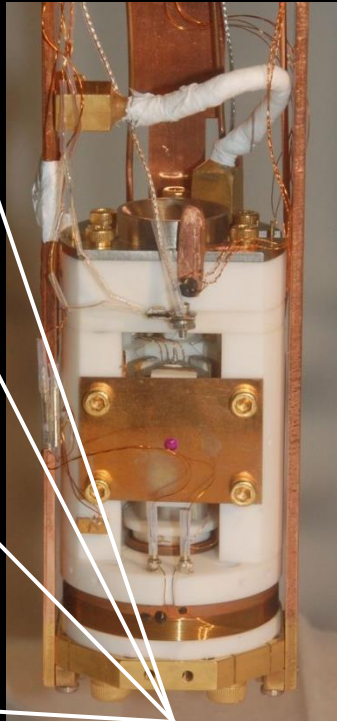


Hoffman Lab Local Probes



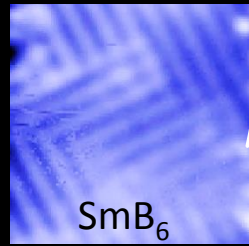
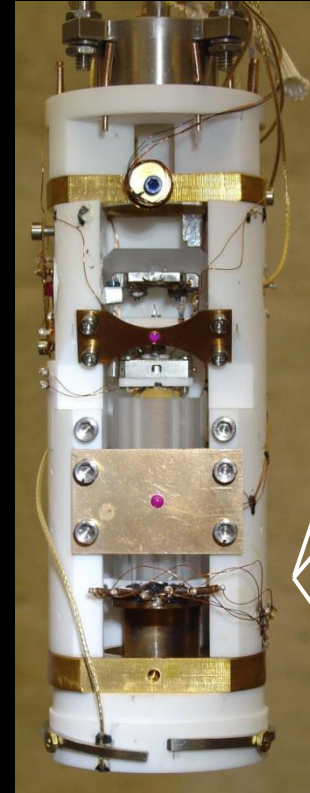
Scanning Tunneling
Microscope



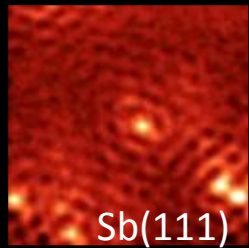
Force Microscope



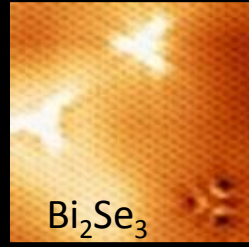
Ultra-high vacuum STM



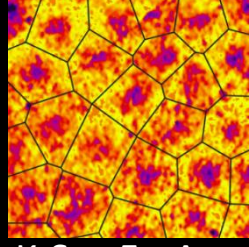
SmB_6



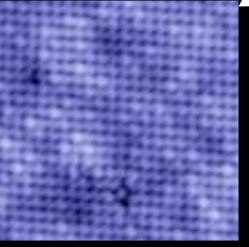
$\text{Sb}(111)$



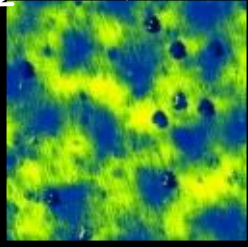
Bi_2Se_3



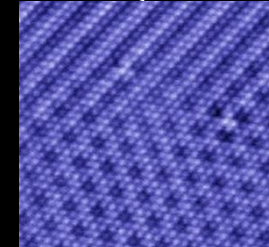
$\text{K}_x\text{Sr}_{1-x}\text{Fe}_2\text{As}_2$



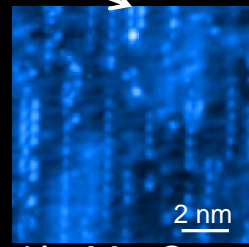
Bi-2201



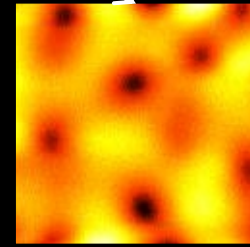
$\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$



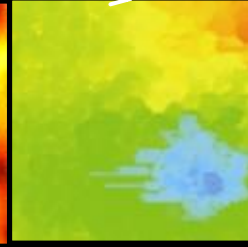
NbSe_2



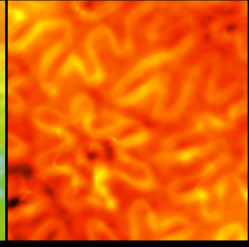
$\text{Li}_{0.9}\text{Mo}_6\text{O}_{17}$



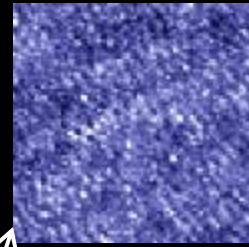
$\text{NdFeAsO}_{1-x}\text{F}_x$



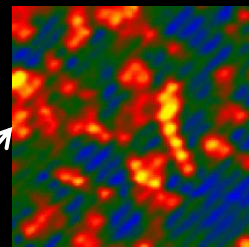
VO_2



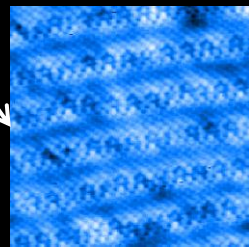
$\text{Nd}_2\text{Fe}_{14}\text{B}$



Ca-YBCO



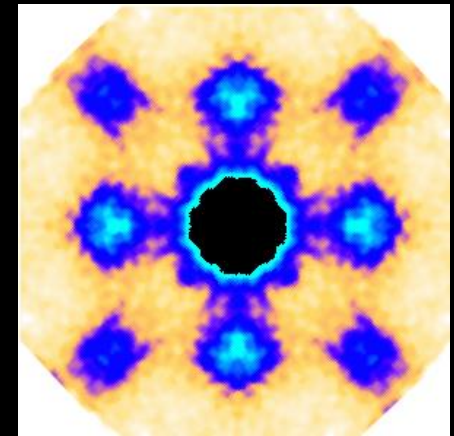
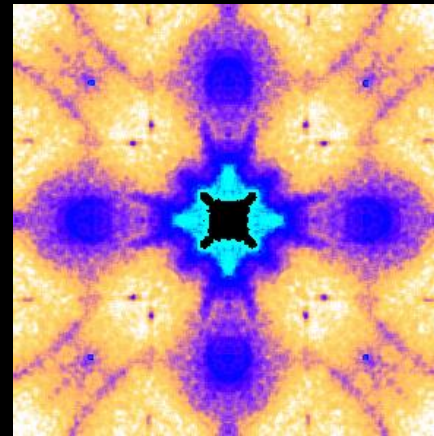
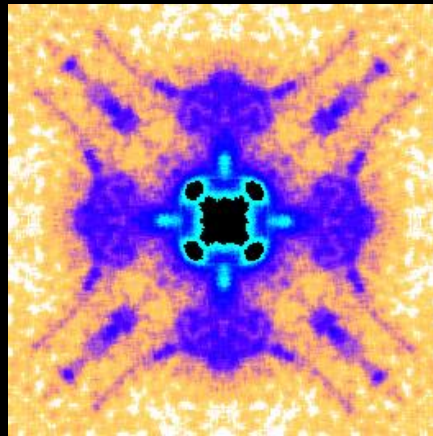
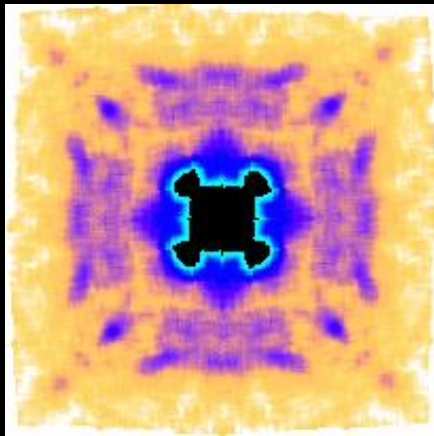
$\text{Pr}_x\text{Ca}_{1-x}\text{Fe}_2\text{As}_2$



Bi-2212

Fermi Surface & Pseudogap Evolution in a Cuprate Superconductor

Jenny Hoffman
Harvard University



Experiments

Harvard

MIT

Samples

Nagoya University

Theory

Northeastern, Harvard

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

Mike Boyer
W. Douglas Wise
Kamalesh Chatterjee
Eric Hudson

Takeshi Kondo
Tsunehiro Takeuchi
Hiroshi Ikuta

Peter Mistark, Arun Bansil
Robert Markiewicz
Subir Sachdev

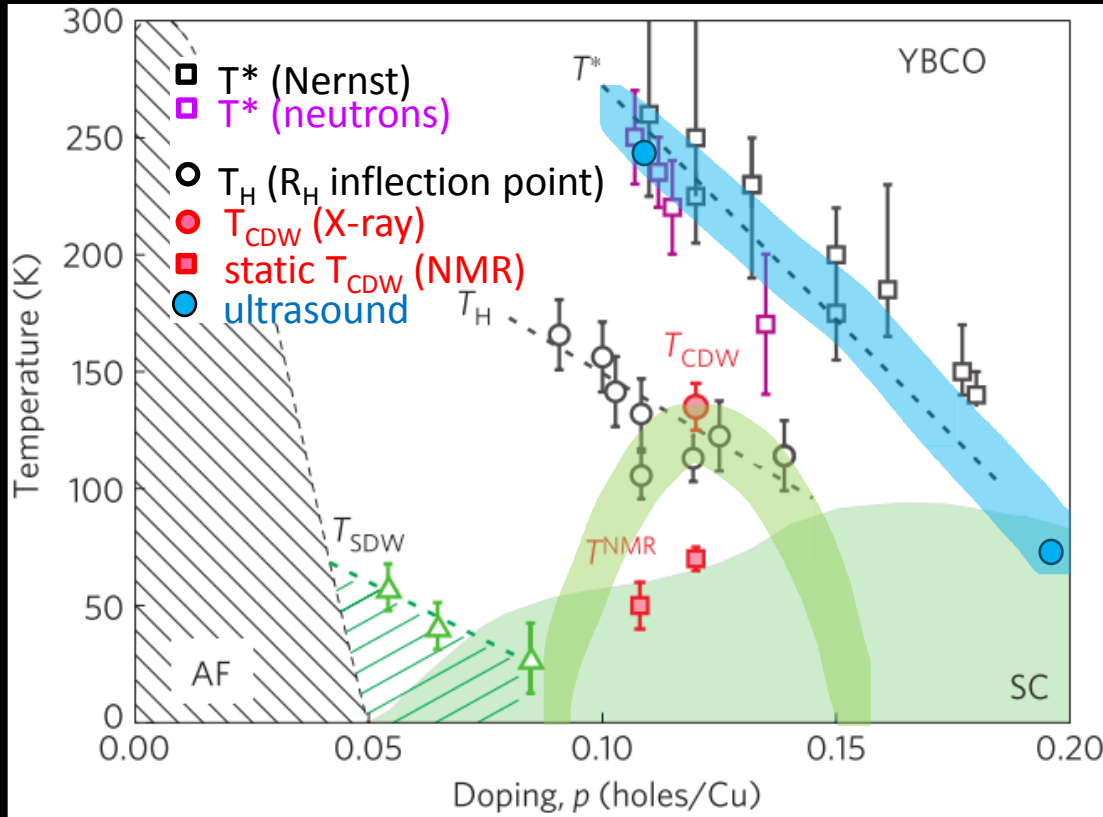
arxiv:1305.2778
to appear in *Science*, May 9



Fermi Surface vs. Pseudogap ?

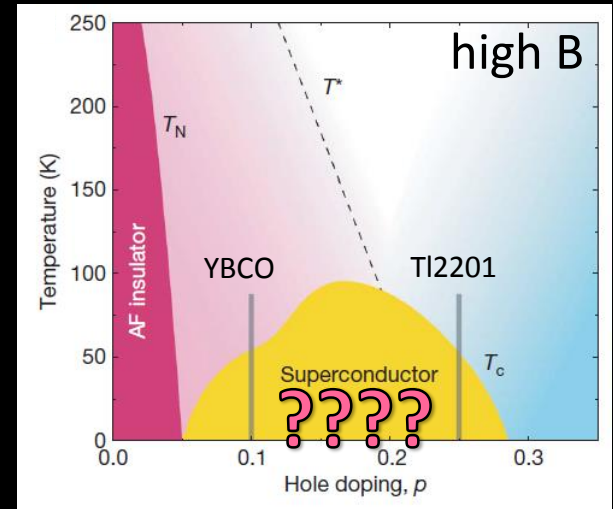


Pseudogap & Charge order



- 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

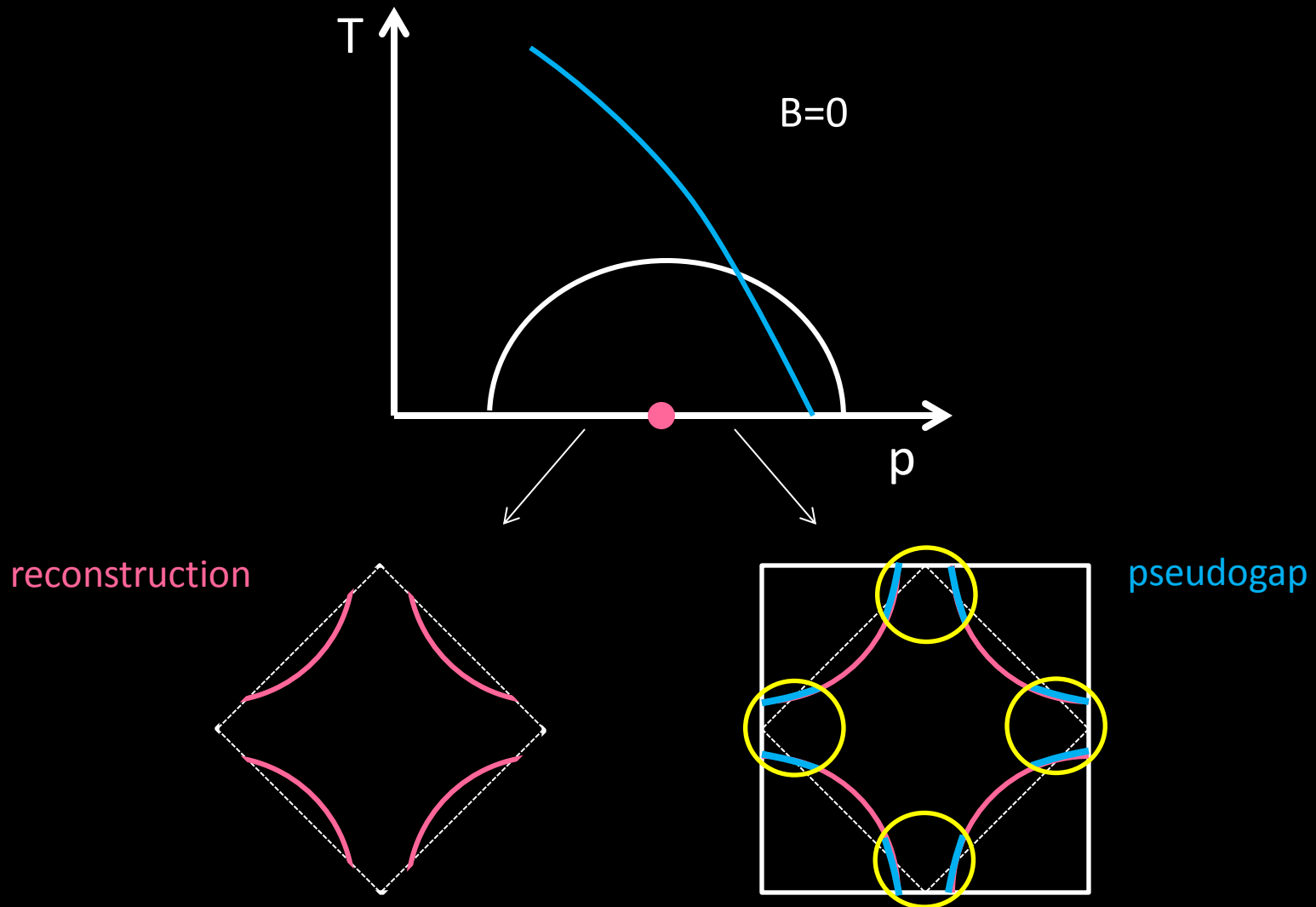


- Doiron-Leyraud, *Nature* 447, 565 (2007)
- Vignolle, *Nature* 455, 952 (2008)

Conclusions (STM on Bi2201)



1. Fermi surface reconstruction \neq pseudogap



2. Superconductivity coexists with pseudogap at the antinode

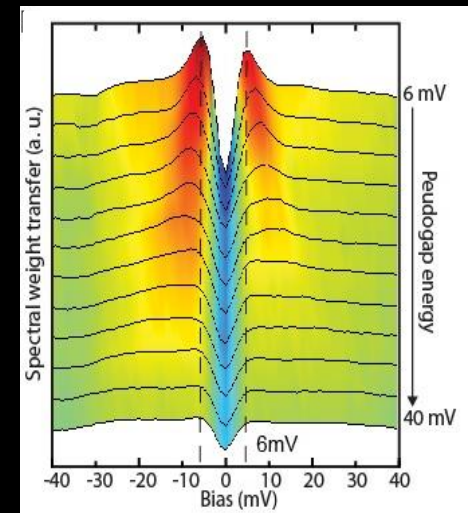
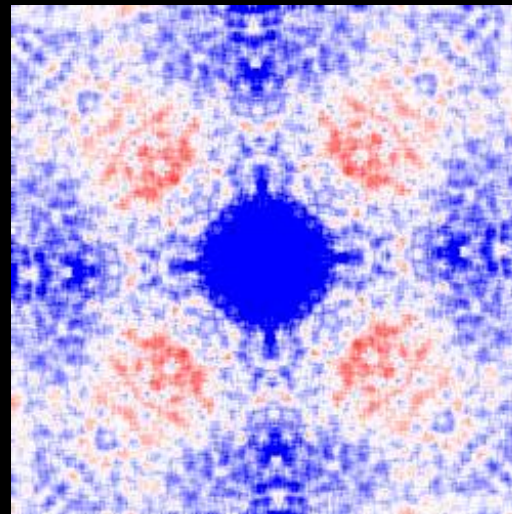
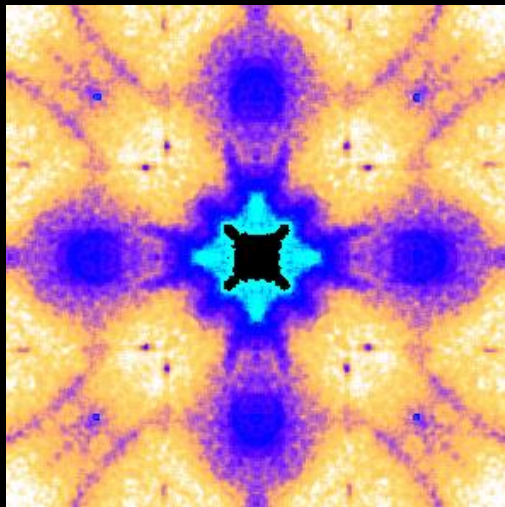
1. Where is the Fermi surface reconstruction?

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

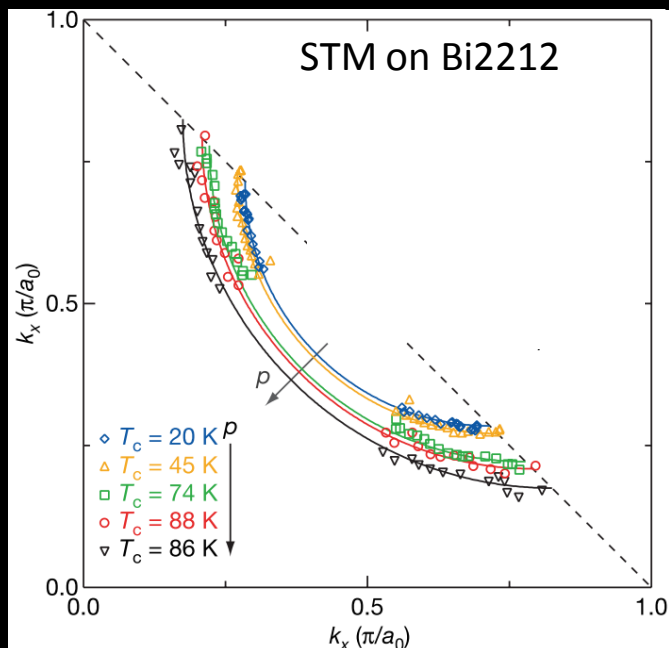


arxiv:1305.2778, to appear in *Science*, May 9 (2014)

Intro to Fermi arc phenomenology in Bi2212

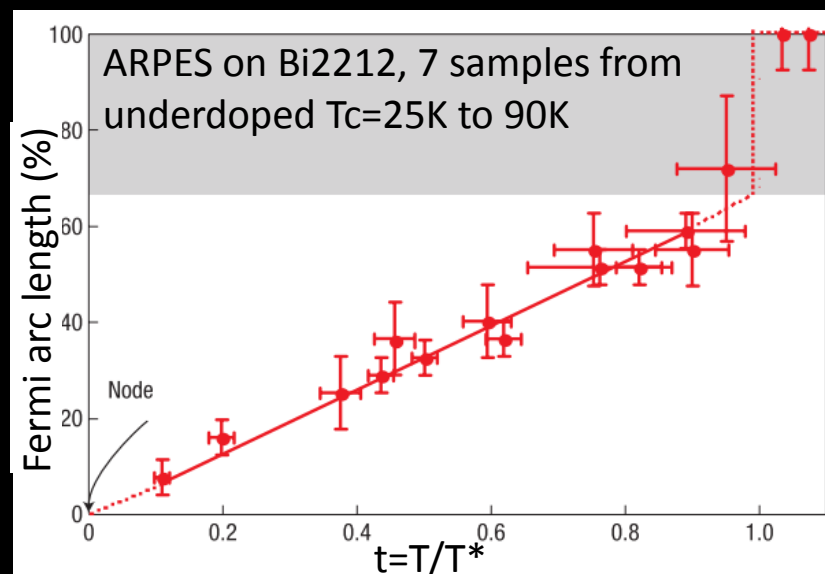


Arc cuts off at AFBZ

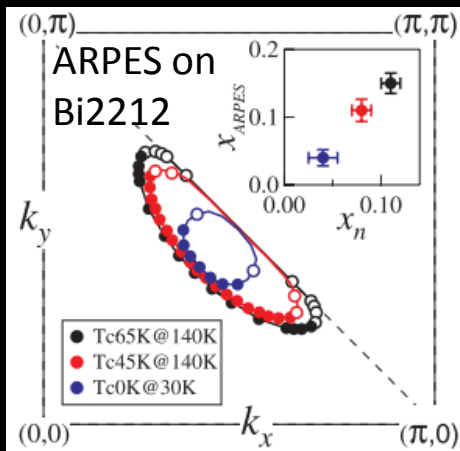


Kohsaka + JC Davis, *Nature* 454, 1072 (2008)

