Next up: vortices as a window to the "normal" state…

And other things I would like to get to today:

- comparison of charge order in several cuprates
- internal form factor of charge order
- Fermi surface
- nematicity in cuprates & pnictides
- bosons

Superconductivity Tunneling Milestones

1960: gap measurement (Pb)

1965: boson energies & coupling (Pb)

1985: charge density wave ($TaSe_2$)

1989: vortex lattice ($NbSe_2$)

1997: single atom impurities (Nb)

2002: quasiparticle interference

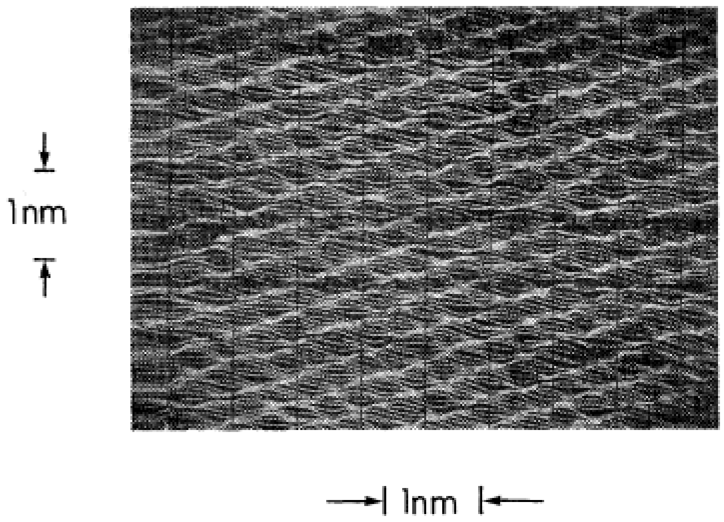
→ band structure & gap symmetry (BSCCO)

2009: phase-sensitive gap measurement (Na-CCOC)

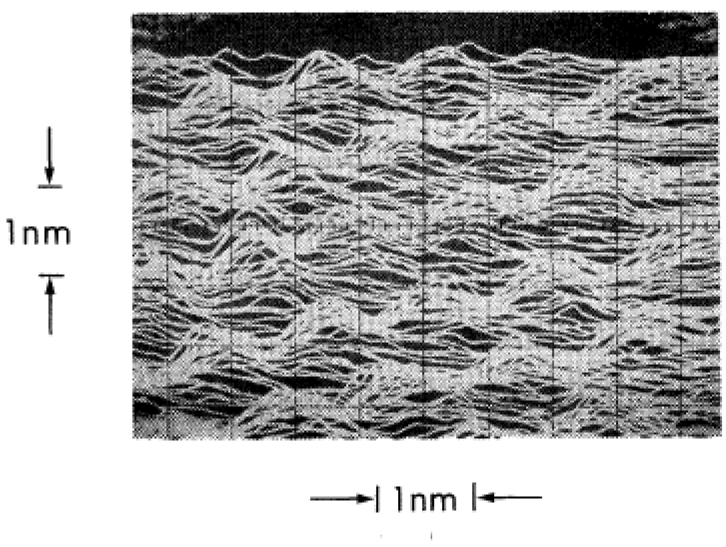
2010: intra-unit-cell structure (BSCCO)

1985: charge density wave

$TaSe_2$ (T_c=133 mK)



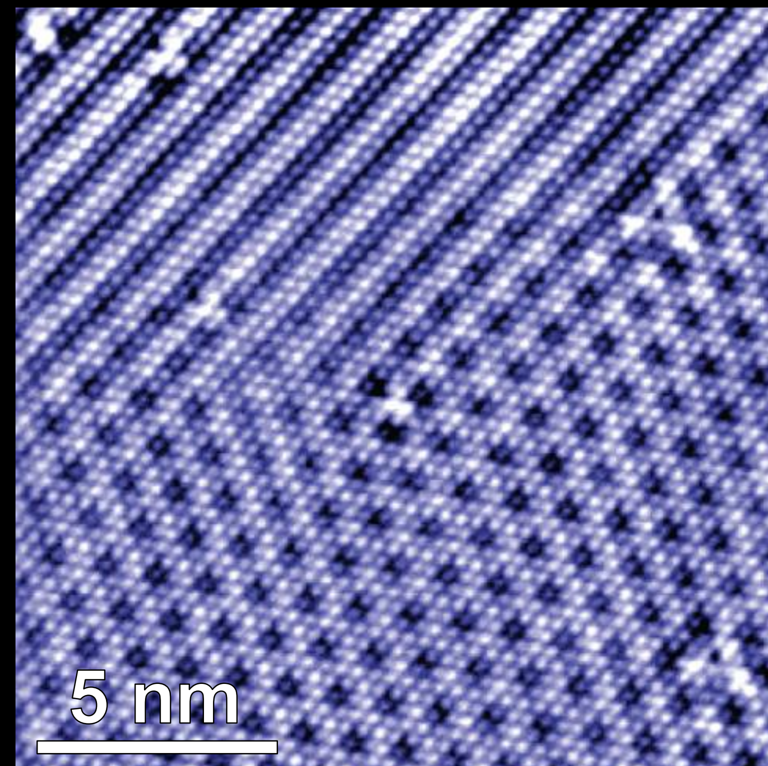
$$\lambda_{CDW} = (3.5 \pm 0.3)a_0$$



Coleman, PRL 55, 394 (1985)

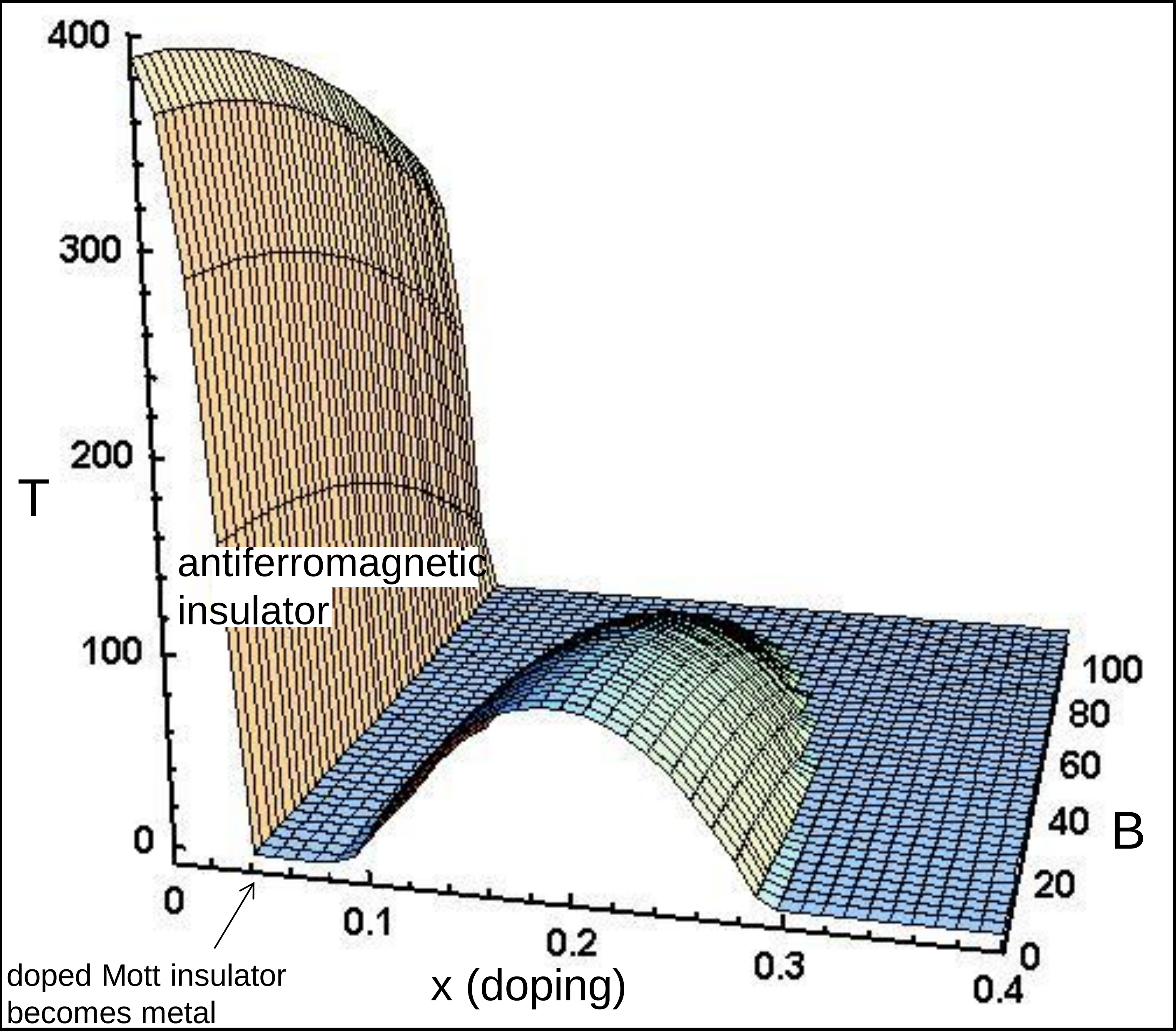
push tip closer to surface

2013: quantum phase transition between 1D & 2D CDW phases in $NbSe_2$



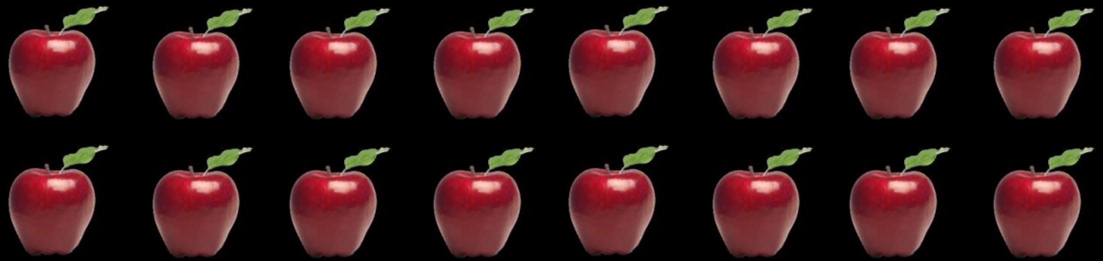
Soumyanarayanan & JEH, PNAS 110, 1623 (2013)

Cuprate Phase Diagram



Mott Transition

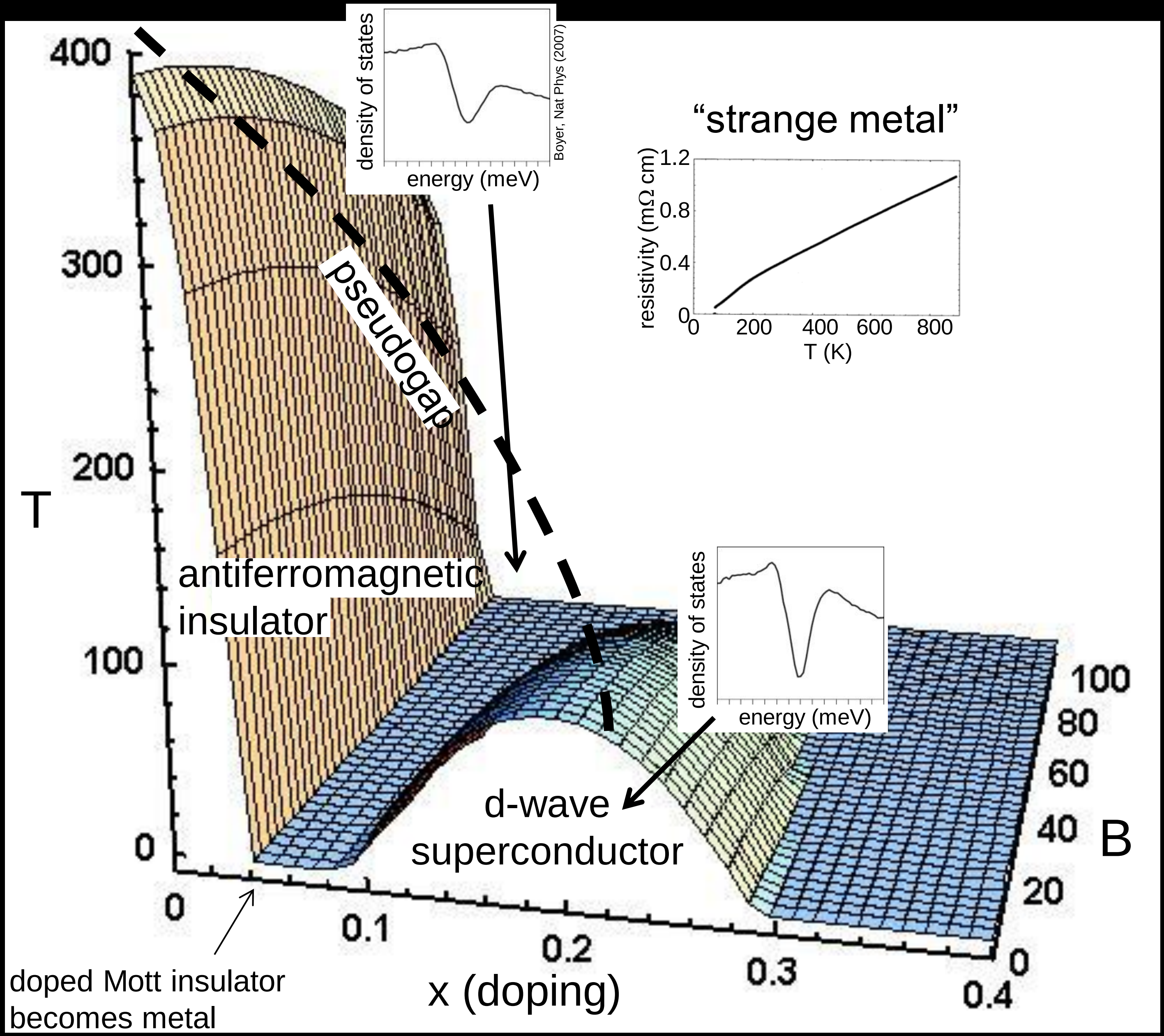
localized



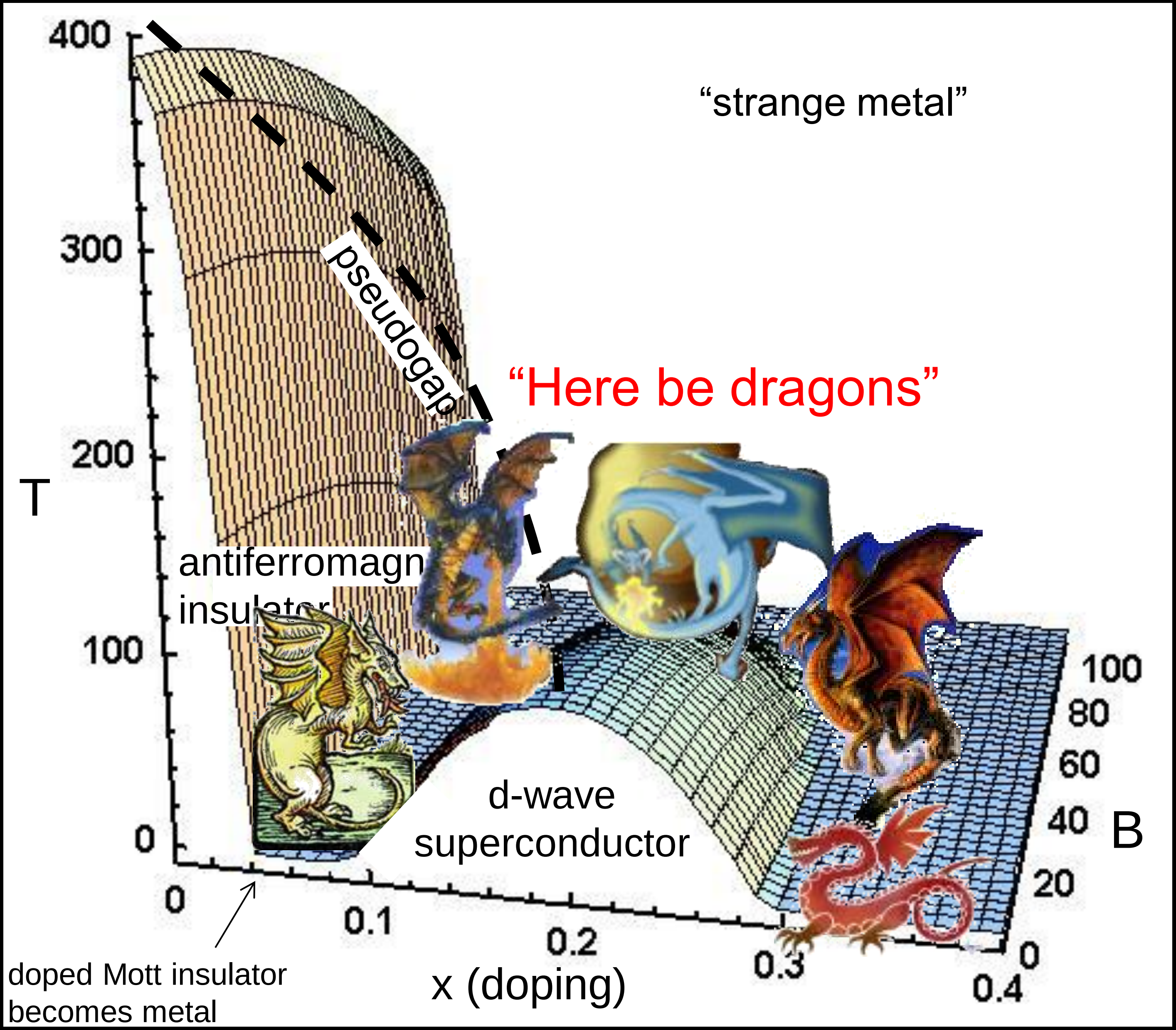
delocalized

further delocalized

Cuprate Phase Diagram

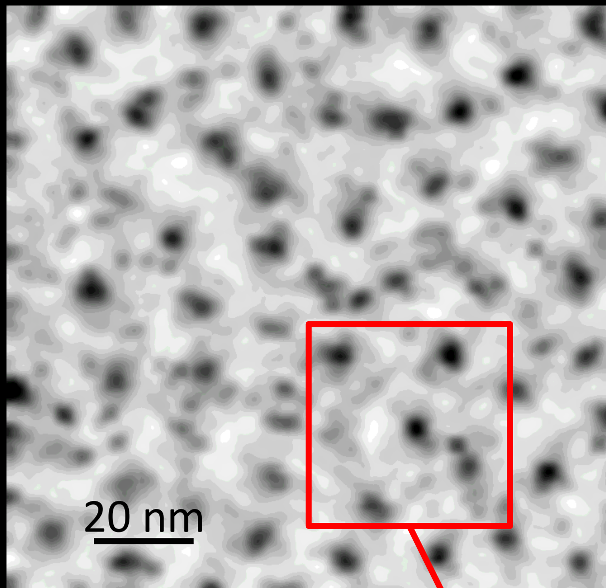


Cuprate Phase Diagram



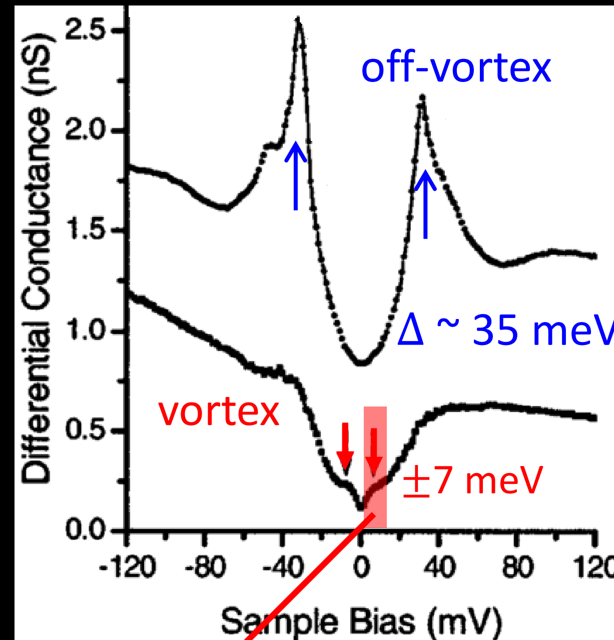
Look back at those Bi2212 vortices…

BSCCO



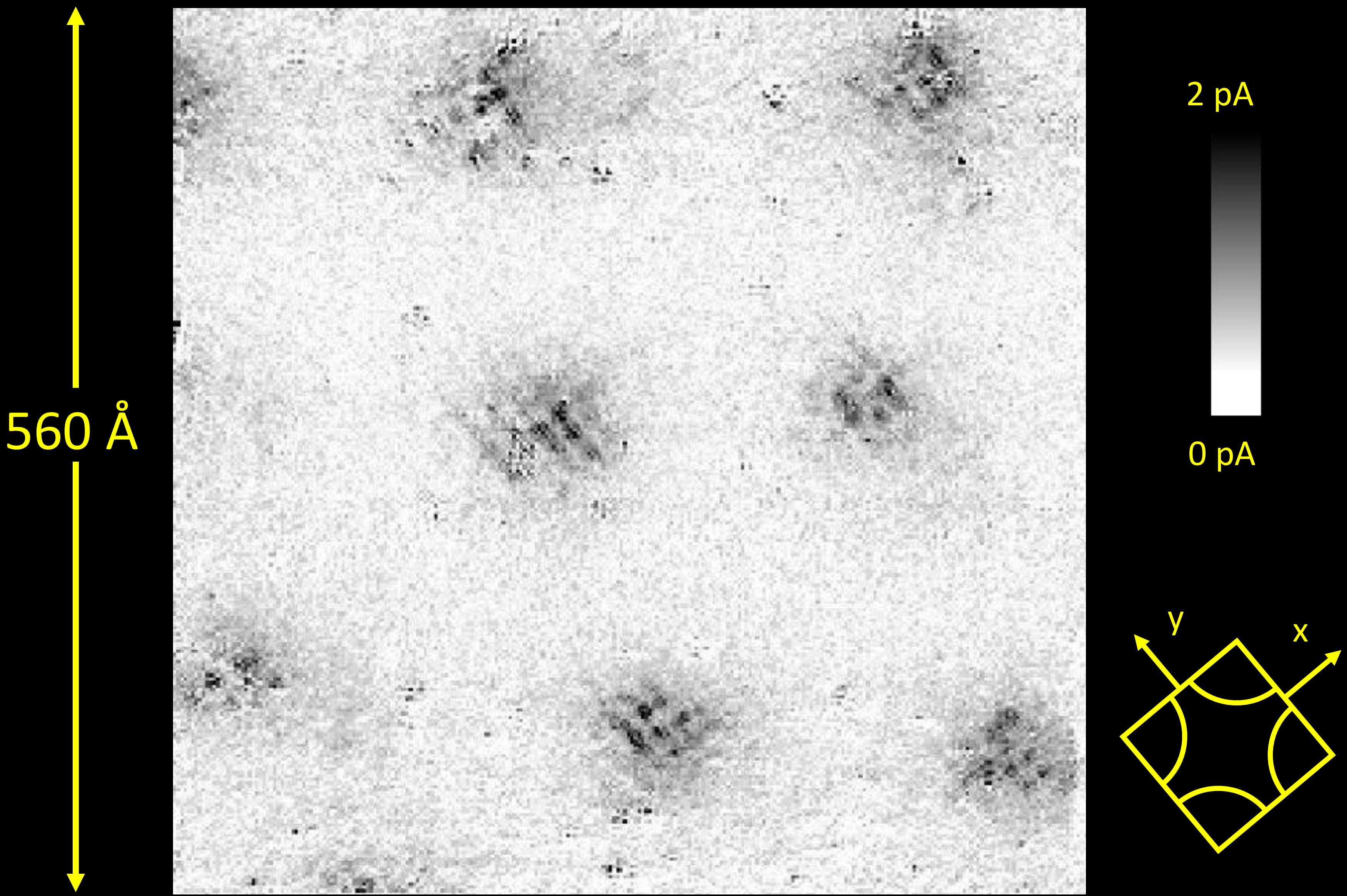
Pan, PRL 85, 1536 (2000)

zoom in



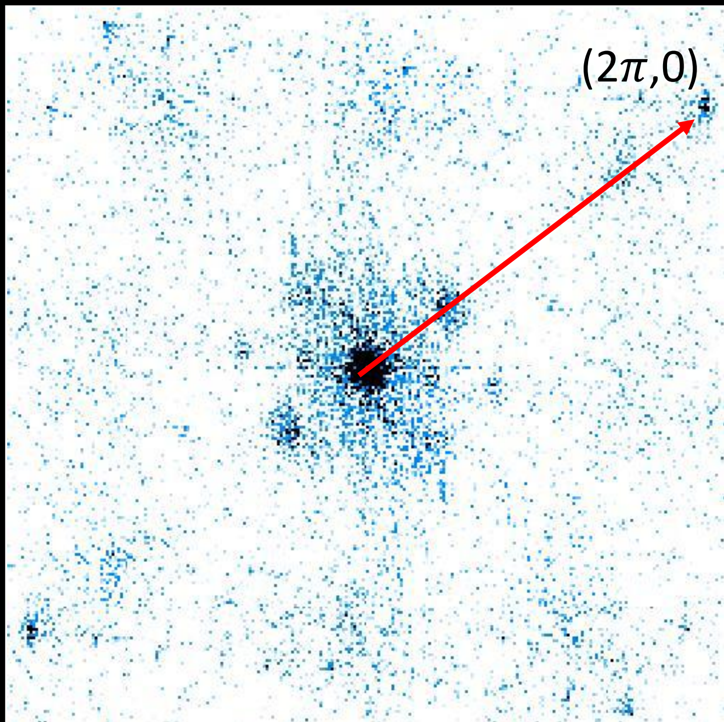
integrate over the core state energy range

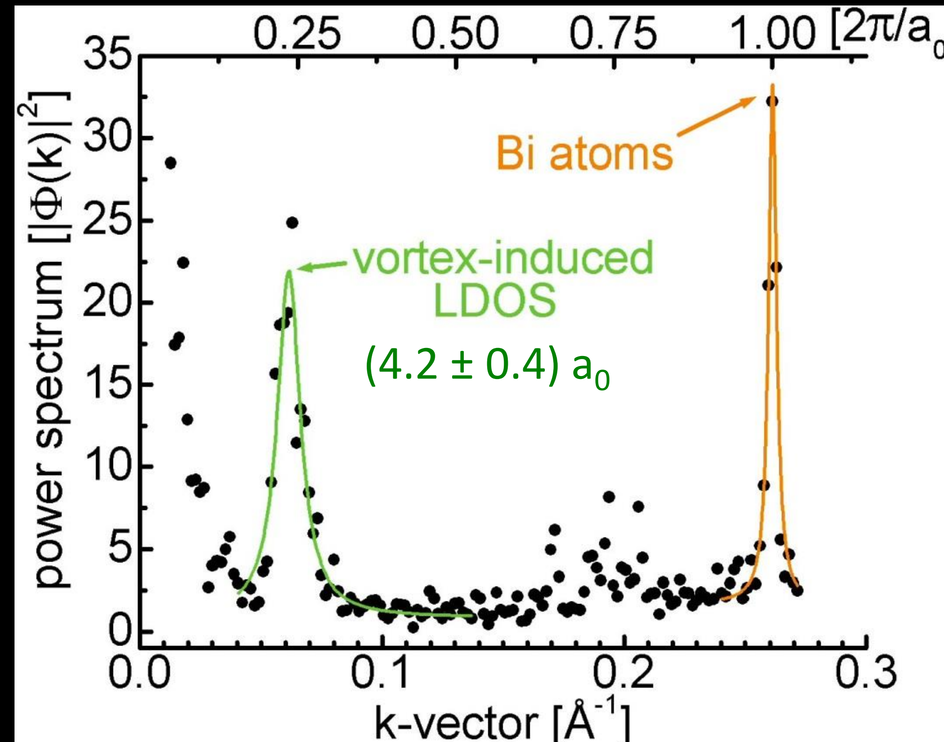
Bi2212: Vortex-induced checkers



Hoffman, Science 266, 455 (2002)

Bi2212 vortices: Fourier transform

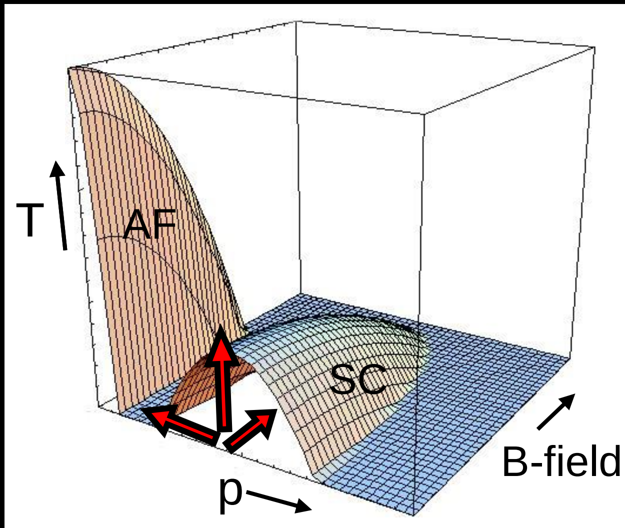




One might conclude that these core state are non-dispersive because they were identified by energy integration (!)

But vortex diameter is D~100 Å~25a_0 in diameter.
The *q*-space resolution is therefore δq=2π/D ~ 4% (2π/a_0)
→ too coarse to resolve band structure dispersion

Bi2212: Destroy SC → Static Order?



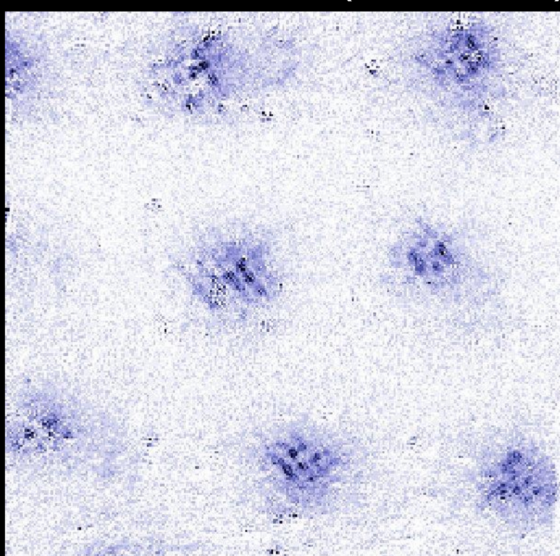
Suppression of Superconductivity in optimal Bi2212:

→ Pseudogap Spectra

→ "checkerboard" LDOS Modulations

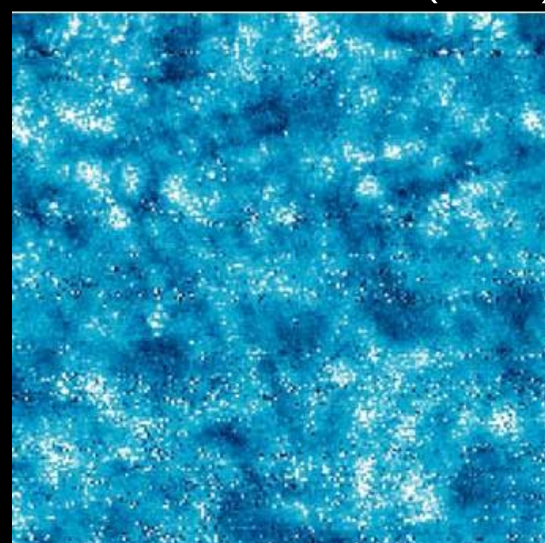
→ Incommensurate: $4.3a_0$, $4.5a_0$, $4.6a_0$

B = 5T (E = 7 meV)



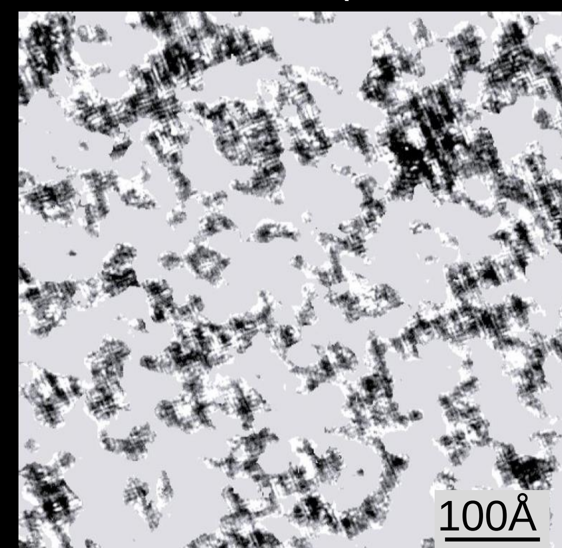
J. Hoffman, … J.C. Davis
Science 295, 466 (2002)

T = 100K (E < Δ)



M. Vershinin, … A. Yazdani
Science 303, *1995 (2004)*

Δ > 65 meV (E > 65 meV)

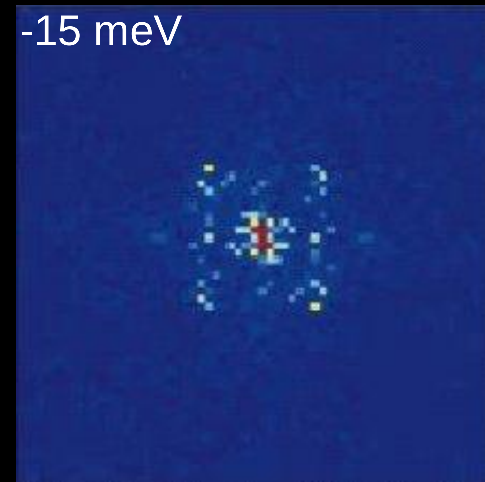


K. McElroy, … J.C. Davis
PRL 94, 197005 (2005)

Superconducting State: Dispersing vs. Static?

Real space:
(160 Å)^2

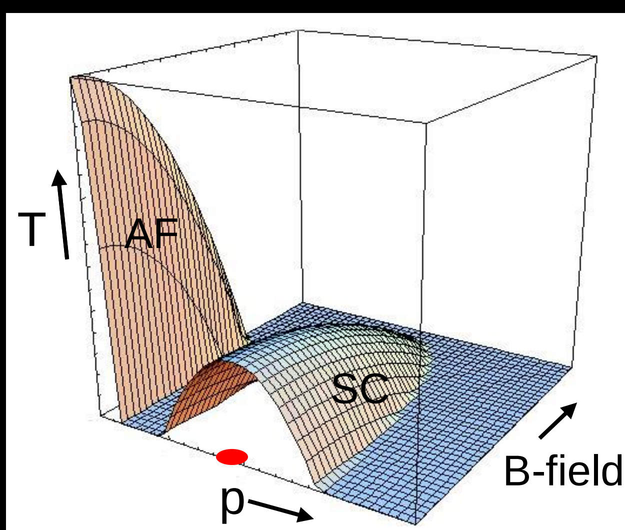
q-space: 2.4% BZ resolution

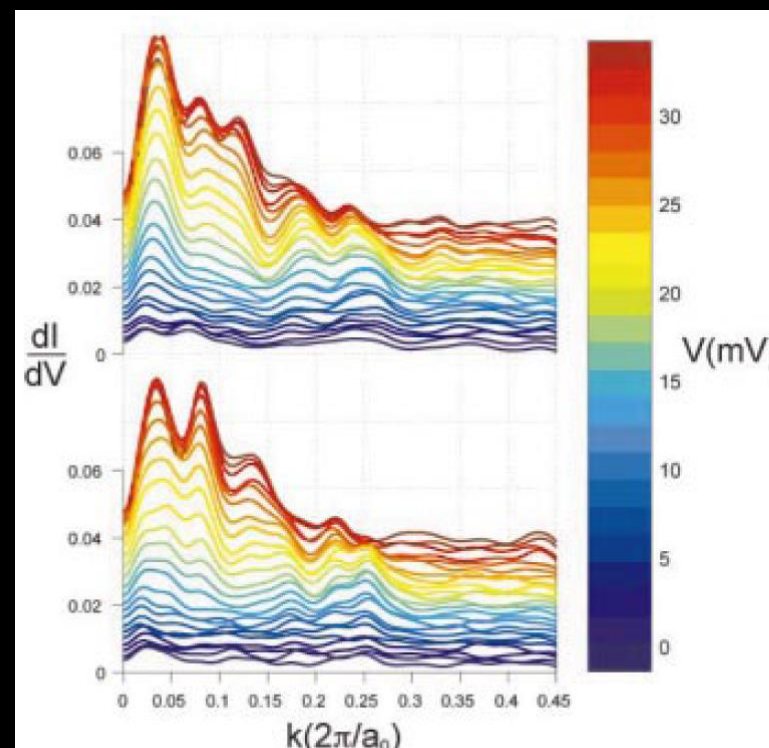


Setup: V_{sample} = -200 meV, R = 2 GΩ

Howald, … Kapitulnik
PRB 67, 014533 (2003).

Claim: static order in low-energy (sub-gap) DOS in the superconducting state.

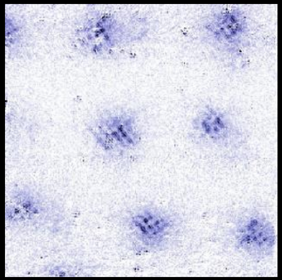




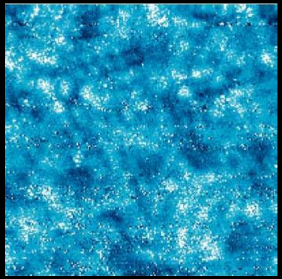
Another Cuprate for STM: $Na_xCa_{2-x}CuO_2Cl_2$

Motivation: previous reports of static checkerboards occurred in small areas (vortices, underdoped areas) & in very disordered BSCCO. Need cleaner, lower T_c sample.

