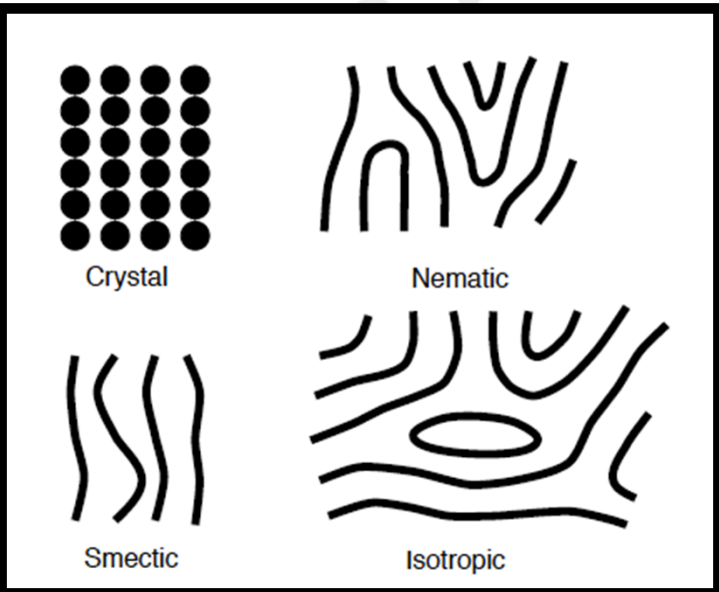
Breaks time-reversal
and inversion
but not the produce of TI.

Kivelson, Fradkin: 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

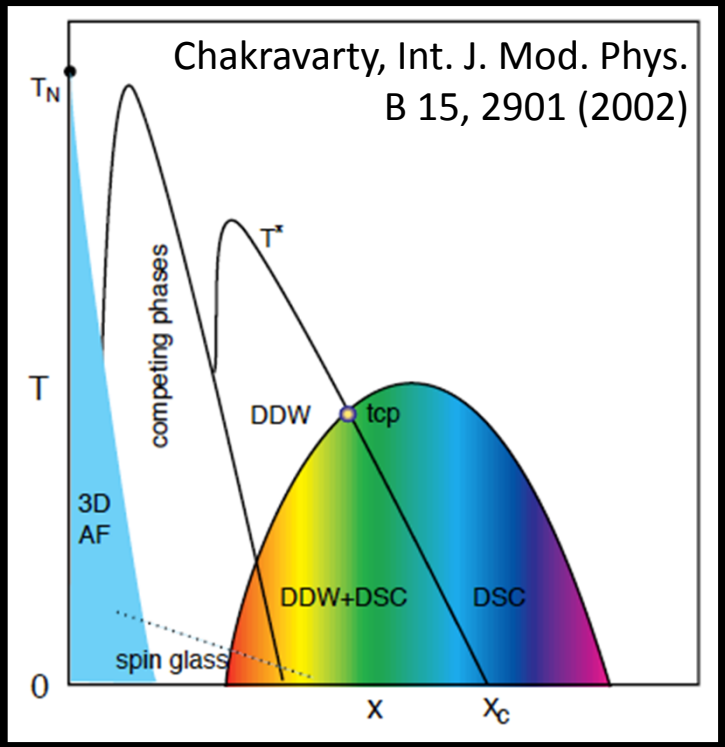
Kivelson, Fradkin, and Emery, Nature **393**, 550 (1998).

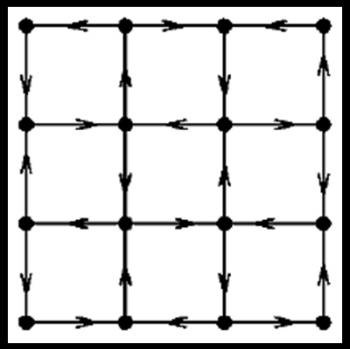
Nayak & Chakravarty: d-density wave

The pseudo-gap has broken translational symmetry and a corresponding partial gapping and restructuring of the FS.

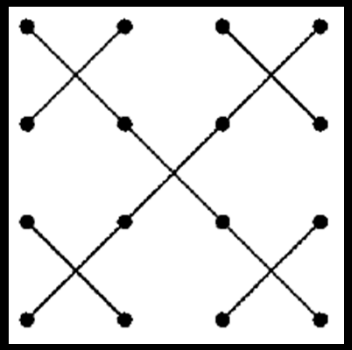
The order parameter is "hidden" in the sense that it is intrinsically difficult to see directly in experiment.

Breaks time reversal and translational symmetry, but preserves the product.

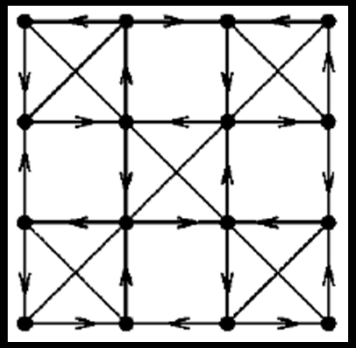




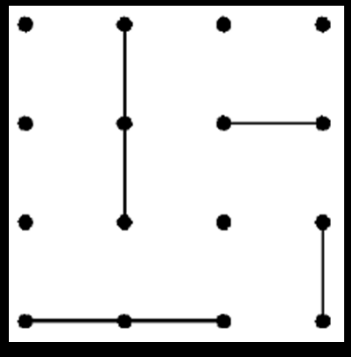
$d_{x^2-y^2}$



d_{xy}



$d_{x^2-y^2} + i d_{xy}$



incommensurate, T-preserving $d_{x^2-y^2}$

Nayak, PRB 62, 4880 (2000)

Some broken symmetry states in the pseudo-gap (for which there is direct experimental evidence):

Electron Nematic: Uniform (translation symmetry unbroken)
Fluid (metallic or superconducting)
With spontaneously broken point group symmetry
(e.g. electronic orthorhombicity)

Electron smectic: Unidirectional metallic (or superconducting) charge density wave

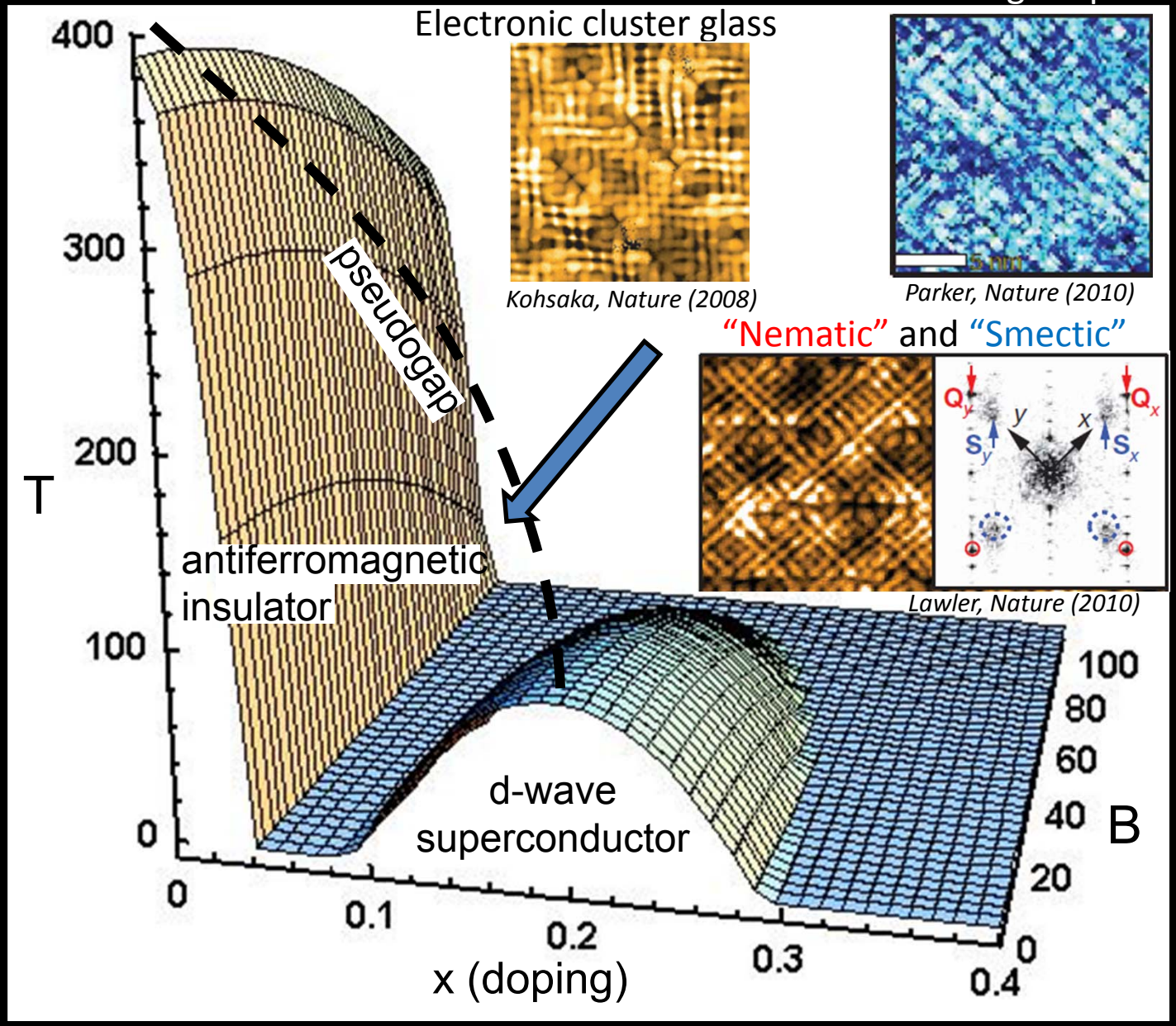
Stripe phase: Unidirectional colinear spin density wave with coexisting CDW with ½ the wavelength
(Both insulating and conducting versions)
In the presence of weak disorder, this becomes a "cluster spin-glass" with only short-range stripe order.

Intra-unit cell antiferromagnet: Breaks time-reversal and some point-group symmetries (Chandra's-loops)

d-density wave: Breaks time reversal and translational symmetry, but preserves the product.

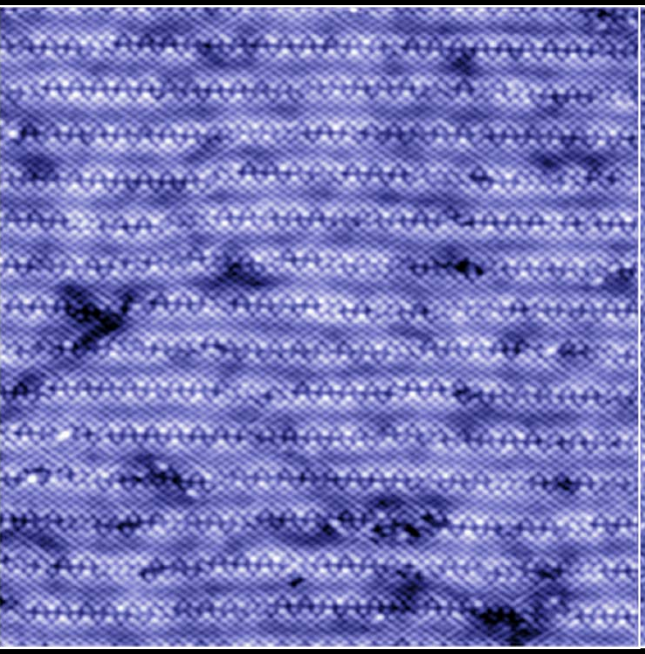
slide stolen from Steve Kivelson!

Lots of candidates for pseudogap from STM

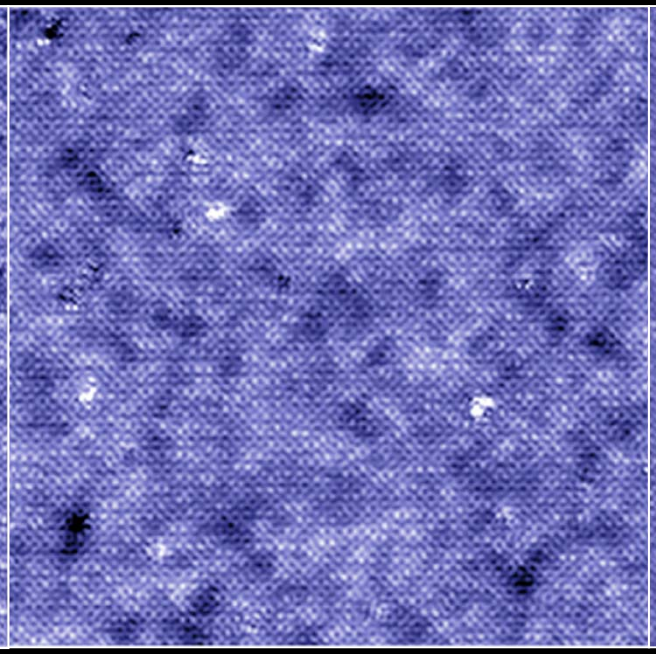


? Structural ←→Electronic ?

