The nodal-antinodal dichotomy and competing orders in high temperature superconductors

Dung-Hai Lee, Berkeley

STM

J. C. Davis (Cornell)
J.E. Hoffman (Harvard)
K. McElroy (Berkeley)

ARPES

Z.-X. Shen (Stanford)
X.-J. Zhou (LBNL)

ARPES

A. Lanzara (Berkeley)
G.H. Gweon (LBNL)

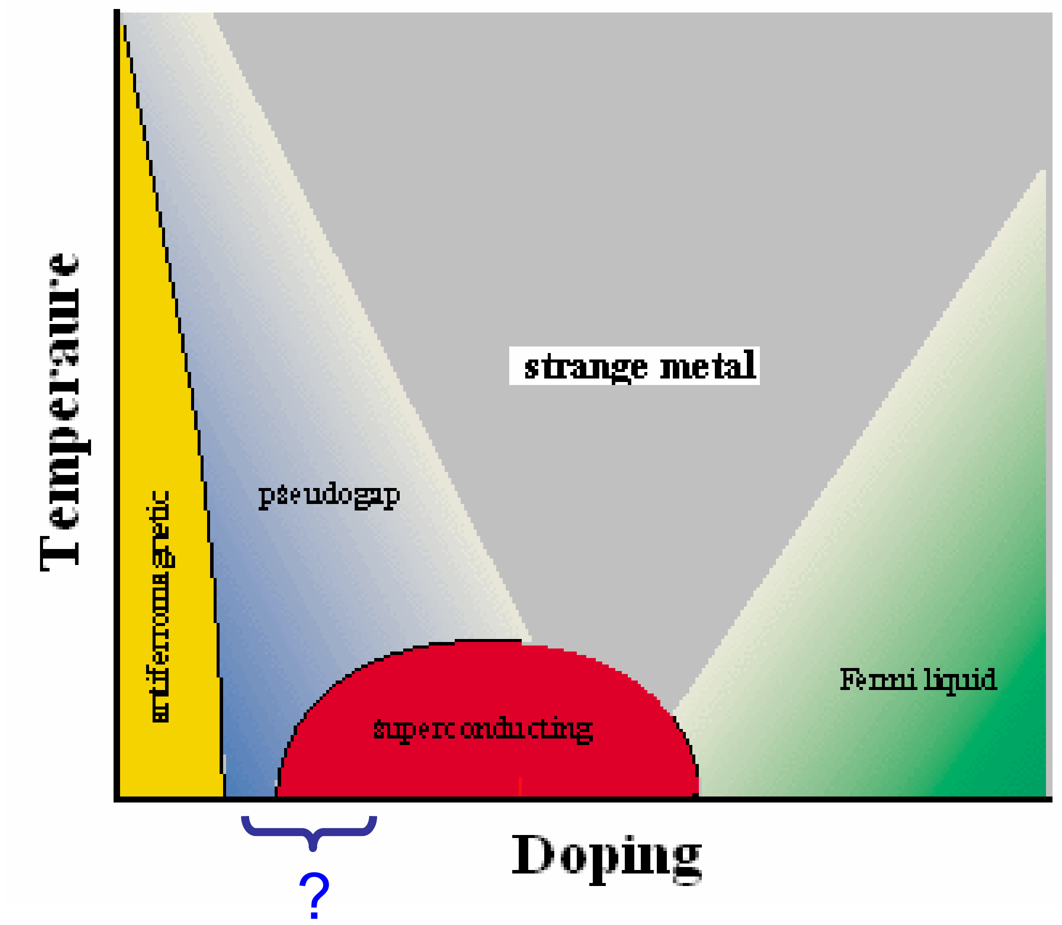
Theory

H. Fu (Berkeley)
C. Honerkamp (Max Plank)
Q.H. Wang (Nanjing Univ.)

Outline

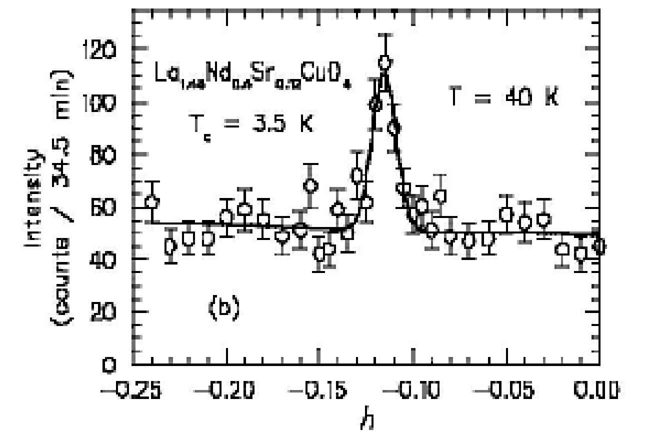
- Some background knowledge.
- The nodal-antinodal dichotomy in ARPES.
- Effect of disorder on nodal/antinodal excitations.
- The coupling of N/AN excitations to phonons.
- The coupling between N/AN excitations to charge order.
- Theoretical discussions
- Conclusion

Competing order



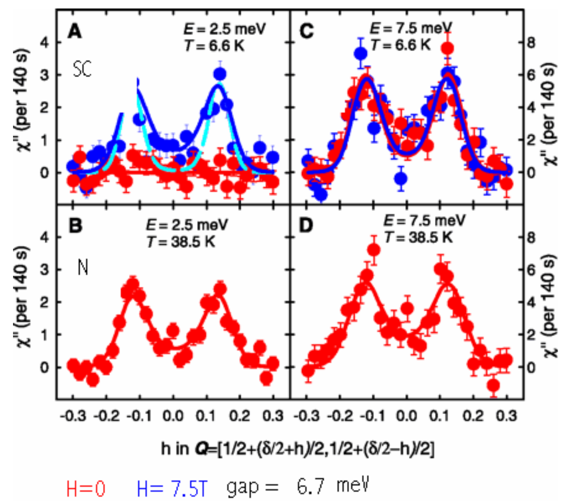
The incommensurate magnetism

Tranquada *et al*
Nature, (1995)