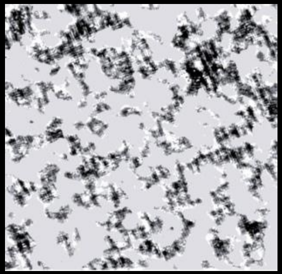
vortices:
- small area

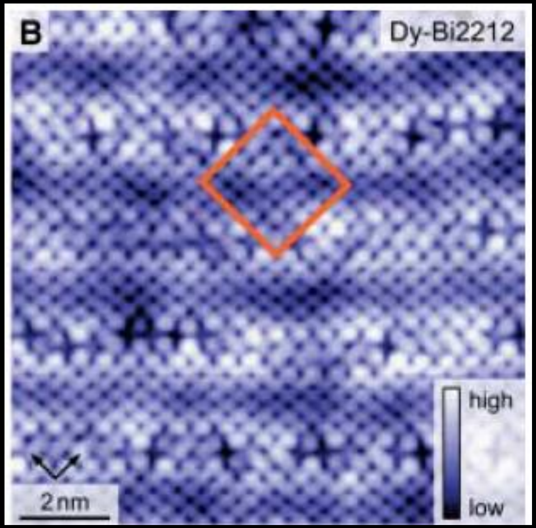


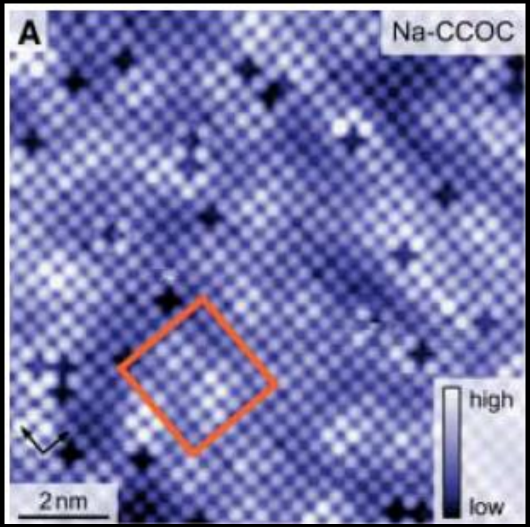
> T_c:
- low E resolution
- large spatial disorder

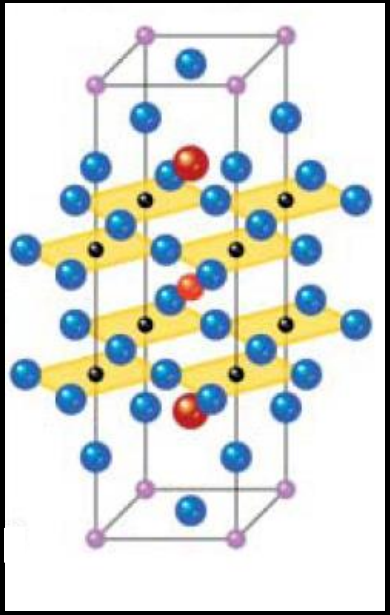


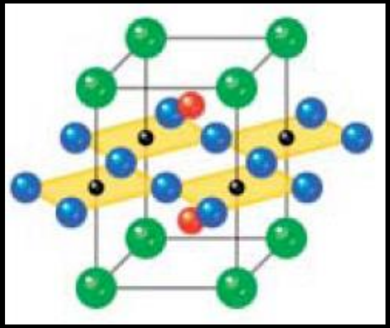
low p:
- small area
- spatial disorder





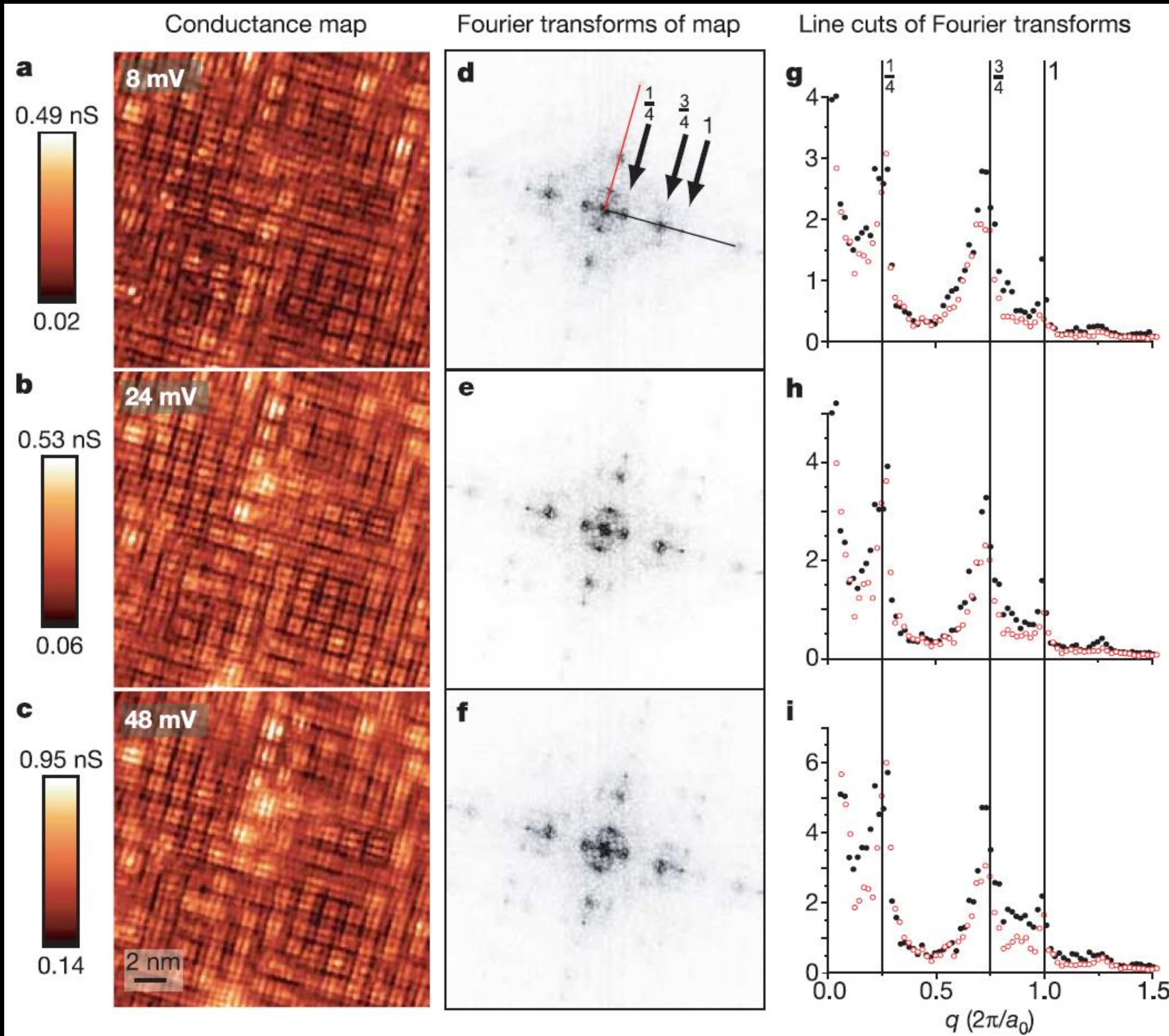






Hanaguri, … Davis, Nature 430, 1001 (2004)

$Na_xCa_{2-x}CuO_2Cl_2$ checkerboard does not disperse



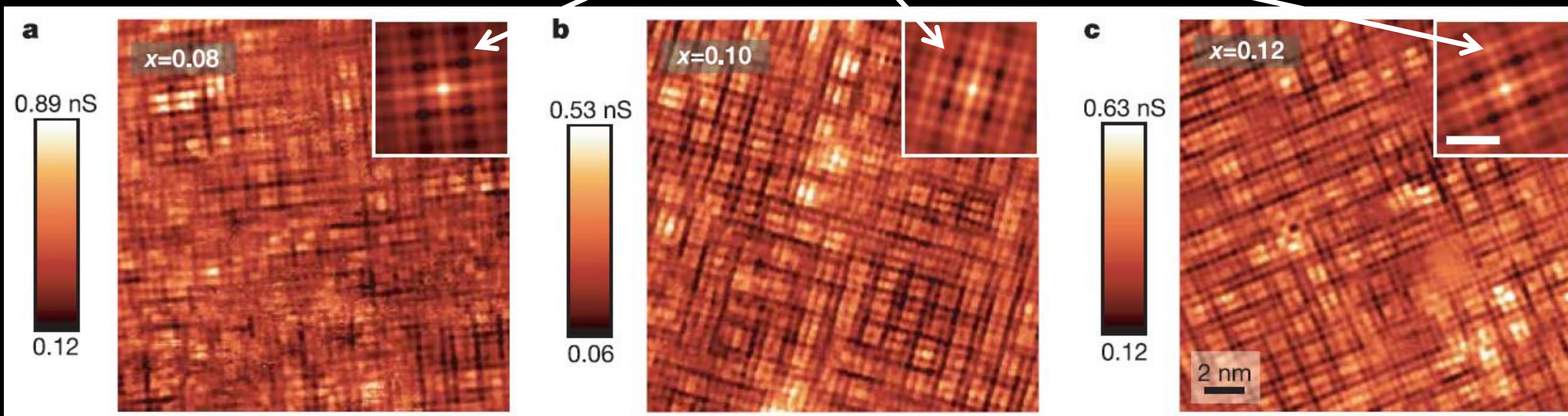
x = 0.12
T_c = 20 K

Experiment:
T=100mK

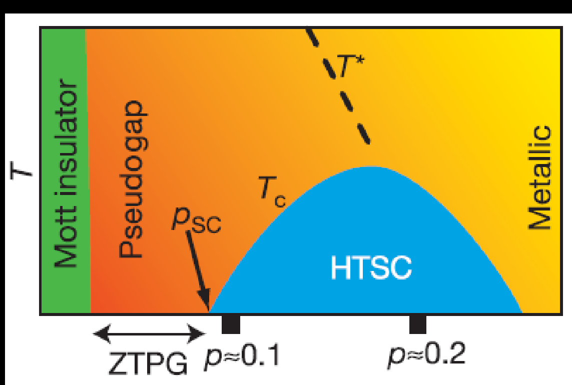
Hanaguri, … Davis, Nature 430, 1001 (2004)

$Na_xCa_{2-x}CuO_2Cl_2$ checkerboard does not depend on doping

autocorrelation shows 4-unit-cell plaquette,
with 3 internal maxima,
for all 3 dopings



T_c = 0 K T_c = 15 K T_c = 20 K



Setup: V_{sample} = +200 meV, R = 2 GΩ

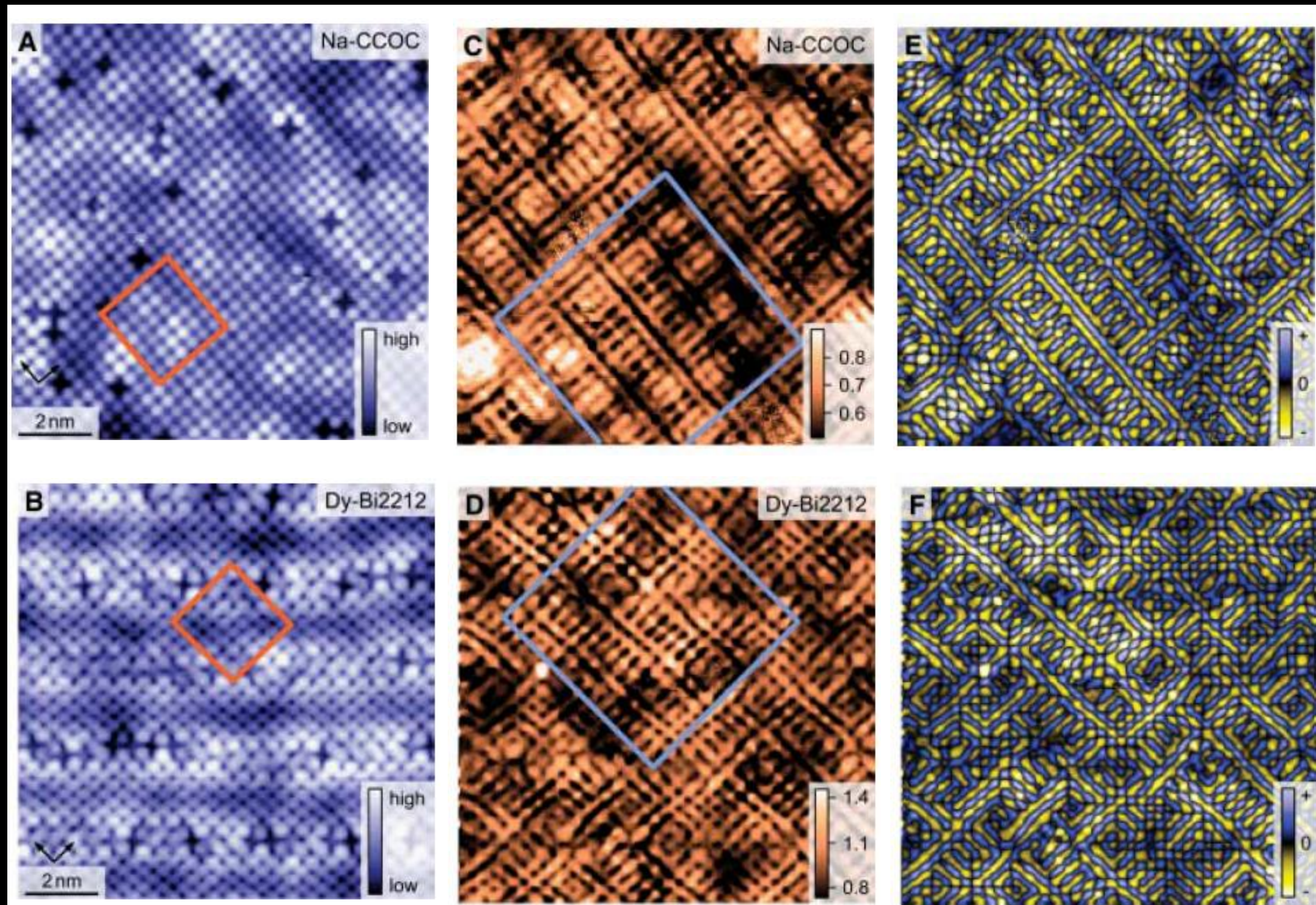
Hanaguri, … Davis, Nature 430, 1001 (2004)

Checkerboard comparison: Na-CCOC vs. BSCCO

Topography | R-map (150 meV) | Laplacian: $\nabla^2(R)$

Na-CCOC
x = 0.12
T_c = 21 K

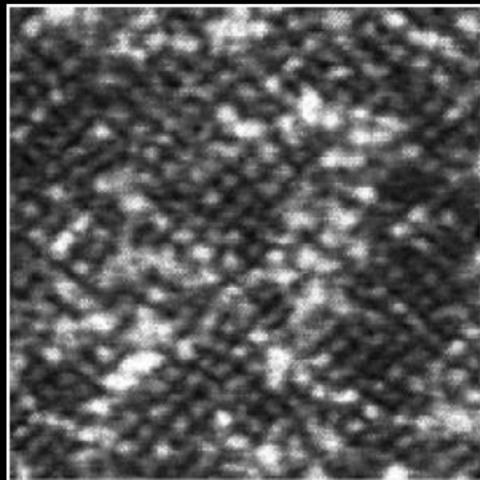
Dy-BSCCO
p ~ 0.08
T_c = 45 K



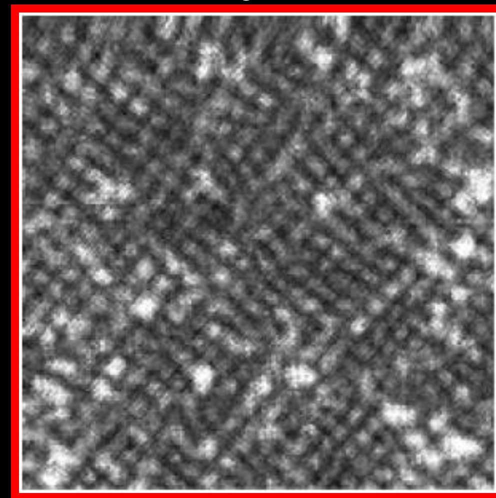
Kohsaka, … Davis, Science 315, 1380 (2007)

Bi-2201: charge density wave

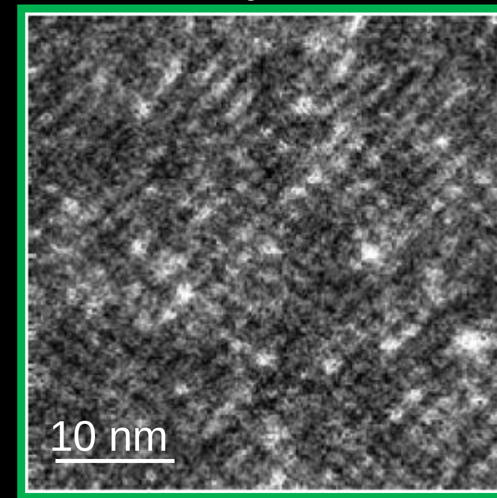
OP, T_c = 35 K

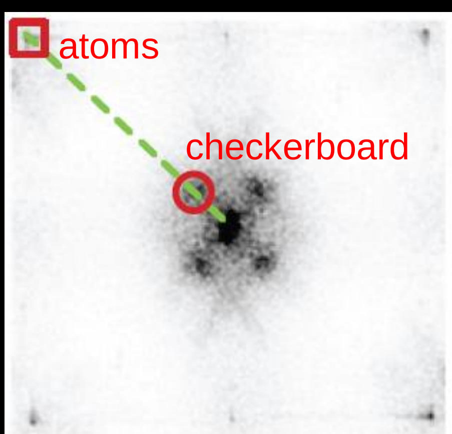


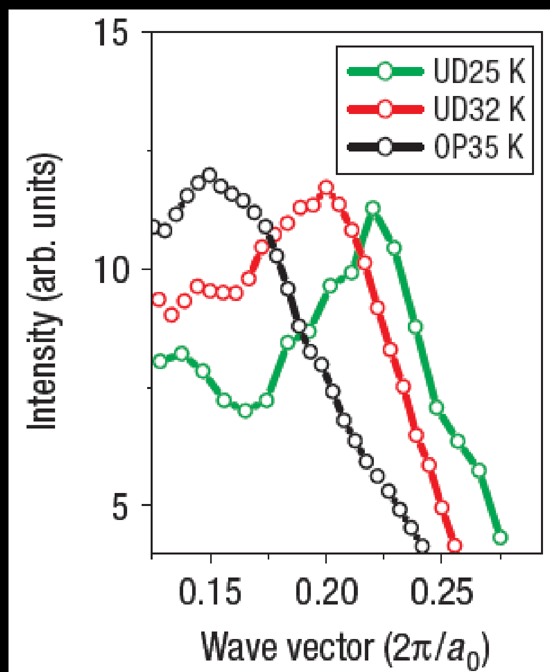
UD, T_c = 32 K

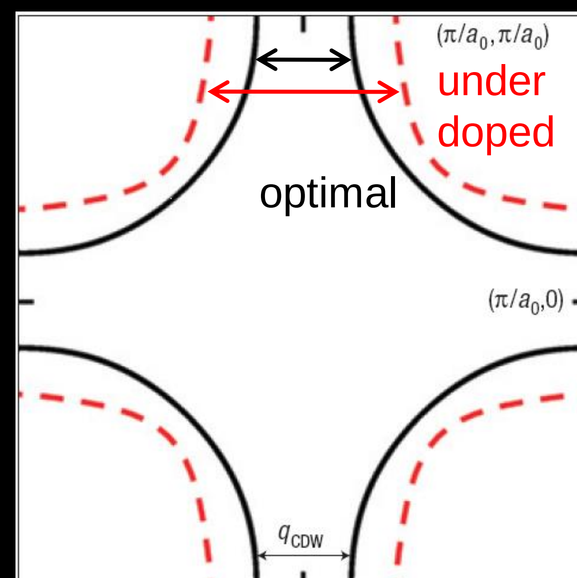


UD, T_c = 25 K









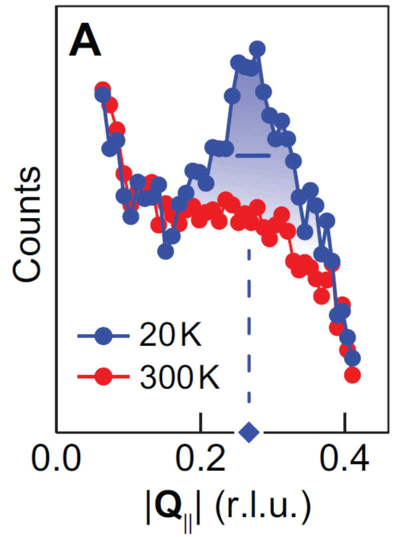
Wise, … Hudson, Nat Phys 4, 696 (2008)

Bulk charge order

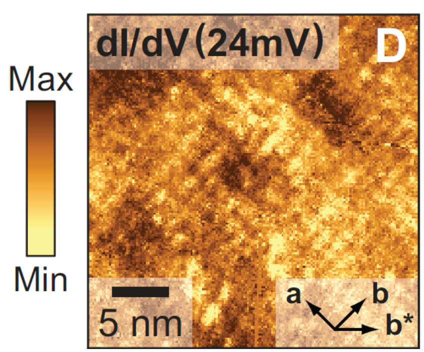
NMR (YBCO)
- *Wu+Julien, Nature 477, 191 (2011)*
- *Wu+Julien, Nat. Comm. 4, 2113 (2013)*

REXS (YBCO)
- *Ghiringhelli, Science 337, 821 (2012)*
- *Chang, Nat. Phys. 8, 871 (2012)*

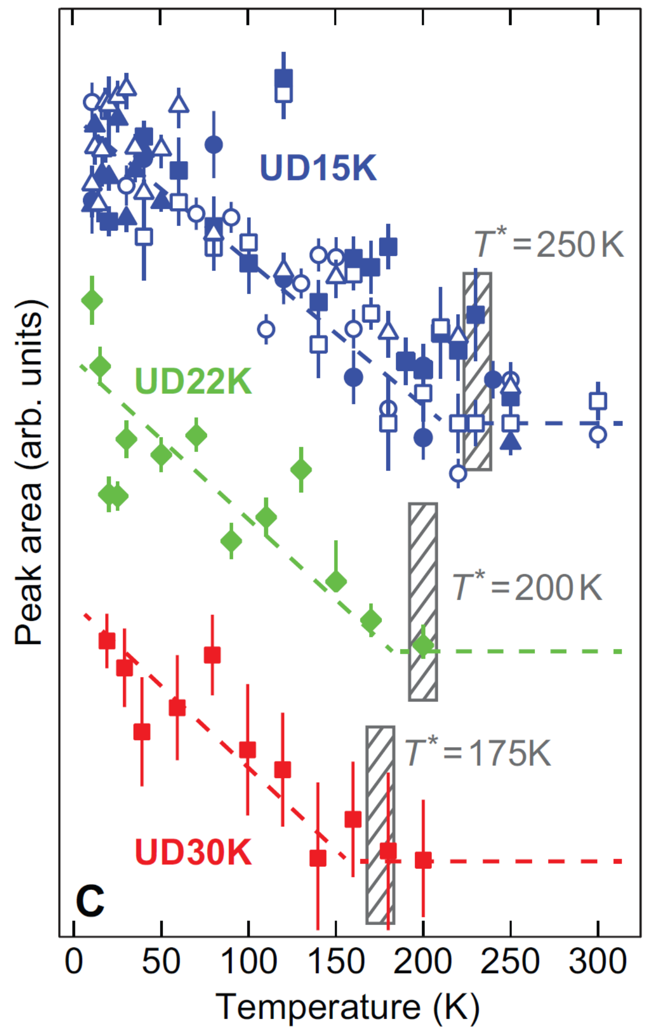
Bi2201: First ever reconciliation of surface and bulk charge order!



Resonant X-ray Scattering



Scanning Tunneling Microscopy



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

Charge Order Questions

1. What is the doping, T, and B dependence of charge order?
2. Is the charge order = pseudogap, or within PG?
3. Are we within the CDW phase or just disorder-pinned fluctuations?
4. Does charge order compete with superconductivity?
5. What is the wavevector of charge order – where is it living on FS?
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7. Is charge order responsible for small FS?
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   hard to say… maybe strongest at +E, maybe strongest at Δ_{PG}
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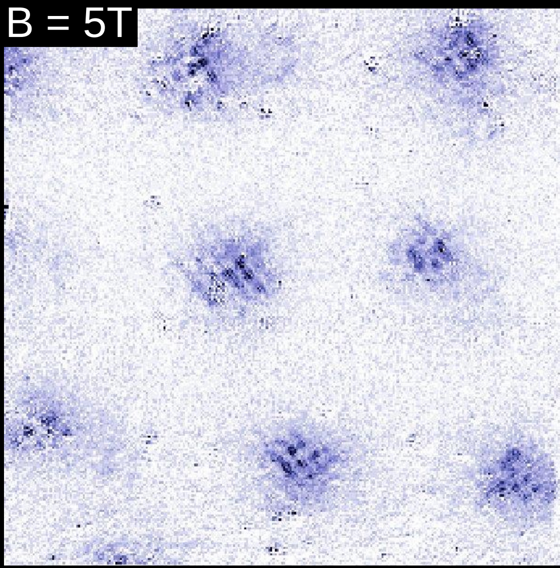
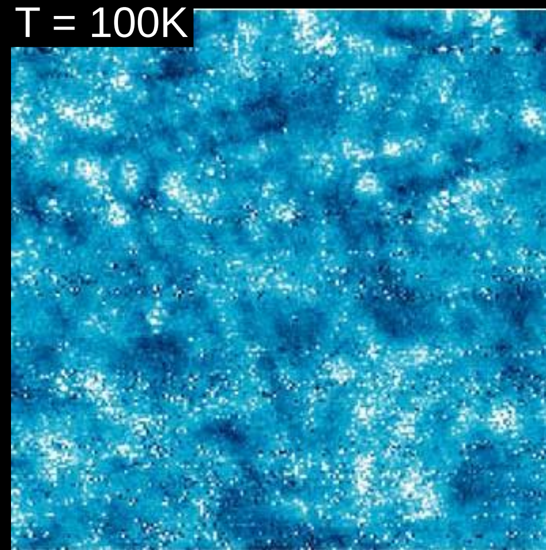
   Bi2212: claim is yes; Bi2201: CDW constant while FS evolves
8. Is it 1D or 2D? Does it have some internal form factor?
   local 1D patches? d-wave form factor

Doping, B, and T dependence?

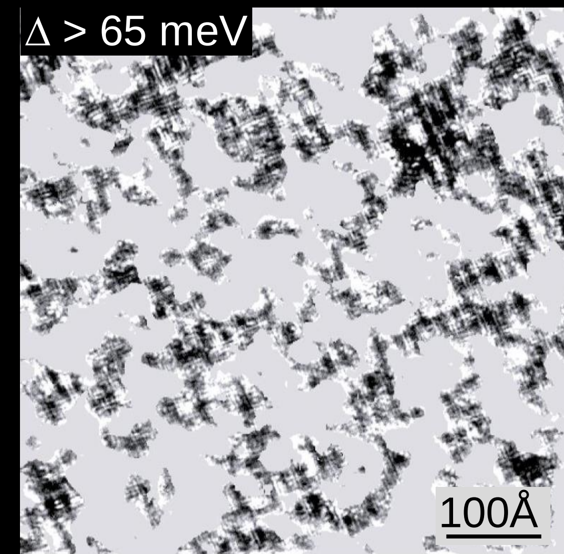
Bi2212: strengthens when SC is suppressed



Hoffman *Science* 295, 466 (2002)

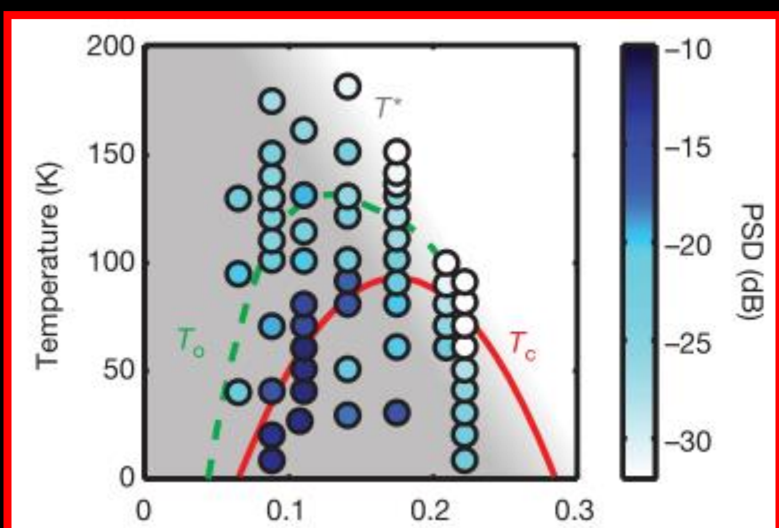


Vershinin, *Science* 303, *1995 (2004)*

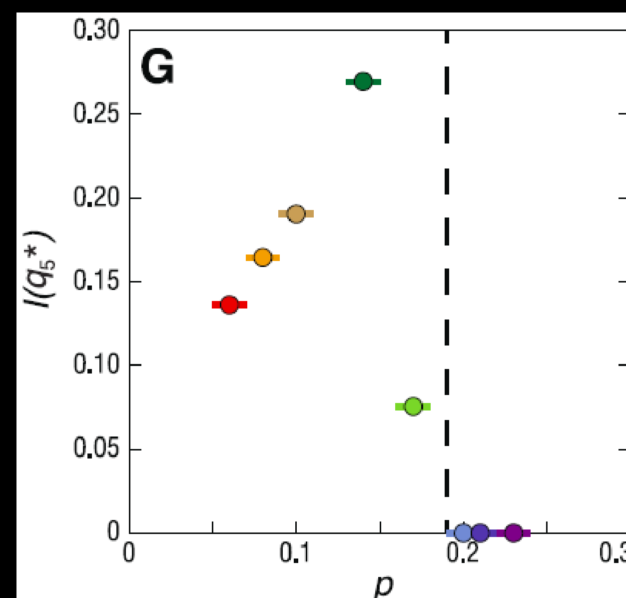


McElroy, *PRL 94, 197005 (2005)*

But: CDW dies gradually or abruptly near p=0.19



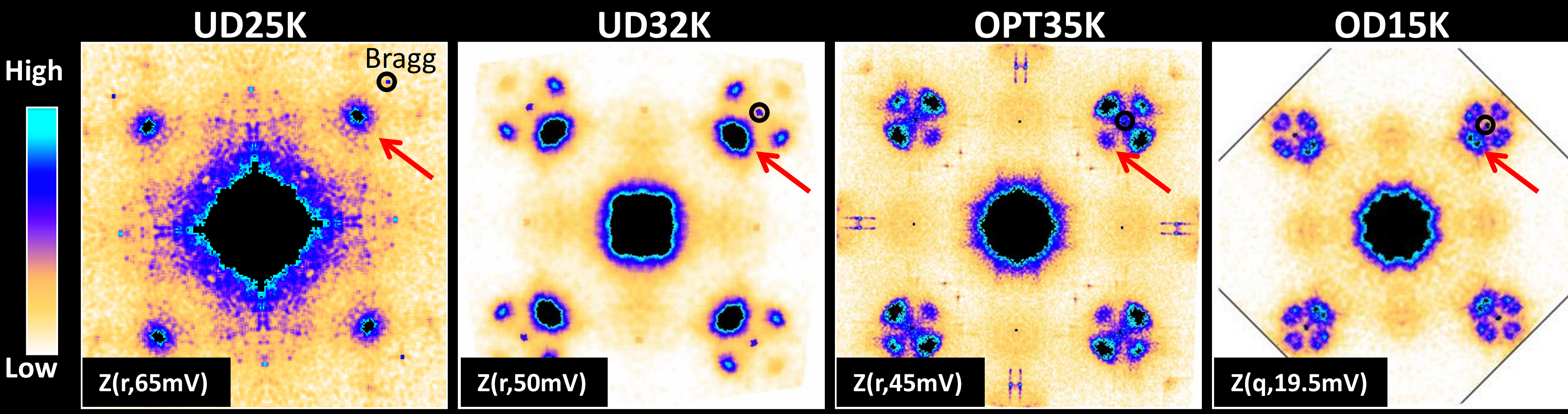
Parker+Yazdani, Nature (2010)



Fujita, Science (2014)

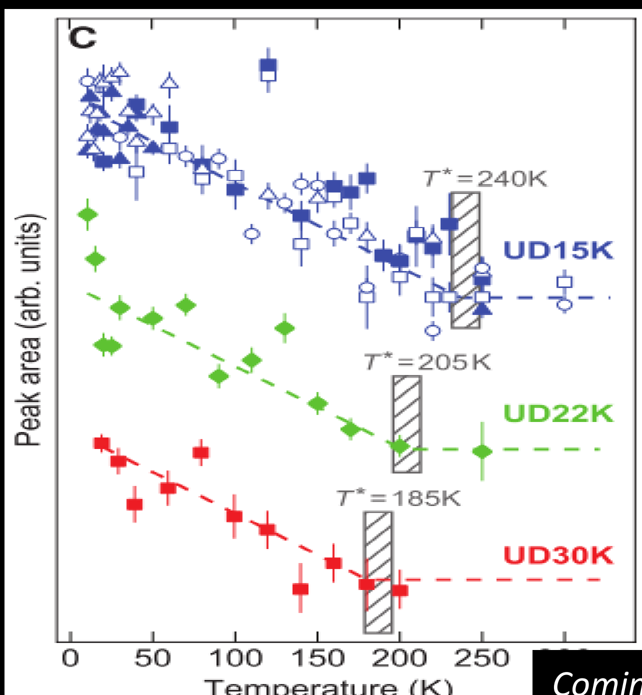
Doping, B, and T dependence?

Bi2201: at T=6K, CDW is present at all dopings, no obvious trend in strength or lengthscale



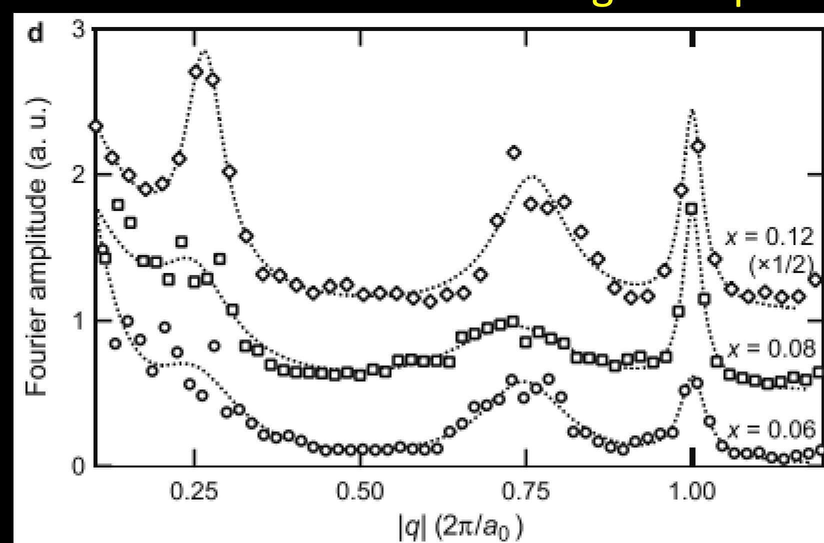
He+JEH, Science (May 2014)

But T_{onset} decreases with doping



Comin+JEH, Science (Jan 2014)

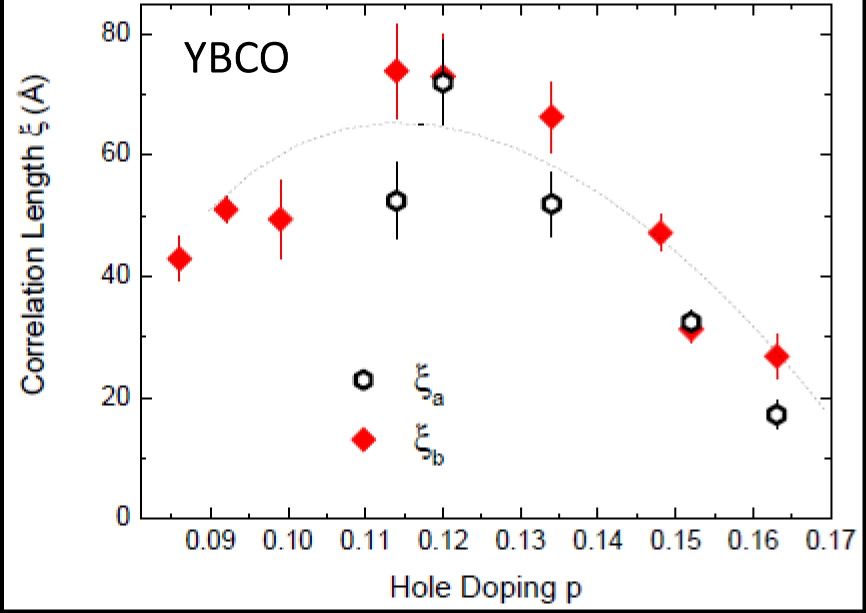
Na-CCOC: CDW present at p=0.06-0.12;
strongest at p=0.12

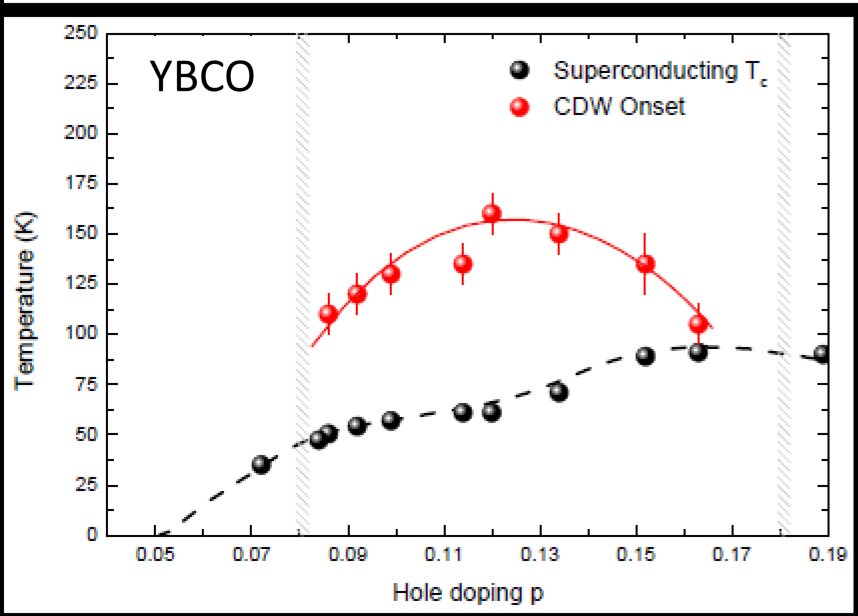


Kohsaka, Nat Phys (2012)

Doping, B, and T dependence?

YBCO (from XRD):

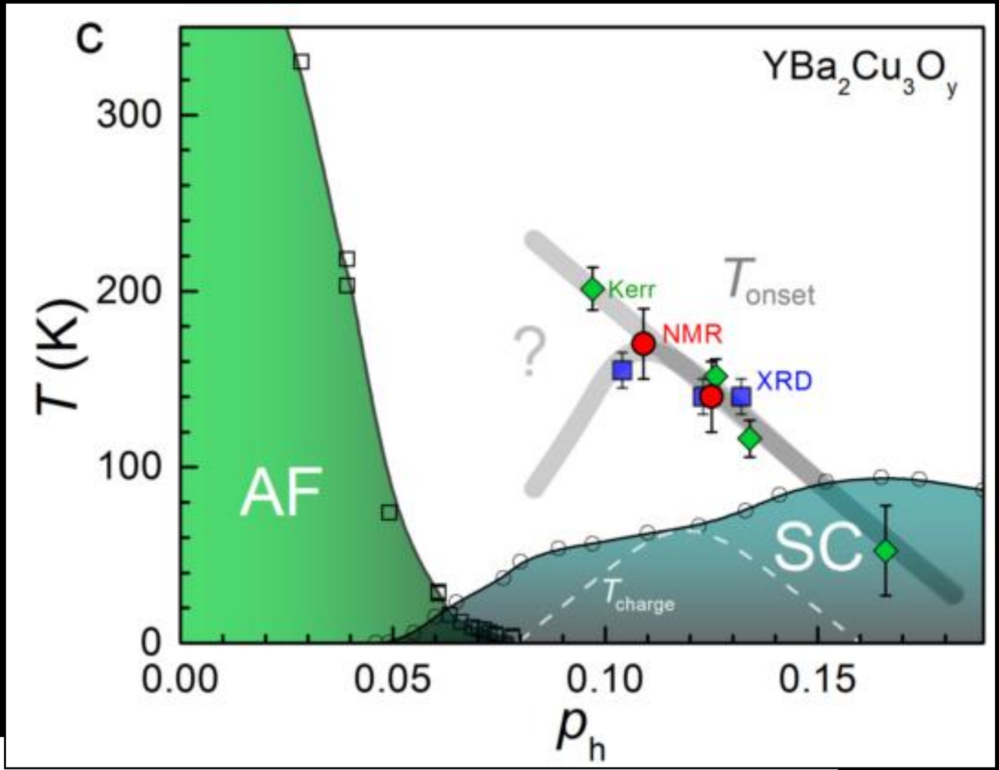


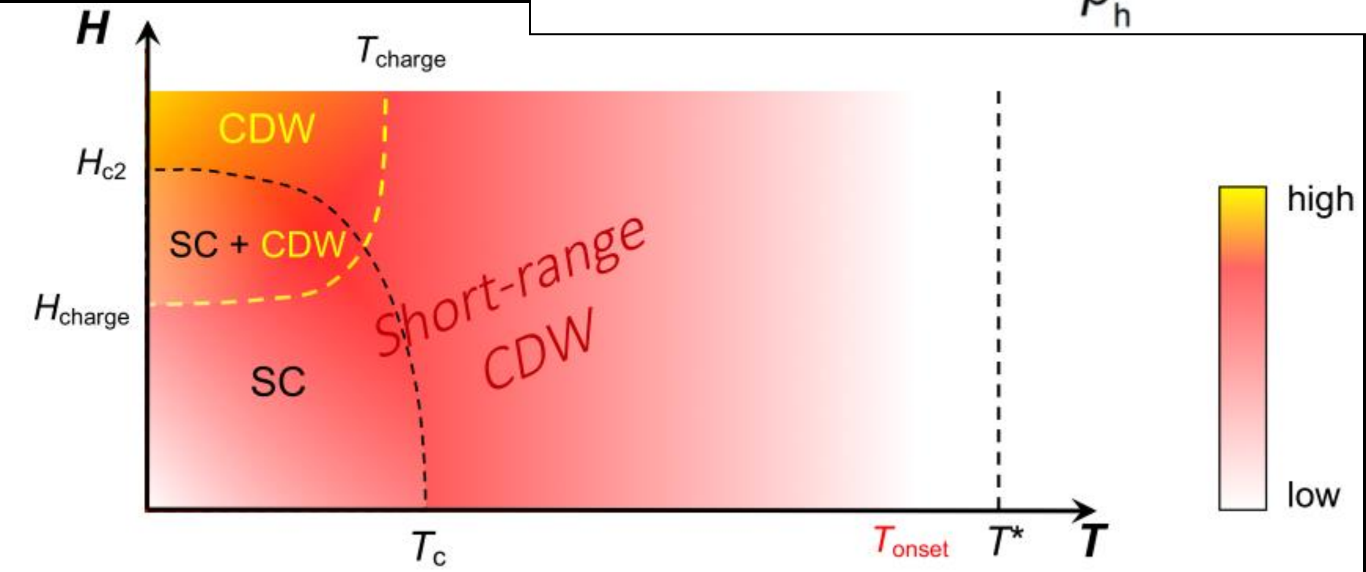


Blanco-Canosa, arxiv: 1406.1595

Doping, B, and T dependence?

YBCO (from NMR): distinguishes between T_{CDW} (long-range order) and T_{onset}





Wu+Julien, arxiv:1404.1617

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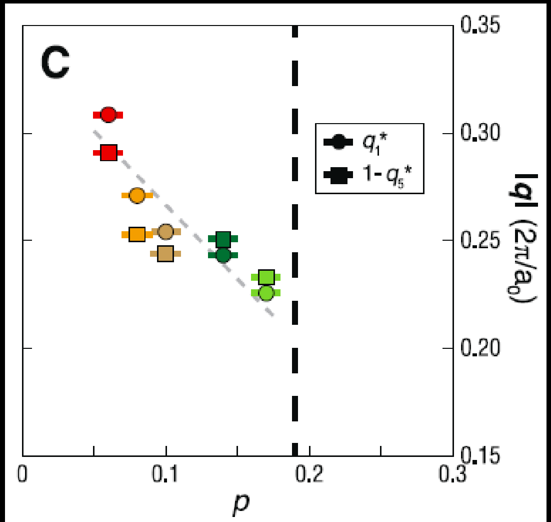
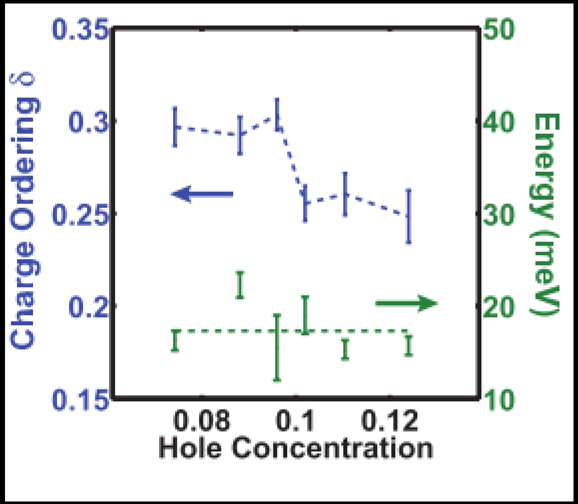
Wavevector of CDW?