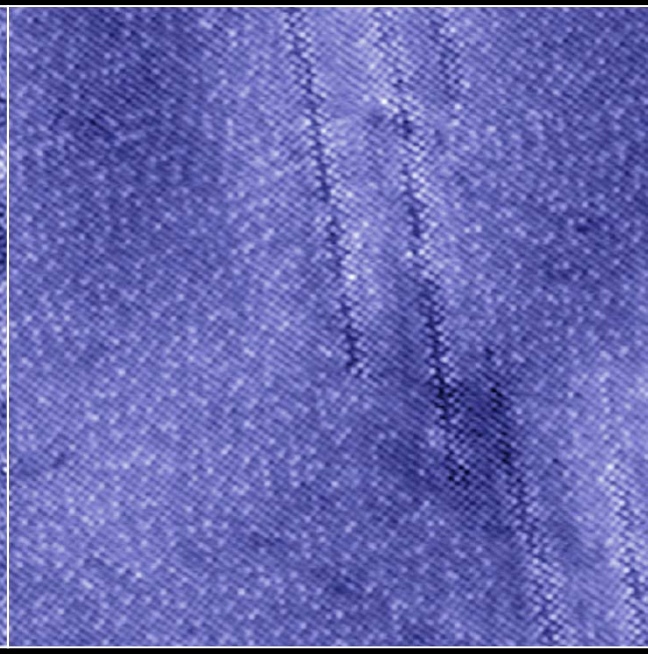
Bi-2212



Bi-2201, Pb-doped

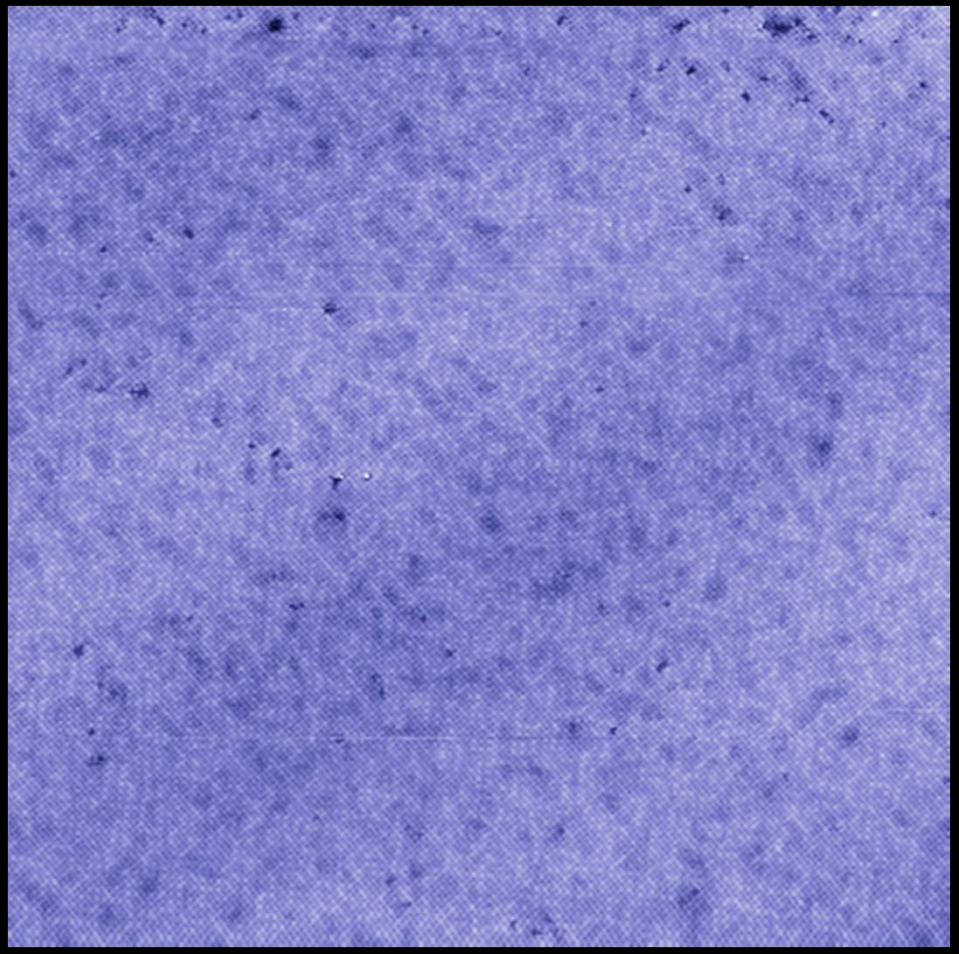


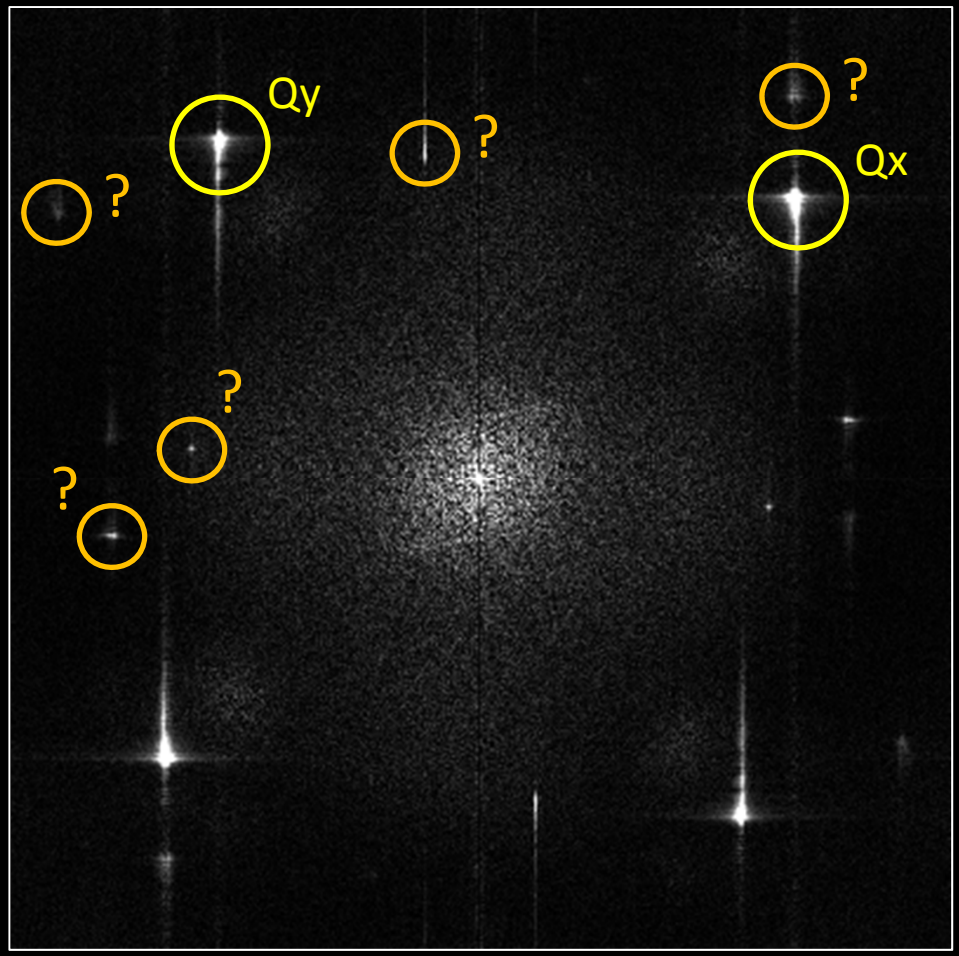
another Bi-2201, Pb-doped



Raw data

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



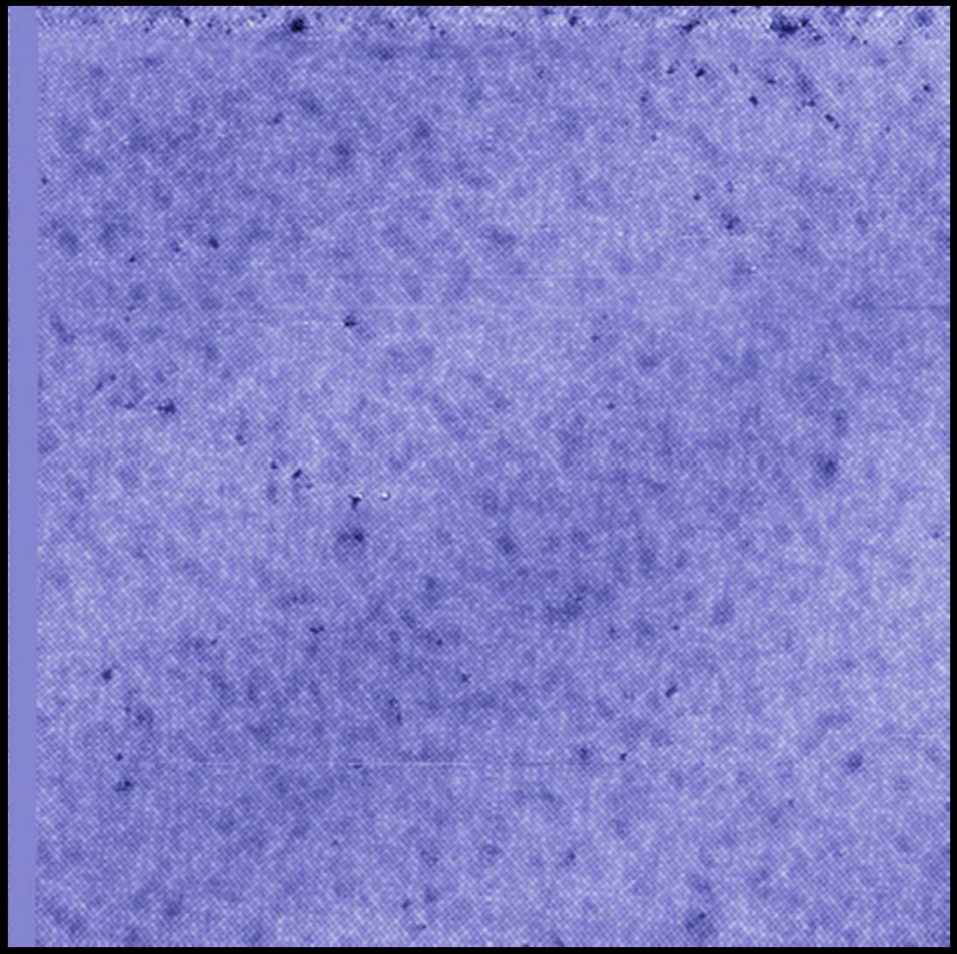


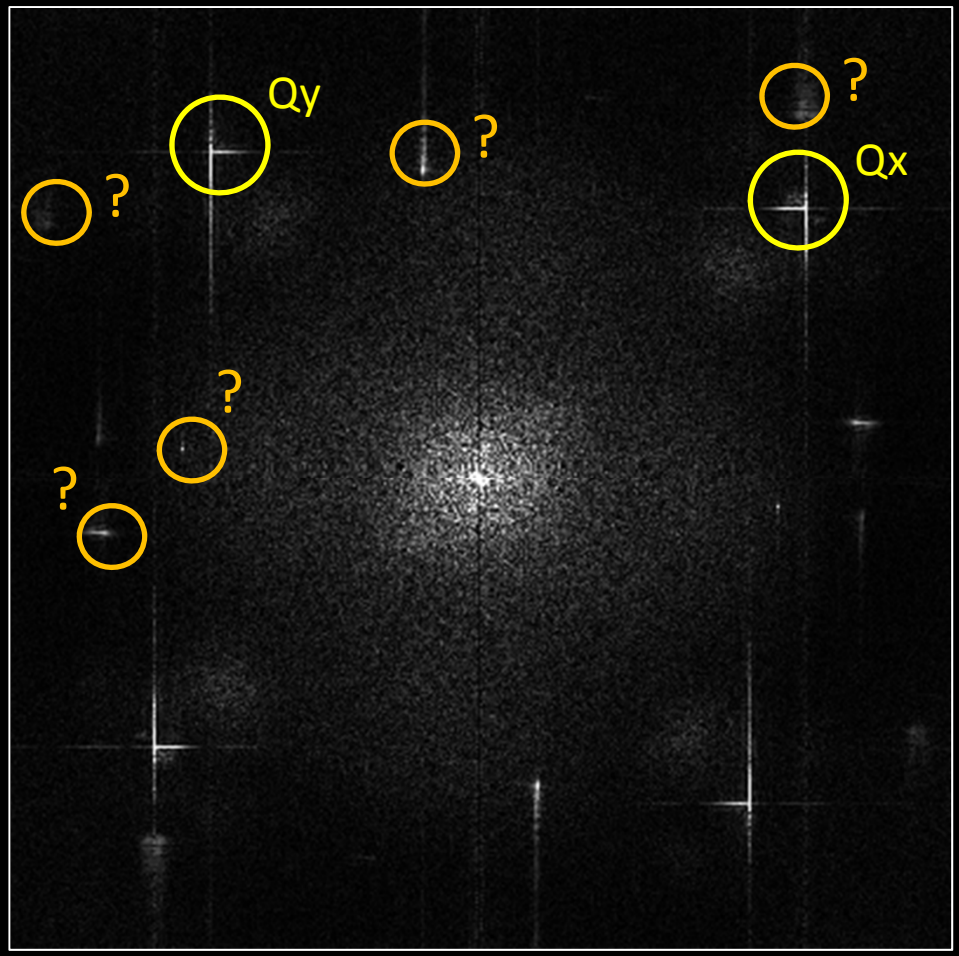
66x66 nm^2

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

Drift-corrected data

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



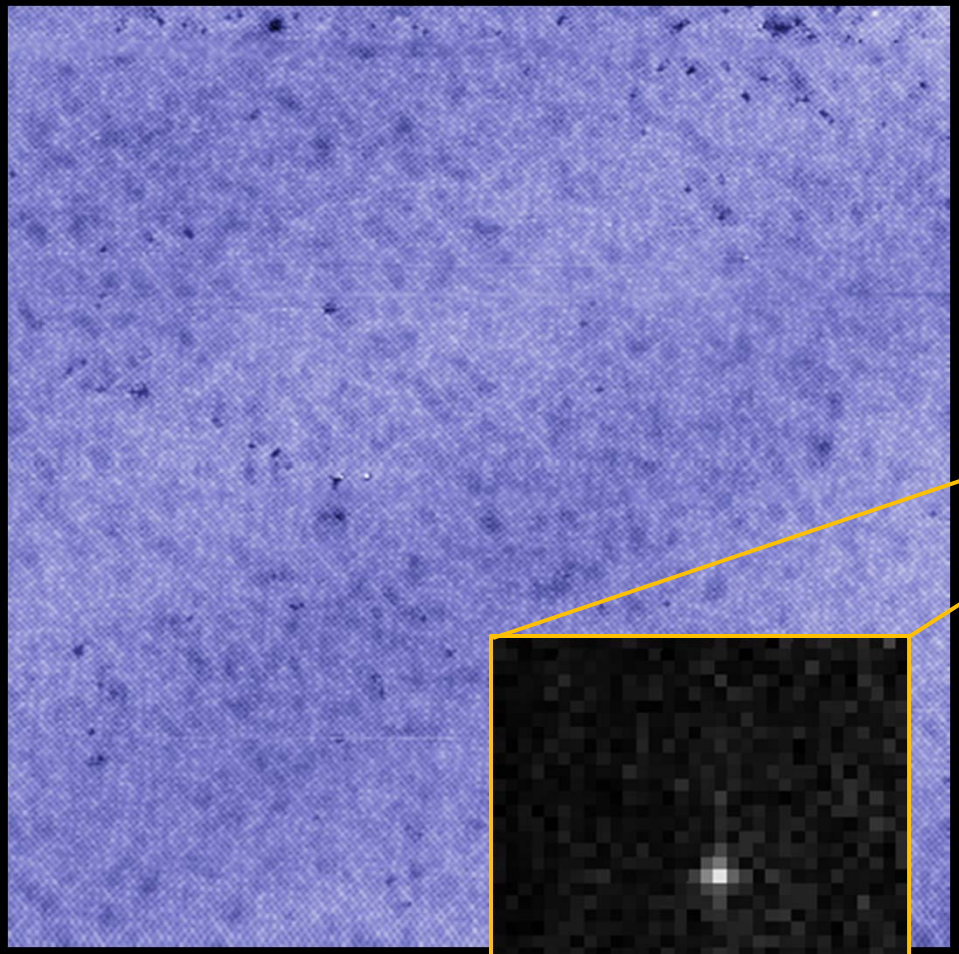


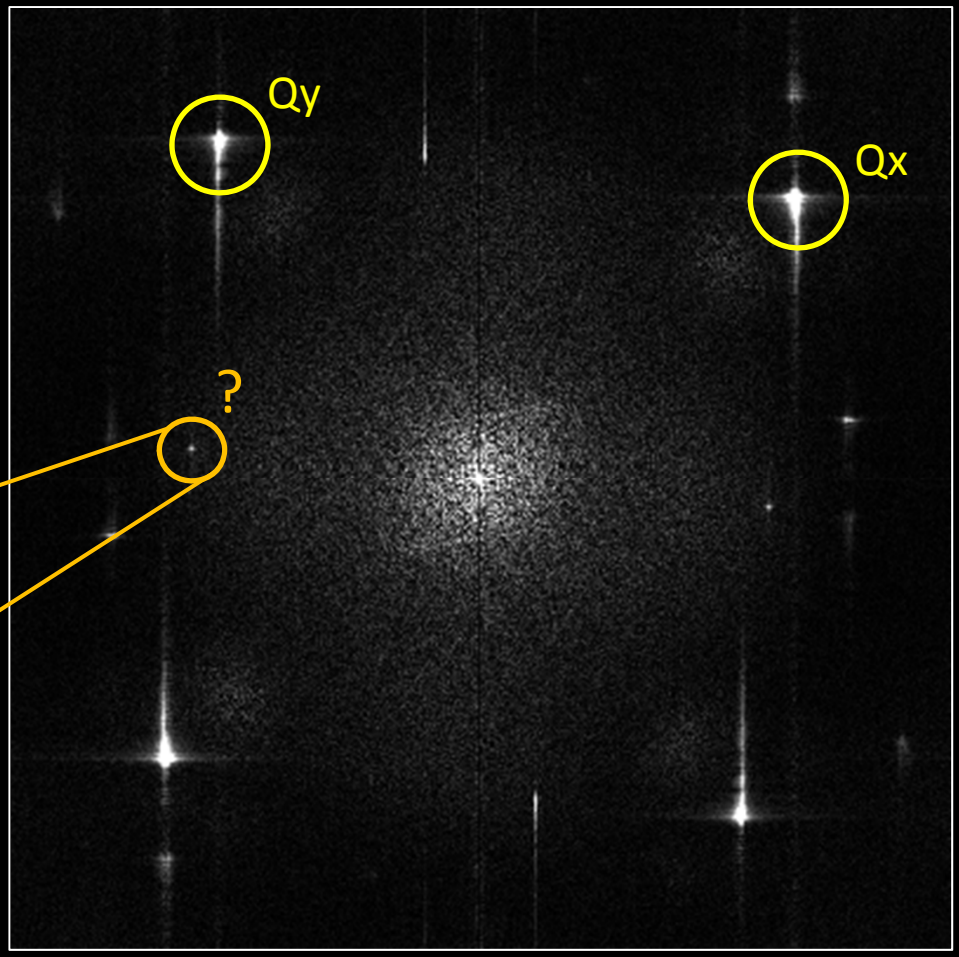
Bragg peaks sharpen up → they are true structure