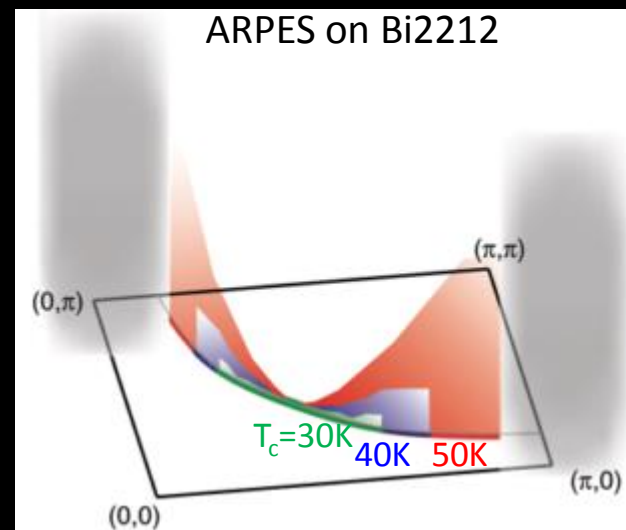
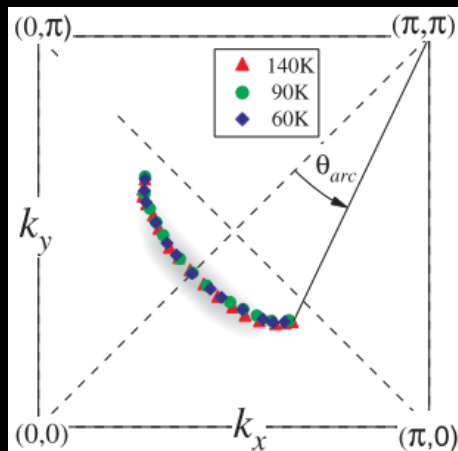
Arc length evolves with T, ρ



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



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

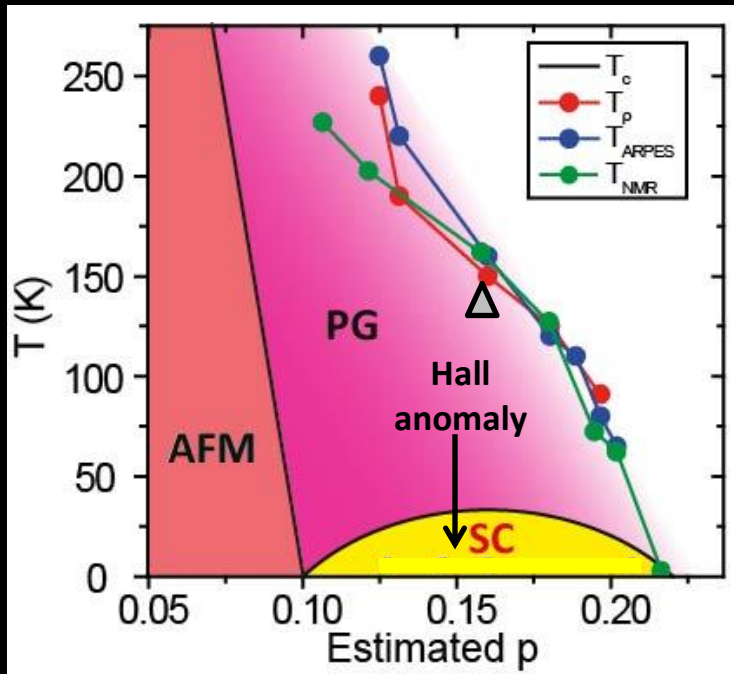


Tanaka + ZX Shen, *Science* 314, 1910 (2006)

Motivation to study Pb-doped Bi2201

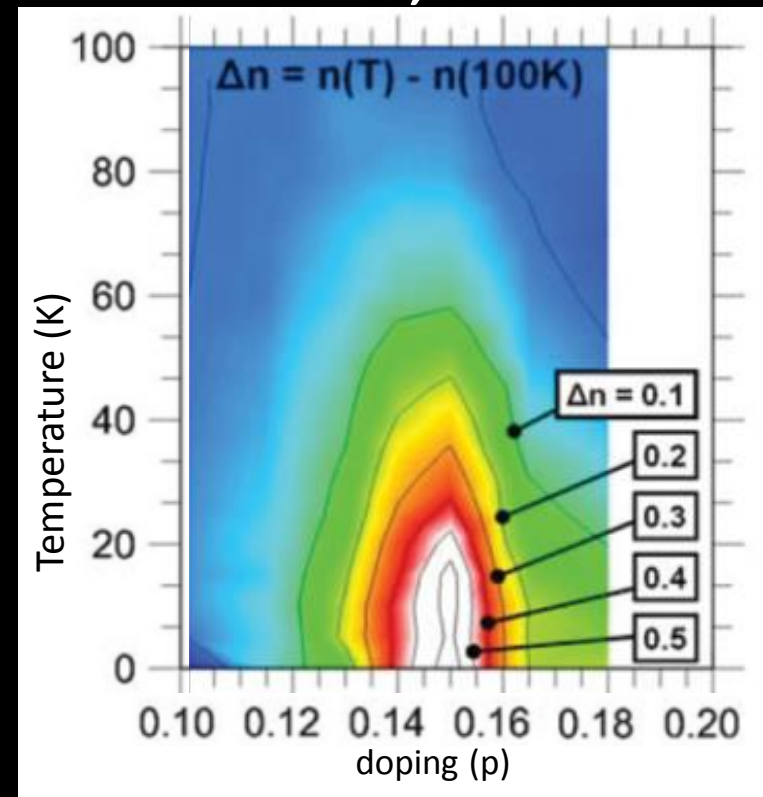


- No supermodulation or bilayer splitting artifacts
- Well-characterized pseudogap persists throughout the phase diagram
- Evidence for a quantum critical point near optimal doping (at high B)



- 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, $B > 30 T$

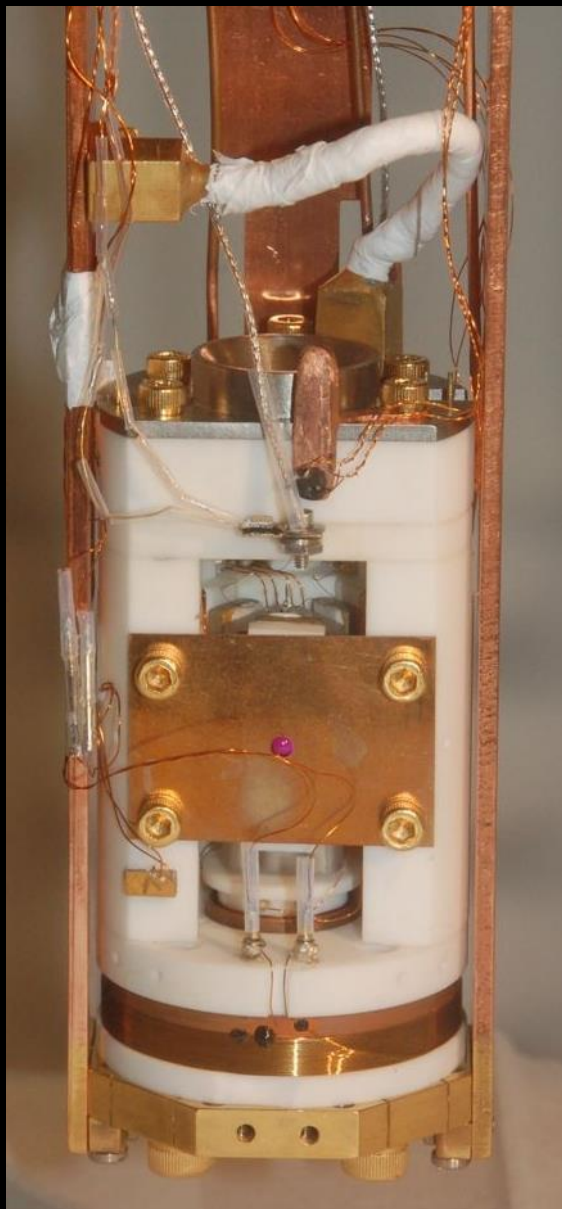


Balakirev, *Nature* 424, 912 (2003)
Balakirev, *PRL* 102, 017004 (2009)

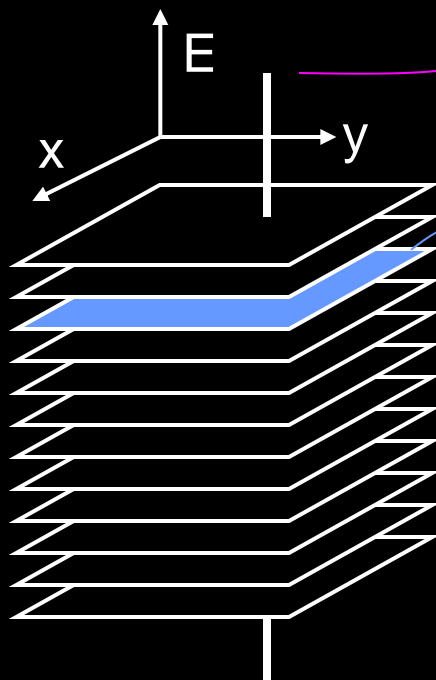
Does the FS reconstruct at $B=0$ Tesla?

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

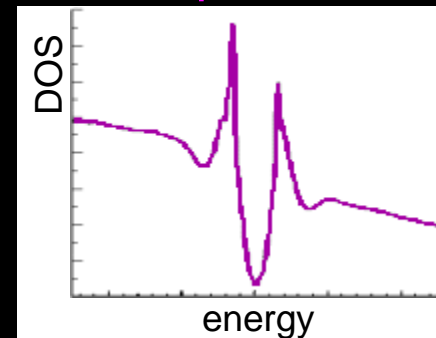
Scanning Tunneling Microscopy



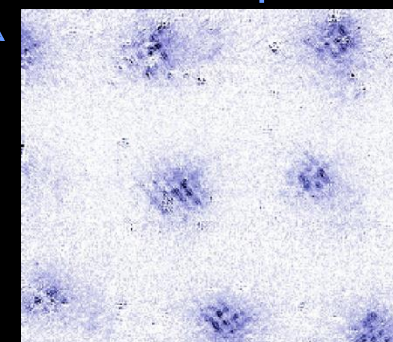
Local Density of States (x, y, E)



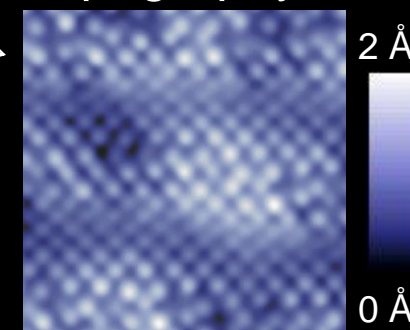
dI/dV Spectrum



dI/dV Map



Topography



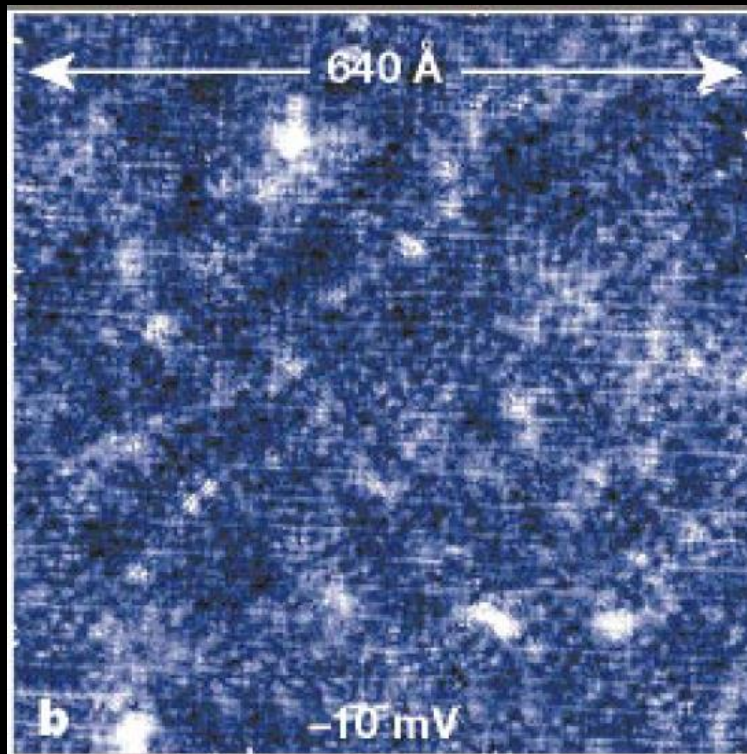
Constant current mode:

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

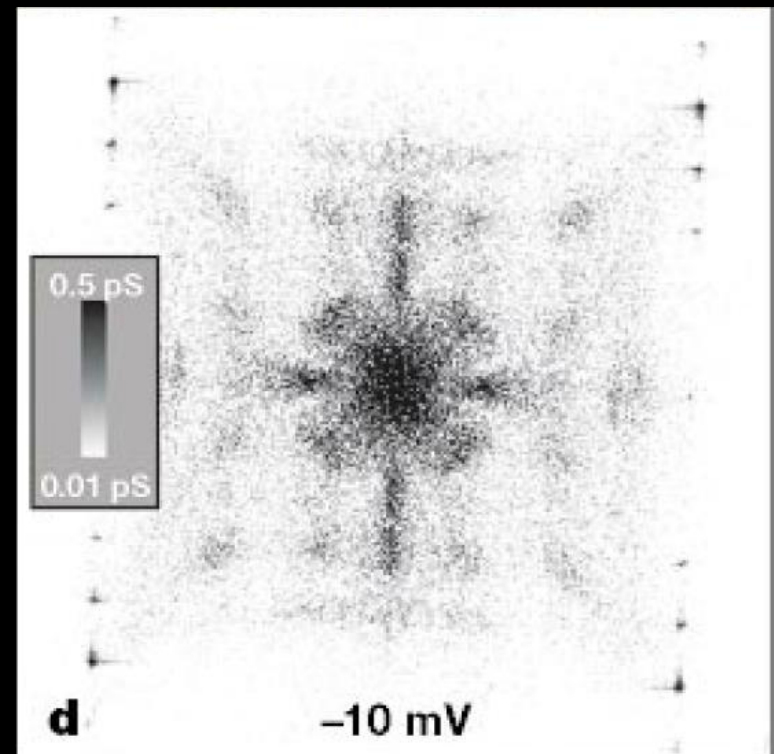
Quasiparticle interference in Bi2212



STM local density of states



q space QPI

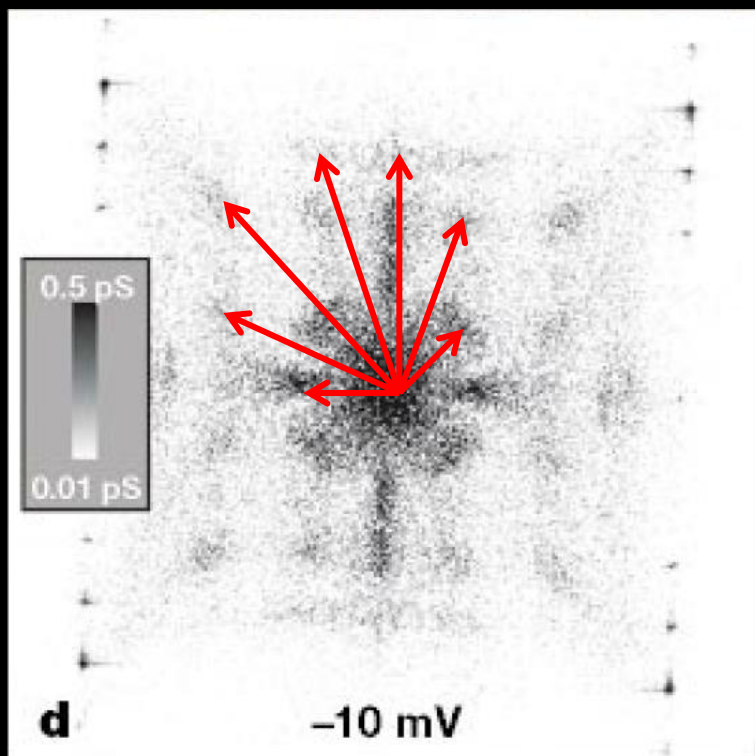


Hoffman, Science 297, 1148 (2002)
McElroy, Nature 422, 592 (2003)
Wang & Lee, PRB 67, 020511 (2003)

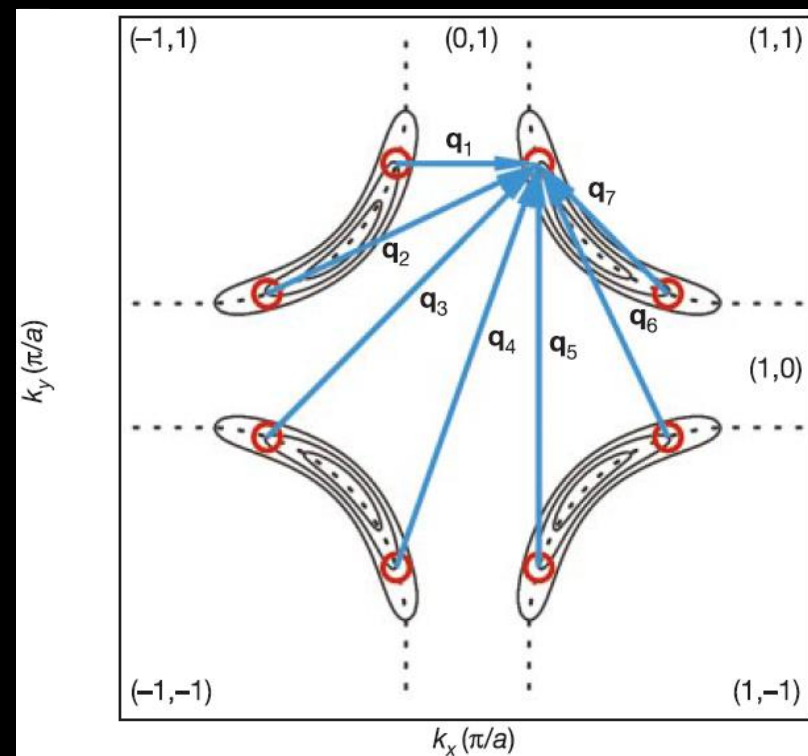
Quasiparticle interference in Bi2212



q space QPI



“Octet model”

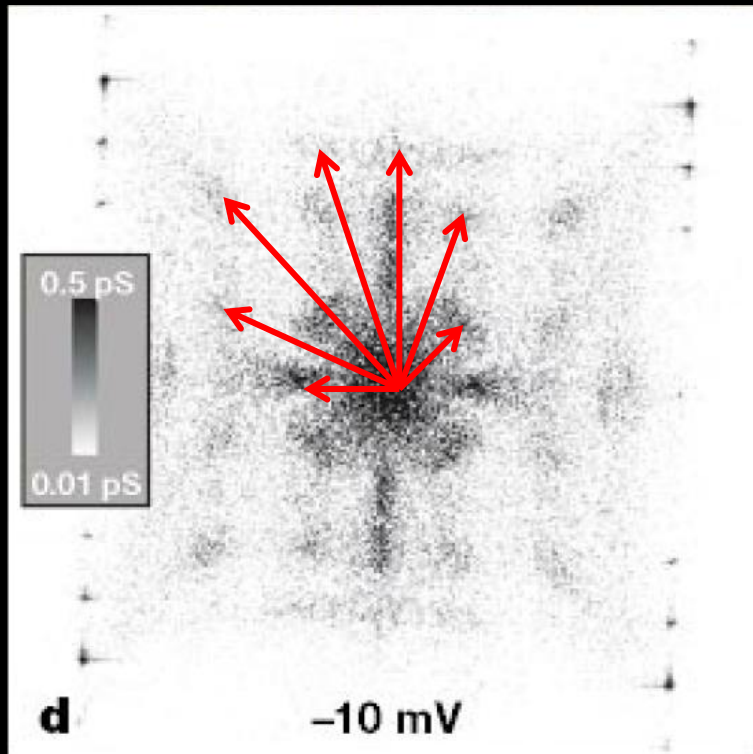


Hoffman, Science 297, 1148 (2002)
McElroy, Nature 422, 592 (2003)
Wang & Lee, PRB 67, 020511 (2003)