Bi2212: continuous evolution vs. step function with doping

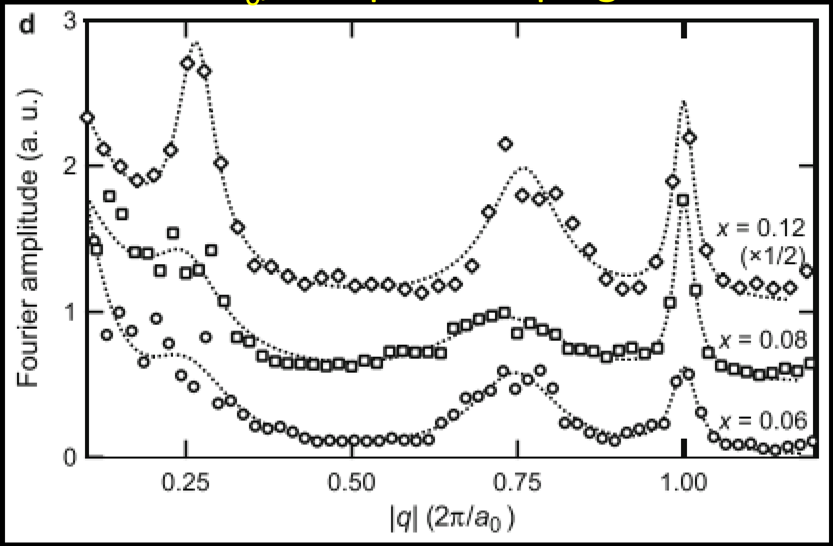


Fujita+Davis, Science (May 2014)



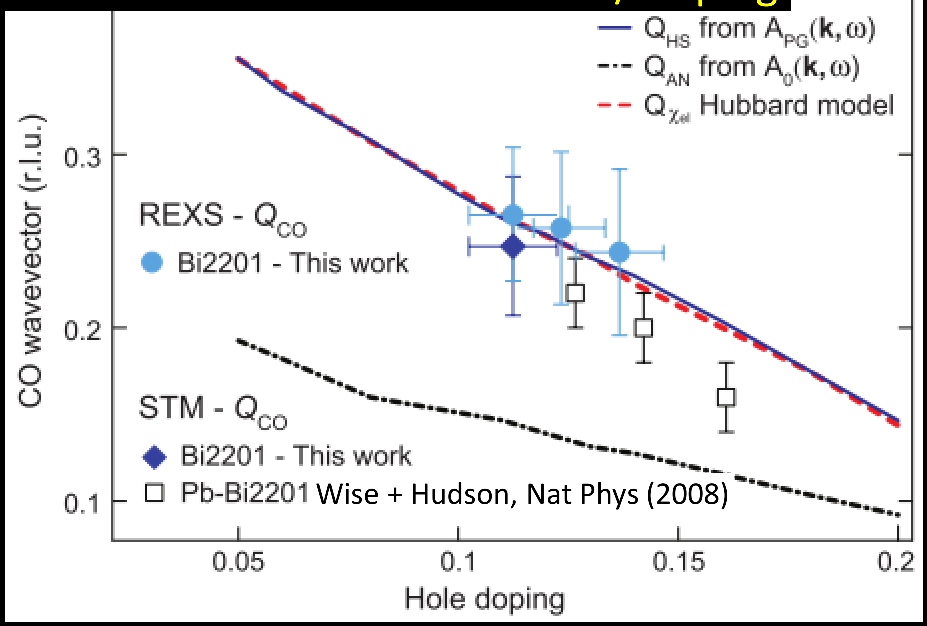
da Silva Neto+Yazdani, Science (Jan 2014)

Na-CCOC: $4a_0$, indept. of doping



Kohsaka, Nat Phys (2012)

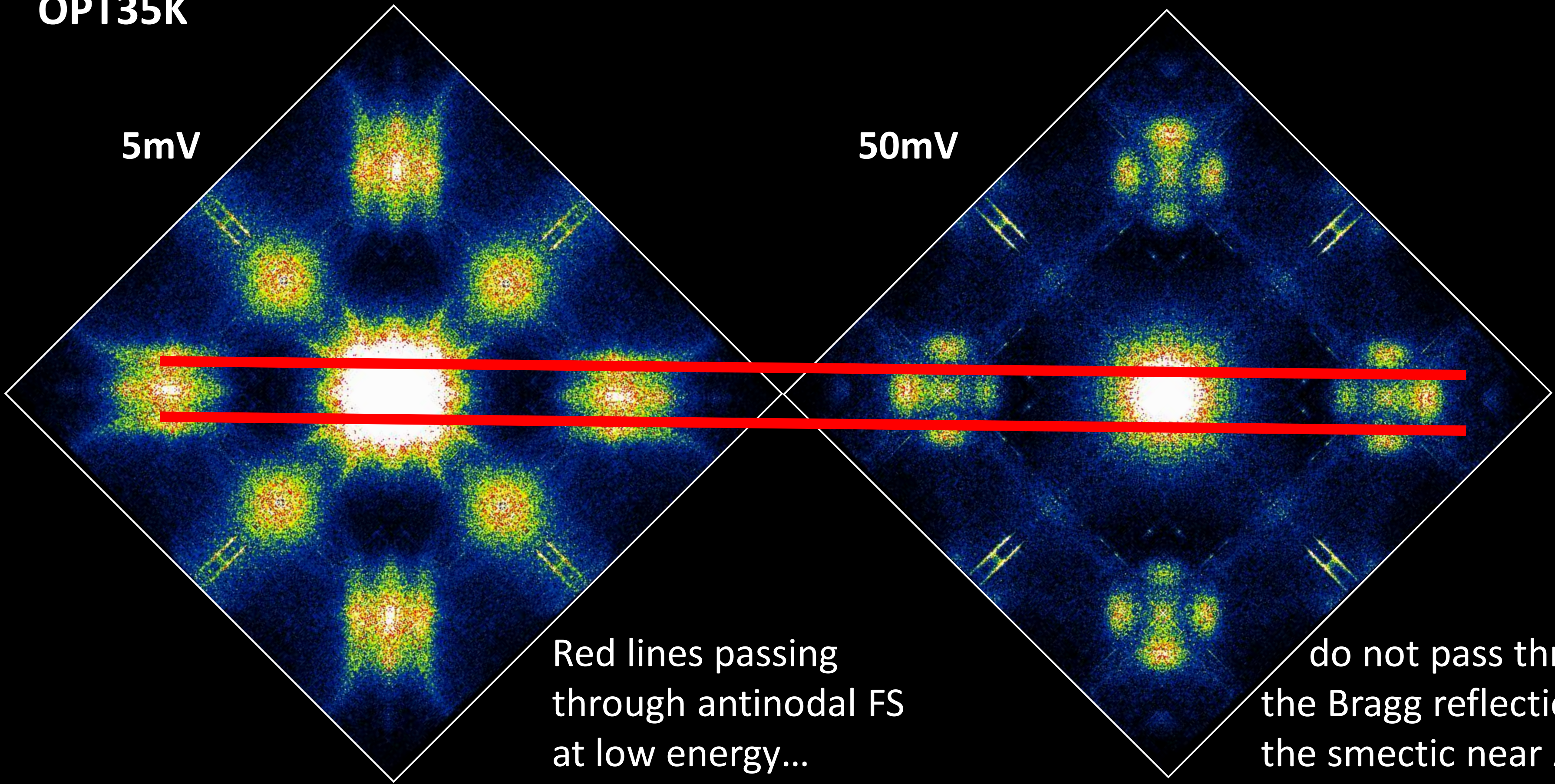
Bi2201: continuous evolution w/ doping



Comin+JEH, Science (Jan 2014)

CDW is hotspot wavevector, not antinodal nesting

Bi2201
OPT35K

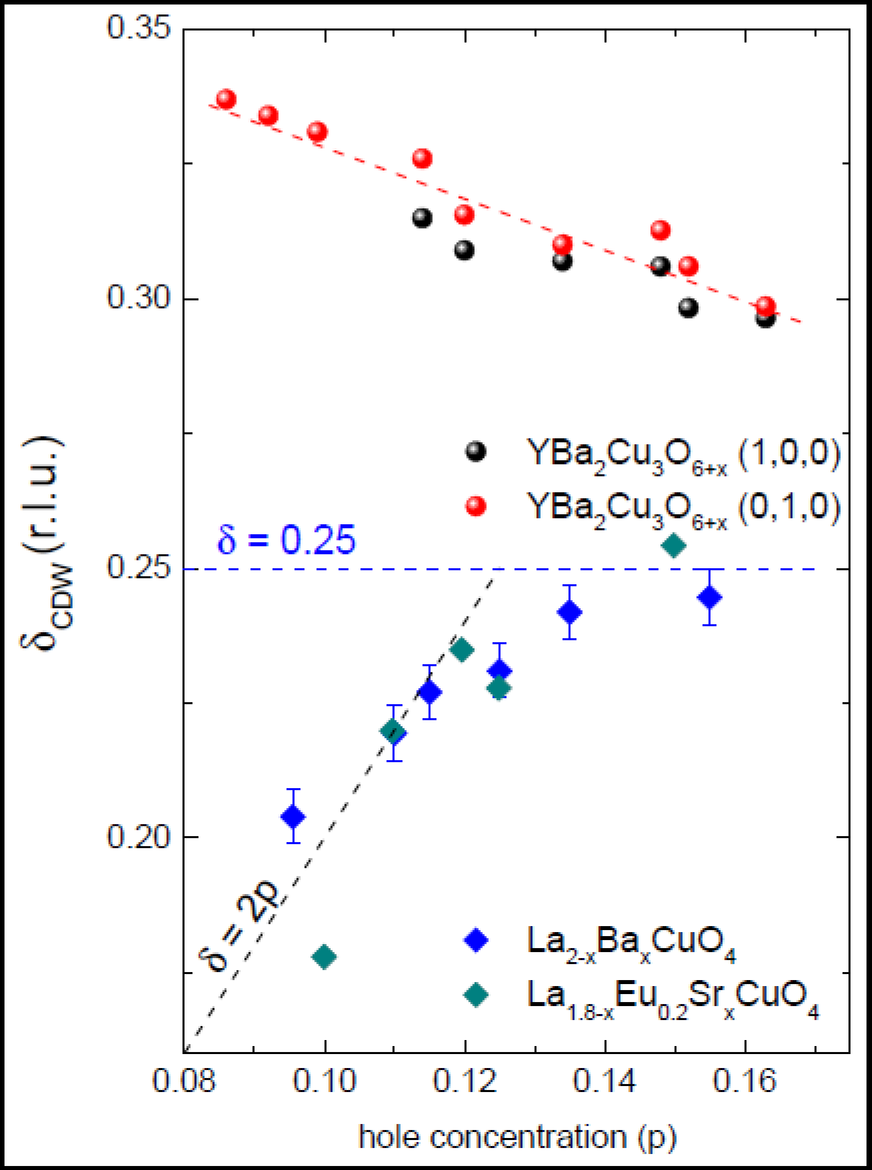


Red lines passing through antinodal FS at low energy…

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

YBCO, LSCO, LBCO from bulk probes

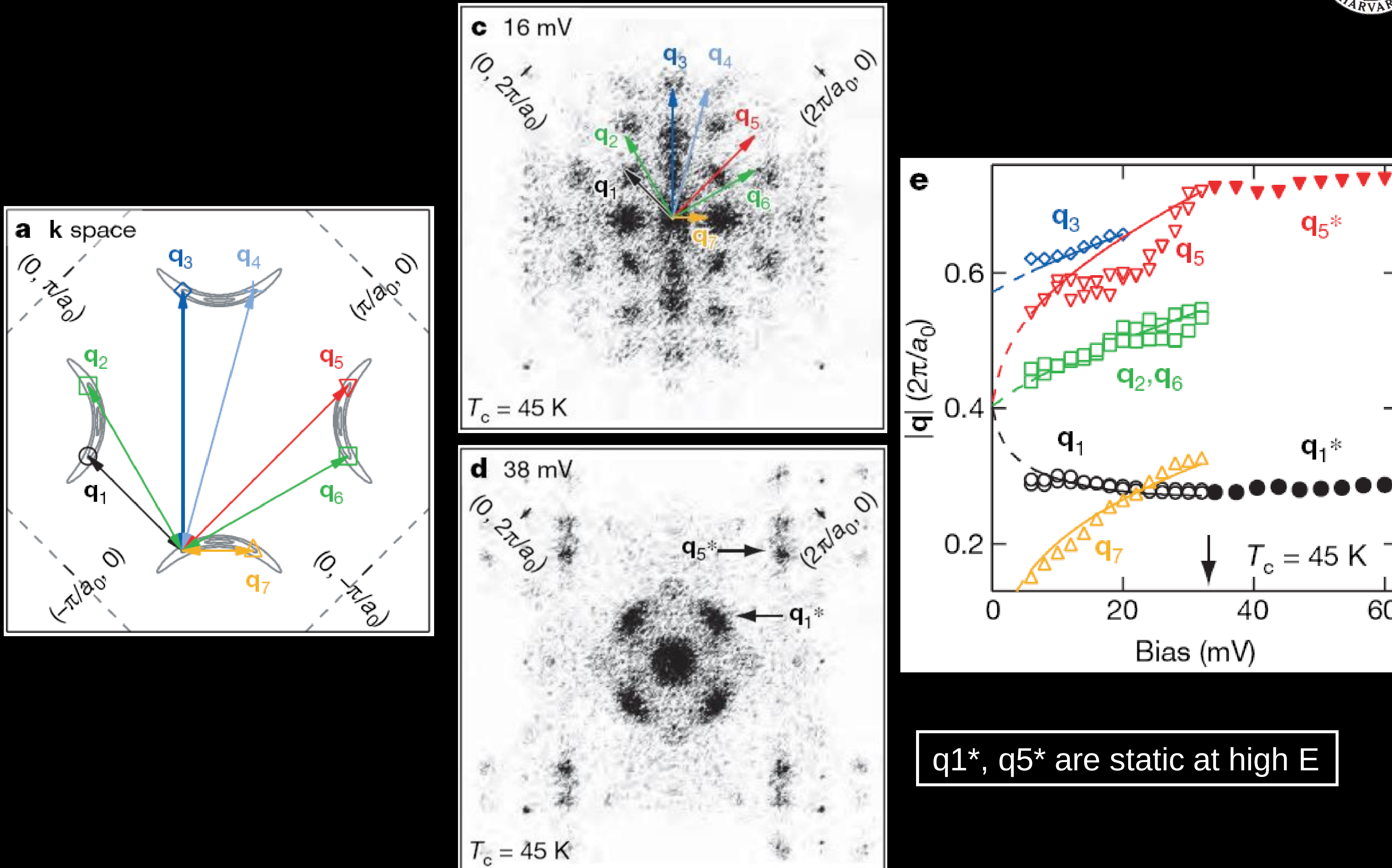


Blanco-Canosa, arxiv: 1406.1595

Charge Order Questions

1. What is the doping, T, and B dependence of charge order?
   strongest near p=1/8, and in applied B
2. Is the charge order = pseudogap, or within PG?
   appears to be within the PG
3. Are we within the CDW phase or just disorder-pinned fluctuations?
   YBCO can be long-range-ordered; BSCCO is pinned fluctuations?
4. Does charge order compete with superconductivity?
   yes! (vortex cores, dip in dome, etc.)
5. What is the wavevector of charge order – where is it living on FS?
   varies continuously w/ doping; connects AFBZ hotspots
6. What is the energy dependence of charge order?
   hard to say… maybe strongest at +E, maybe strongest at Δ_{PG}
7. Is charge order responsible for small FS?
   Bi2212: claim is yes; Bi2201: CDW constant while FS evolves
8. Is it 1D or 2D? Does it have some internal form factor?
   local 1D patches? d-wave form factor

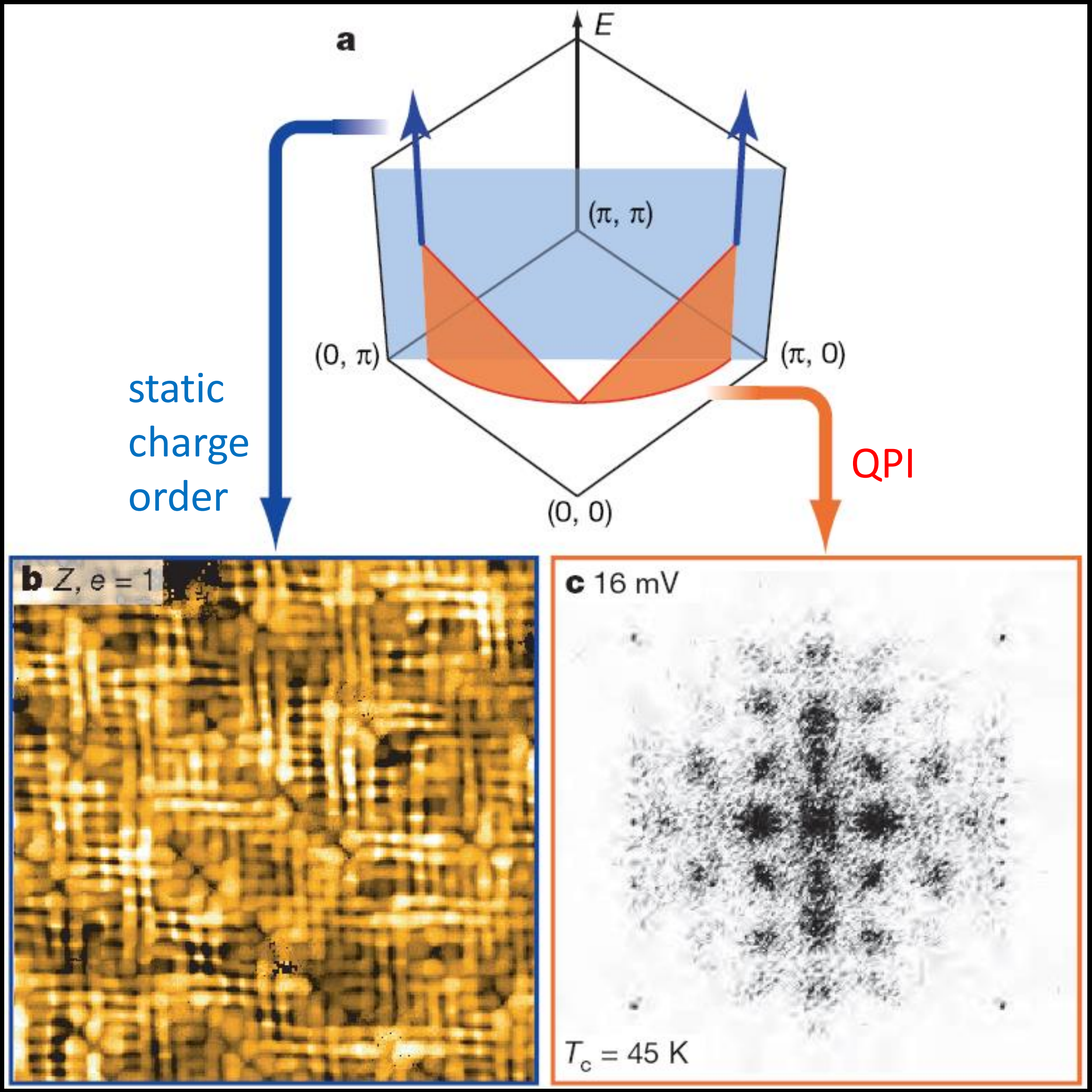
Bi-2212: Energy crossover: dispersing → static



q1*, q5* are static at high E

Kohsaka, … Davis, Nature 454, 1072 (2008)

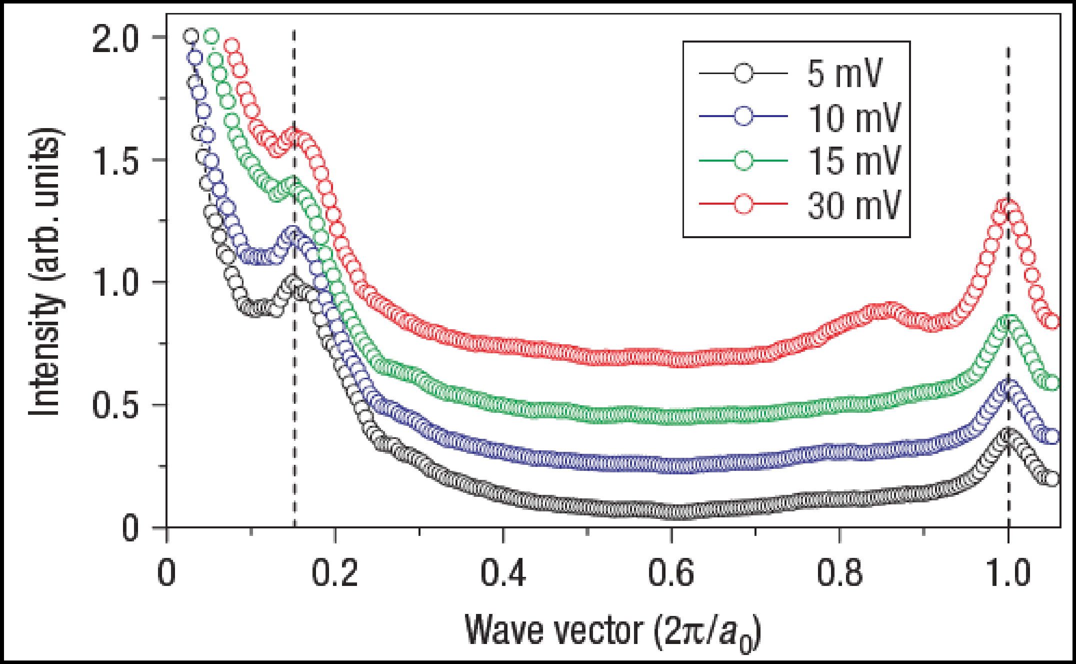
Bi2212: 2 energy scales



Kohsaka, … Davis, Nature 454, 1072 (2008)

Bi2201 energy dependence

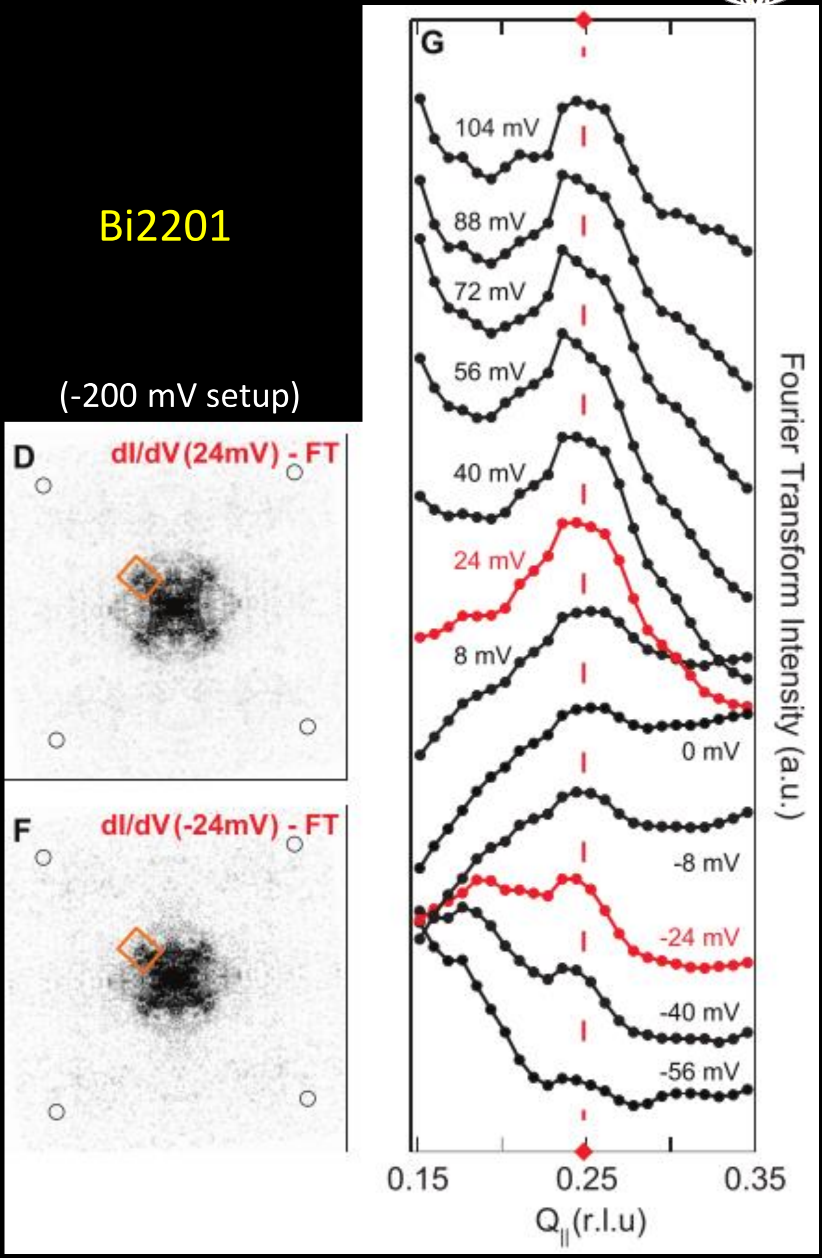
Pb-Bi2201



Wise, Nat Phys (2008)

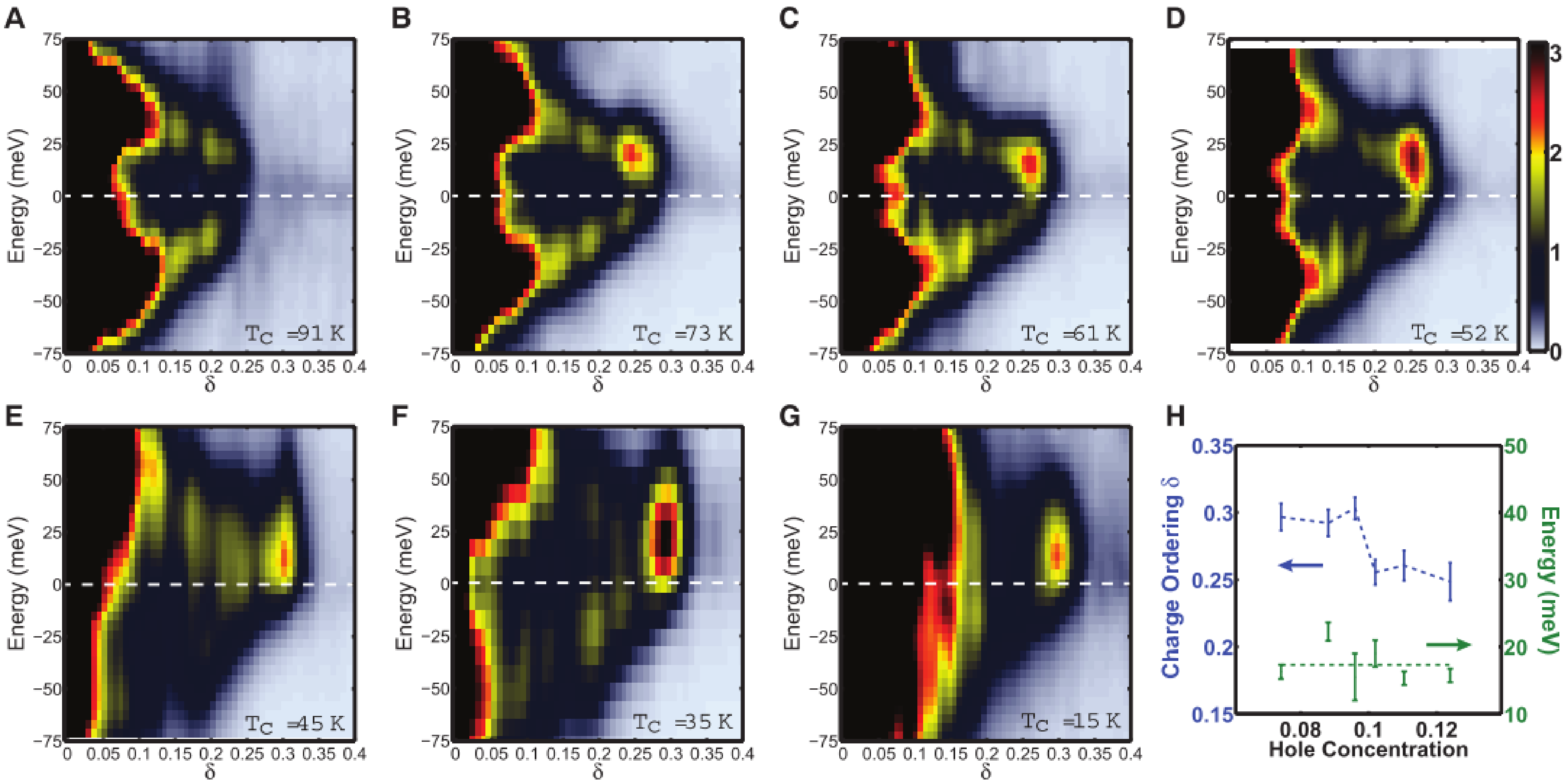
Bi2201

(-200 mV setup)



Comin, Science (Jan 2014)

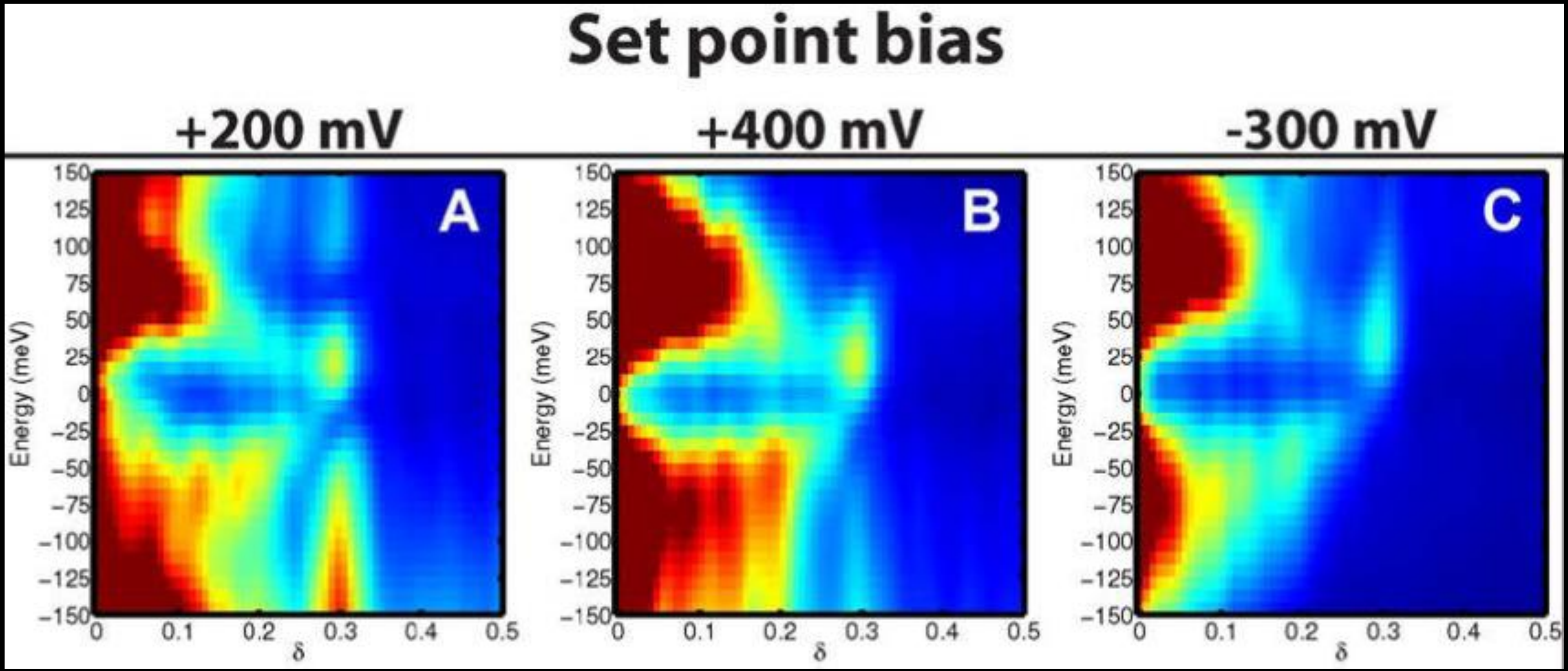
Bi2212: CDW energy dependence?



(what setpoints are used?)

da Silva Neto + Yazdani, Science 343, 393 (2014)

Bi2212: CDW energy dependence?



(which sample is this?)

da Silva Neto + Yazdani, Science 343, 393 (2014)

Charge Order Questions

1. What is the doping, T, and B dependence of charge order?
   strongest near p=1/8, and in applied B
2. Is the charge order = pseudogap, or within PG?
   appears to be within the PG
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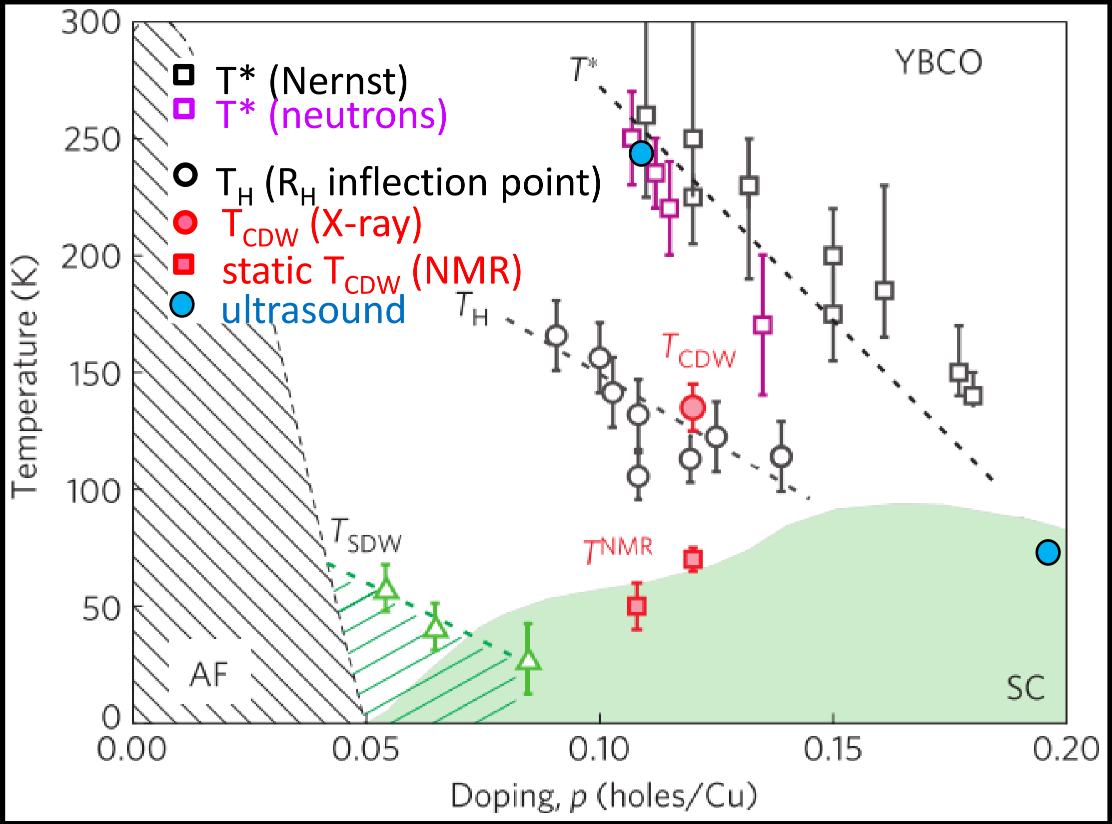
   Bi2212: claim is yes; Bi2201: CDW constant while FS evolves
8. Is it 1D or 2D? Does it have some internal form factor?
   local 1D patches? d-wave form factor

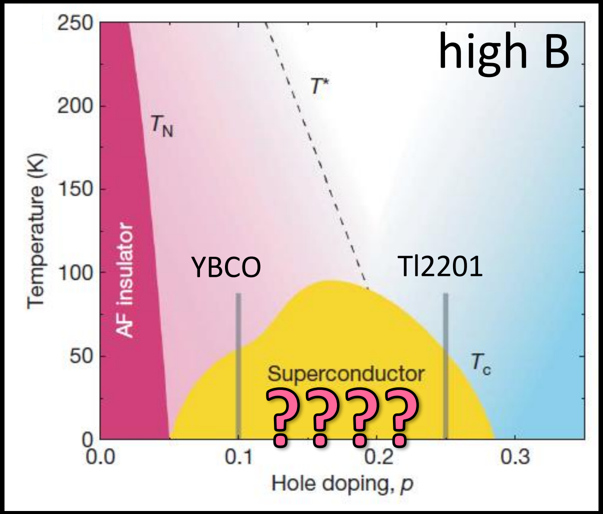
Fermi Surface vs. Pseudogap ?

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)

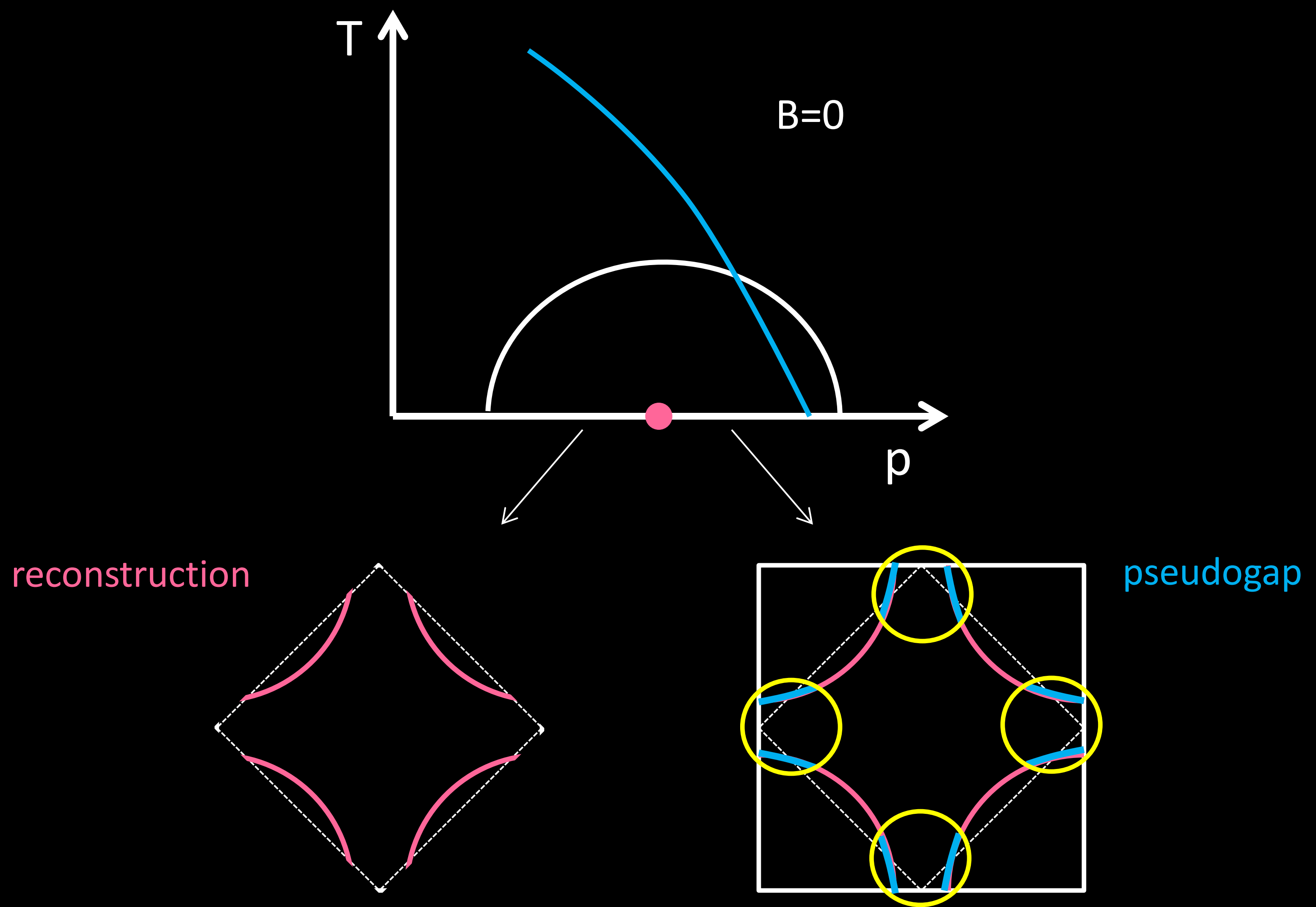
Fermi surface



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

Our Conclusions (STM on Bi2201)

1. Fermi surface reconstruction ≠ pseudogap

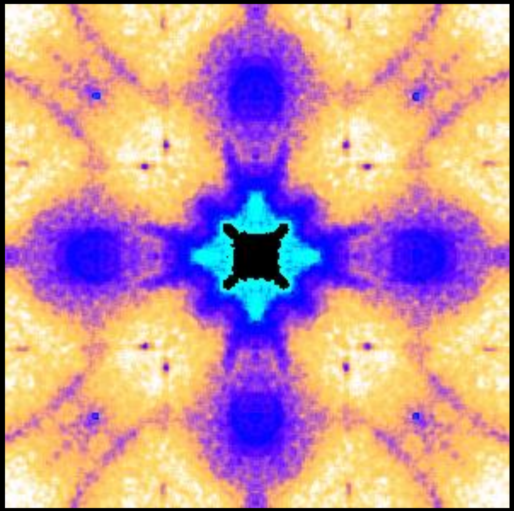


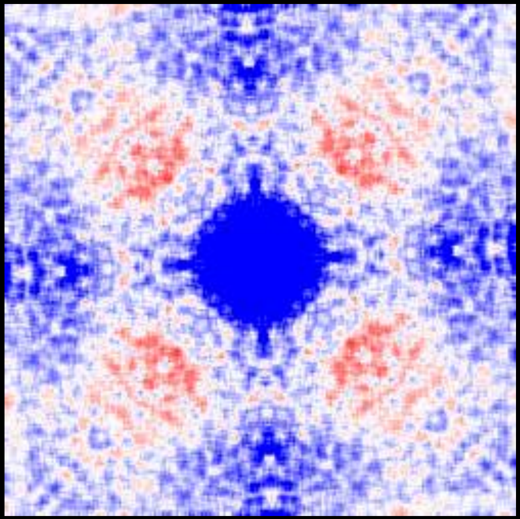
2. Superconductivity coexists with pseudogap at the antinode

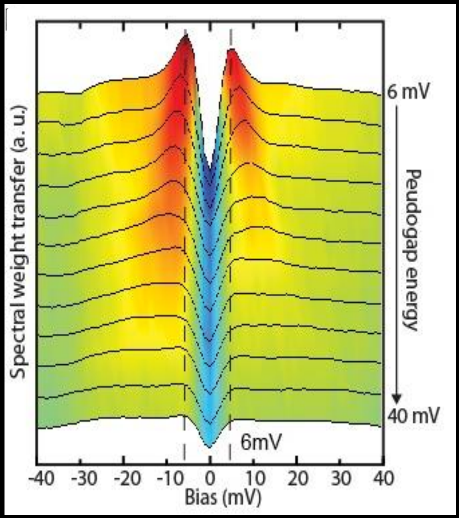
Outline

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



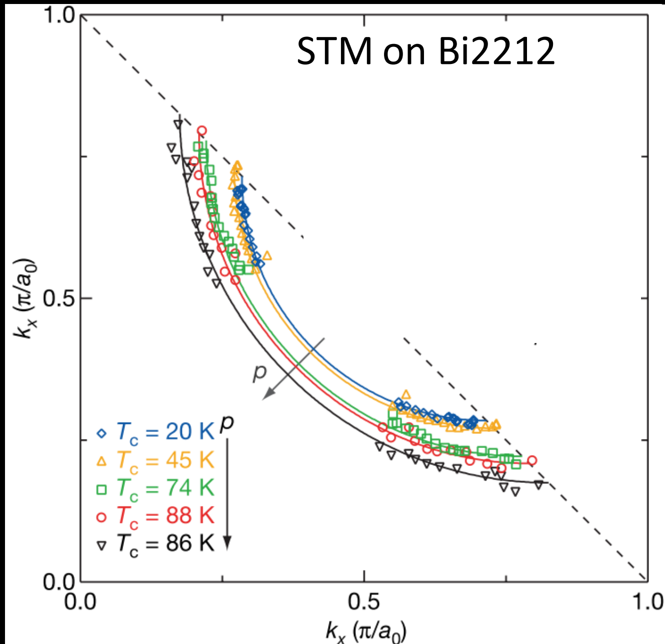




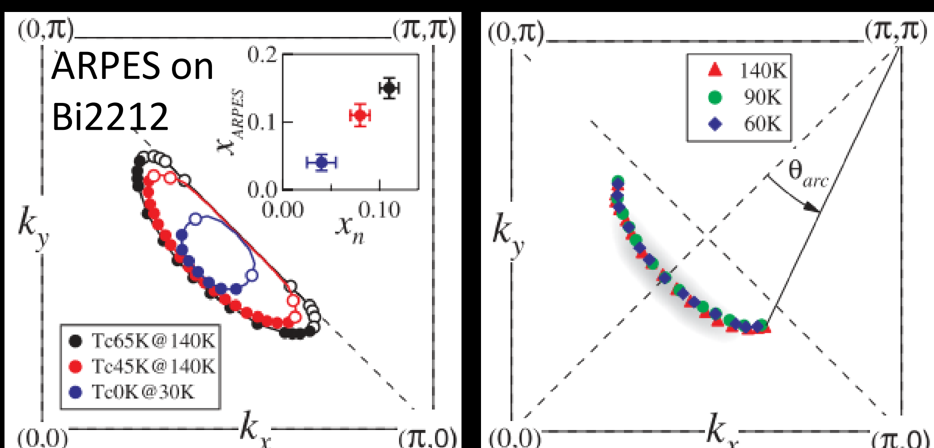
arxiv:1305.2778, He et al, ***Science***, May 9 (2014)

Intro to Fermi arc phenomenology in Bi2212

Arc cuts off at AFBZ

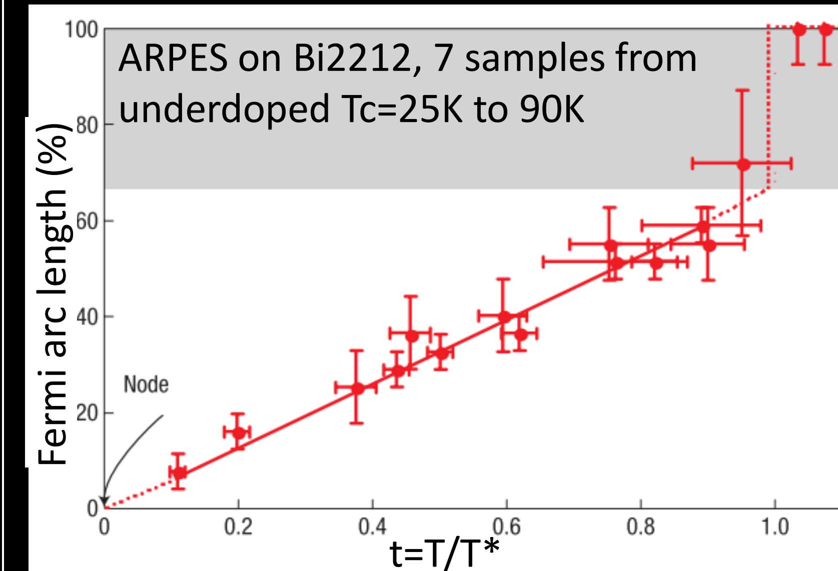


Kohsaka + JC Davis, Nature 454, 1072 (2008)