Most other peaks broaden out → they are noise

Raw data

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

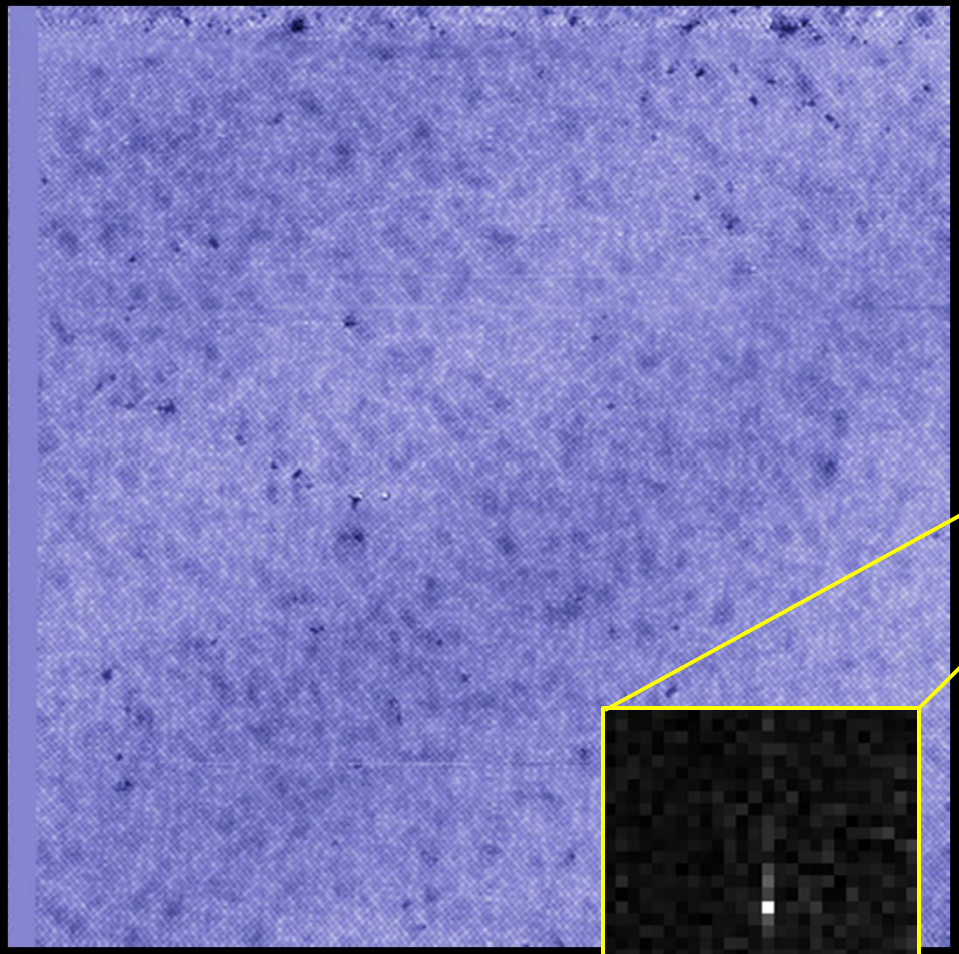


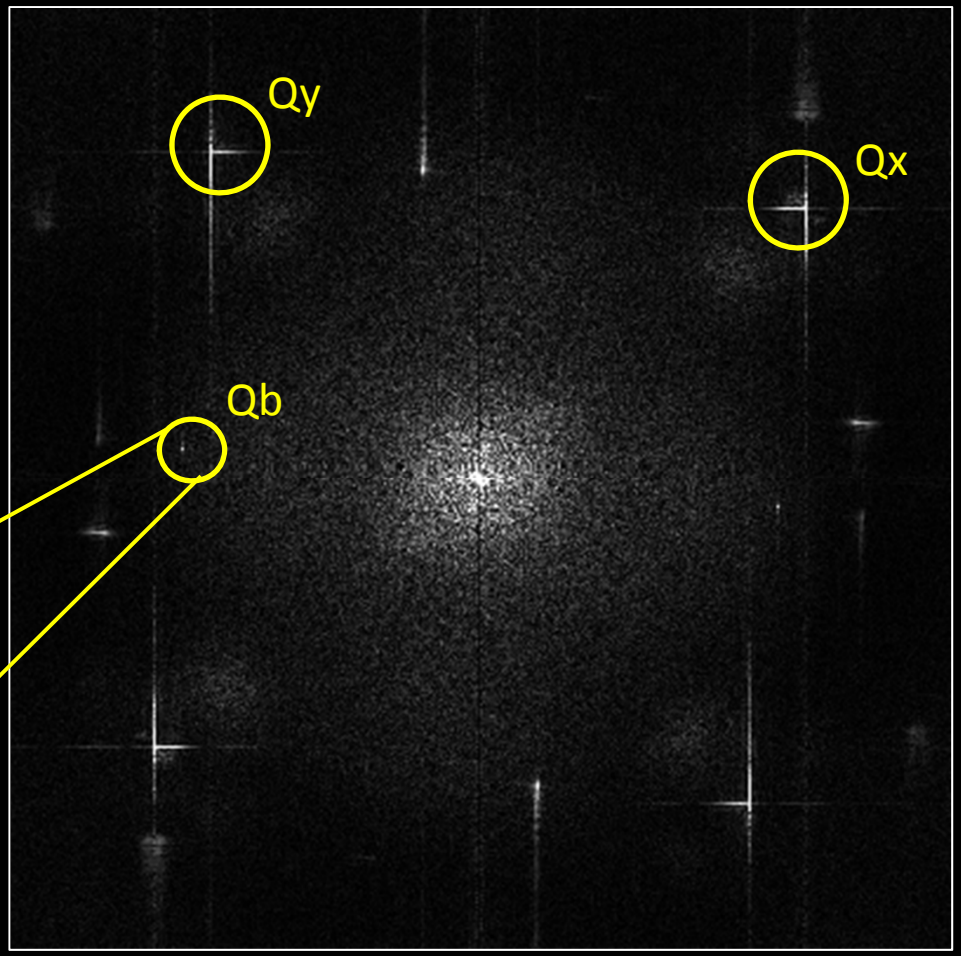


center pix only 20% brighter than nearest neighbors

Drift-corrected data

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

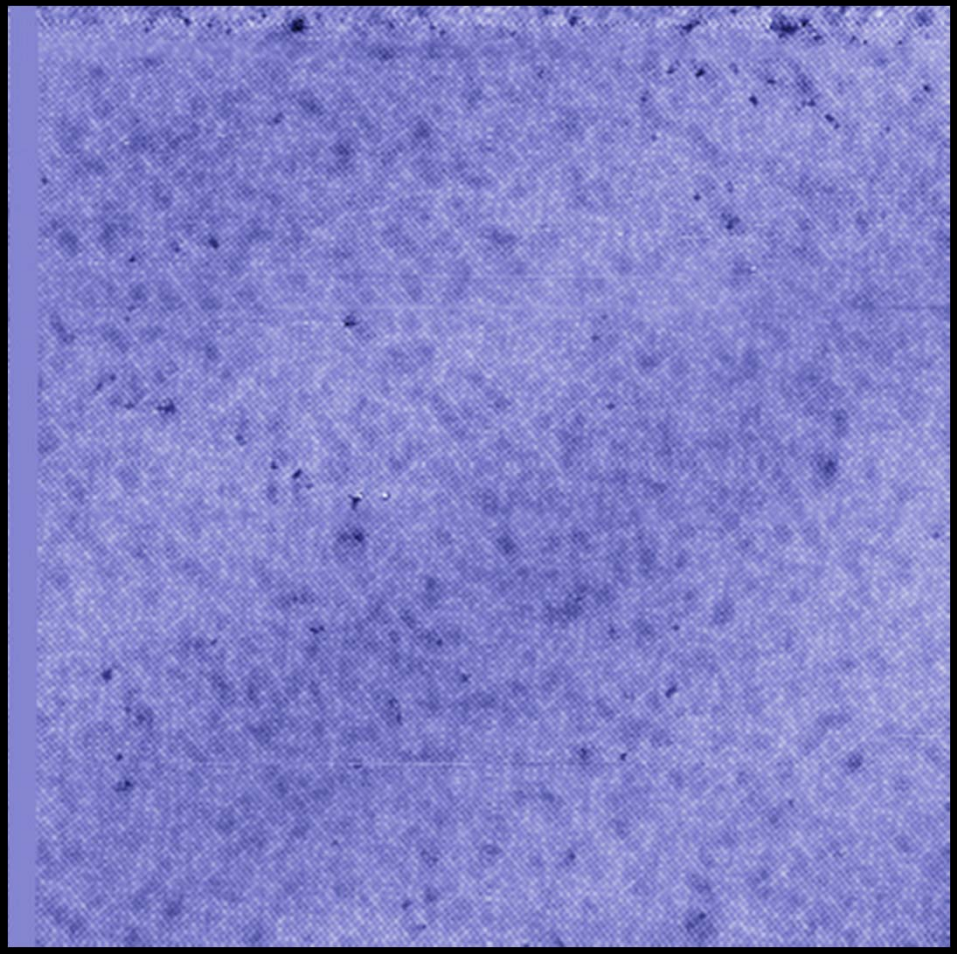


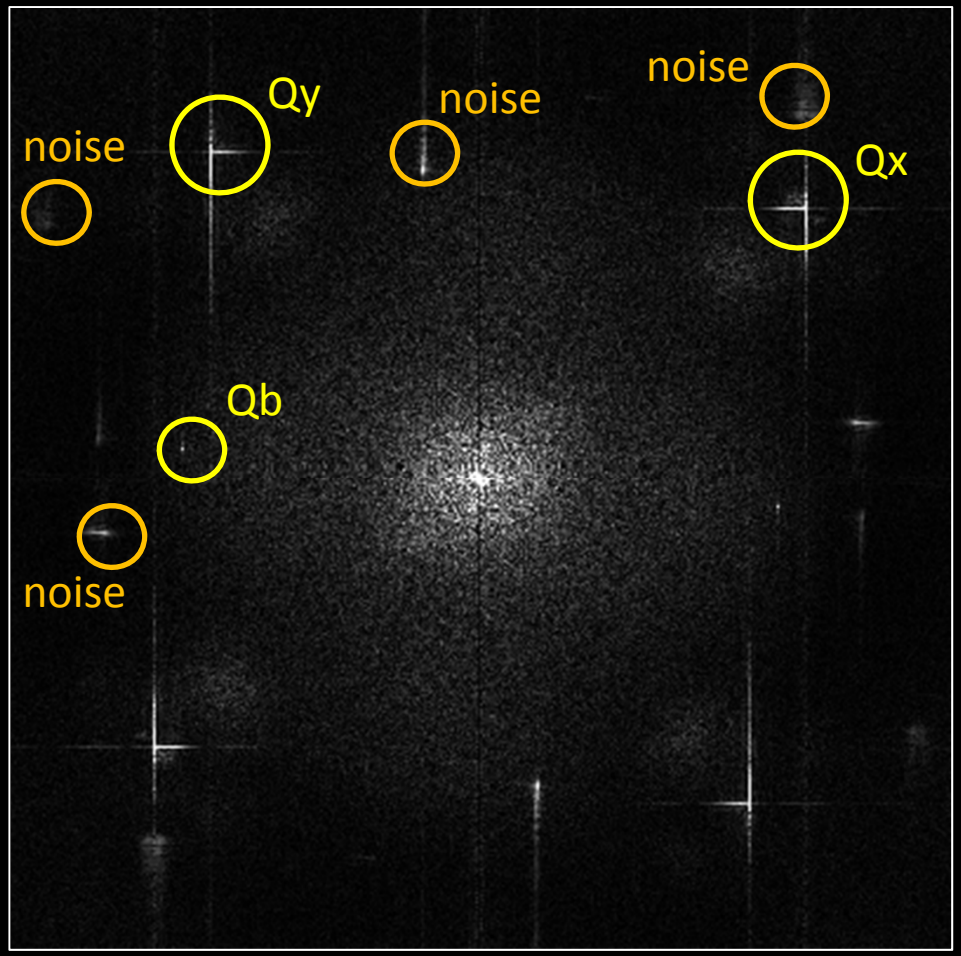


center pix > 5x brighter than nearest neighbors

Drift-corrected data

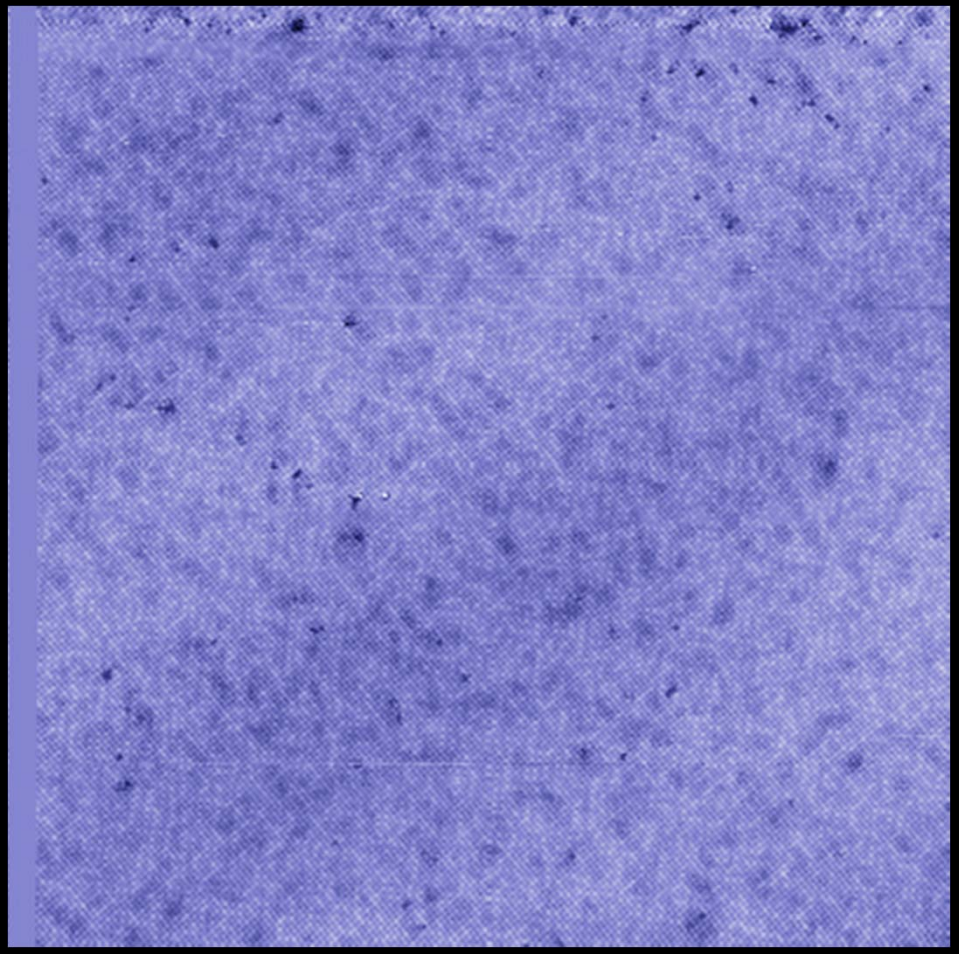
(Bi-2201, Tc=32K, slightly underdoped)

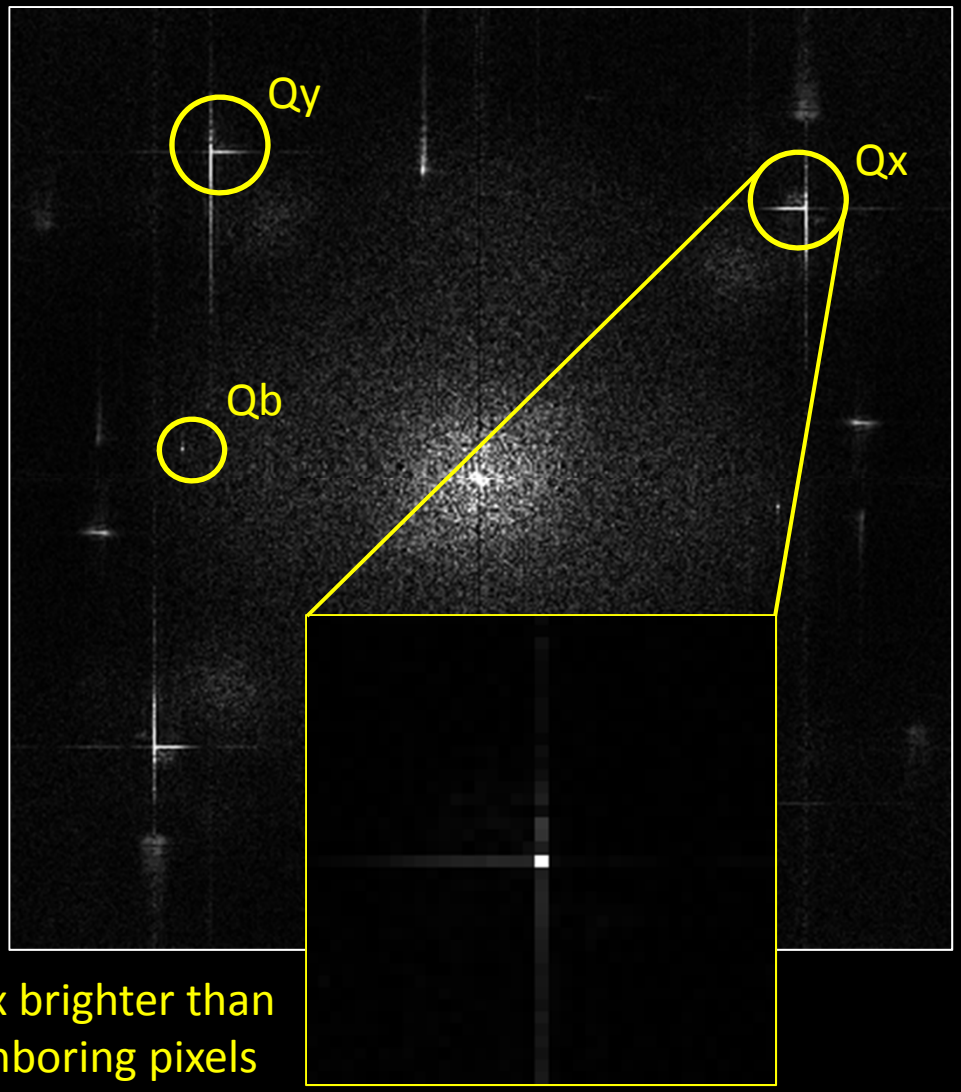




Drift-corrected data

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





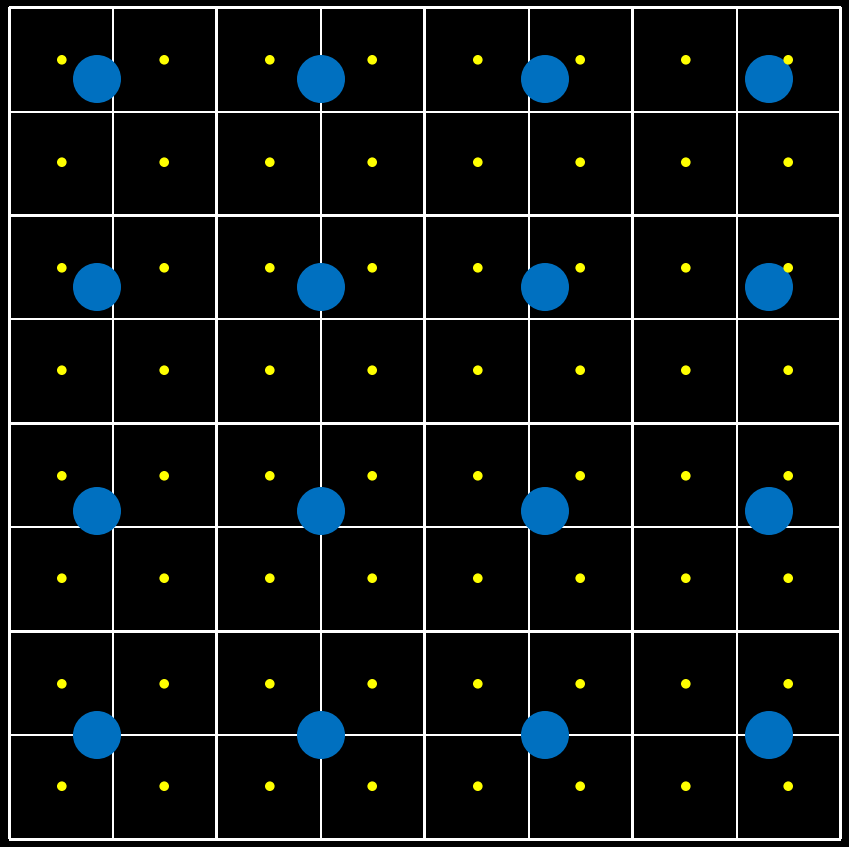
> 10x brighter than neighboring pixels

Make Average Unit Cell

— Pixel grid

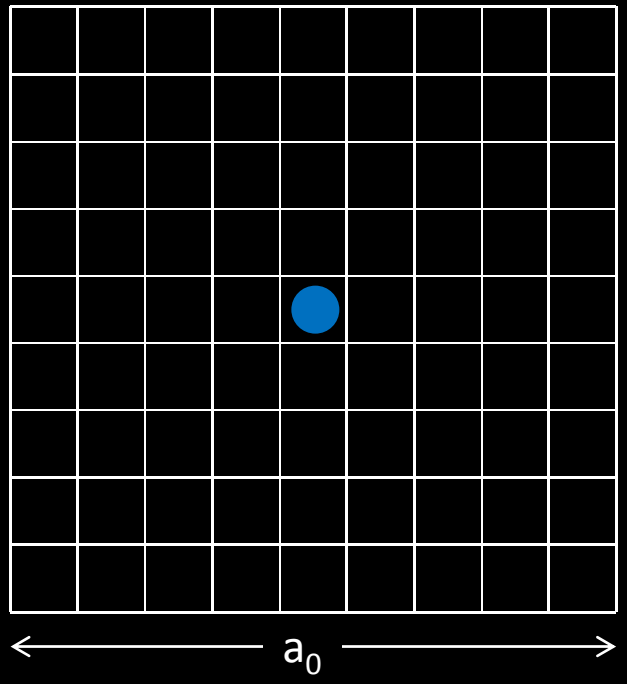
• exact tip location when data acquired

● Bi atom



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

Center Bi in center of this unit cell.