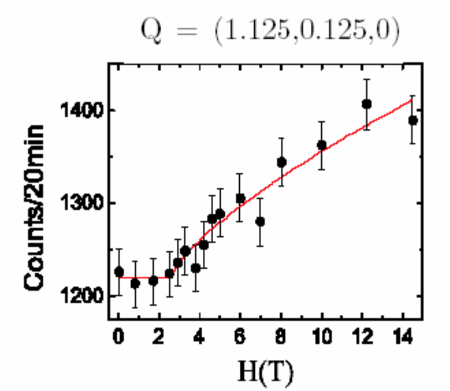
Lake et al, Science, (1999)

Enhanced SDW fluctuation in the vortex cores



Khaykovich et al, cond-mat/0411355

B-induced SC→ SC+SDW phase transition

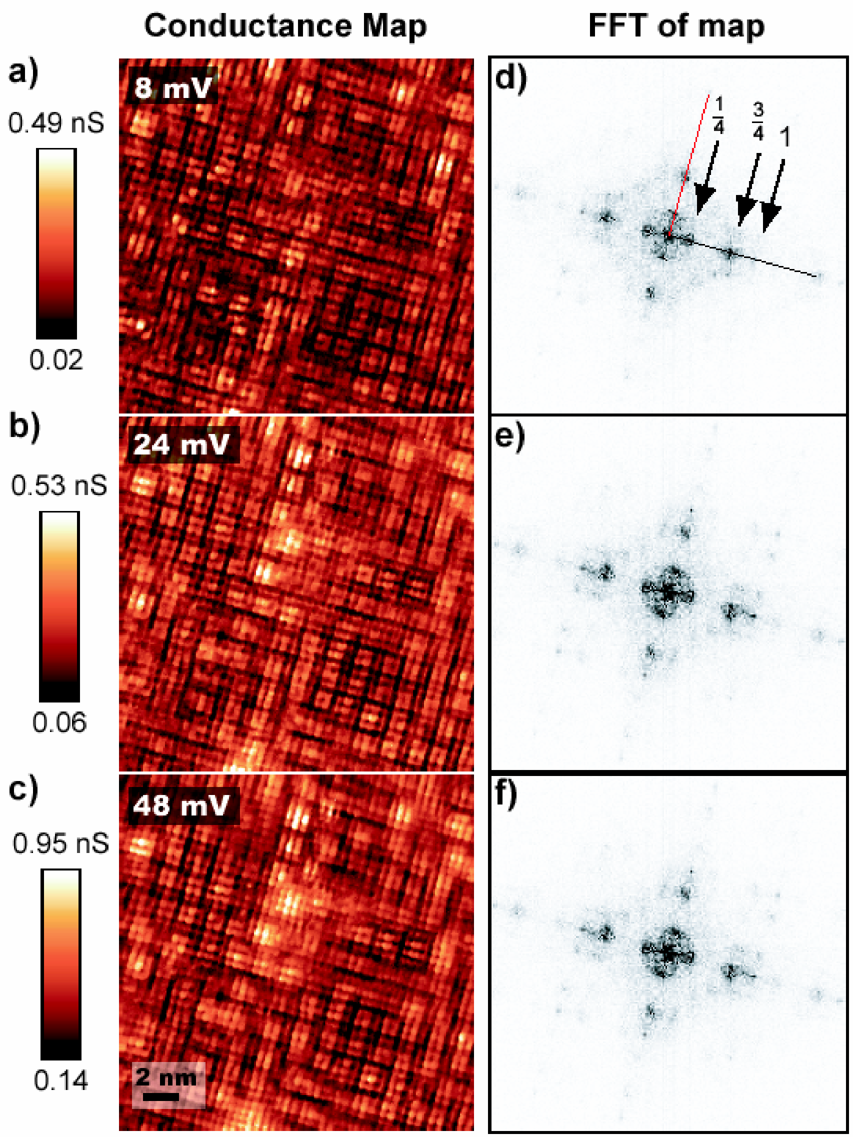


Stripe interpretation
Zaanen & Gunnarsson,PRB (89).
Emery & Kivelson, Physica C (93).

Competitive nature of SC and SDW

$Na_{0.1}Ca_{1.9}CuO_2Cl_2$ $T_c = 15K$

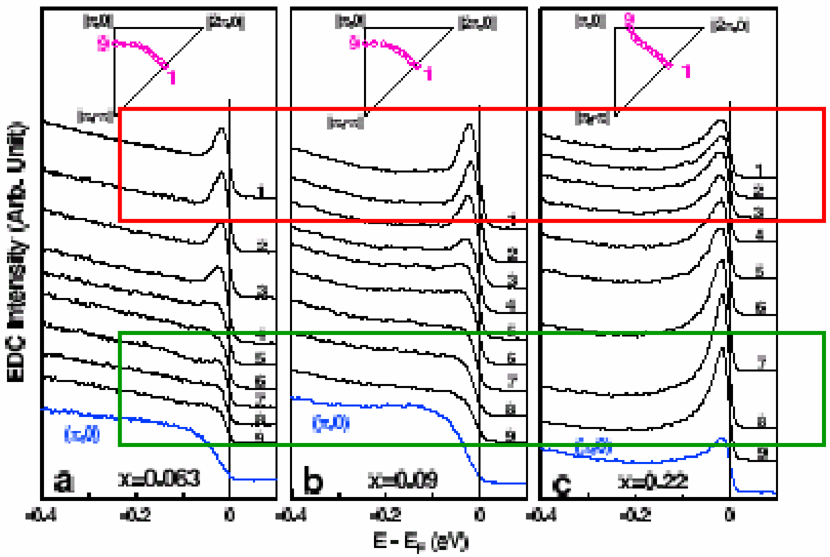
Hanaguri *et al, Nature* (2004)