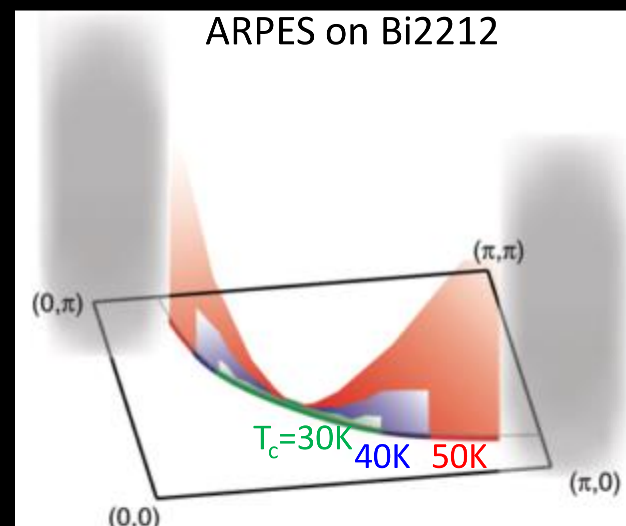


Yang + PD Johnson, PRL 107, 047003 (2011)

Arc length evolves with T, p

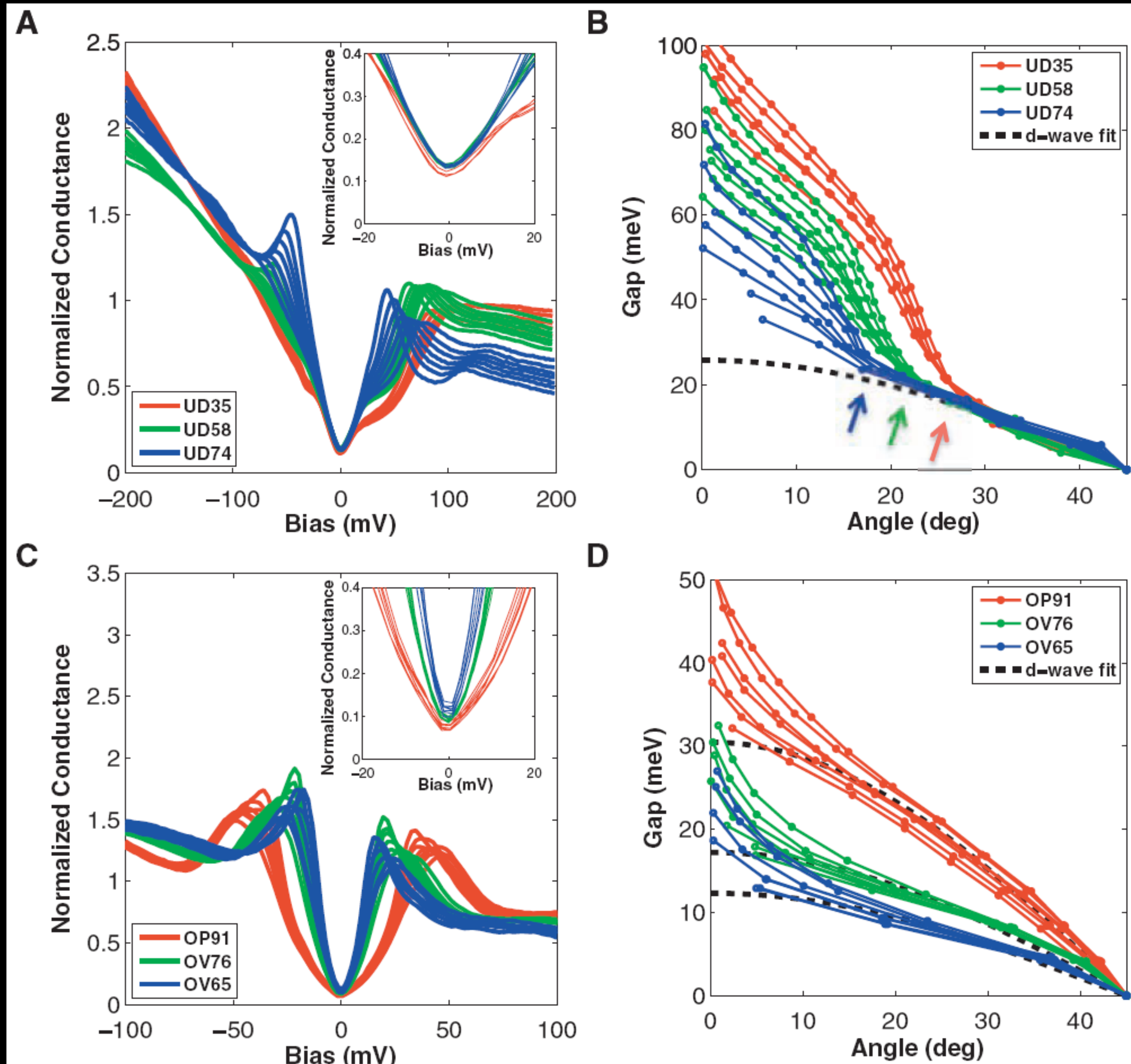


Kanigel + Norman + Campuzano, Nat Phys 2, 447 (2006)



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

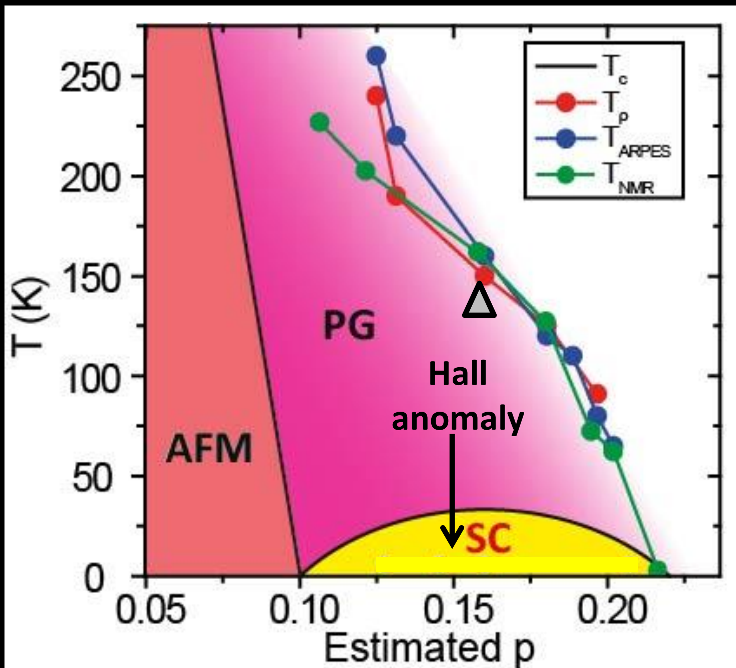
Bi2212 k-space info, a different way



Pushp, … Yazdani, Science 324, 1689 (2009)

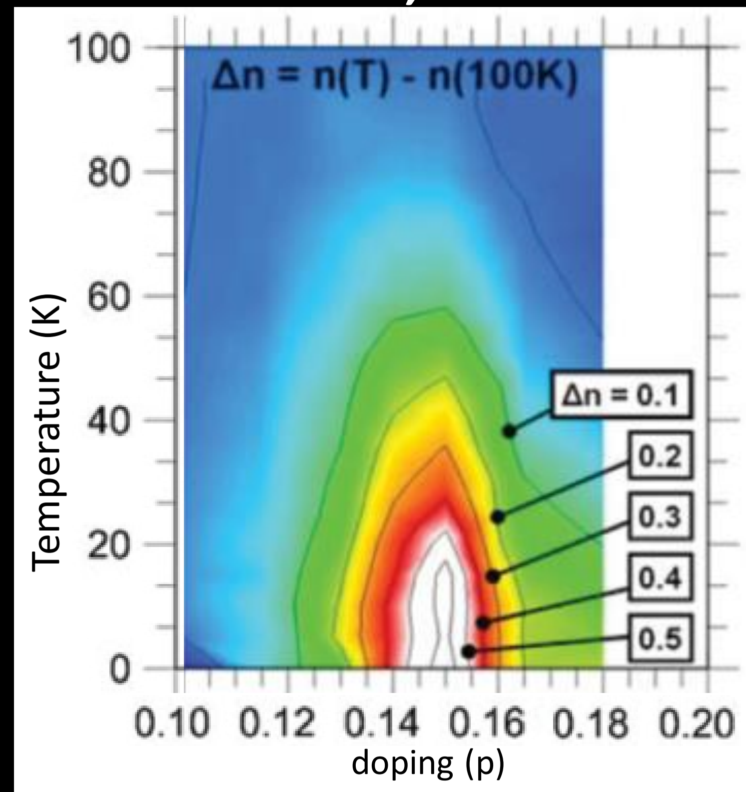
Motivation to study Pb-doped Bi2201

- 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)

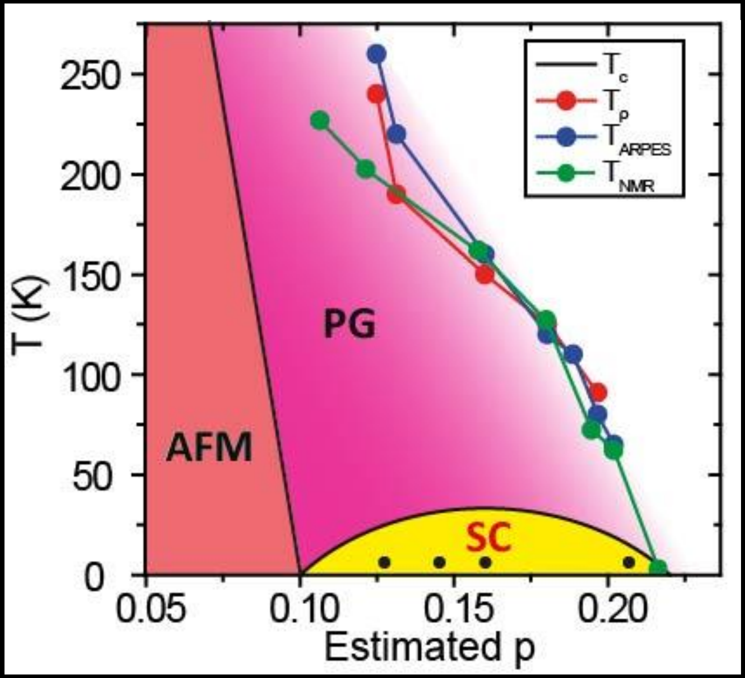
Hall coeff, B > 30 T

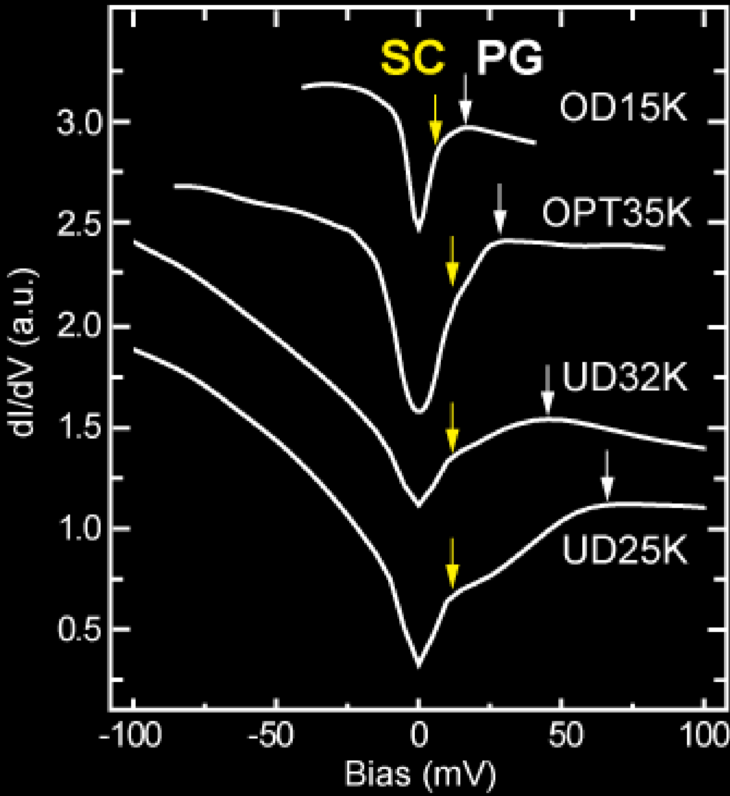


Balakirev, Nature 424, 912 (2003)
Balakirev, PRL 102, 017004 (2009)

Does the FS reconstruct at B=0 Tesla?
Does the FS reconstruction correspond to Hall QCP (p~0.15) or PG (p~0.23)?

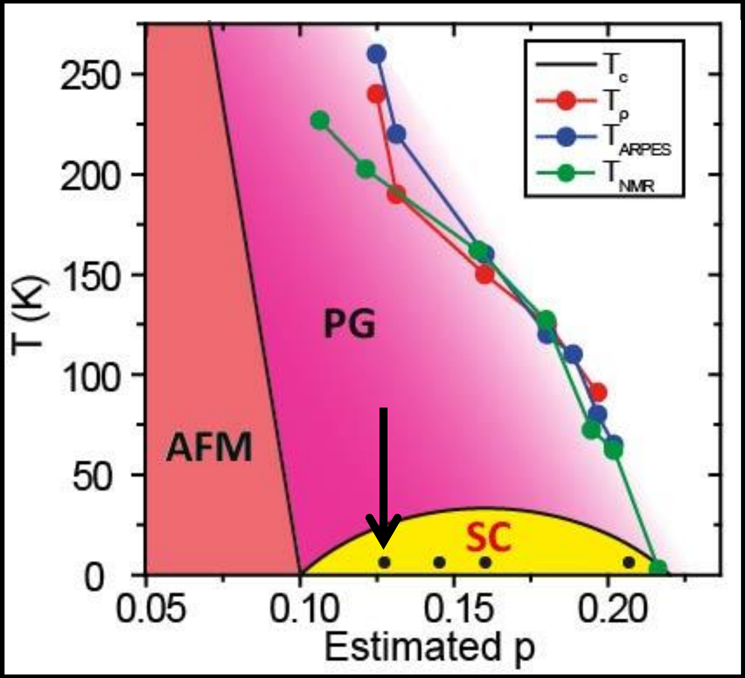
STM studies of Pb-doped Bi2201

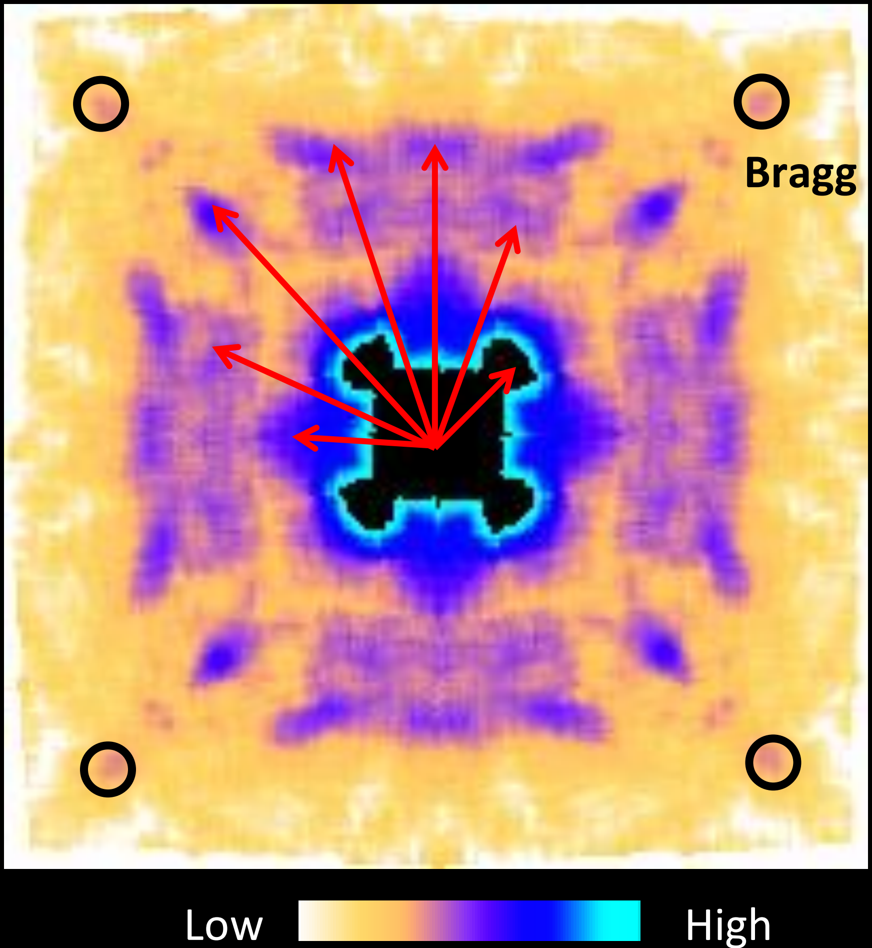




arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

Octet QPI in UD25K Bi2201

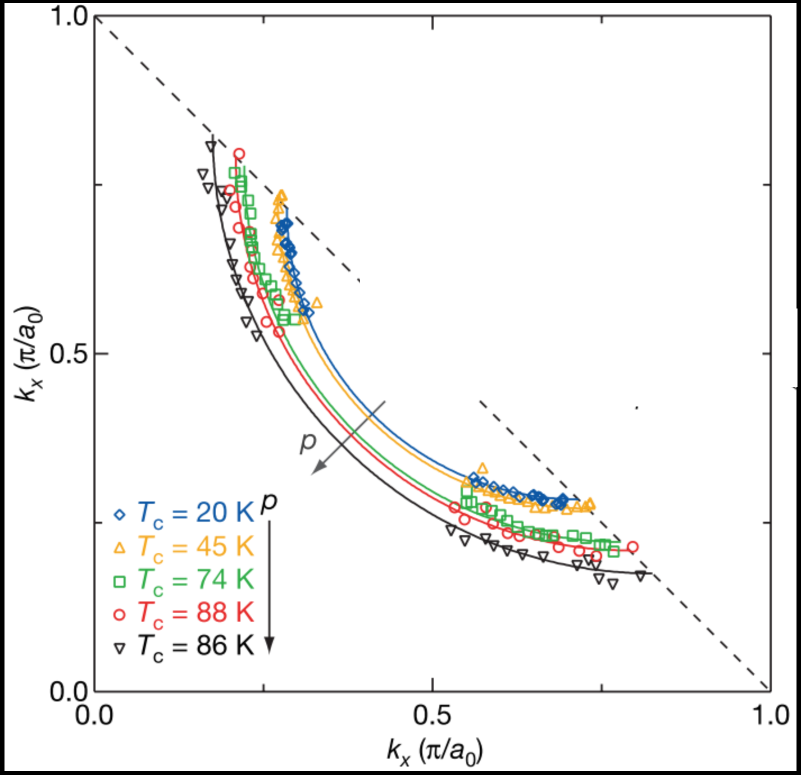




(Fourier transform of a real space dI/dV map)

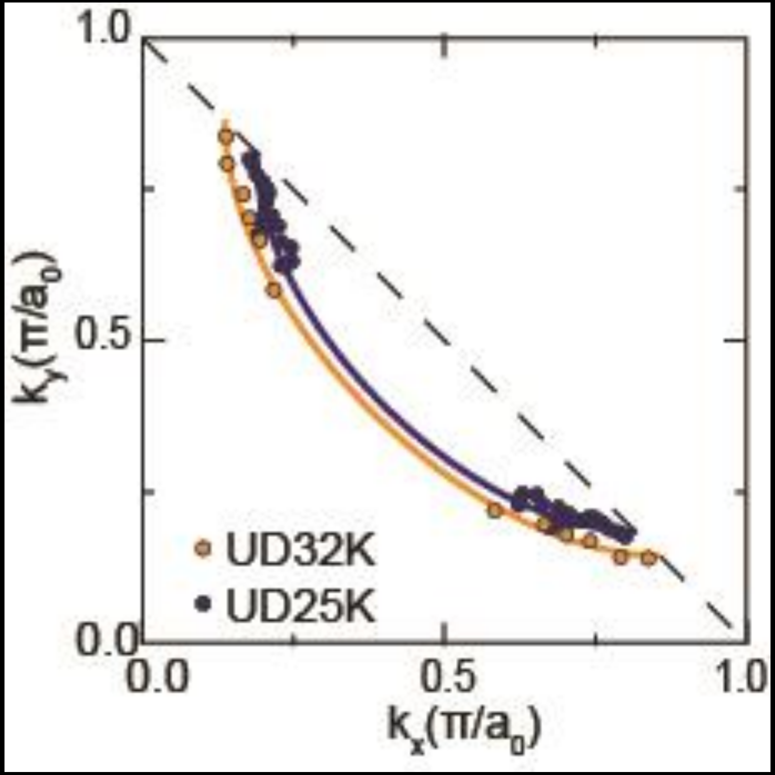
Extinction of octet QPI

Previous work: Bi2212



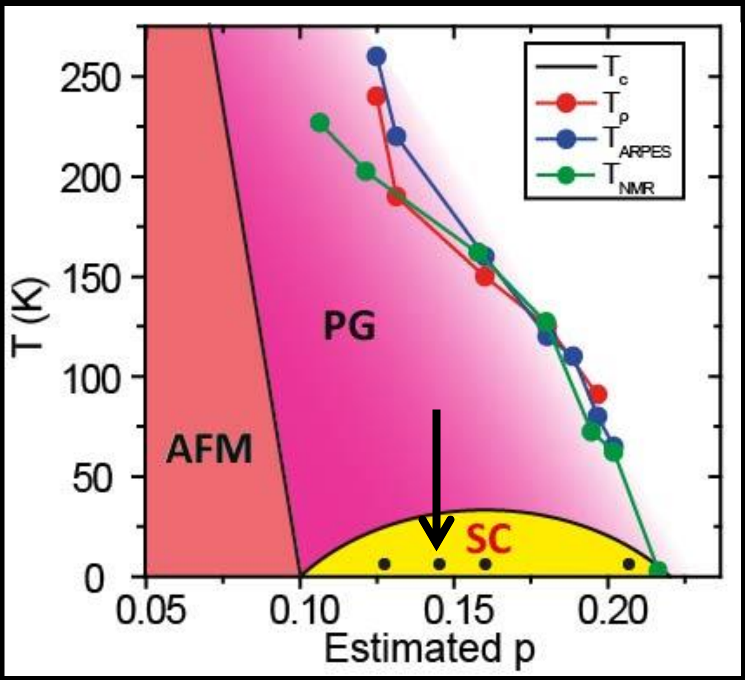
Kohsaka, Nature 454, 1072 (2008)

Our data: Bi2201

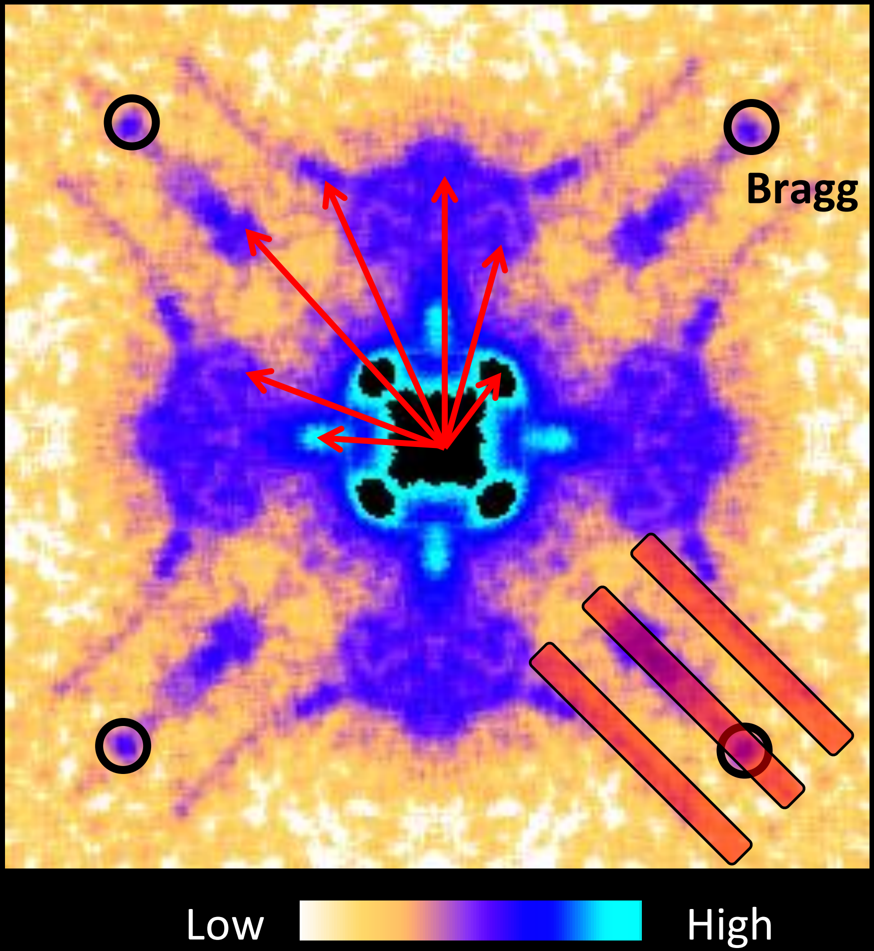


arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

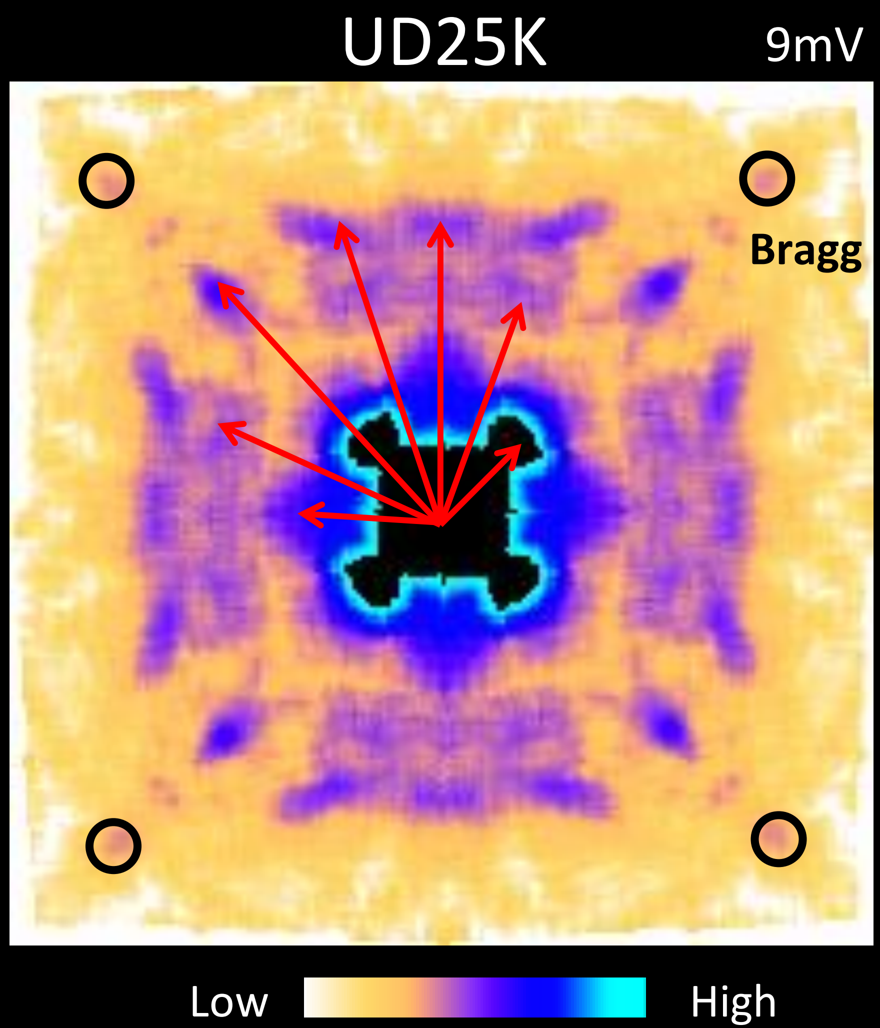
QPI in UD32K Bi2201

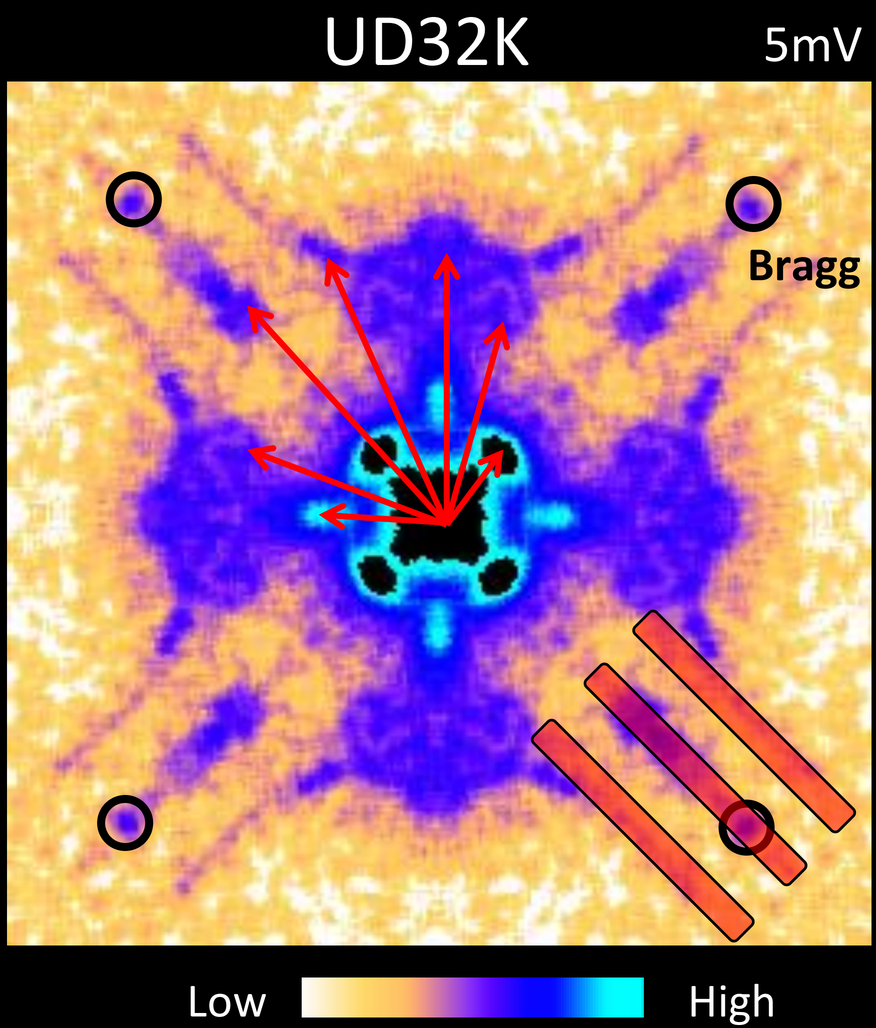


UD32K 5mV

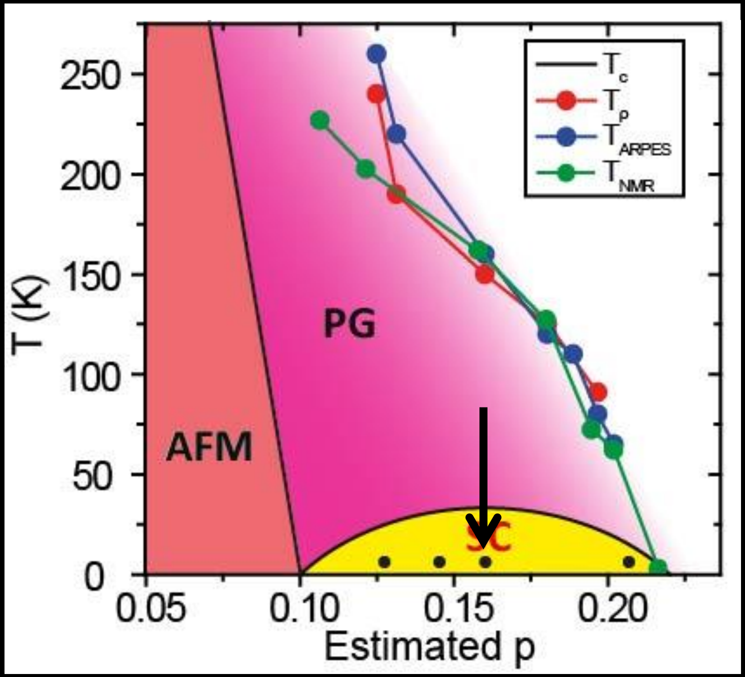


Compare QPI in UD25K and UD32K



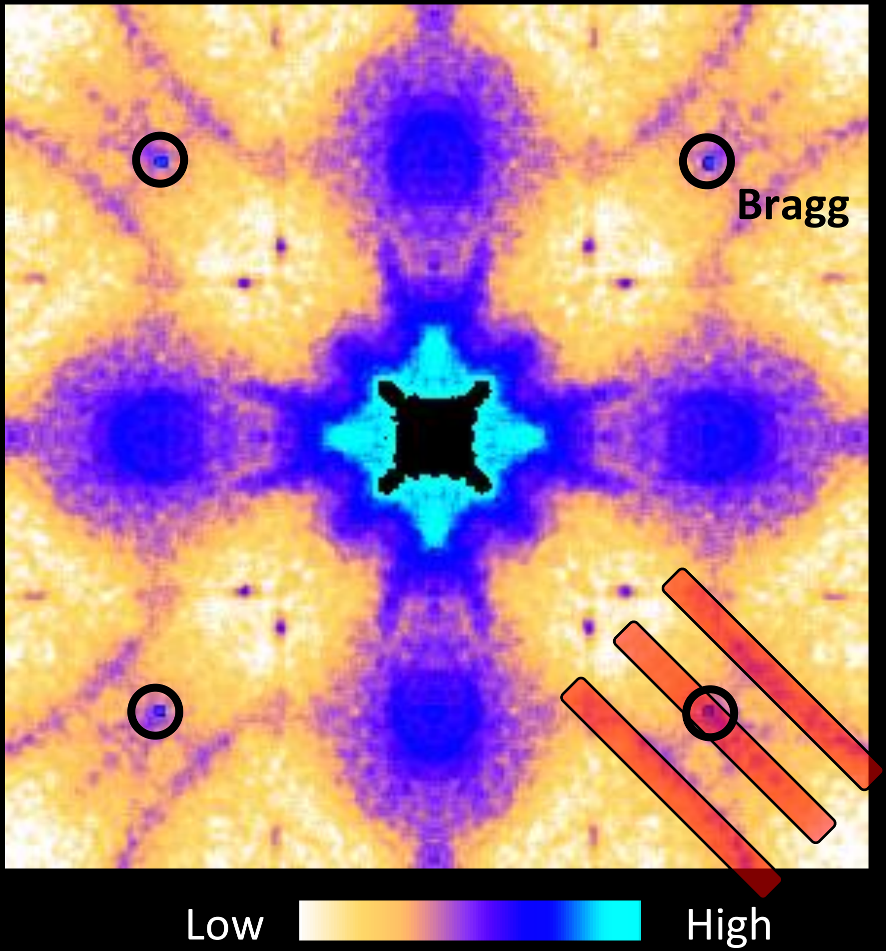


QPI in OPT35K

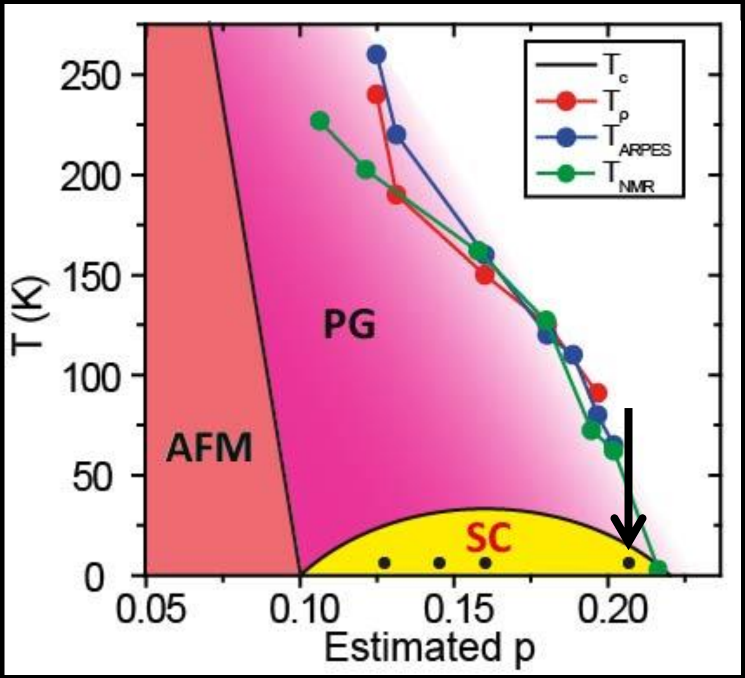


OPT35K

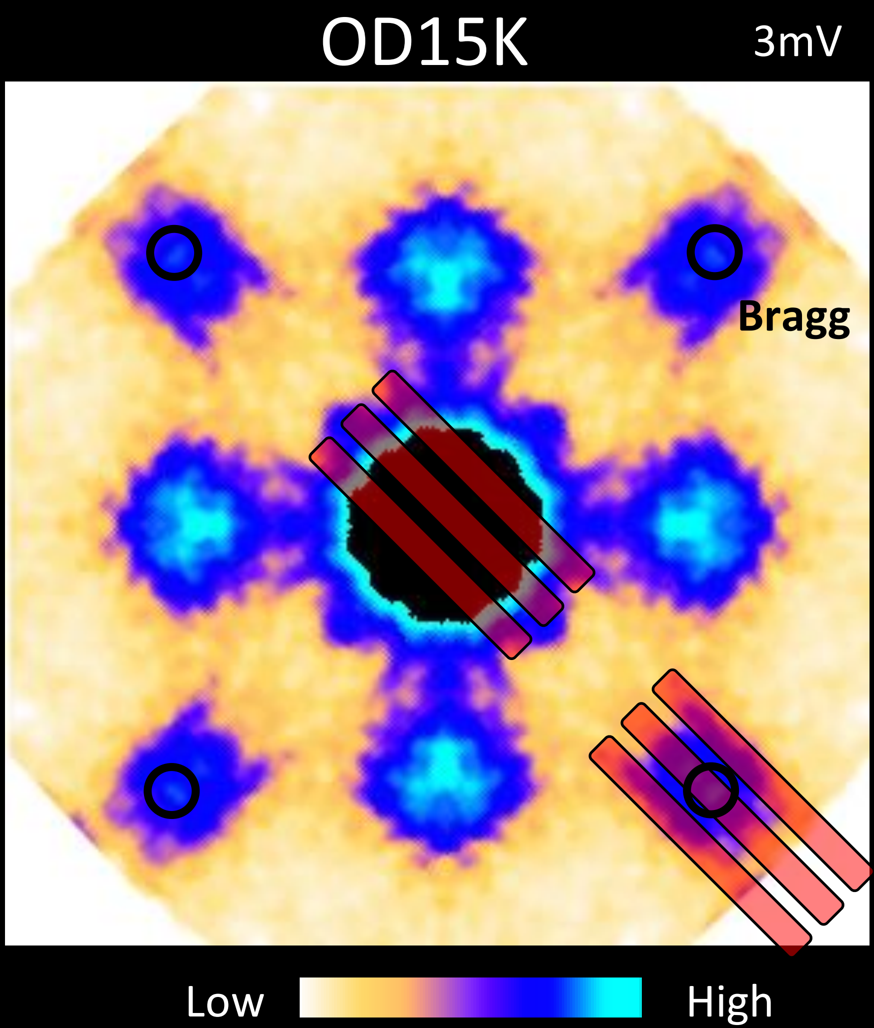
5mV



QPI in OD15K



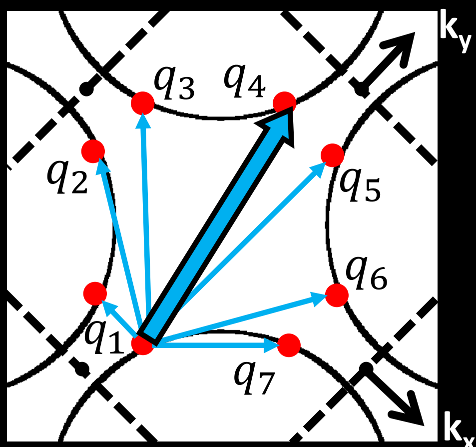
T (K)
250
200
150
100
50
0
0.05
0.10
0.15
0.20
Estimated p
AFM
PG
SC
T_c
T_ρ
T_{ARPES}
T_{NMR}



