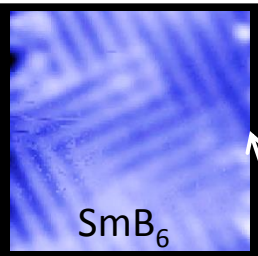
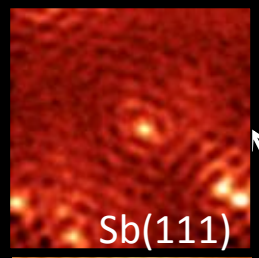
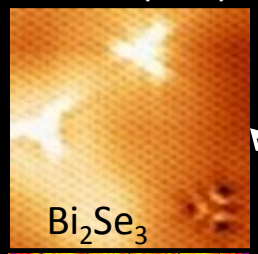
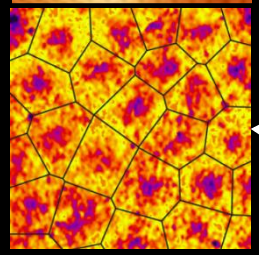
Hoffman Lab Local Probes

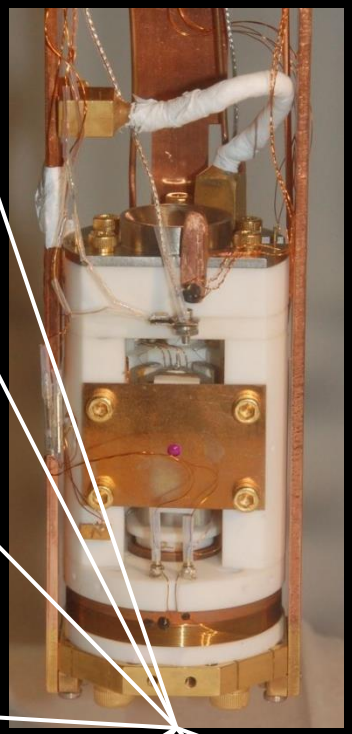






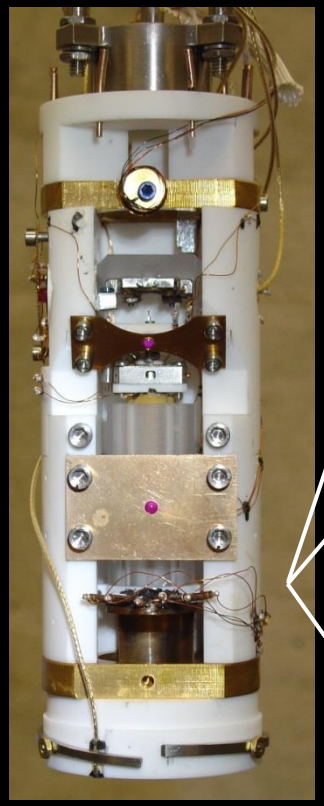


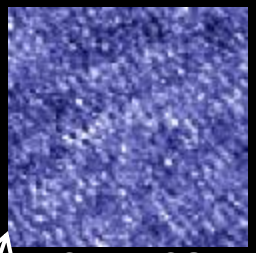
Scanning Tunneling Microscope

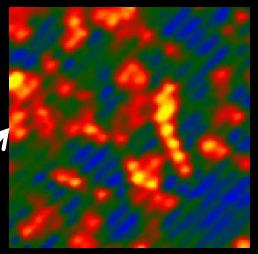


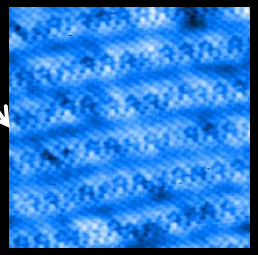
Force Microscope

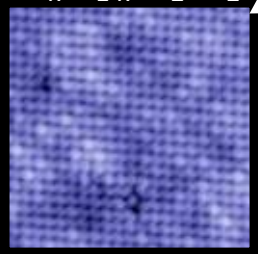
Ultra-high vacuum STM

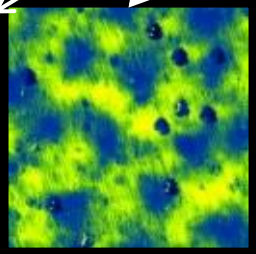


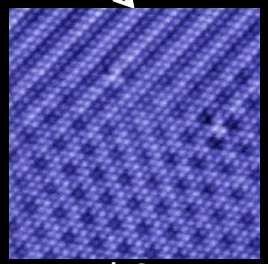


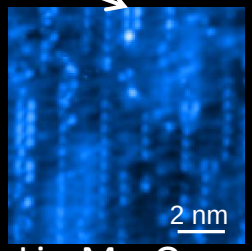


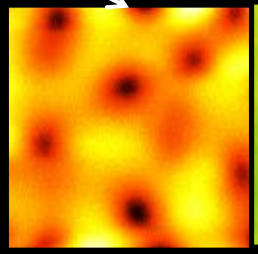


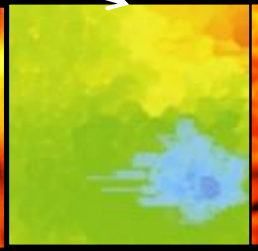


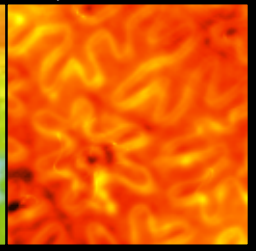






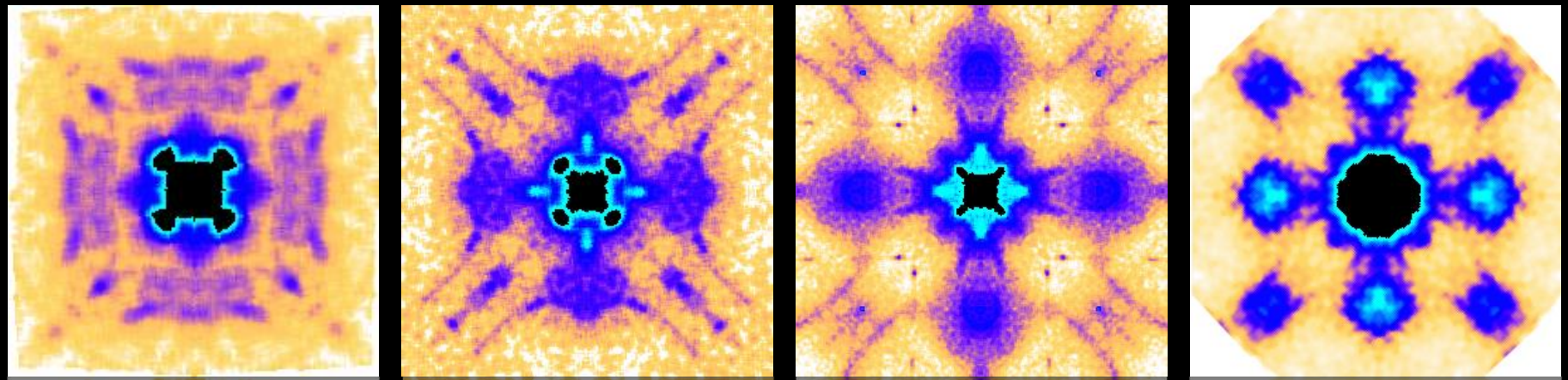






Fermi Surface & Pseudogap Evolution in a Cuprate Superconductor

Jenny Hoffman
Harvard University



Experiments

Harvard
Yang He, Yi Yin, Martin Zech
Anjan Soumyanarayanan
Ilija Zeljkovic, Michael Yee

MIT
Mike Boyer
W. Douglas Wise
Kamalesh Chatterjee
Eric Hudson

Samples

Nagoya University
Takeshi Kondo
Tsunehiro Takeuchi
Hiroshi Ikuta

Theory

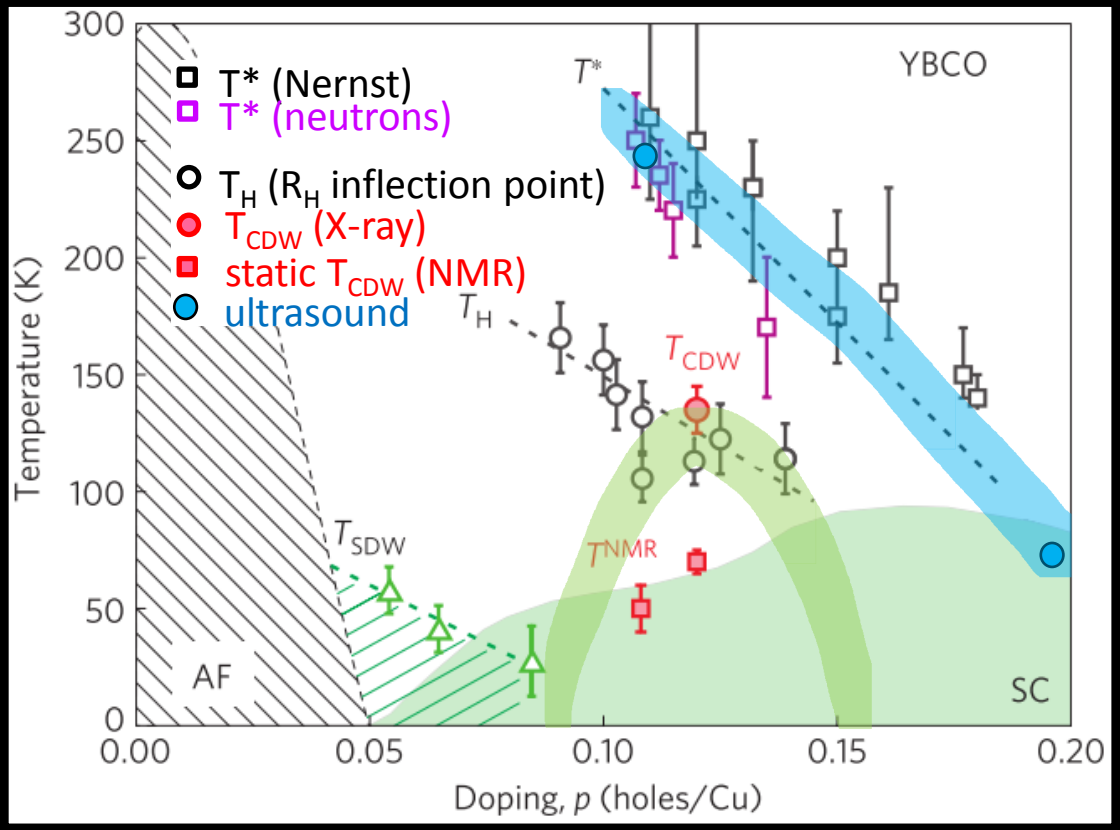
Northeastern, Harvard
Peter Mistark, Arun Bansil
Robert Markiewicz
Subir Sachdev

arxiv:1305.2778
to appear in ***Science***, May 9

Agency for Science, Technology and Research
NSERC CRSNG
Alfred P. Sloan Foundation
Air Force Office of Scientific Research
NSF

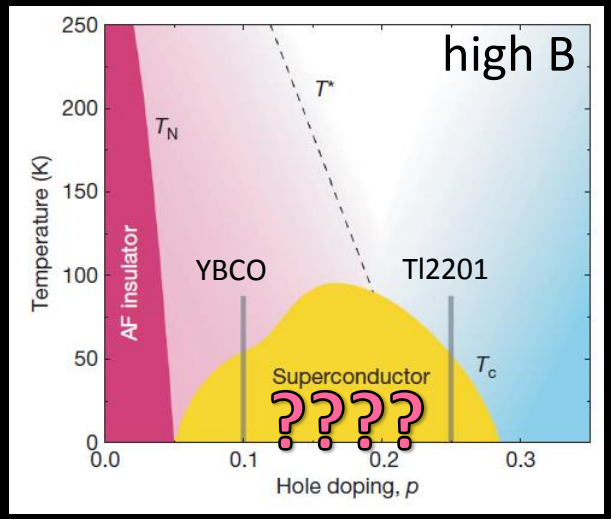
Fermi Surface vs. Pseudogap ?

Pseudogap & Charge order



X-rays: Chang + Forgen + Hayden, Nat Phys 8, 871 (2012)
neutrons: Li + Greven, Nature 455, 372 (2008)
Nernst: Daou + Taillefer, Nature 463, 519 (2010)
Hall: LeBoeuf + Taillefer, PRB 83, 054506 (2011)
NMR: Wu + Julien, Nature 477, 191 (2011)
ultrasound: Shekhter + Ramshaw, Nature 498, 75 (2013)

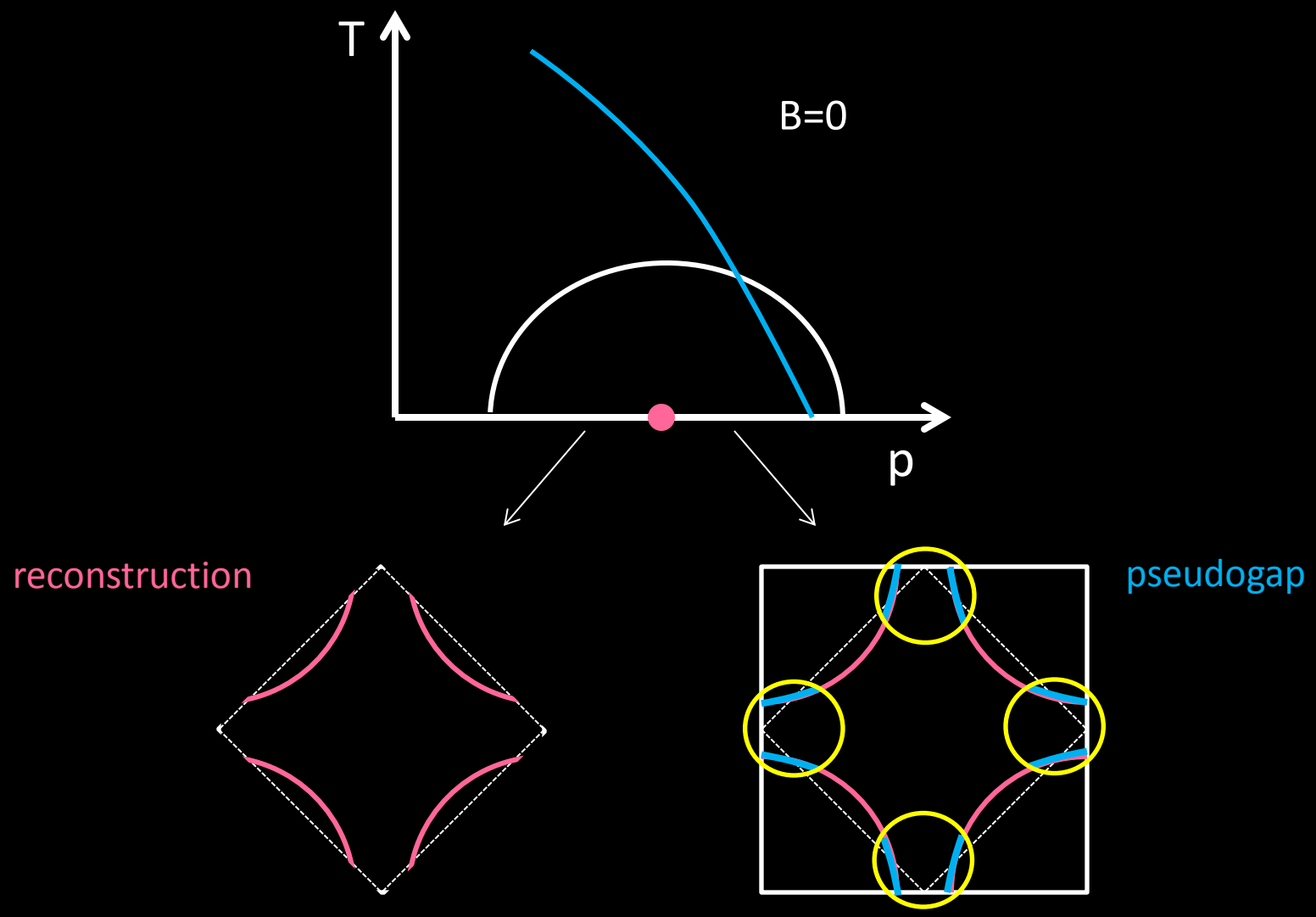
Fermi surface



Doiron-Leyraud, Nature 447, 565 (2007)
Vignolle, Nature 455, 952 (2008)

Conclusions (STM on Bi2201)

1. Fermi surface reconstruction ≠ pseudogap



2. Superconductivity coexists with pseudogap at the antinode

Outline

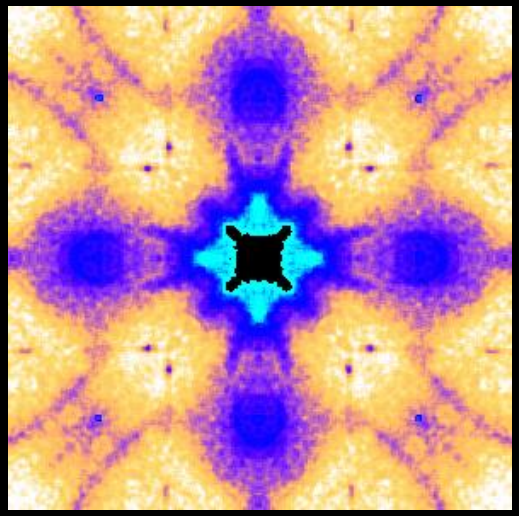
1. Where is the Fermi surface reconstruction?

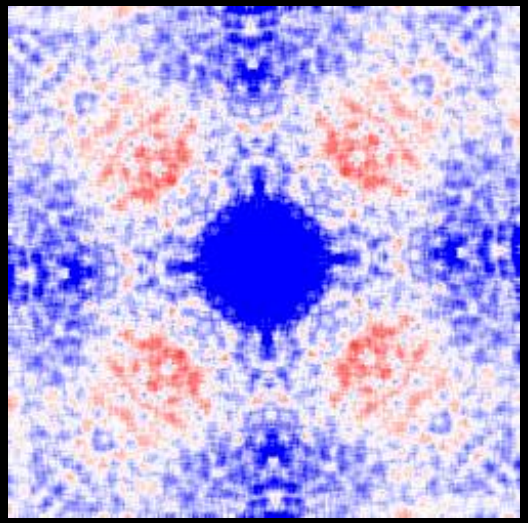
   Answer: coincides with QCP near optimal doping at B=0

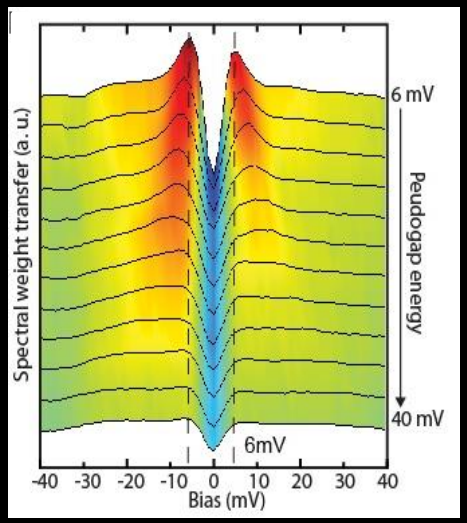
2. What is the role of the pseudogap?

   Answer:

   - separate occurrence
   - coexists with superconductivity at the antinode
   - causes decoherence at the nanoscale



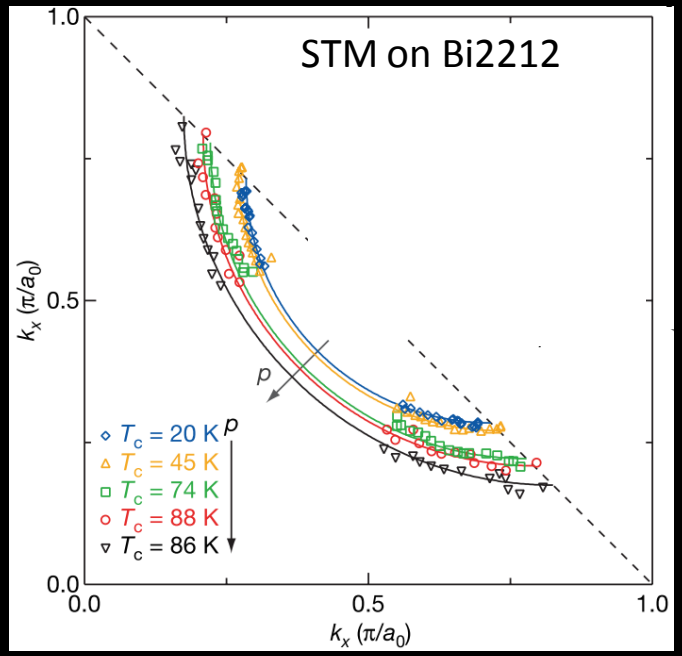




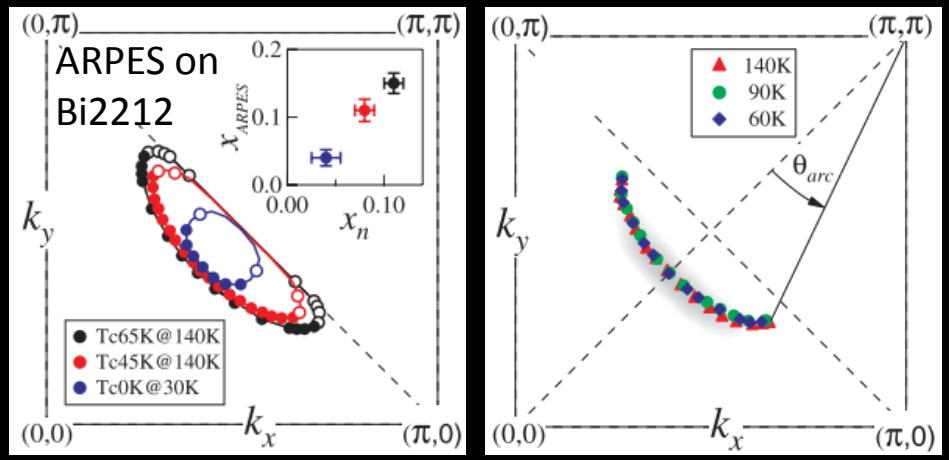
arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

Intro to Fermi arc phenomenology in Bi2212

Arc cuts off at AFBZ

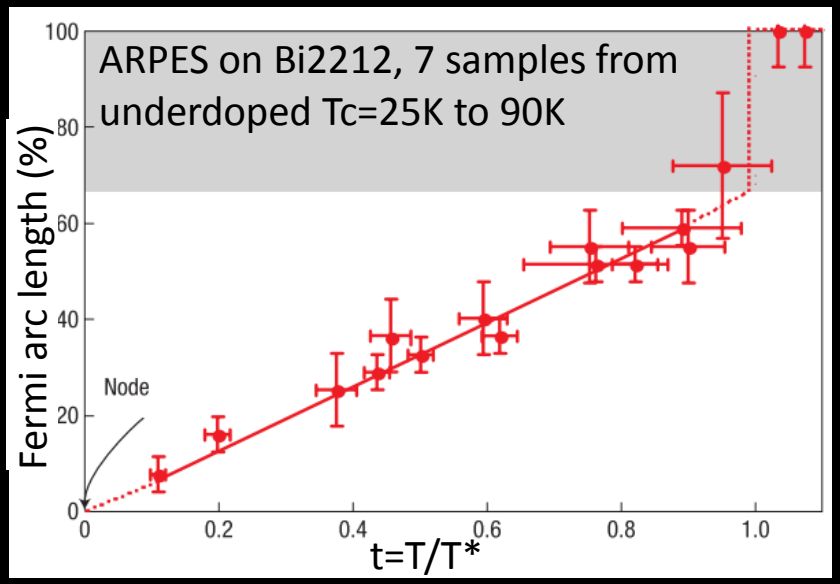


Kohsaka + JC Davis, Nature 454, 1072 (2008)