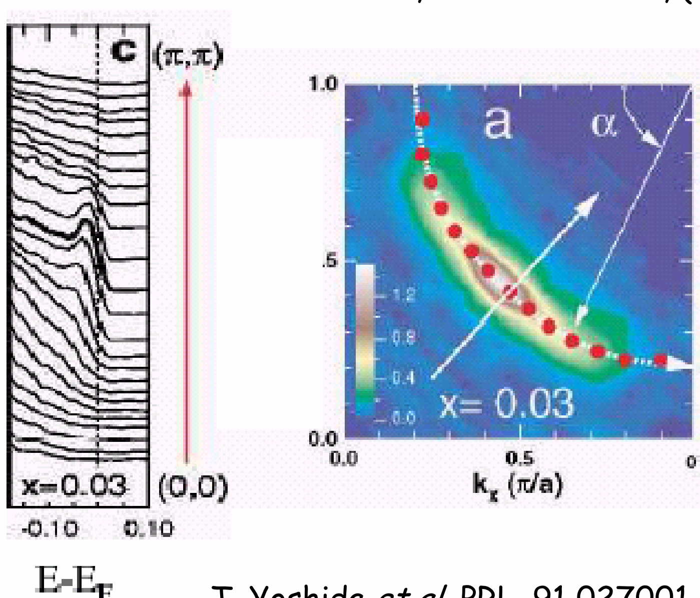
- No bias dependent modulation is observed. → quasiparticle interference is different from static ordering.
- Commensurate 4a.
- Checkerboard pattern independent of doping → lattice pinning.

The nodal and antinodal dichotomy in ARPES spectra

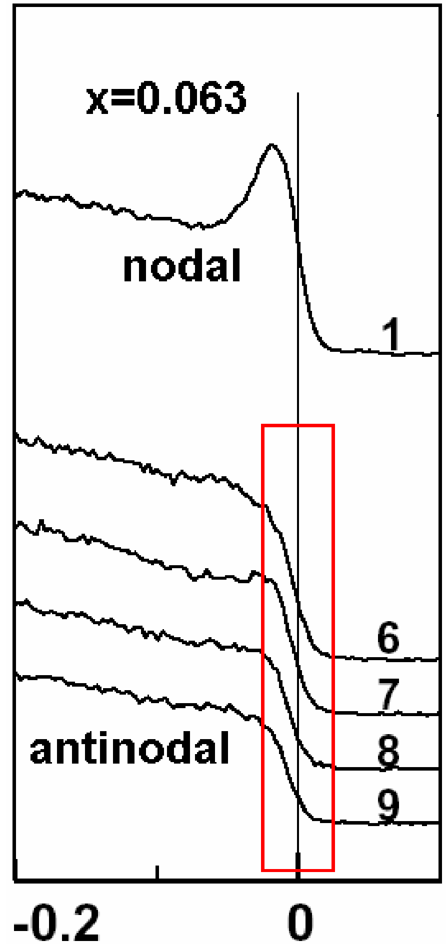
The nodal-antinodal dichotomy



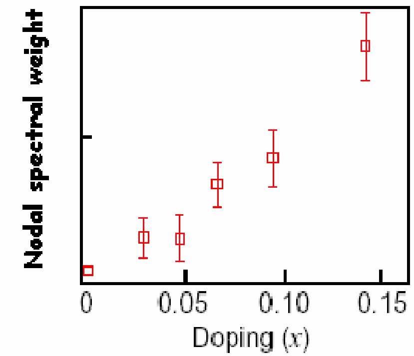
X.J. Zhou *et al*, PRL. 92 187001, (2004).



T. Yoshida *et al*, PRL. 91 027001, (2003).



Tiny pseudogap !



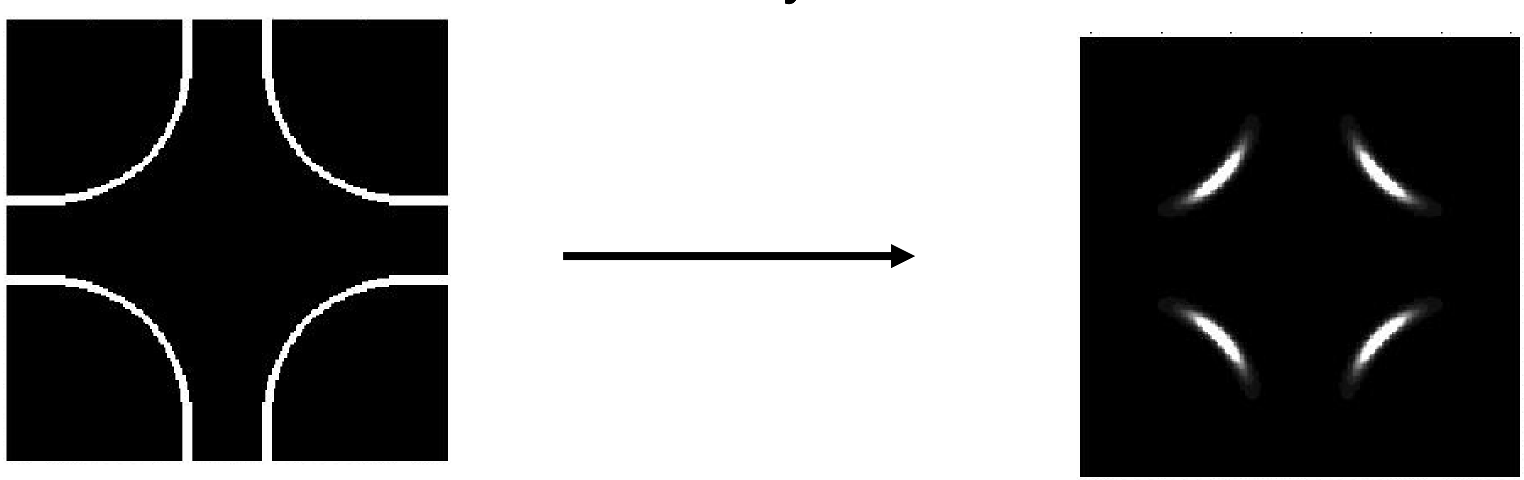
Nodal Z → 0 as x→0.