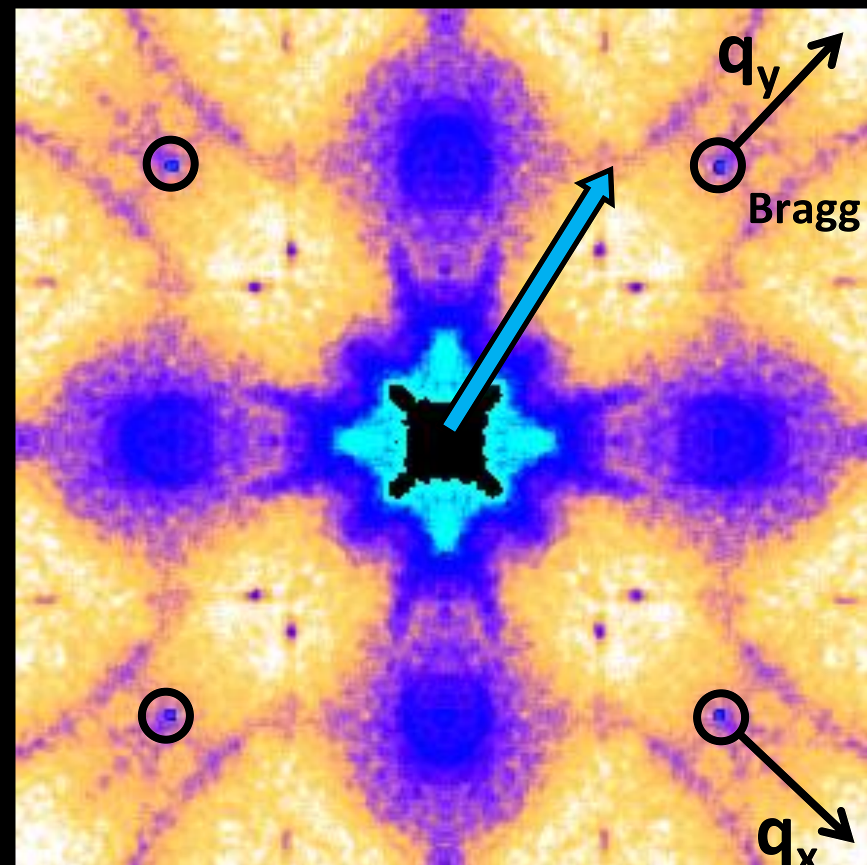
OD15K
3mV
Bragg
Low
High

Compare Fermi surface to QPI

k space Fermi surface



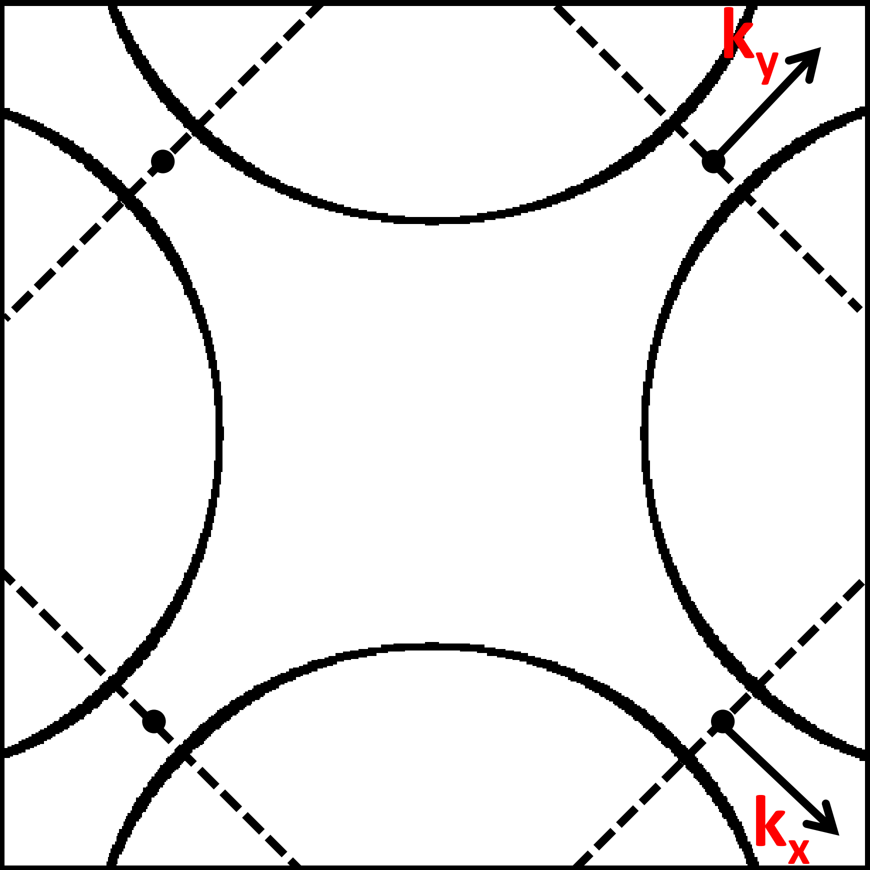
q space QPI OPT35K 5mV

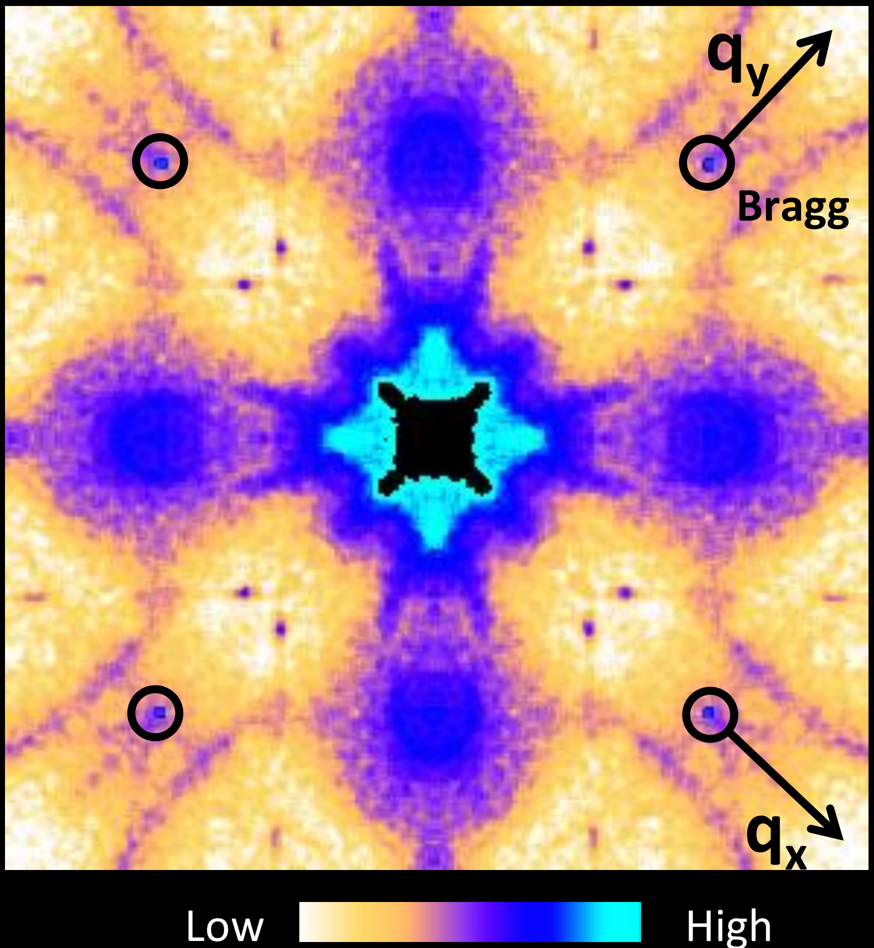


Low High

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

Compare Fermi surface to QPI

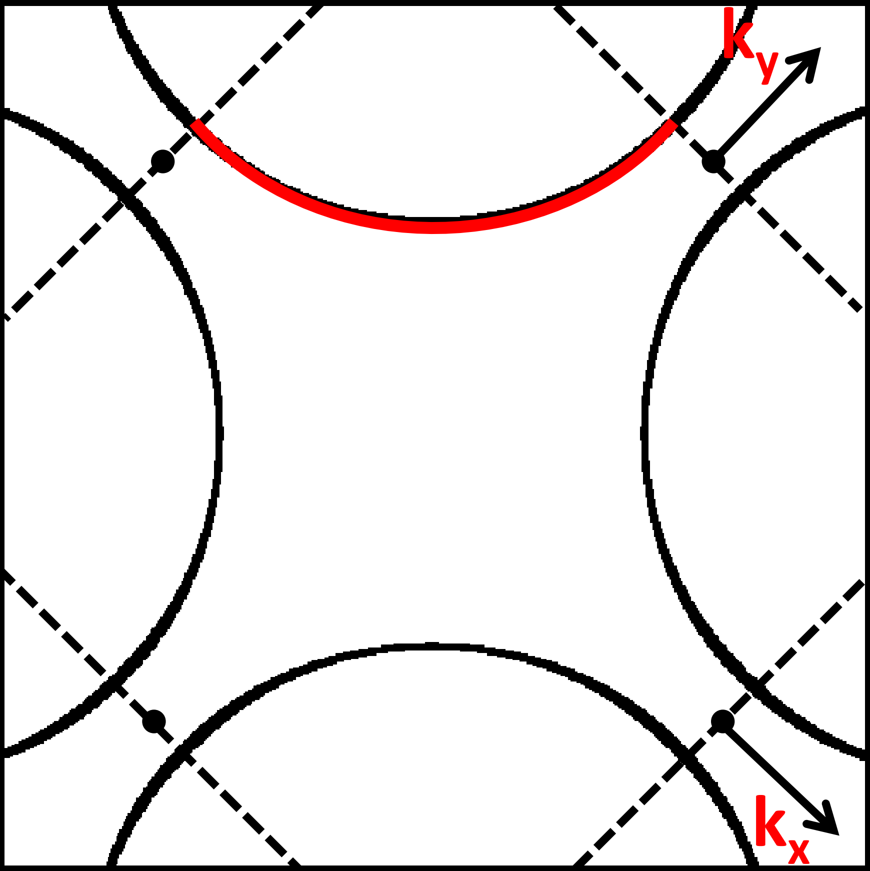




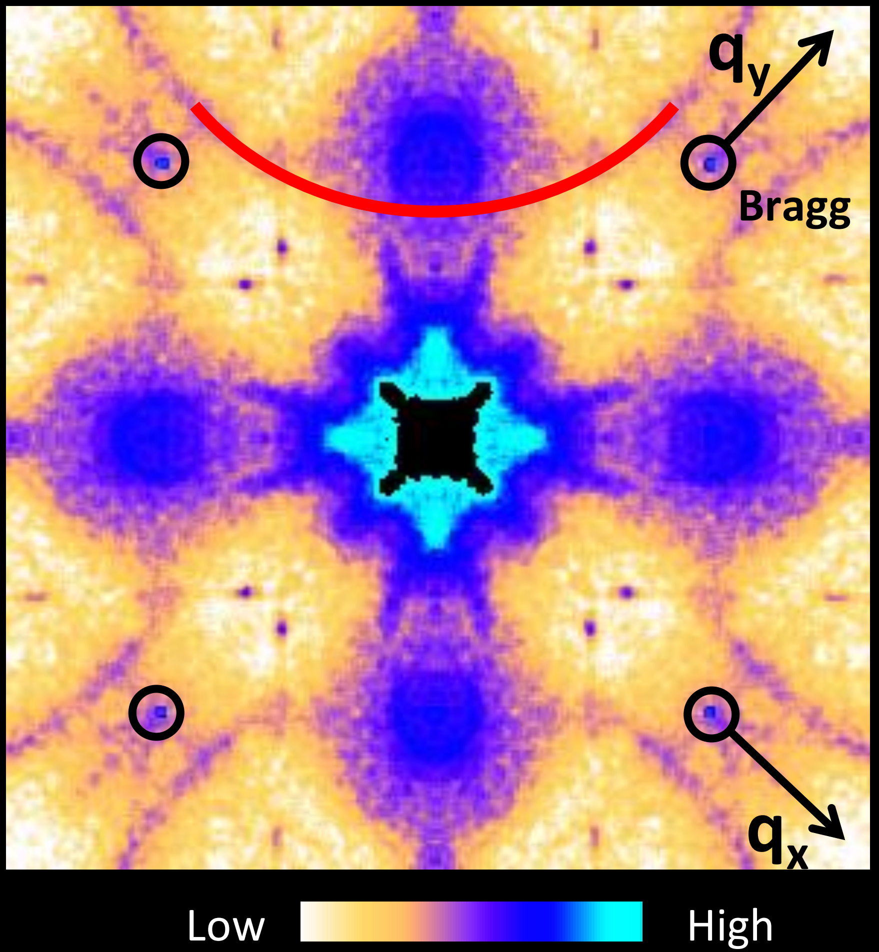
$q_4 = (2k_x, 2k_y)$ which follows the Fermi surface

Compare Fermi surface to QPI

2 x k space Fermi surface



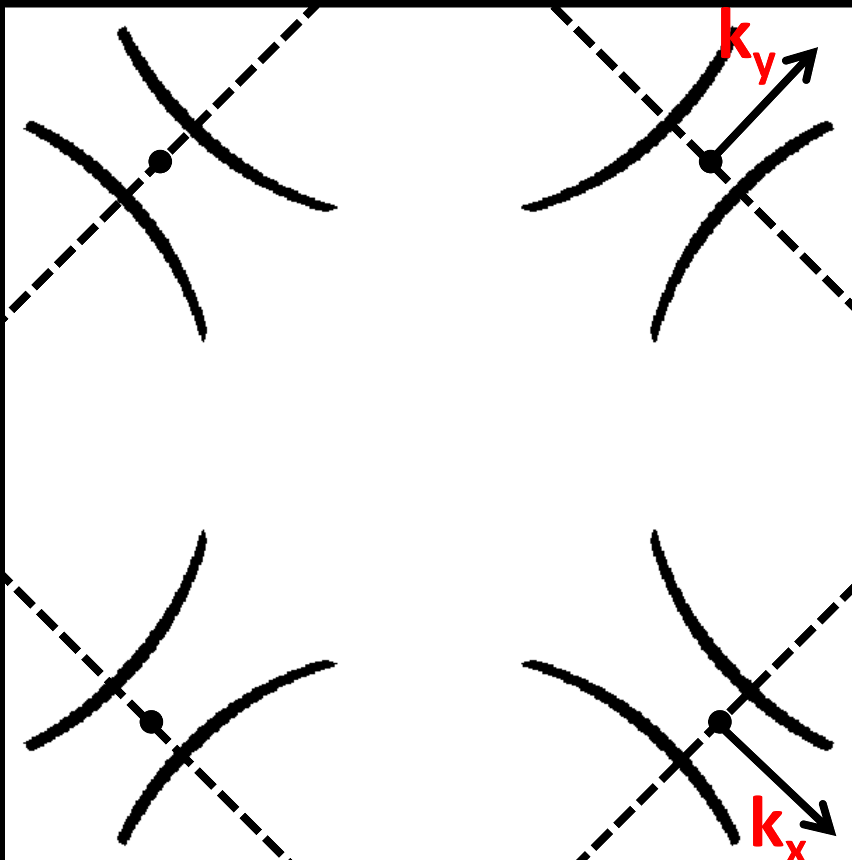
q space QPI OPT35K 5mV



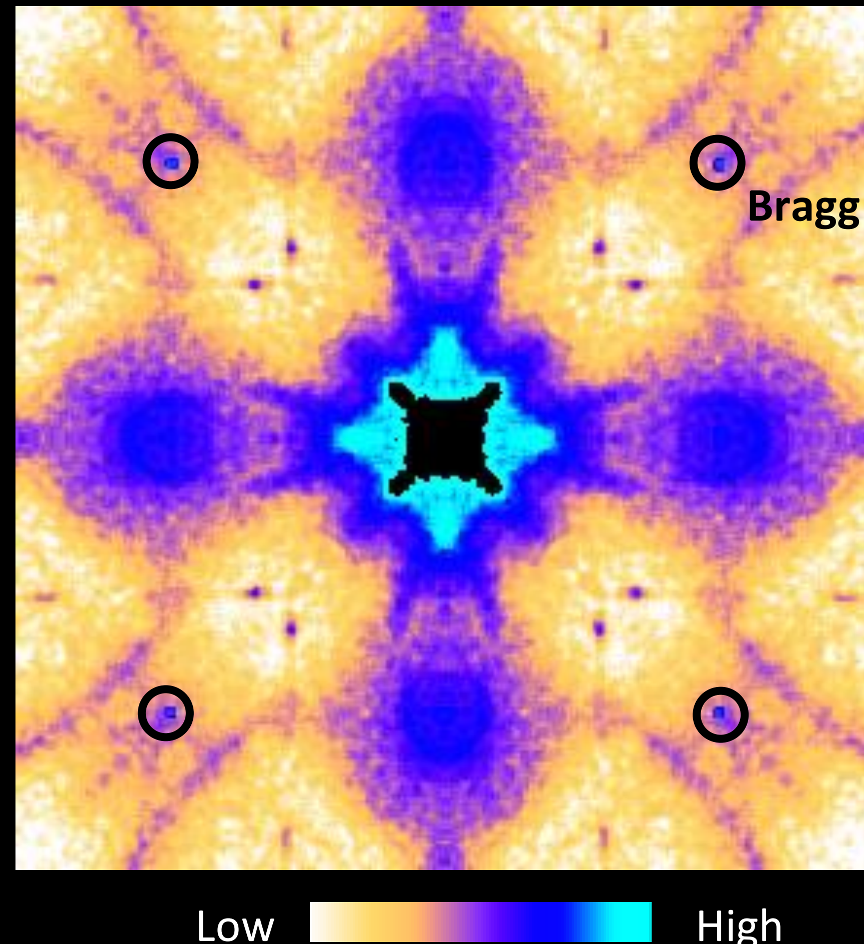
$q_4 = (2k_x, 2k_y)$ which follows the Fermi surface

Autocorrelate just the antinodal Fermi surface

2 x Antinodal Fermi surface

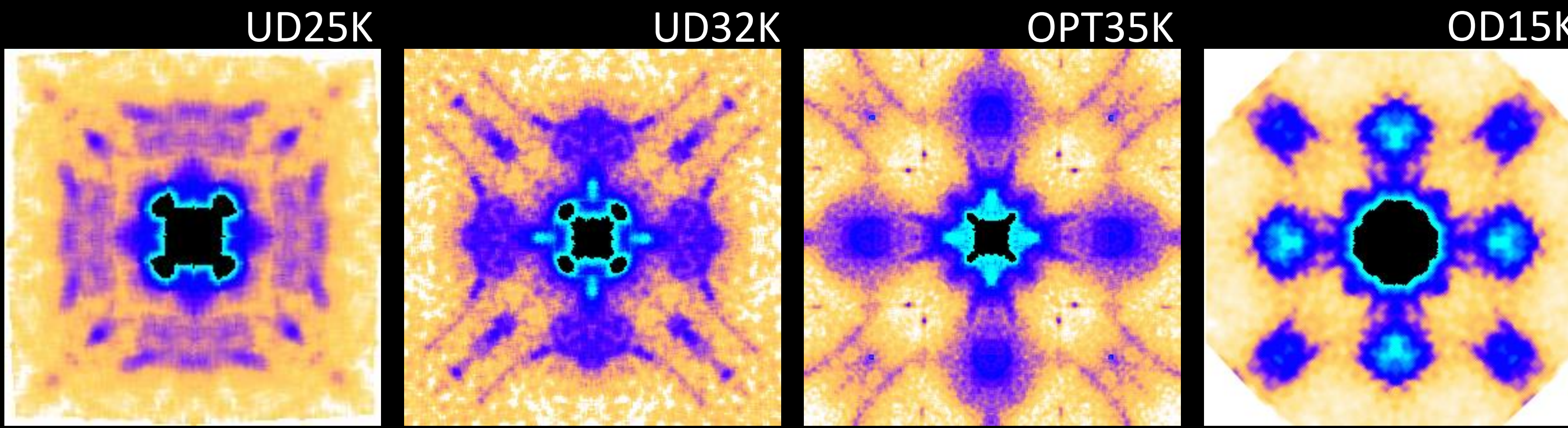


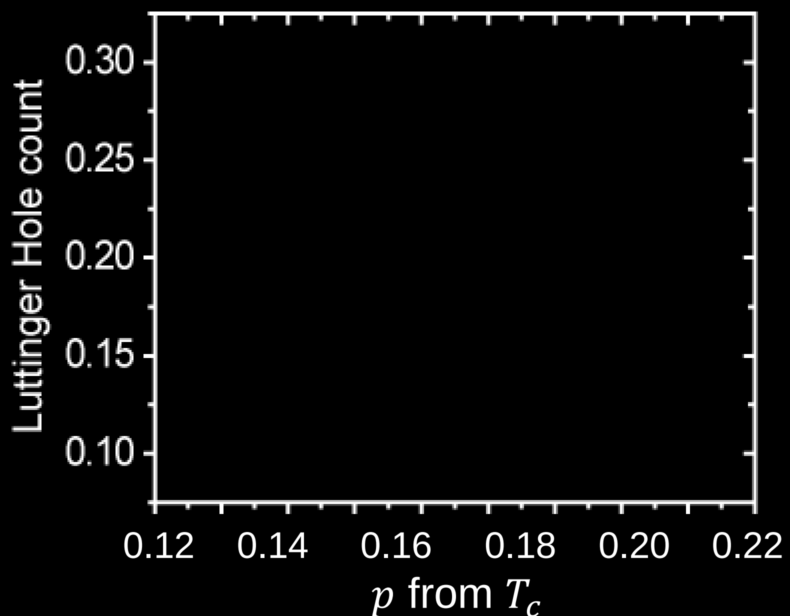
q space QPI OPT35K 5mV



Triplet feature comes from antinode.

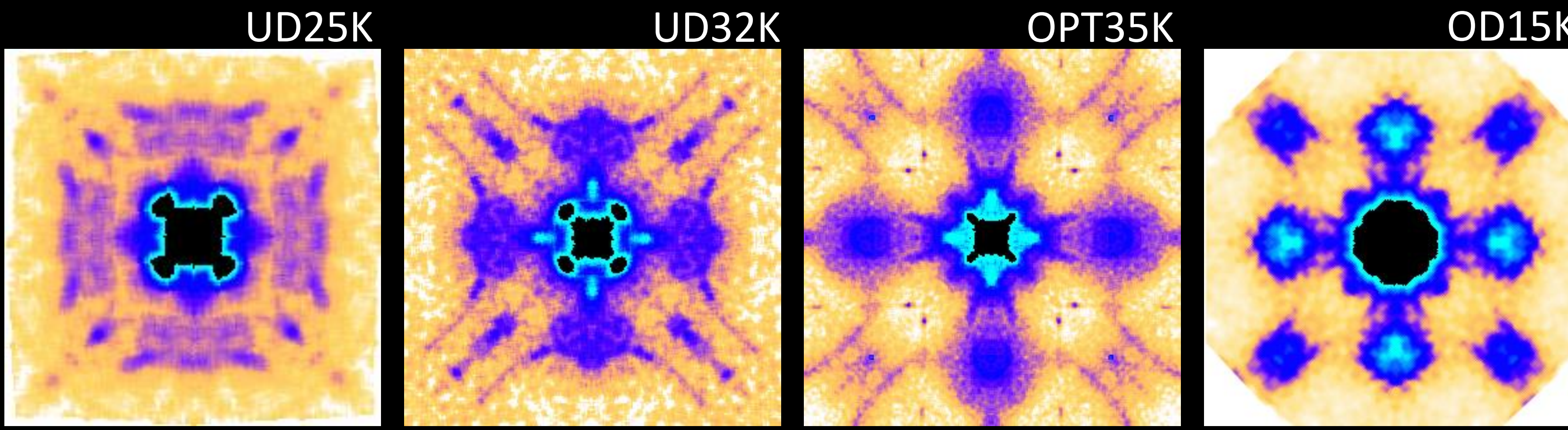
Luttinger count

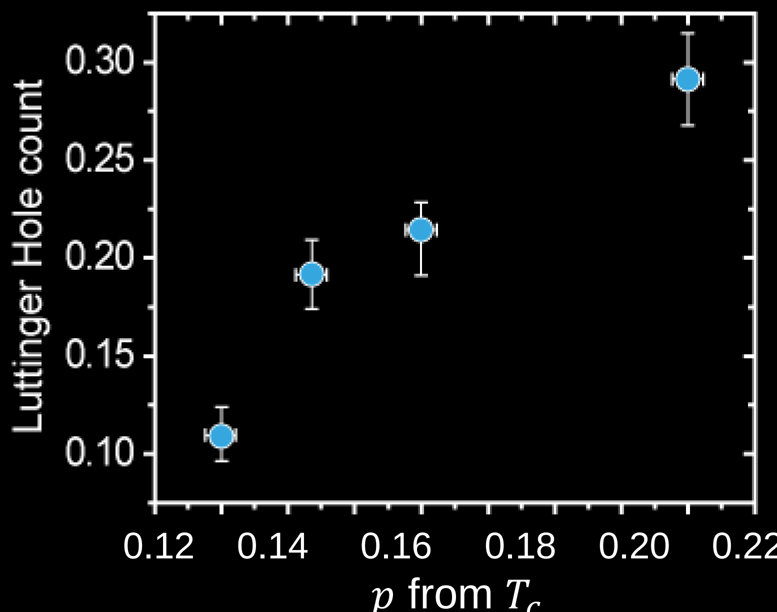




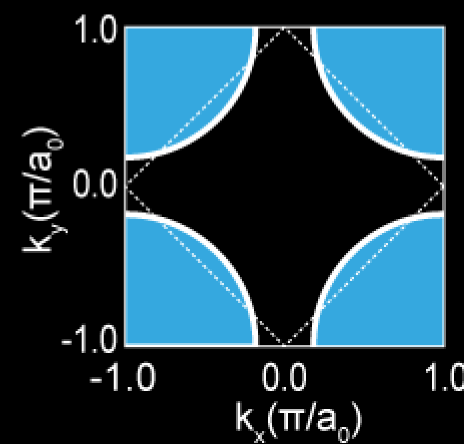
Ando, PRB 61, R14956 (2000)

Luttinger count





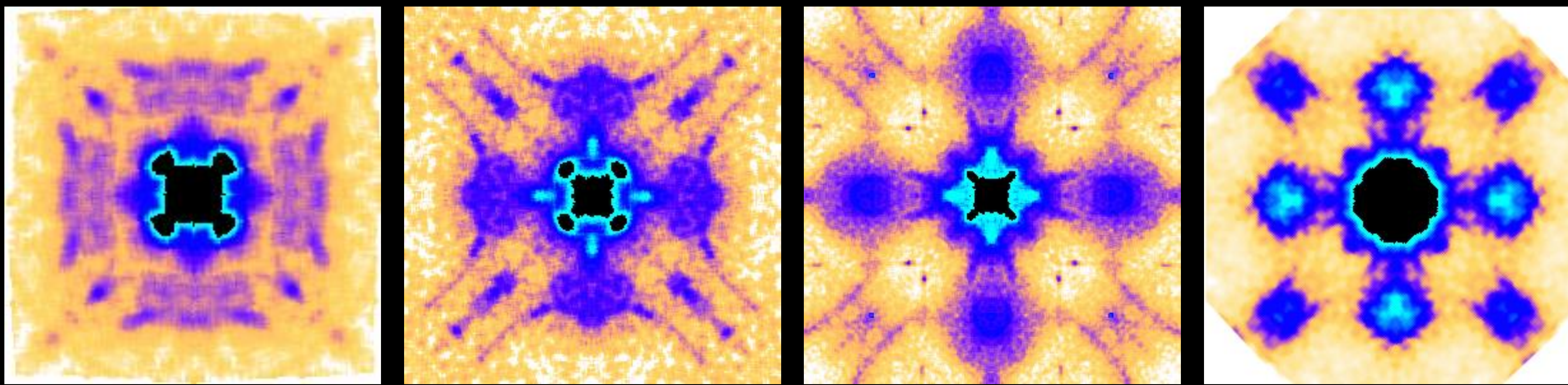
Ando, PRB 61, R14956 (2000)

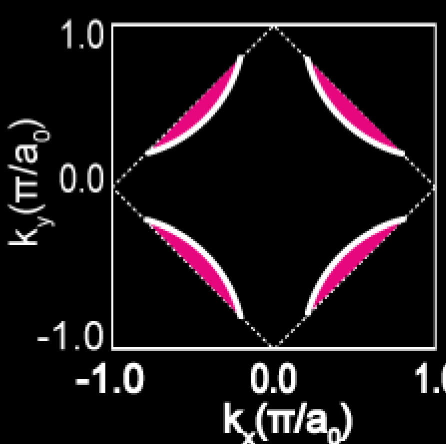


$$p_{\text{large}} = \frac{2A_{\text{blue}}}{A_{\text{BZ}}} - 1$$

Luttinger count

UD25K UD32K OPT35K OD15K

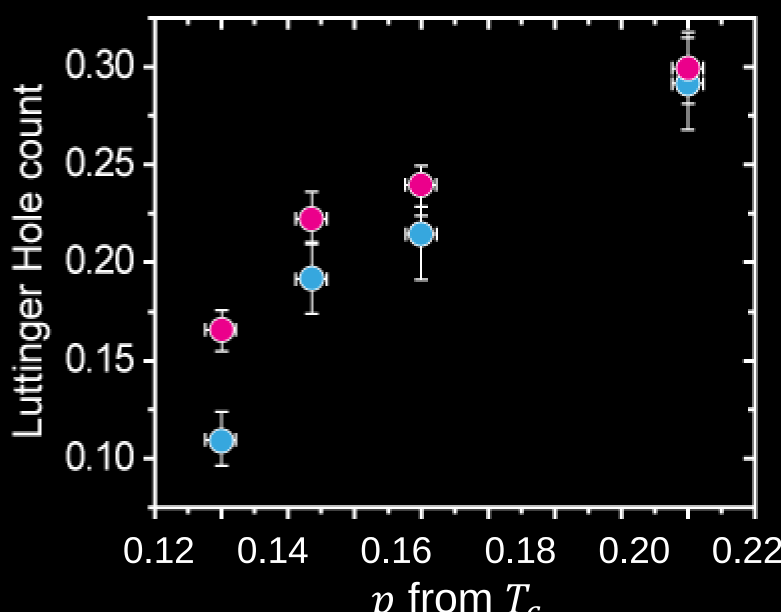




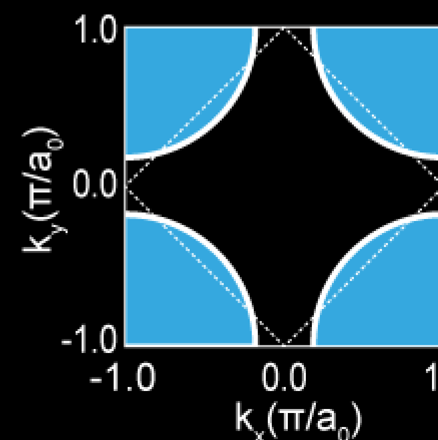
$$p_{\text{small}} = \frac{2A_{\text{pink}}}{A_{\text{BZ}}}$$

YRZ, PRB 73, 174501 (2006)

Qi + Sachdev, PRB 81, 115129 (2010)

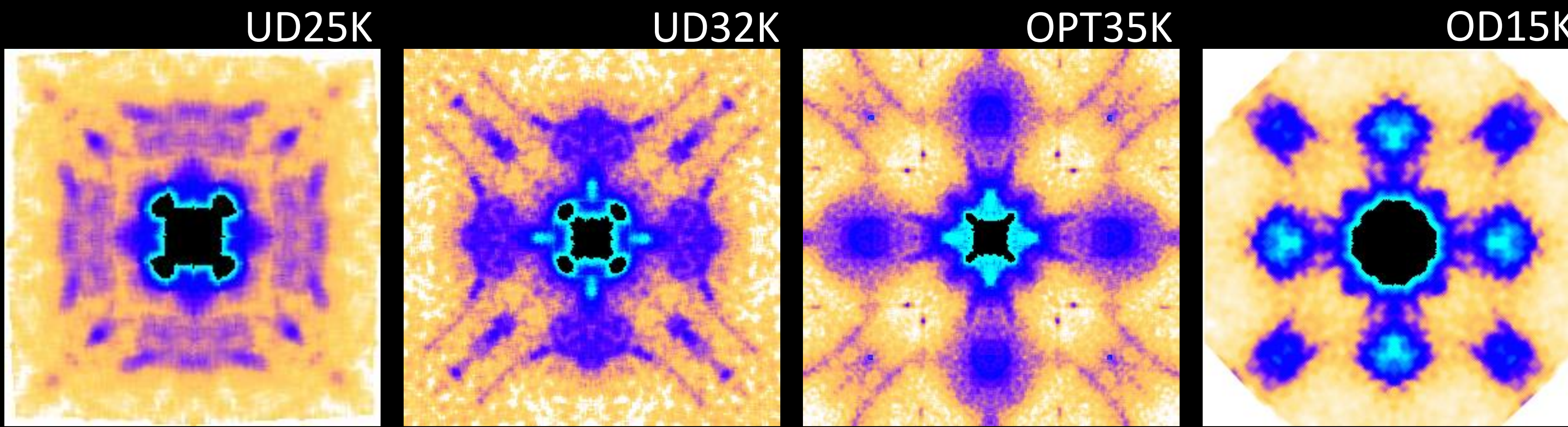


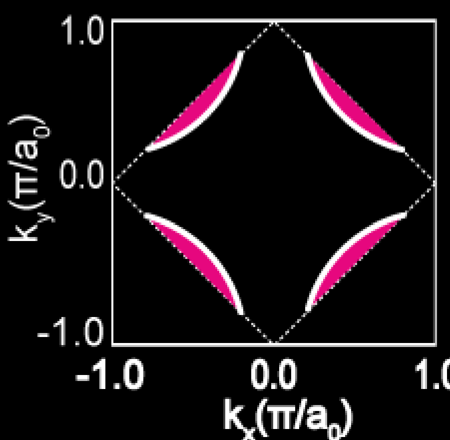
Ando, PRB 61, R14956 (2000)



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

Luttinger count

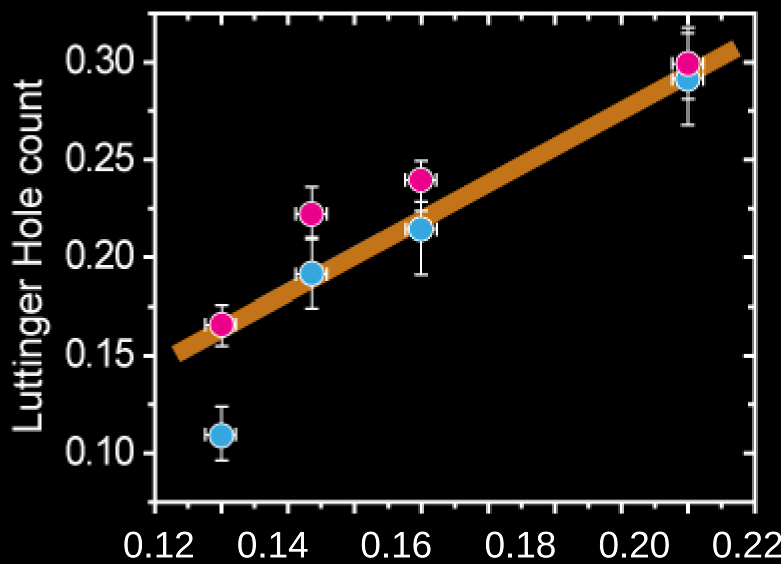




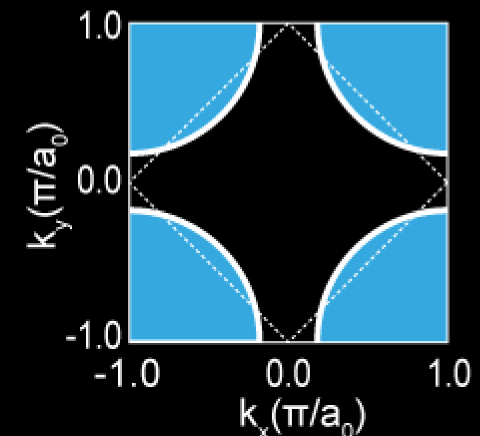
$$p_{\text{small}} = \frac{2A_{\text{pink}}}{A_{\text{BZ}}}$$

YRZ, PRB 73, 174501 (2006)

Qi + Sachdev, PRB 81, 115129 (2010)

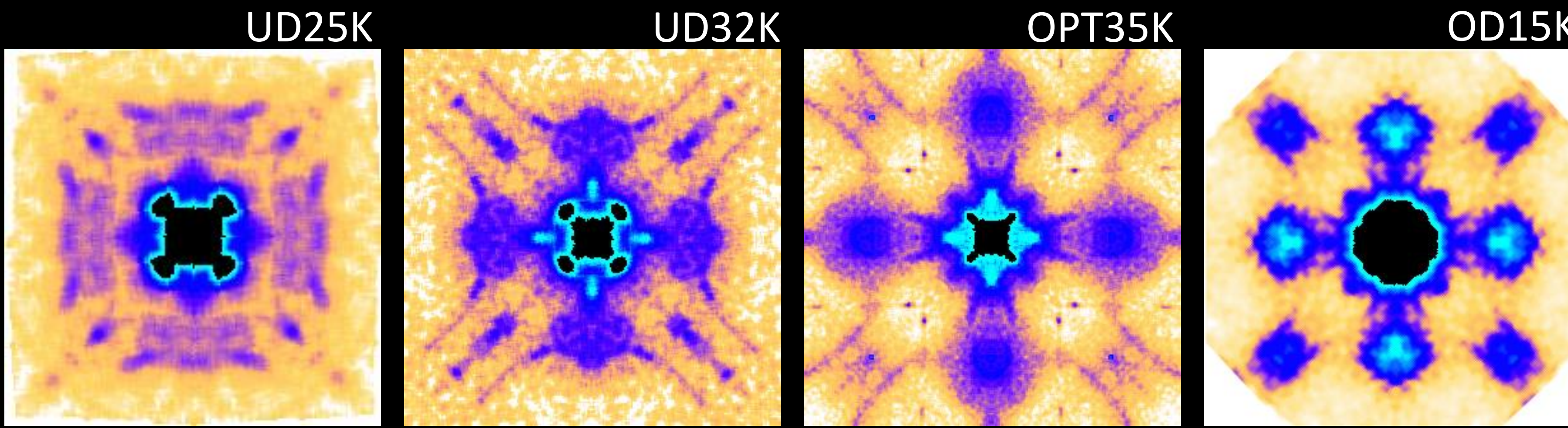


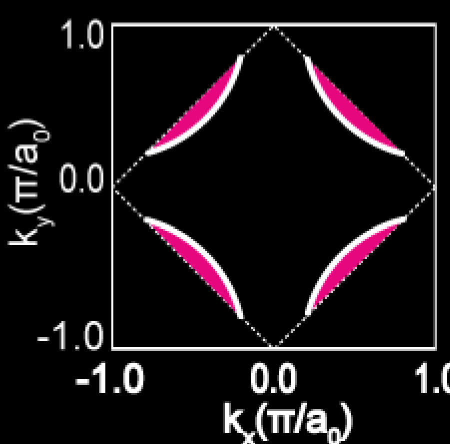
Ando, PRB 61, R14956 (2000)



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

Luttinger count

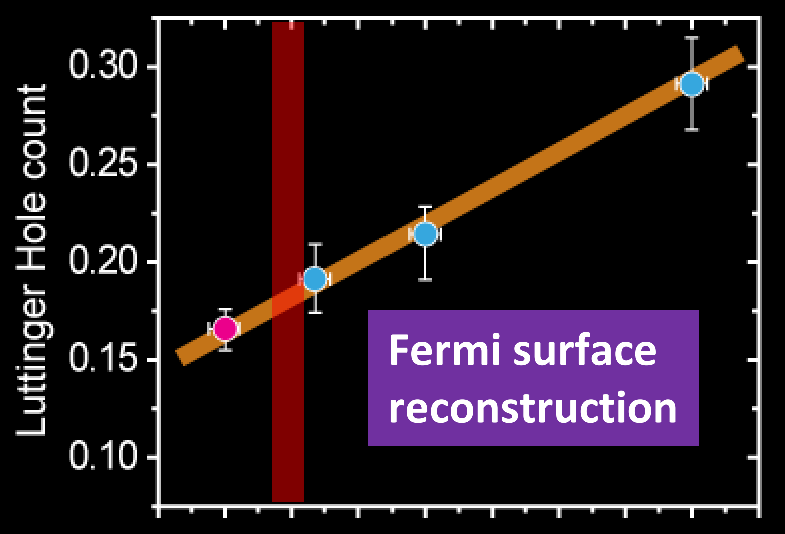




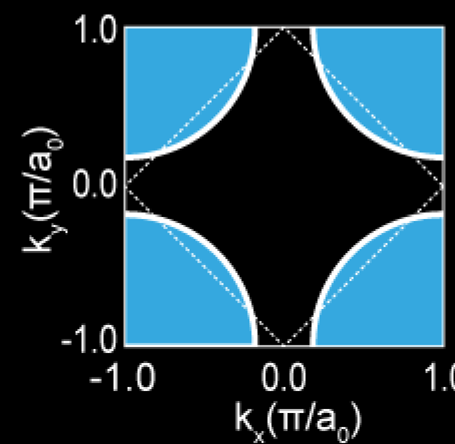
$$p_{\text{small}} = \frac{2A_{\text{pink}}}{A_{\text{BZ}}}$$

YRZ, PRB 73, 174501 (2006)

Qi + Sachdev, PRB 81, 115129 (2010)

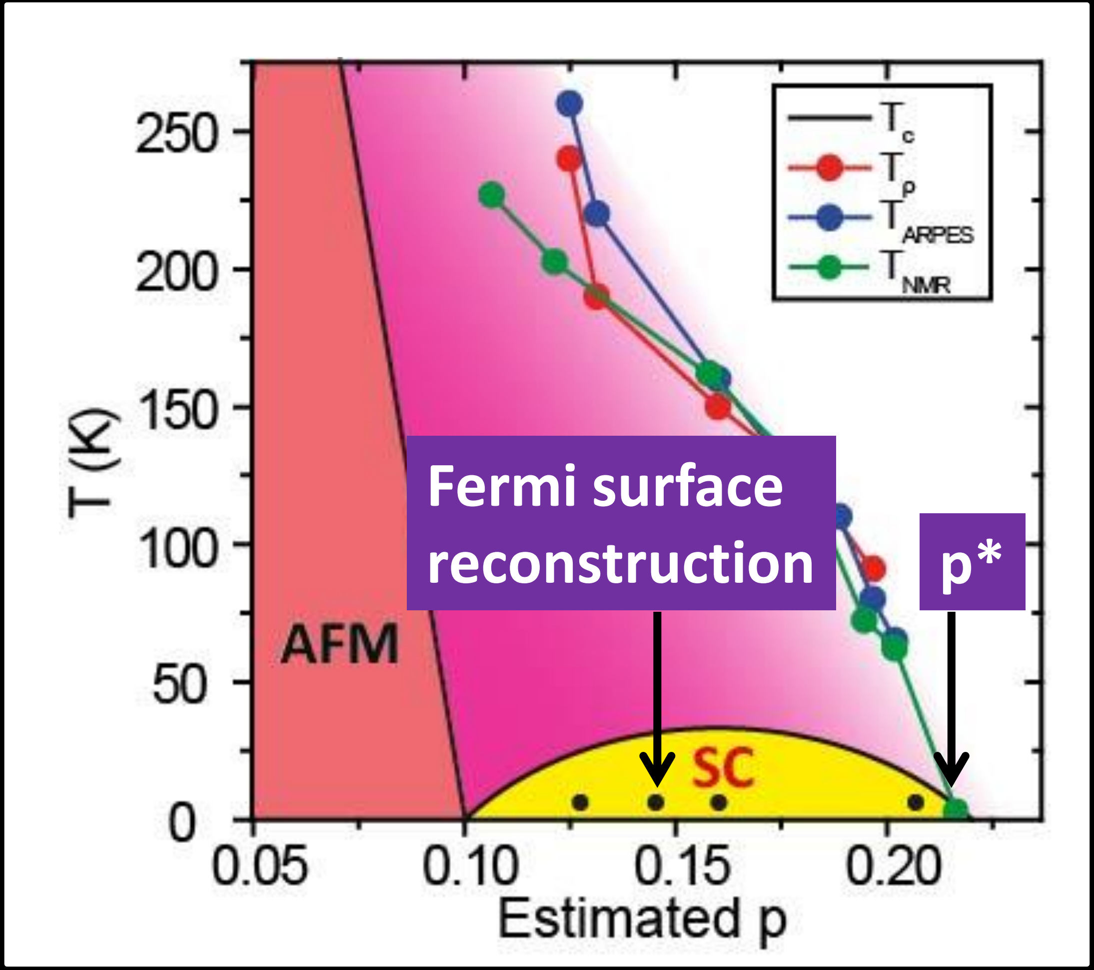


Ando, PRB 61, R14956 (2000)



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

FS reconstruction & pseudogap



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

Outline

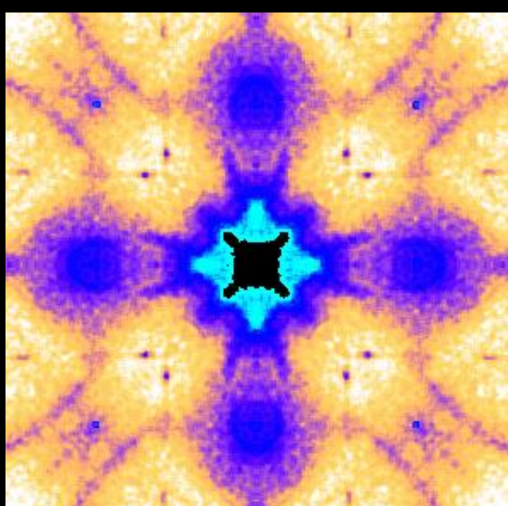
1. Where is the Fermi surface reconstruction?