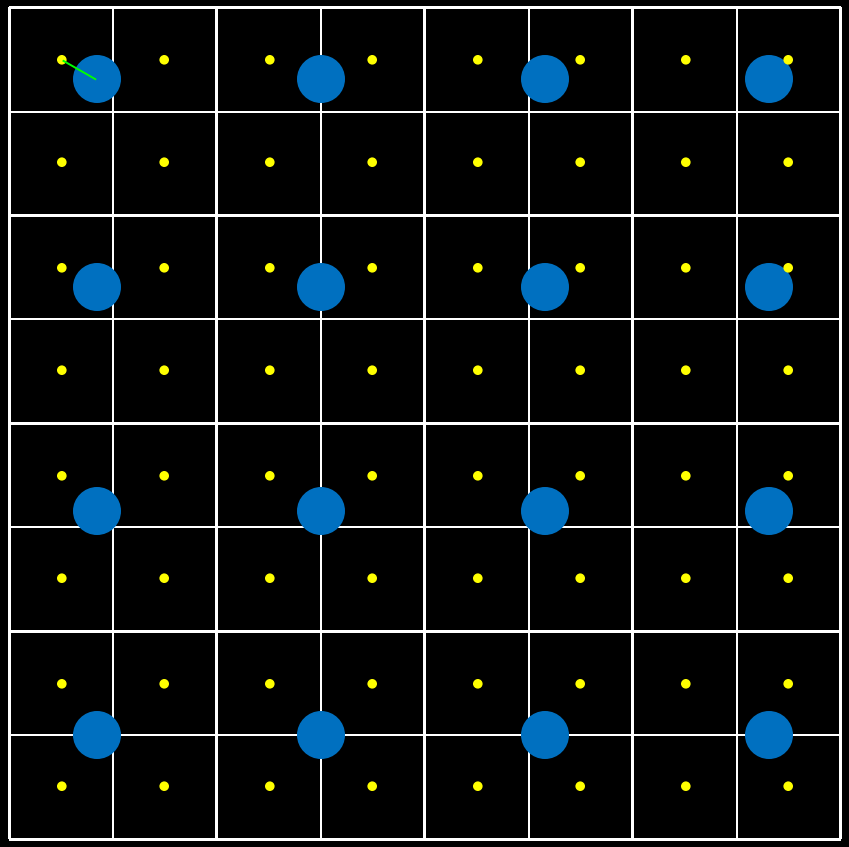
Note: data acquisition only slightly better than Nyquist frequency for atoms!

Make Average Unit Cell

— Pixel grid

• exact tip location when data acquired

● Bi atom



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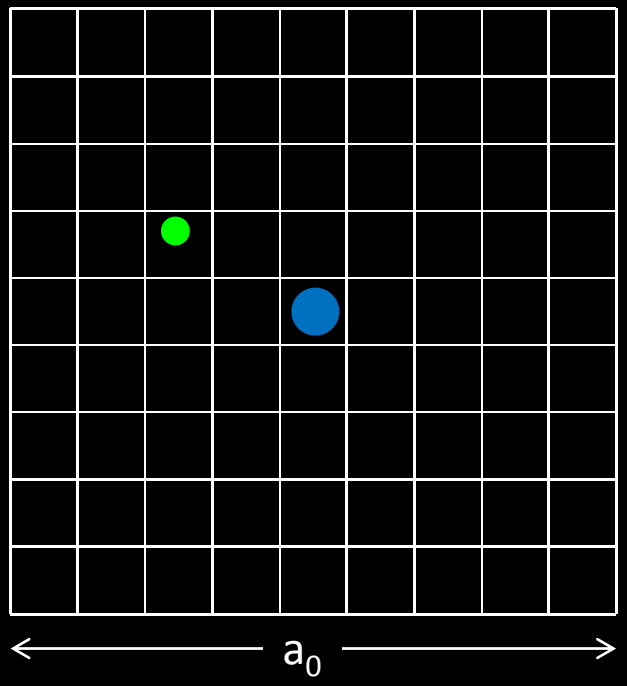
but with more pixels than we have in raw data.

Center Bi in center of this unit cell.

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



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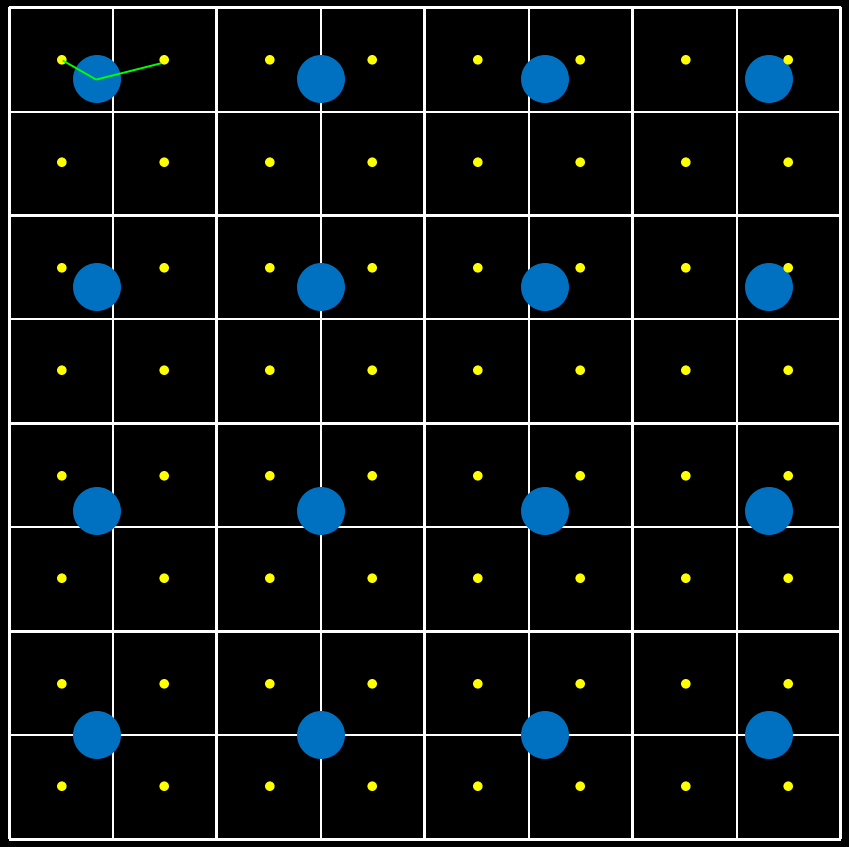
Make Average Unit Cell

Pixel grid

exact tip location when data acquired

Bi atom



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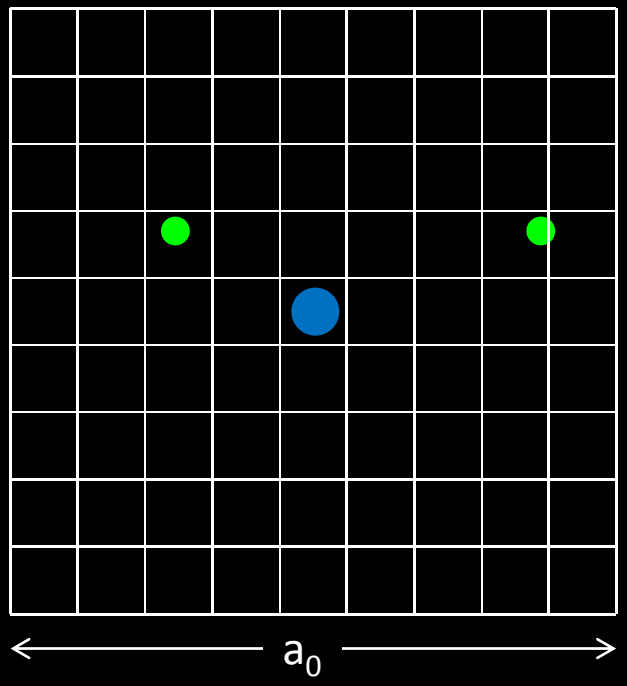

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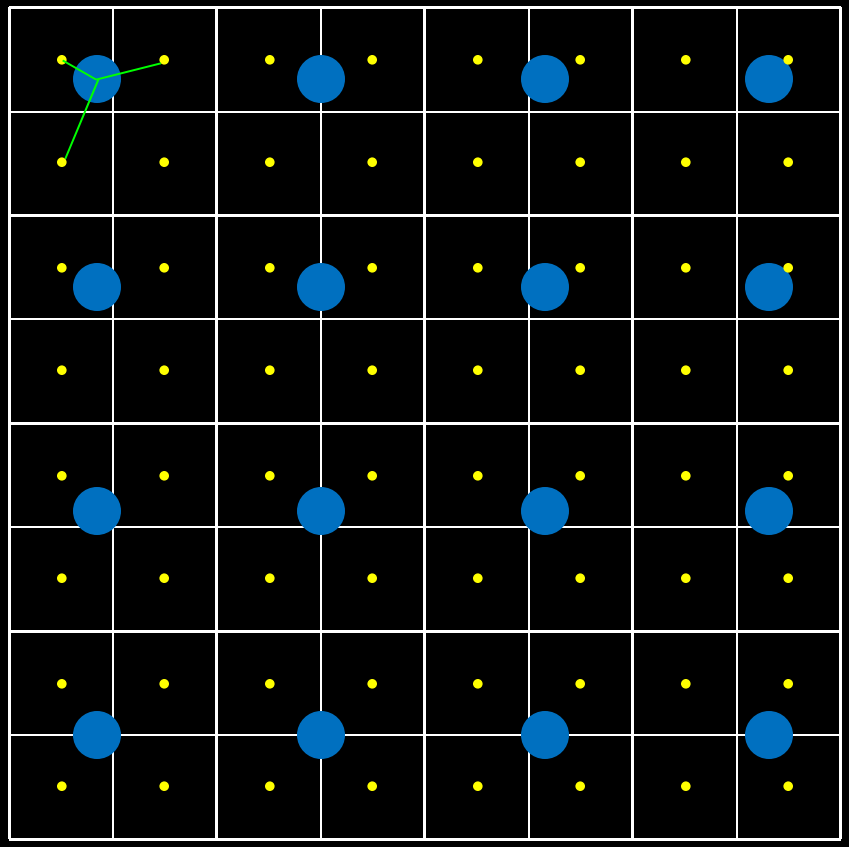
Make Average Unit Cell

— Pixel grid

• exact tip location when data acquired

● Bi atom



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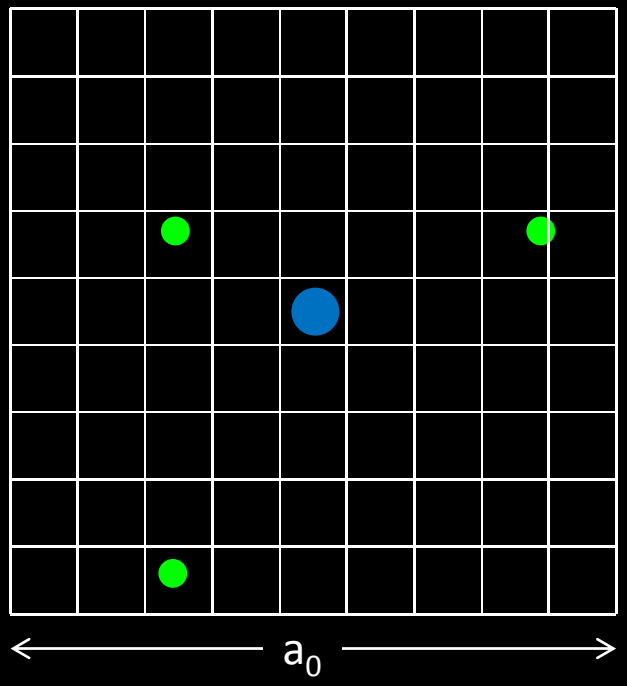

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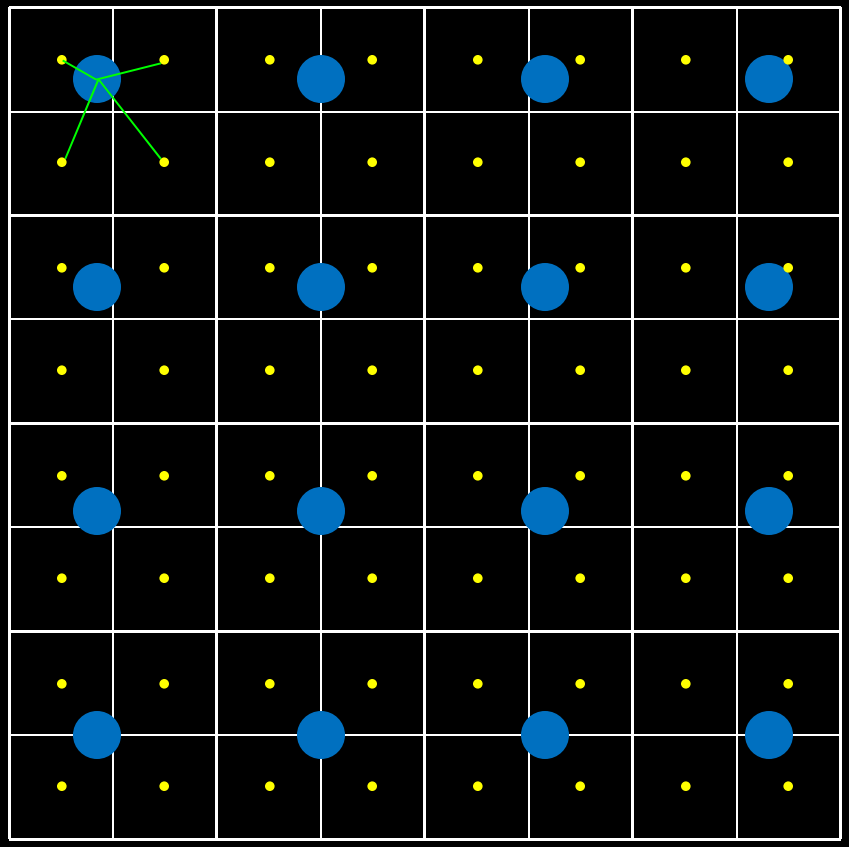
Make Average Unit Cell

Pixel grid

exact tip location when data acquired

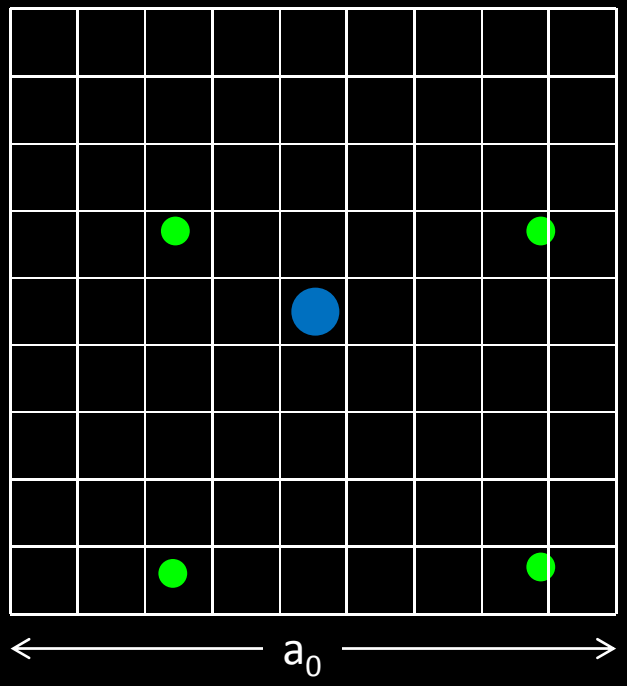
Bi atom



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

Center Bi in center of this unit cell.

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

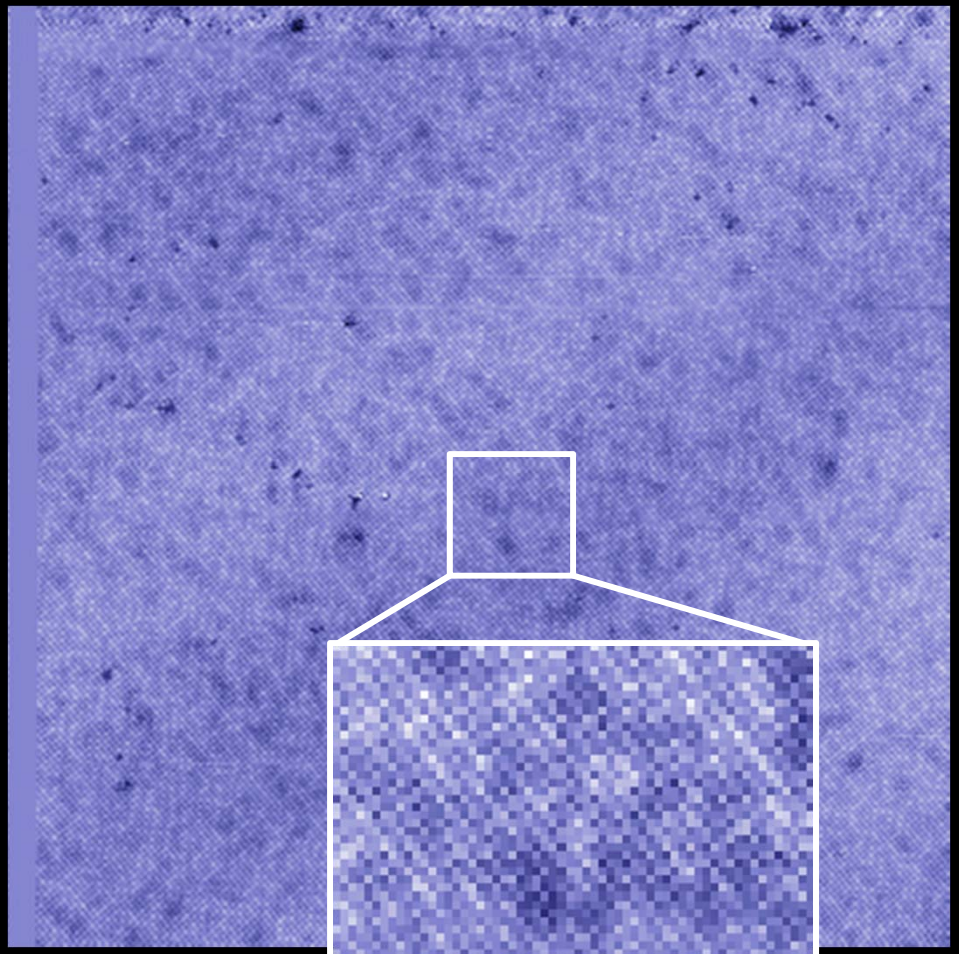


Note: data acquisition only slightly better than Nyquist frequency for atoms!