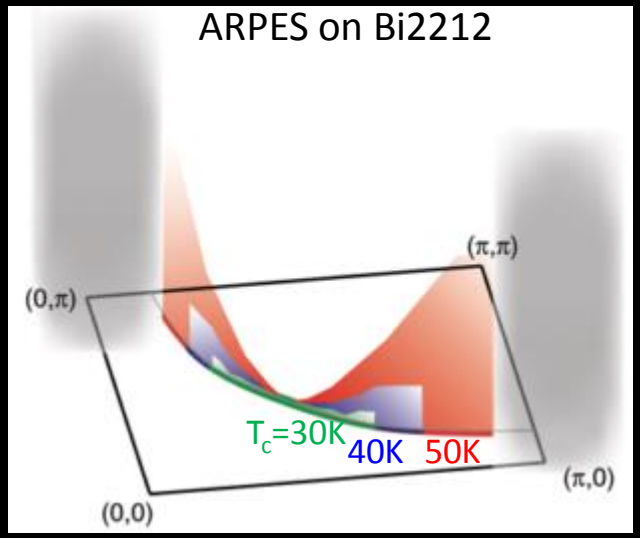


Yang + PD Johnson, PRL 107, 047003 (2011)

Arc length evolves with T, p



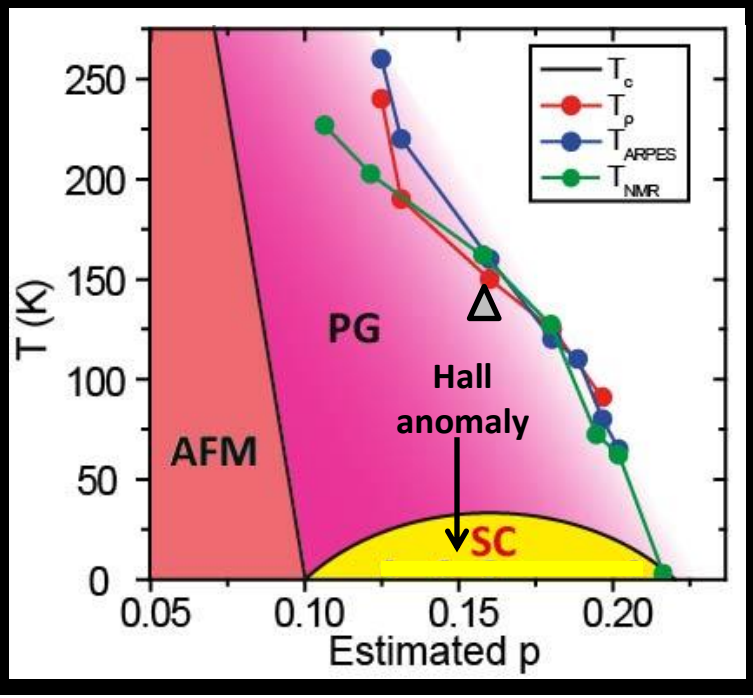
Kanigel + Norman + Campuzano, Nat Phys 2, 447 (2006)



Tanaka + ZX Shen, Science 314, 1910 (2006)

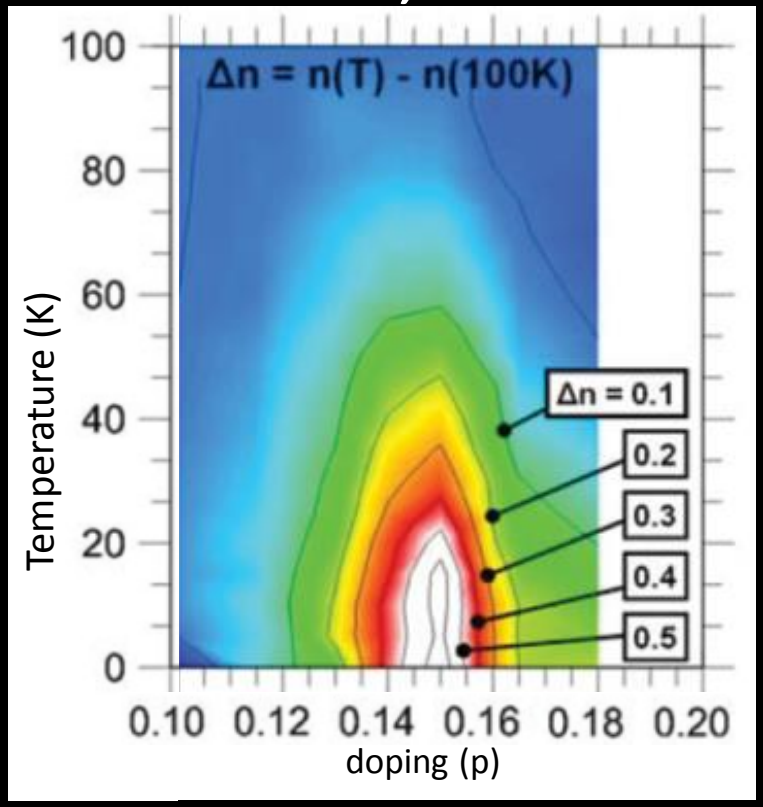
Motivation to study Pb-doped Bi2201

- No supermodulation or bilayer splitting artifacts
- Well-characterized pseudogap persists throughout the phase diagram
- Evidence for a quantum critical point near optimal doping (at high B)



- resistivity, B=0, Kondo, Nat Phys 7, 21 (2010)
- ARPES, B=0, Kondo, Nat Phys 7, 21 (2010)
- NMR,B=28-43T, Zheng, PRL 94, 047006 (2005)
- Kerr, ARPES, time-resolved reflectivity
  He + Kivelson + Kapitulnik + Orenstein + ZX Shen, Science 331, 1579 (2011)
- SC dome, Ando, PRB 61, R14956 (2000)

Hall coeff, B > 30 T

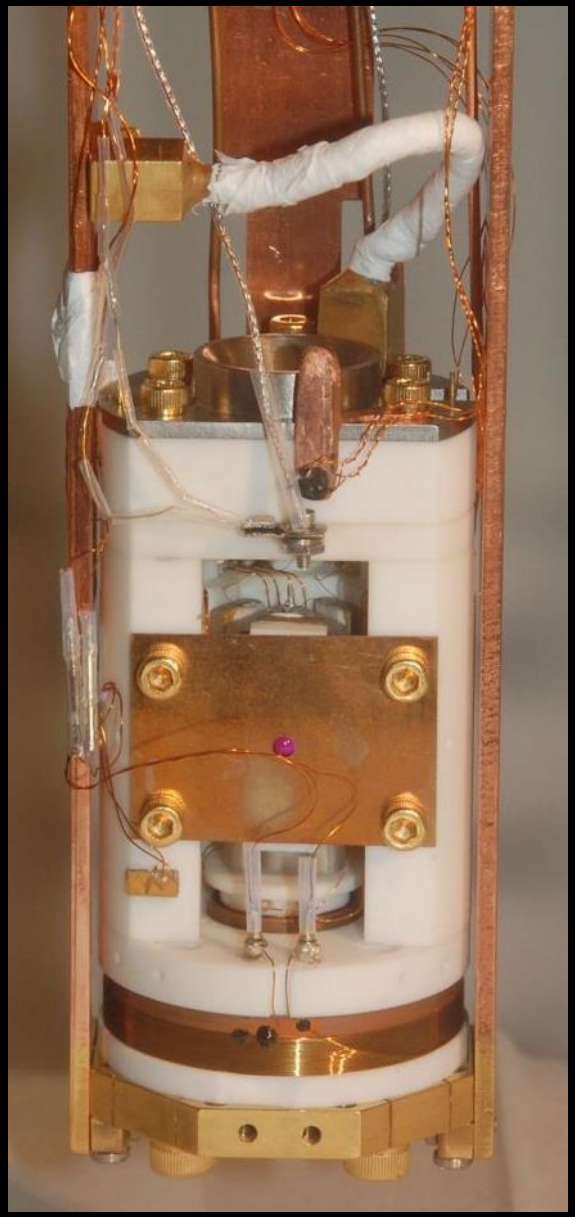


Balakirev, Nature 424, 912 (2003)
Balakirev, PRL 102, 017004 (2009)

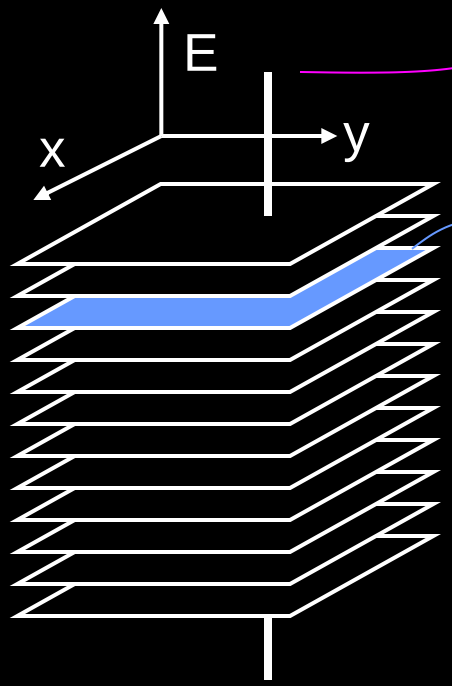
Does the FS reconstruct at B=0 Tesla?

Does the FS reconstruction correspond to Hall QCP (p~0.15) or PG (p~0.23)?

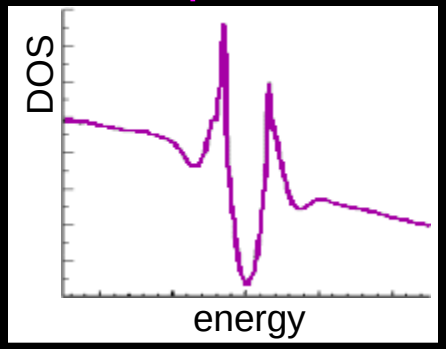
Scanning Tunneling Microscopy



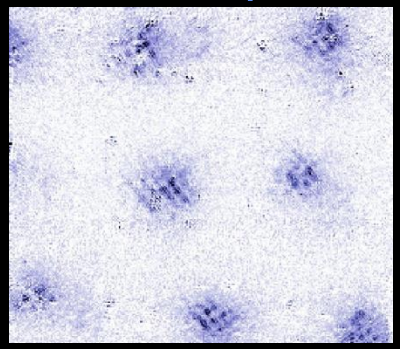
Local Density of States (x, y, E)



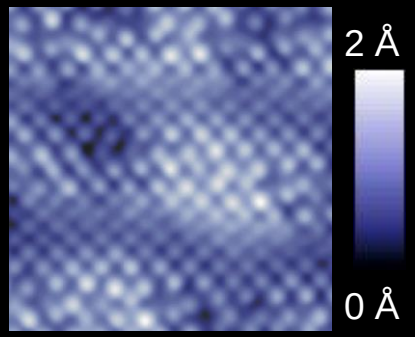
dI/dV Spectrum



dI/dV Map



Topography

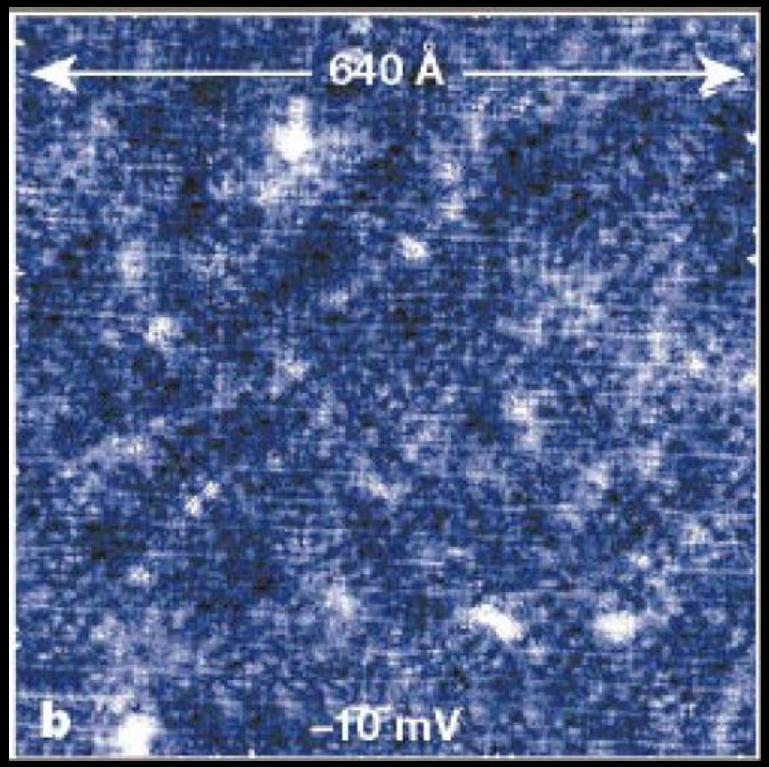


Constant current mode:

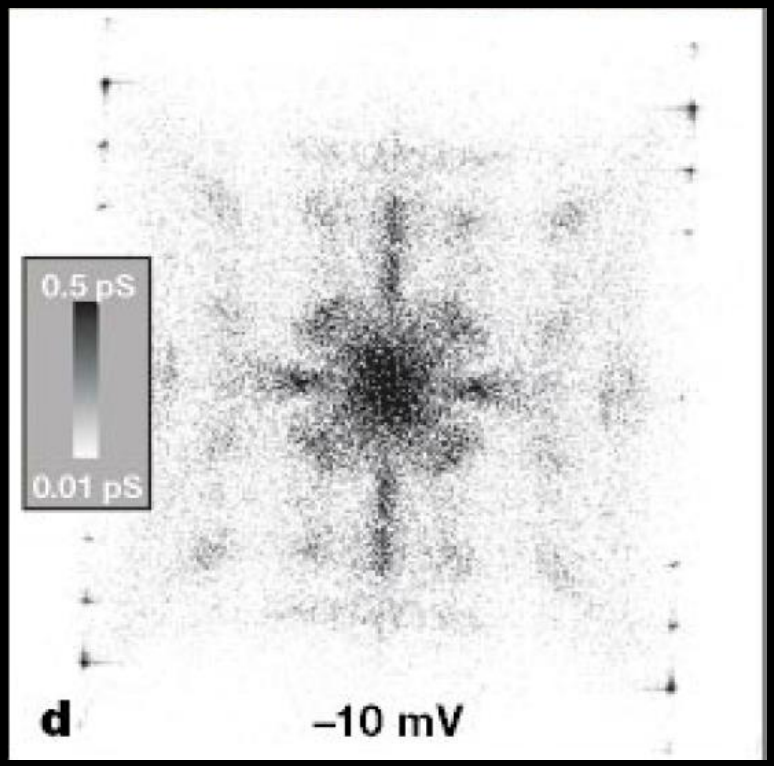
$$\int \frac{dI}{dV}$$

Quasiparticle interference in Bi2212

STM local density of states



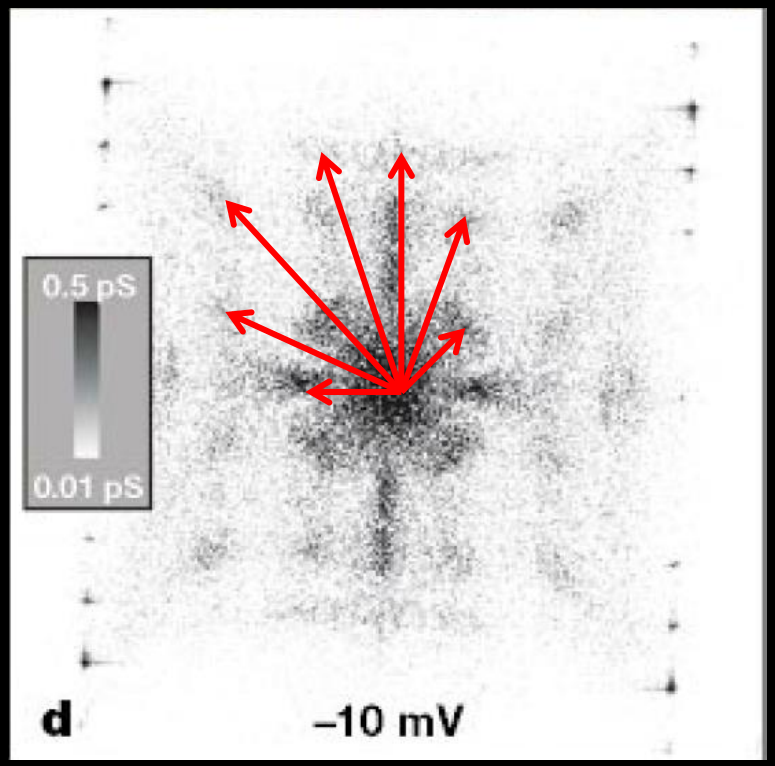
q space QPI



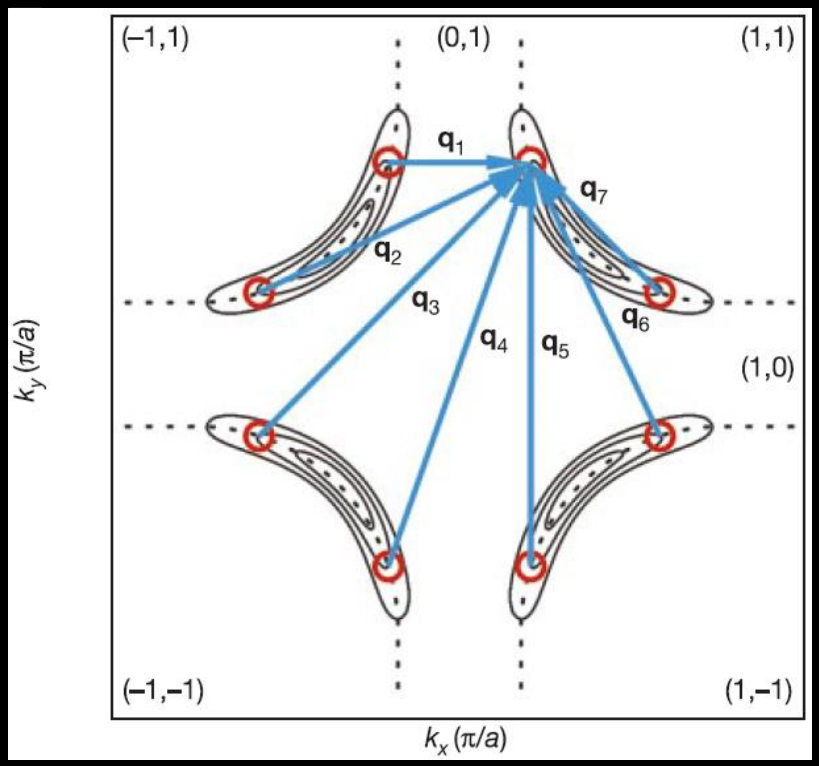
Hoffman, Science 297, 1148 (2002)
McElroy, Nature 422, 592 (2003)
Wang & Lee, PRB 67, 020511 (2003)

Quasiparticle interference in Bi2212

q space QPI



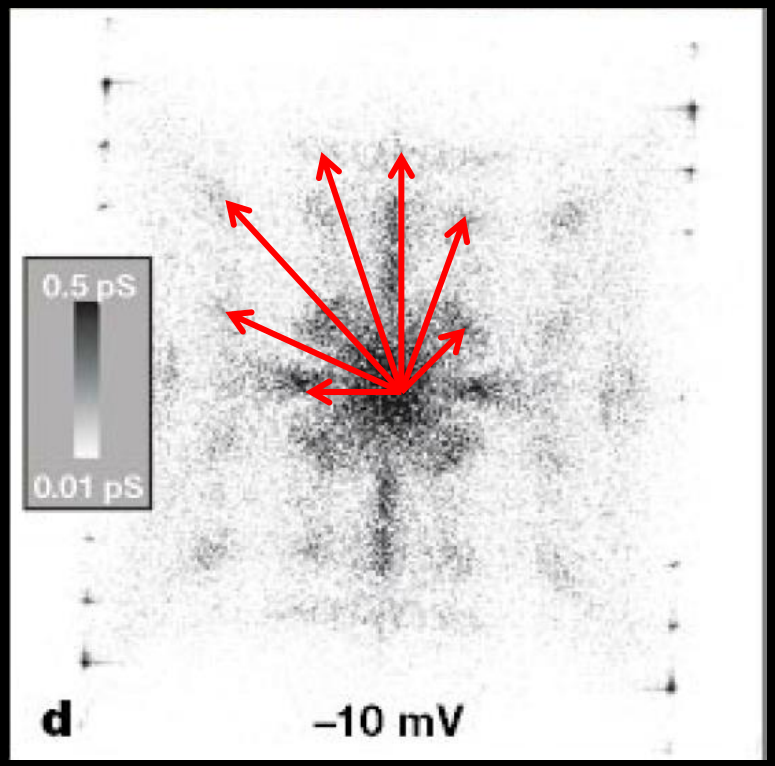
"Octet model"



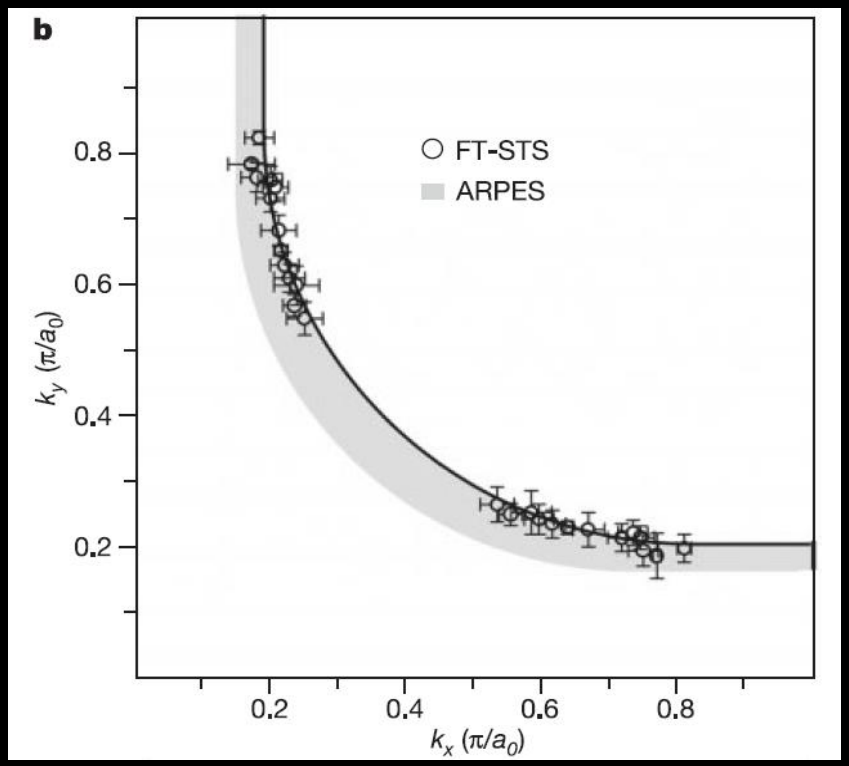
Hoffman, Science 297, 1148 (2002)
McElroy, Nature 422, 592 (2003)
Wang & Lee, PRB 67, 020511 (2003)