Prediction from theories that take the electronic correlation in a mean-field fashion

Decreasing doping →

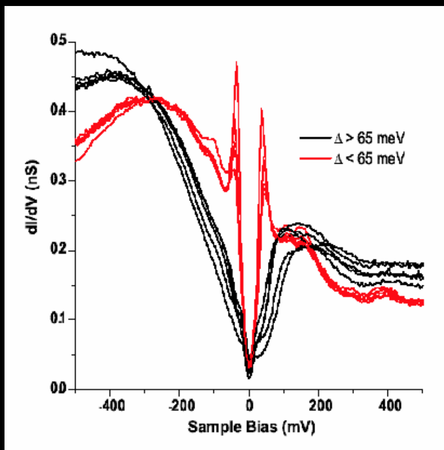
Anderson, Science (86), Kotliar & Liu PRB (88), Suzumura et al, J. Phys. Soc. Jpn. (88) , Anderson *et al*, J. Phys. Cond. Mat. (04), Randeria *et al* Cond-mat/0412096

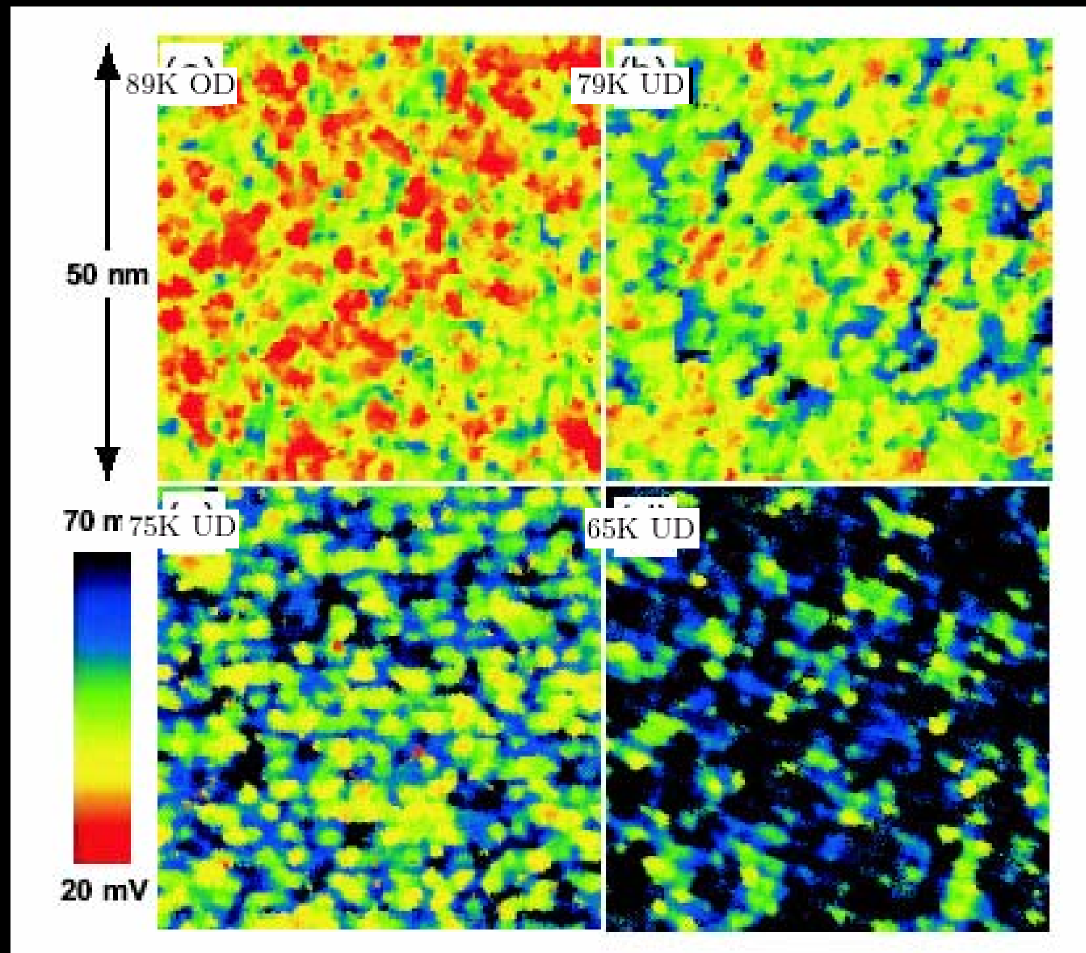
Reality