Perfect registry allows sub-unit-cell resolution!

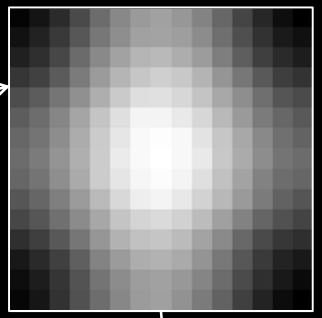
Make Average Unit Cell

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

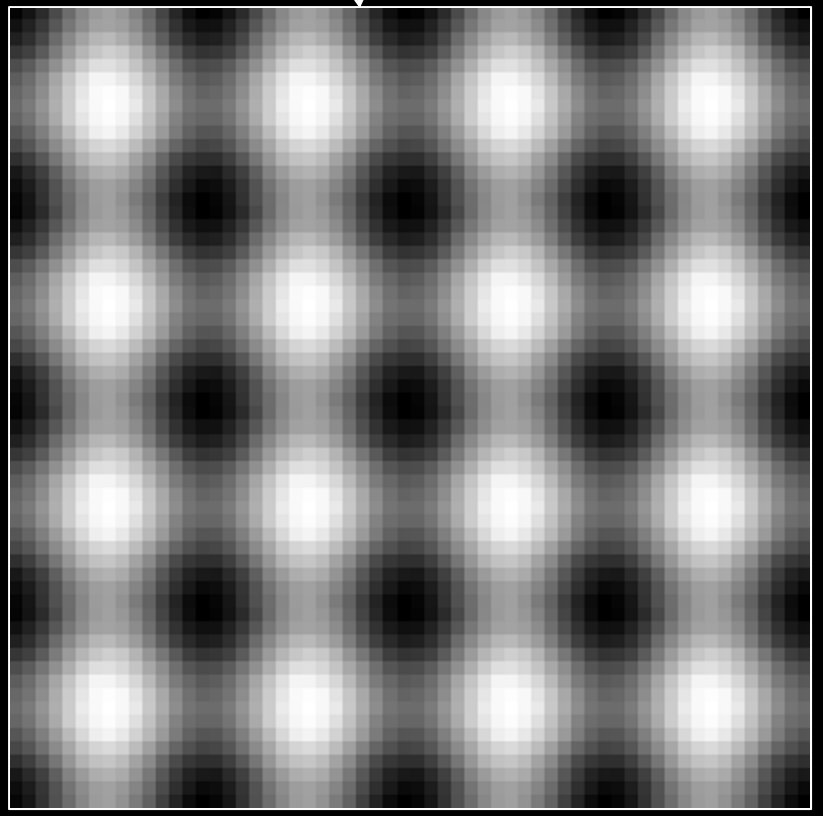


66x66 nm^2

make average unit cell

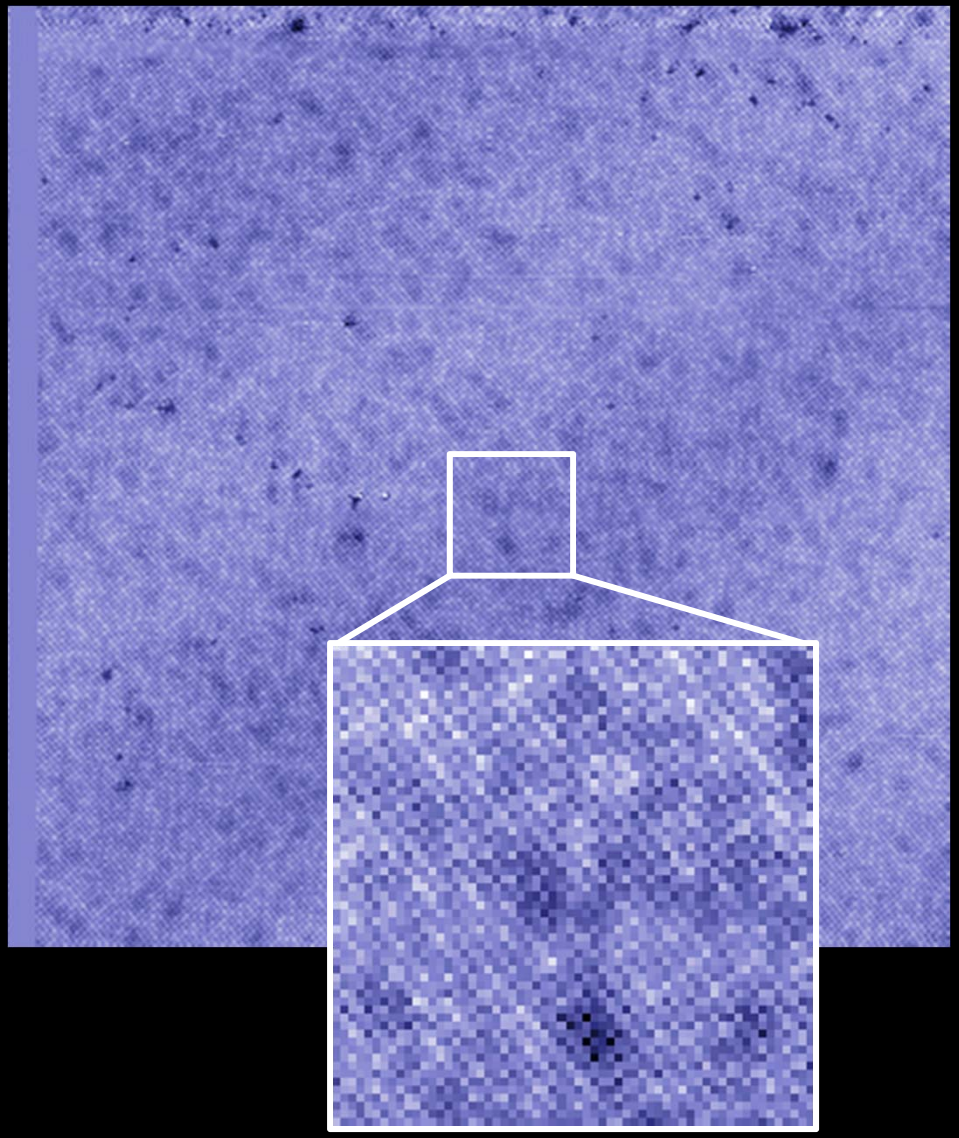


tile 4x4

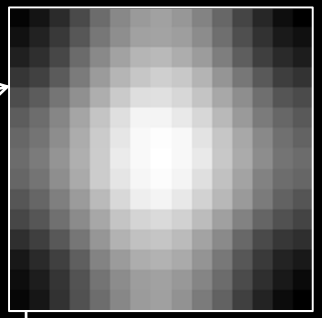


Make Average Unit Cell

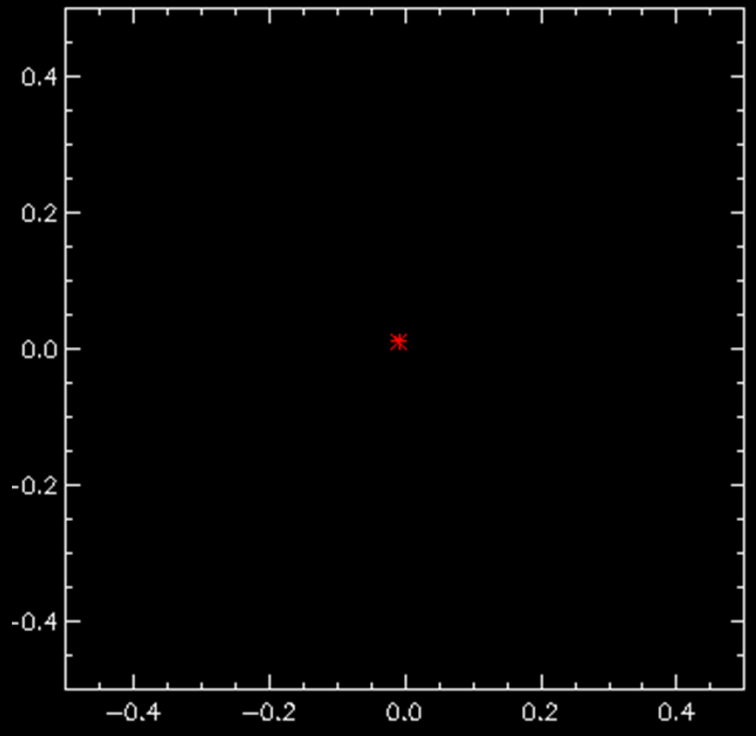
(Bi-2201, Tc=32K, slightly underdoped)



make average unit cell

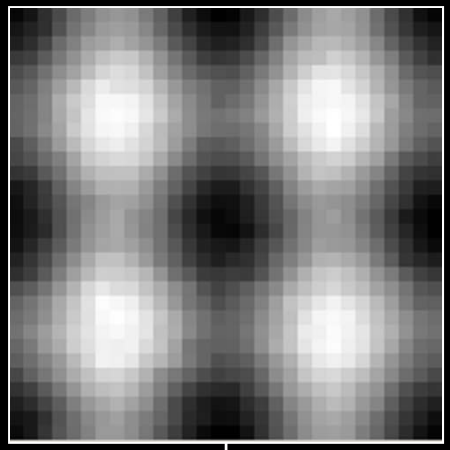


fit to make sure Bi is at center, where we think it should be

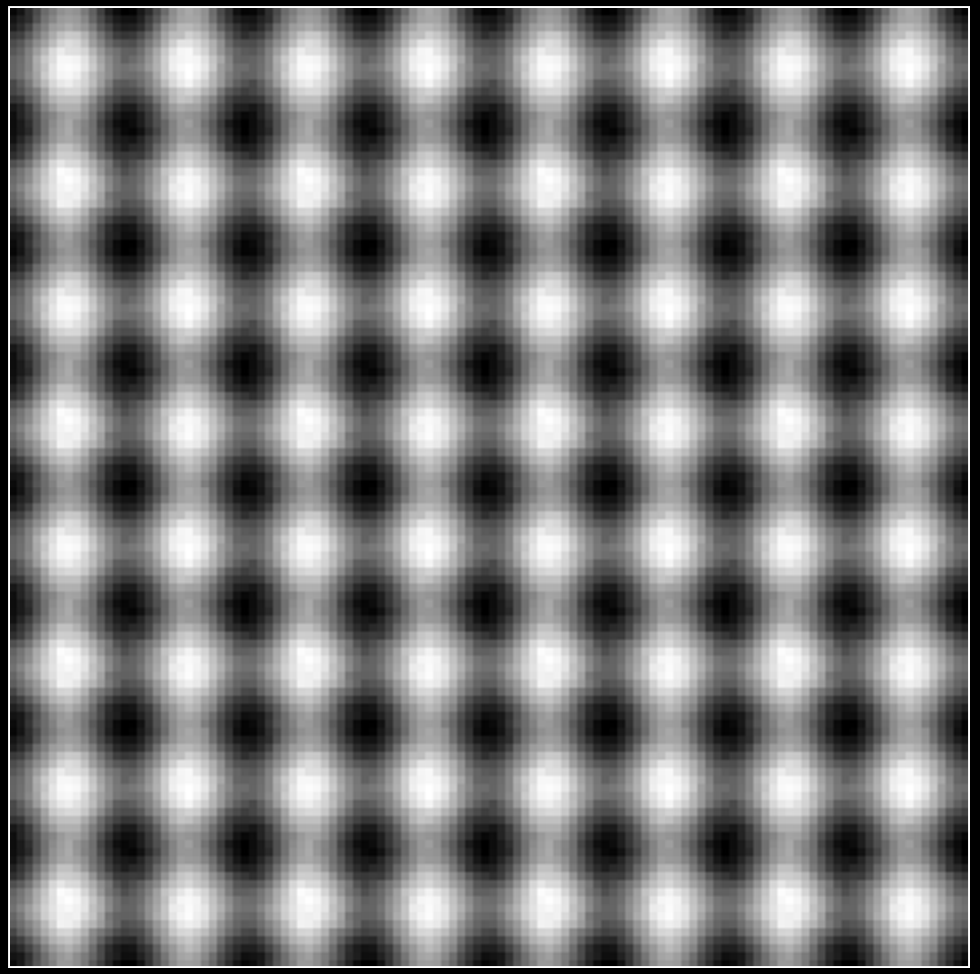


Make Average Supercell: 2x2

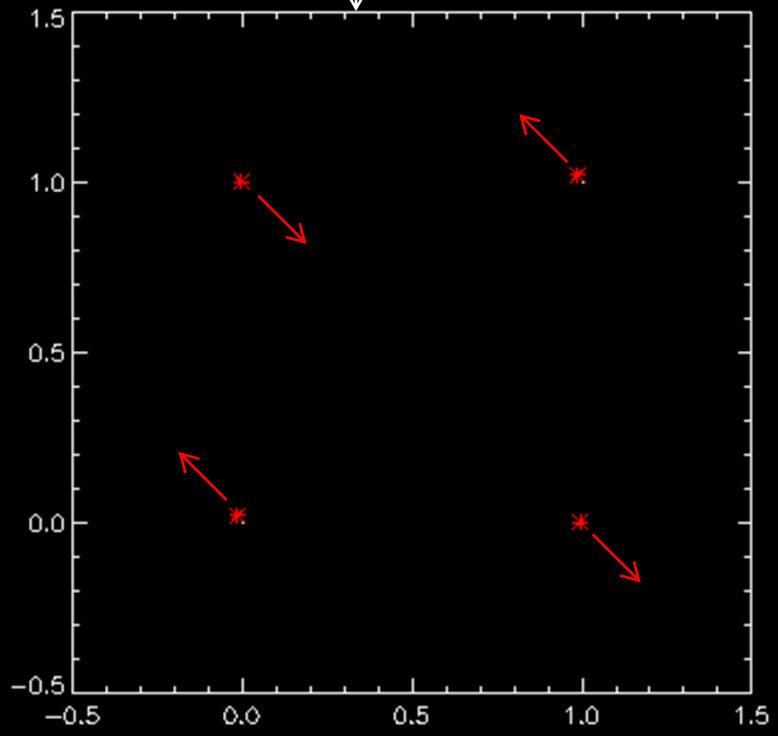
(Bi-2201, Tc=32K, slightly underdoped)



tiled



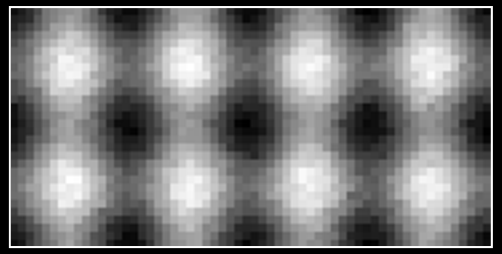
fit



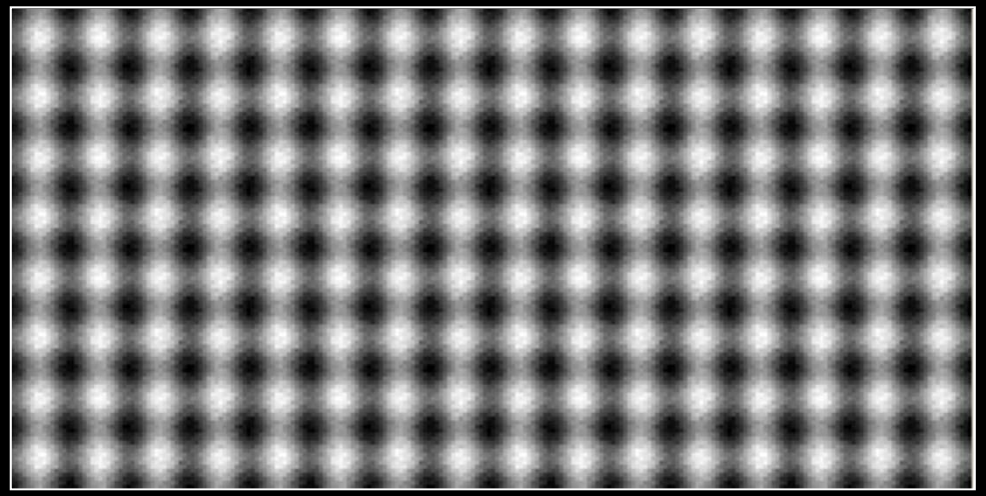
shift by ~1% of unit cell

Make Average Supercell: 4x2

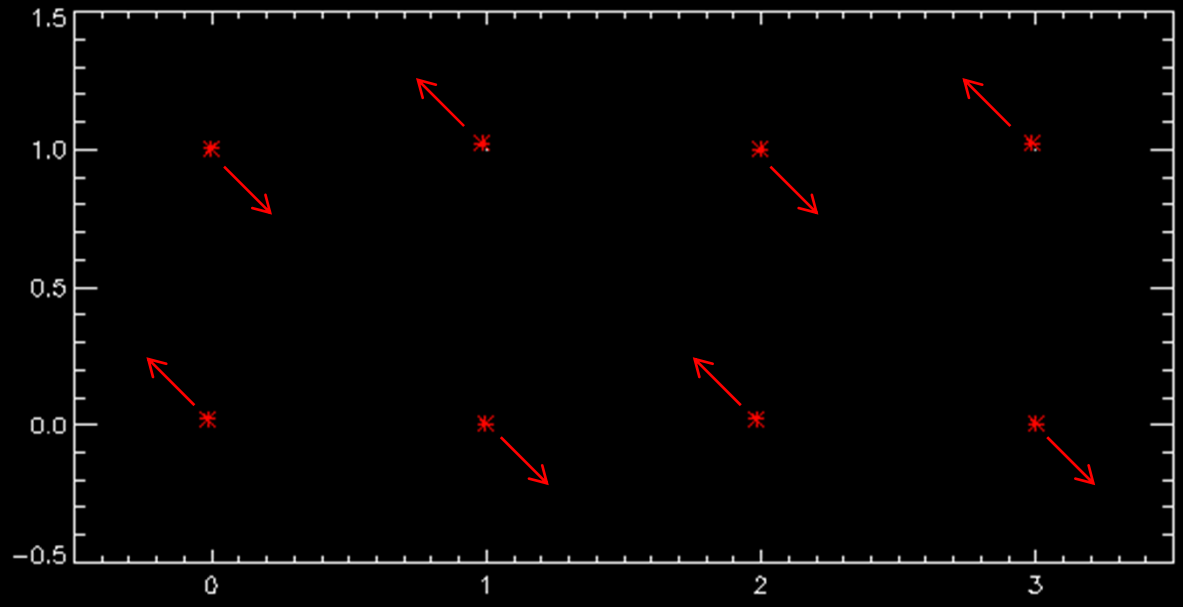
(Bi-2201, Tc=32K, slightly underdoped)