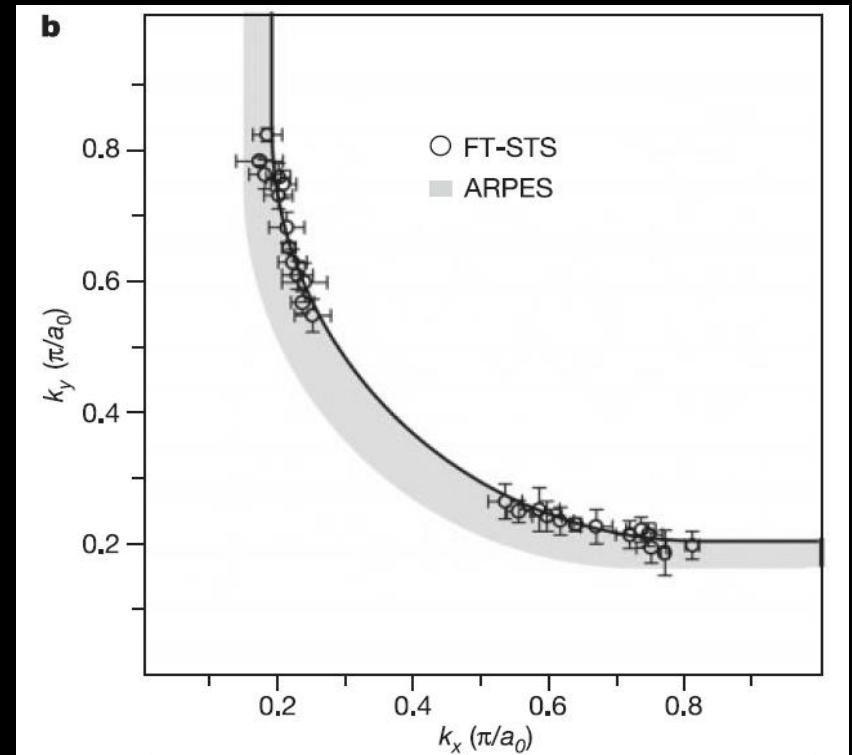
Quasiparticle interference in Bi2212



q space QPI

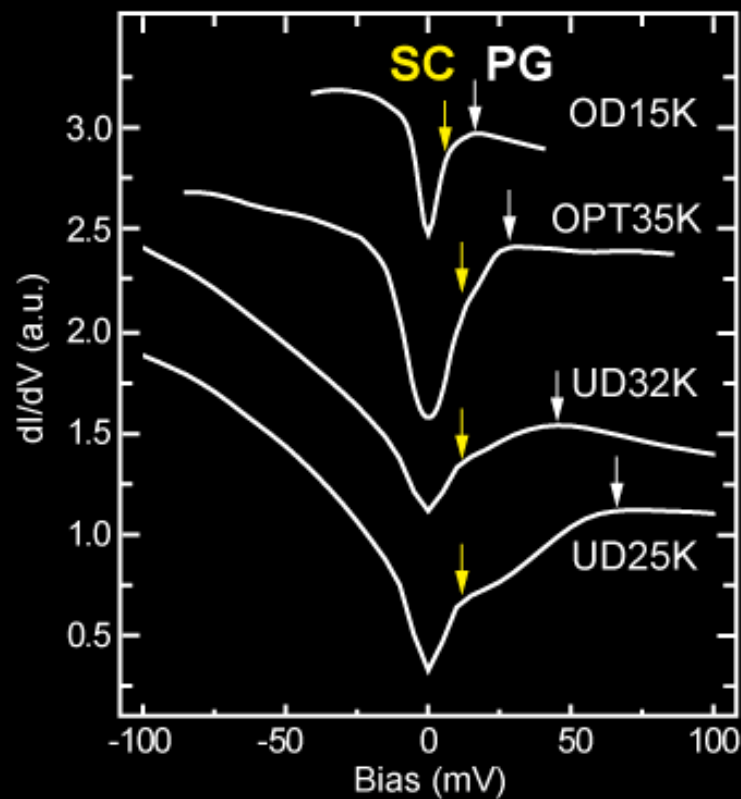
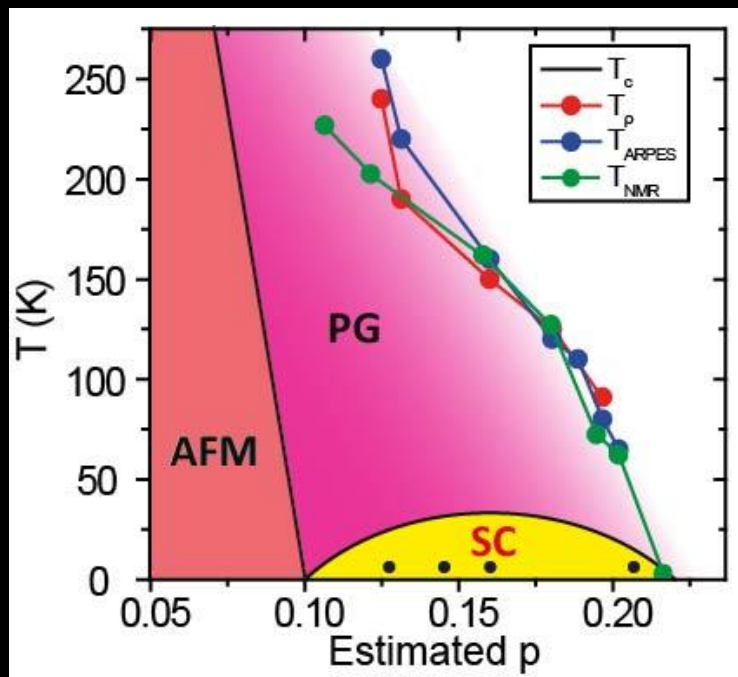


k-space Fermi surface



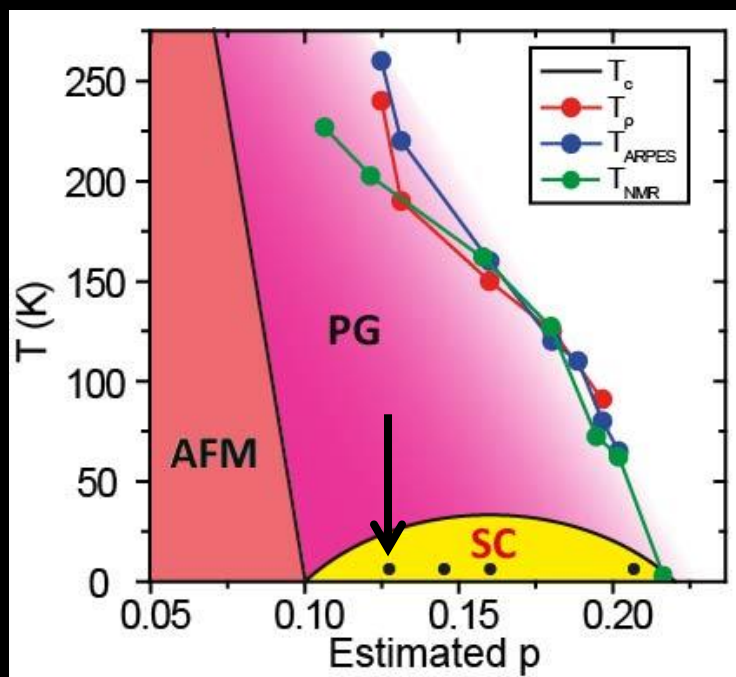
Hoffman, Science 297, 1148 (2002)
McElroy, Nature 422, 592 (2003)
Wang & Lee, PRB 67, 020511 (2003)

STM studies of Pb-doped Bi2201



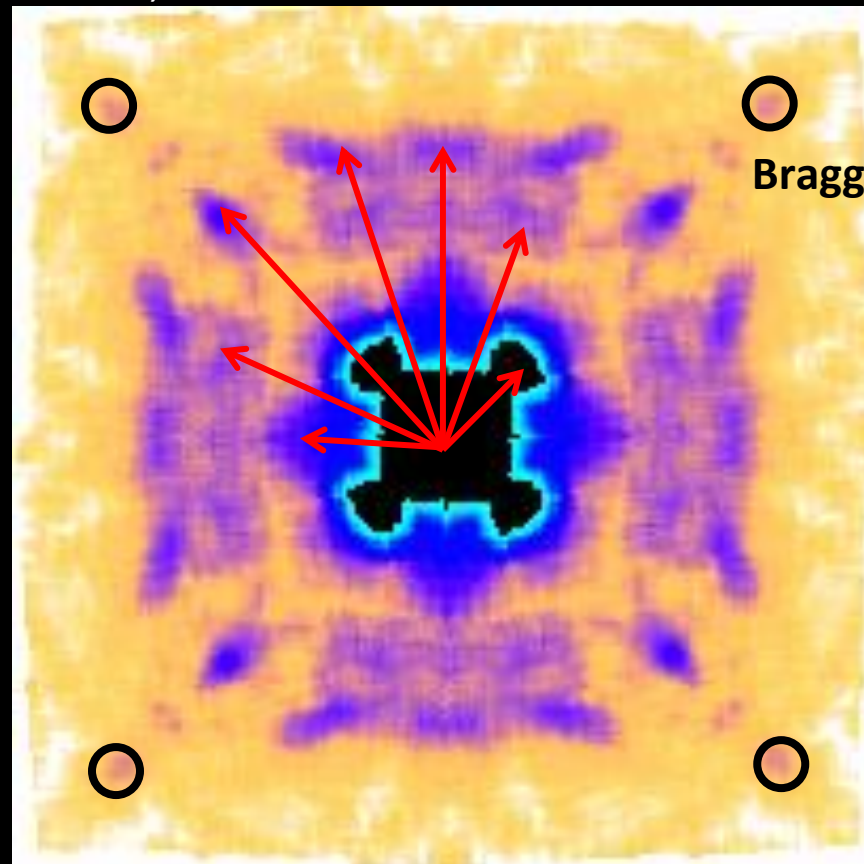
arxiv:1305.2778, to appear in *Science*, May 9 (2014)

Octet QPI in UD25K Bi2201



Bi2201, UD25K

9mV



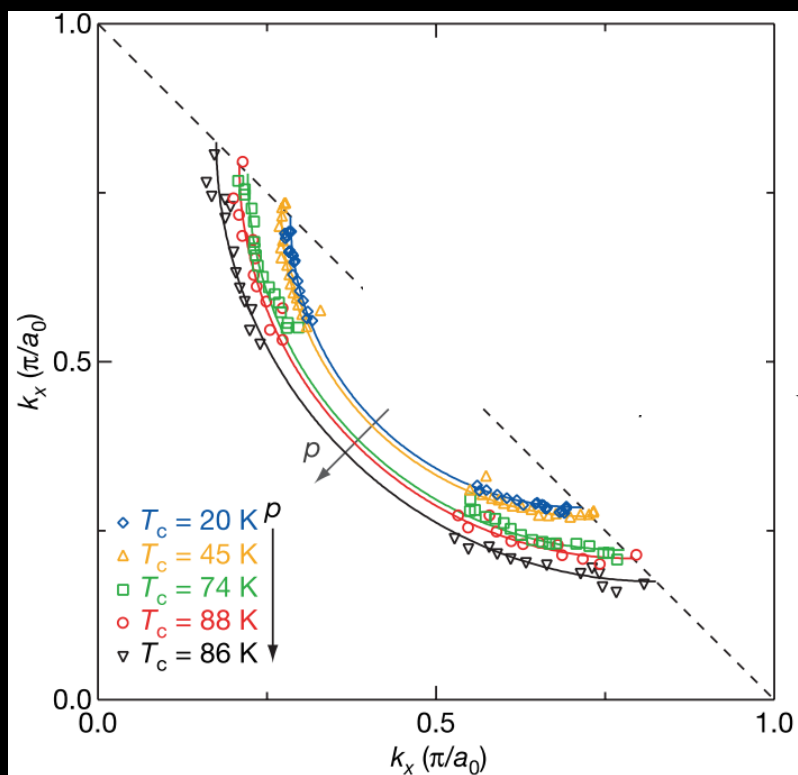
Low  High

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

Extinction of octet QPI

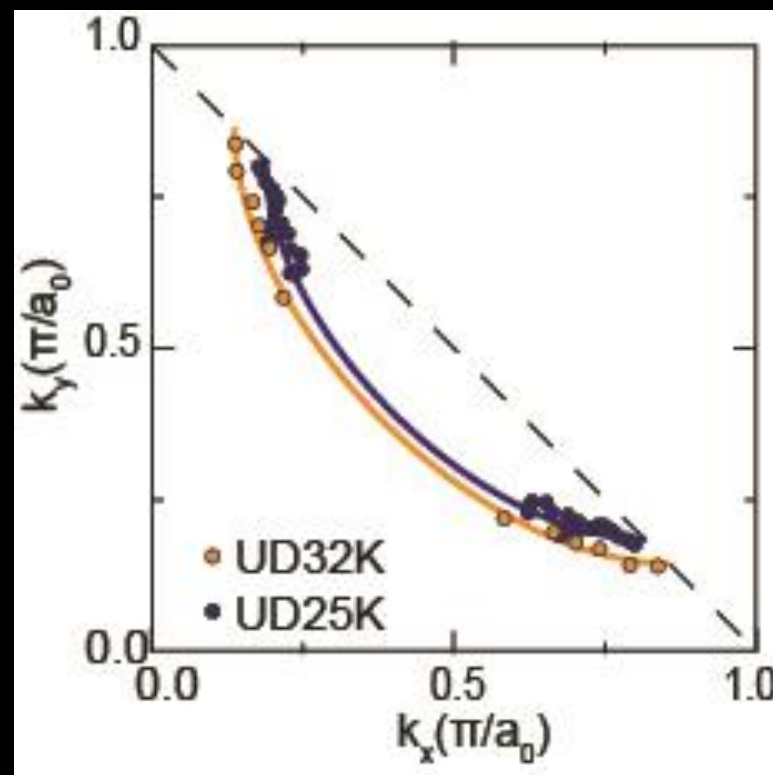


Previous work: Bi2212



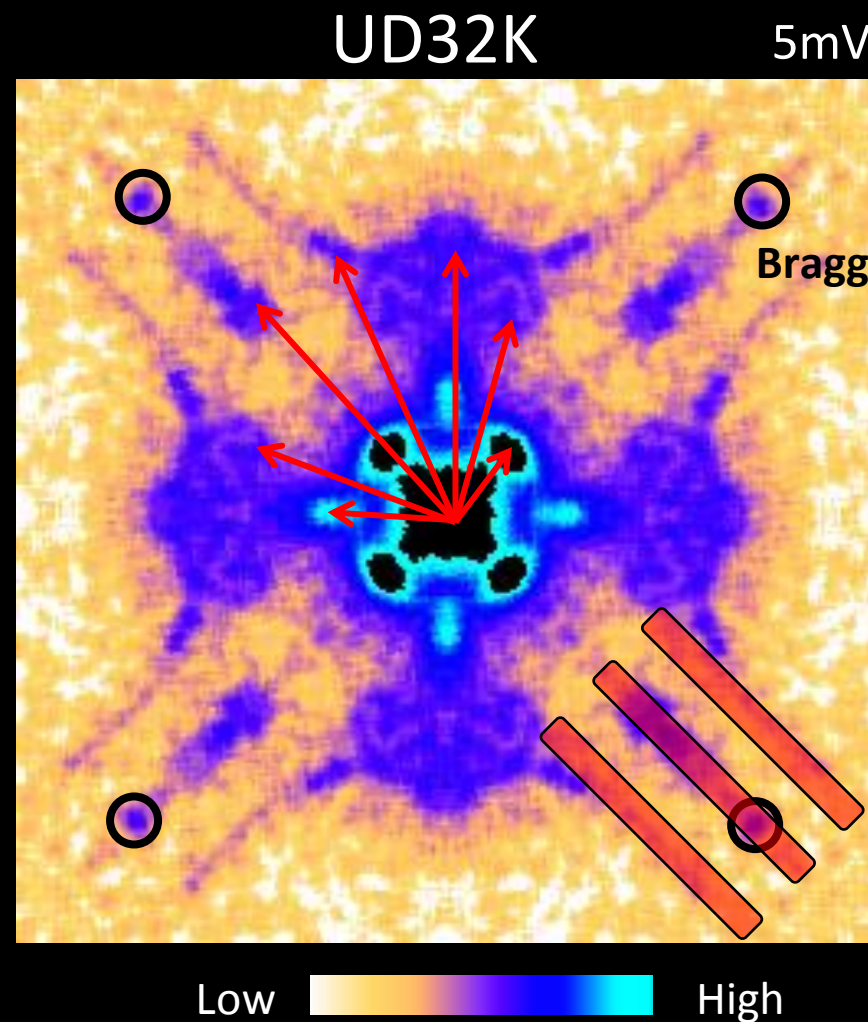
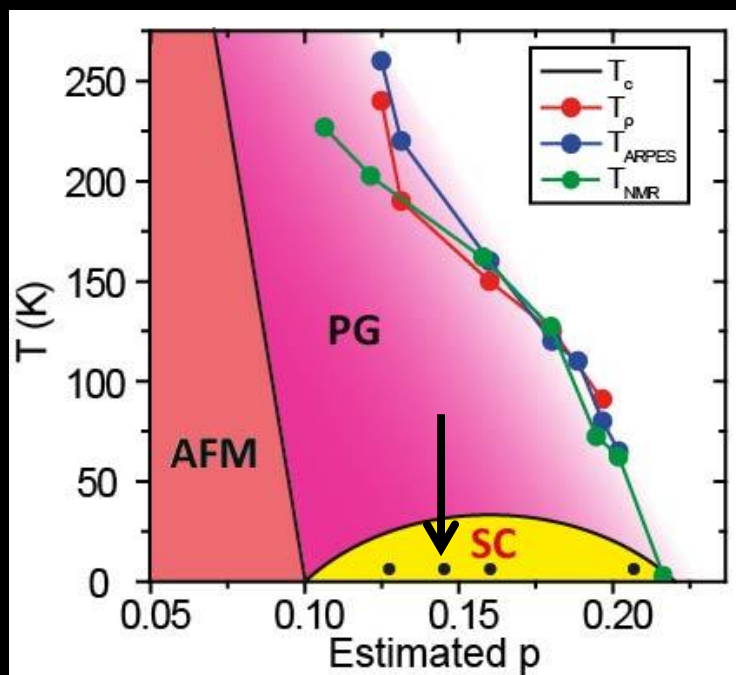
Kohsaka, Nature 454, 1072 (2008)

Our data: Bi2201



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

QPI in UD32K Bi2201

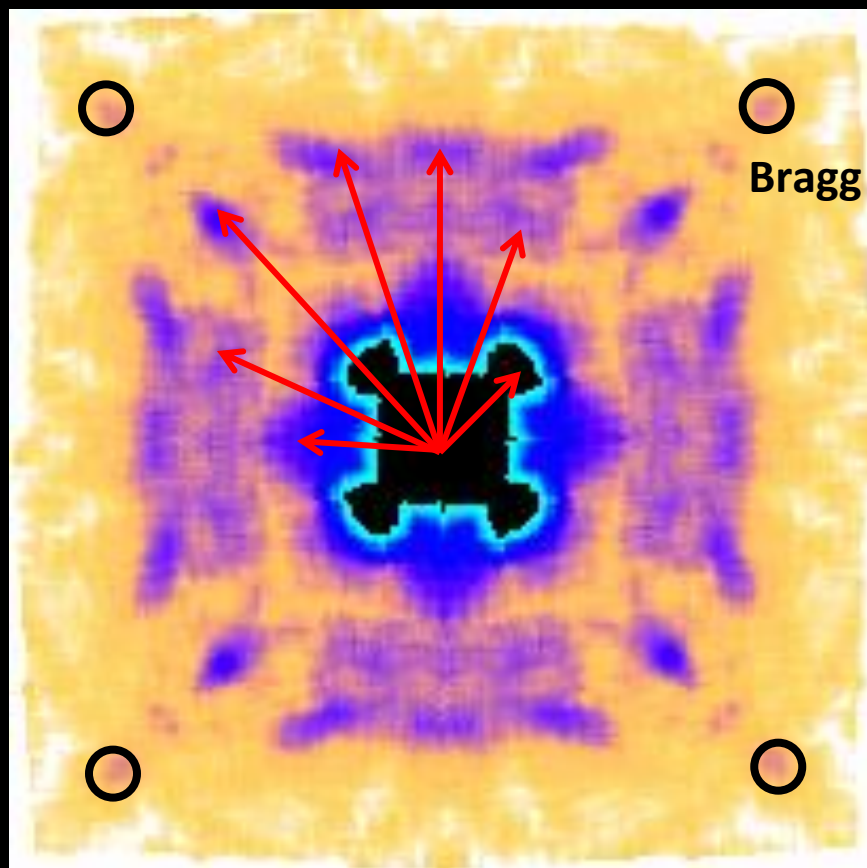


Compare QPI in UD25K and UD32K



UD25K

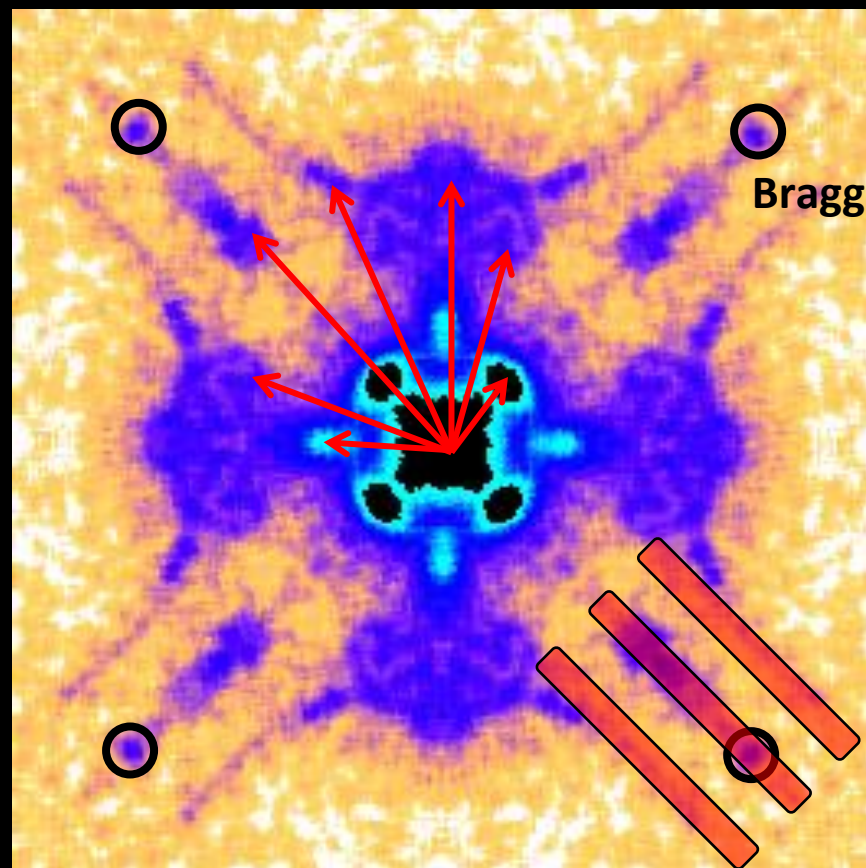
9mV



Low  High

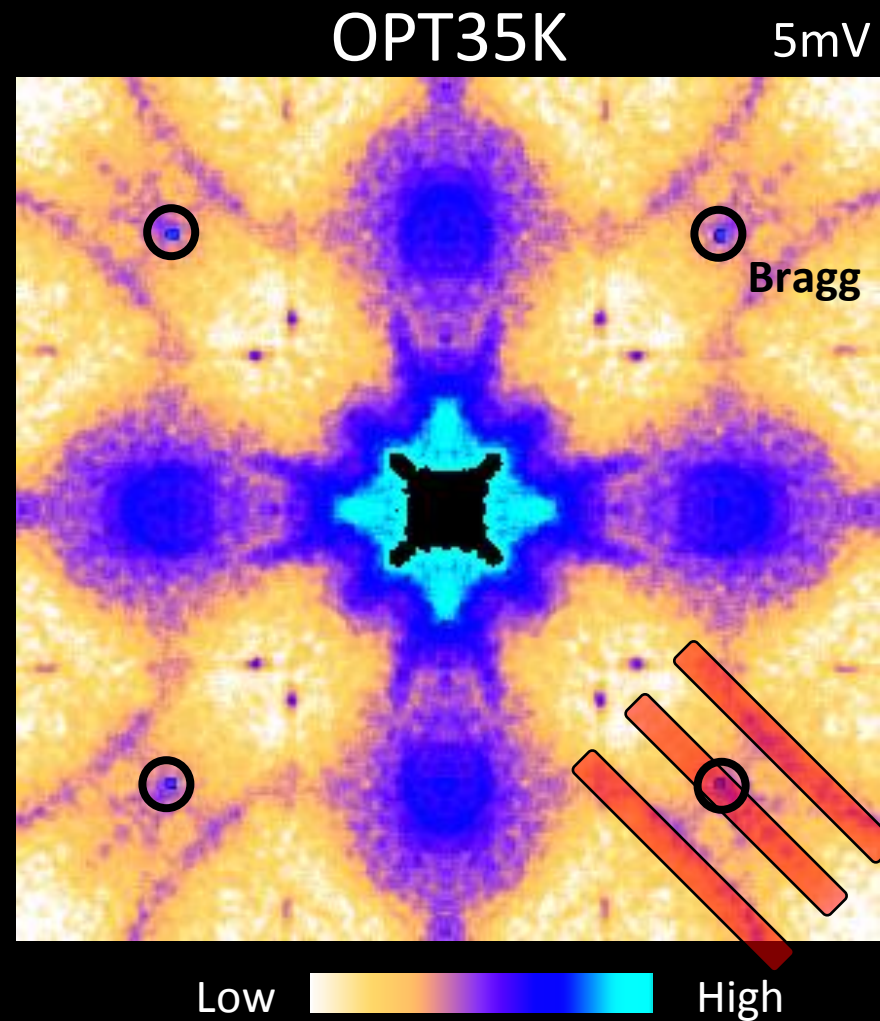
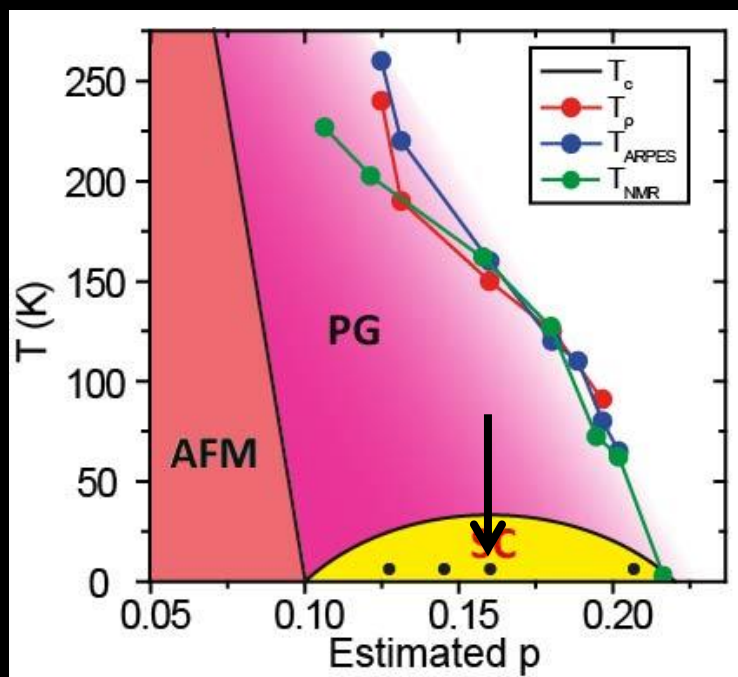
UD32K