The coupling of nodal and antinodal excitations to disorder

Bi-2212 Gap inhomogeneity

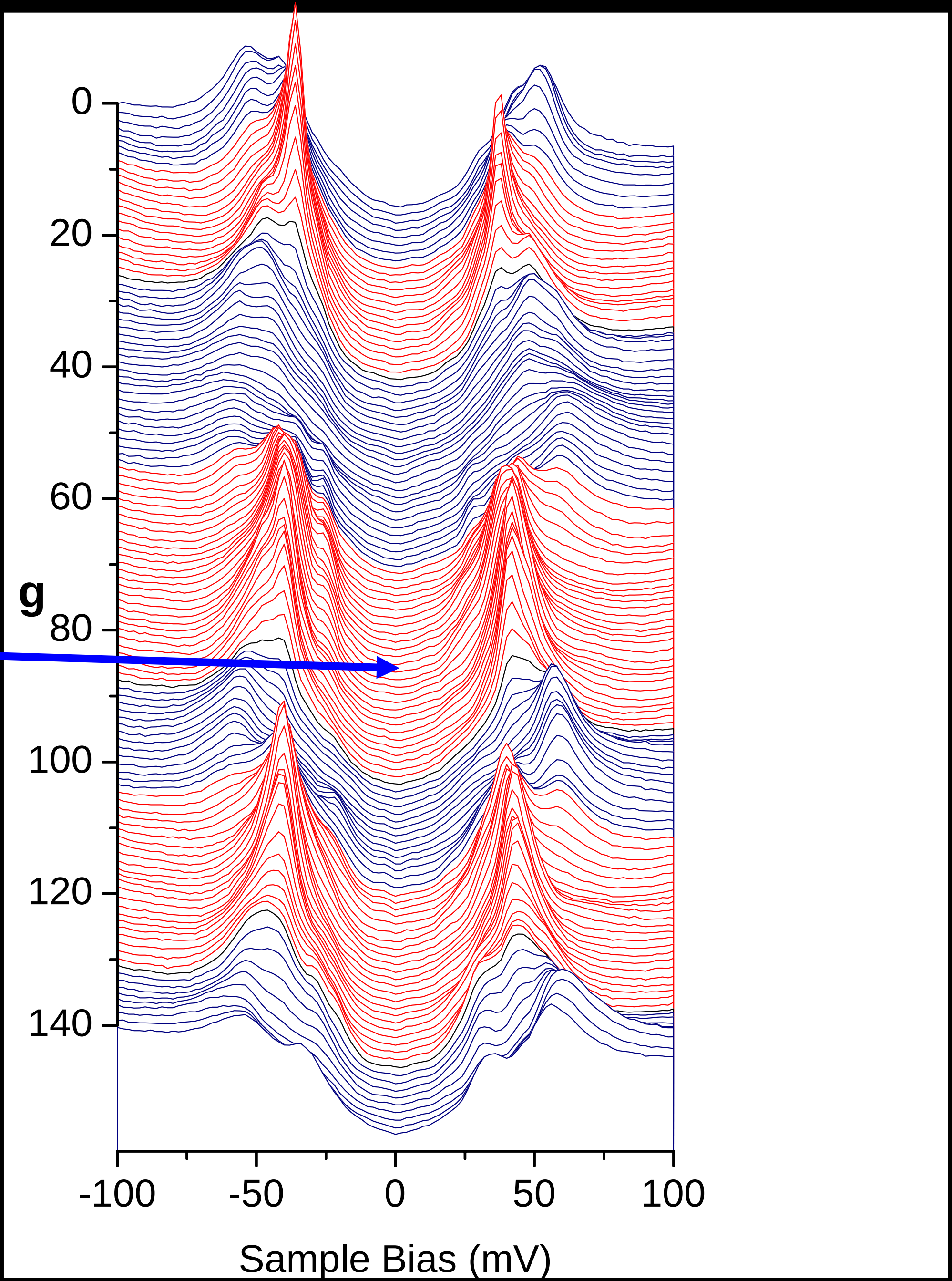




Liu et al, *PRL* (91)
Chang et al, *PRB* (92). Howald *et al., PRB* (01). Cren et al, *Eu.Phys.Lett.* (01)
Matsuda *et al*. *J. Chem. Phys. Solids* (01).
Pan et al, *Nature* (01).
Lang et al, *Nature* (02).
McElroy et al, *cond-mat* 0404005, 0406491.