Quasiparticle interference in Bi2212

q space QPI

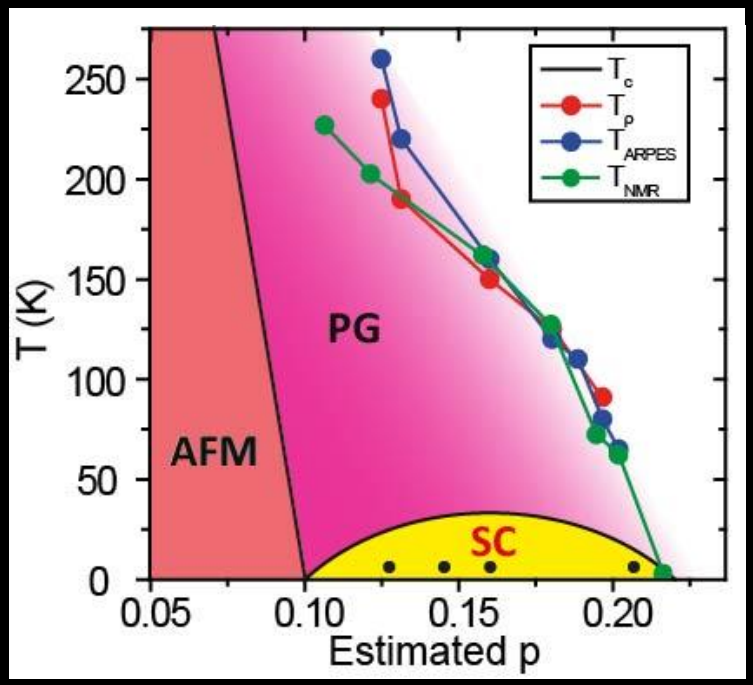


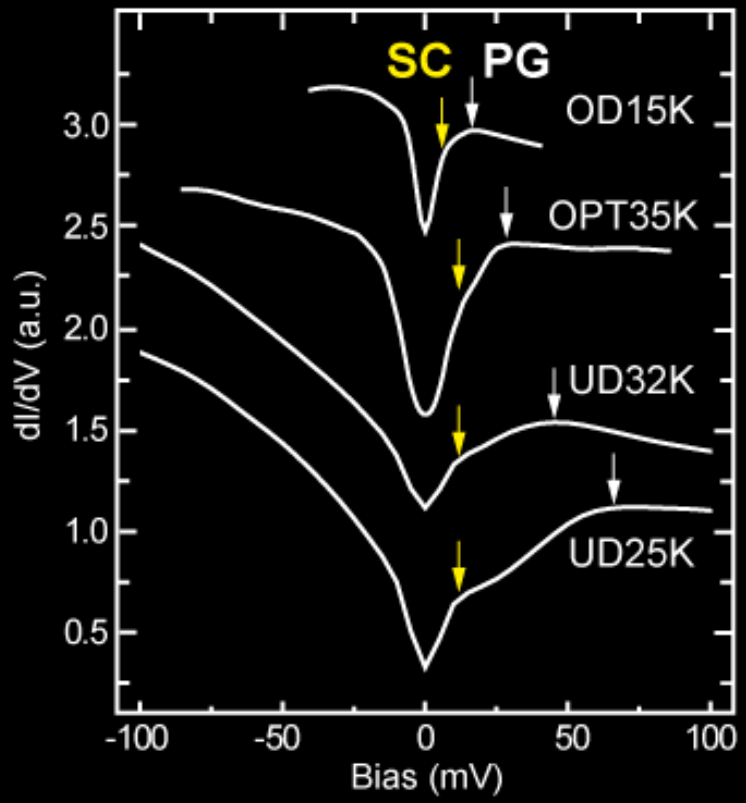
k-space Fermi surface



Hoffman, Science 297, 1148 (2002)
McElroy, Nature 422, 592 (2003)
Wang & Lee, PRB 67, 020511 (2003)

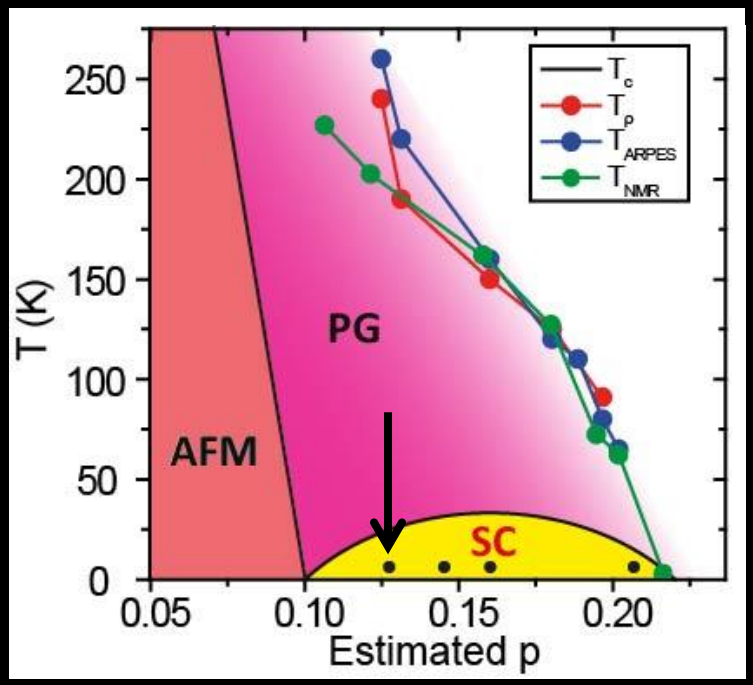
STM studies of Pb-doped Bi2201





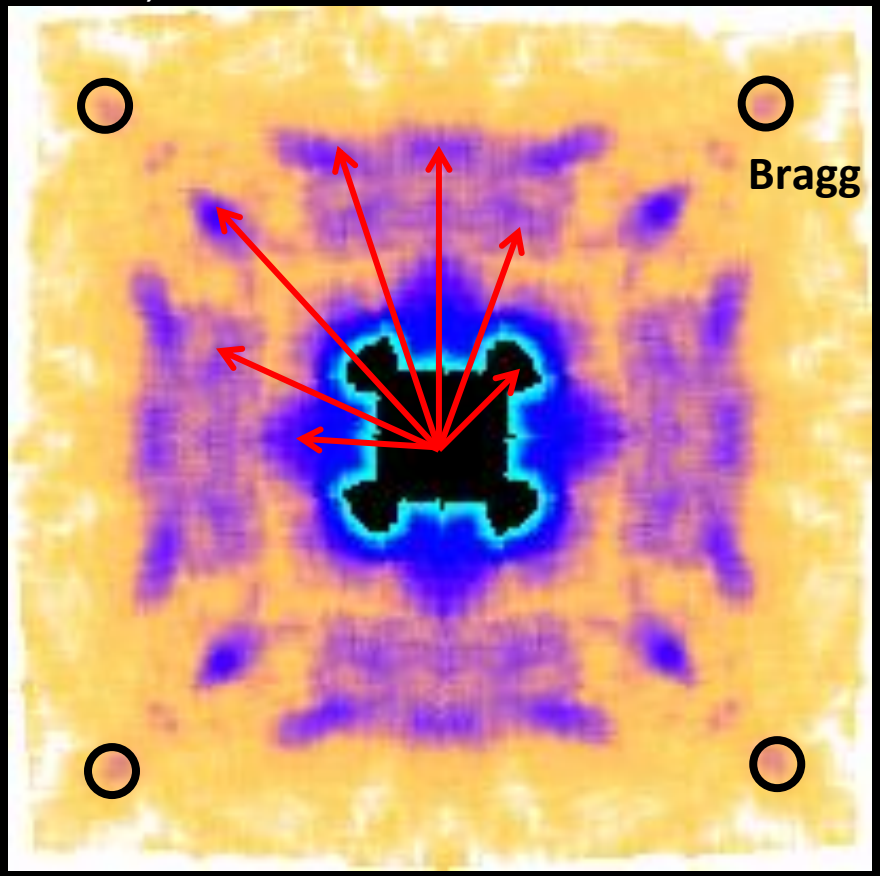
arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

Octet QPI in UD25K Bi2201



Bi2201, UD25K

9mV

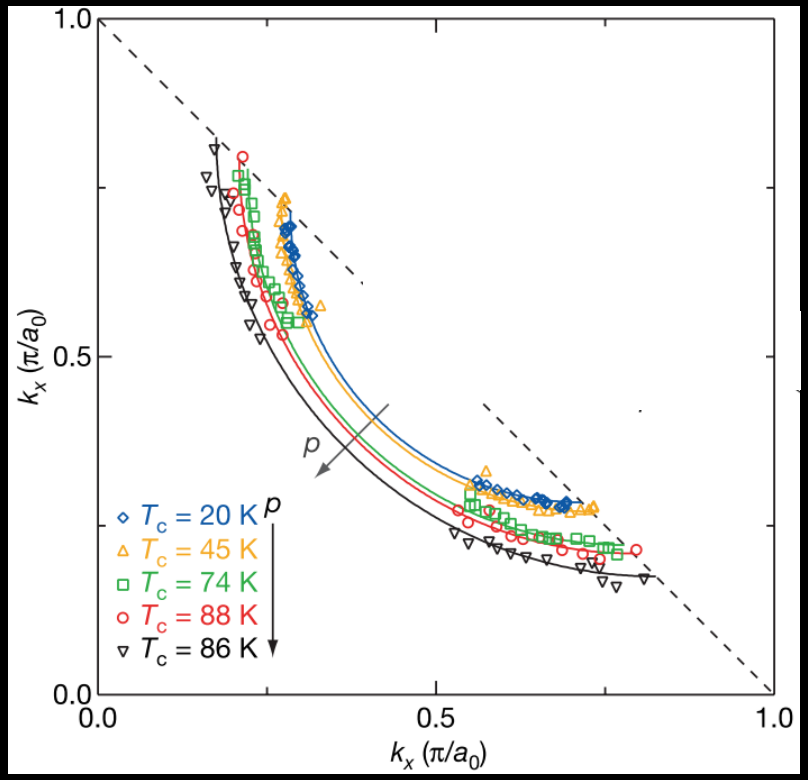


Low High

(Fourier transform of a real space dI/dV map)

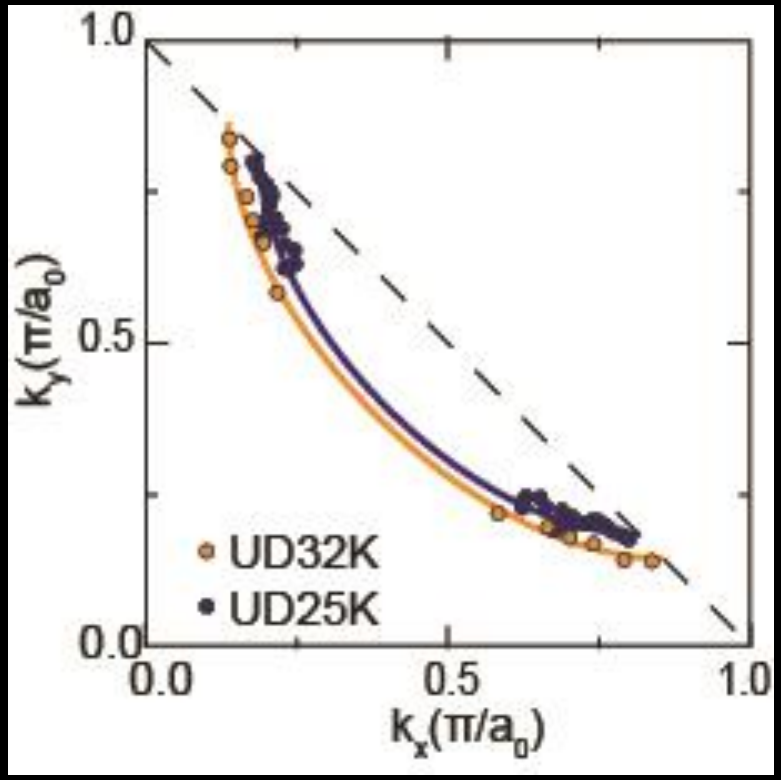
Extinction of octet QPI

Previous work: Bi2212



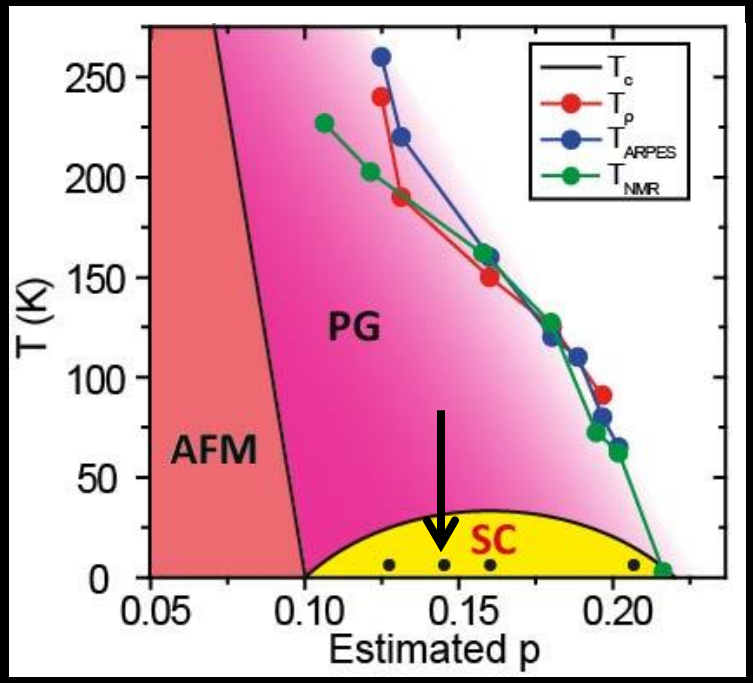
Kohsaka, Nature 454, 1072 (2008)