5mV

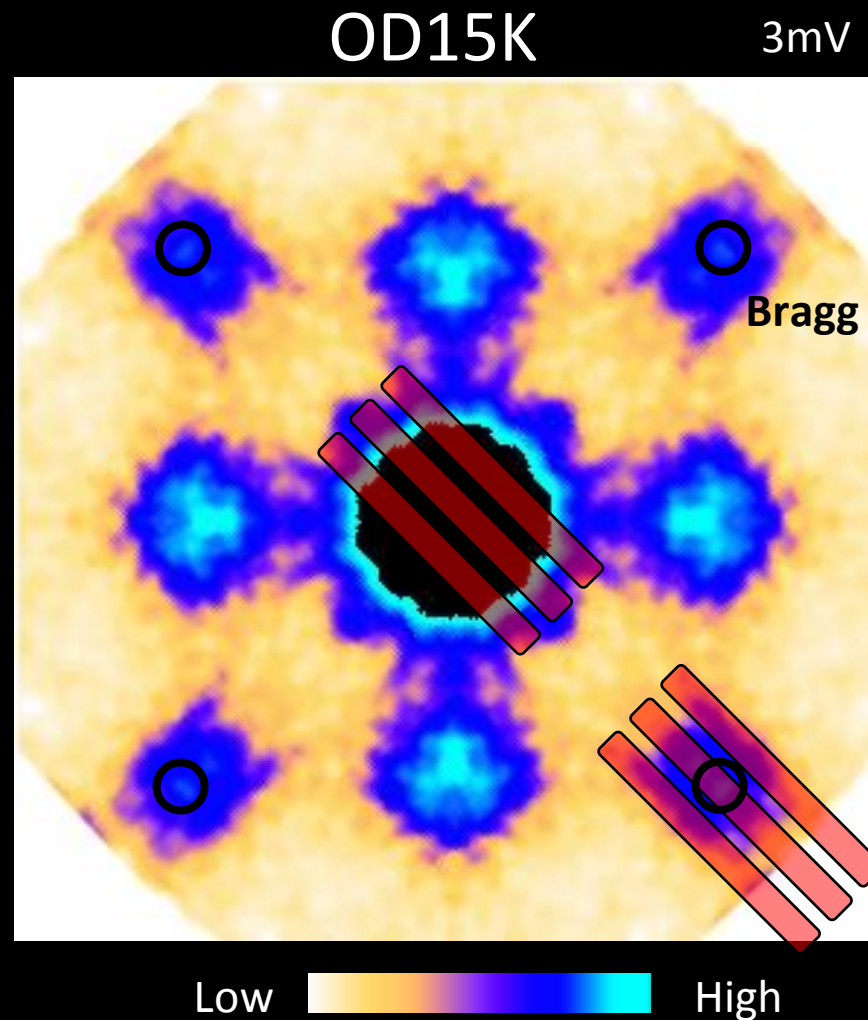
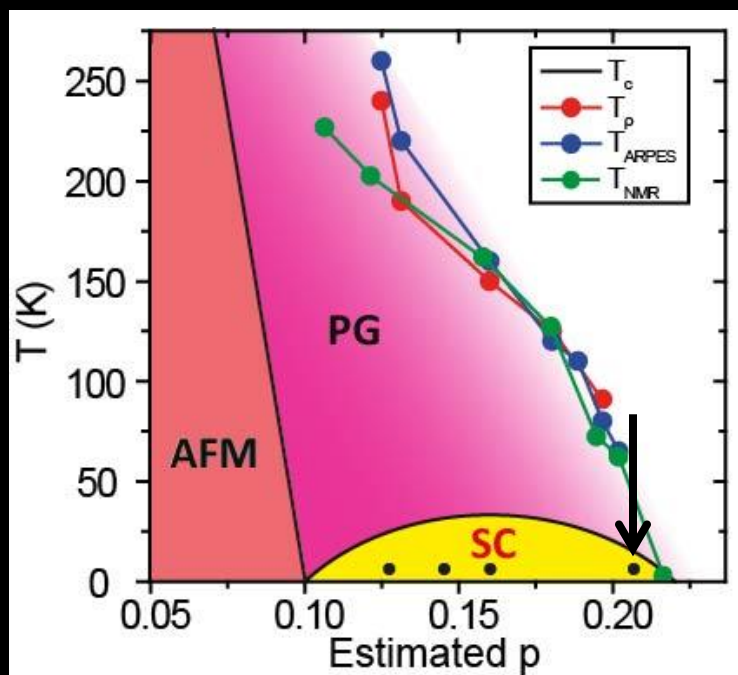