Bi-2212 $T_c = 75K$

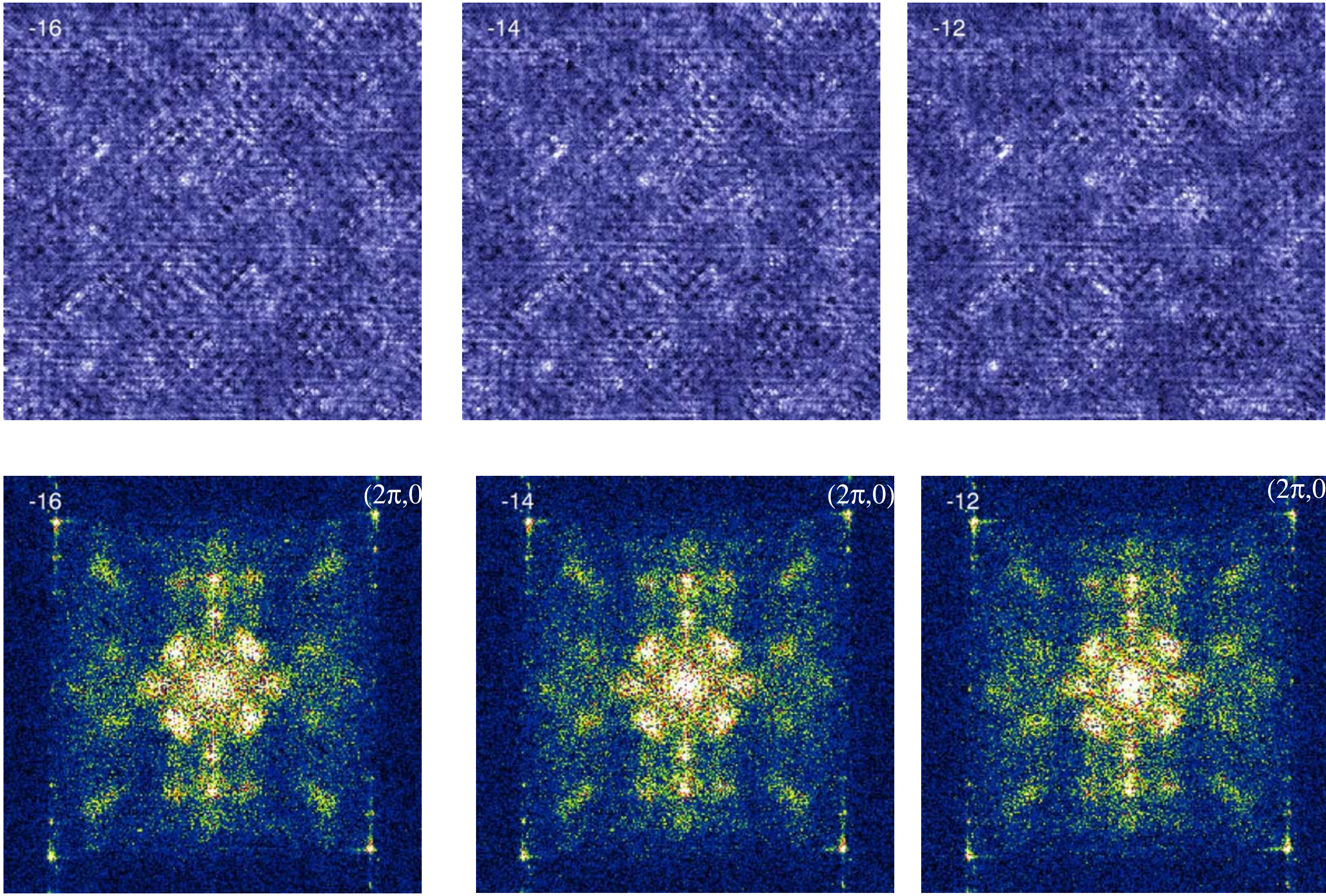
homogeneous sub-gap conductance



Howald *et al., PRB* (01).
Pan *et al*, *Nature* (01).
Lang *et al, Nature* (02)

Quasiparticle interference

Bi-2212 $T_c = 76K$ Measured @ 4.2 K

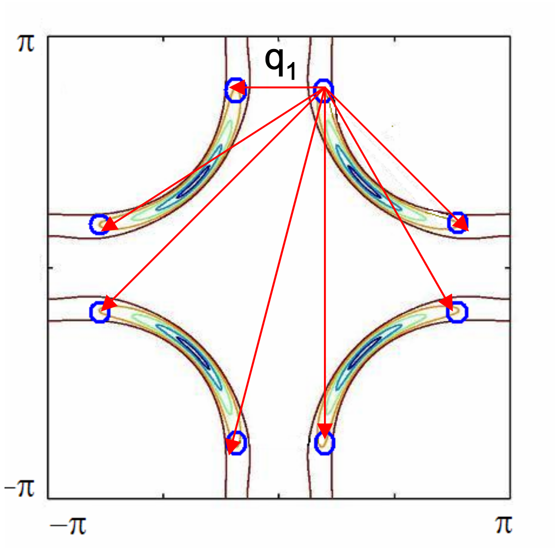


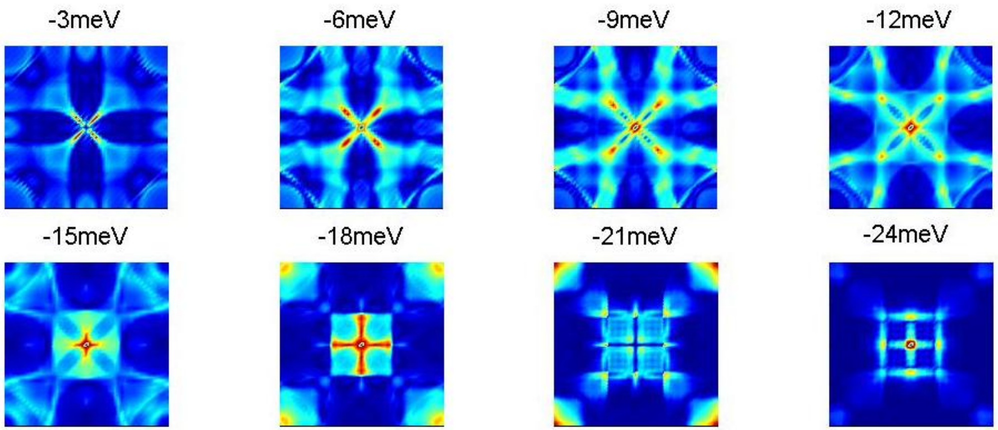
1. Exists for *subgap* energies.
2. Peak positions change with bias voltage.

Hoffman *et al*, *Science* (2002)
McElroy *et al*, *Nature* (2003)

The quasiparticle interference model

A toy model: Wang, Lee PRB (03)





LDOS~$|\Psi_1 + \Psi_2 + \ldots + \Psi_8|^2$

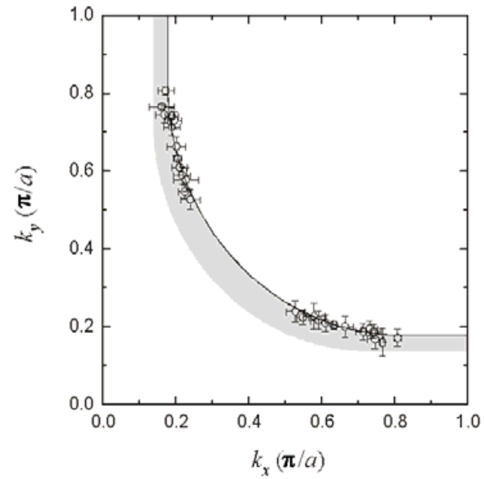
32 different vectors

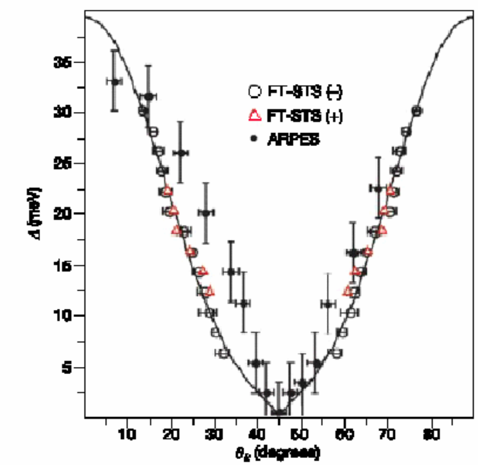
Problem: q_1 modulation at low bias is too weak.