tiled

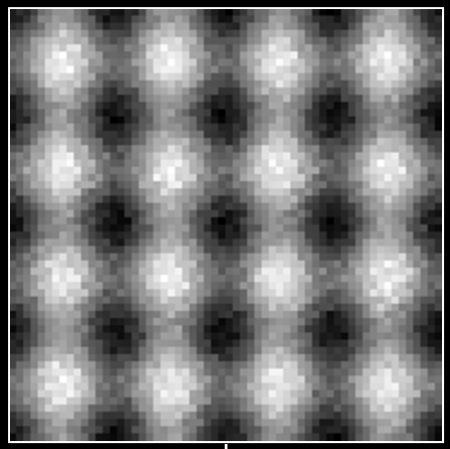


fit

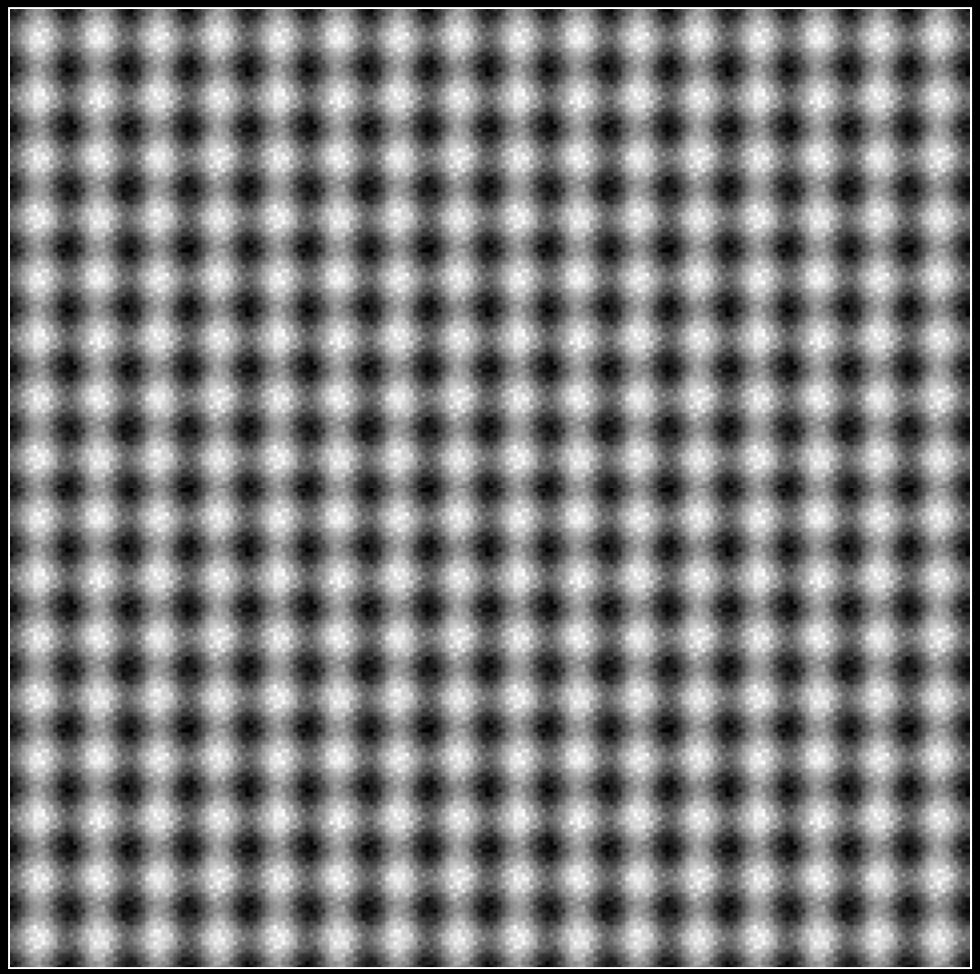


Make Average Supercell: 4x4

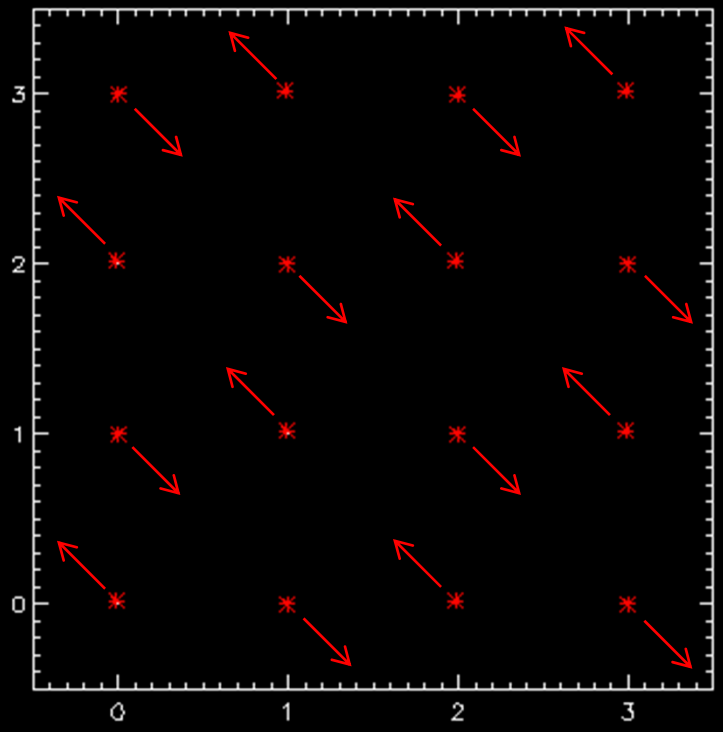
(Bi-2201, Tc=32K, slightly underdoped)



tiled →



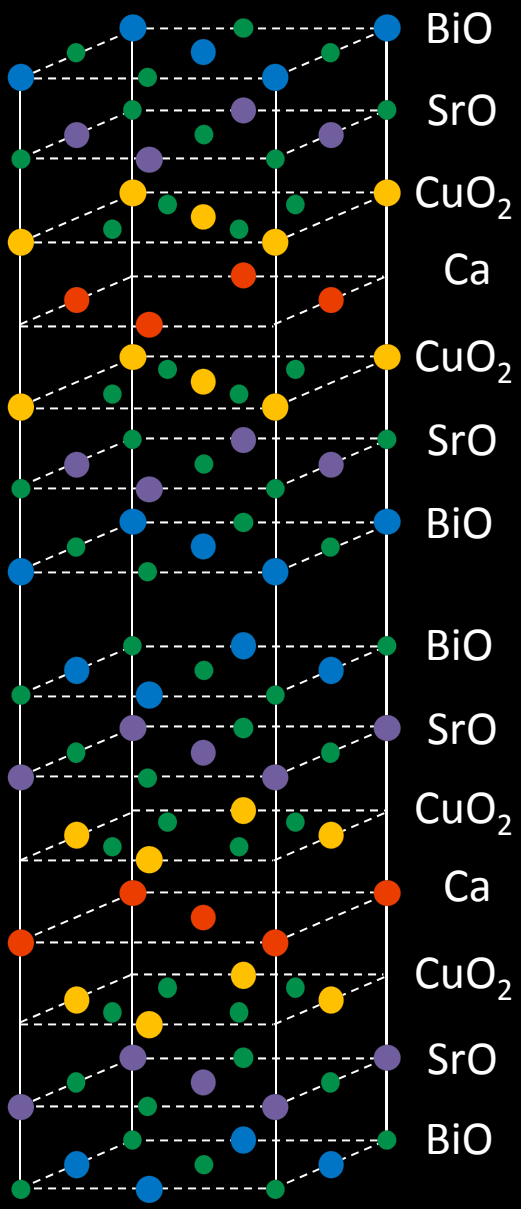
↓ fit

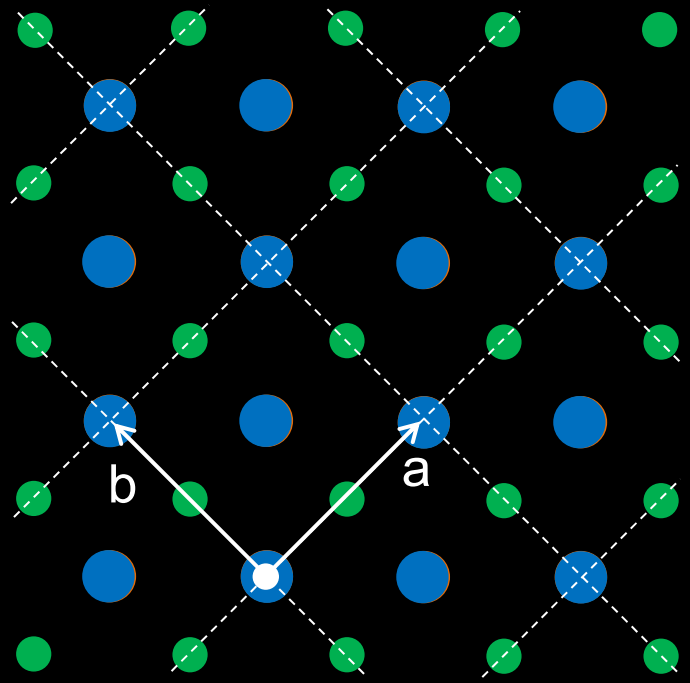


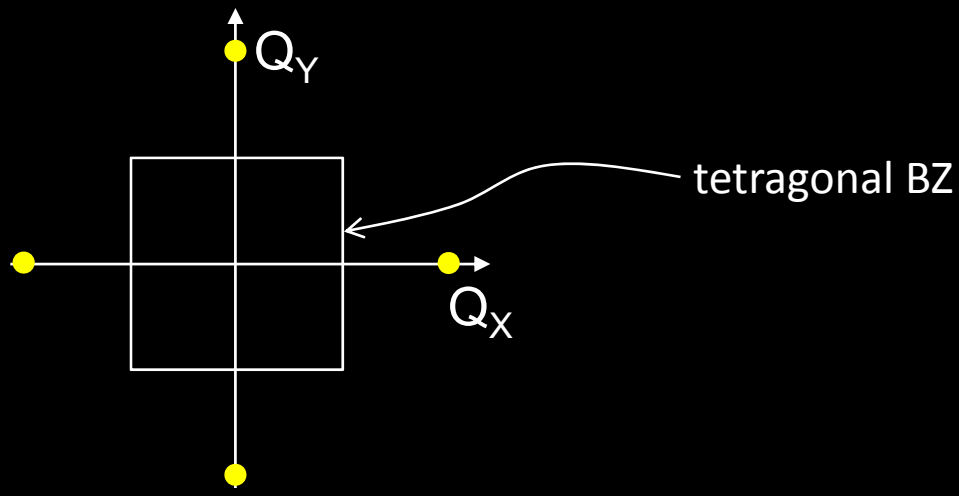
16 inequivalent sites:
average displacement: 1.1%
standard deviation: 0.36%
(error bar ~1/3 of effect → inconsistent with zero)