Low  High

QPI in OPT35K



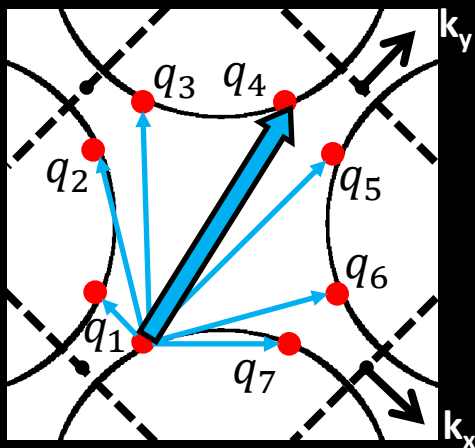
QPI in OD15K



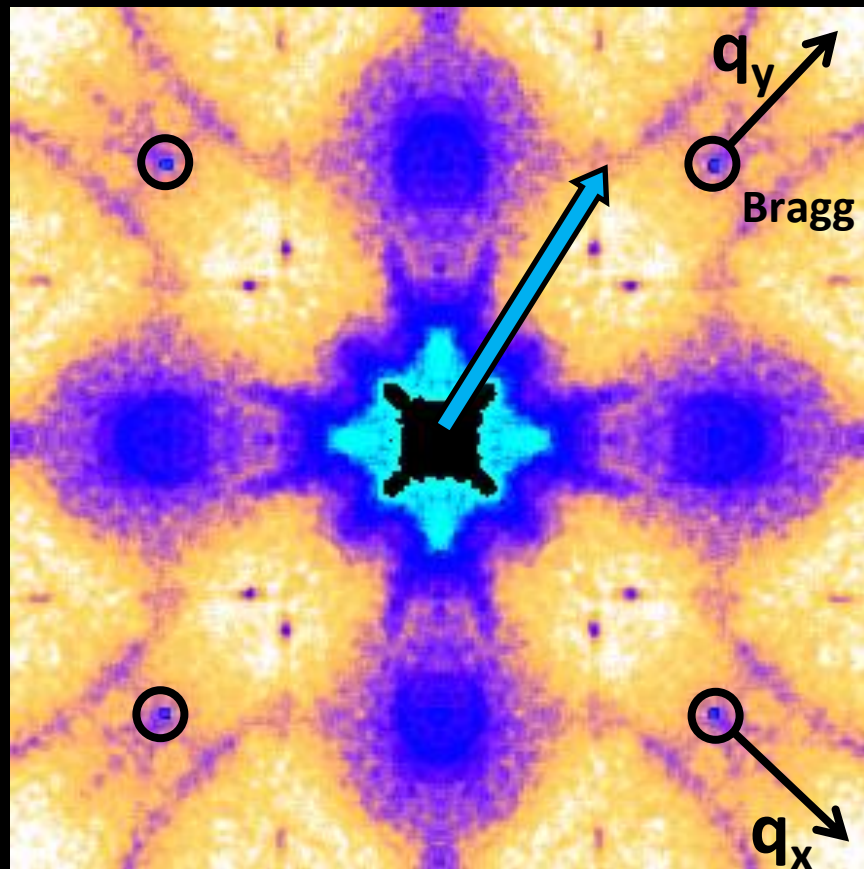
Compare Fermi surface to QPI



k space Fermi surface



q space QPI



OPT35K 5mV

Low

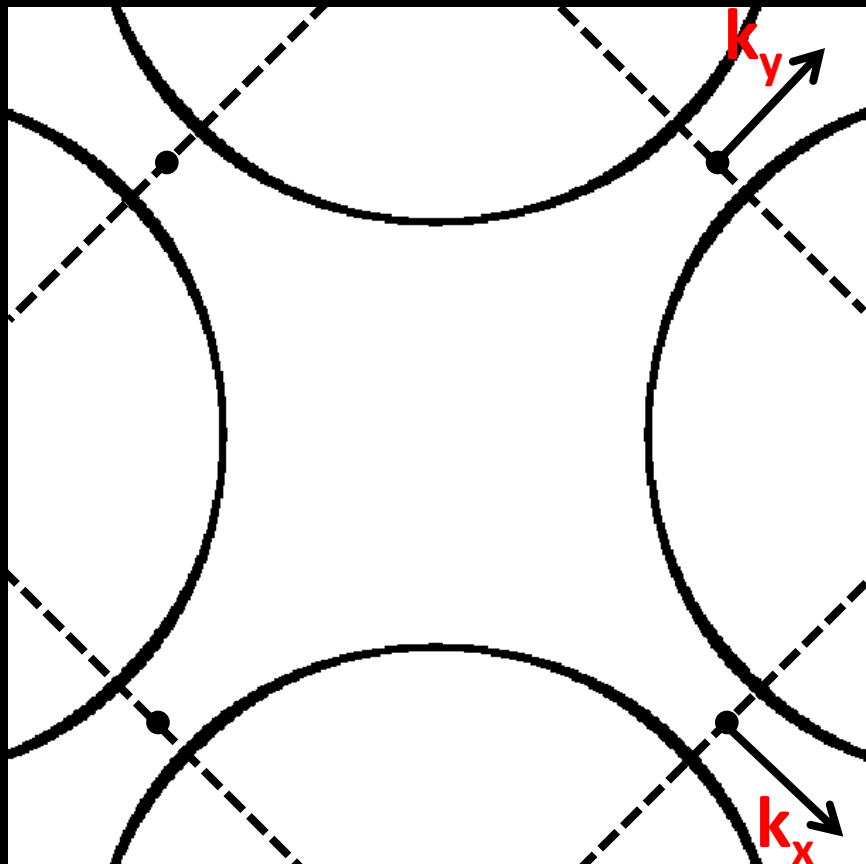
High

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

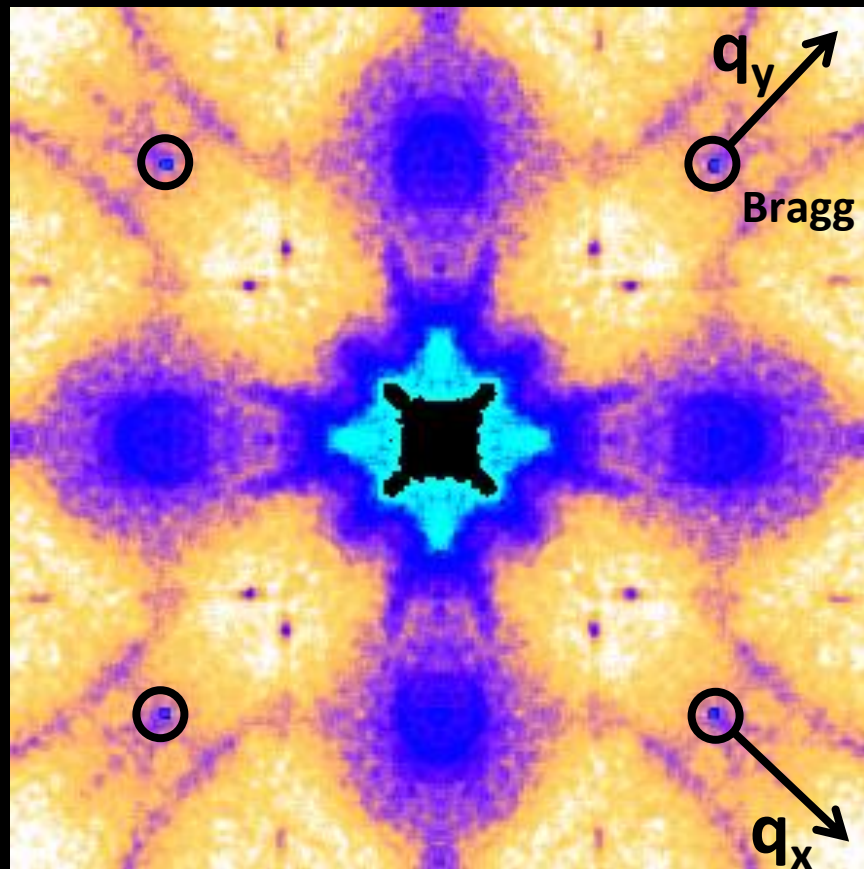
Compare Fermi surface to QPI



2 x k space Fermi surface



q space QPI



OPT35K 5mV

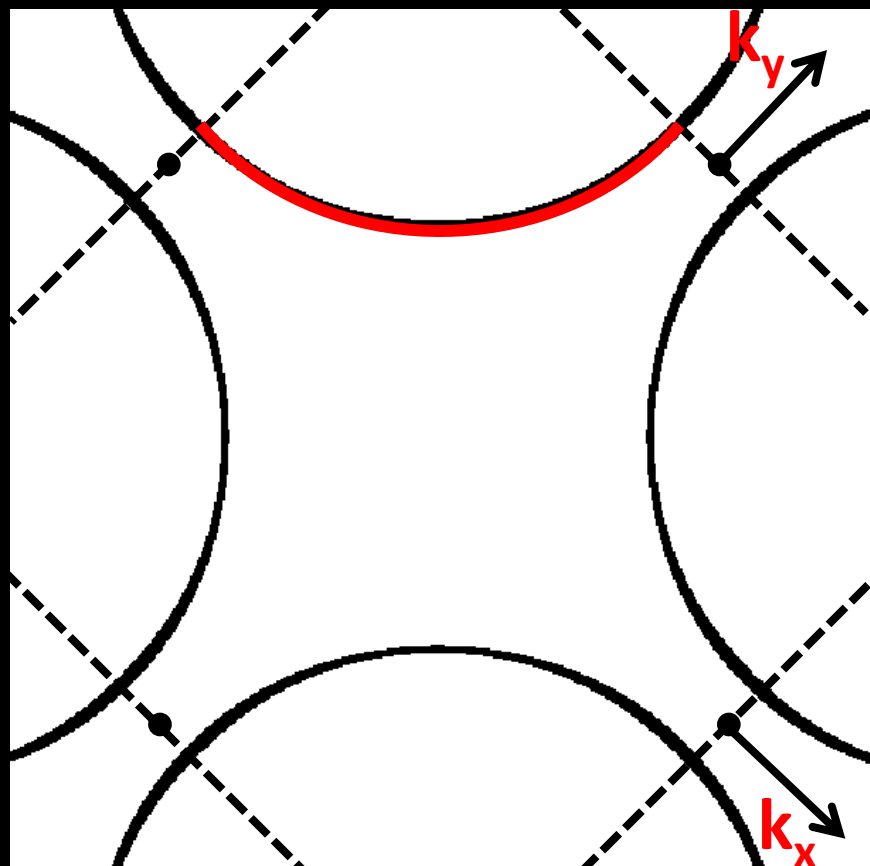
Low  High

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

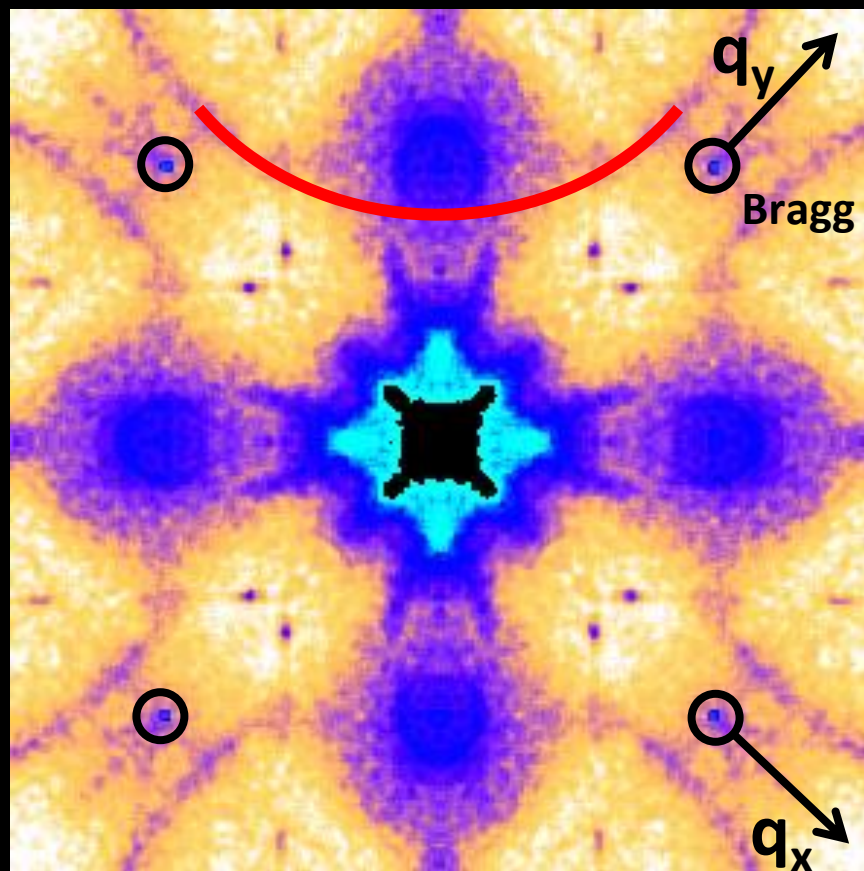
Compare Fermi surface to QPI



2 x k space Fermi surface



q space QPI



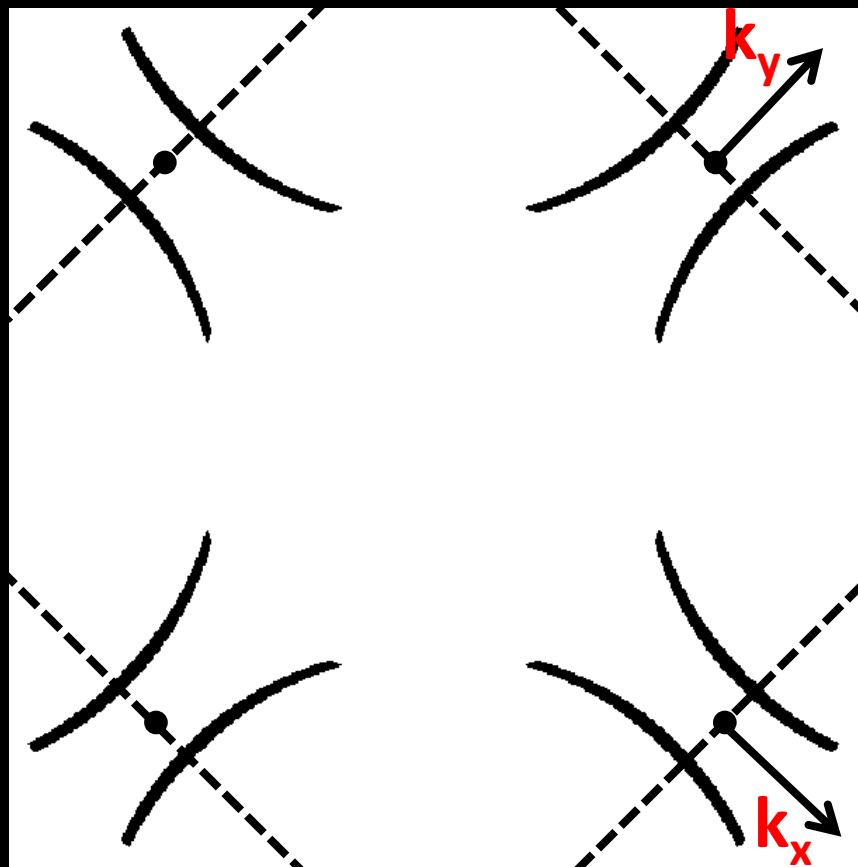
Low  High

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

Autocorrelate just the antinodal Fermi surface

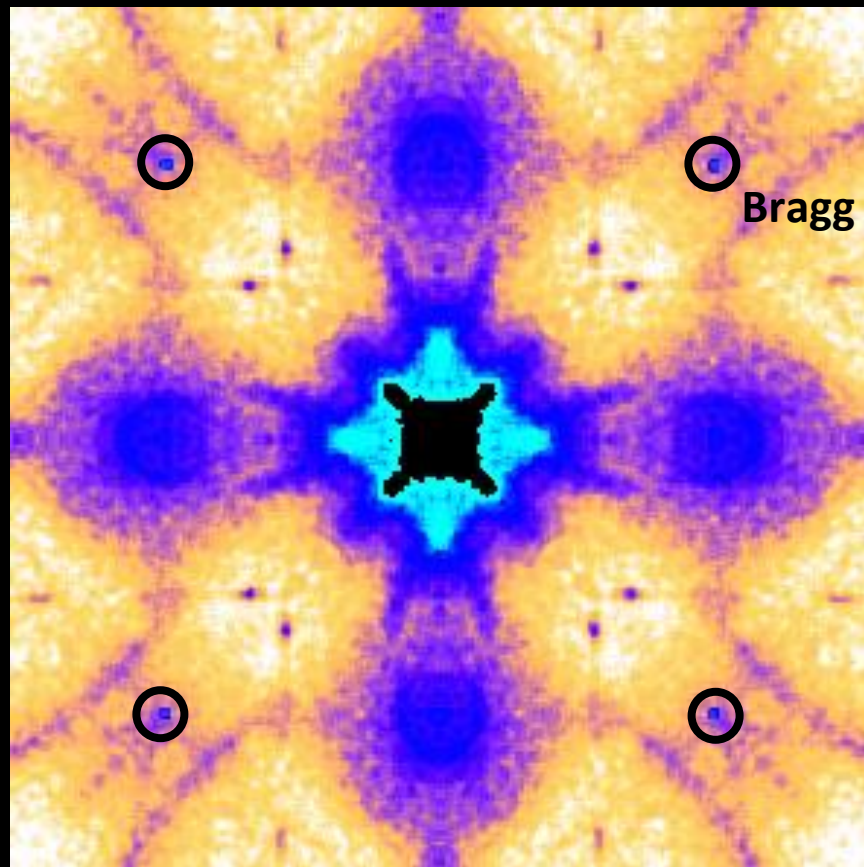


2 x Antinodal Fermi surface



q space QPI

OPT35K 5mV



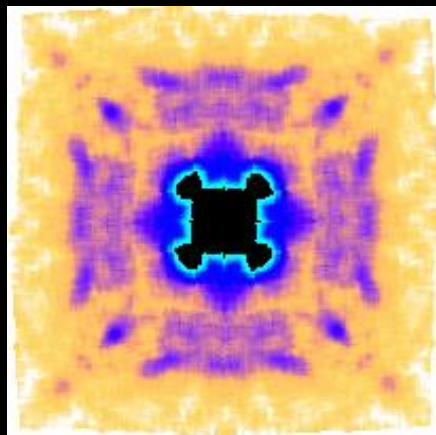
Low  High

Triplet feature comes from antinode.

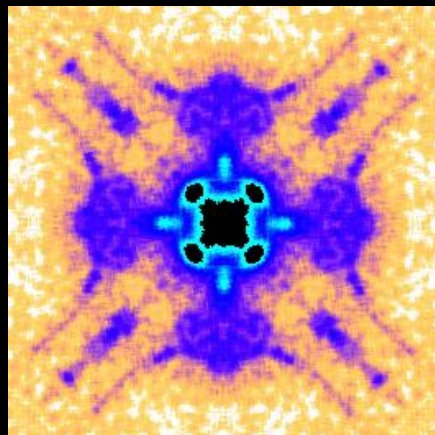
Luttinger count



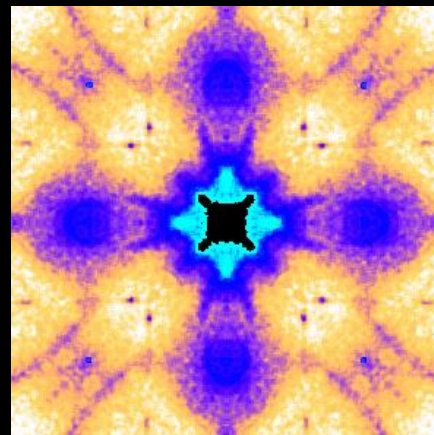
UD25K



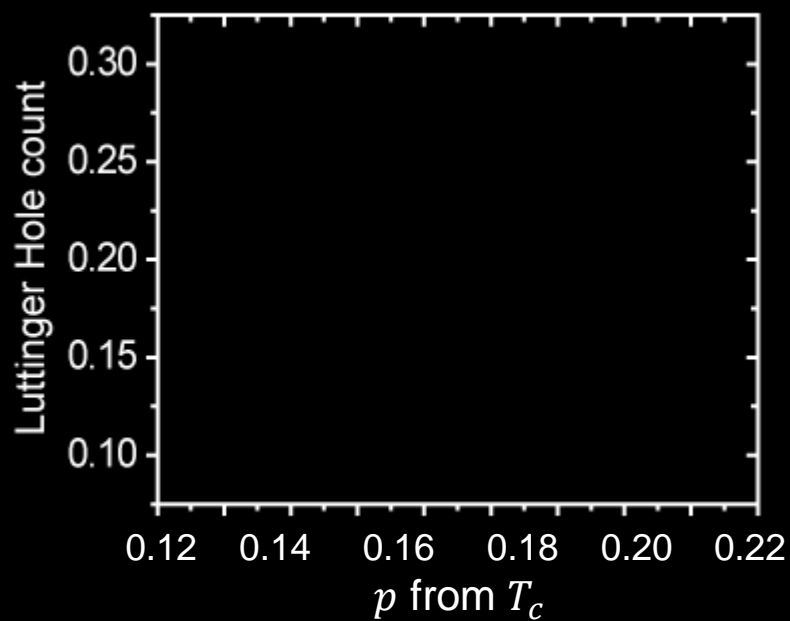
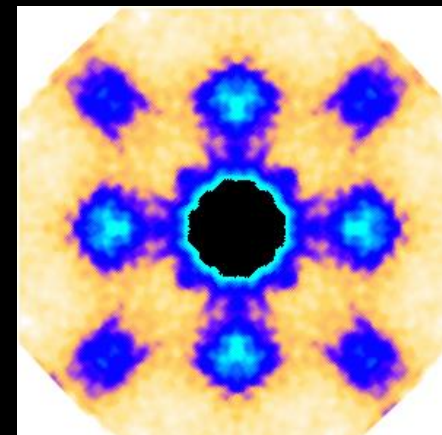
UD32K



OPT35K



OD15K

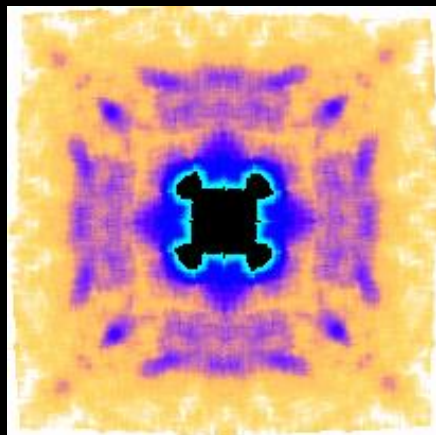


Ando, PRB 61, R14956 (2000)

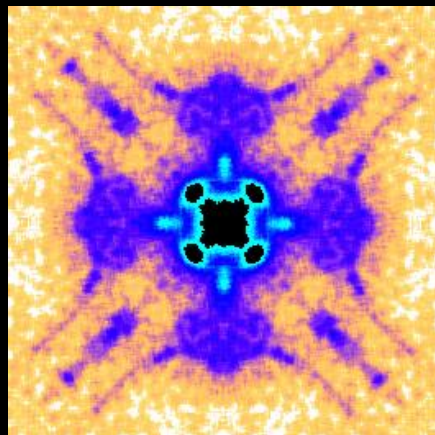
Luttinger count



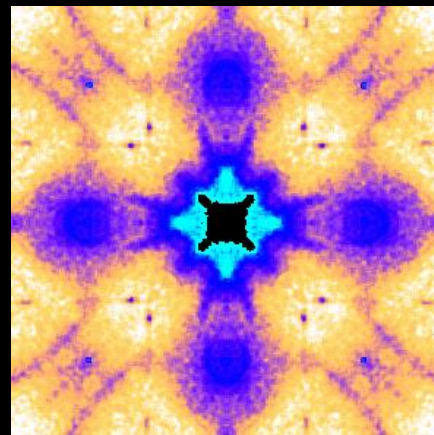
UD25K



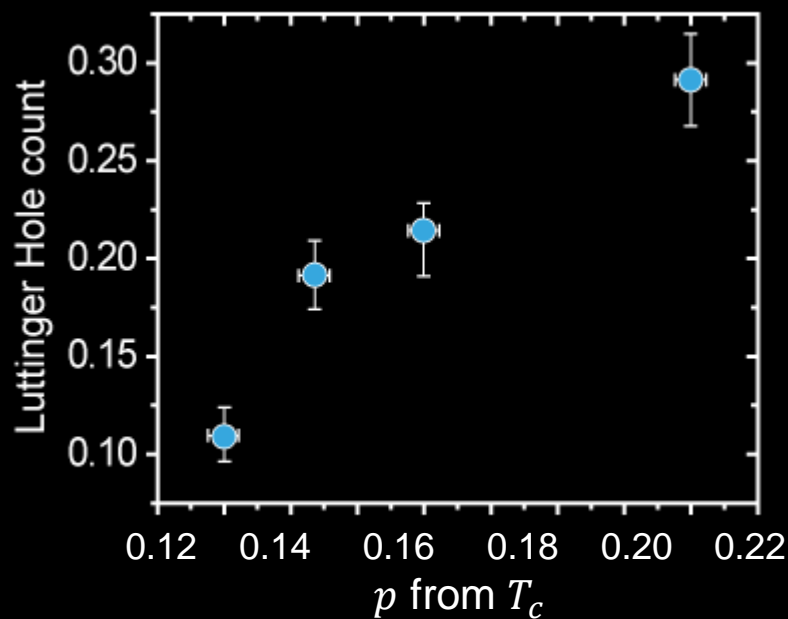
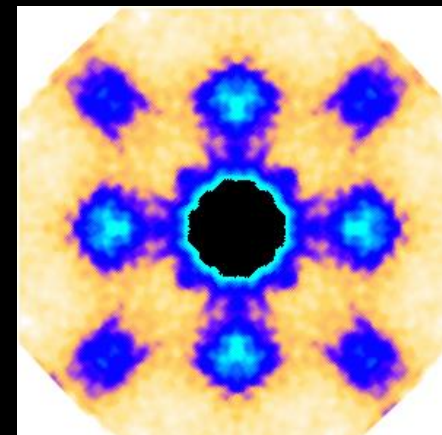
UD32K



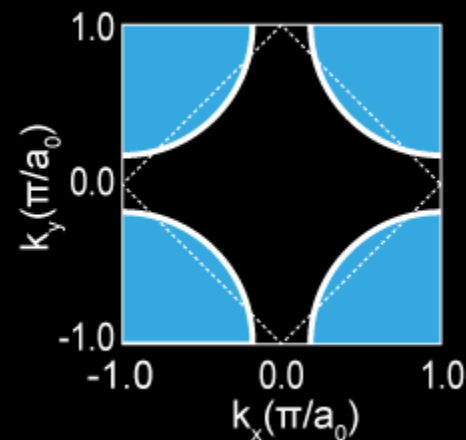
OPT35K



OD15K



Ando, PRB 61, R14956 (2000)

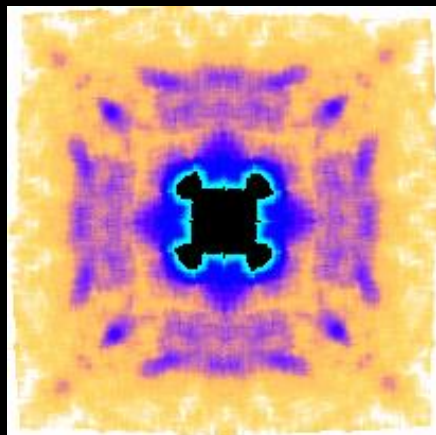


$$p_{\text{large}} = \frac{2A_{\text{blue}}}{A_{\text{BZ}}} - 1$$

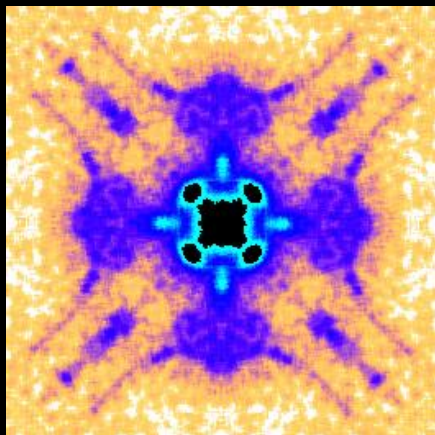
Luttinger count



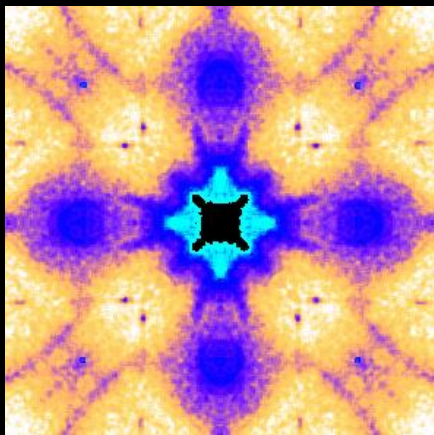
UD25K



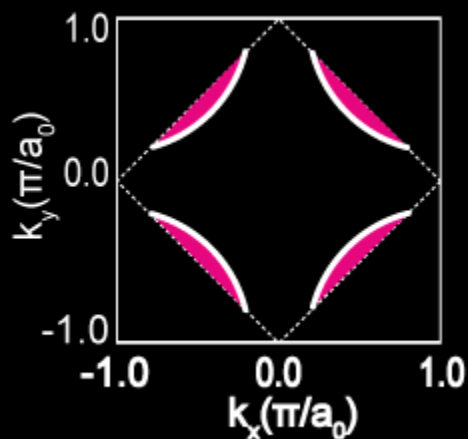
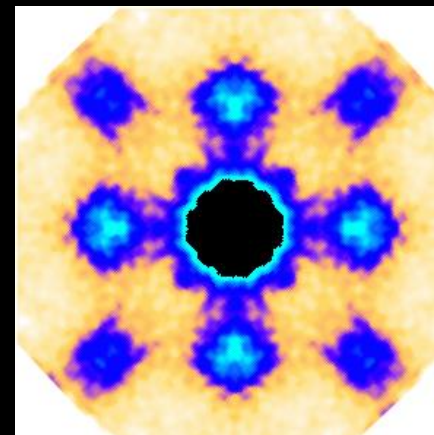
UD32K



OPT35K



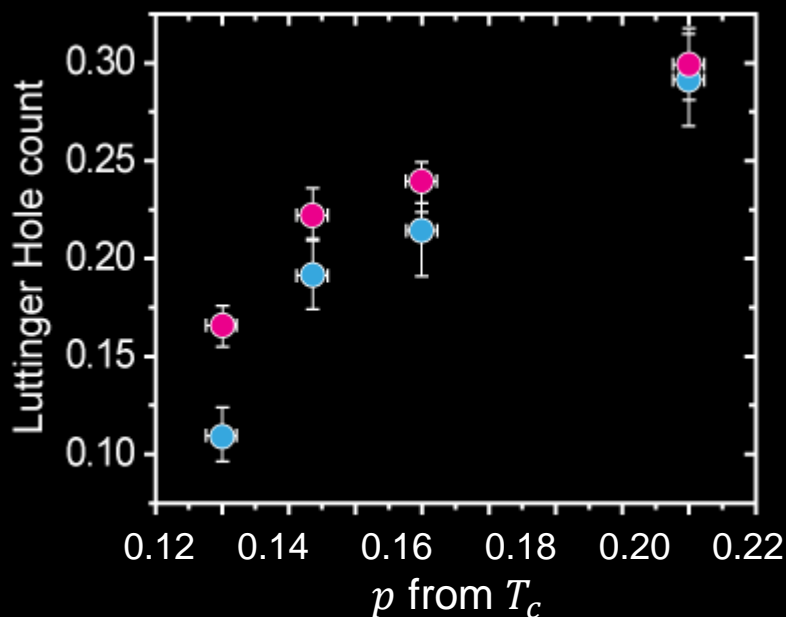
OD15K



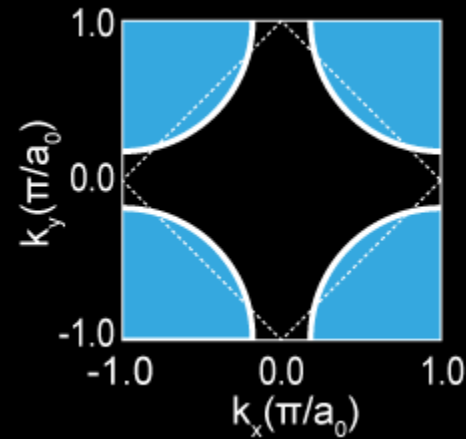
$$p_{\text{small}} = \frac{2A_{\text{pink}}}{A_{\text{BZ}}}$$

YRZ, PRB 73, 174501 (2006)

Qi + Sachdev, PRB 81, 115129 (2010)



Ando, PRB 61, R14956 (2000)

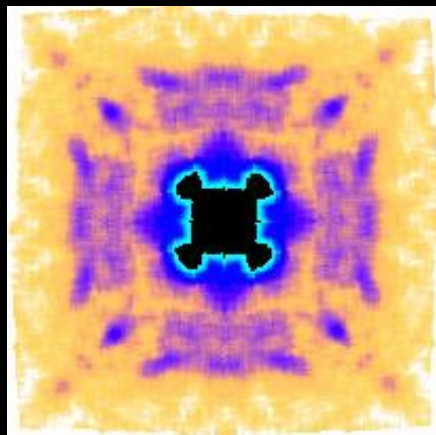


$$p_{\text{large}} = \frac{2A_{\text{blue}}}{A_{\text{BZ}}} - 1$$

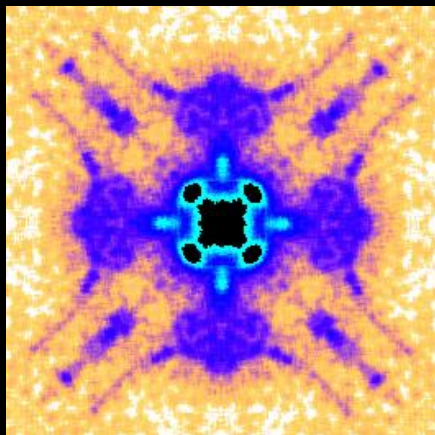
Luttinger count



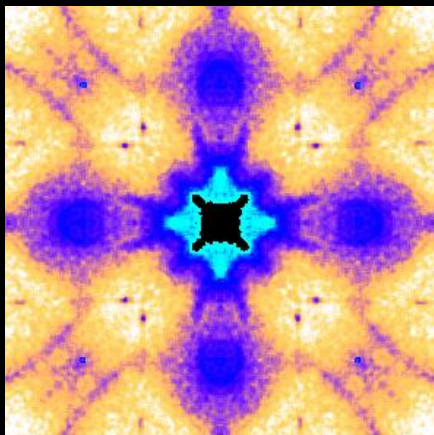
UD25K



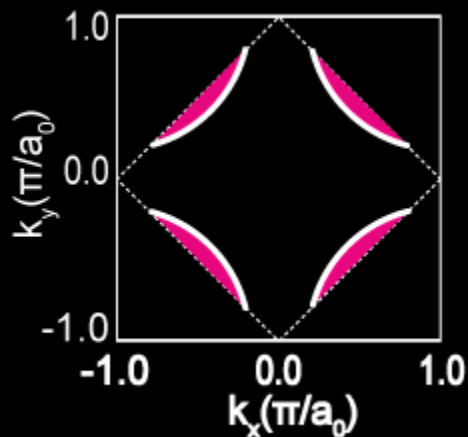
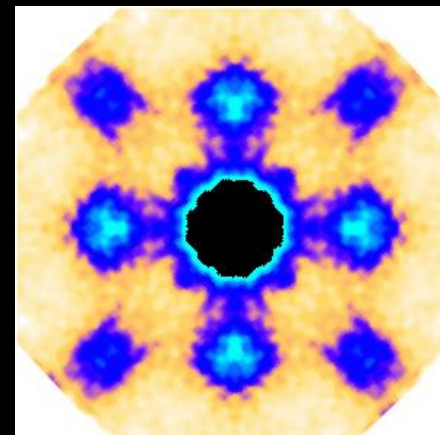
UD32K