The Octet model

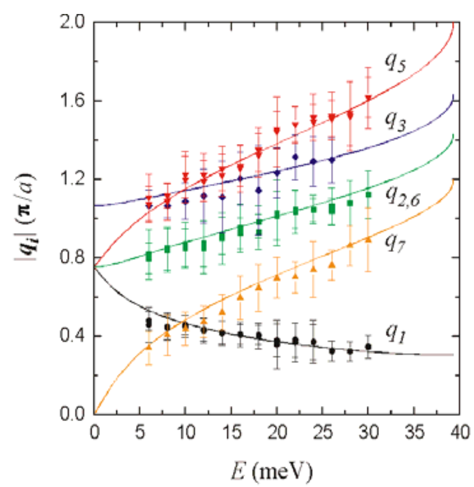
Hoffman et al, Science (2002)
McElroy et al, Nature (2003)

Fit data to model →

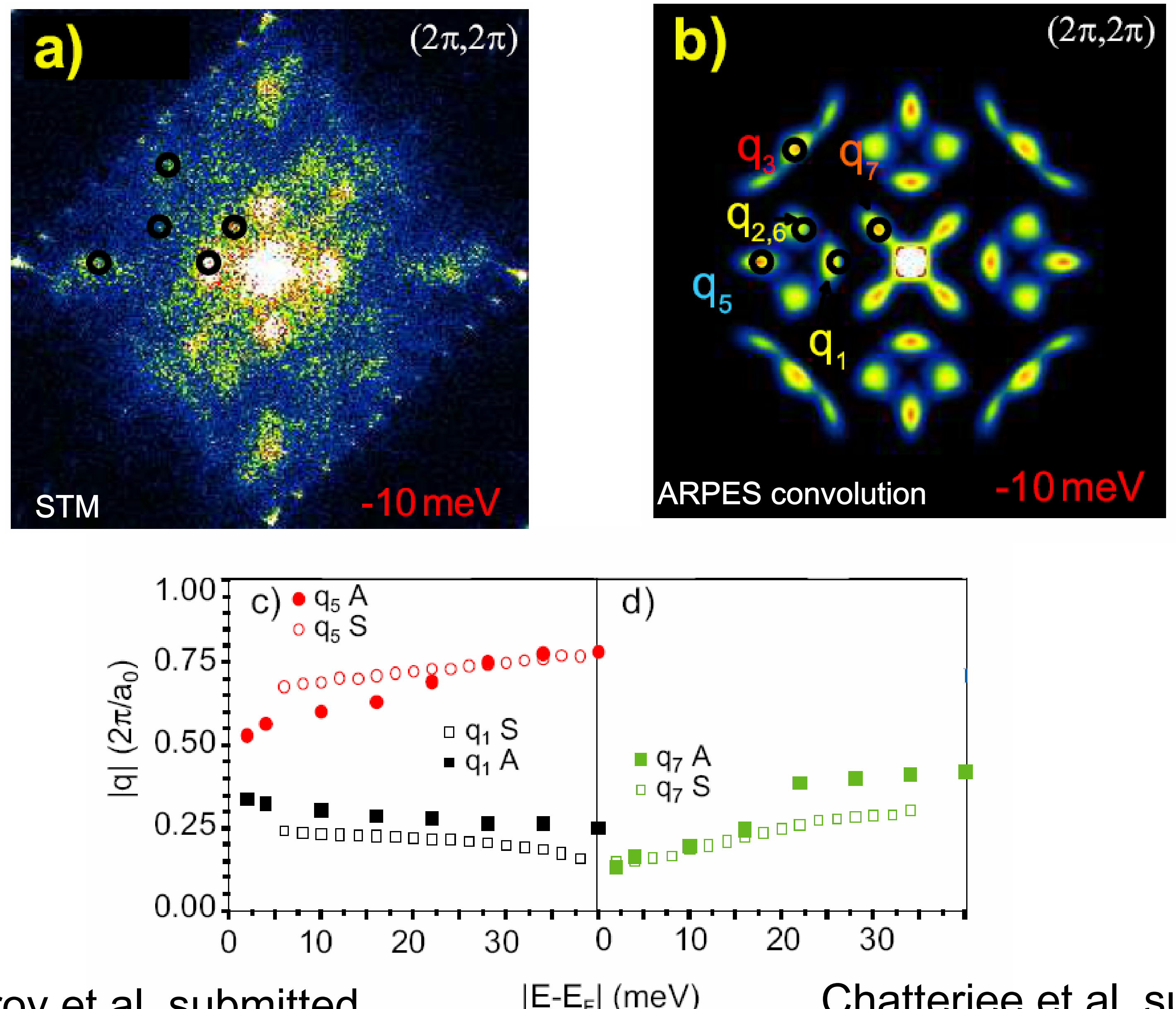




Quality of the (*extremely over-constrained*) fit



Comparison between FTSTS and convolution of ARPES spectra



McElroy et al, submitted

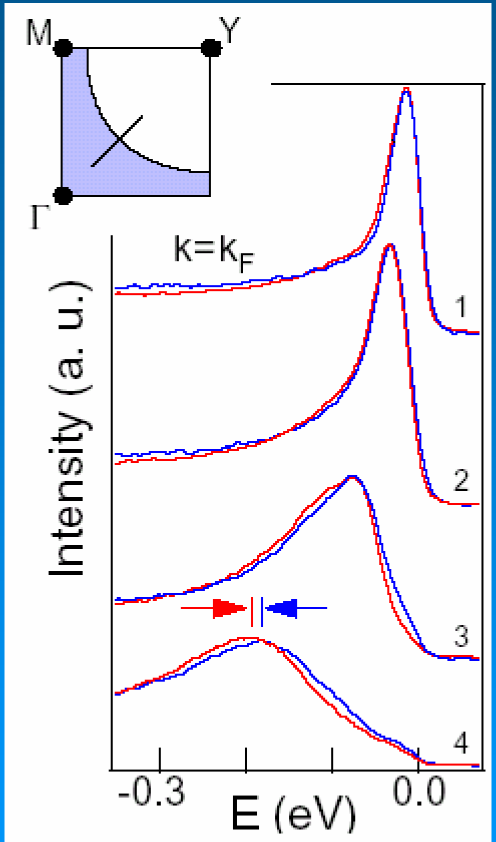
Chatterjee et al, submitted

The coupling of N/AN excitations to lattice vibtation

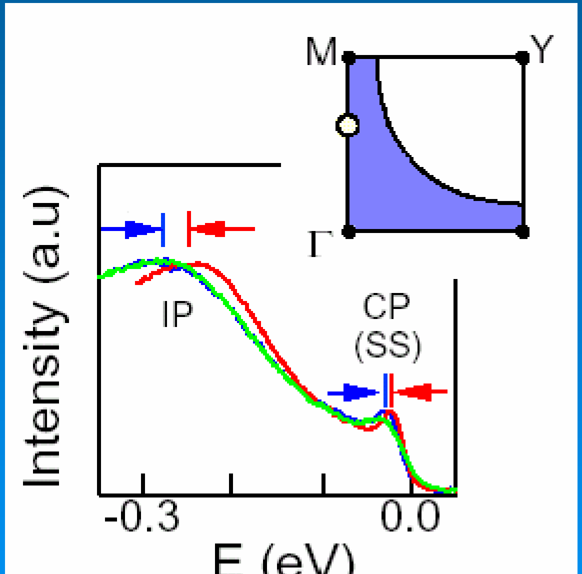