Crystal Structure

$Bi_2Sr_2CaCu_2O_8$

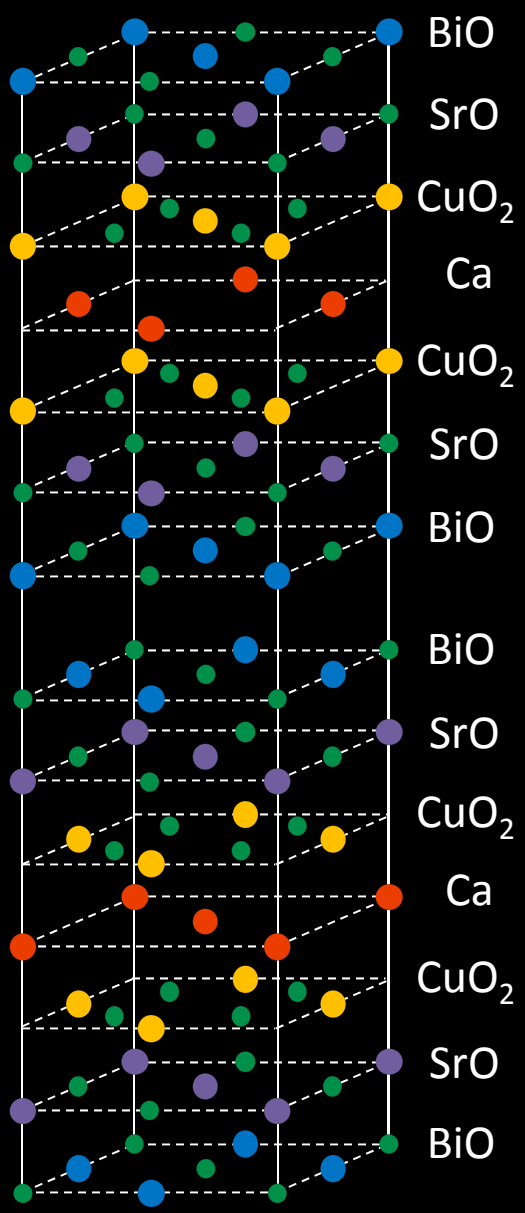


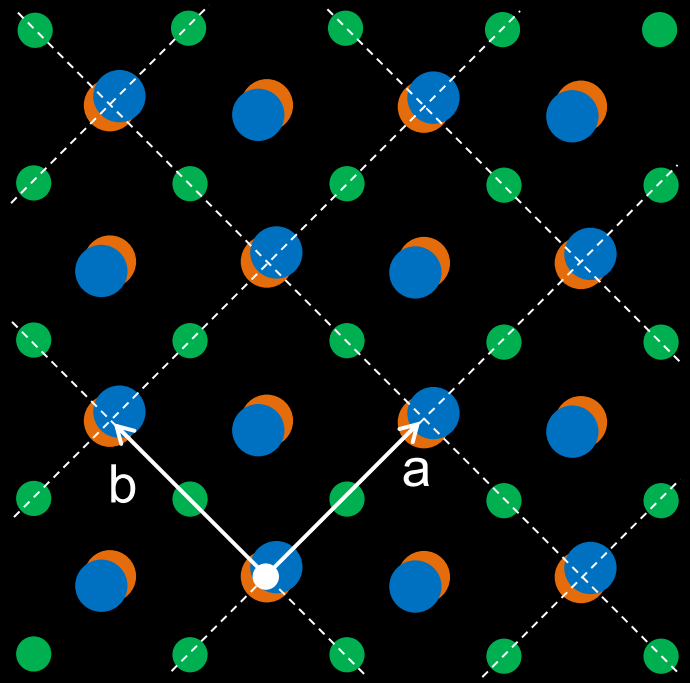


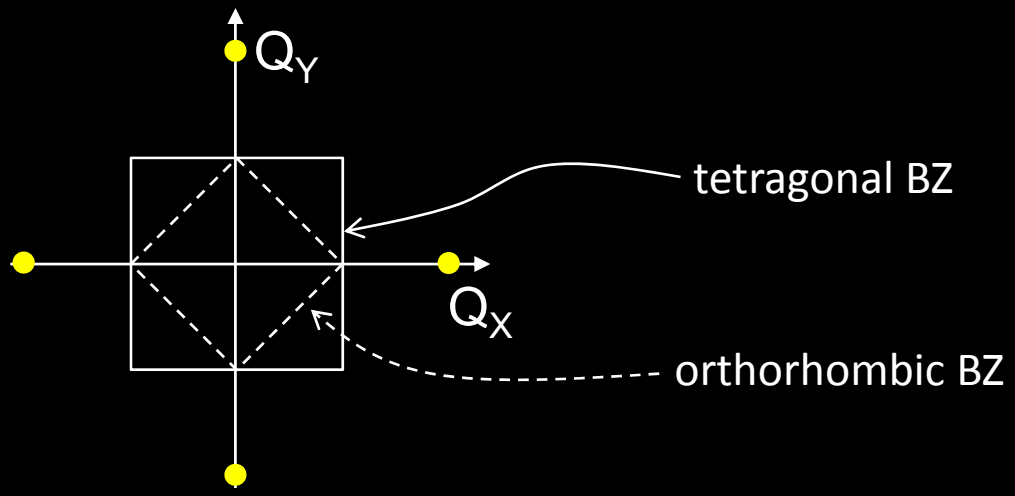


Crystal Structure

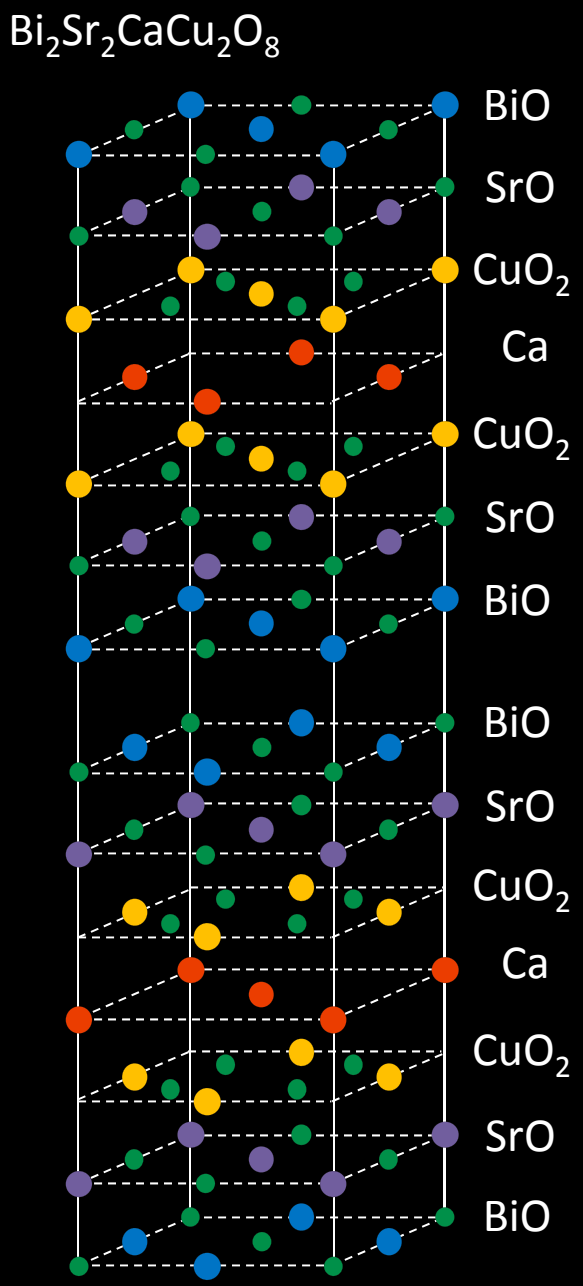
$Bi_2Sr_2CaCu_2O_8$

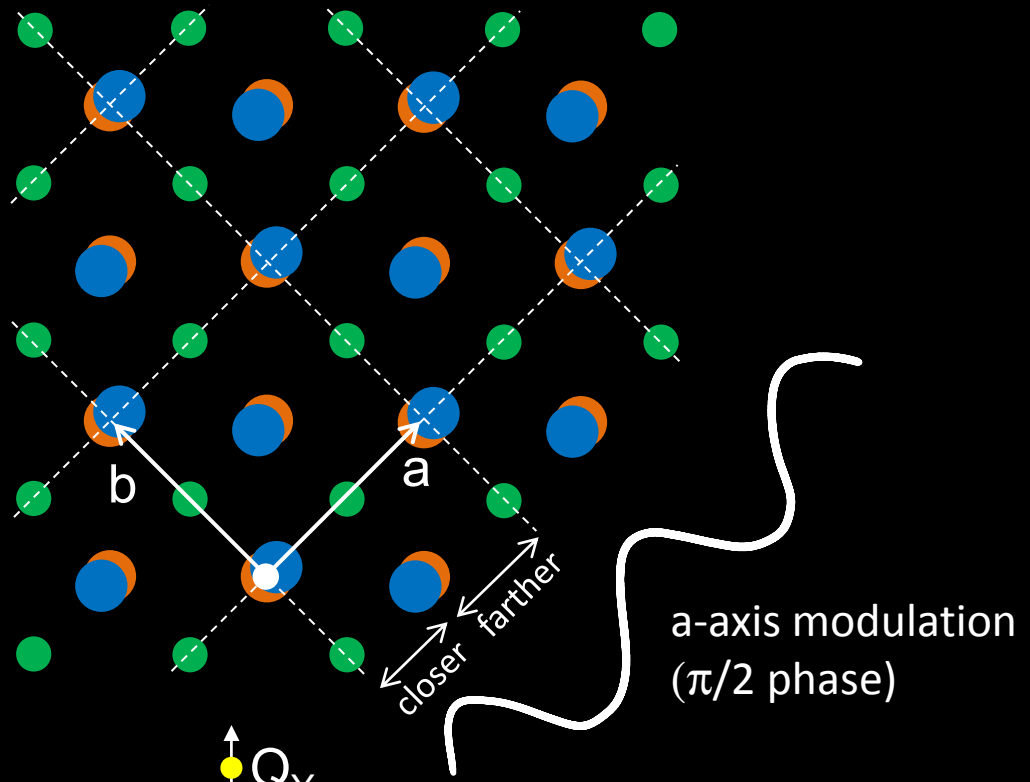


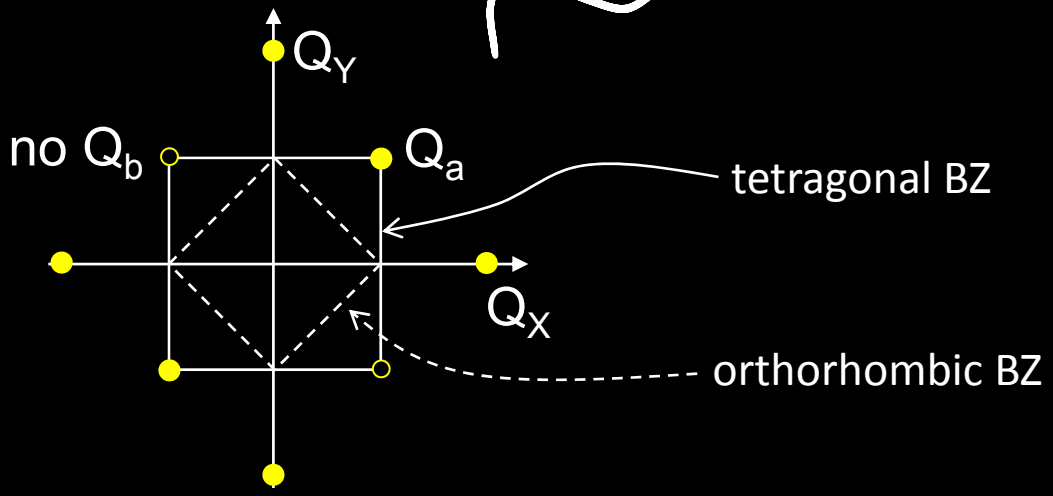




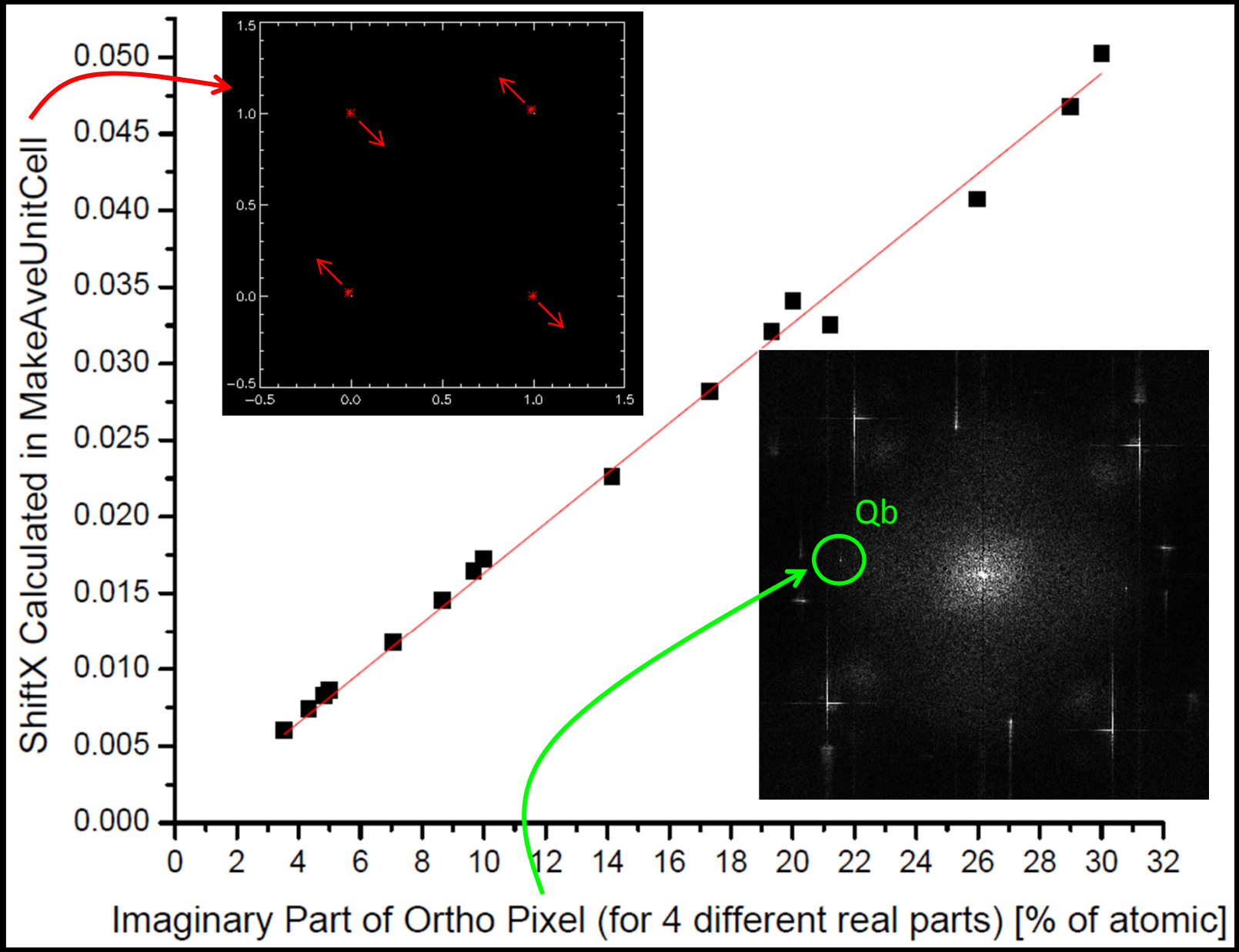
Crystal Structure



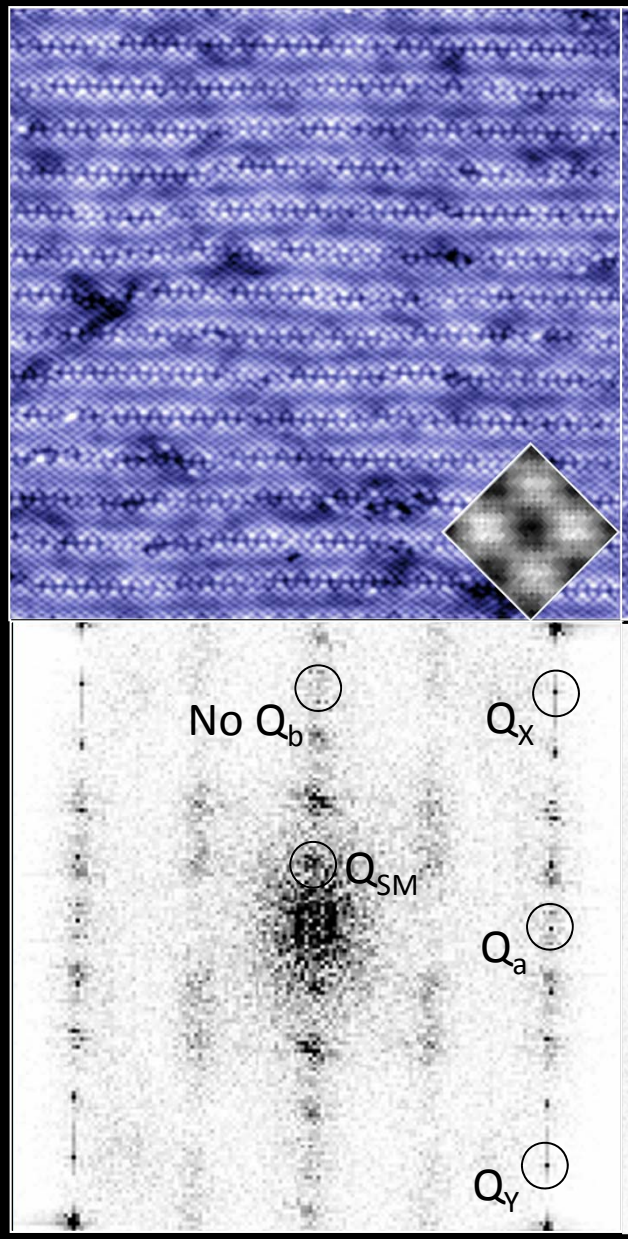


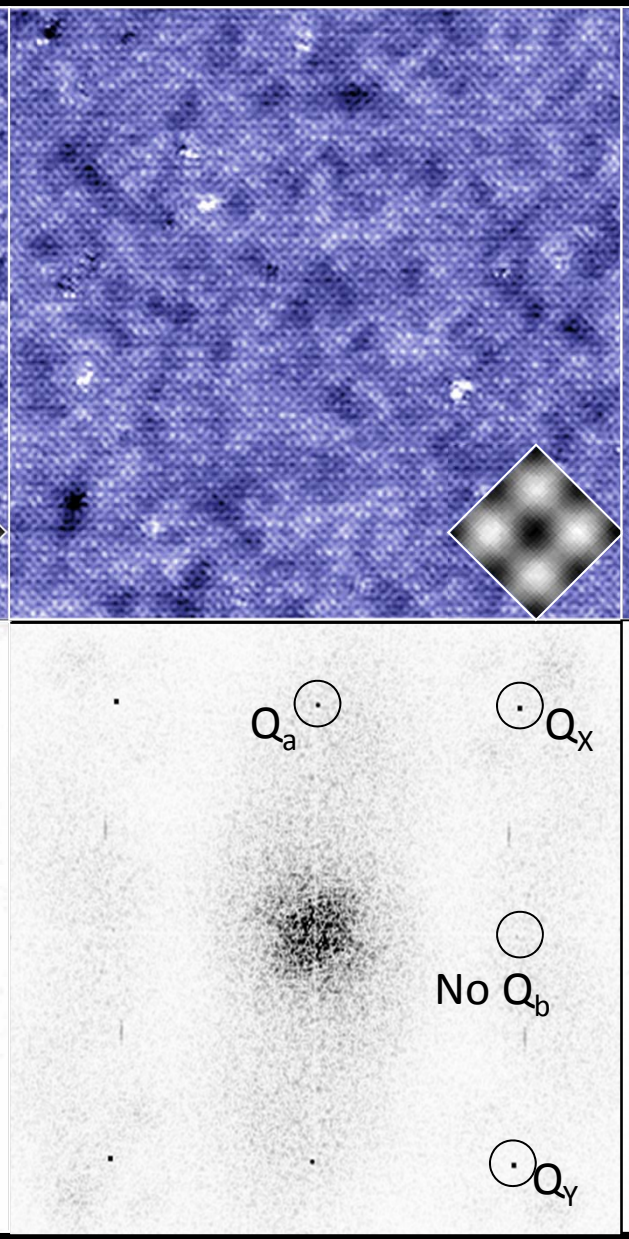


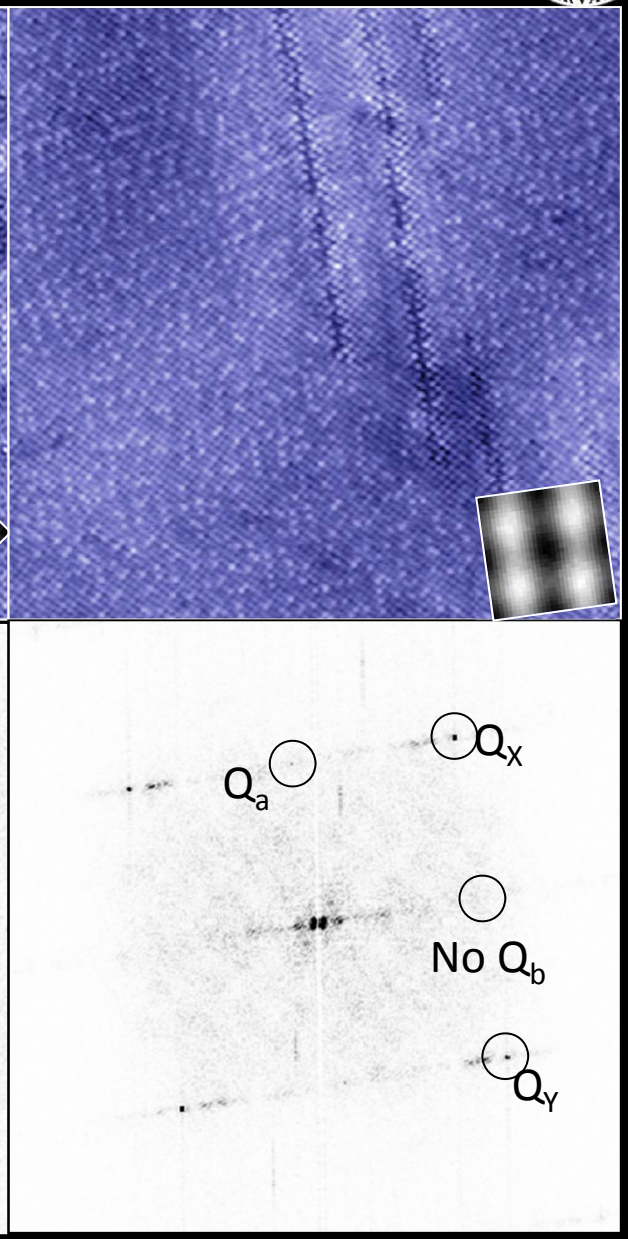
Back to q-space: does it check out?