OPT35K



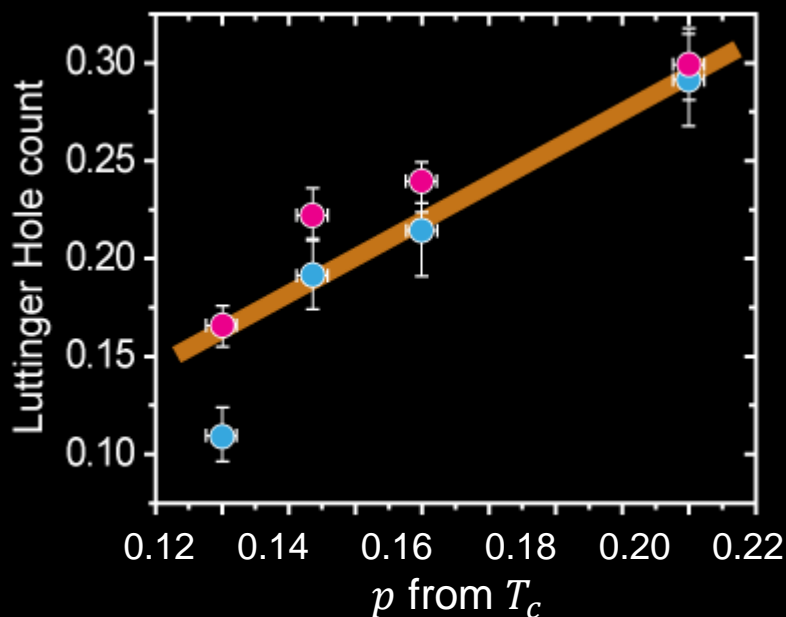
OD15K



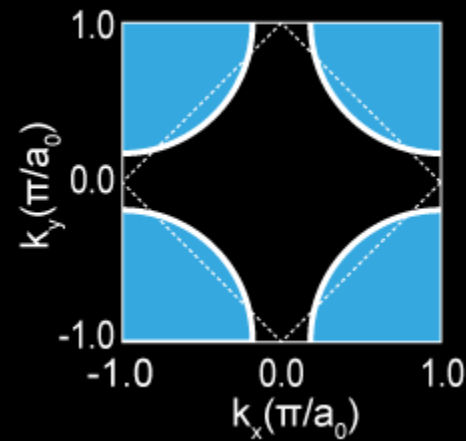
$$p_{\text{small}} = \frac{2A_{\text{pink}}}{A_{\text{BZ}}}$$

YRZ, PRB 73, 174501 (2006)

Qi + Sachdev, PRB 81, 115129 (2010)



Ando, PRB 61, R14956 (2000)

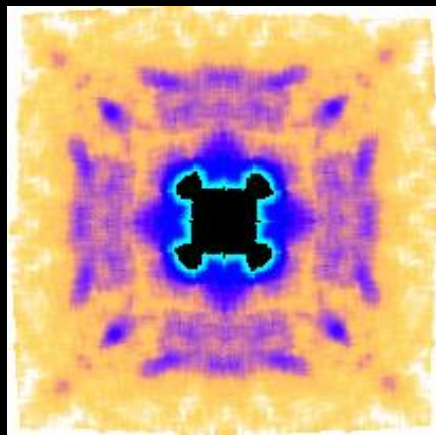


$$p_{\text{large}} = \frac{2A_{\text{blue}}}{A_{\text{BZ}}} - 1$$

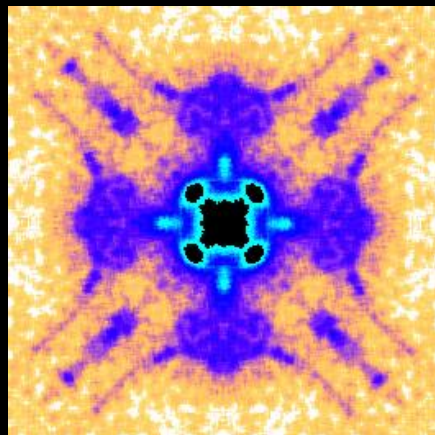
Luttinger count



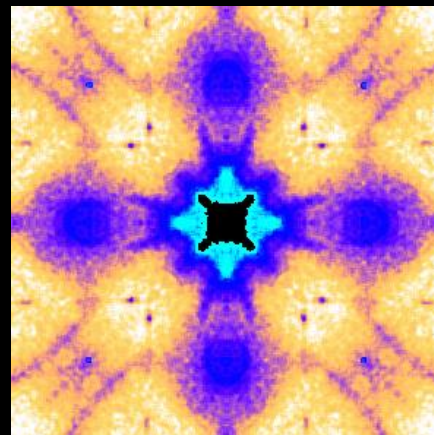
UD25K



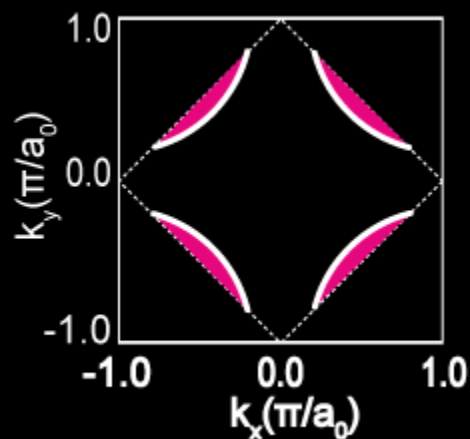
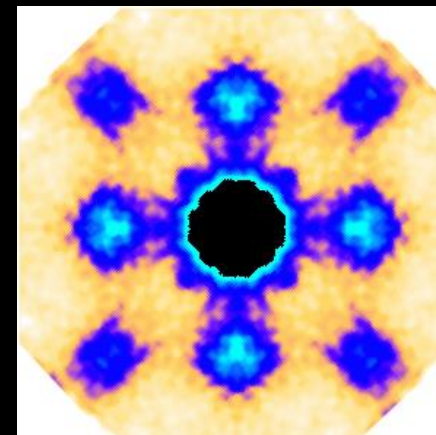
UD32K



OPT35K



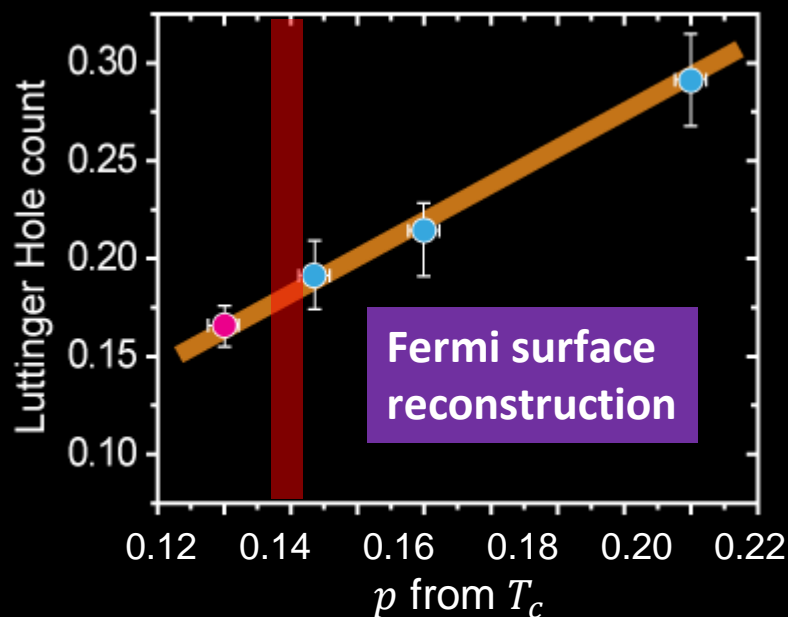
OD15K



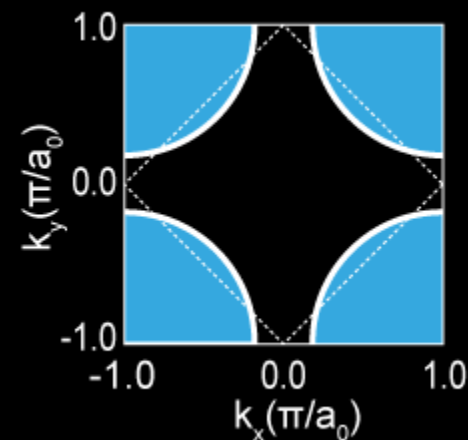
$$p_{\text{small}} = \frac{2A_{\text{pink}}}{A_{\text{BZ}}}$$

YRZ, PRB 73, 174501 (2006)

Qi + Sachdev, PRB 81, 115129 (2010)

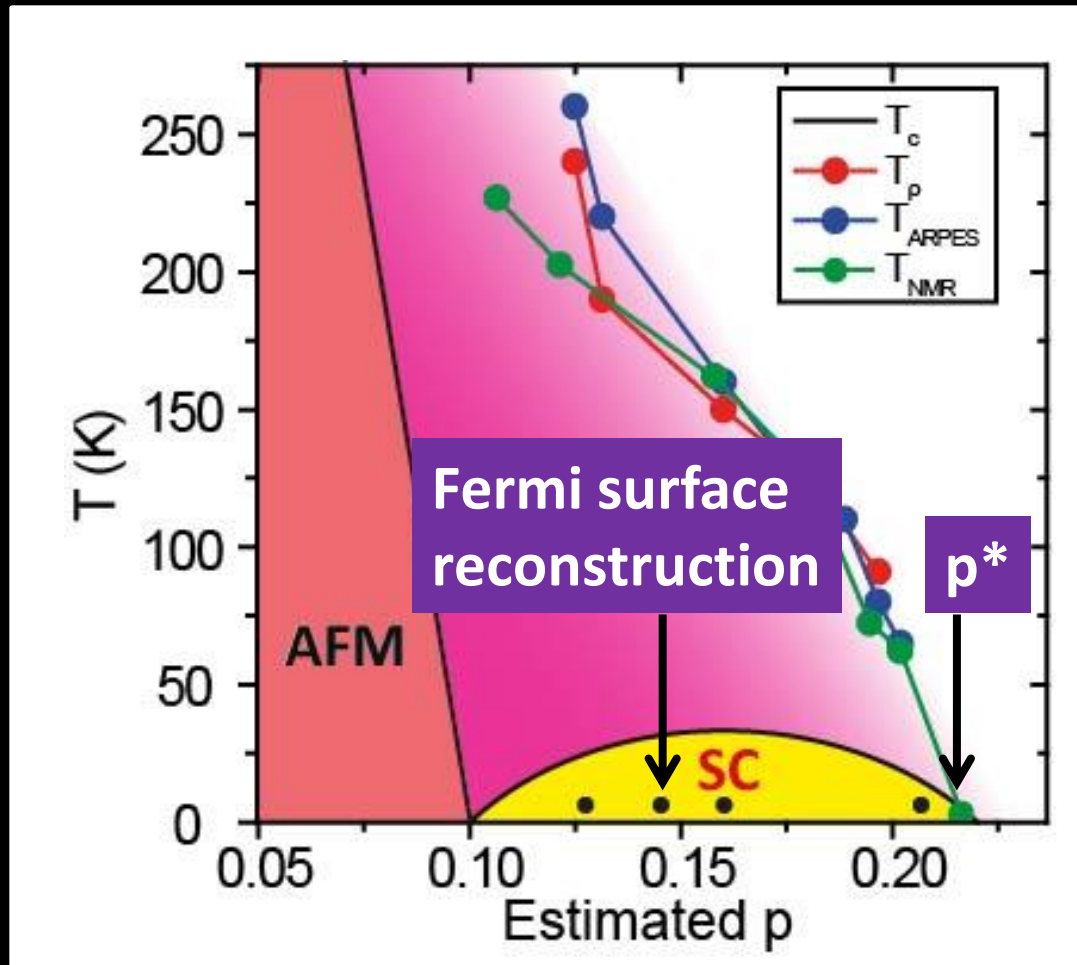


Ando, PRB 61, R14956 (2000)



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

FS reconstruction & pseudogap



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

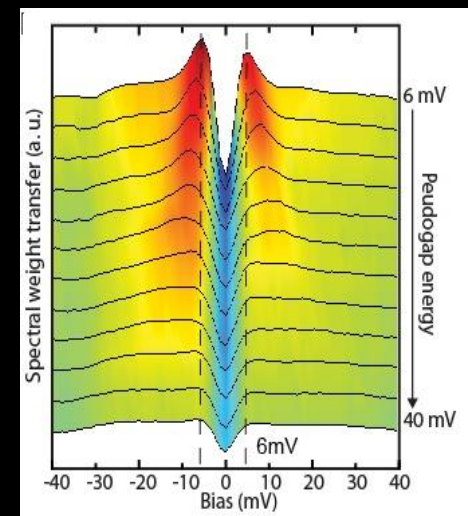
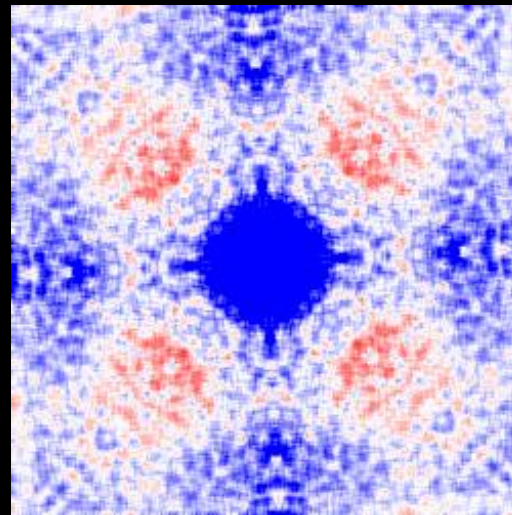
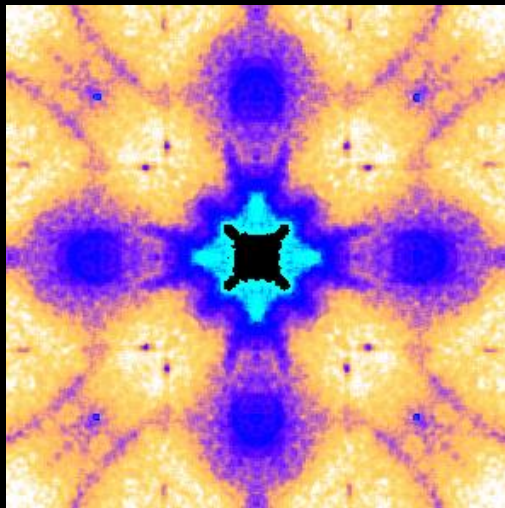
1. Where is the Fermi surface reconstruction?

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

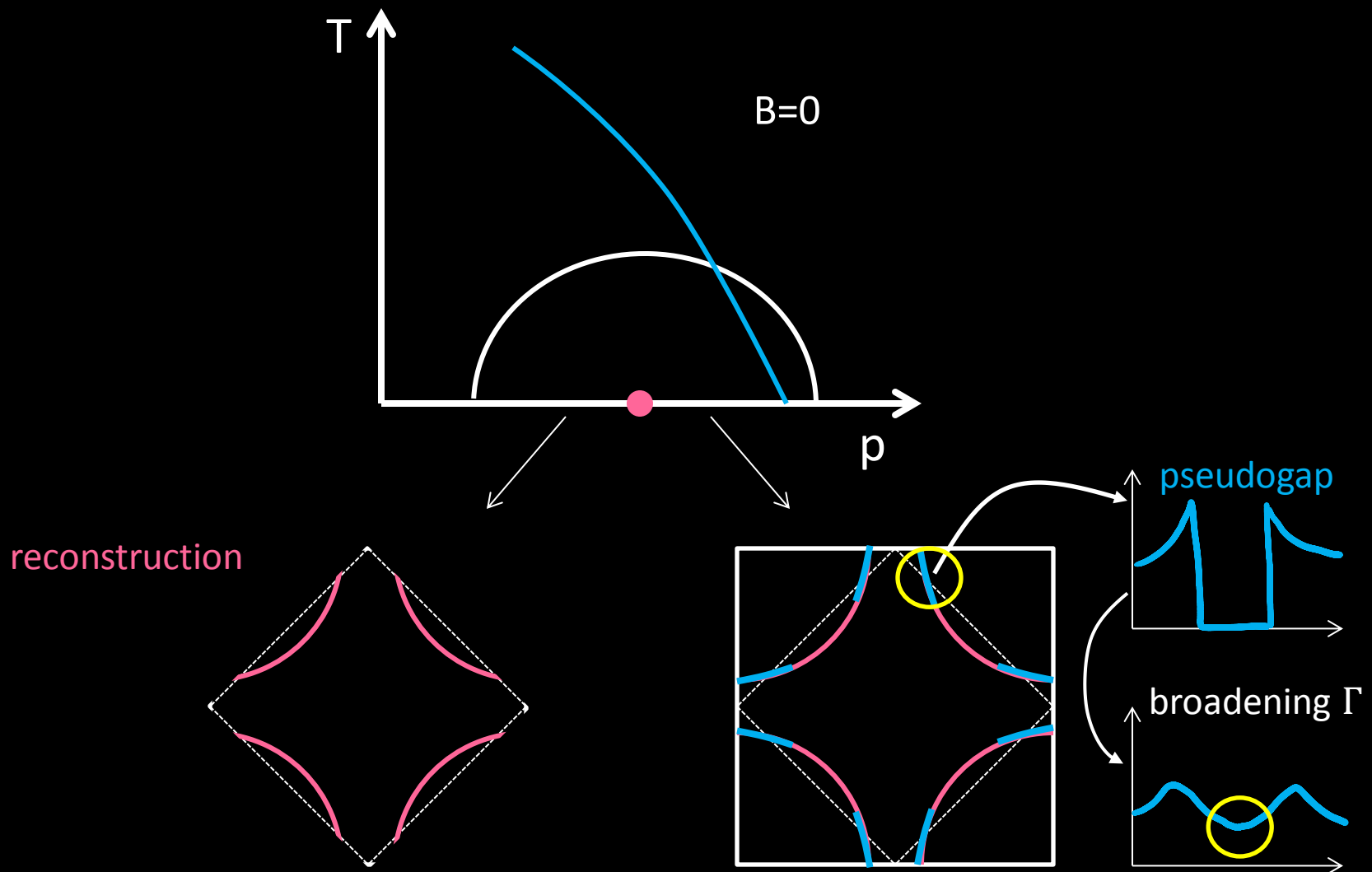


arxiv:1305.2778, to appear in *Science*, May 9 (2014)

What about **superconductivity**?



1. Fermi surface reconstruction \neq pseudogap

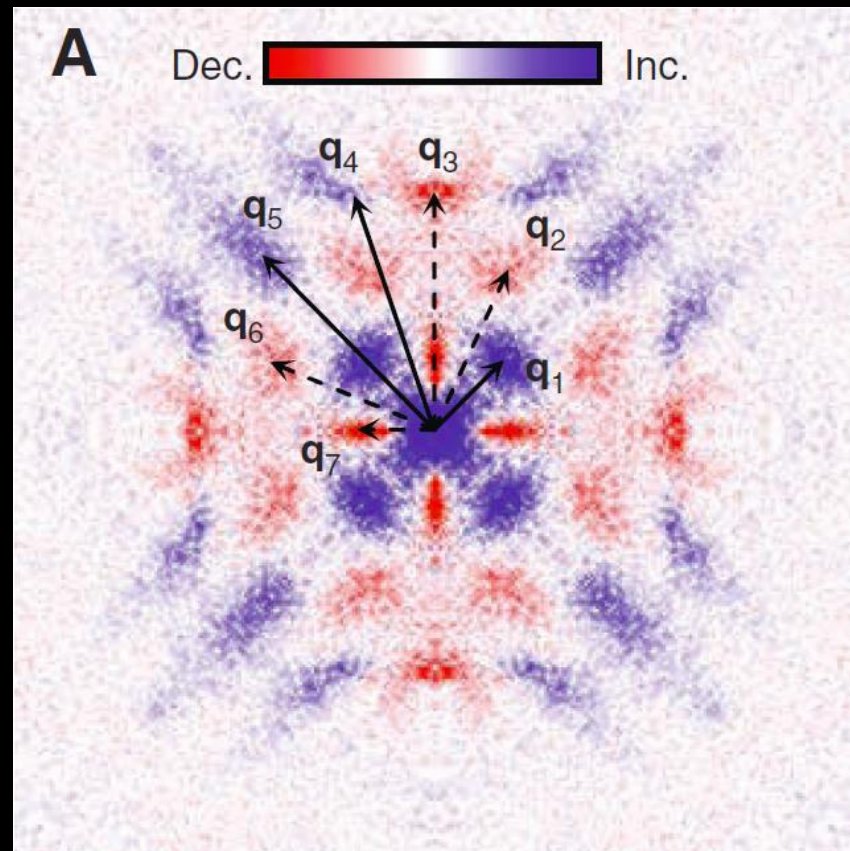
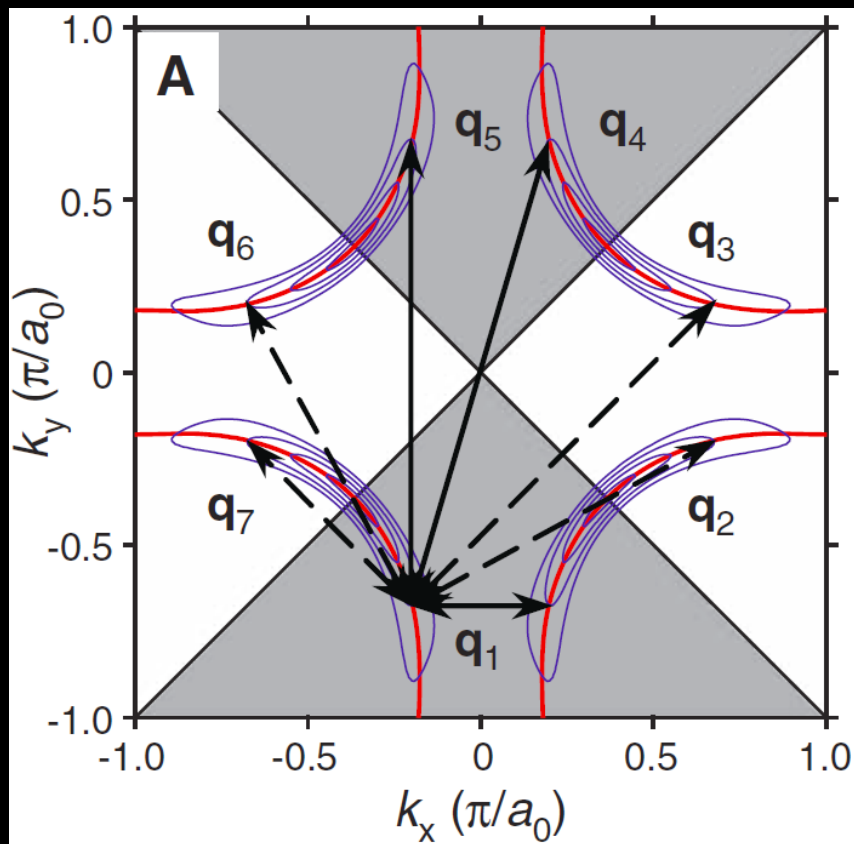


Can **superconductivity** live here too?