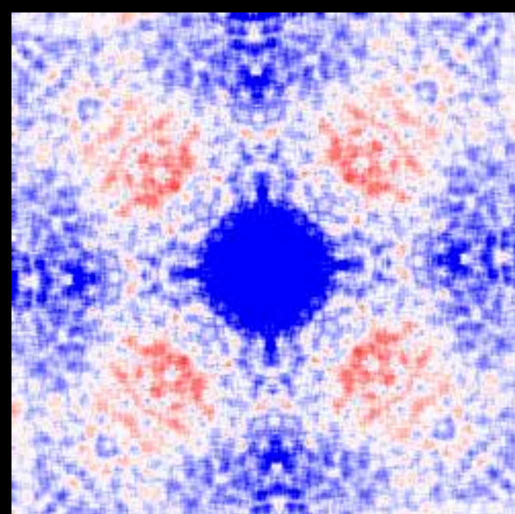
   Answer: coincides with QCP near optimal doping at B=0

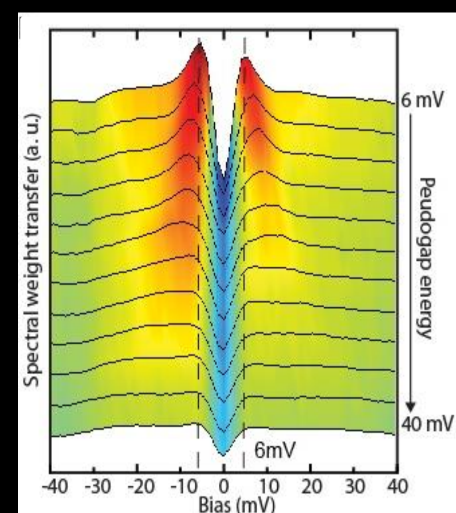
2. What is the role of the pseudogap?

   Answer:

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



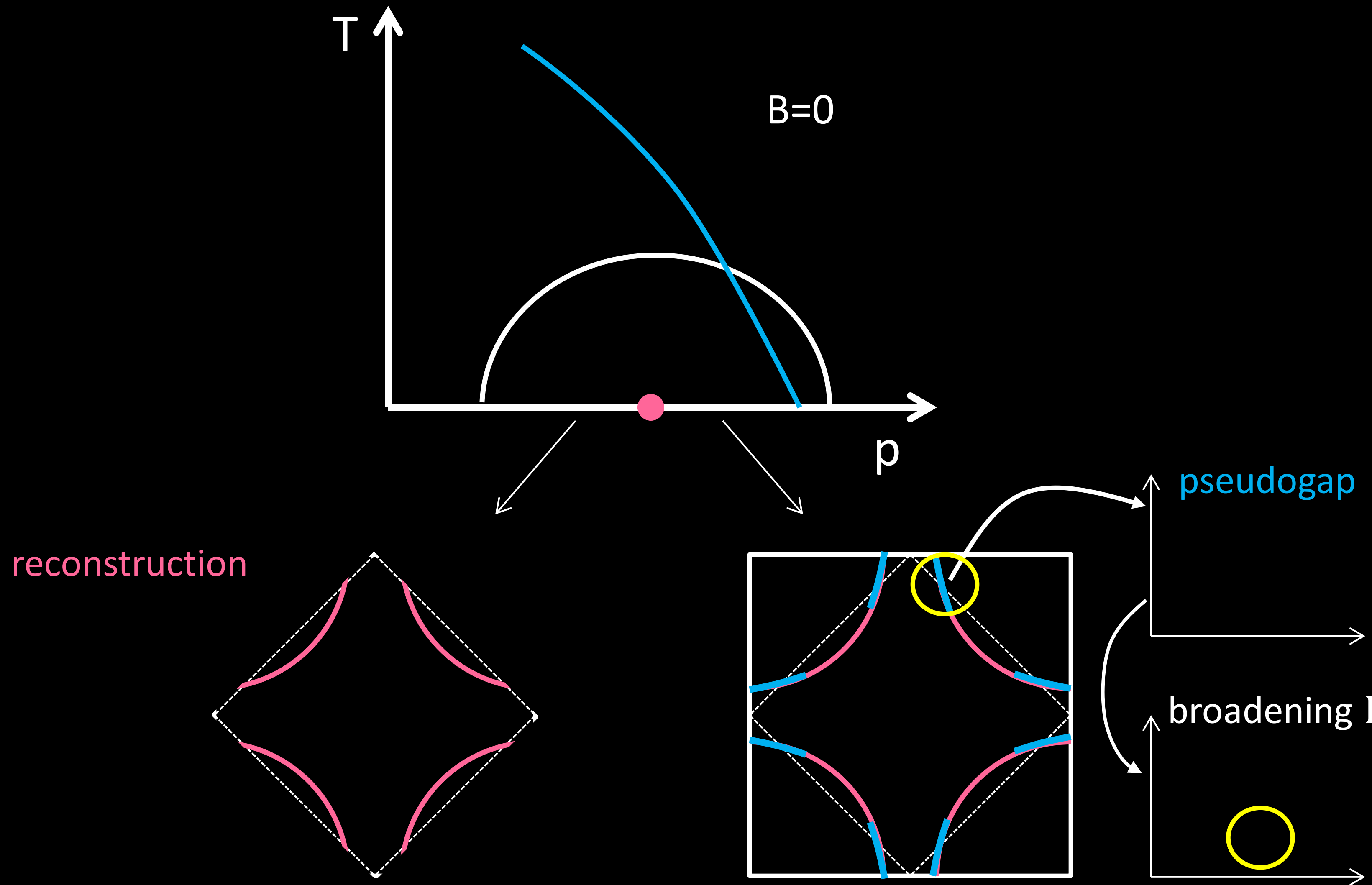




arxiv:1305.2778, He et al, ***Science***, May 9 (2014)

What about superconductivity?

1. Fermi surface reconstruction ≠ pseudogap

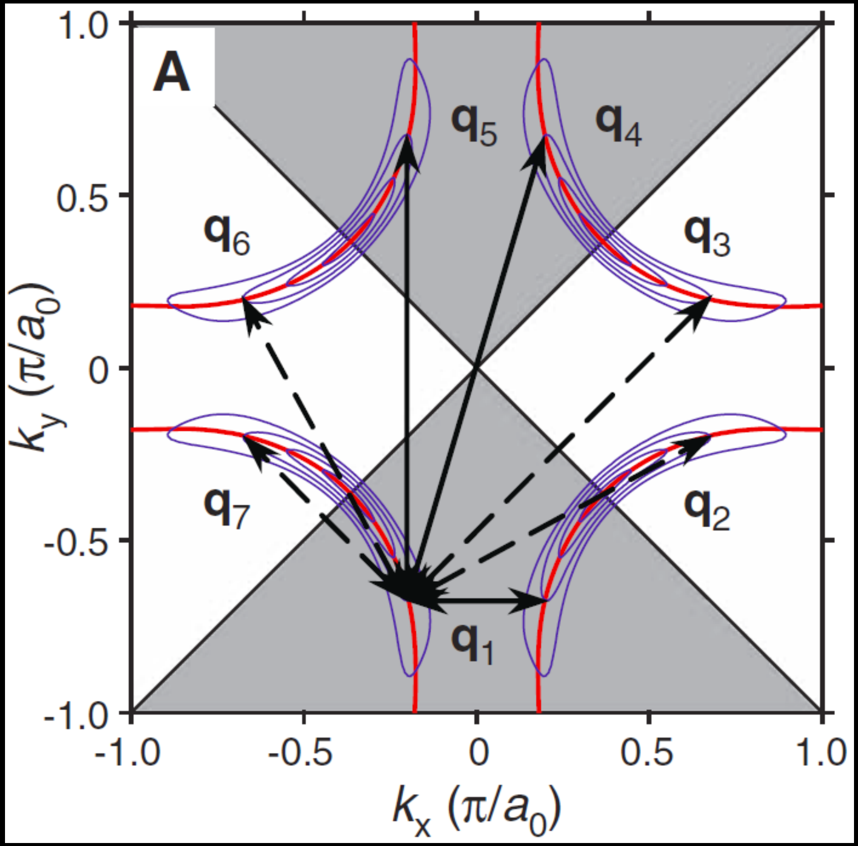


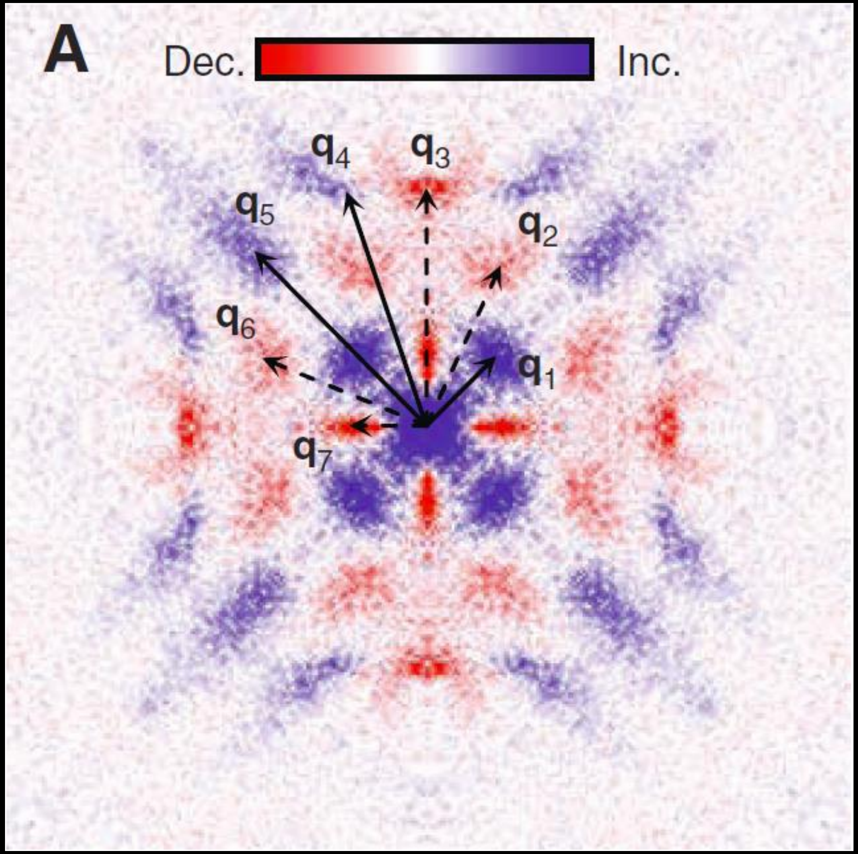
Can superconductivity live here too?

d-wave coherence factors in Bi2212

sign flipping → **decreasing in field**

sign preserving → **increasing in field**

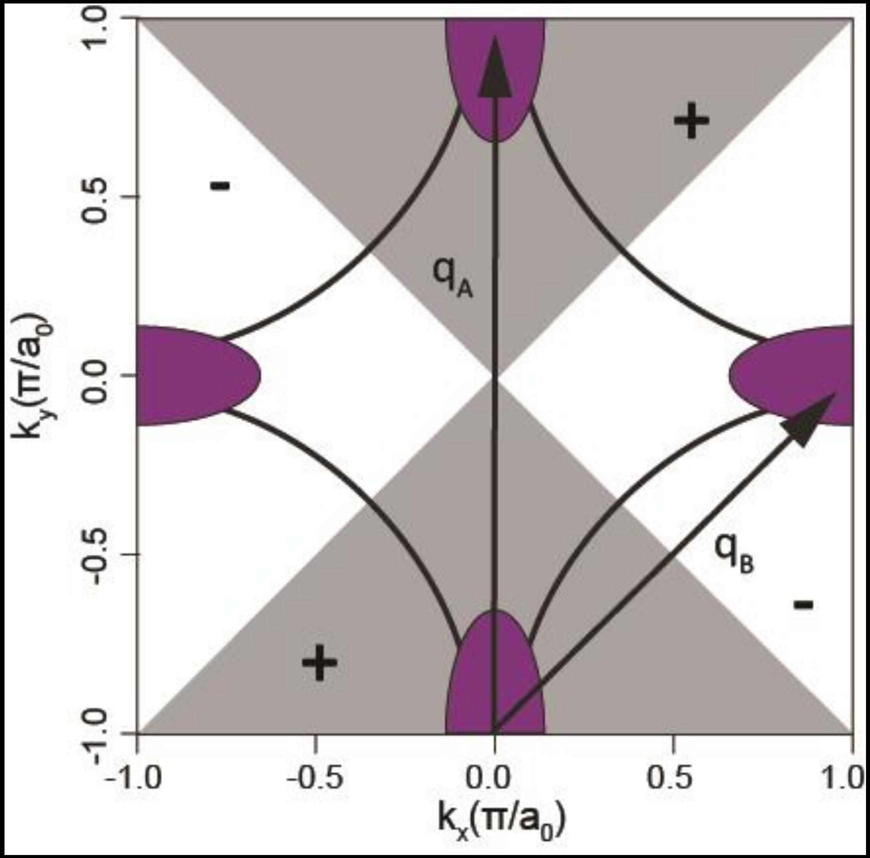


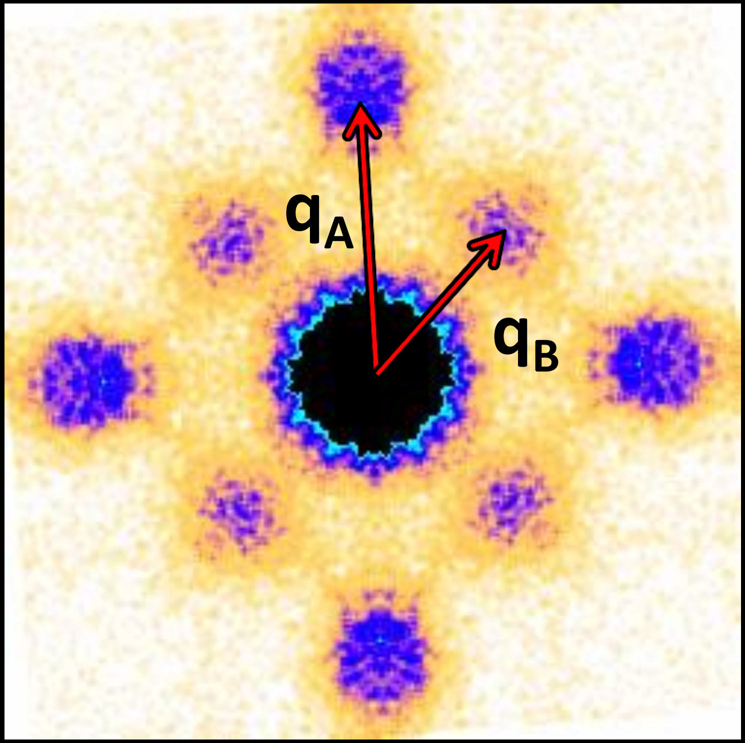


Hanaguri, et al, Science 323, 923 (2009)
suggested by Tami Pereg-Barnea & Marcel Franz
PRB 78, 020509 (2008)

antinodal *d*-wave coherence in Bi2201

OD15K 6mV, 0T



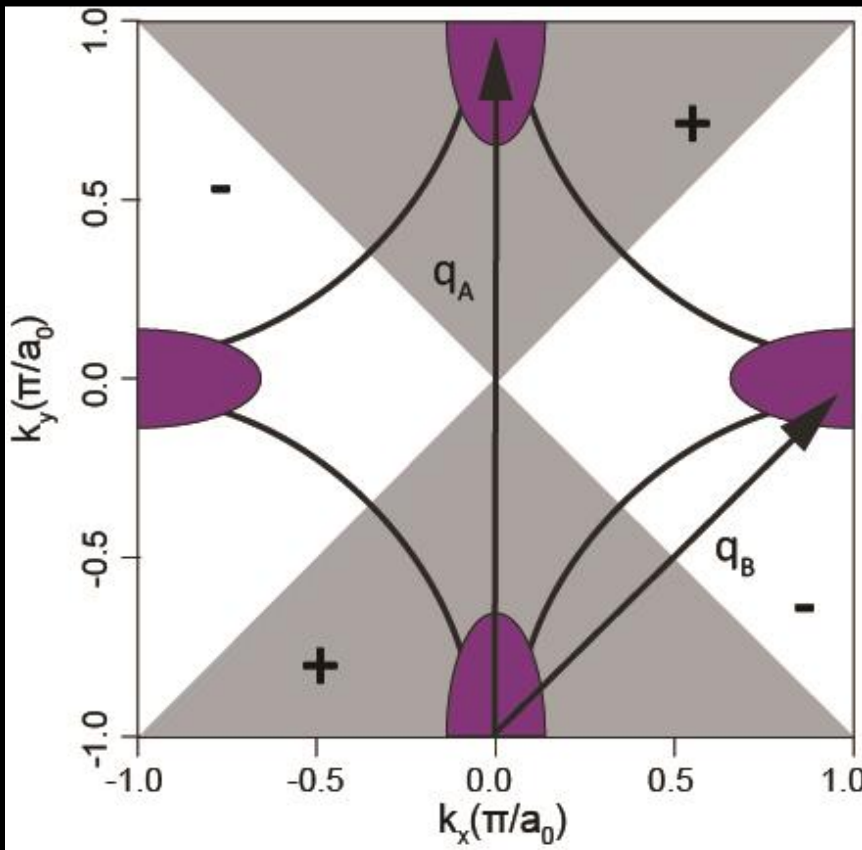


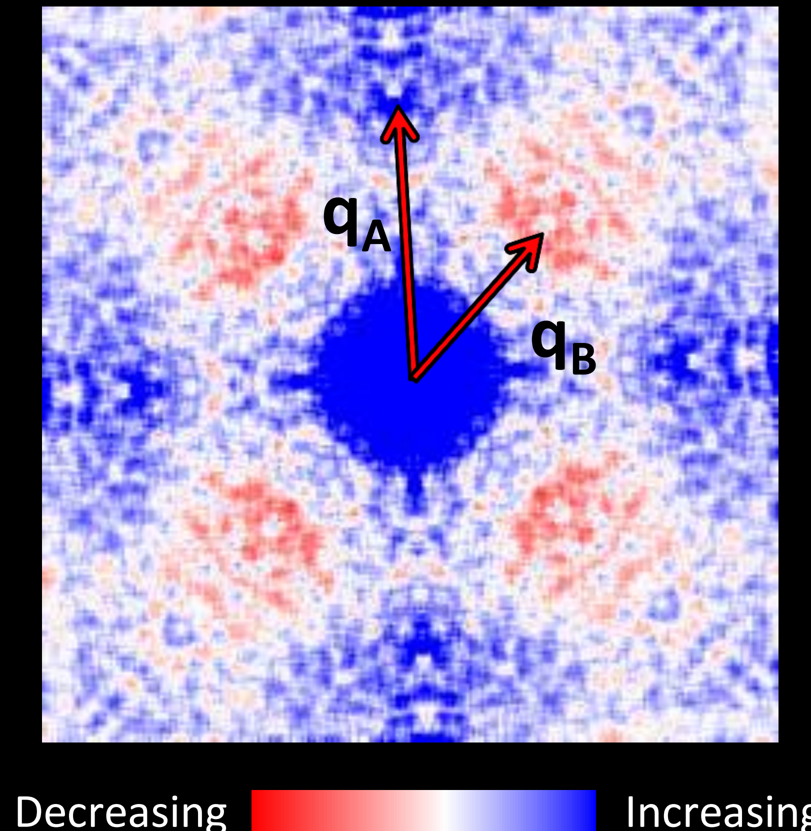
antinodal *d*-wave coherence in Bi2201

sign flipping → decreasing in field

sign preserving → increasing in field

OD15K 6mV, 9T-0T





Field dependence

→ Antinodal quasiparticles show d-wave coherence

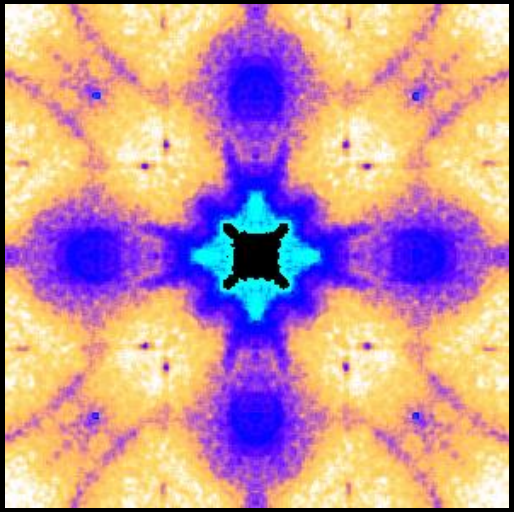
Outline

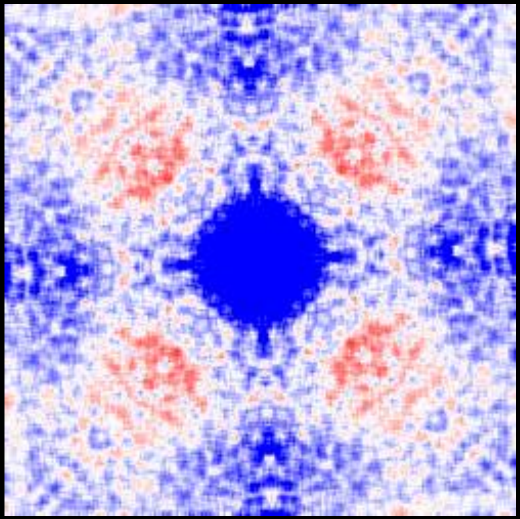
1. Where is the Fermi surface reconstruction?

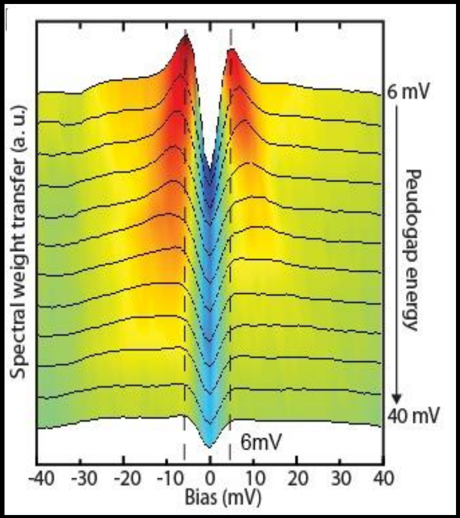
   Answer: coincides with QCP near optimal doping at B=0

2. What is the role of the pseudogap?

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





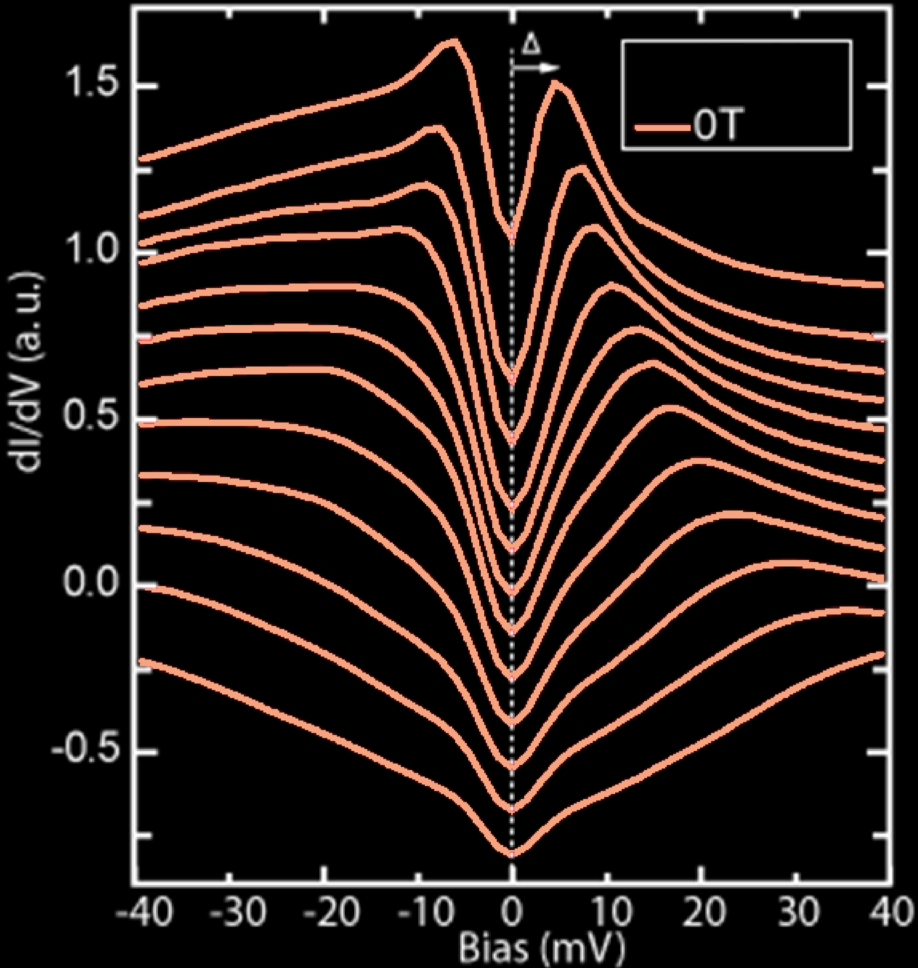


arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

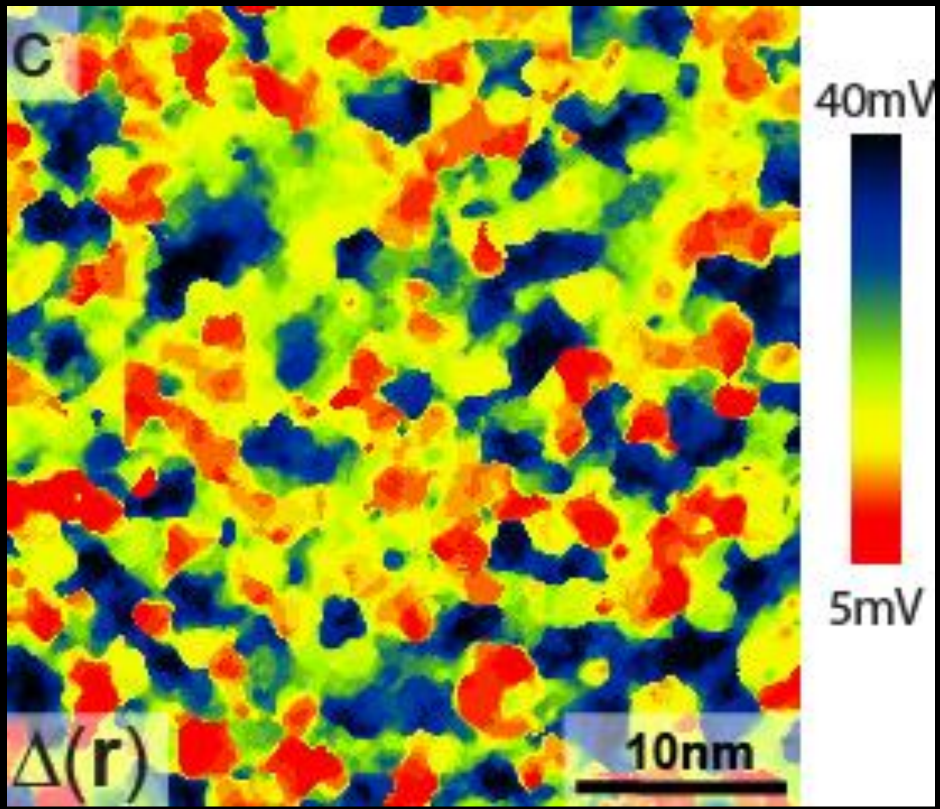
Two gap scenario: coexist spatially?

superconductivity vs. pseudogap at antinode?

OD15K

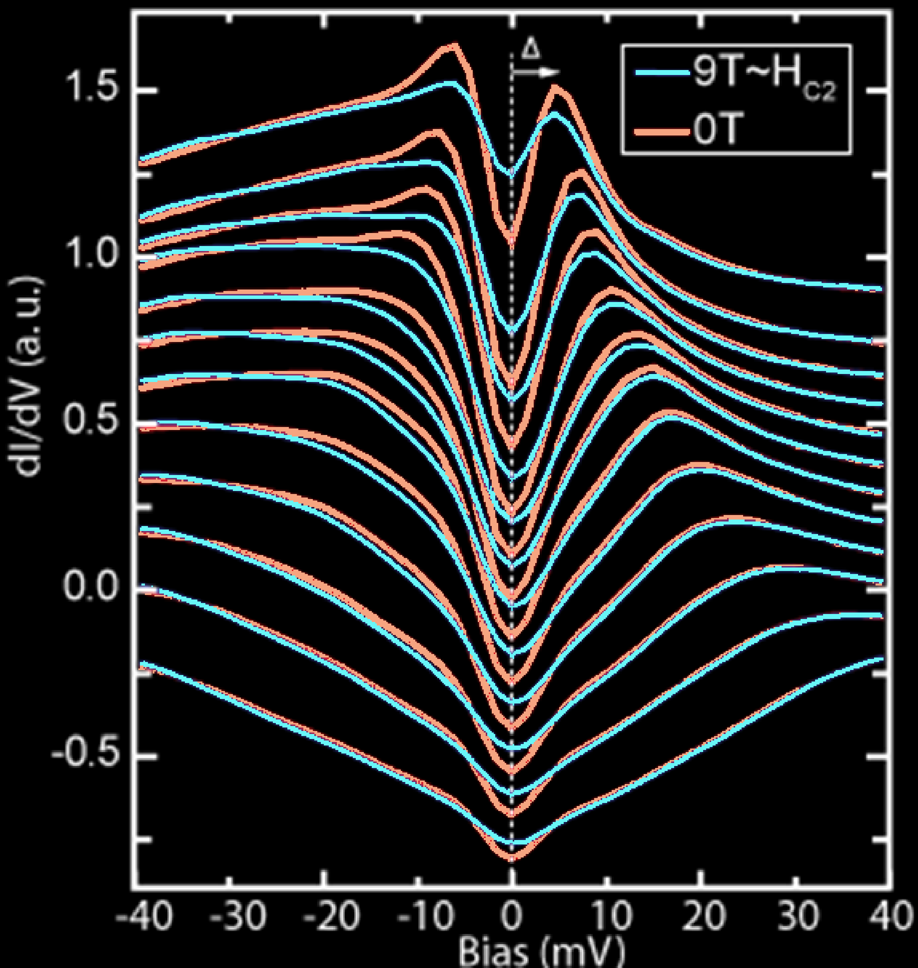


Δ_{PG}

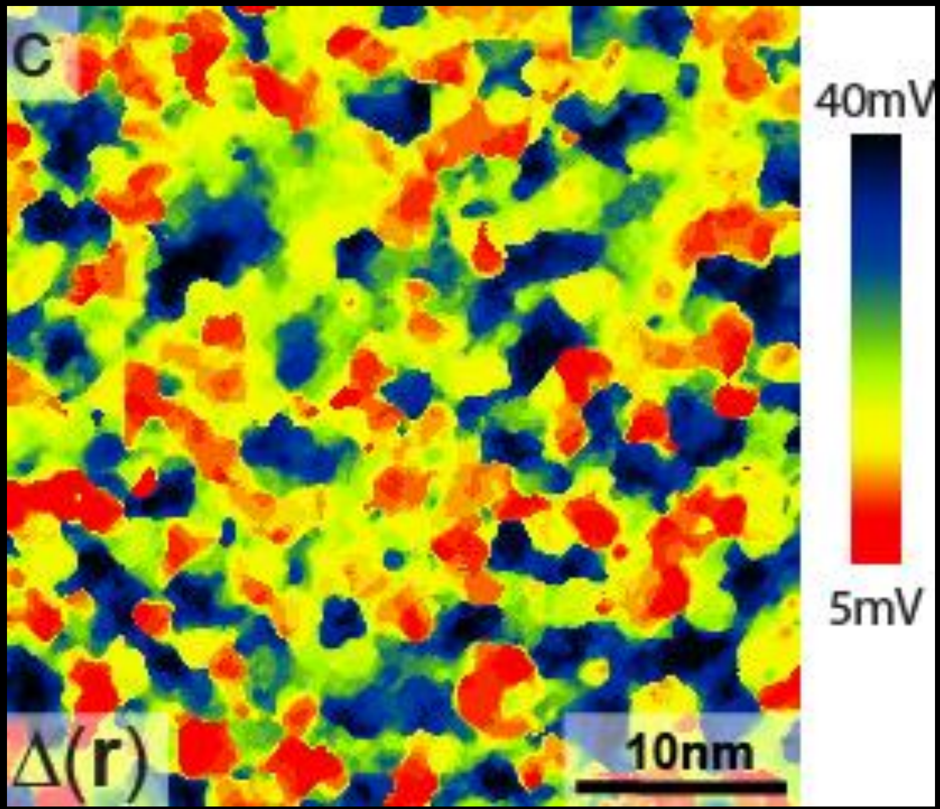


Two gap scenario: coexist spatially?

OD15K

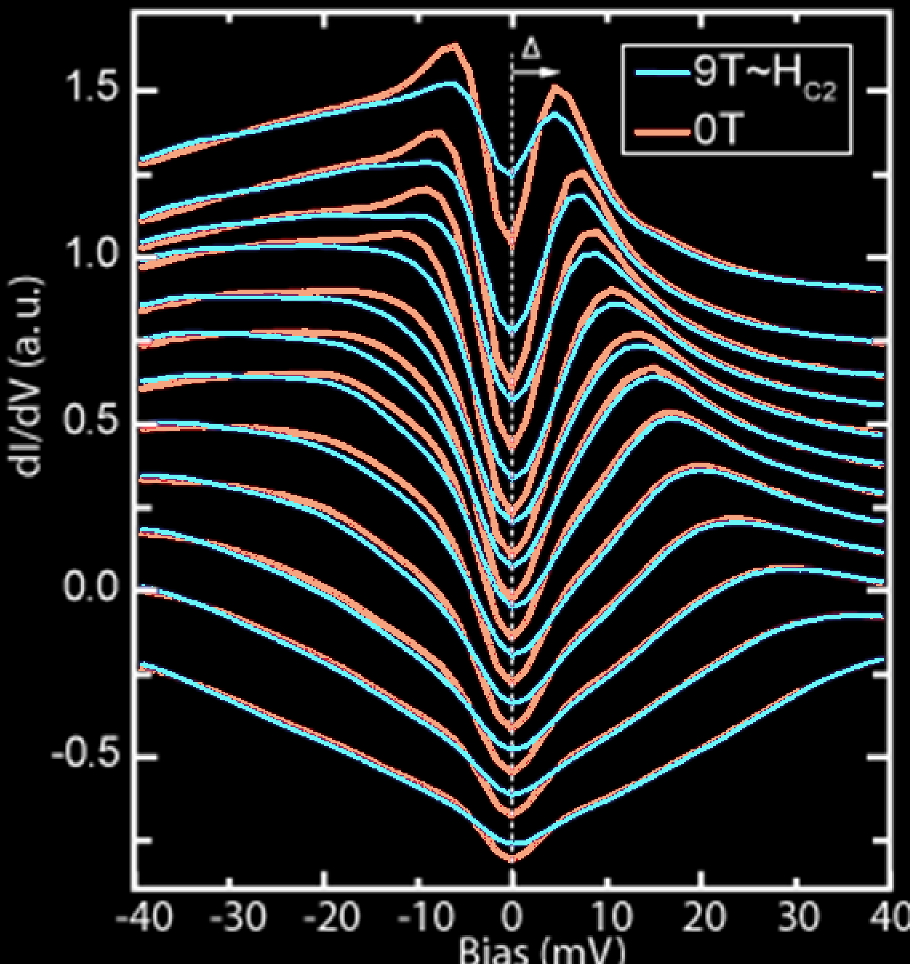


Δ_{PG}



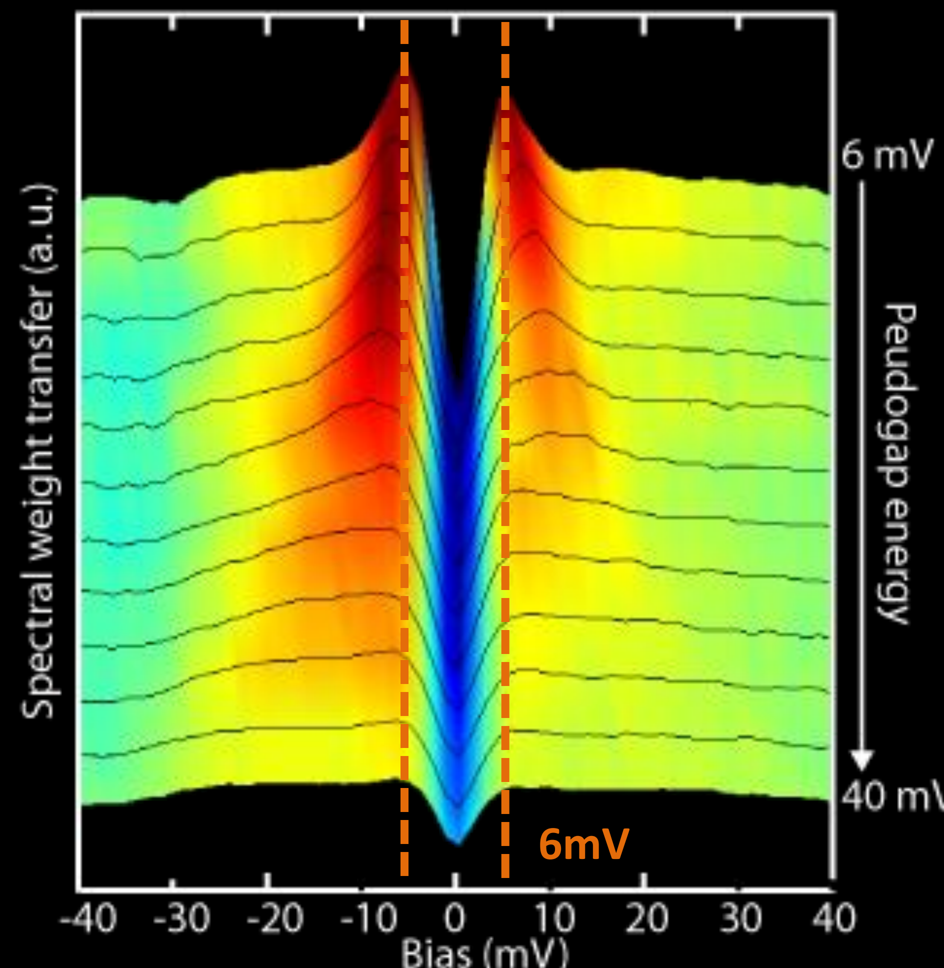
Two gap scenario: coexist spatially?

OD15K



Field-induced spectral weight transfer:

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

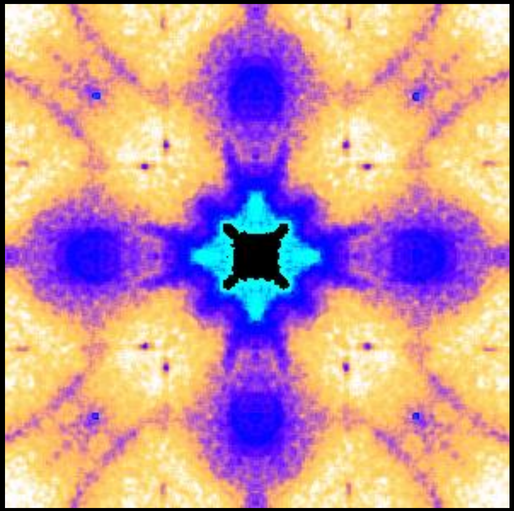


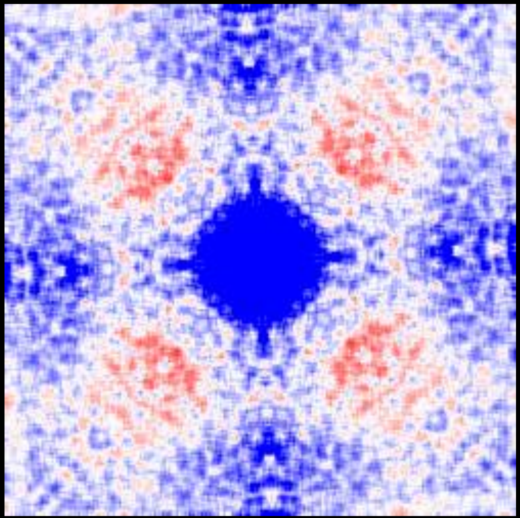
1. PG suppresses SC coherence.
2. PG does not affect SC order parameter amplitude.