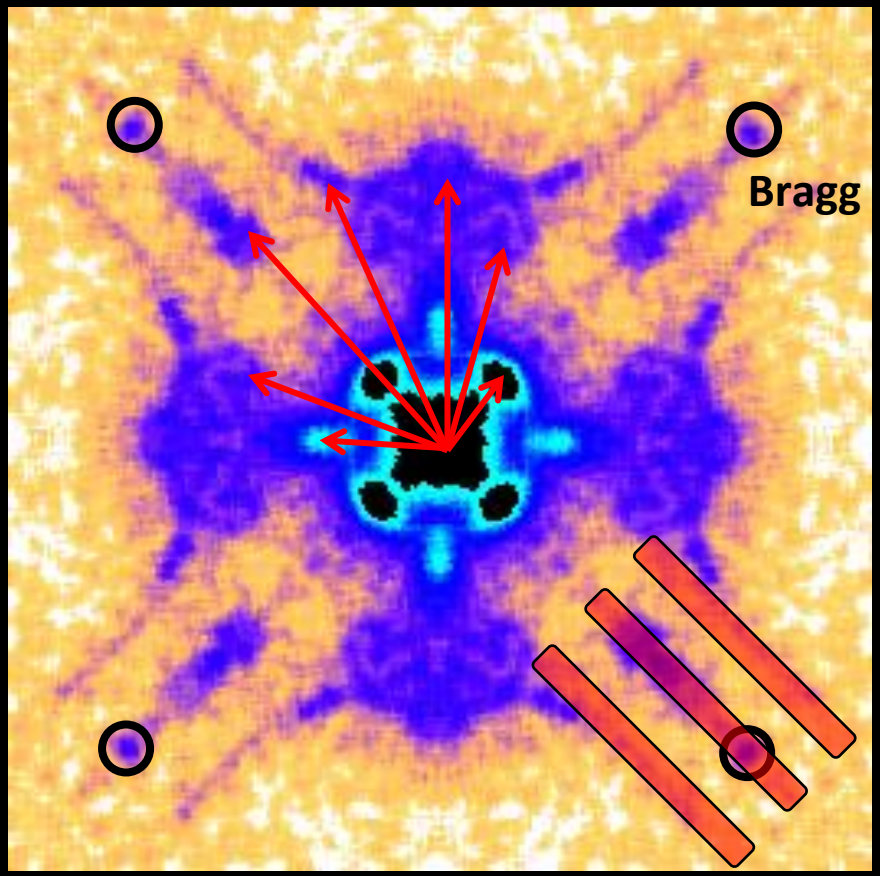
Our data: Bi2201



arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

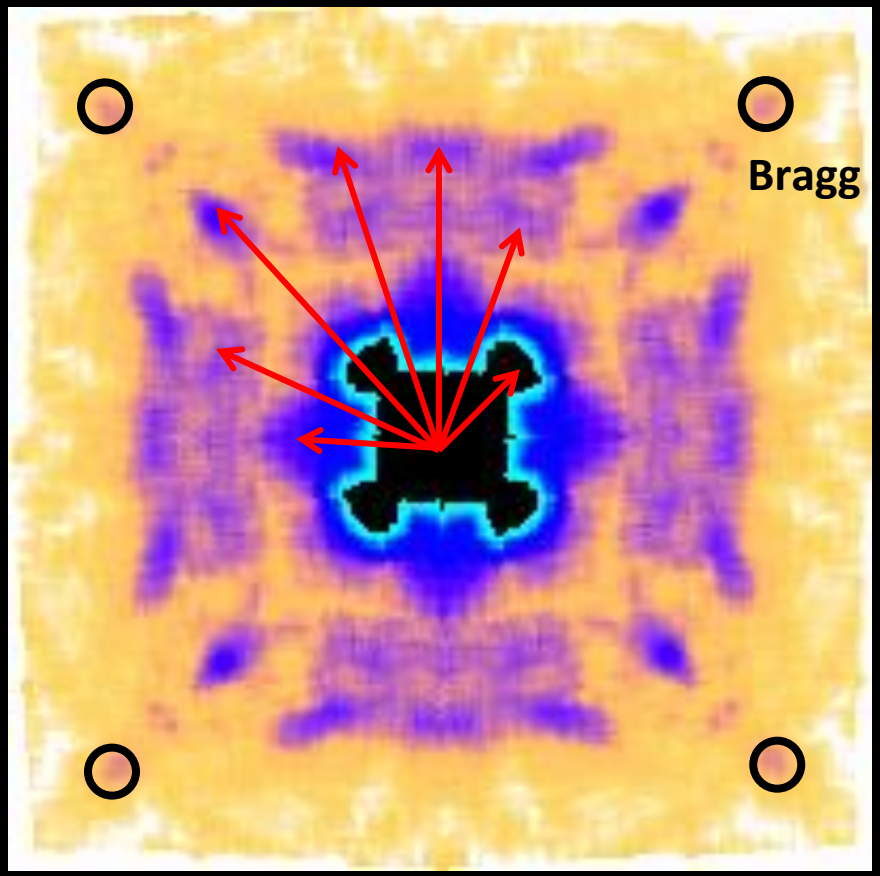
QPI in UD32K Bi2201





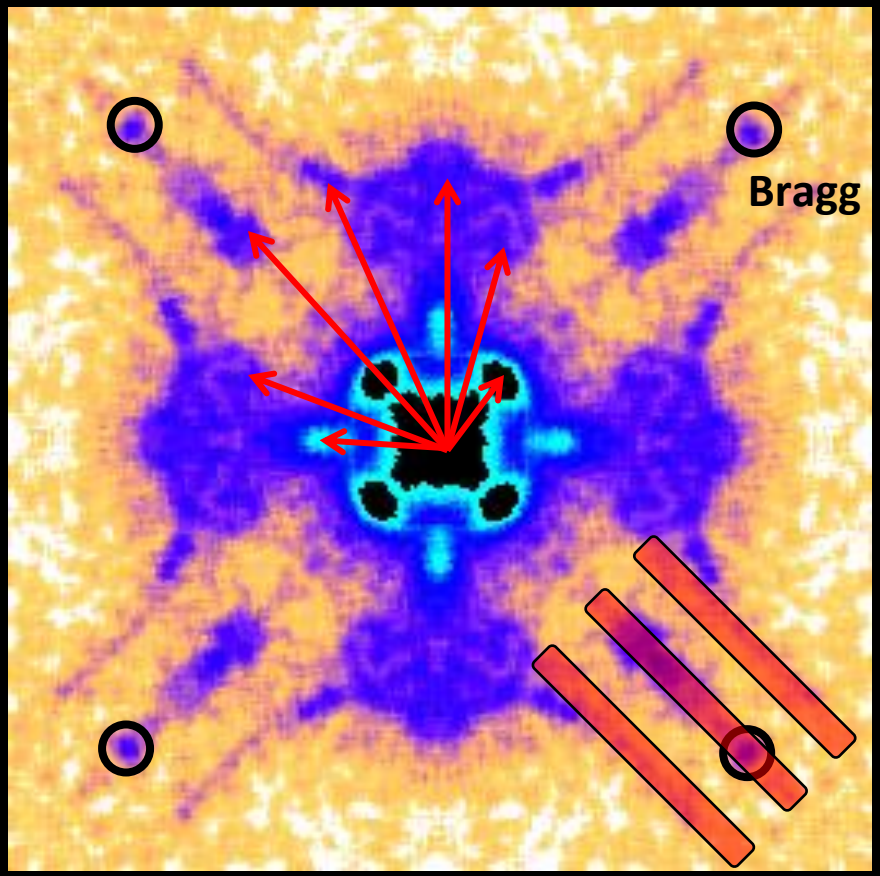
Compare QPI in UD25K and UD32K

UD25K 9mV



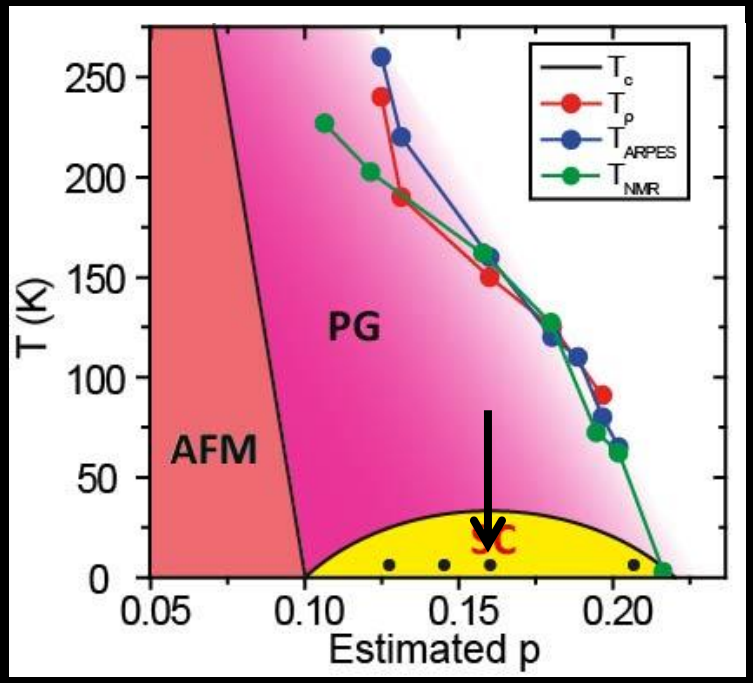
Low High

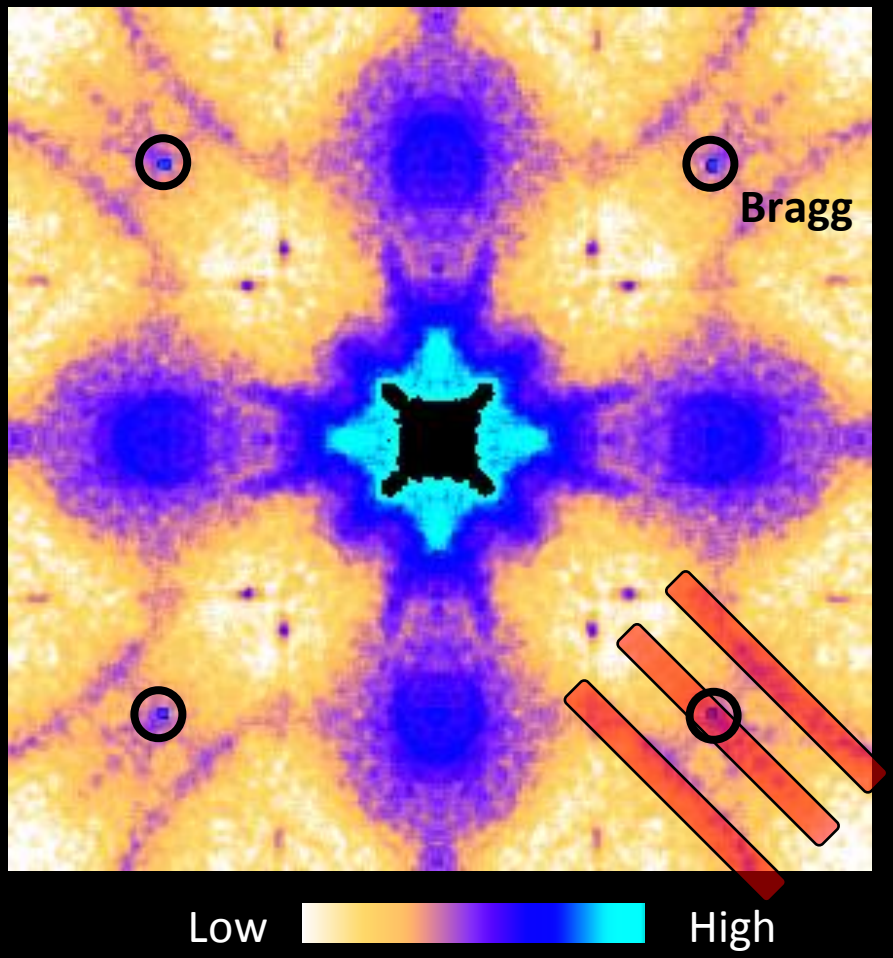
UD32K 5mV



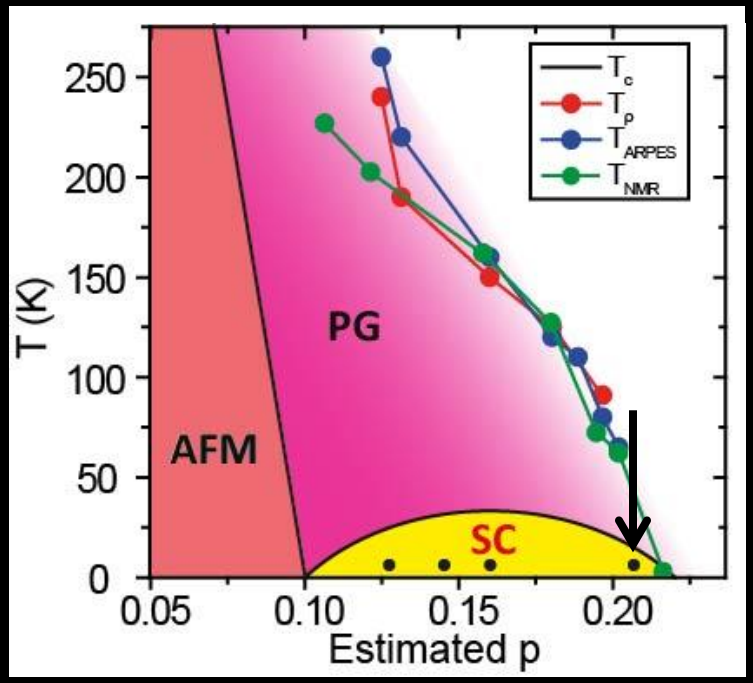
Low High

QPI in OPT35K



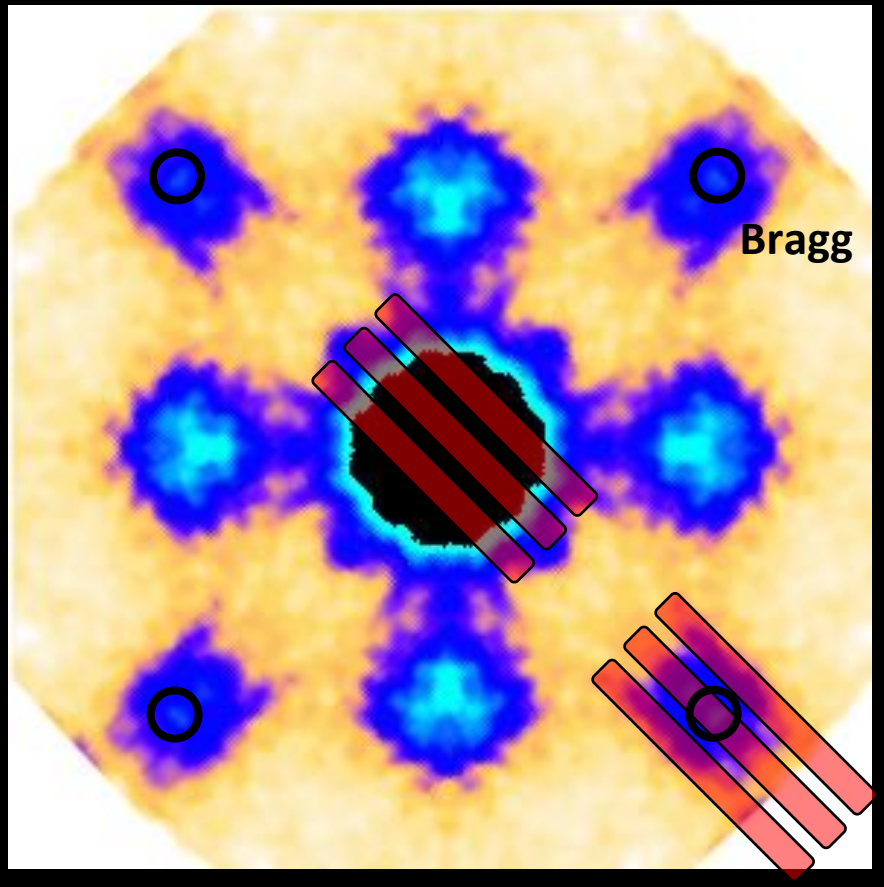


QPI in OD15K



OD15K

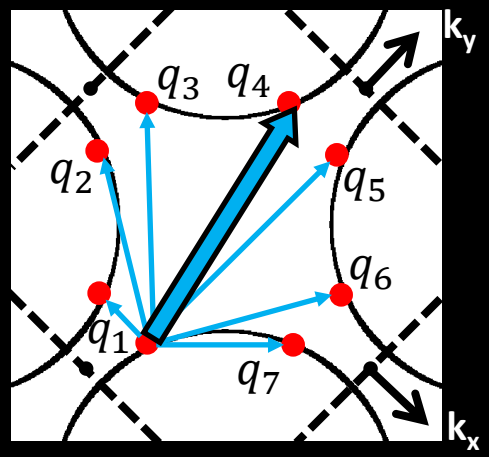
3mV



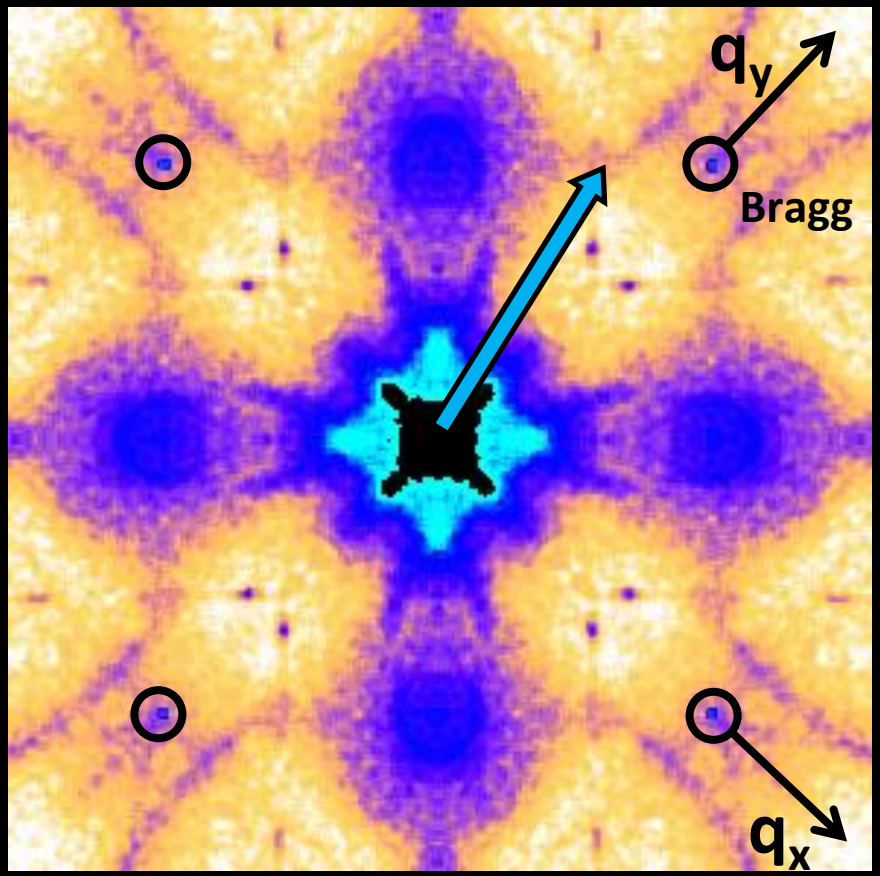
Low High

Compare Fermi surface to QPI

k space Fermi surface



q space QPI OPT35K 5mV

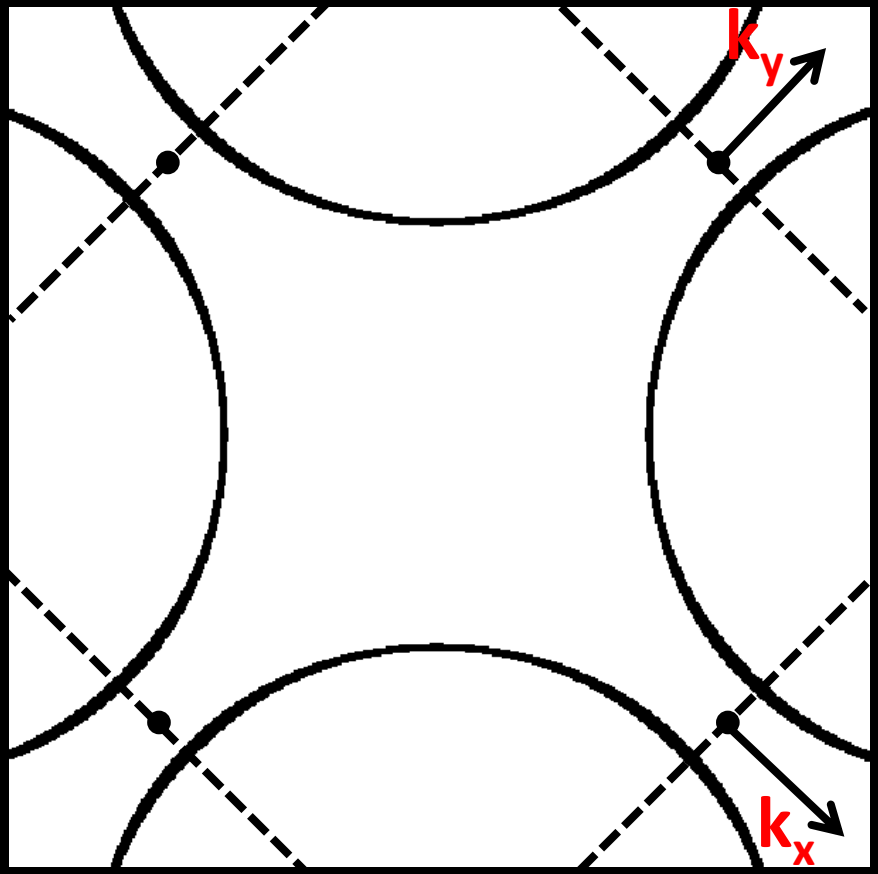


Low High

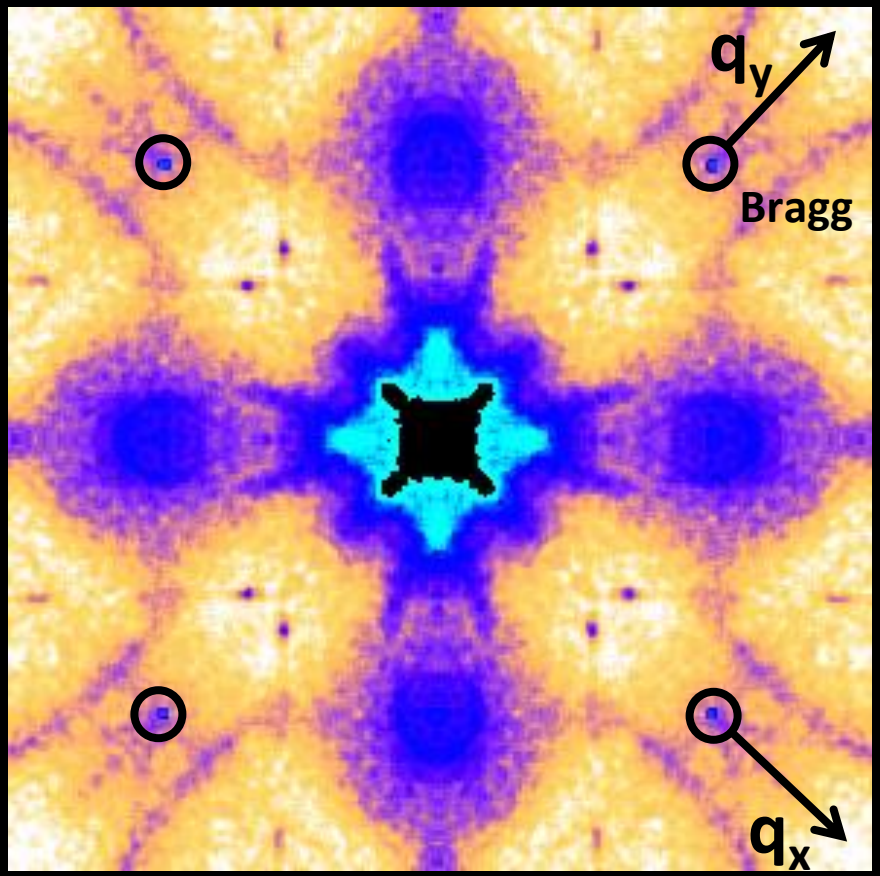
$q_4 = (2k_x, 2k_y)$ which follows the Fermi surface

Compare Fermi surface to QPI

2 x k space Fermi surface



q space QPI OPT35K 5mV

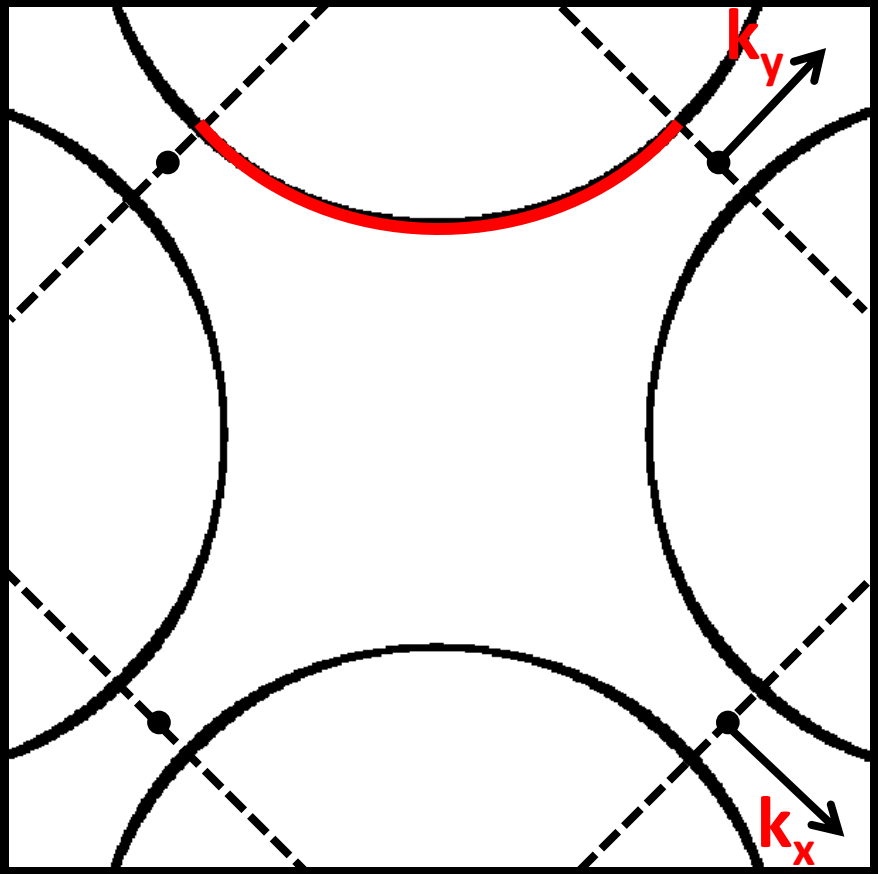


Low High

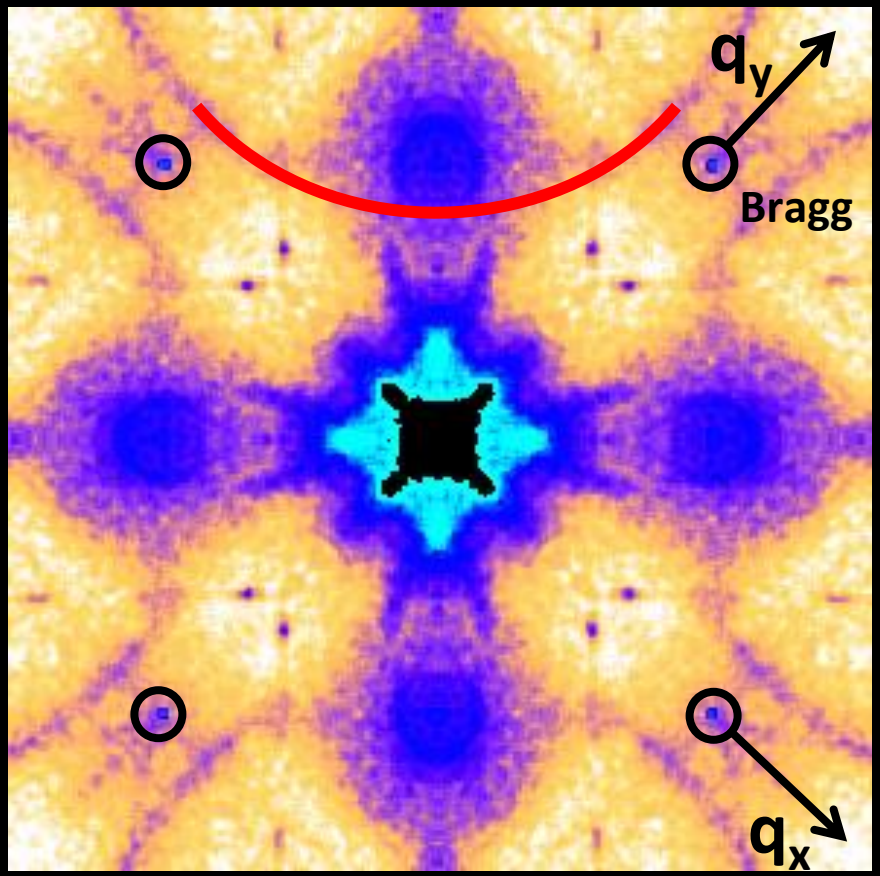
$q_4 = (2k_x, 2k_y)$ which follows the Fermi surface

Compare Fermi surface to QPI

2 x k space Fermi surface



q space QPI OPT35K 5mV

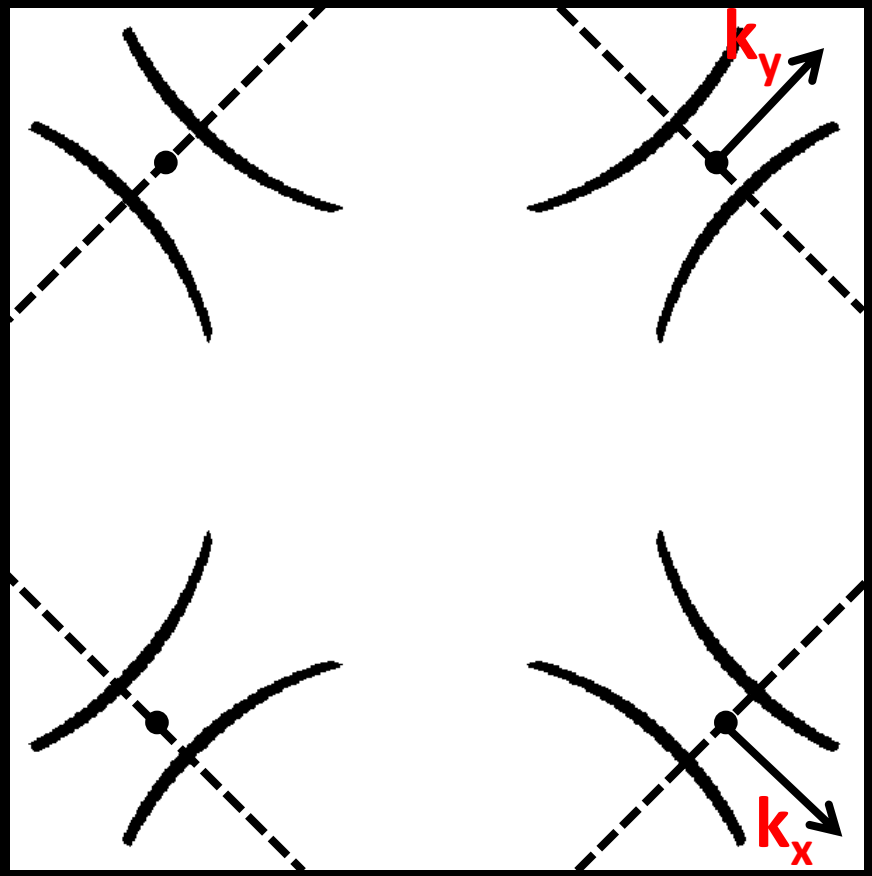


Low High

$q_4 = (2k_x, 2k_y)$ which follows the Fermi surface

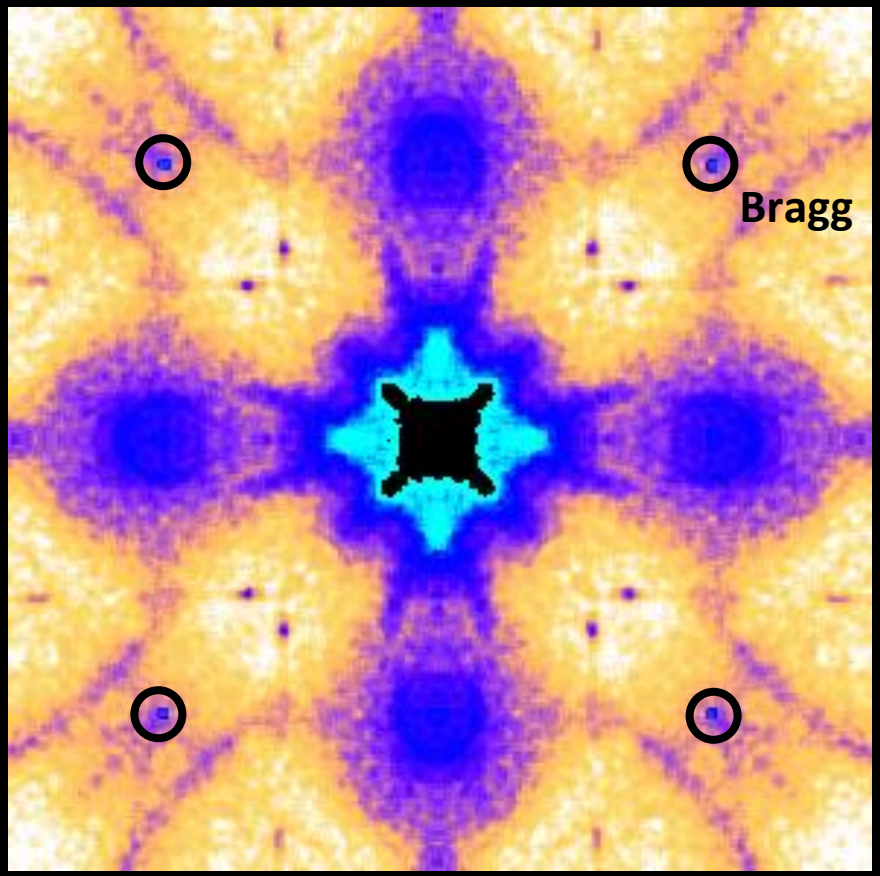
Autocorrelate just the antinodal Fermi surface

2 x Antinodal Fermi surface



q space QPI

OPT35K 5mV

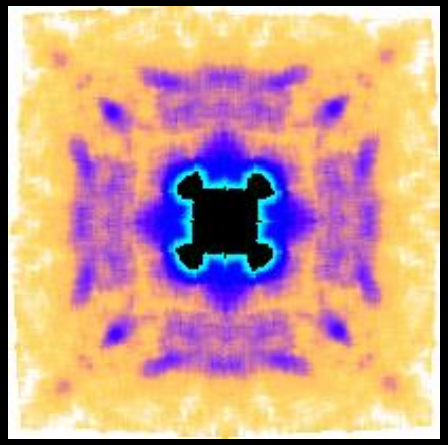


Low  High

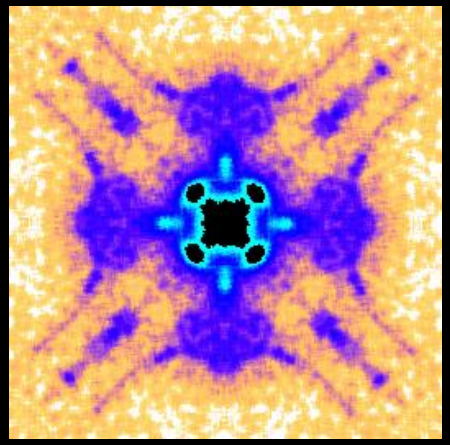
Triplet feature comes from antinode.