d -wave coherence factors in Bi2212

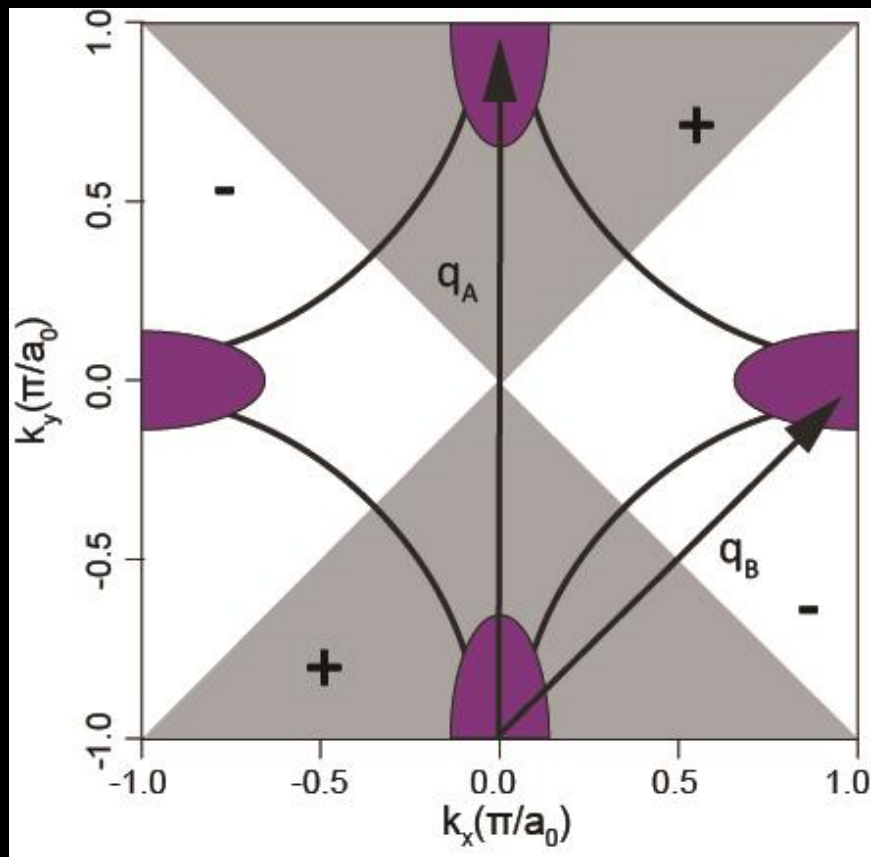


sign flipping \longrightarrow decreasing in field
sign preserving \longrightarrow increasing in field

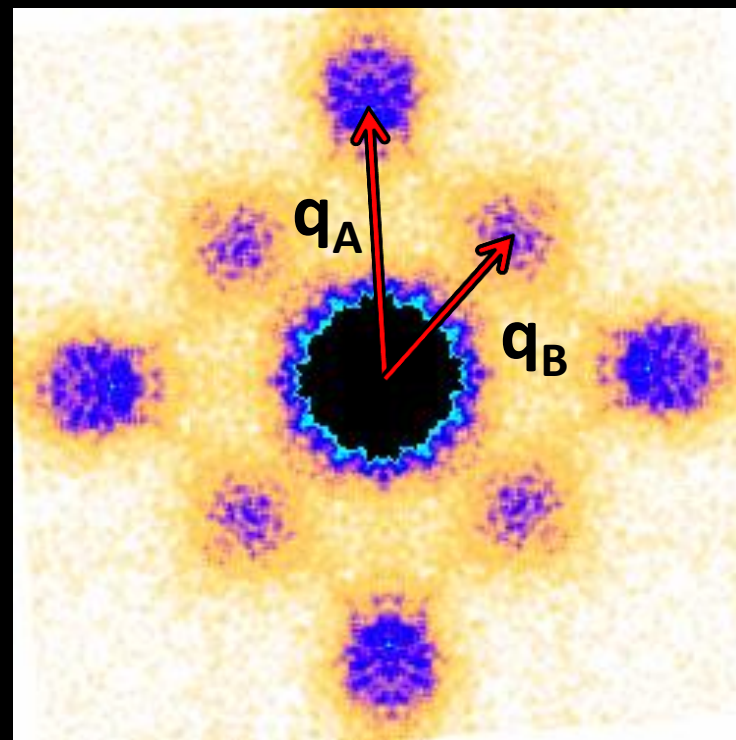


Hanaguri, et al, *Science* 323, 923 (2009)
suggested by Tami Pereg-Barnea & Marcel Franz
PRB 78, 020509 (2008)

antinodal d -wave coherence in Bi2201



OD15K 6mV, 0T

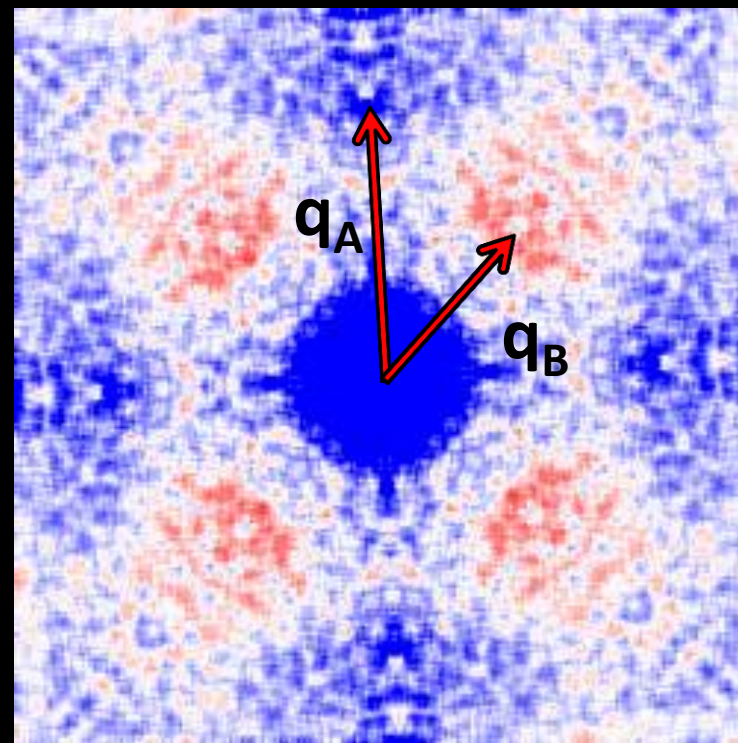
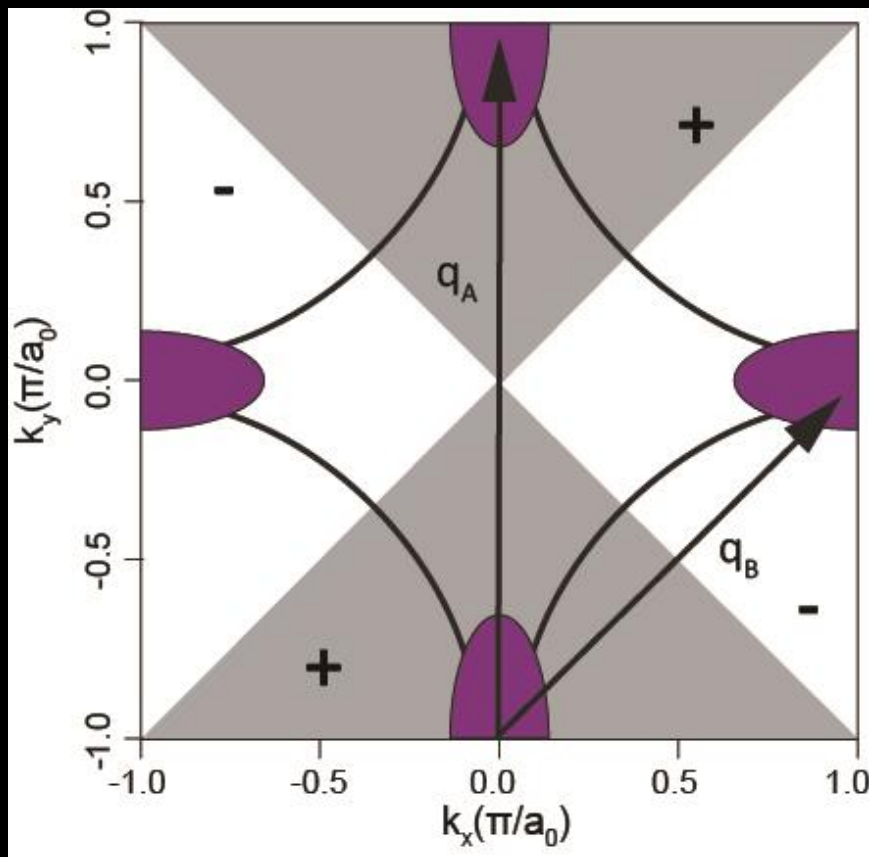


antinodal d -wave coherence in Bi2201



sign flipping \longrightarrow decreasing in field
sign preserving \longrightarrow increasing in field

OD15K 6mV, 9T-0T



Decreasing  Increasing

Field dependence

\longrightarrow Antinodal quasiparticles show d -wave coherence

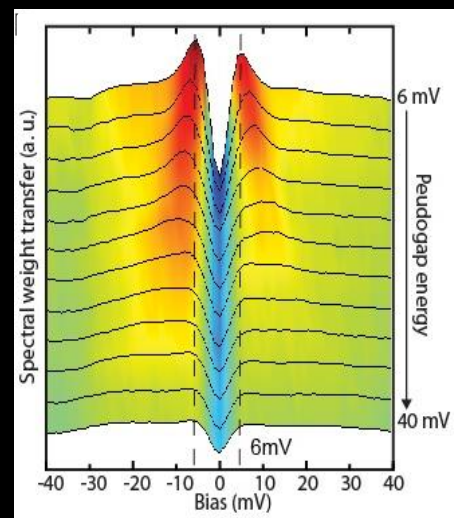
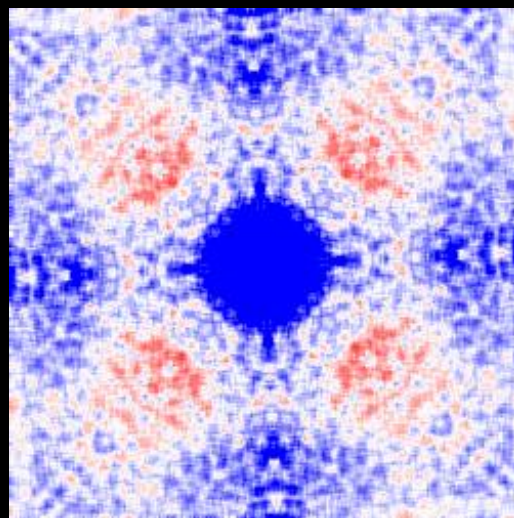
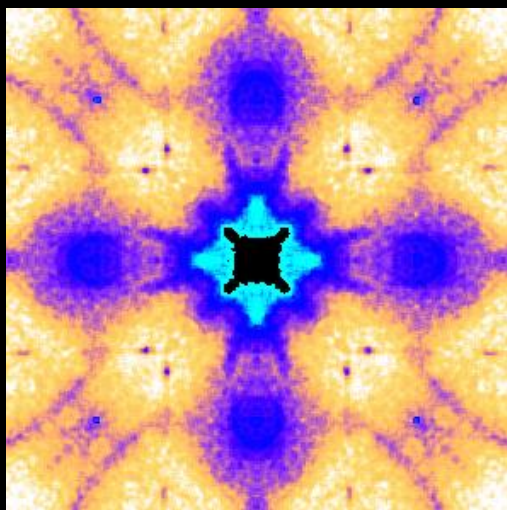
1. Where is the Fermi surface reconstruction?

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)

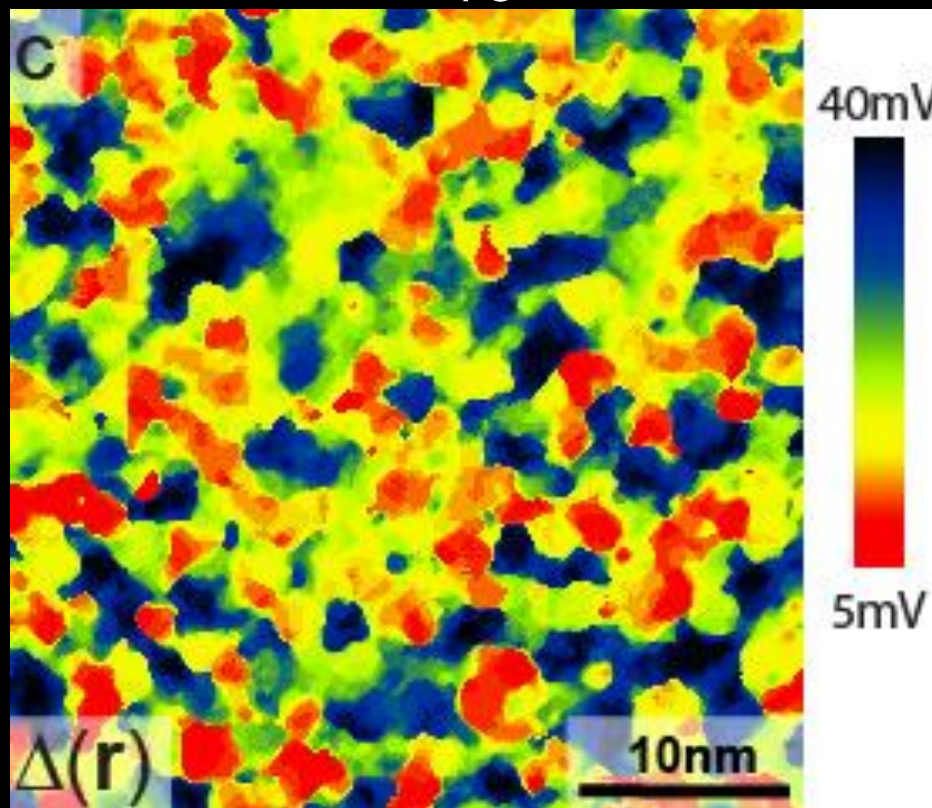
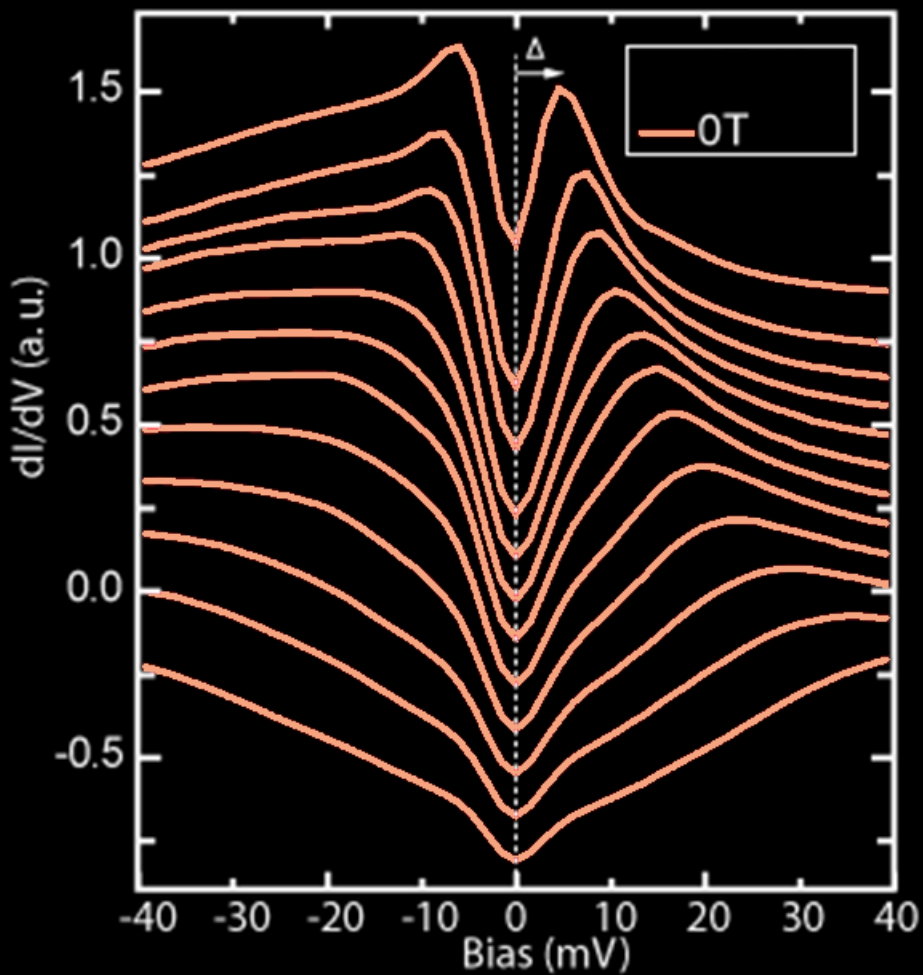
Two gap scenario: coexist spatially?

superconductivity vs. **pseudogap** at antinode?



OD15K

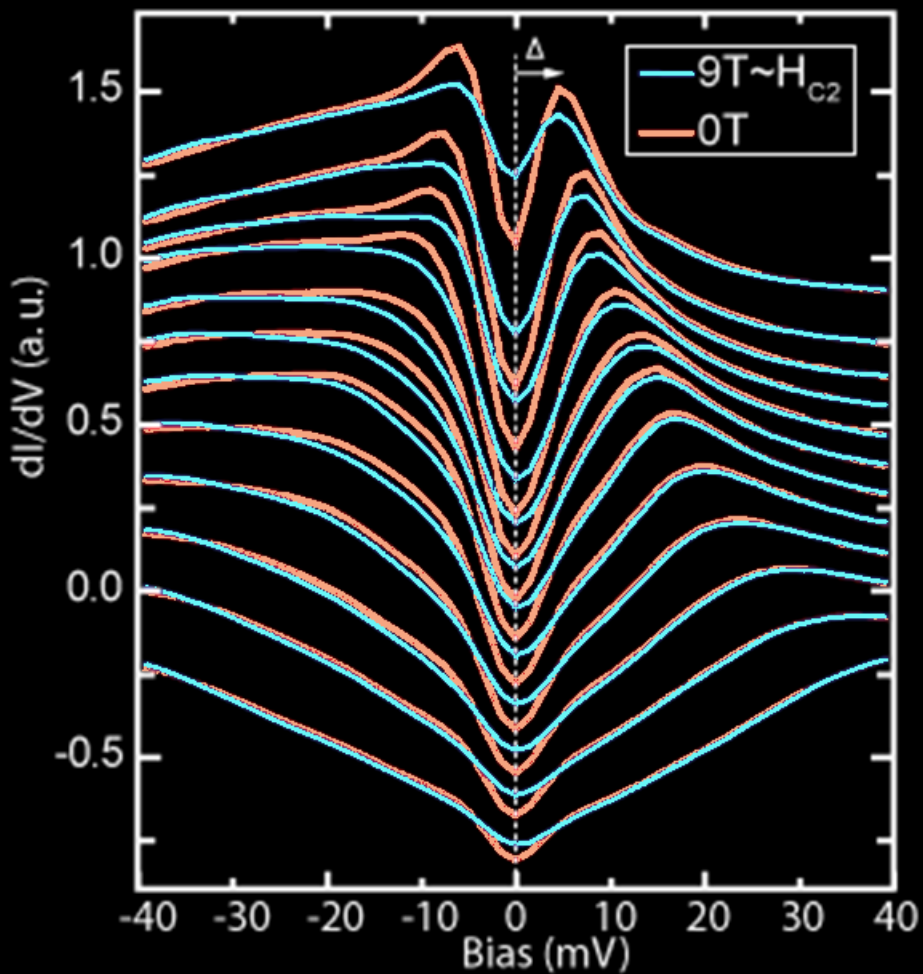
Δ_{PG}



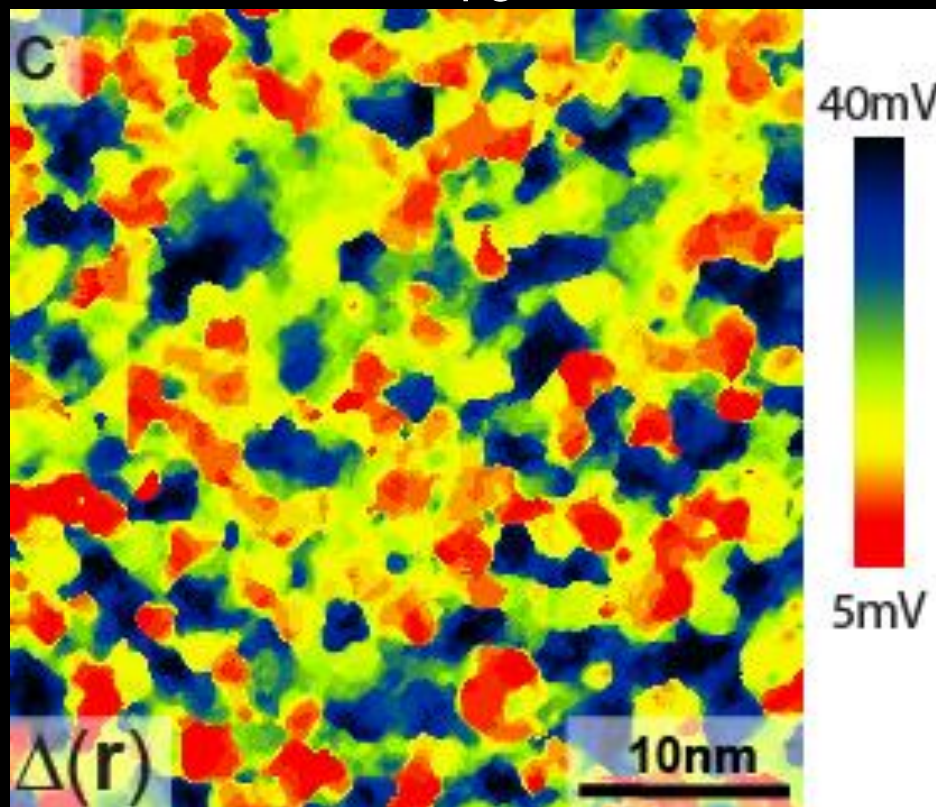
Two gap scenario: coexist spatially?