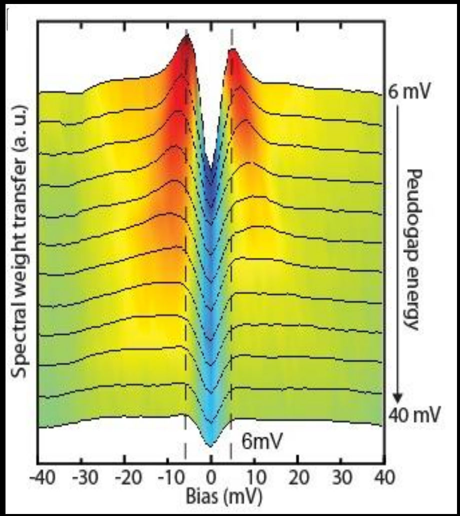
Conclusions

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



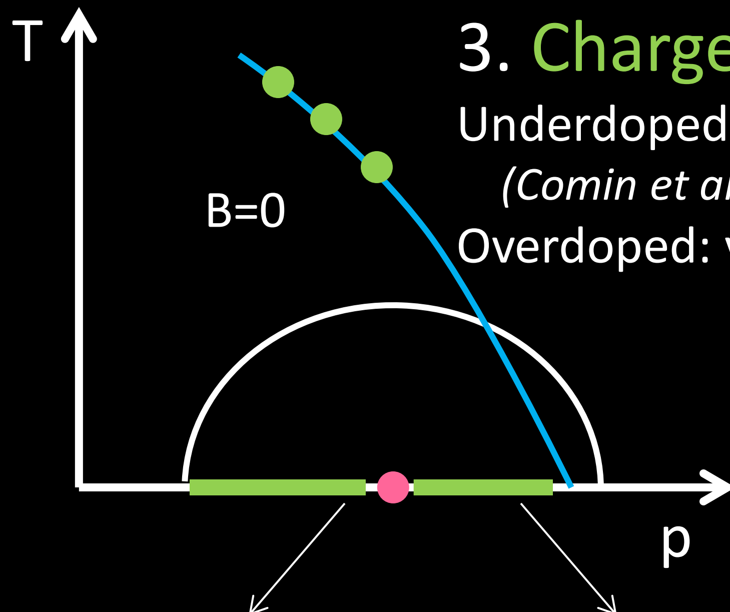




arxiv:1305.2778, to appear in ***Science***, May 9 (2014)

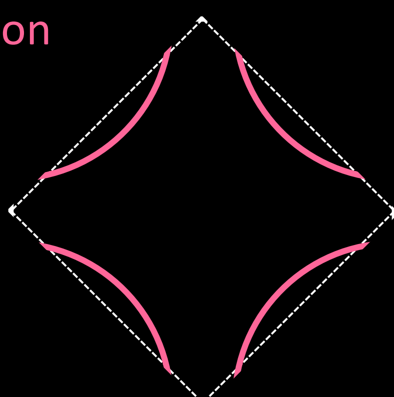
Conclusions (STM on Bi2201)

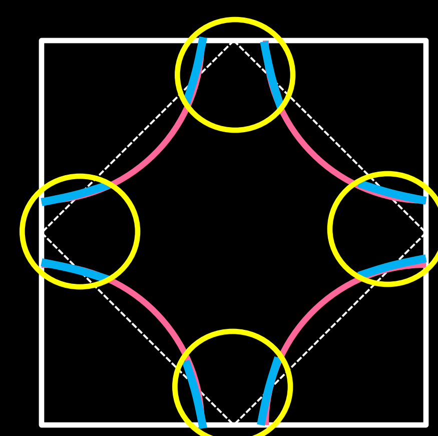
1. Fermi surface reconstruction ≠ pseudogap



3. Charge order

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

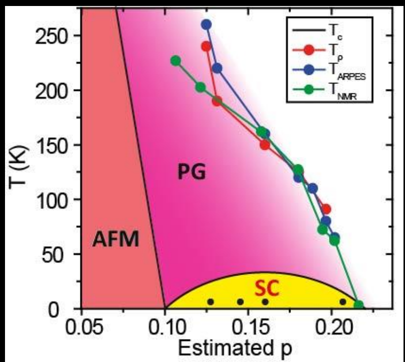




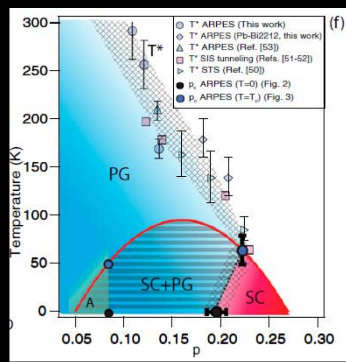
2. Superconductivity coexists with pseudogap at the antinode

Forest of Phase Diagrams

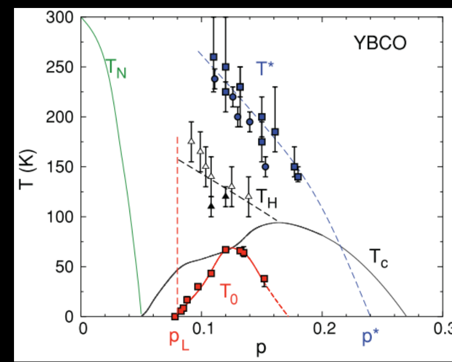
Bi2201	Bi2212	YBCO	Eu-LSCO



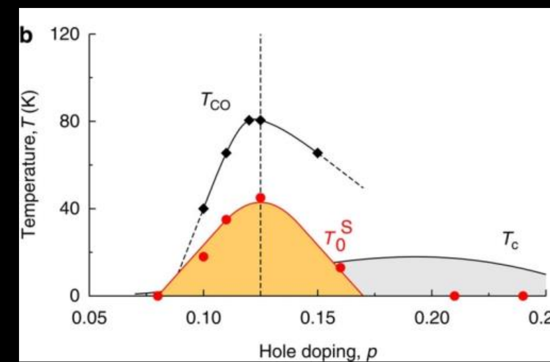
This talk



Vishik, PNAS 2012



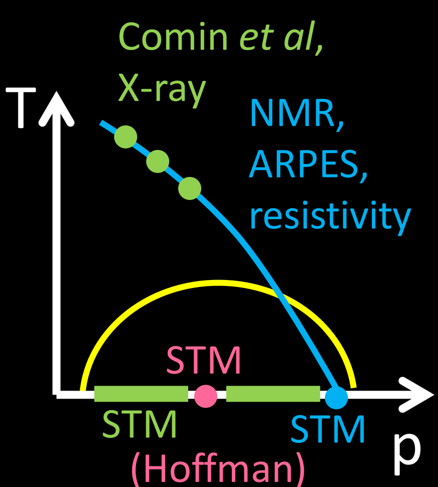
LeBouef, PRB 2011

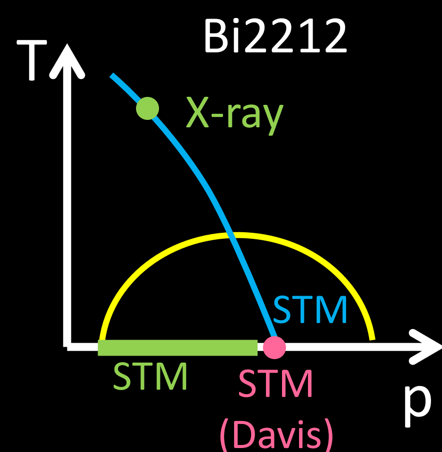


Laliberte, Nature Comm 2012

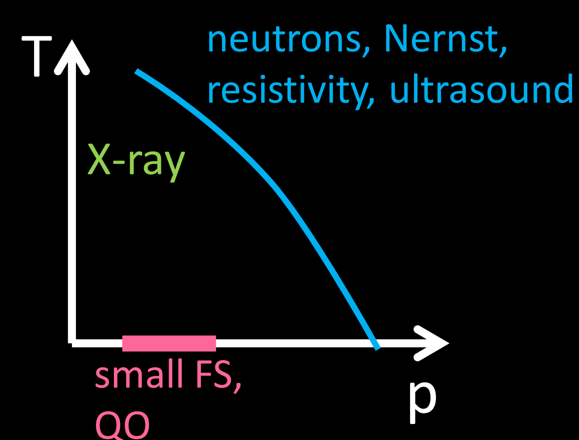
- Pseudogap
- Charge order
- FS reconstruction
- Superconductivity

Bi2201





YBCO & LSCO



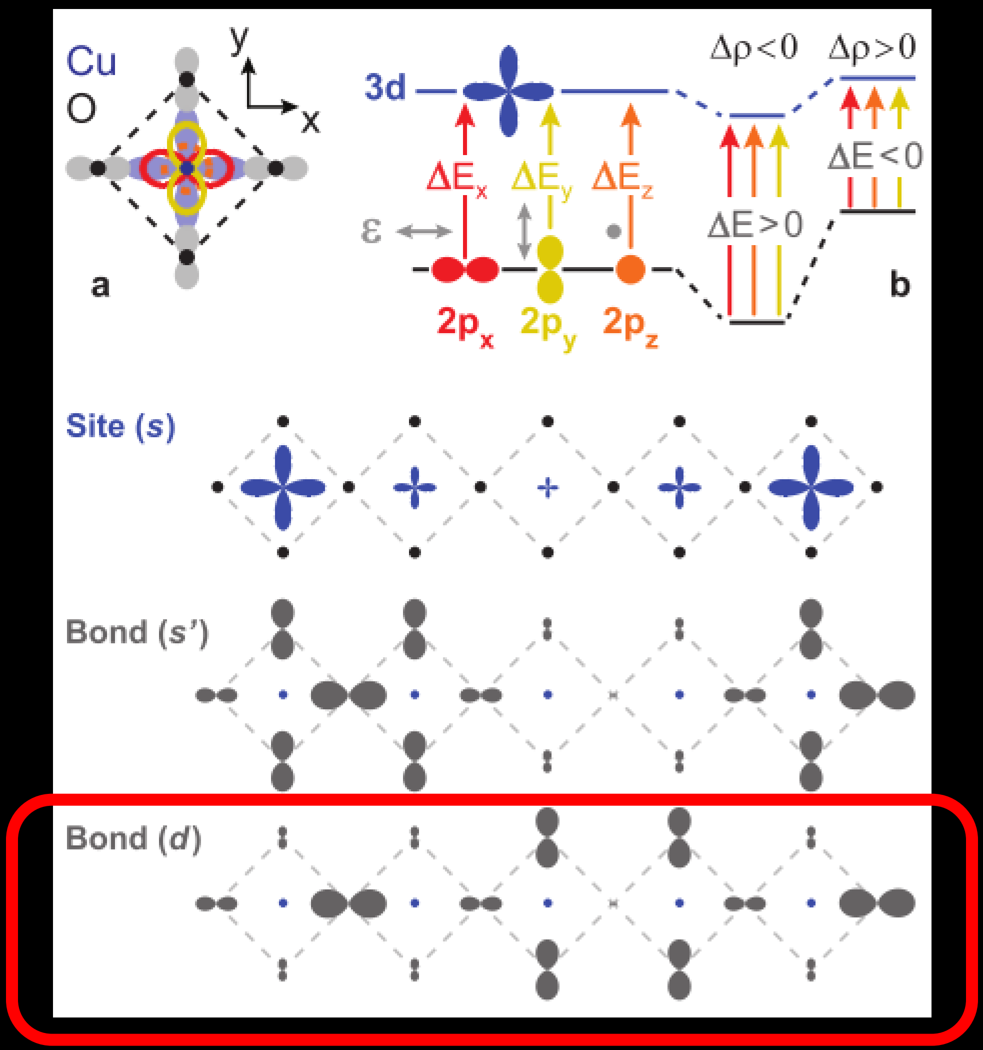
Why does Bi2212 have no fluctuating CDW regime?

Is the T* line in cuprates something else entirely?

Charge Order Questions

1. What is the doping, T, and B dependence of charge order?
   strongest near p=1/8, and in applied B
2. Is the charge order = pseudogap, or within PG?
   appears to be within the PG
3. Are we within the CDW phase or just disorder-pinned fluctuations?
   YBCO can be long-range-ordered; BSCCO is pinned fluctuations?
4. Does charge order compete with superconductivity?
   yes! (vortex cores, dip in dome, etc.)
5. What is the wavevector of charge order – where is it living on FS?
   varies continuously w/ doping; connects AFBZ hotspots
6. What is the energy dependence of charge order?
   hard to say… maybe strongest at +E, maybe strongest at Δ_{PG}
7. Is charge order responsible for small FS?
   Bi2212: claim is yes; Bi2201: CDW constant while FS evolves
8. Is it 1D or 2D? Does it have some internal form factor?
   local 1D patches? d-wave form factor

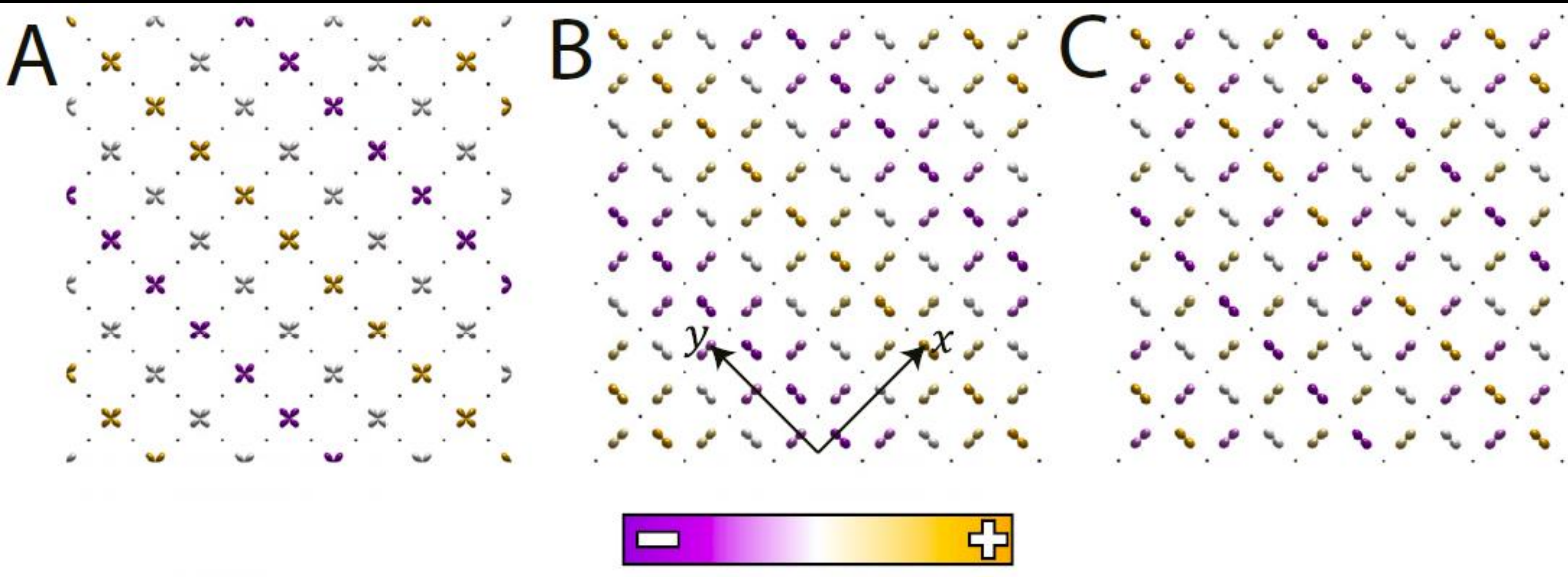
d-wave form factor of CDW



Comin, arxiv:1402.5415

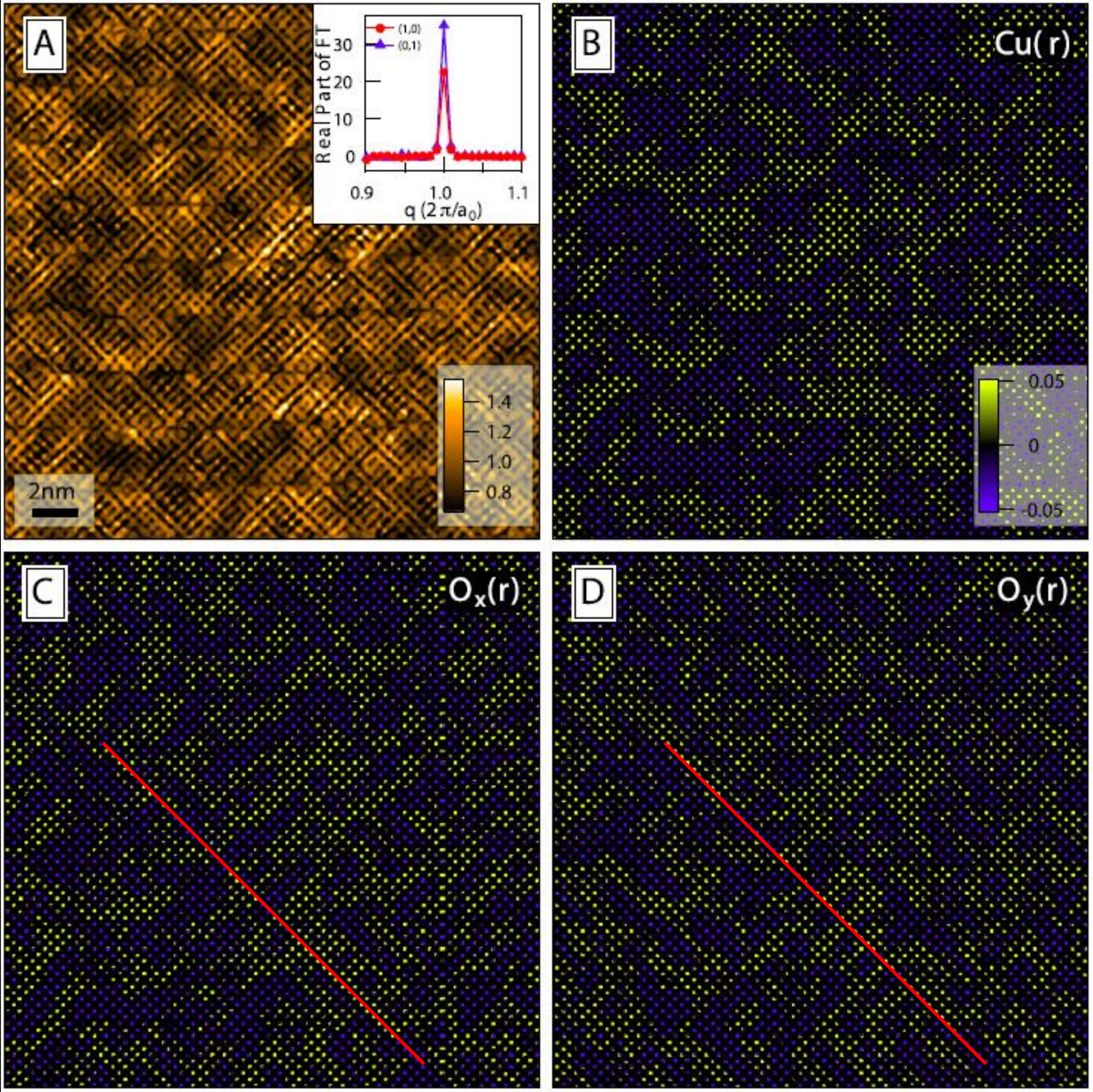
d-wave form factor of CDW

3 possibilities (consider 1D case for simplicity)



Fujita, PNAS (June 2014)

d-wave form factor of CDW



Fujita, PNAS (June 2014)

Superconductivity Tunneling Milestones

1960: gap measurement (Pb)

1965: boson energies & coupling (Pb)

1985: charge density wave ($TaSe_2$)

1989: vortex lattice ($NbSe_2$)

1997: single atom impurities (Nb)

2002: quasiparticle interference

→ band structure & gap symmetry (BSCCO)

2009: phase-sensitive gap measurement (Na-CCOC)

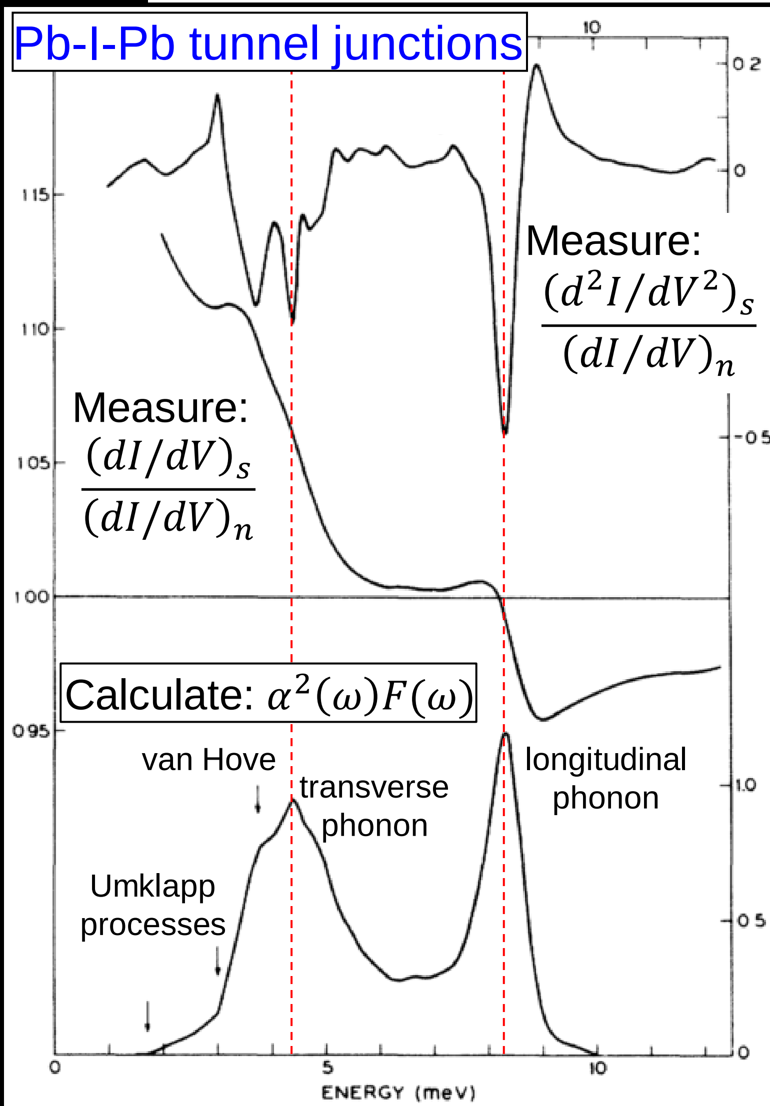
2010: intra-unit-cell structure (BSCCO)

1965: tunneling measurements of phonons

VOLUME 14, NUMBER 4 PHYSICAL REVIEW LETTERS 25 JANUARY 1965

LEAD PHONON SPECTRUM CALCULATED FROM SUPERCONDUCTING DENSITY OF STATES

W. L. McMillan and J. M. Rowell
Bell Telephone Laboratories, Murray Hill, New Jersey



$F(\omega)$ = phonon density of states

$\alpha^2(\omega)$ = coupling

How to compute $\alpha^2(\omega)F(\omega)$

1. Measure $N_s(\omega)$
2. Guess a functional form for $\alpha^2(\omega)F(\omega)$ (recalling that they are both integrals over a full BZ)

$$F(\omega) = \sum_\lambda \int \frac{d^3q}{(2\pi)^3}\delta(\omega-\omega_{q\lambda})$$

$$\alpha^2(\omega)F(\omega) = \int_S d^2p \int_{S'} \frac{d^3p}{2\pi^2 v_F{}'}\sum_\lambda g_{pp'\lambda} \times \delta(\omega-\omega_{p-p'\lambda}) \Big/ \int_S d^2p,$$

where $g_{pp'\lambda}{}'$ is the dressed electron-phonon coupling constant, $\omega_{q\lambda}$ is the phonon energy for polarization λ and wave number q (reduced to the first zone), and v_F is the Fermi velocity. The two surface integrations are performed over the Fermi surface.

3. Plug in the guessed $\alpha^2(\omega)F(\omega)$ to compute $\Delta(\omega)$

$$\varphi(\omega) = \int_{\Delta_0}^{\omega_c} d\omega' \,\mathrm{Re}\left[\frac{\Delta'}{(\omega'^2-\Delta'^2)^{1/2}}\right] \times\left\{\int d\omega_q\, \alpha^2(\omega_q)F(\omega_q)[D_q(\omega'+\omega) + D_q(\omega'-\omega)] - U_c\right\},$$

where $D_q(\omega) = (\omega+\omega_q - i0^+)^{-1}$, $\Delta(\omega) = \varphi(\omega)/Z(\omega)$

4. Plug in the computed $\Delta(\omega)$ to compute $N_s(\omega)$ and compare back to measured $N_s(\omega)$

$$\frac{N_s(\omega)}{N(0)} = \mathrm{Re}\left\{\frac{|\omega|}{[\omega^2-\Delta^2(\omega)]^{1/2}}\right\}$$

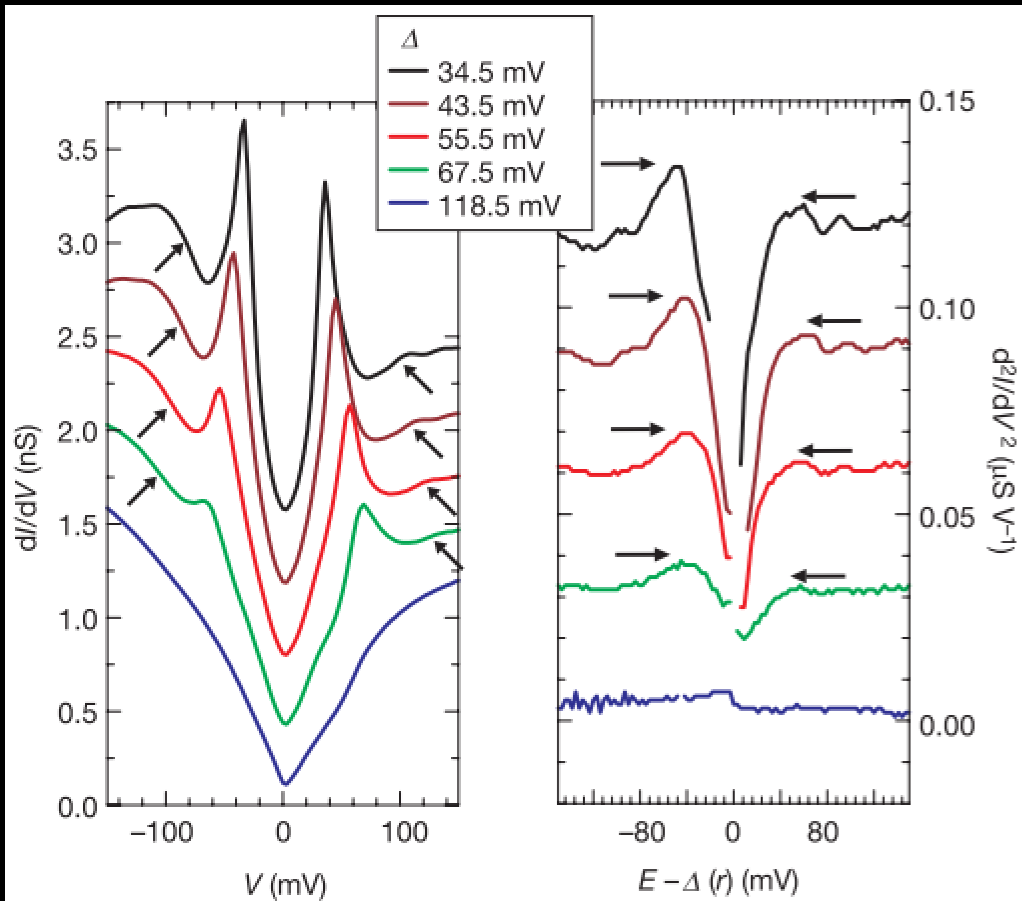
5. Compute the error and iterate

$$\delta[\alpha^2(\omega)] = \int d\omega' \left\{\frac{\delta N(\omega')}{\delta[\alpha^2(\omega)F(\omega)]}\right\}^{-1} \times [N_s^{\mathrm{expt}}(\omega') - N_s^{\mathrm{calc}}(\omega')]$$

McMillan & Rowell, PRL 14, 108 (1965)

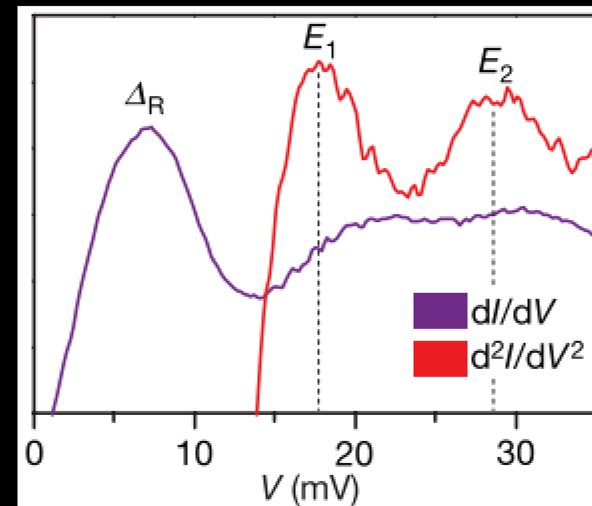
Electron-boson coupling in cuprates

$Bi_2Sr_2CaCu_2O_{8+d}$ (T_c^{max} = 91K)



Lee, Nature 442, 546 (2006)

$Pr_{0.88}LaCe_{0.12}CuO_4$ (T_c=24K)

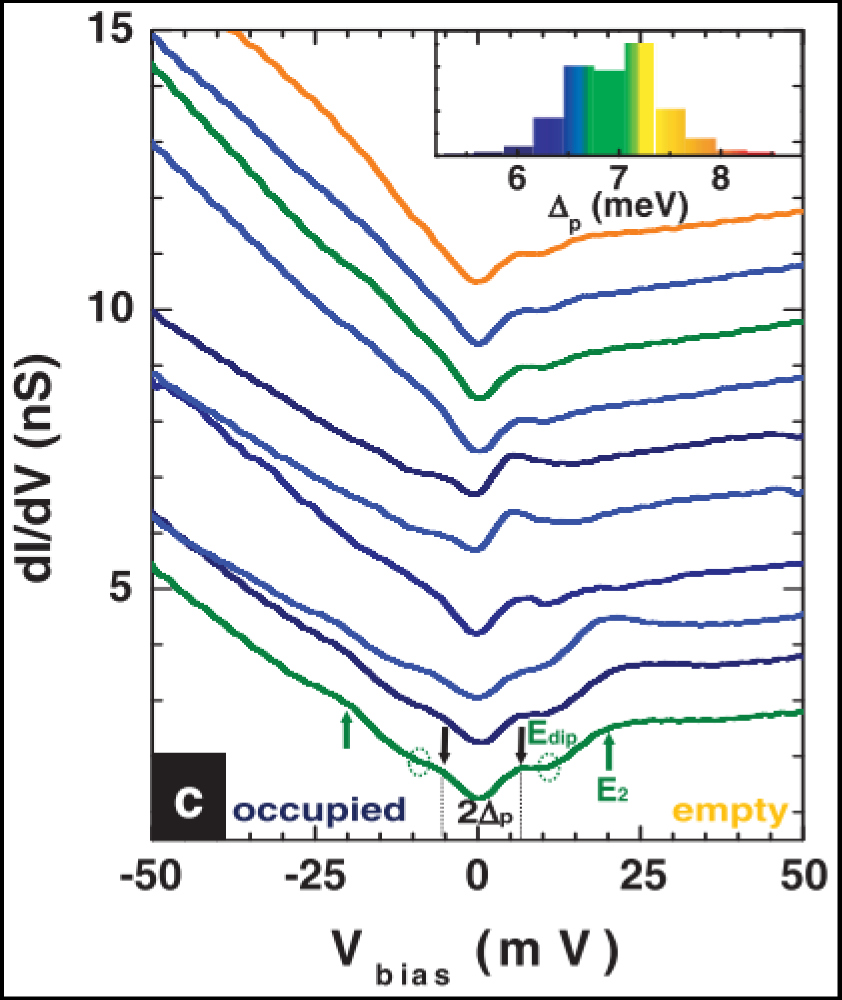


Niestemski, Nature 450, 1058 (2007)

$$\Omega = E \text{ (peak in } d^2I/dV^2) - \Delta$$

1111 Fe-superconductors

$SmFeAsO_{0.8}F_{0.2}$ (T_c=45K)

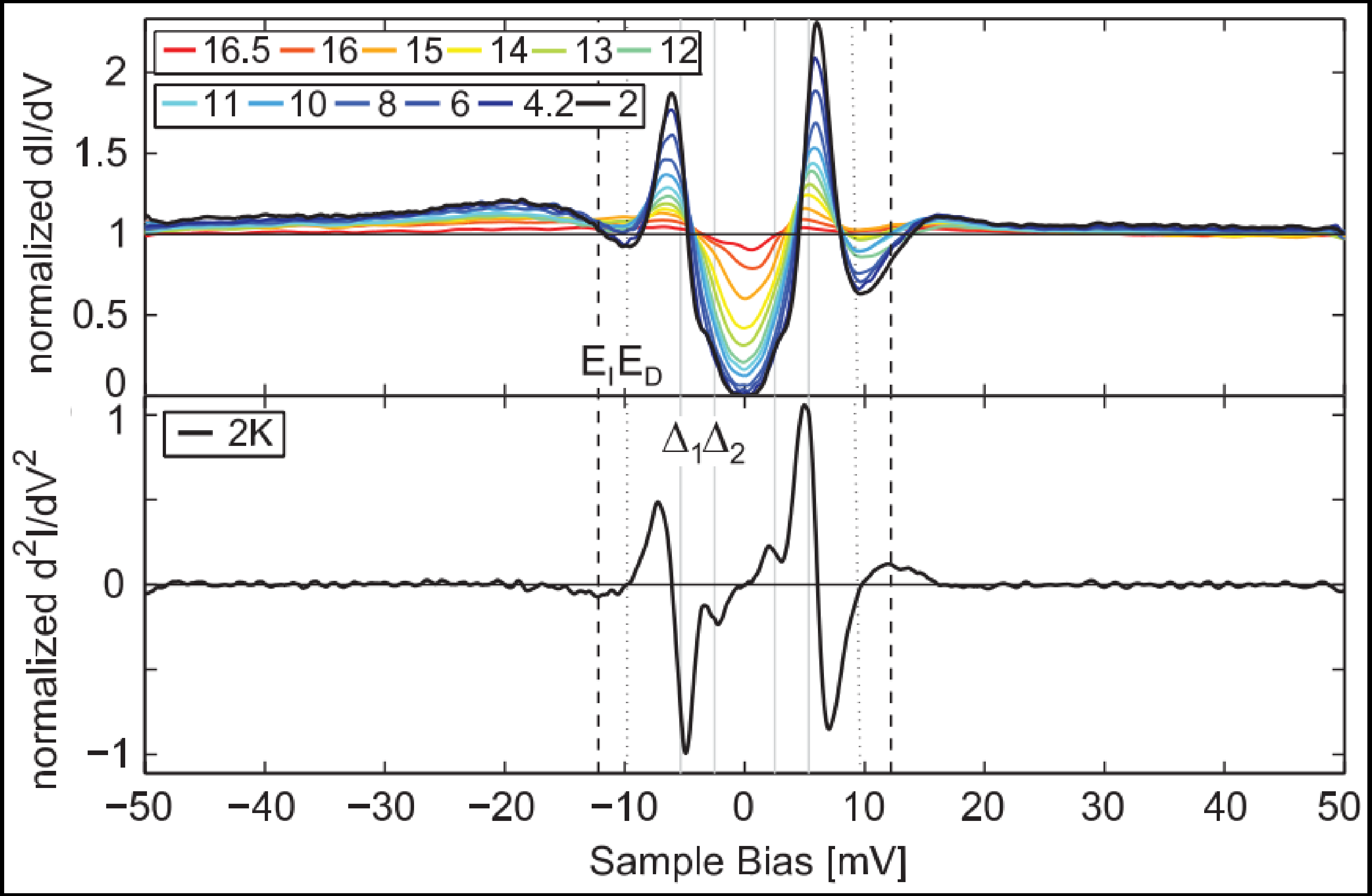


Fasano, PRL 105, 167005 (2010)

$$\Omega = E \text{ (dip in } dI/dV) - \Delta$$

111 Fe-superconductors

LiFeAs (T_c=17K)



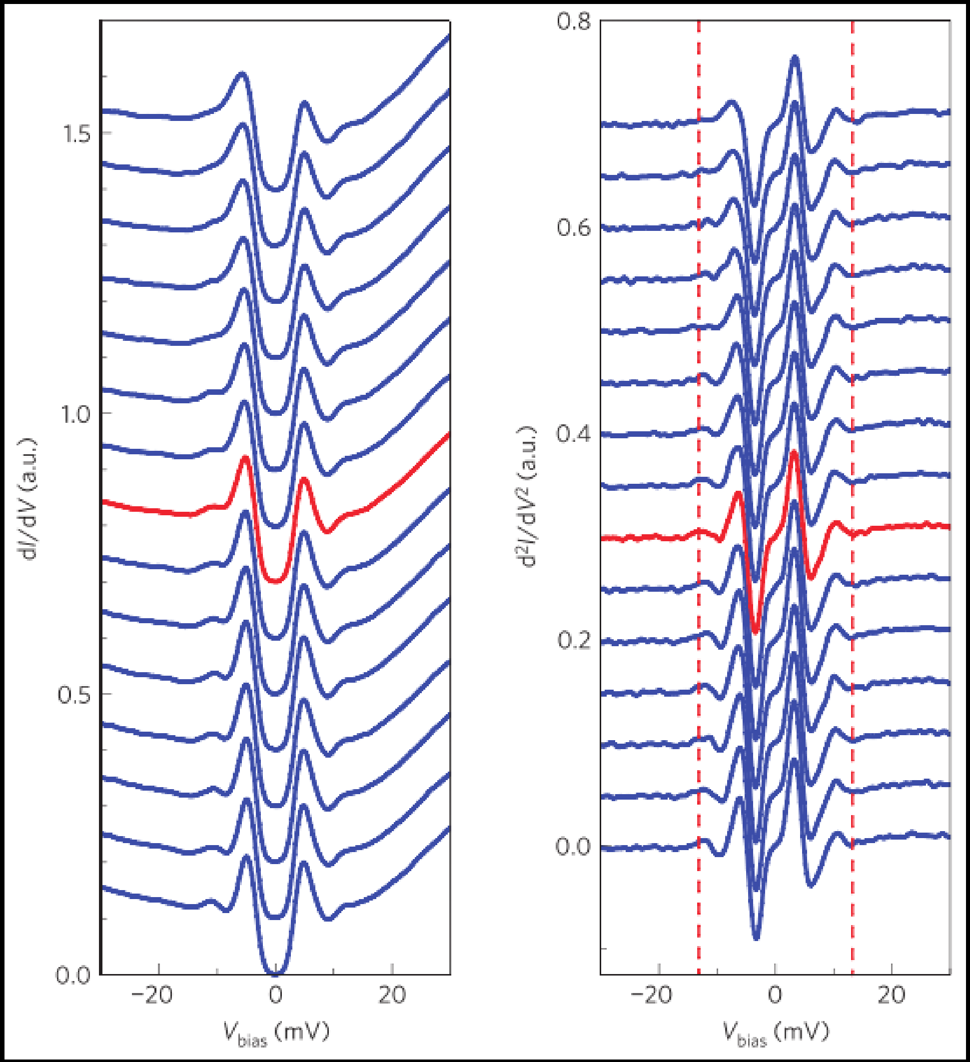
Chi, PRL 109, 087002 (2011)

$$\Omega = E \text{ (dip in } dI/dV) - \Delta$$

111 Fe-superconductors

$Na(Fe_{0.975}Co_{0.025})As$ (T_c=21 K)

E (hump in dI/dV) = 13.3 ± 0.8



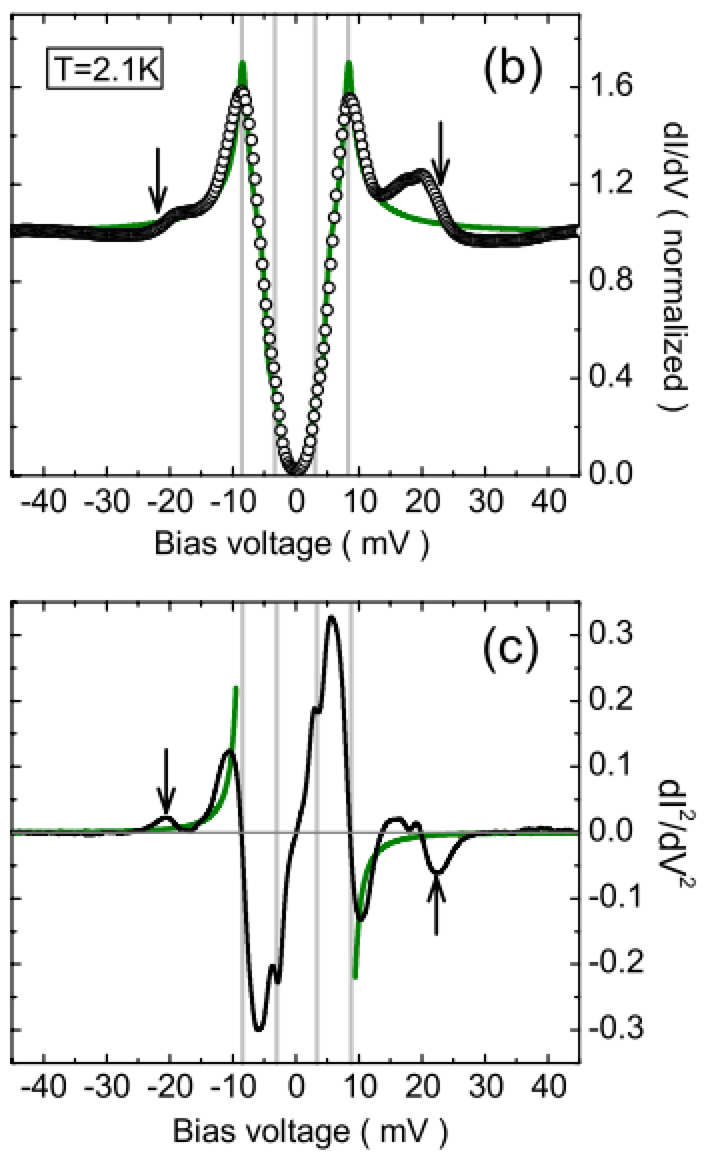
E (dip in d^2I/dV^2)
= 13.3 ± 0.8 (main text)
= 13.5 (figure caption)

Shan, Nat Phys 9, 42 (2012)

$\Omega = E$ (dip in d^2I/dV^2) $-\Delta$ **???**

122 Fe-superconductors

$Ba_{0.6}K_{0.4}Fe_2As_2$ (T_c=38K)



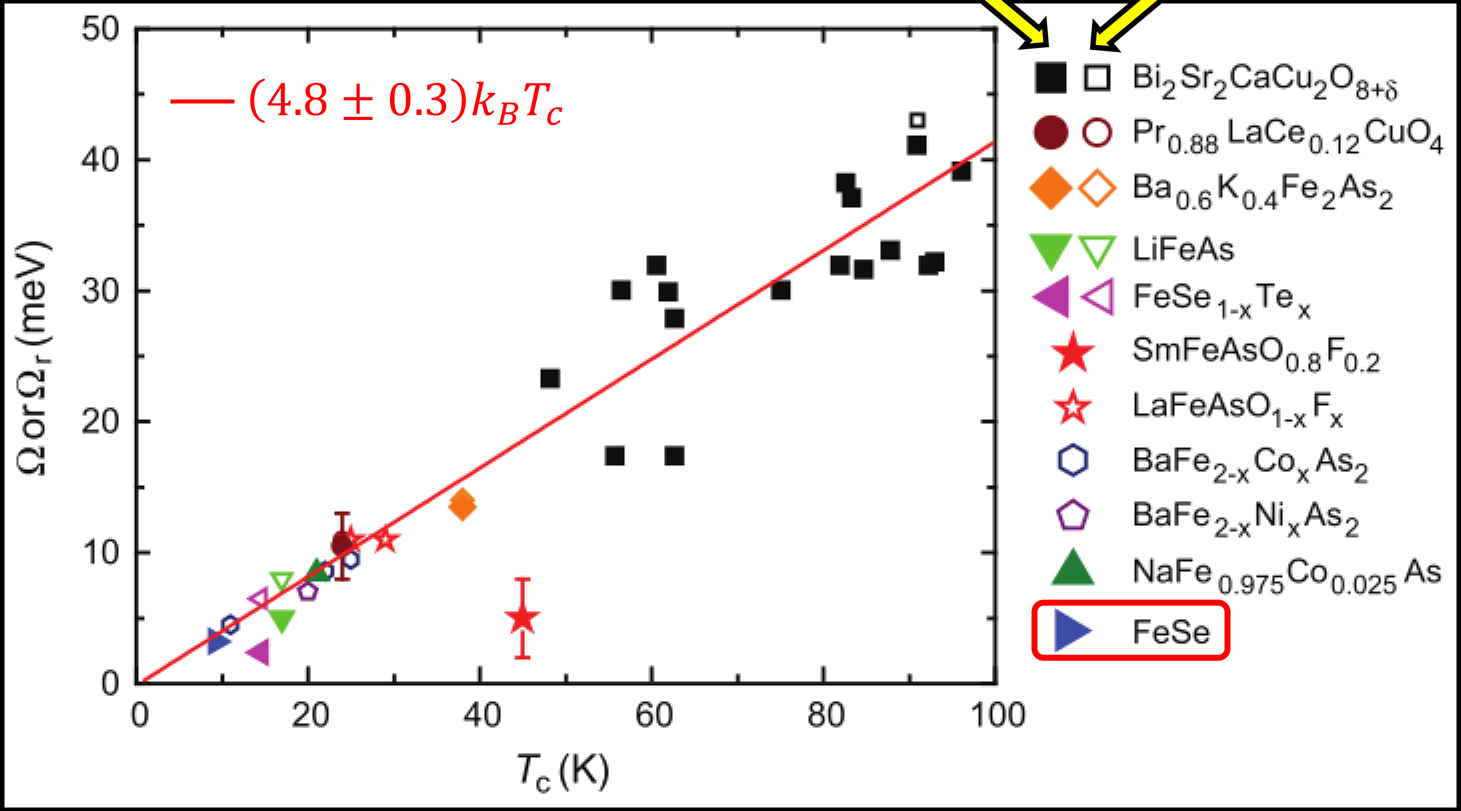
Shan, PRL 108, 227002 (2012)

$$\Omega = E\ (\text{dip in } d^2I/dV^2) - \Delta$$

Ω in cuprates and Fe-superconductors

solid symbols = Ω
(from STM)

open symbols = Ω_r
(from neutron scattering)