Luttinger count

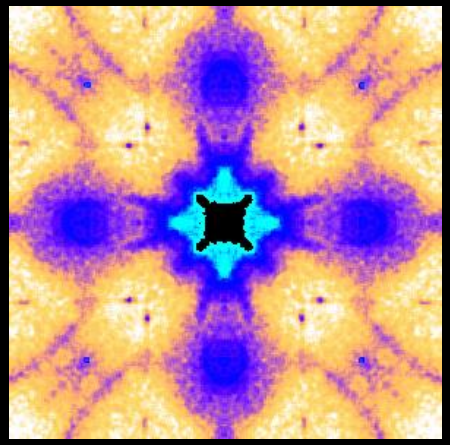
UD25K



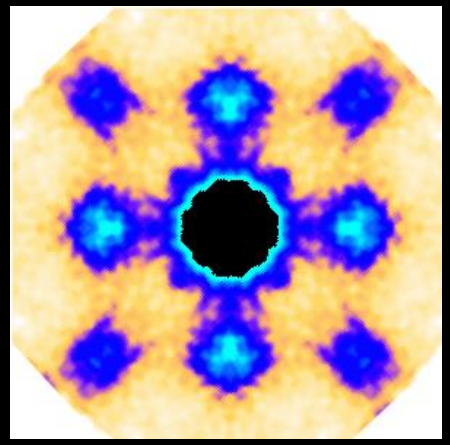
UD32K

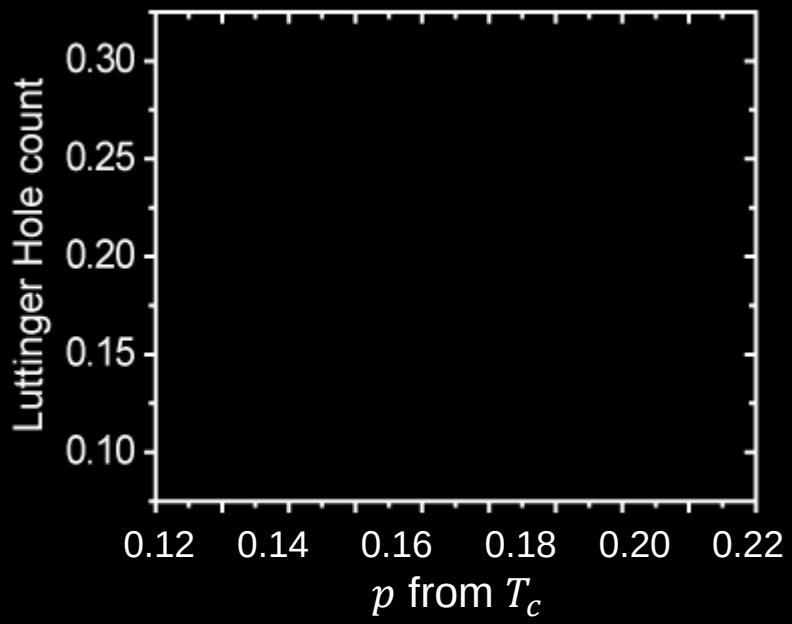


OPT35K



OD15K

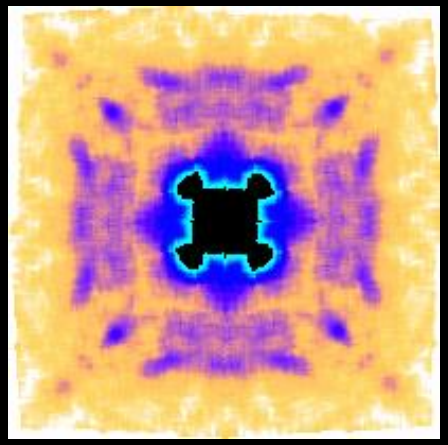




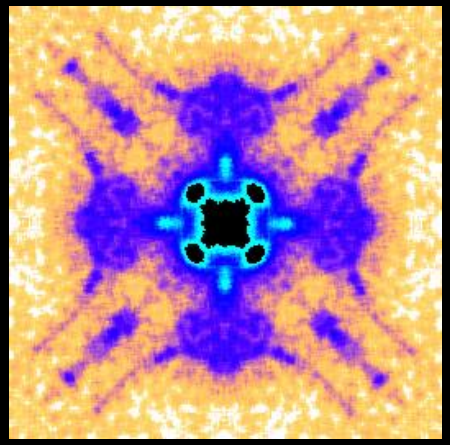
Ando, PRB 61, R14956 (2000)

Luttinger count

UD25K



UD32K



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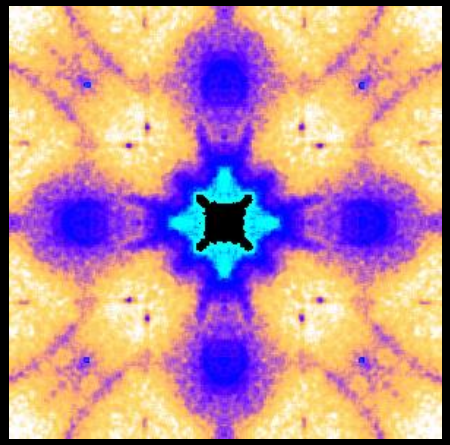
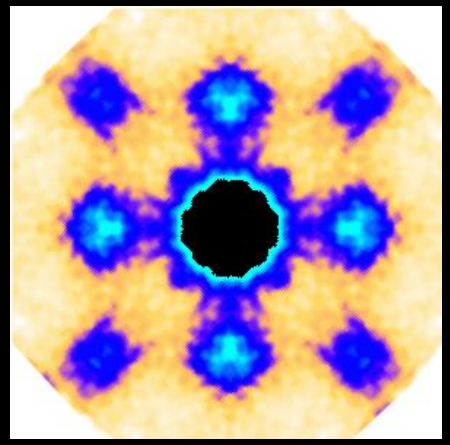
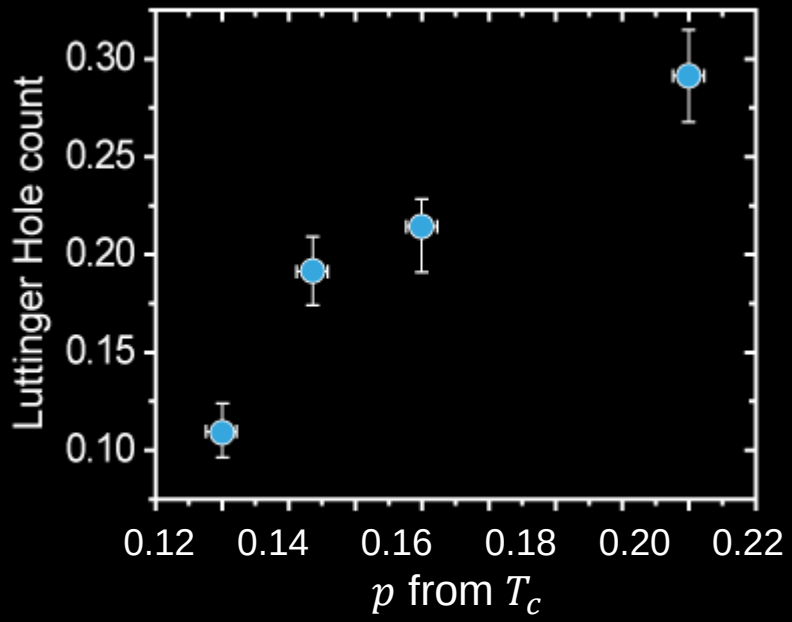
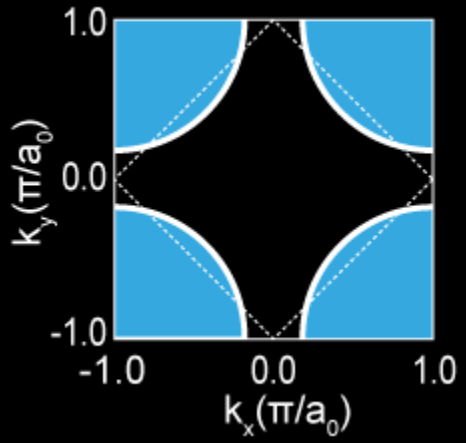


OD15K





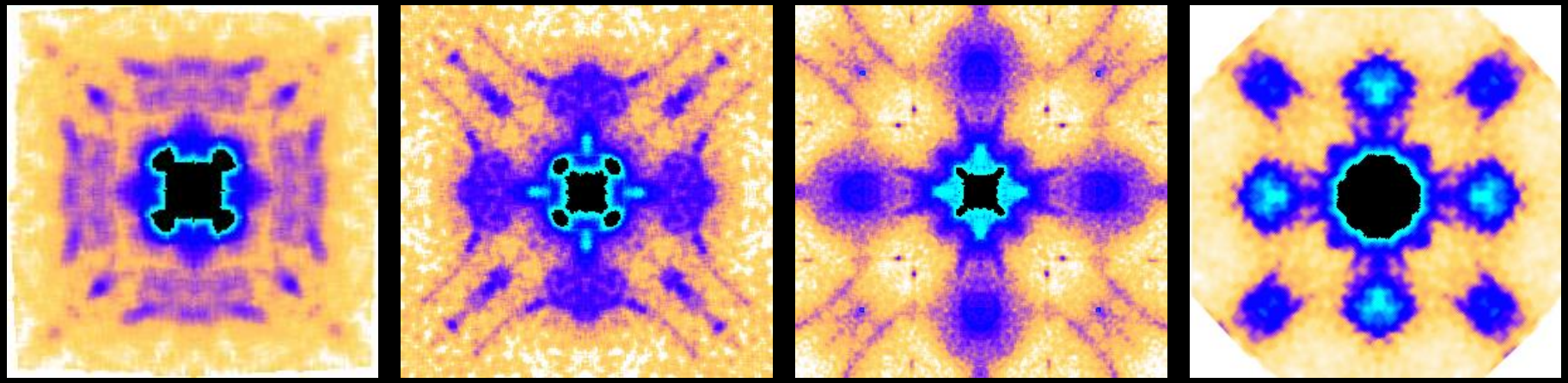
Ando, PRB 61, R14956 (2000)

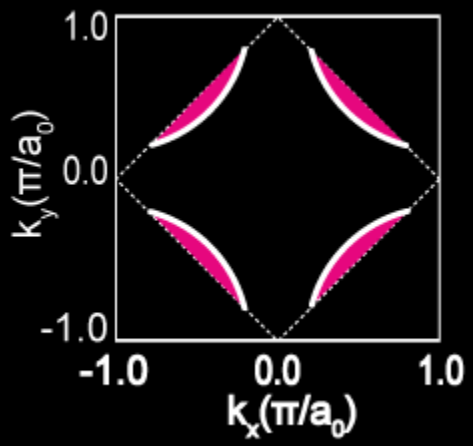


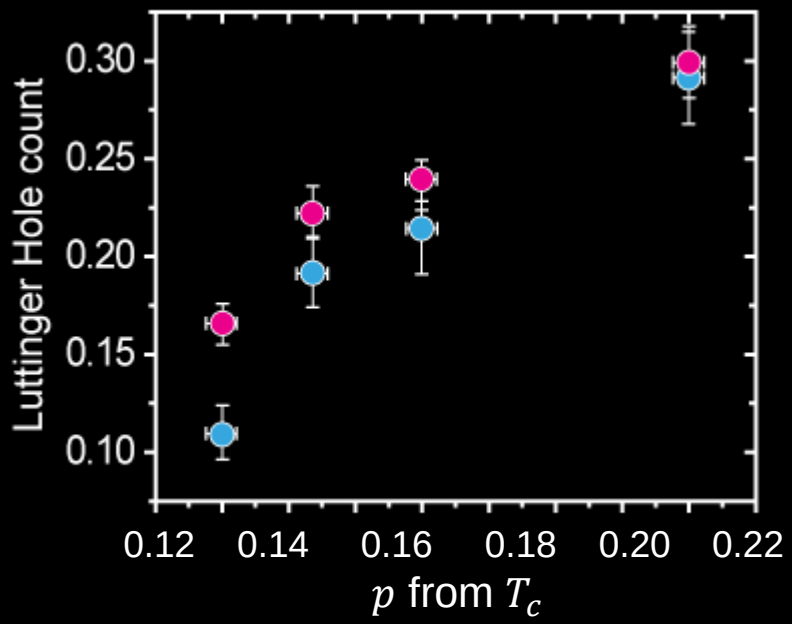
$$p_{\text{large}} = \frac{2A_{\text{blue}}}{A_{\text{BZ}}} - 1$$

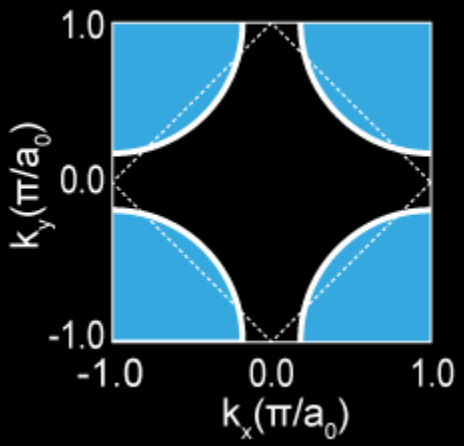
Luttinger count

UD25K UD32K OPT35K OD15K









$$p_{\text{small}} = \frac{2A_{\text{pink}}}{A_{\text{BZ}}}$$

$$p_{\text{large}} = \frac{2A_{\text{blue}}}{A_{\text{BZ}}} - 1$$

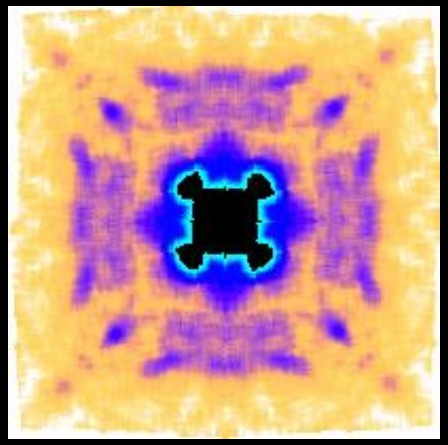
YRZ, PRB 73, 174501 (2006)

Qi + Sachdev, PRB 81, 115129 (2010)

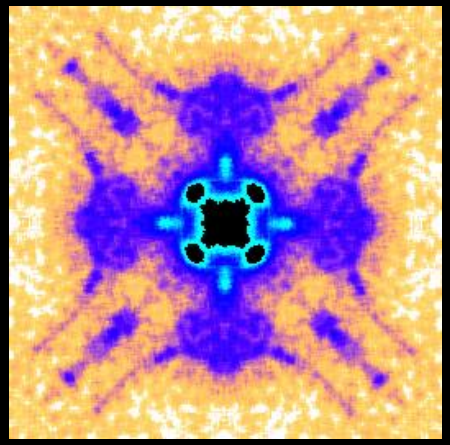
Ando, PRB 61, R14956 (2000)

Luttinger count

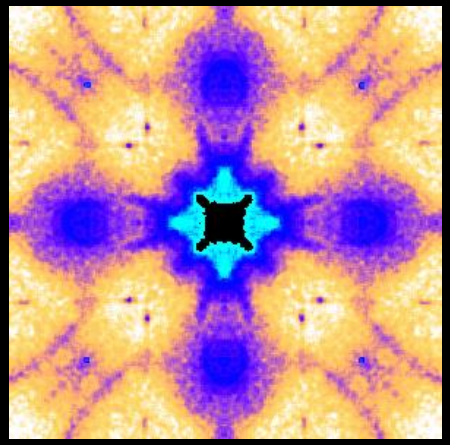
UD25K



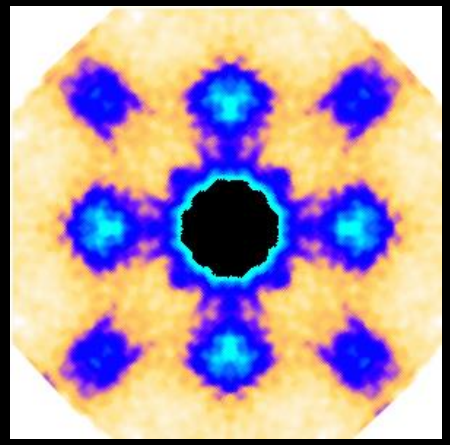
UD32K

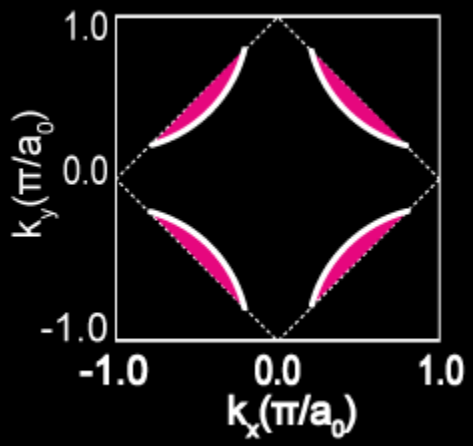


OPT35K



OD15K

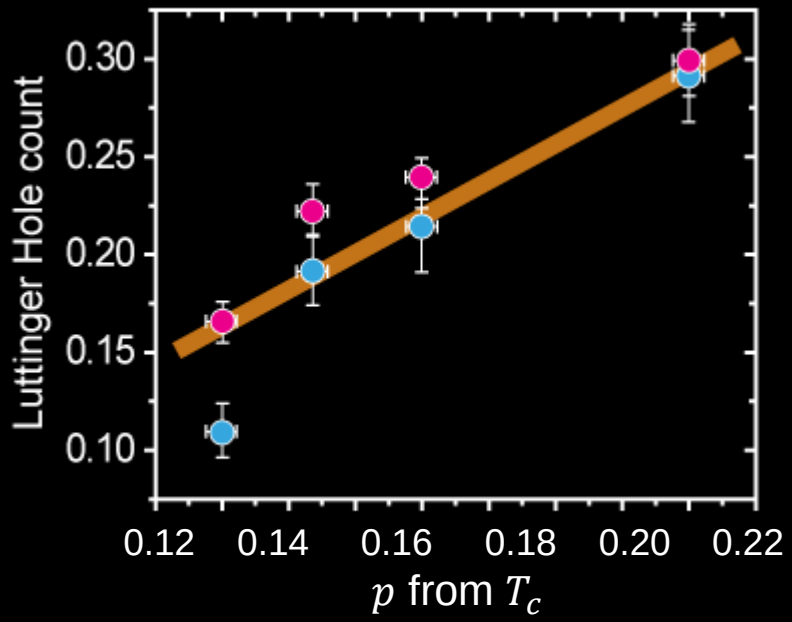




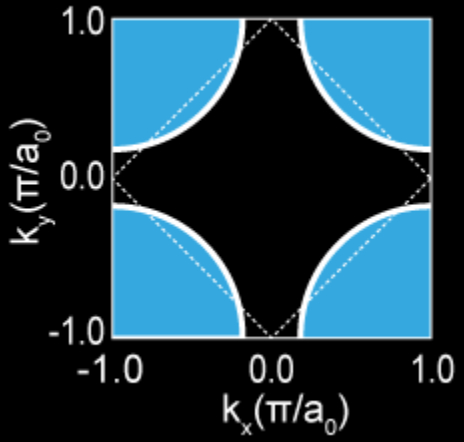
$$p_{\text{small}} = \frac{2A_{\text{pink}}}{A_{\text{BZ}}}$$

YRZ, PRB 73, 174501 (2006)

Qi + Sachdev, PRB 81, 115129 (2010)



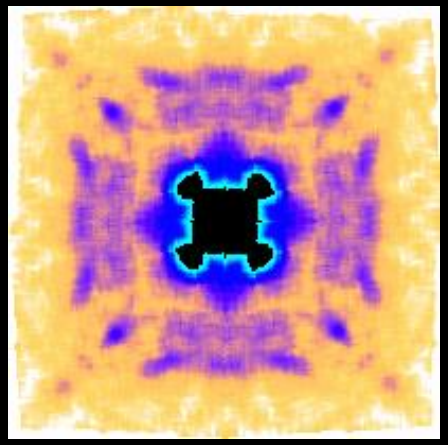
Ando, PRB 61, R14956 (2000)



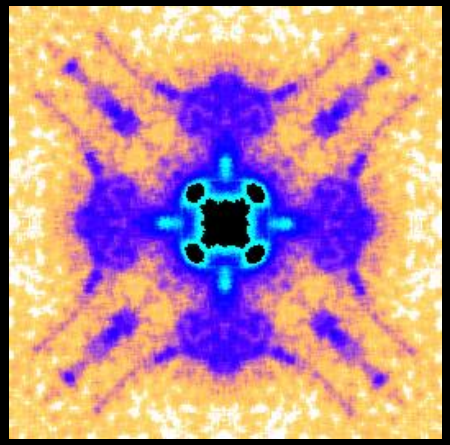
$$p_{\text{large}} = \frac{2A_{\text{blue}}}{A_{\text{BZ}}} - 1$$