OD15K



Δ_{PG}



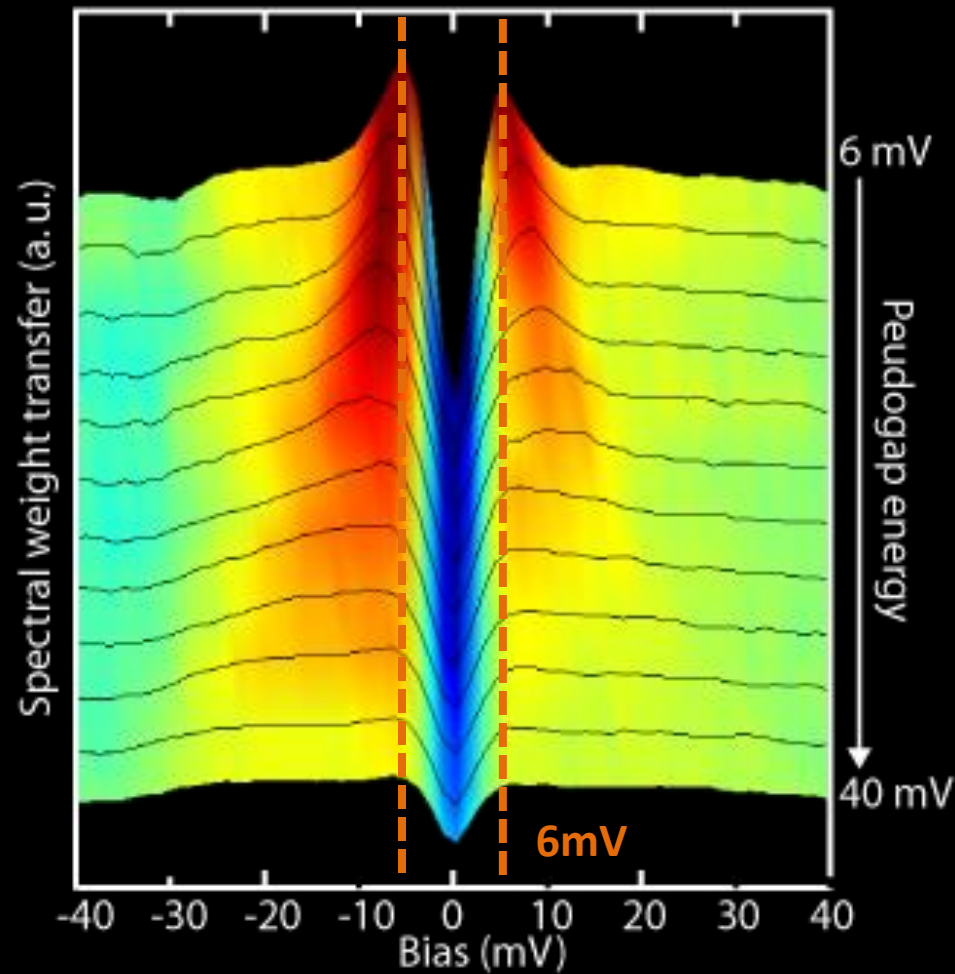
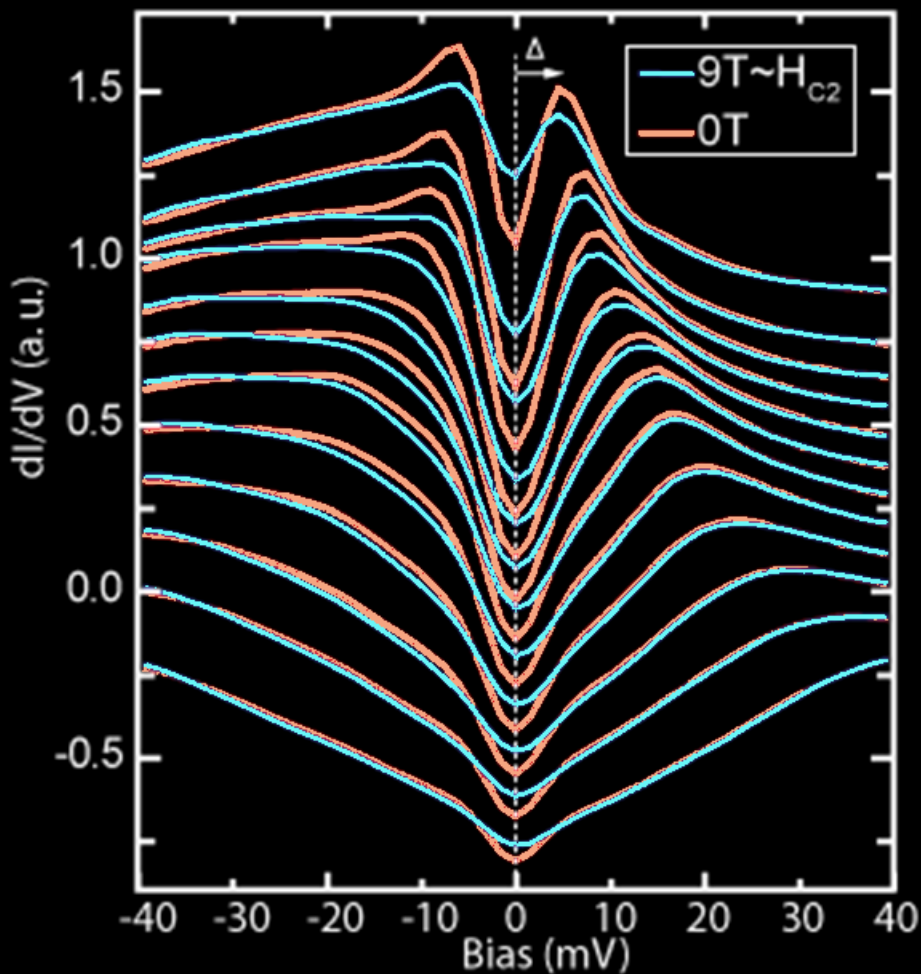
Two gap scenario: coexist spatially?



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



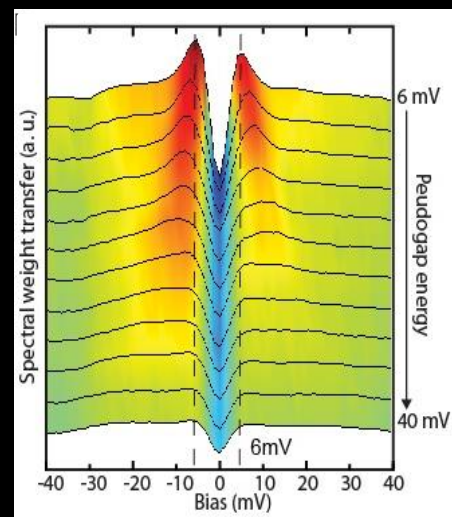
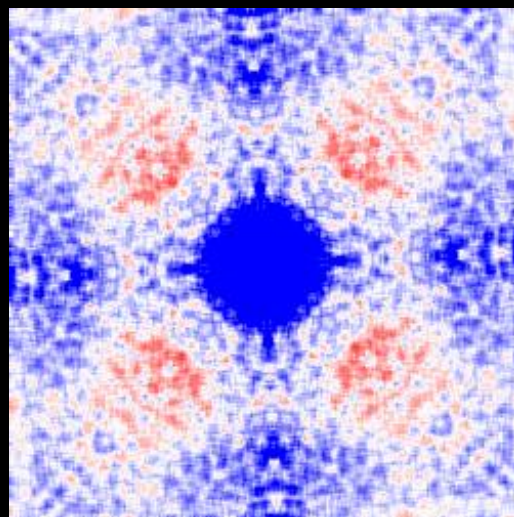
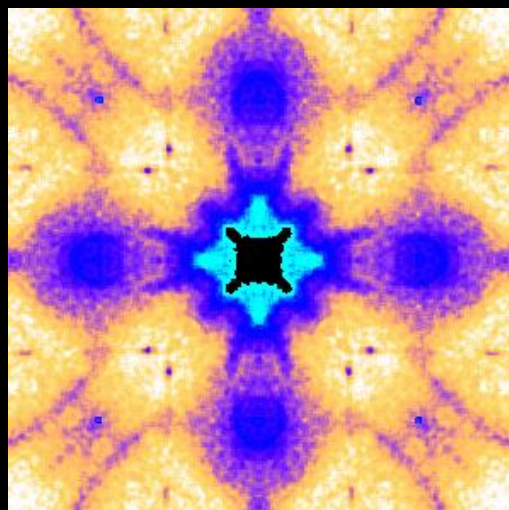
1. Where is the Fermi surface reconstruction?

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

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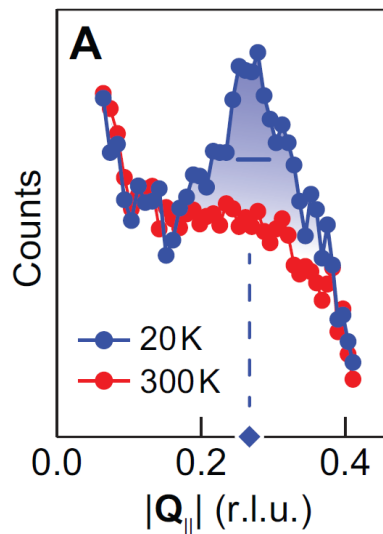


arxiv:1305.2778, to appear in *Science*, May 9 (2014)

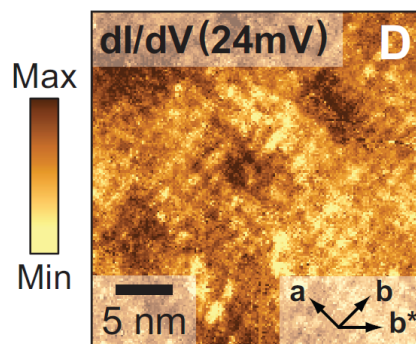
What about charge order?



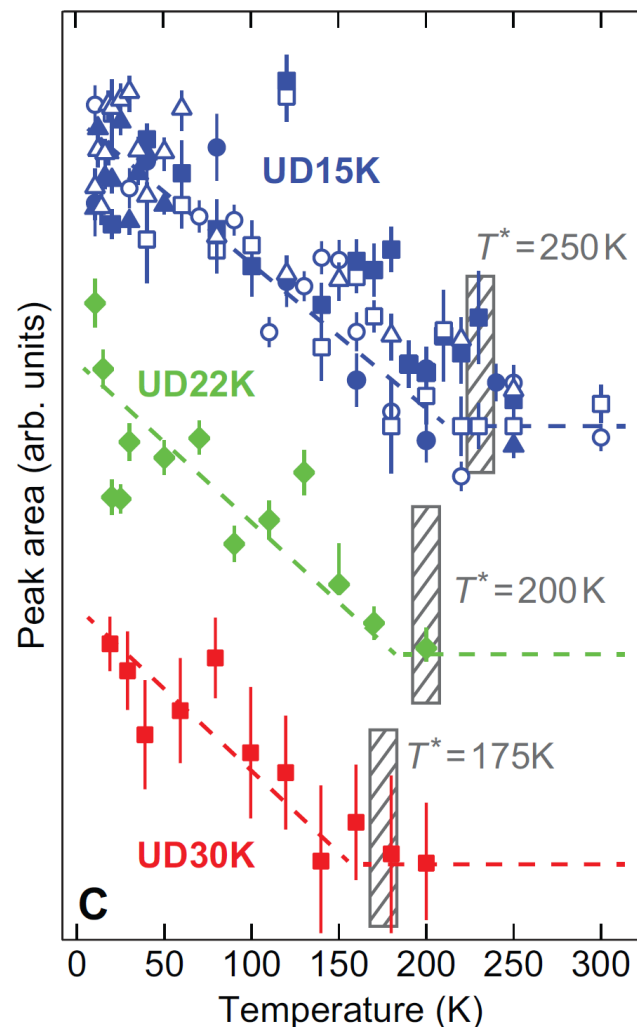
Bi2201: First ever reconciliation of STM-observed and X-ray-observed charge order!



Resonant
X-ray
Scattering



Scanning
Tunneling
Microscopy



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

Charge order is not antinodal nesting



Bi2201
OPT35K

5mV

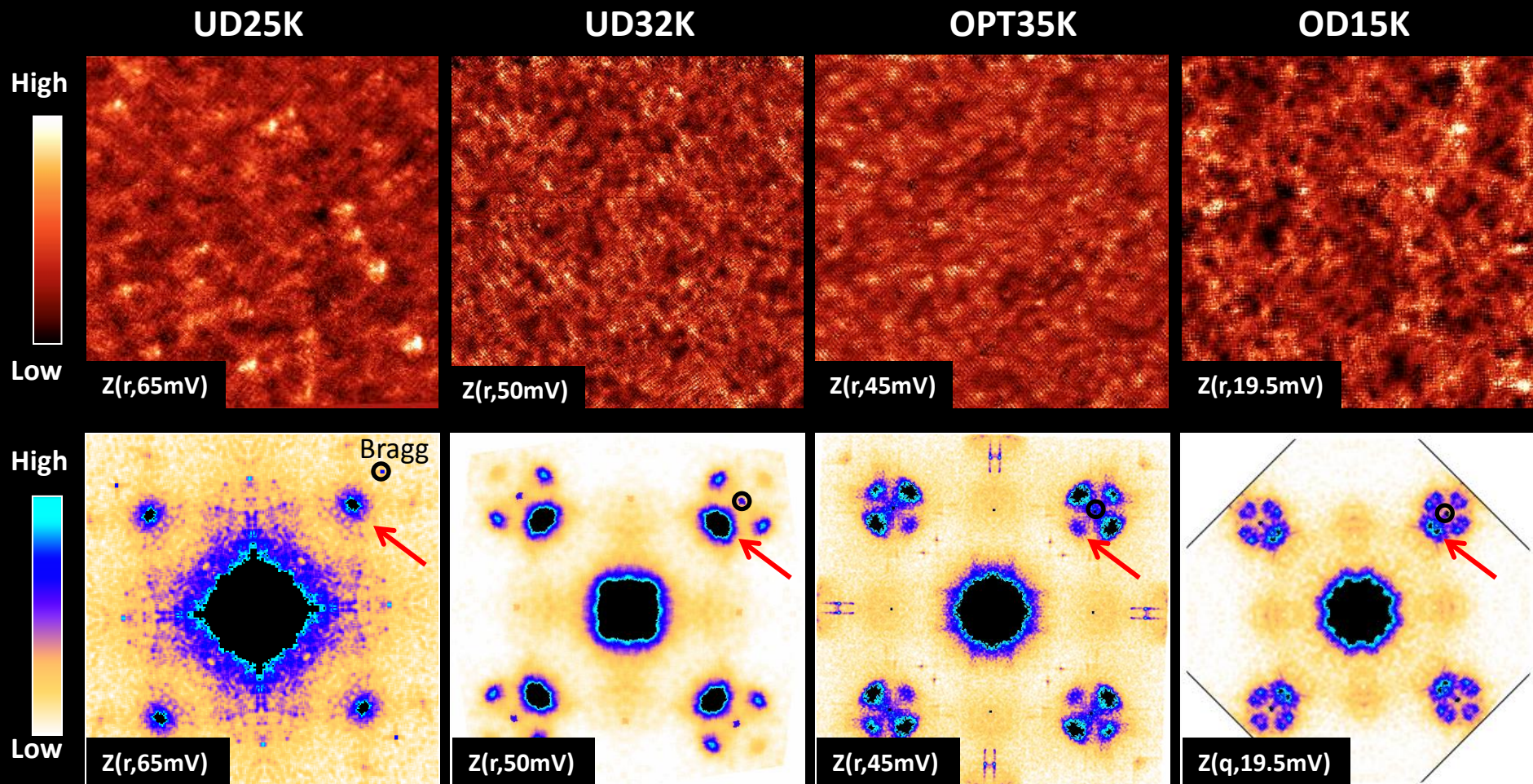
50mV

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

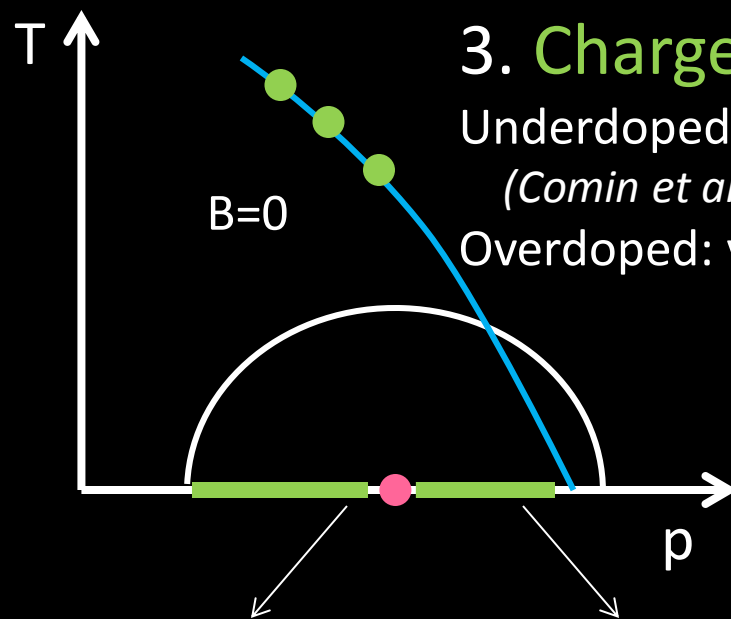


Charge order correlation length shows no trend with doping
(in particular, no longer in the most underdoped sample with small FS)

Conclusions (STM on Bi2201)



1. Fermi surface reconstruction \neq pseudogap

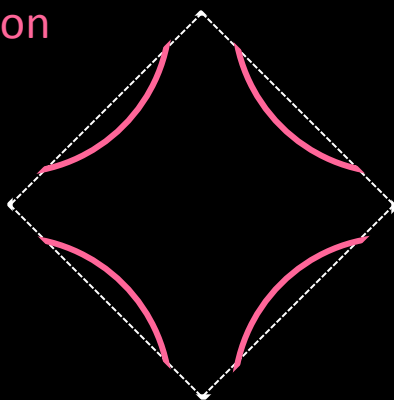


3. Charge order

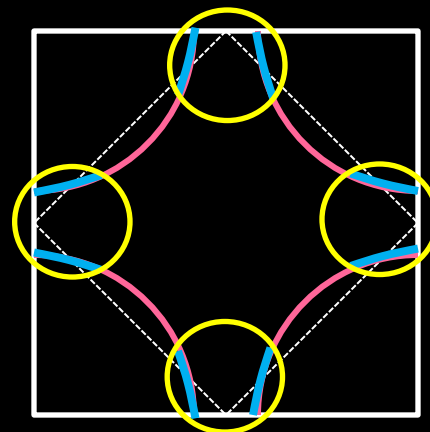
Underdoped: bulk-surface correspondence
(Comin et al, Science 343, 390 2014)

Overdoped: visible on surface to p^*

reconstruction



pseudogap

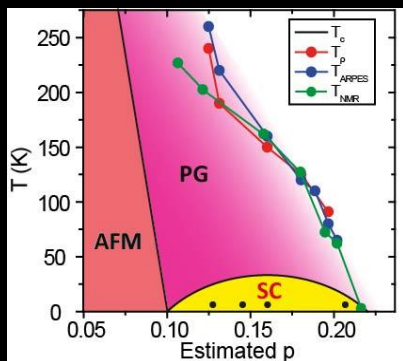


2. Superconductivity coexists with pseudogap at the antinode

Forest of Phase Diagrams

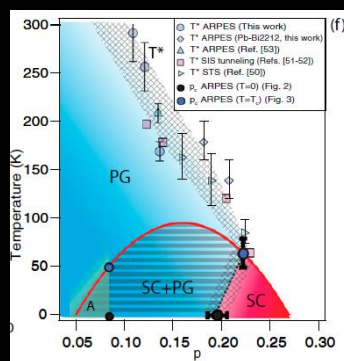


Bi2201



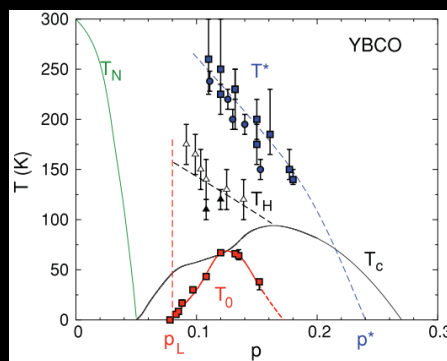
This talk

Bi2212



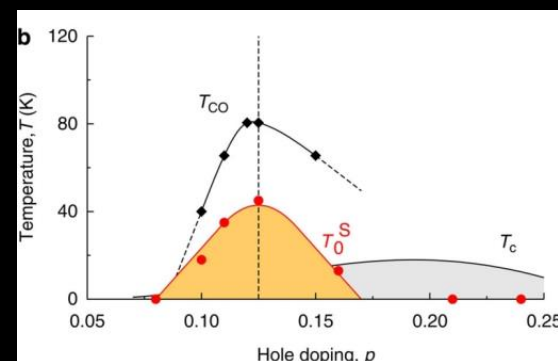
Vishik, PNAS 2012

YBCO

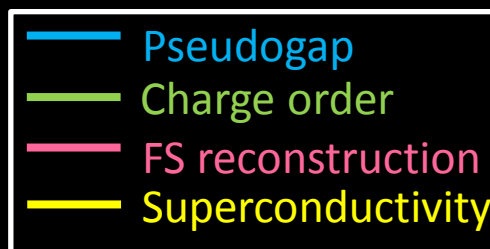


LeBouef, PRB 2011

Eu-LSCO



Laliberte, Nature Comm 2012

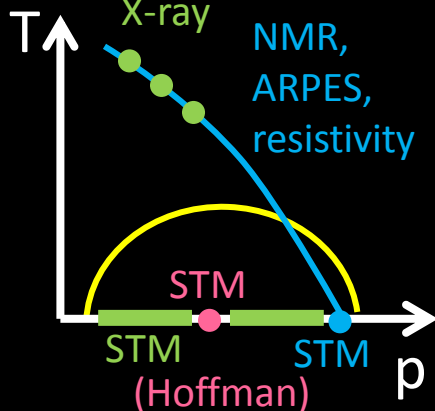


Bi2201

Comin et al,

X-ray

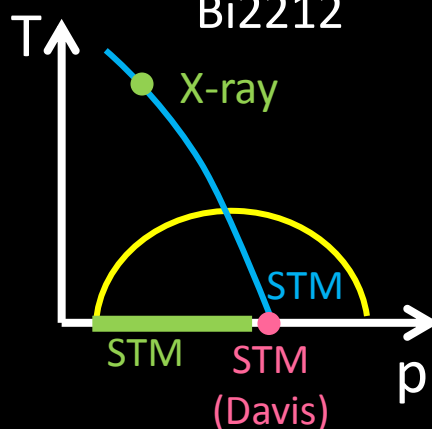
NMR,
ARPES,
resistivity



Bi2212

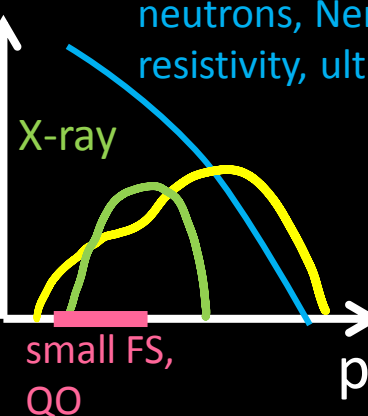
X-ray

STM
(Davis)



YBCO & LSCO

neutrons, Nernst,
resistivity, ultrasound



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