Apply 2 methods to many samples

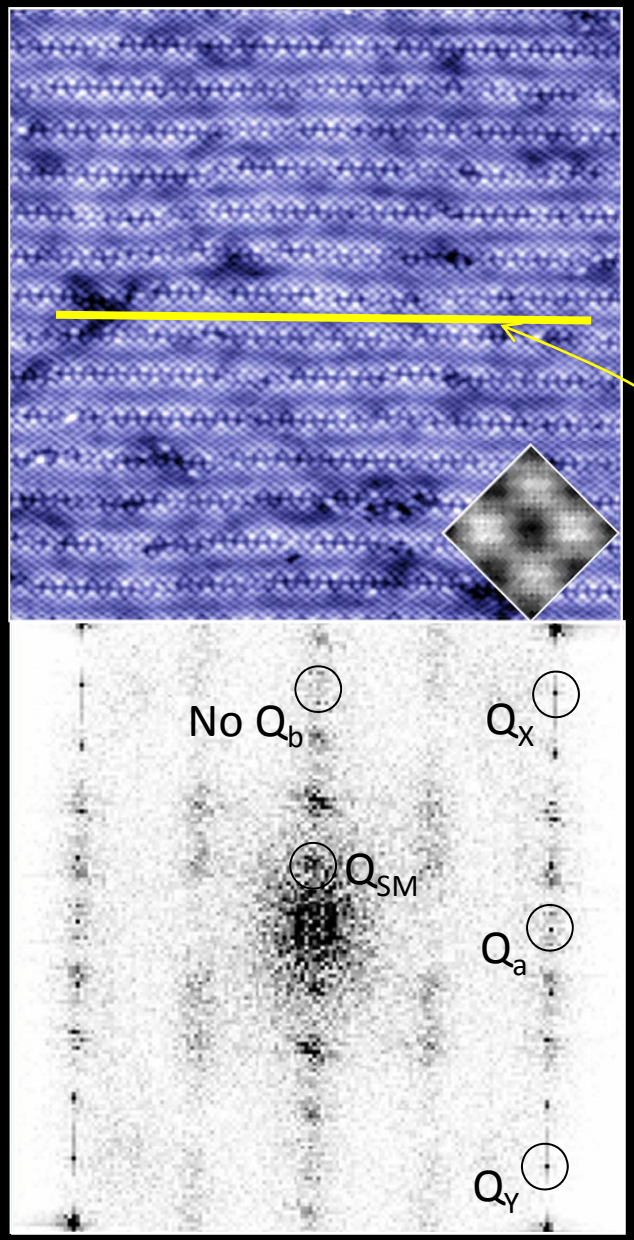






Zeljkovic, arxiv:1104.4342

8 different Bi-2212 samples

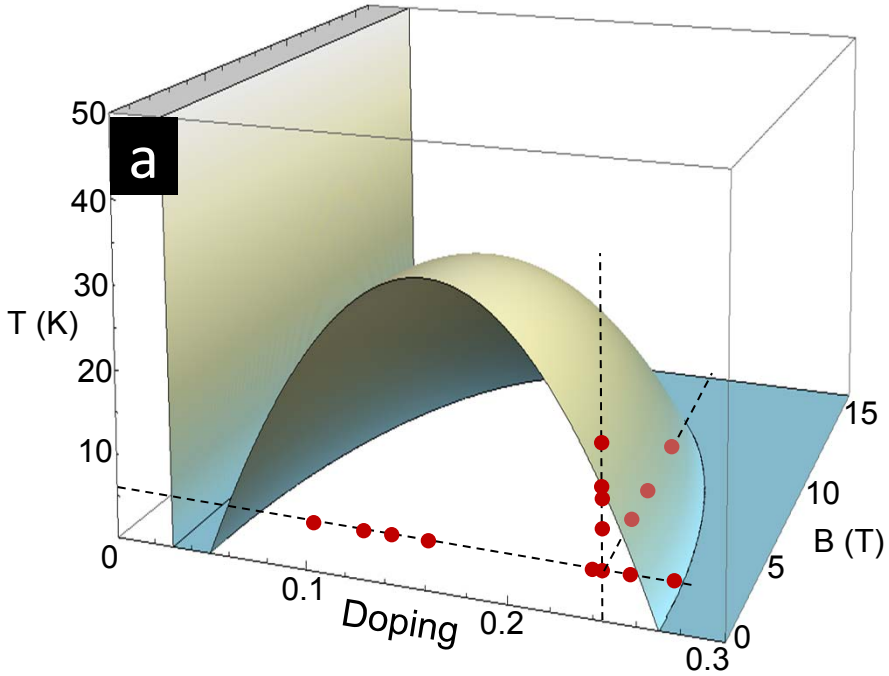


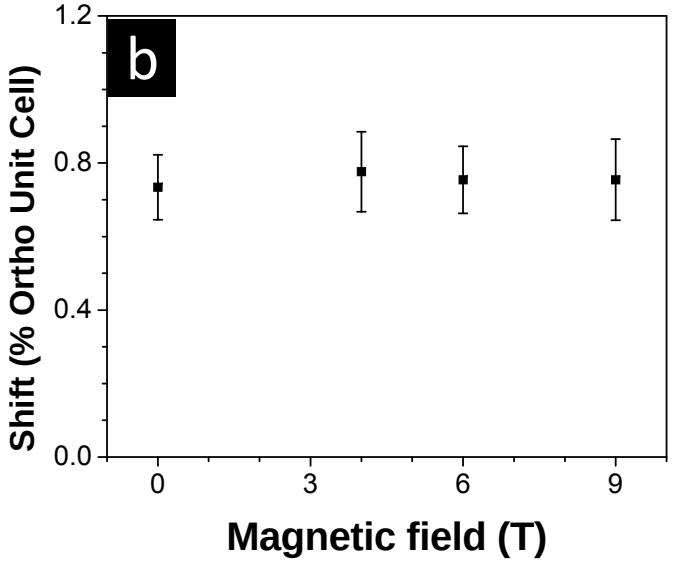
$Q_{SM} \equiv$ crystalline b axis

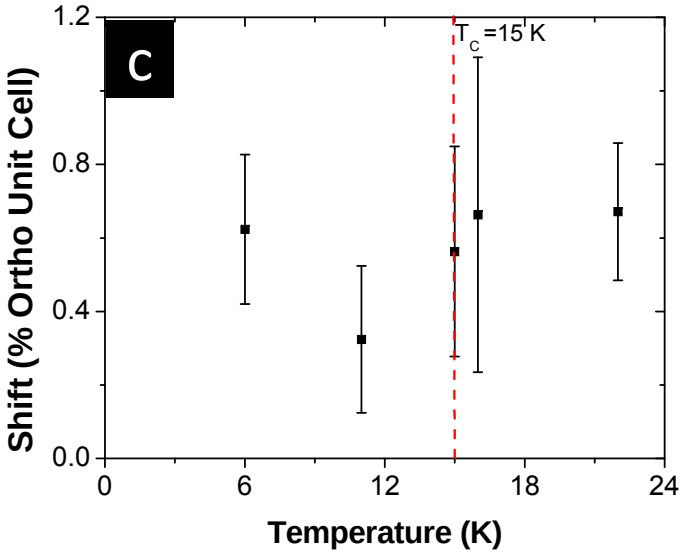
8 samples: ortho distortion along a axis

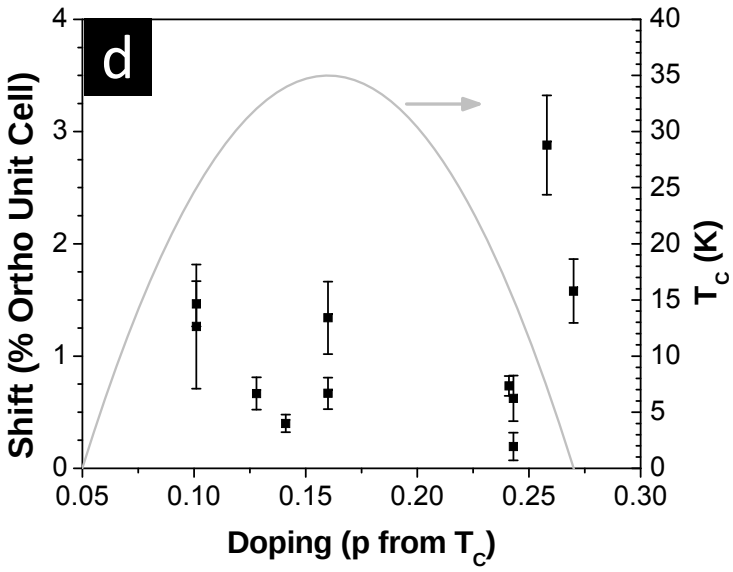
mirror plane always chooses this axis

Bi-2201 throughout the SC dome









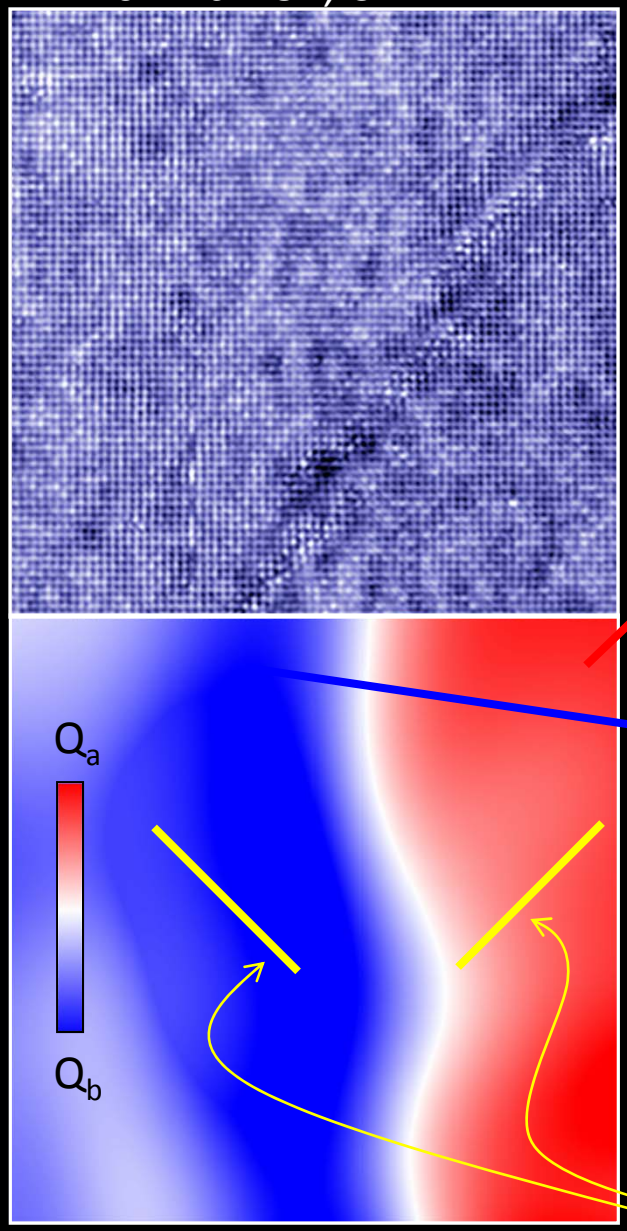
Zeljkovic, arxiv:1104.4342

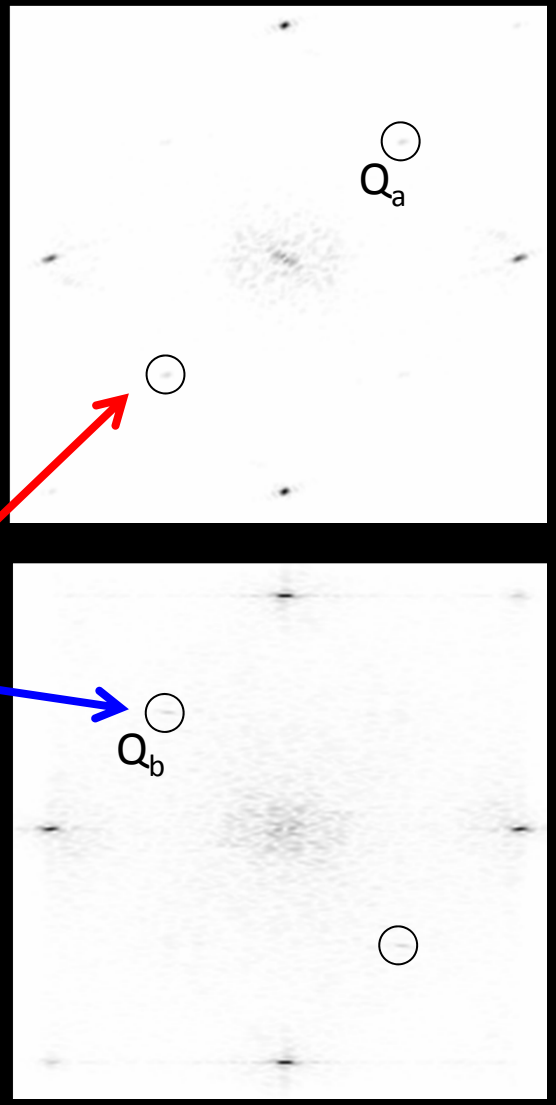
Historical: Structure from Scattering

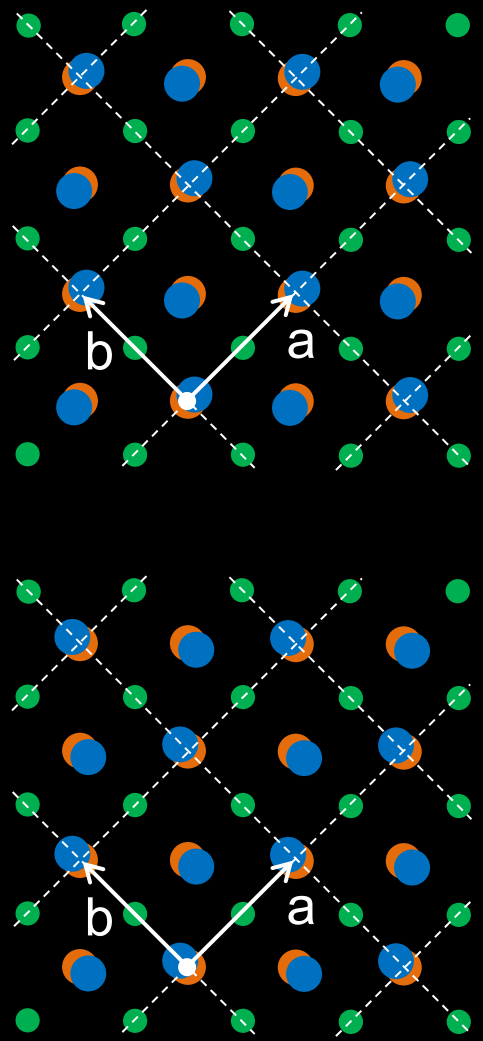
Material	Pb?	Technique	Bi distortion	Cu distortion	Ref
Bi-2223	no	XRD	2.22% (b axis)	-0.01% (b axis)	Subramanian, Science (1988)
Bi-2201	no	XRD	2.58% (b axis)	none	Torardi, PRB (1998)
Bi-2212	no	neutrons	2.55% (a axis)	-0.07% (a axis)	Miles, Physica C (1998)
Bi-2201	yes	XRD	1.82% (a axis) 6.34% (b axis)	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







local mirror planes!

Zeljkovic, arxiv:1104.4342

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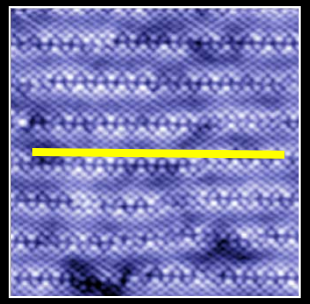
Bi-2201	yes and no	LEED, ARPES	one axis only	can't determine	Mans, PRL (2006)

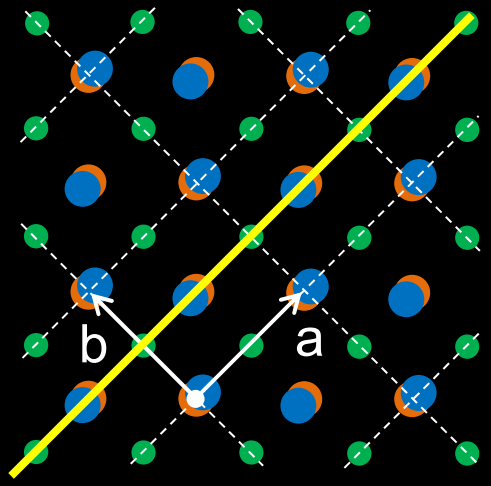
In the absence of supermodulation, there can be twin boundaries
→ leads to the appearance of shifts along 2 axes

Conclusions

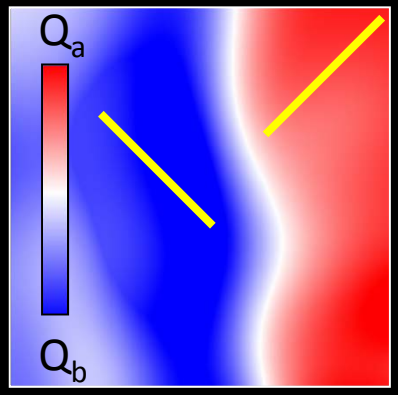
1. structural distortion in BiO plane breaks inversion symmetry at the Bi site, but preserves mirror plane



2. mirror plane is always aligned with supermodulation

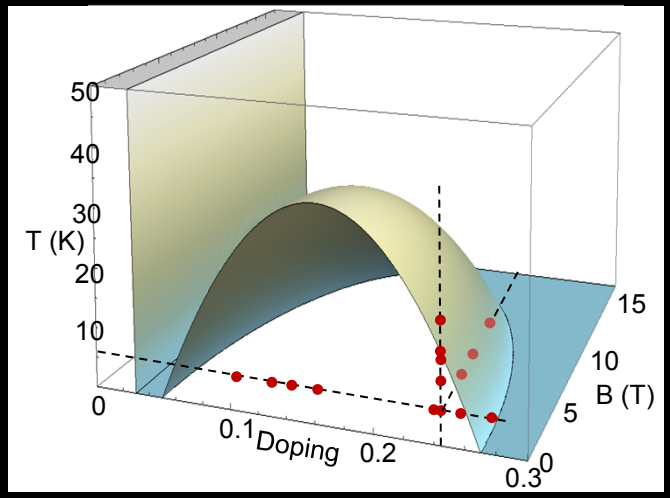


3. can image the local mirror plane



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



Implications

1. Algorithms: we extend Lawler's algorithm for 4 additional purposes
   a. discriminating between noise (broadens) and signal (sharpens)
   b. make average unit cell: can arbitrarily exchange large area for high resolution
   c. make average supercell: can detect any commensurate modulation
   d. use Fourier methods to locally track any structural modulation

2. Structural vs. electronic:
   a. We also see inversion "symmetry breaking" in the electronic signal. It appears larger than structural, but we haven't found a way to make ourselves confident that it is not a normalization artifact.
   b. Investigations of local electronic "symmetry breaking" should take care to state which structural symmetries are already broken, and to compare the magnitudes of electronic and structural symmetry breaking.
   c. If electronic "symmetry breaking" states just reinforce structural symmetries, but can be shown to follow T* line, then of course they are important and interesting.