Luttinger count

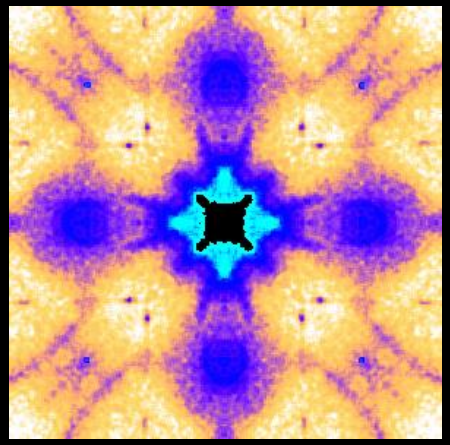
UD25K



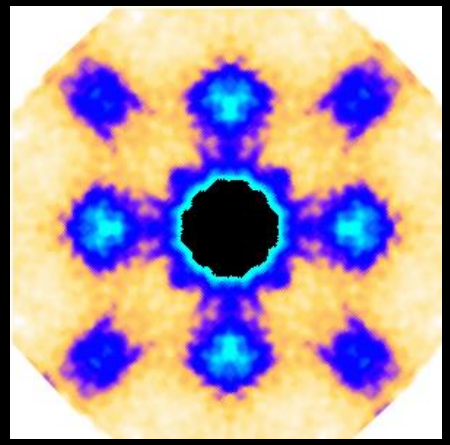
UD32K

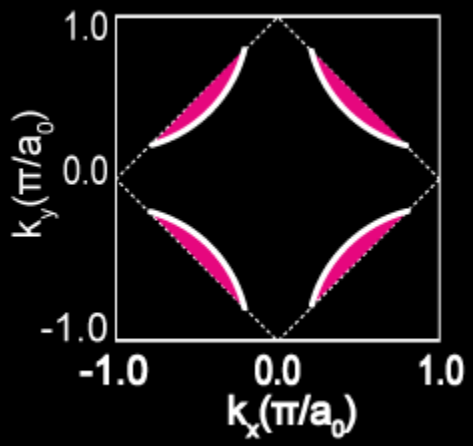


OPT35K



OD15K

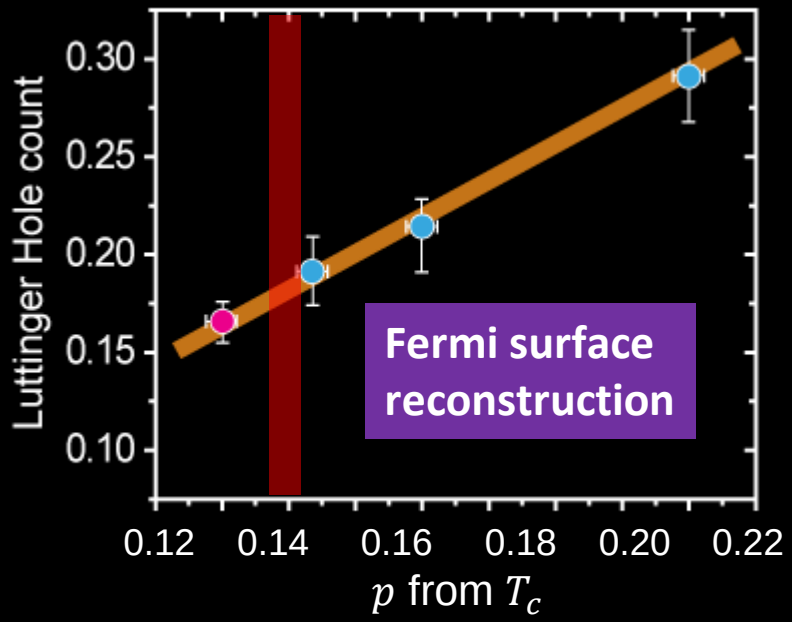




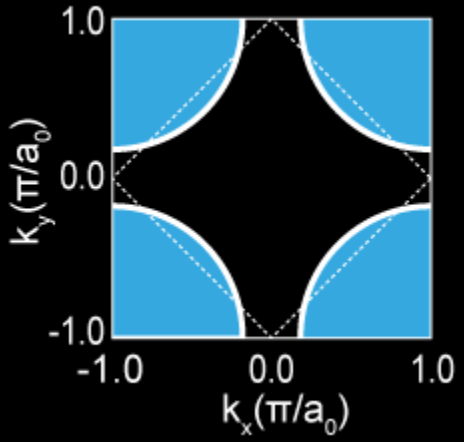
$$p_{\text{small}} = \frac{2A_{\text{pink}}}{A_{\text{BZ}}}$$

YRZ, PRB 73, 174501 (2006)

Qi + Sachdev, PRB 81, 115129 (2010)

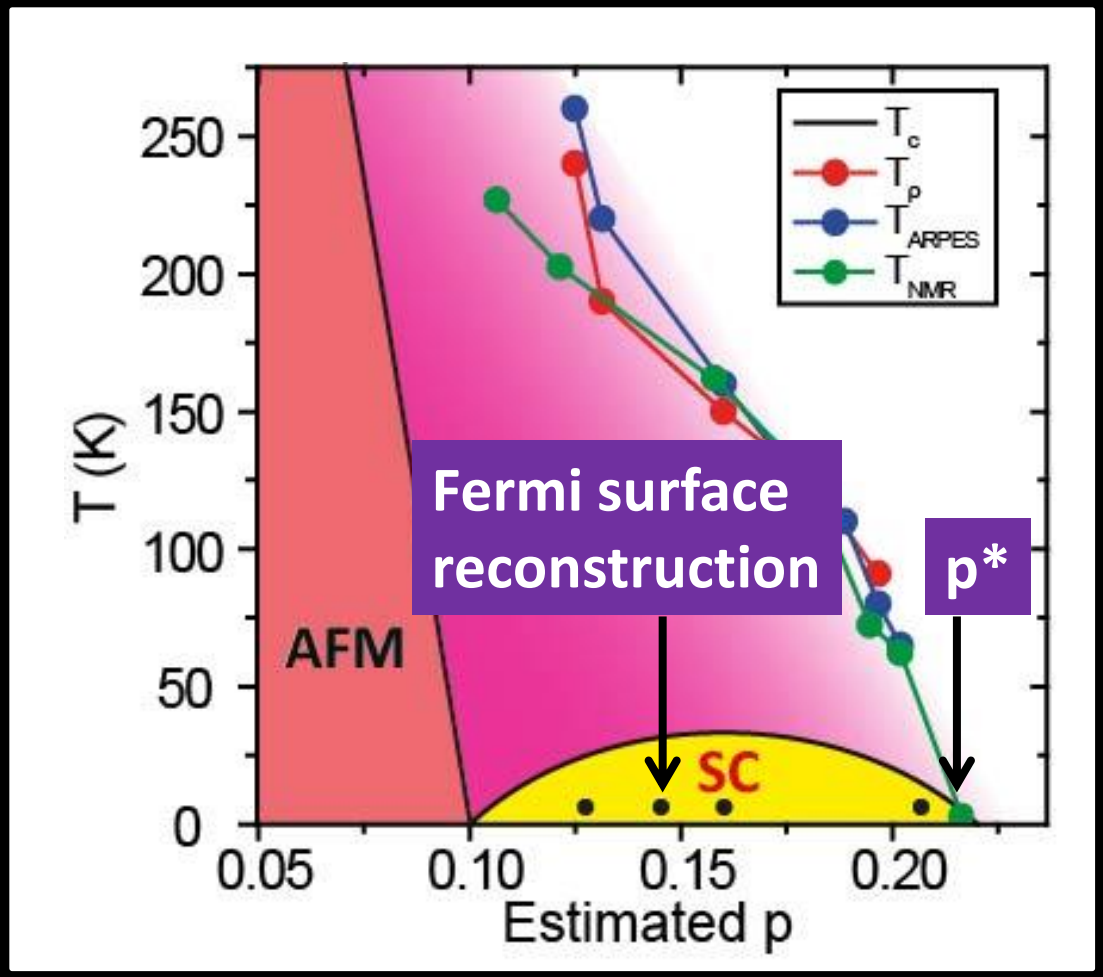


Ando, PRB 61, R14956 (2000)



$$p_{\text{large}} = \frac{2A_{\text{blue}}}{A_{\text{BZ}}} - 1$$

FS reconstruction & pseudogap



In Bi2201, p* does not coincide with Fermi surface reconstruction

Outline

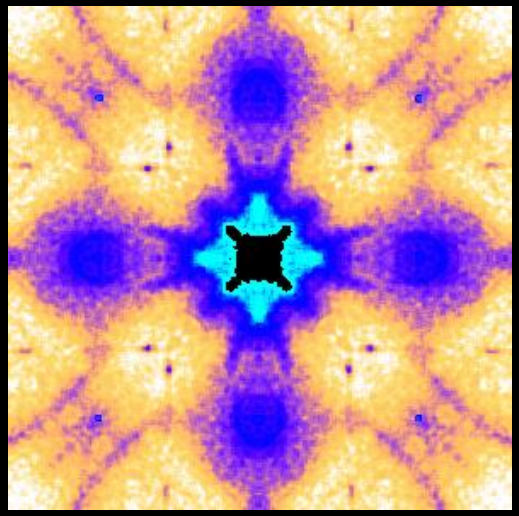
1. Where is the Fermi surface reconstruction?

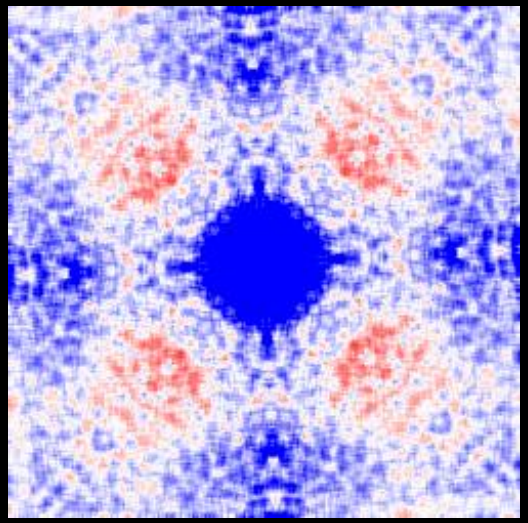
   Answer: coincides with QCP near optimal doping at B=0

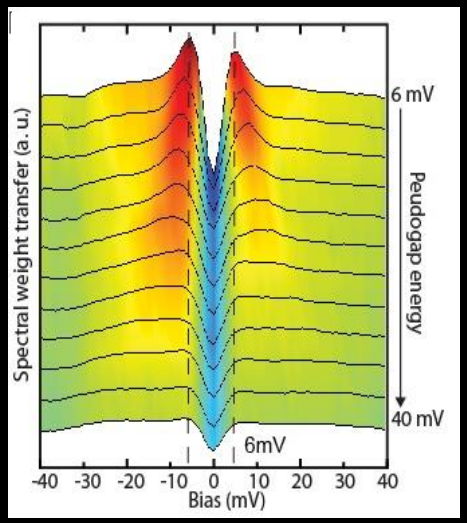
2. What is the role of the pseudogap?

   Answer:

   - separate occurrence
   - coexists with superconductivity at the antinode
   - causes decoherence at the nanoscale



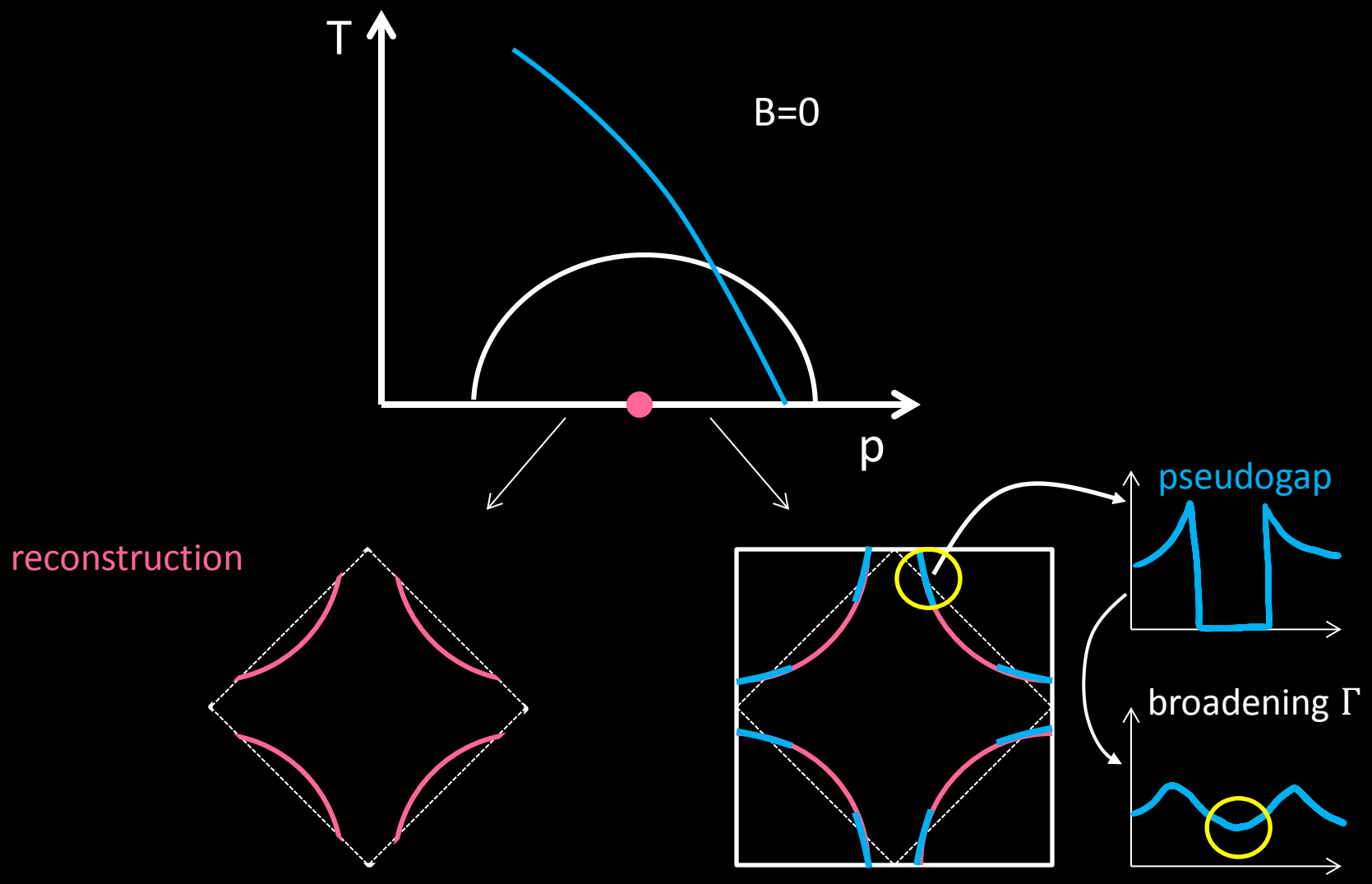




arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

What about superconductivity?

1. Fermi surface reconstruction ≠ pseudogap

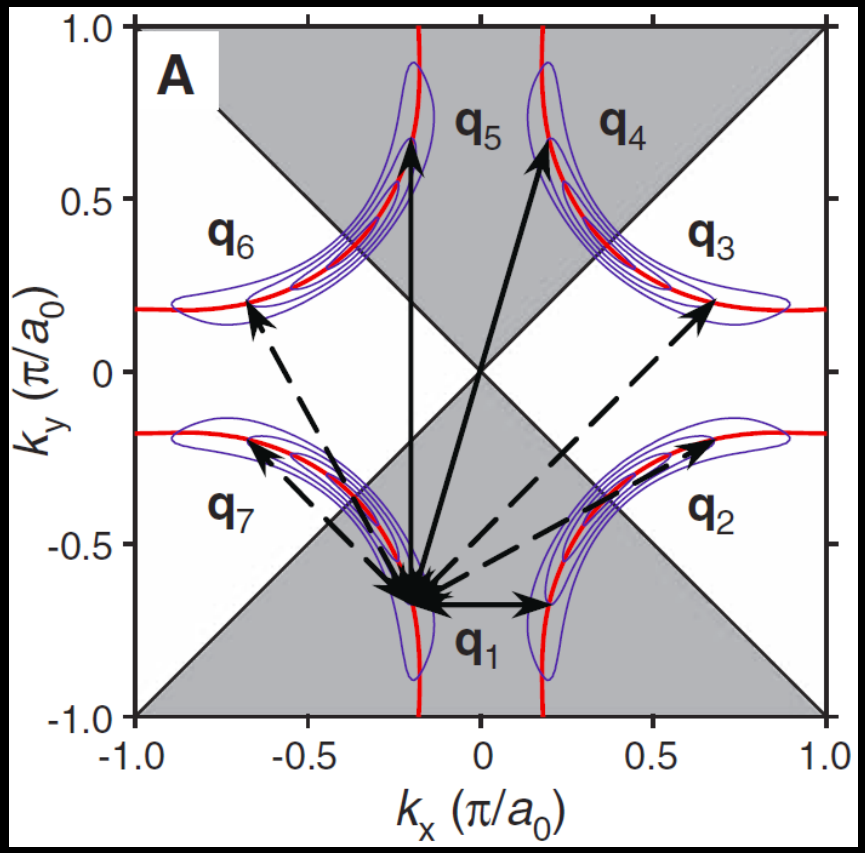


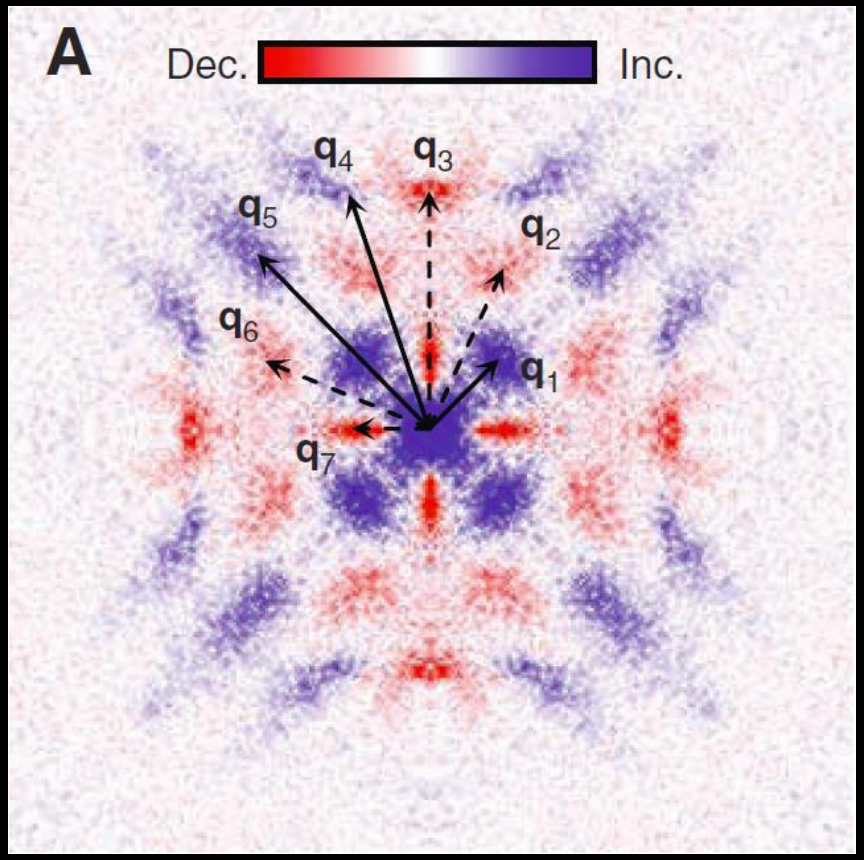
Can superconductivity live here too?

d-wave coherence factors in Bi2212

sign flipping → **decreasing in field**

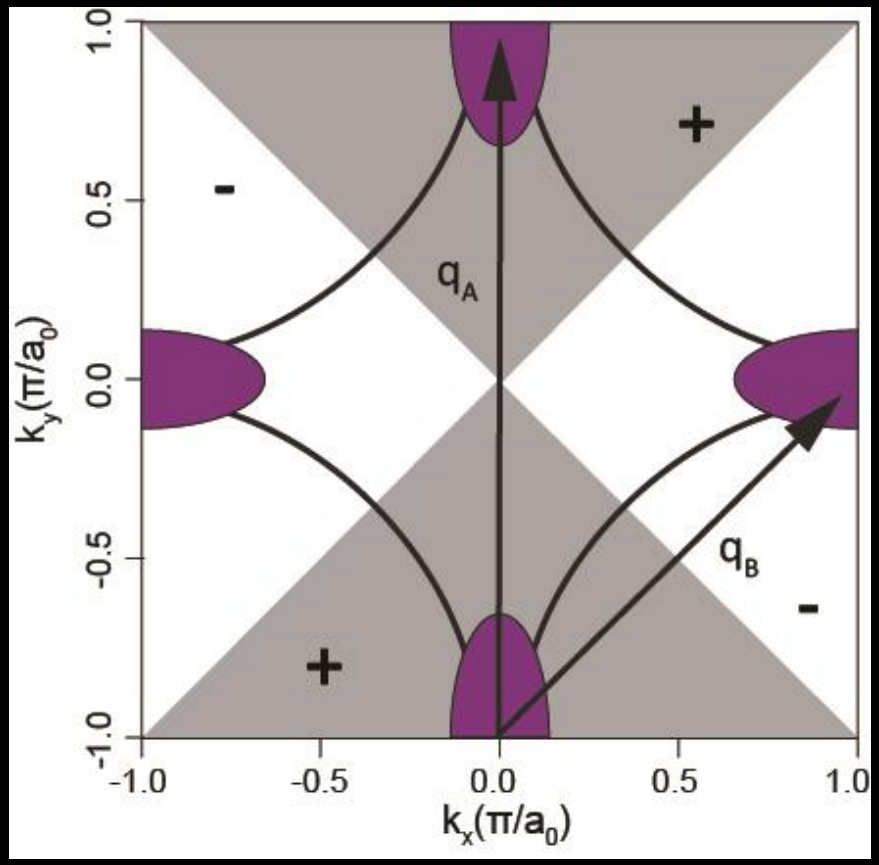
sign preserving → **increasing in field**