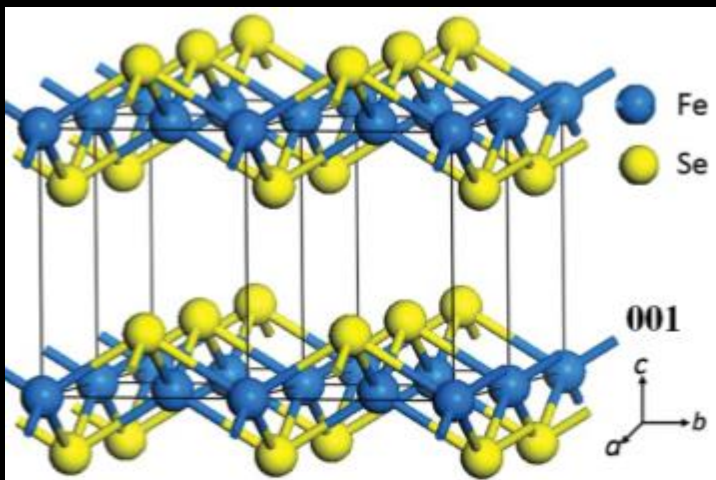


E (dip in dI/dV)
E (peak in d^2I/dV^2)
E (dip in d^2I/dV^2)
E (dip in dI/dV)
E (peak in d^2I/dV^2)
E (dip in dI/dV)
E (dip in d^2I/dV^2)
E (peak in d^2I/dV^2)

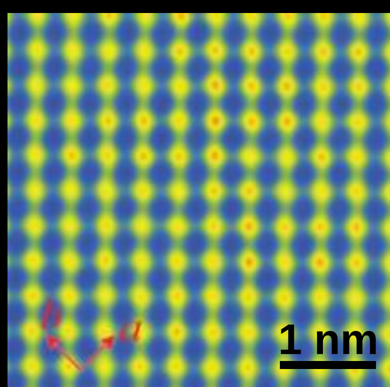
Song + Hoffman, Current Opinion in Solid State and Materials Science 17, 39 (2013)

Boson in 11 superconductor: FeSe

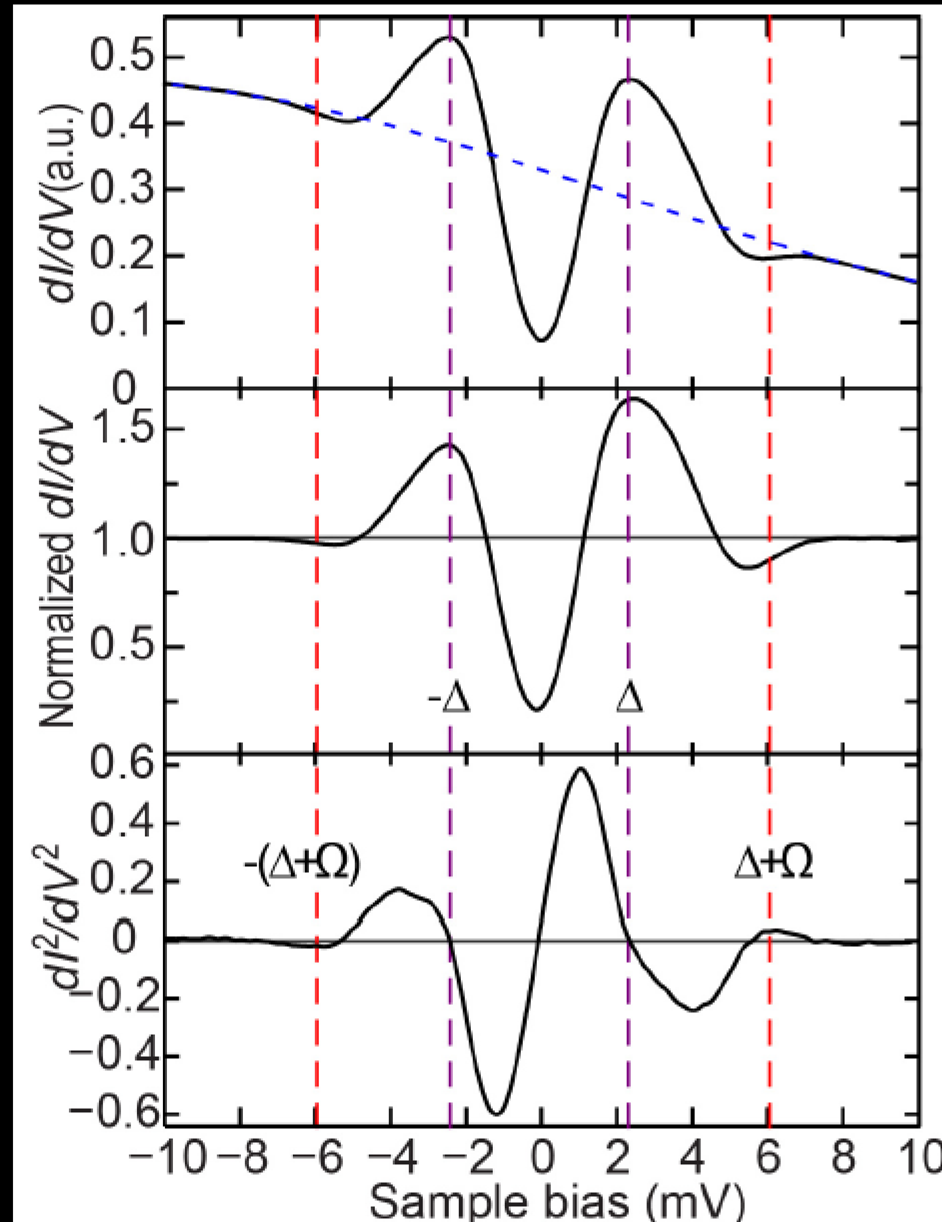
FeSe film on graphene (T_c~8K)



STM topography

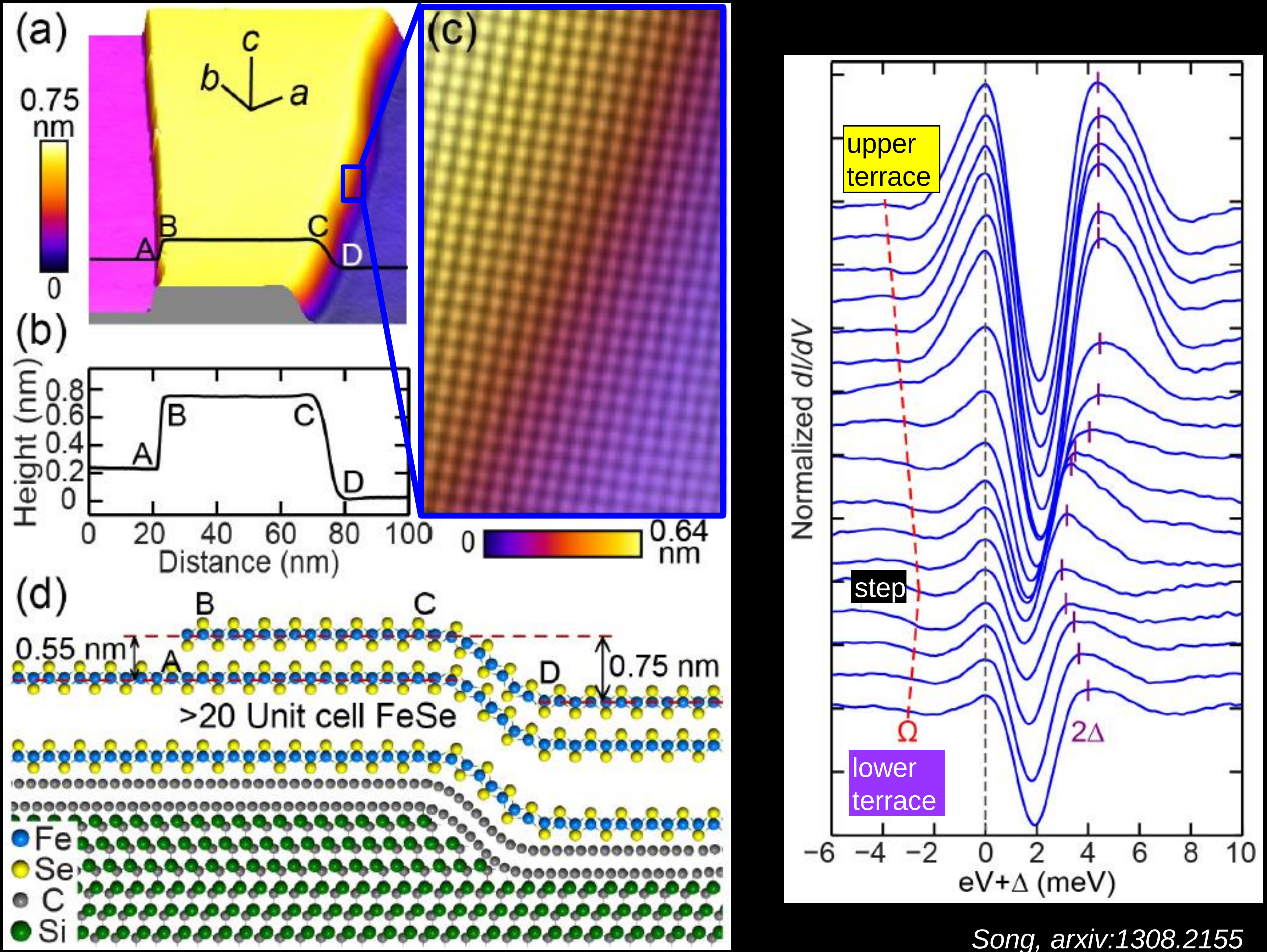


$\Omega = E$ (peak in d^2I/dV^2) $-\Delta$



Song, arxiv:1308.2155

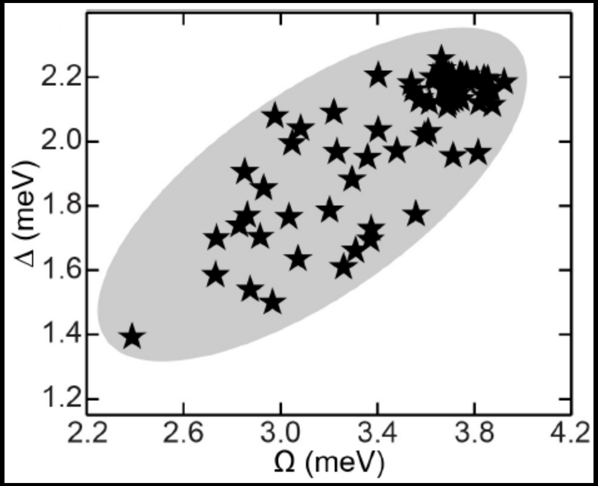
Tensile strain reduces Δ and Ω in FeSe



Song, arxiv:1308.2155

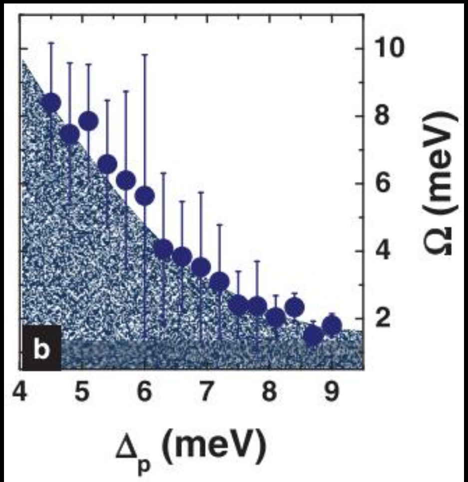
Fe-SCs: local relation between $\Delta(r)$ and $\Omega(r)$

FeSe (T_c=8K)



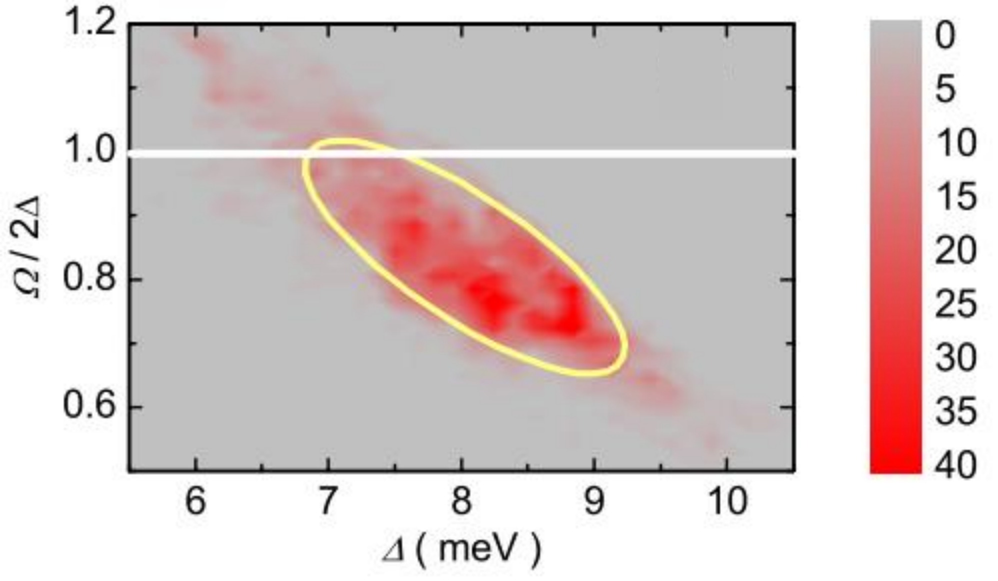
Song, arxiv:1308.2155

SmFeAsO$_{0.8}$F$_{0.2}$ (T_c=45K)



Fasano, PRL 105 167005 (2010)

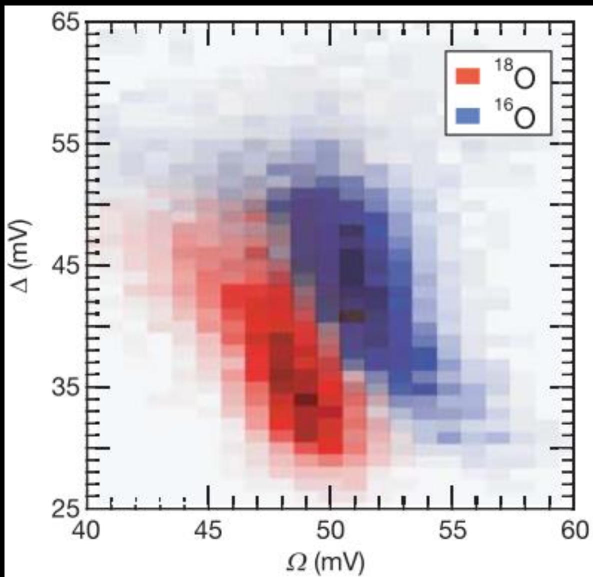
Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ (T_c=38K)



Shan, PRL 108, 227002 (2012)

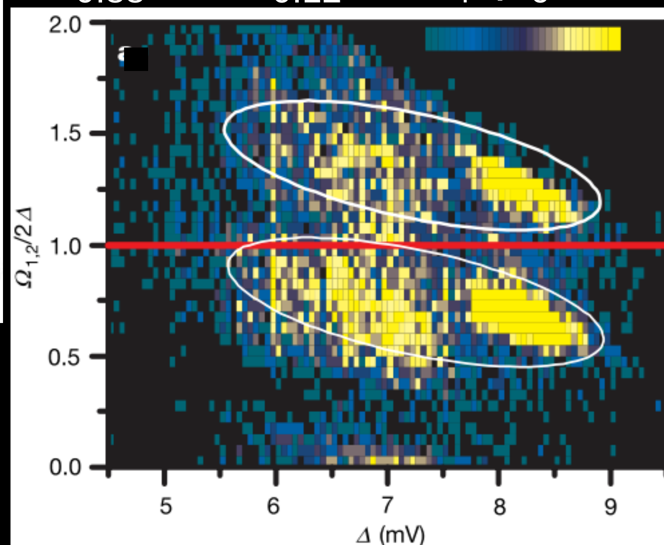
Cuprates: local relation between $\Delta(r)$ and $\Omega(r)$

Bi-2212 ($T_c^{\max} = 91\text{K}$)



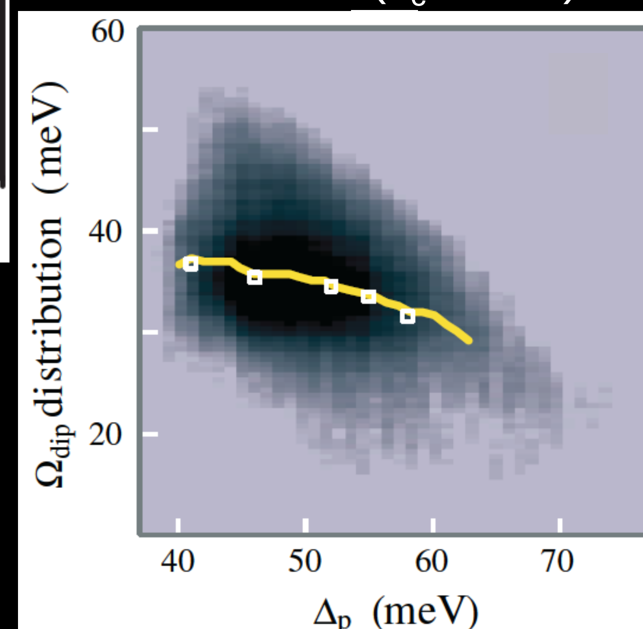
Lee, Nature 442, 546 (2006)

$Pr_{0.88}LaCe_{0.12}CuO_4$ (T_c=21K)



Niestemski, Nature 450, 1058 (2007)

Bi-2223 (T_c=110K)



Jenkins, PRL 103, 227001 (2009)

Local strong-coupling pairing

Solve the local Eliashberg equations with patch size ~2-5 nm:

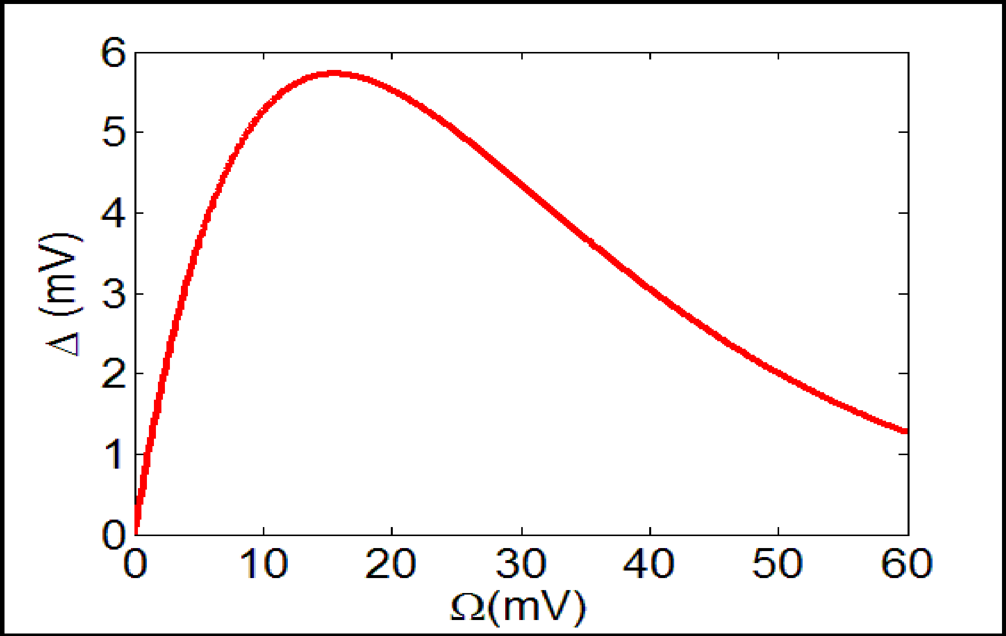
$$\Delta(r) = \Omega(r)\exp\left(\frac{-1}{N_0 g_{\mathrm{eff}}(r)}\right)$$

$g_{\mathrm{eff}}(r)$ = effective coupling constant

$$g_{\mathrm{eff}}(r) = \frac{2g(r)^2}{\Omega(r)}$$

$g(r)$ = local coupling constant

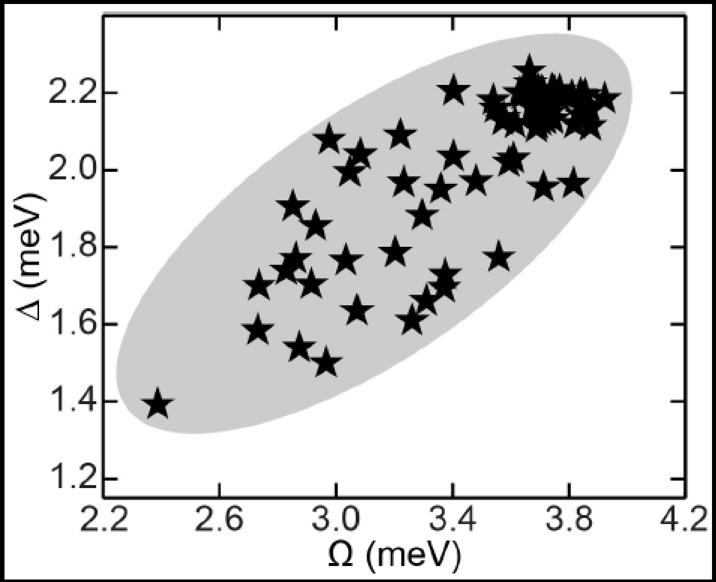
$$\Delta(r) = \Omega(r)\exp\left(\frac{-\Omega(r)}{2N_0 g(r)^2}\right)$$



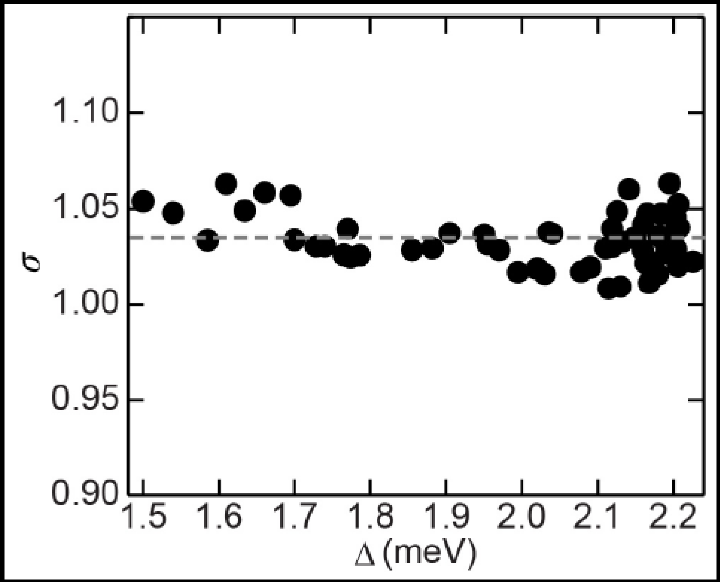
Balatsky + Zhu, PRB 74, 094517 (2006)

What about $g(r)$?

$\Omega(r)$:$\Delta(r)$ → correlation



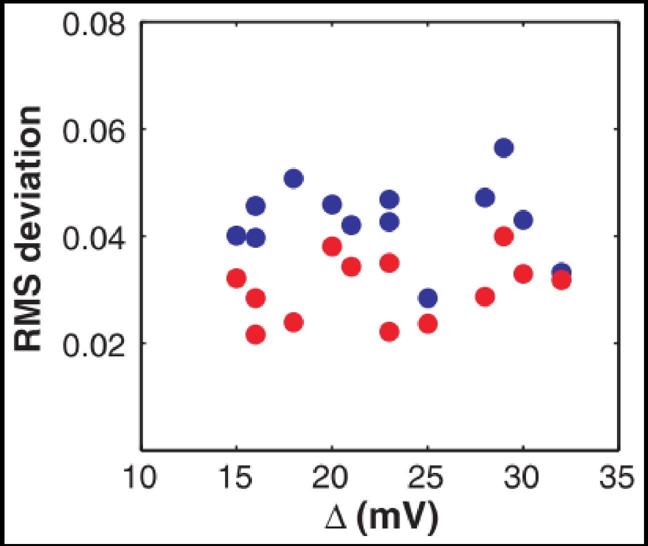
$g(r)$:$\Delta(r)$ → no correlation



Song, arxiv:1308.2155

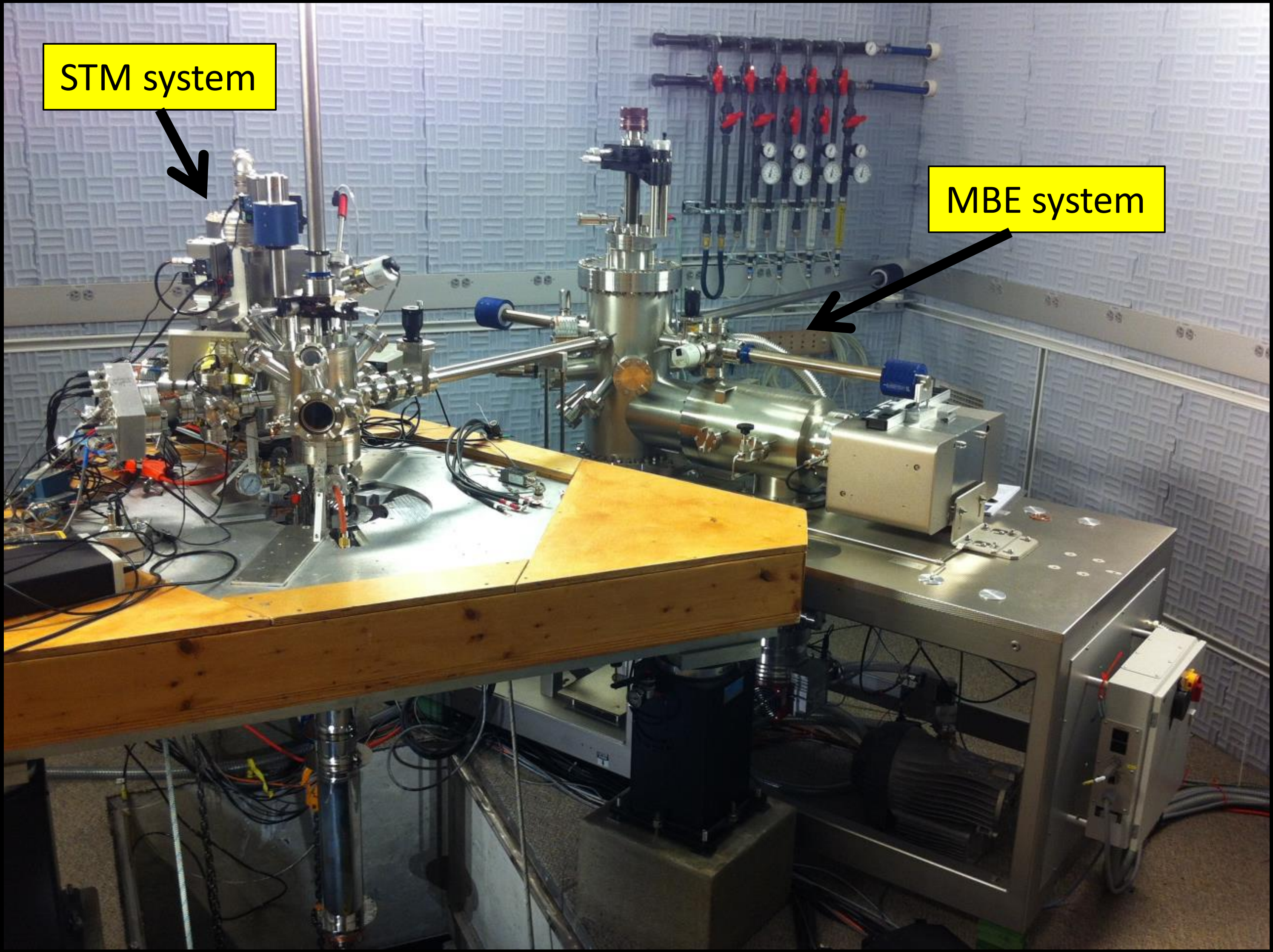
c.f. cuprates:

$g(r)$: $\Delta(r)$ → no correlation in $Bi_2Sr_2CaCu_2O_{8+d}$



Pasupathy, Science 320, 196 (2008)

What's next?



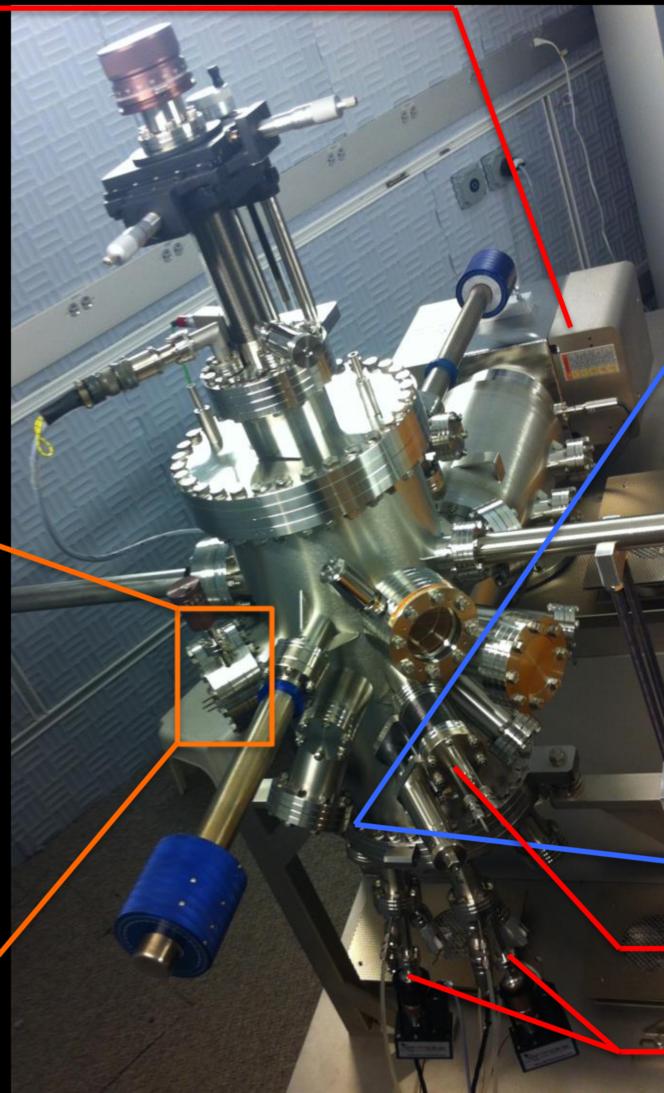
Molecular Beam Epitaxy

Ion getter pump and
titanium sublimation pump
Base pressure: 10^{-10} T

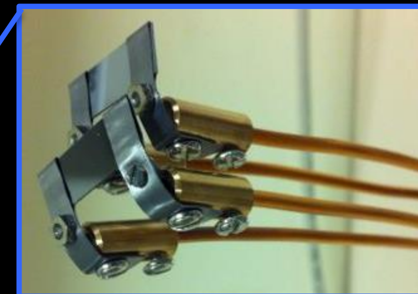
Custom heater stage with
Ta filament

Through viewport:

Homebuilt sample
holder storage



Homebuilt evaporation
source (Si)



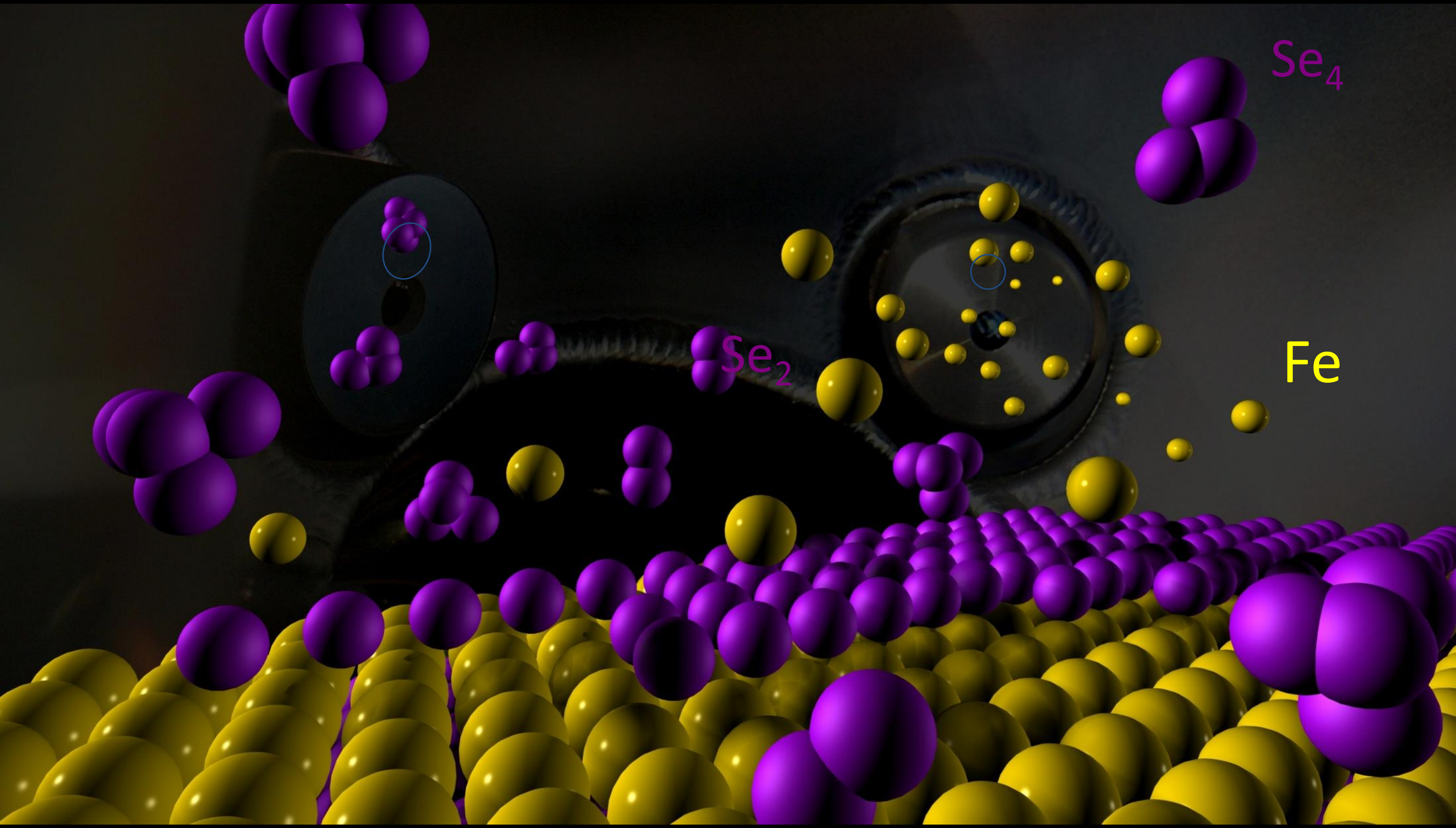
Hombuilt evaporation
source (Ta boats)

Quartz crystal monitor

Oxygen-resistant effusion
cells

Dennis Huang, Can-Li Song

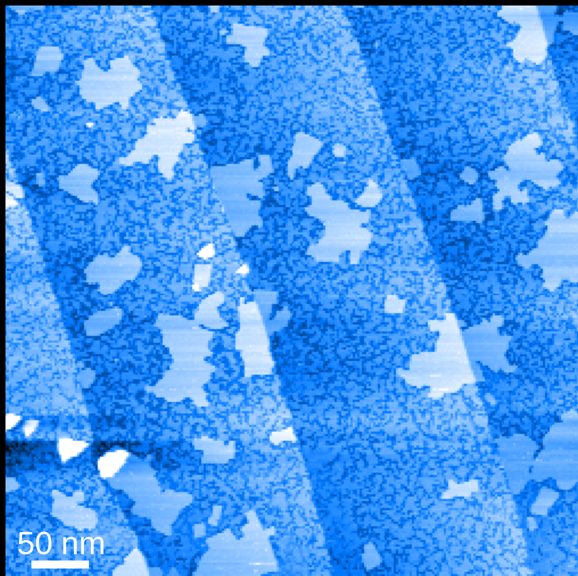
Film Growth



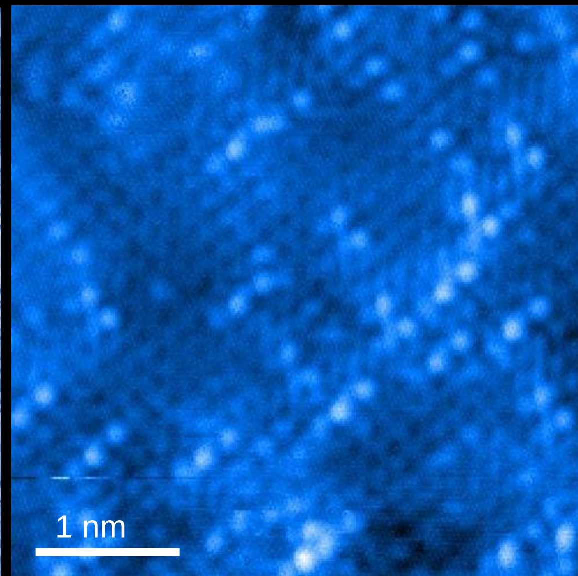
Can-Li Song

Film Growth

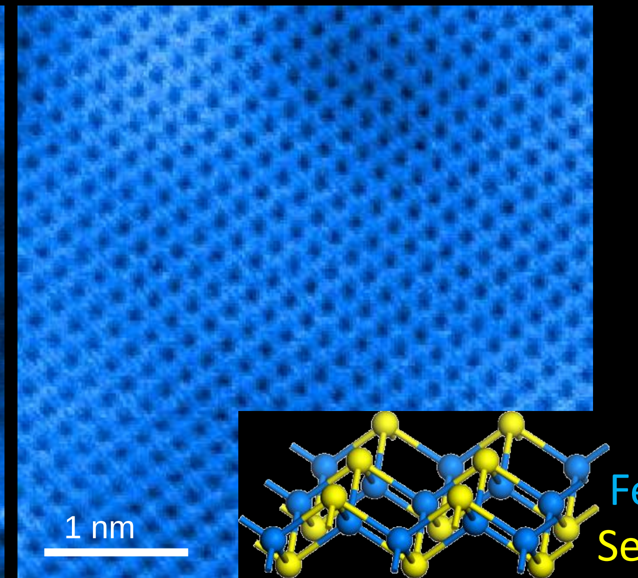
FeSe islands on SiC



as-grown: extra Se



after annealing: clean

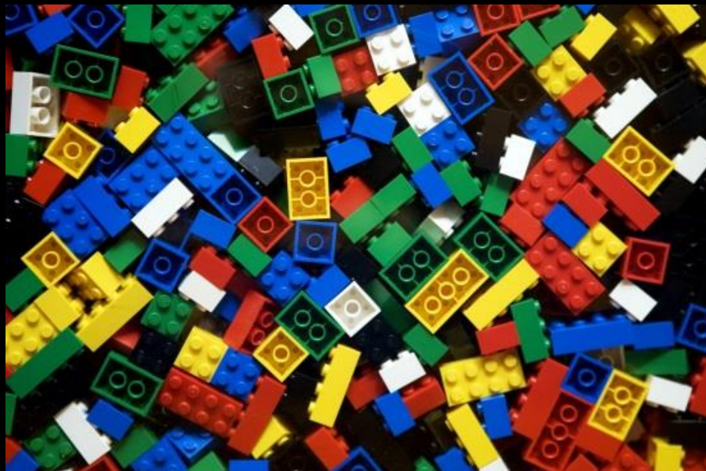


Systems of interest:

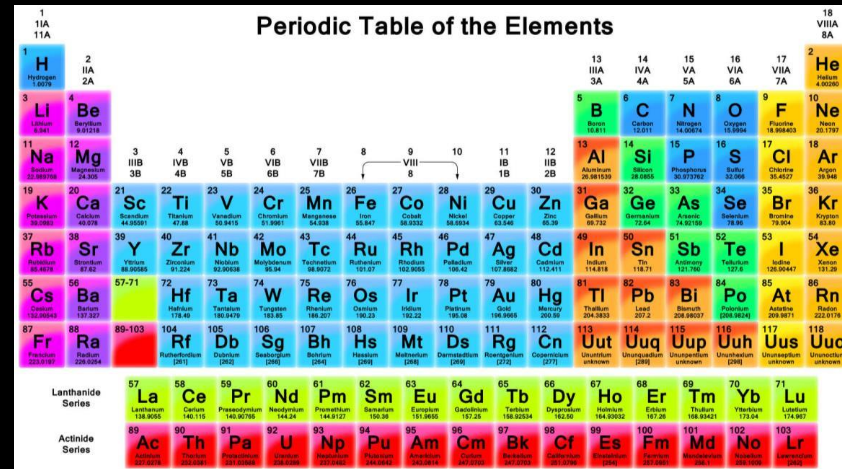
Bulk FeSe: T_c = 8 K → FeSe on $SrTiO_3$: T_c = 110K

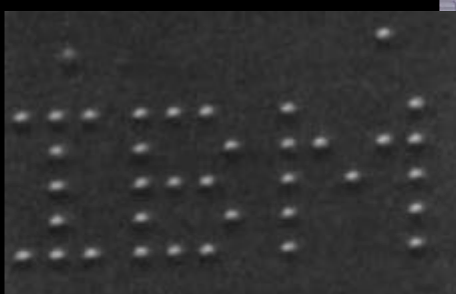
Superconductor on SmB_6
Sb on superconductor
} Majorana fermion?

Construction projects

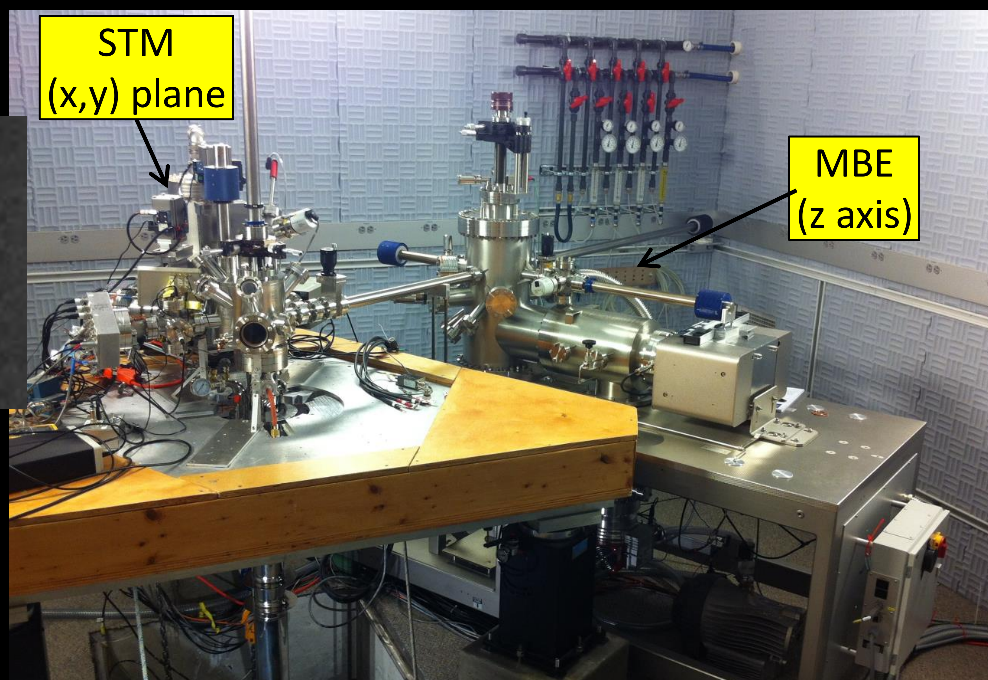


↔





Eigler & Schweizer, Nature 344, 524 (1990)



→ 3D printing with atoms

Moving to Vancouver, looking for postdocs

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email: jhoffman@physics.harvard.edu