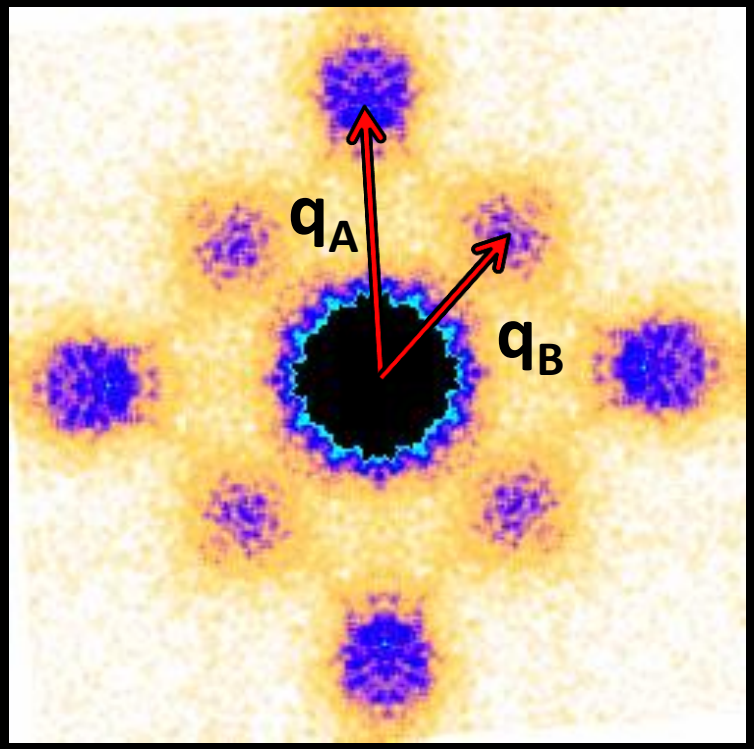


Hanaguri, et al, Science 323, 923 (2009)
suggested by Tami Pereg-Barnea & Marcel Franz
PRB 78, 020509 (2008)

antinodal *d*-wave coherence in Bi2201



OD15K 6mV, 0T

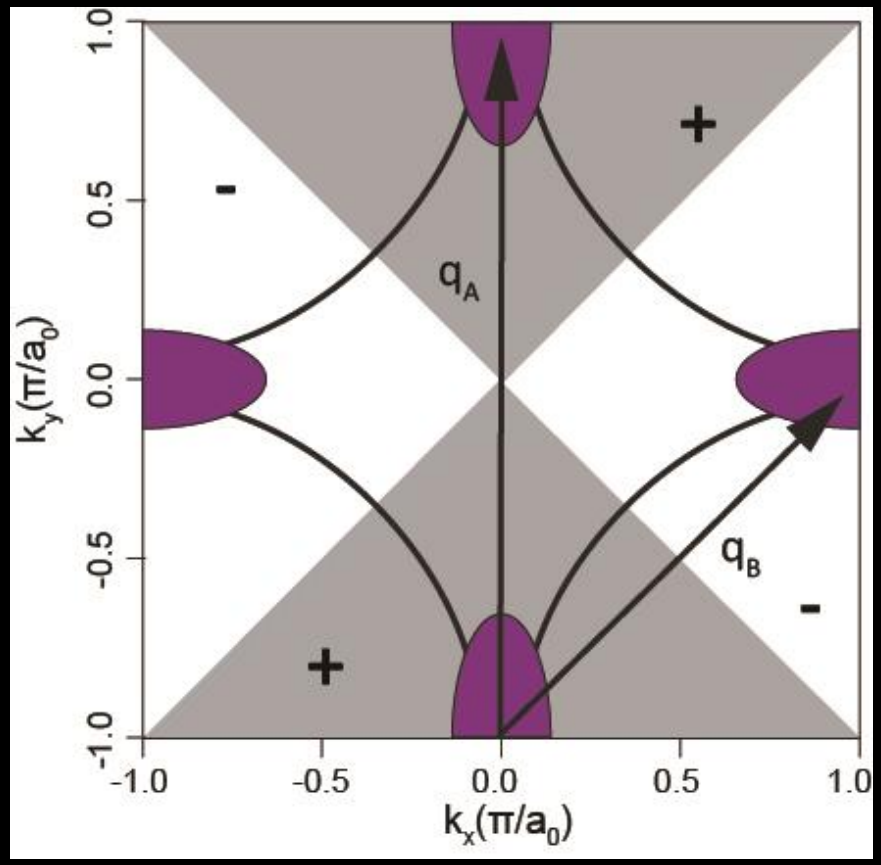


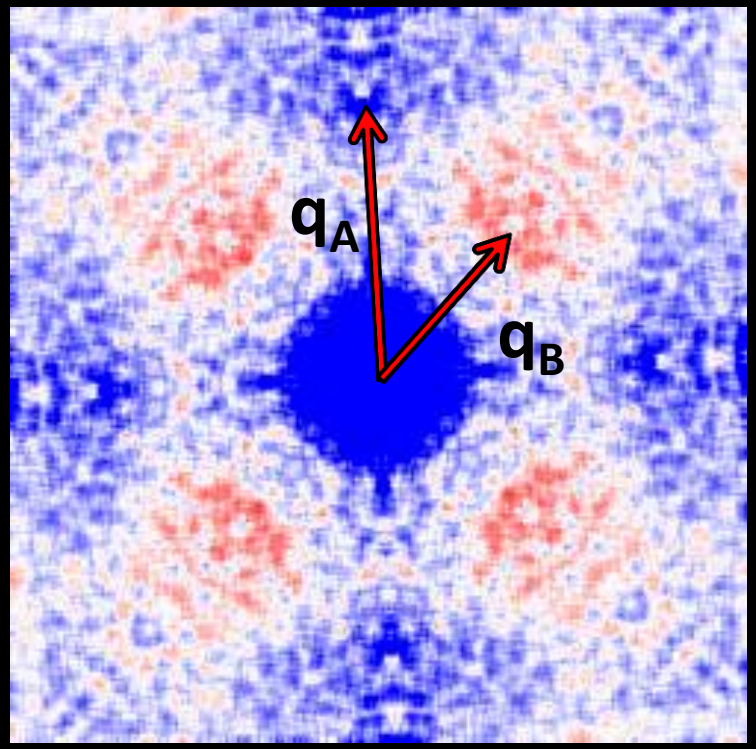
antinodal *d*-wave coherence in Bi2201

sign flipping → **decreasing in field**

sign preserving → **increasing in field**

OD15K 6mV, 9T-0T





Decreasing  Increasing

Field dependence

→ Antinodal quasiparticles show d-wave coherence

Outline

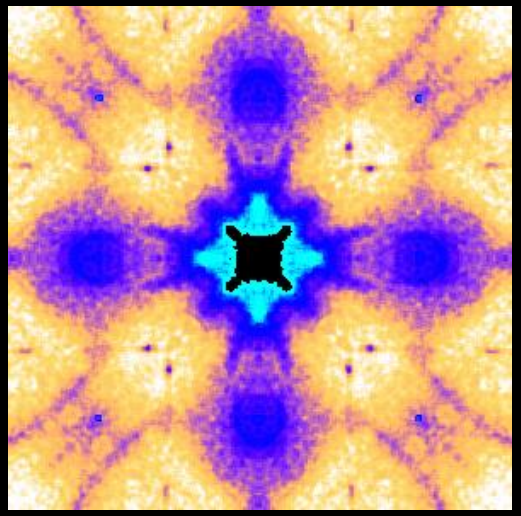
1. Where is the Fermi surface reconstruction?

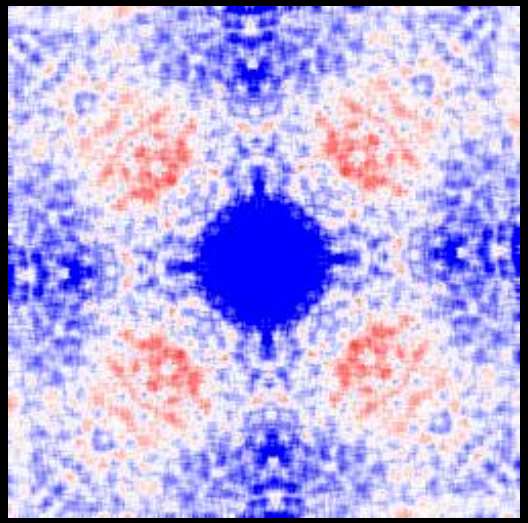
   Answer: coincides with QCP near optimal doping at B=0

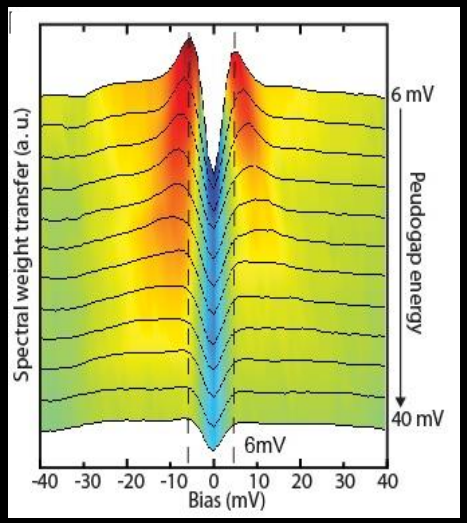
2. What is the role of the pseudogap?

   Answer:

   - separate occurrence
   - coexists with superconductivity at the antinode
   - causes decoherence at the nanoscale





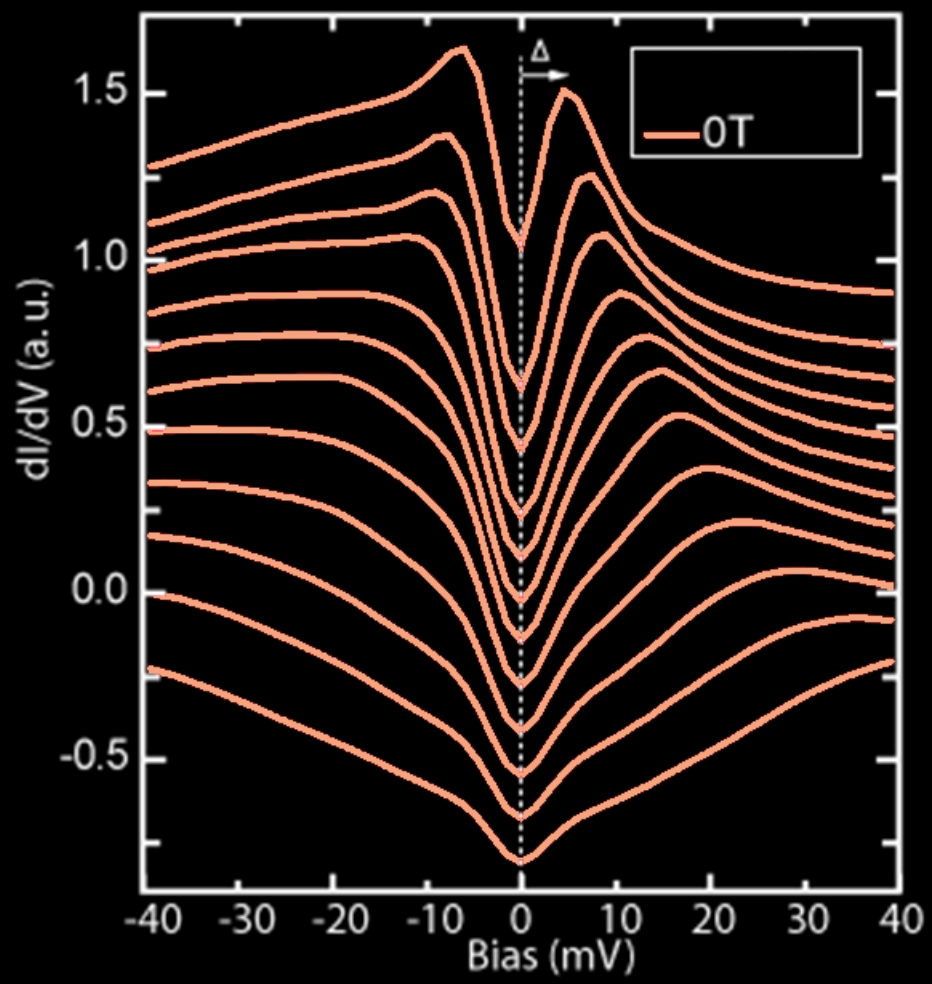


arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

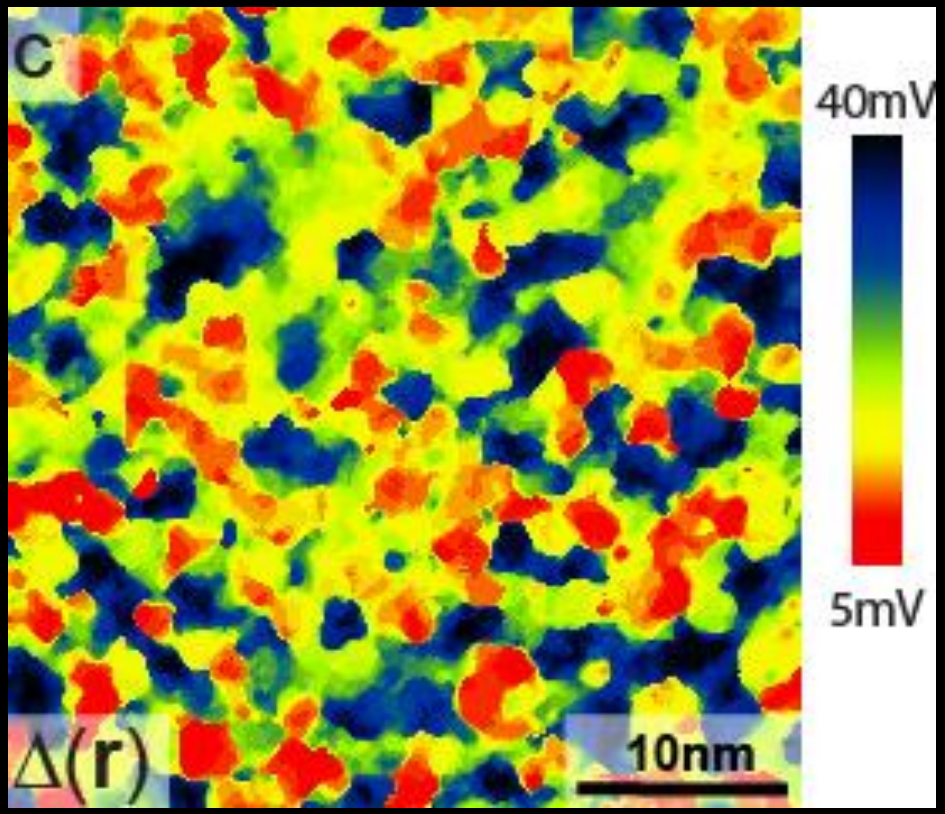
Two gap scenario: coexist spatially?

superconductivity vs. pseudogap at antinode?

OD15K

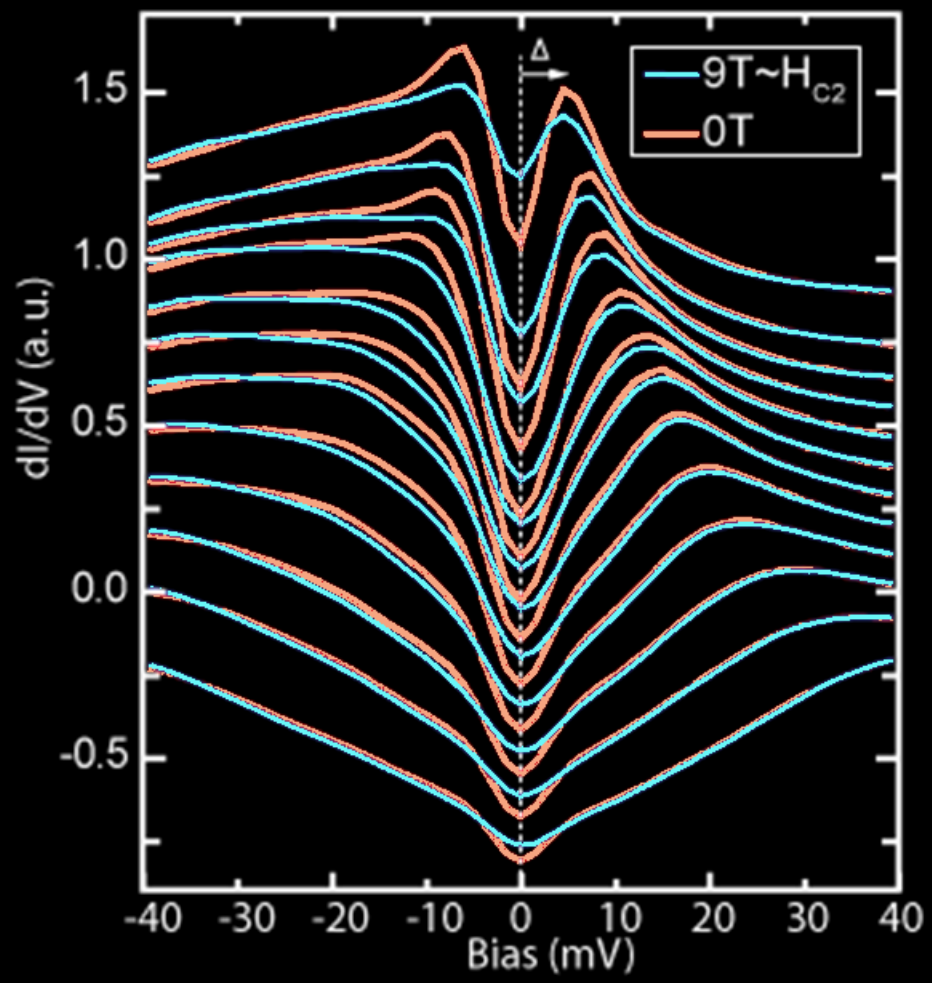


Δ_{PG}

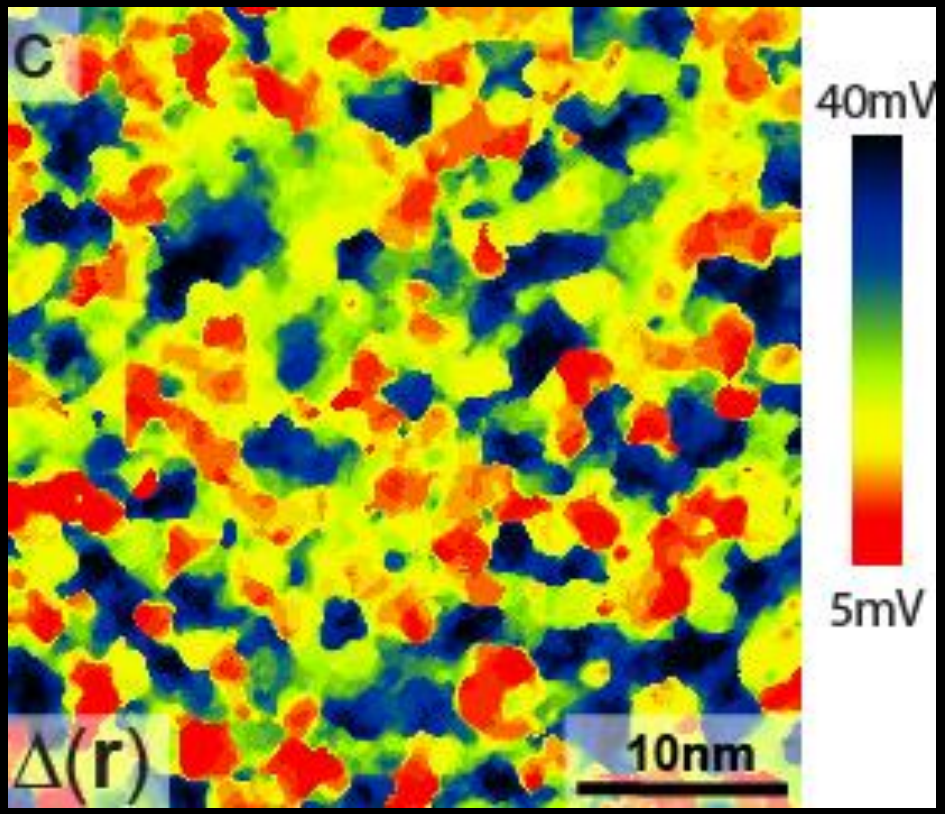


Two gap scenario: coexist spatially?

OD15K



Δ_{PG}

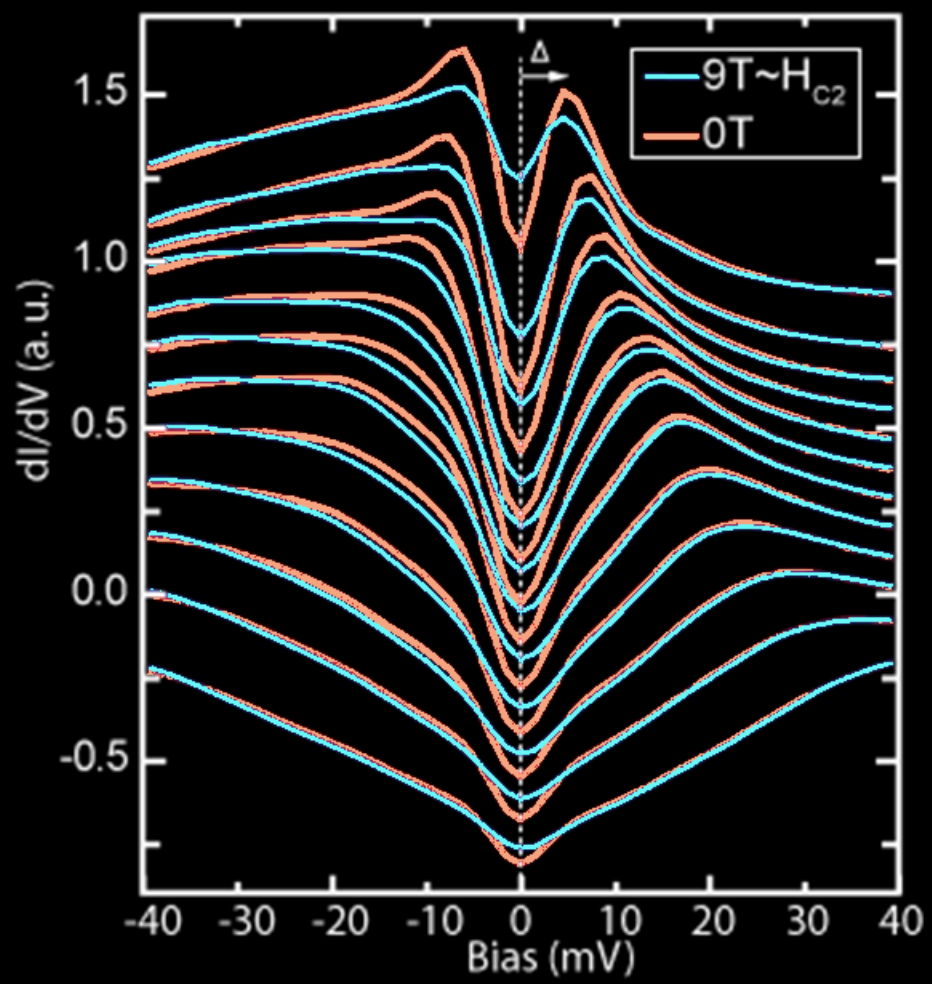


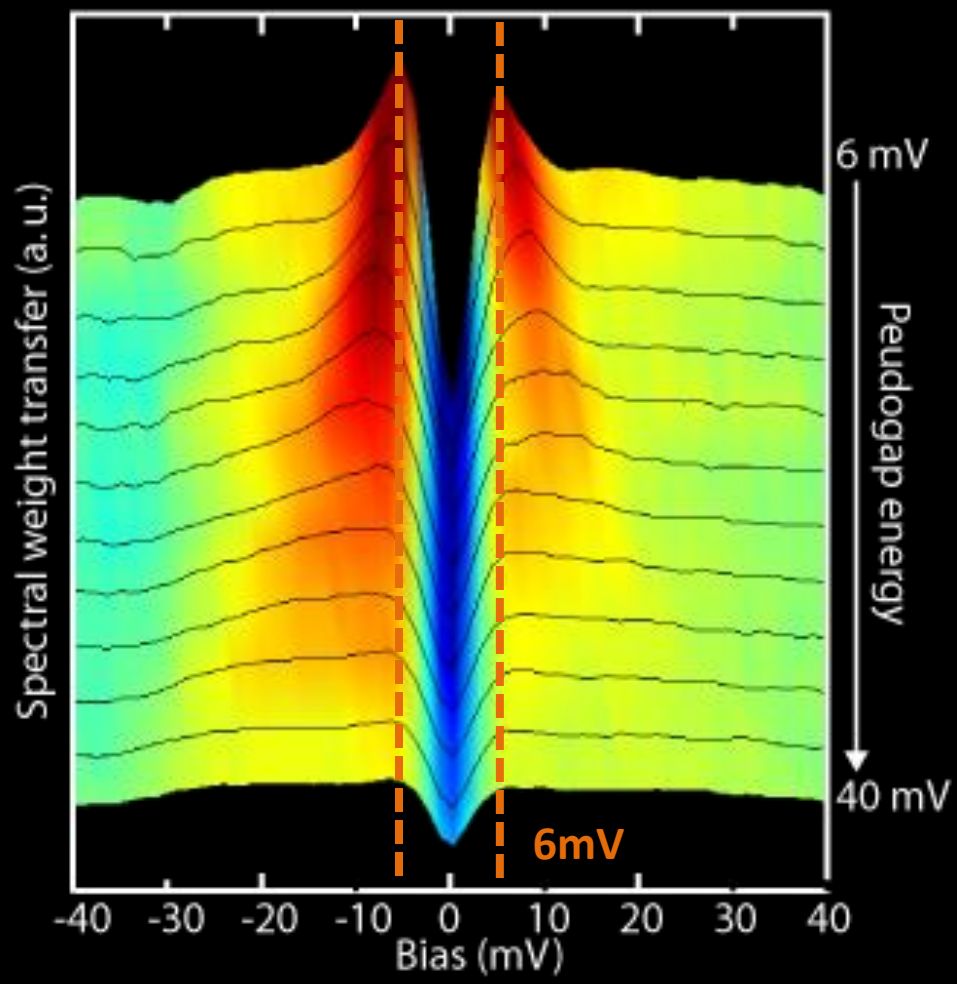
Two gap scenario: coexist spatially?

Field-induced spectral weight transfer:

$S(E) = g(E, 0T) - g(E, 9T)$

OD15K





1. PG suppresses SC coherence.
2. PG does not affect SC order parameter amplitude.

Conclusions

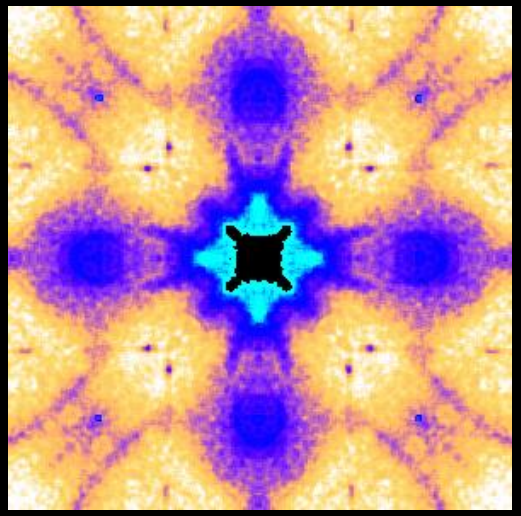
1. Where is the Fermi surface reconstruction?

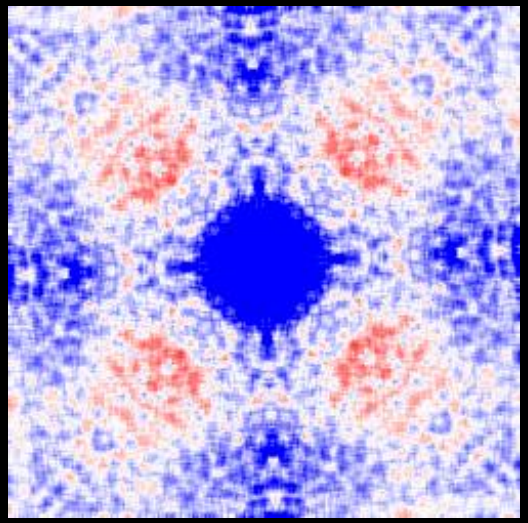
   Answer: coincides with QCP near optimal doping at B=0

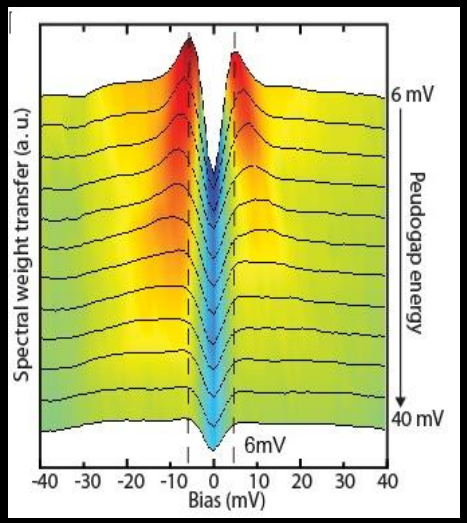
2. What is the role of the pseudogap?

   Answer:

   - separate occurrence
   - coexists with superconductivity at the antinode
   - causes decoherence at the nanoscale



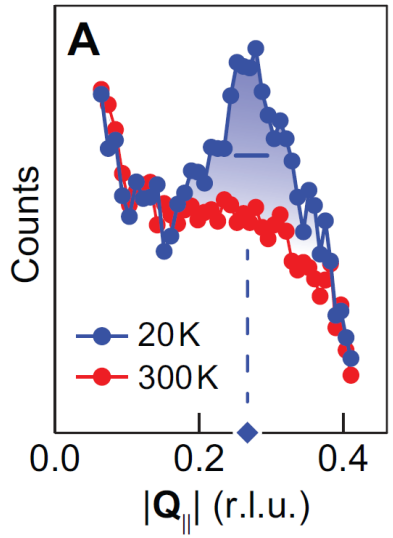




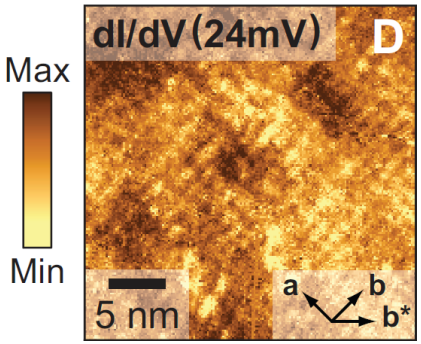
arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

What about charge order?

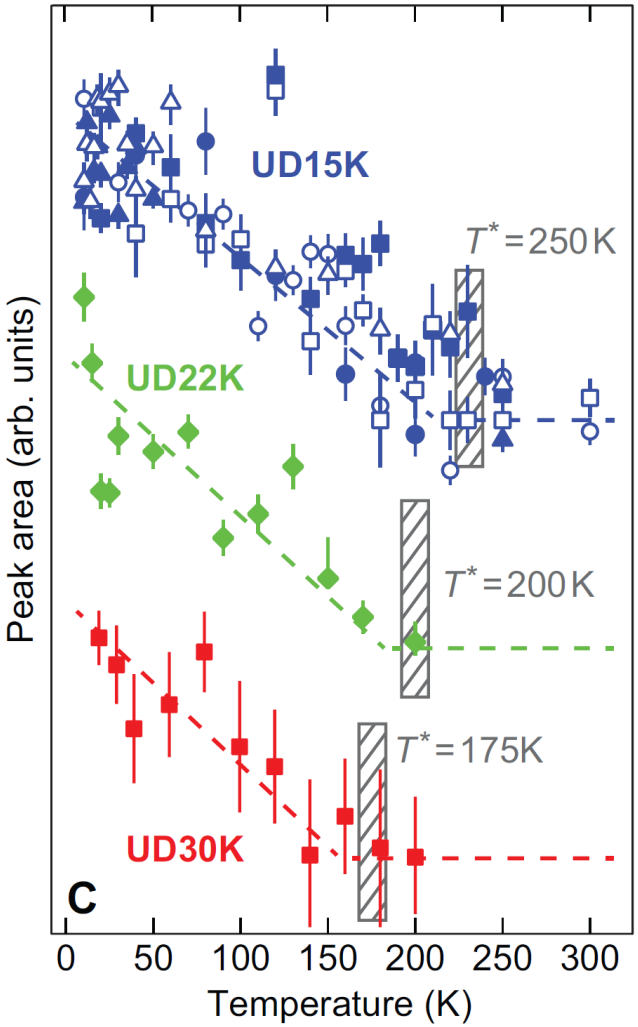
Bi2201: First ever reconciliation of STM-observed and X-ray-observed charge order!



Resonant X-ray Scattering



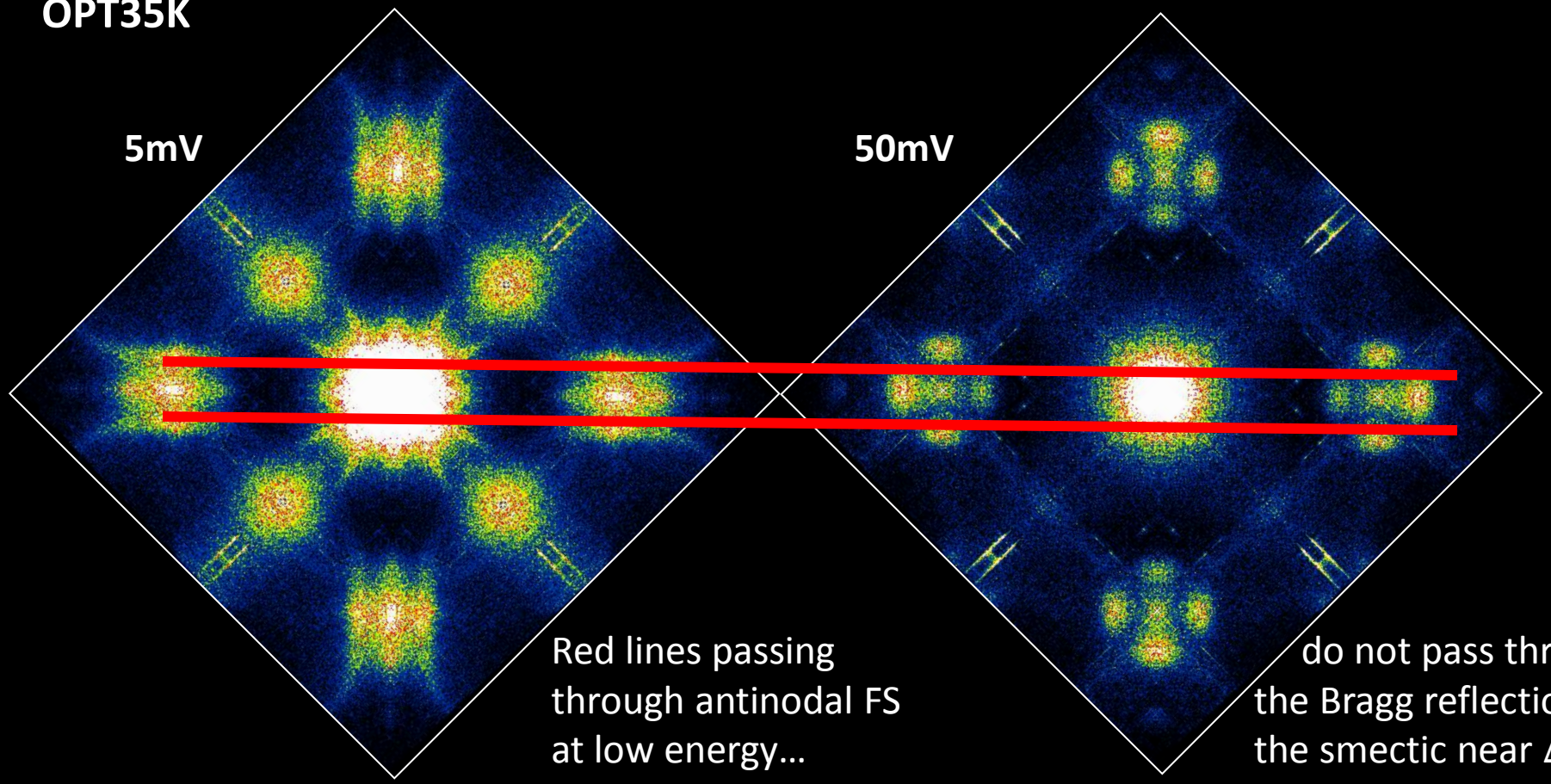
Scanning Tunneling Microscopy



Riccardo Comin *et al*, ***Science*** 343, 390 (2014)

Charge order is not antinodal nesting

Bi2201
OPT35K

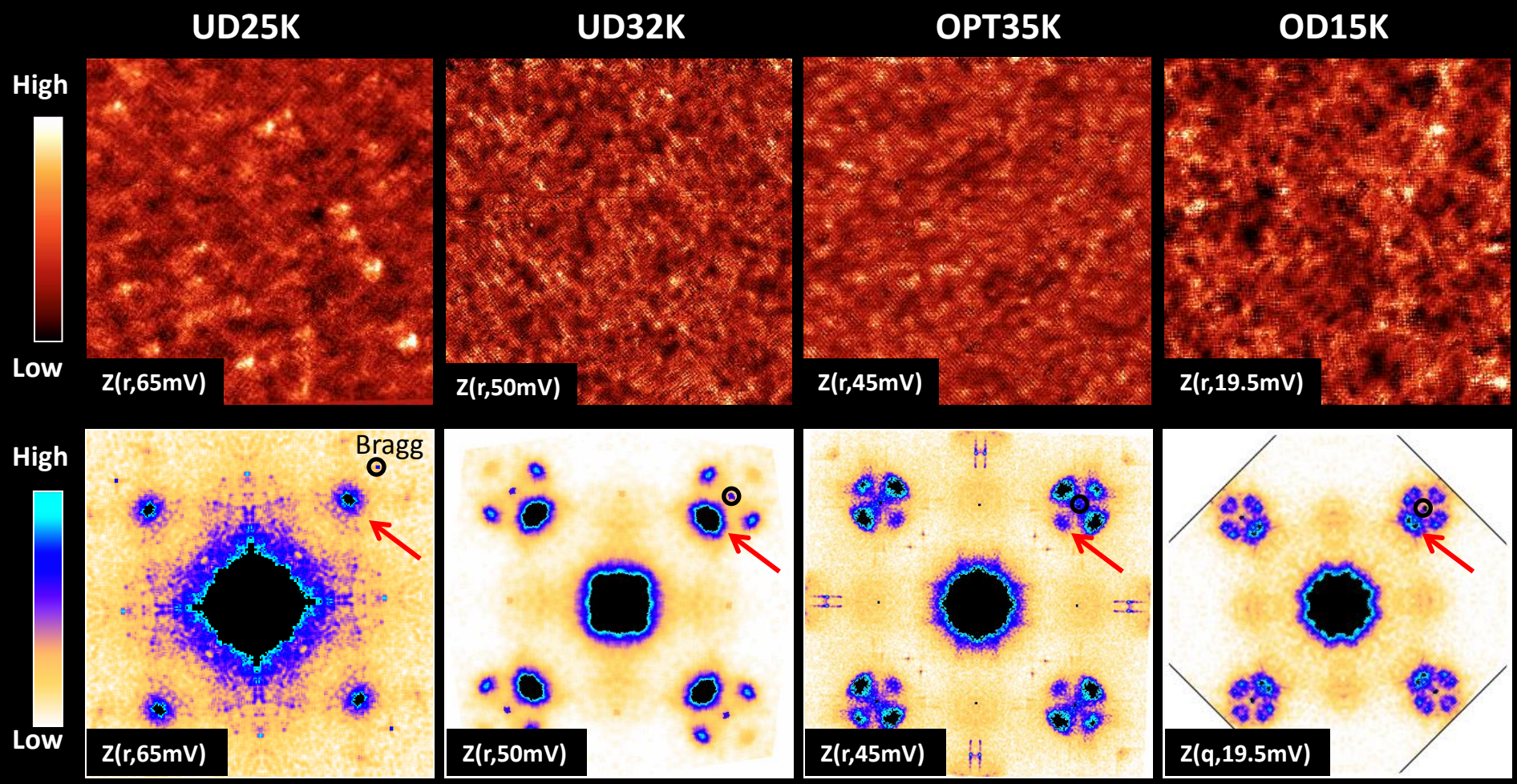


Red lines passing through antinodal FS at low energy…

do not pass through the Bragg reflections of the smectic near Δ_{PG}

→ charge order wavevector is the AFBZ hotspot wavevector, not the antinodal nesting vector

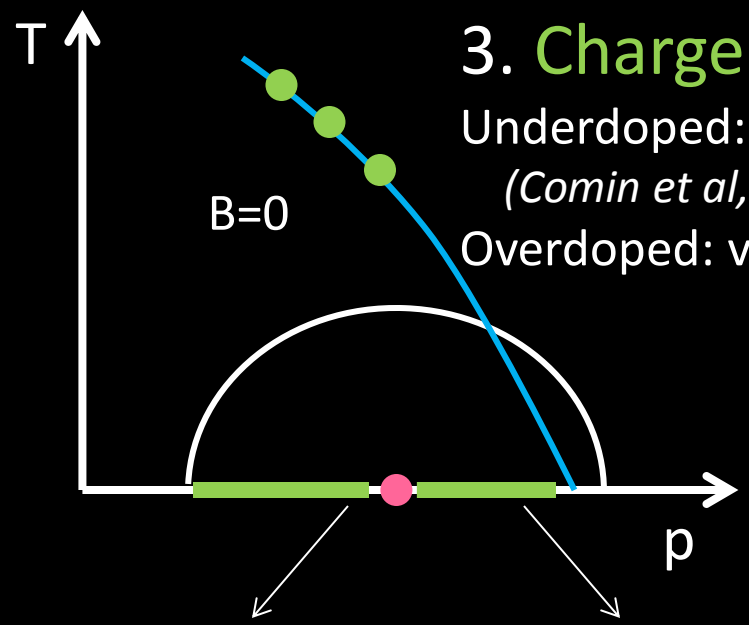
Charge order is present at all dopings in Bi2201



Charge order correlation length shows no trend with doping
(in particular, no longer in the most underdoped sample with small FS)

Conclusions (STM on Bi2201)

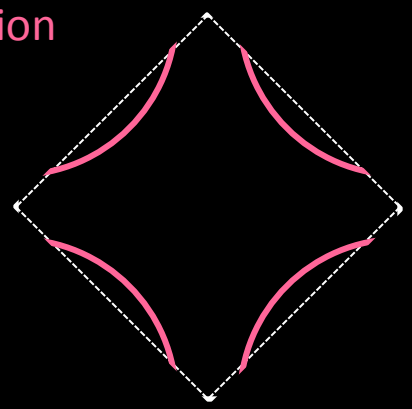
1. Fermi surface reconstruction ≠ pseudogap

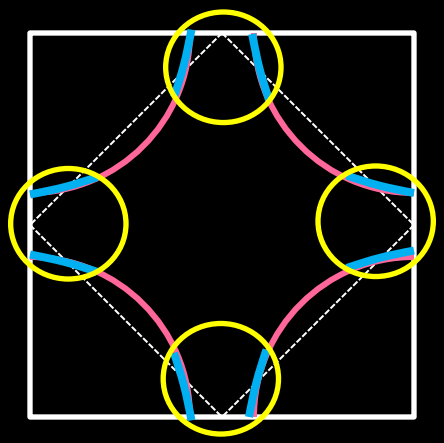


3. Charge order

Underdoped: bulk-surface correspondence
(Comin et al, Science 343, 390 2014)
Overdoped: visible on surface to p*

reconstruction



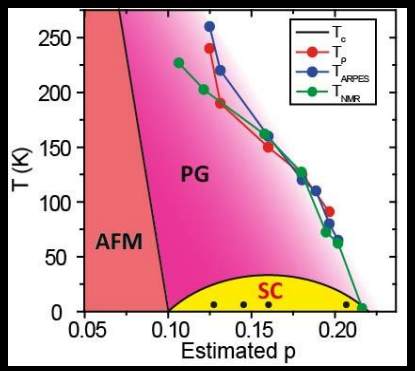


pseudogap

2. Superconductivity coexists with pseudogap at the antinode

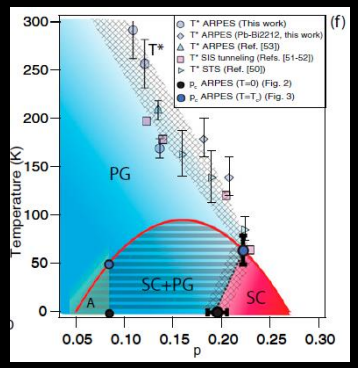
Forest of Phase Diagrams

Bi2201



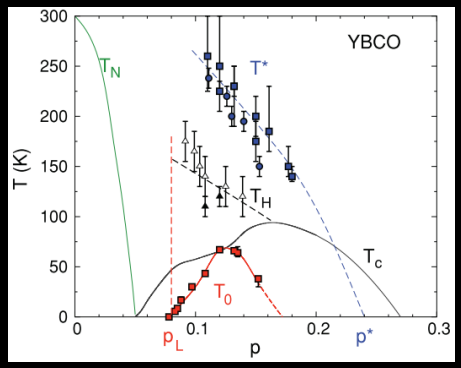
This talk

Bi2212



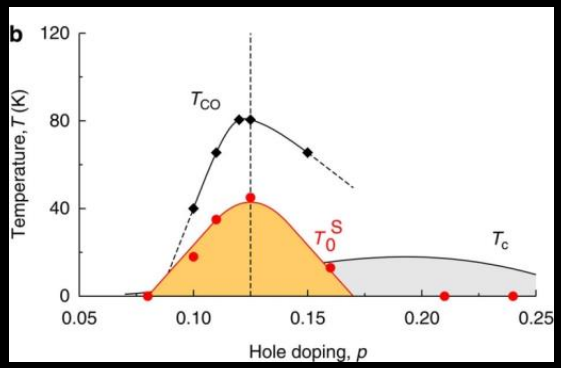
Vishik, PNAS 2012

YBCO



LeBouef, PRB 2011

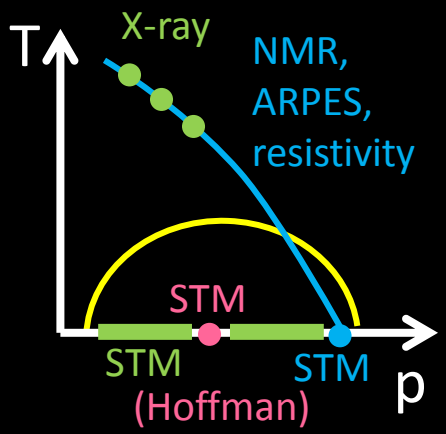
Eu-LSCO



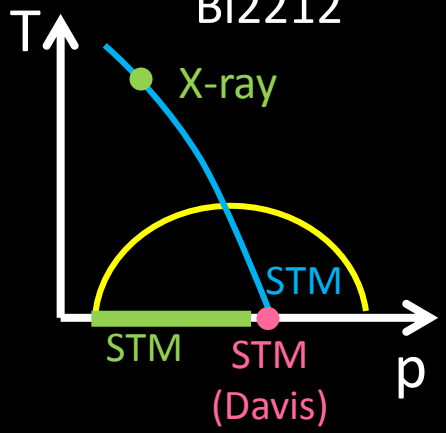
Laliberte, Nature Comm 2012

- Pseudogap
- Charge order
- FS reconstruction
- Superconductivity

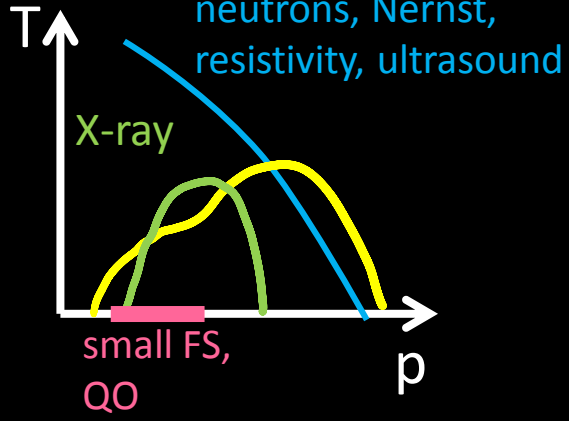
Bi2201



Bi2212



YBCO & LSCO



Why does Bi2212 have no fluctuating CDW regime?
Is the T* line in cuprates something else entirely?