Nodal and antinodal excitations couple to lattice differently

Isotope dependence Bi-2212, $T_c = 90$ K

Measured @ 25K



Nodal direction



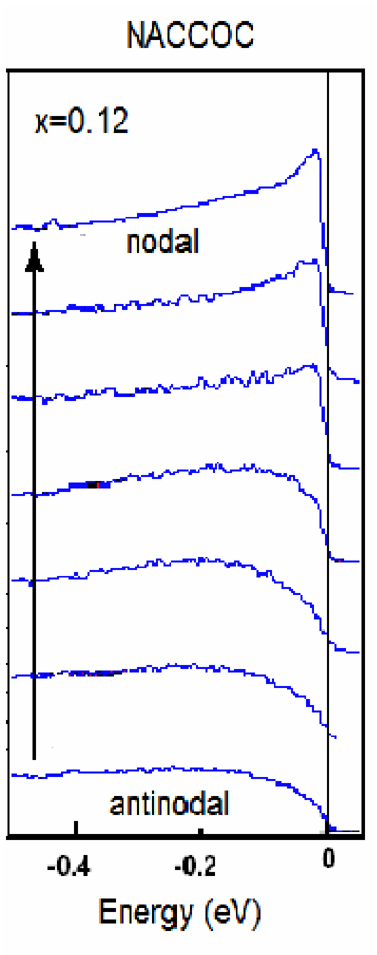
Near the antinode

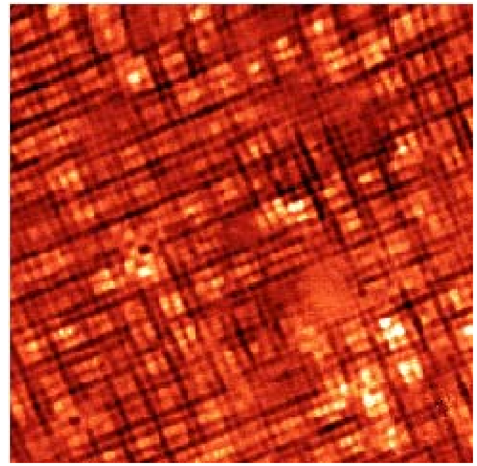
Gweon *et al*, *Nature* (04)

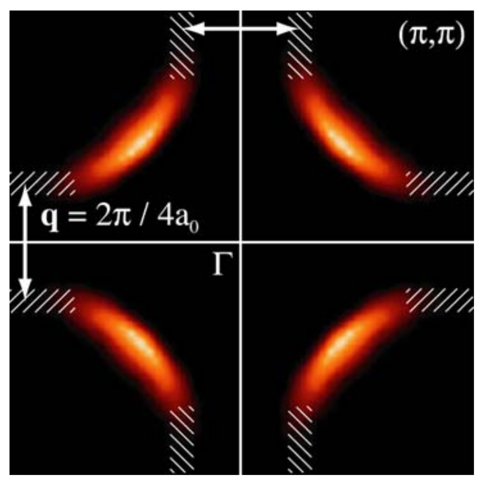
The coupling of N/AN excitations to charge order

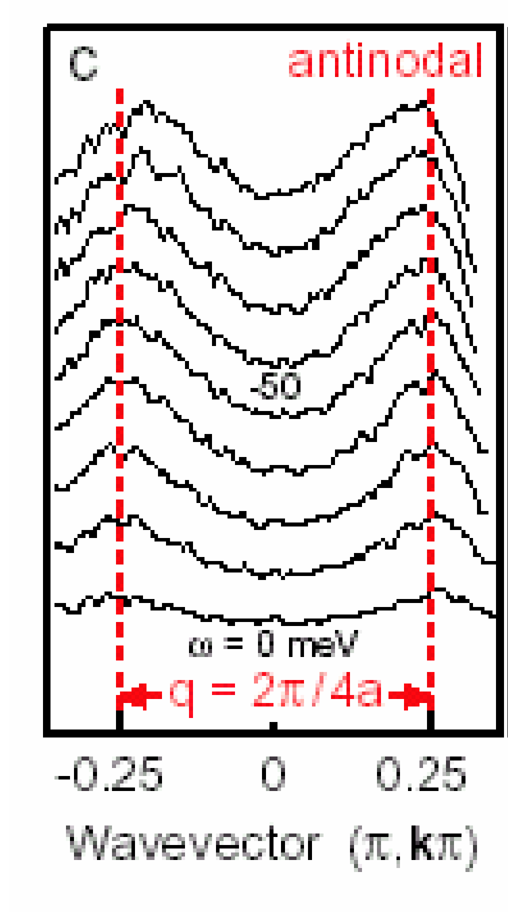
ARPES of checkerboard ordered $Na_xCa_{2-x}CuO_2Cl_2$

K. Shen *et al* Science (04).



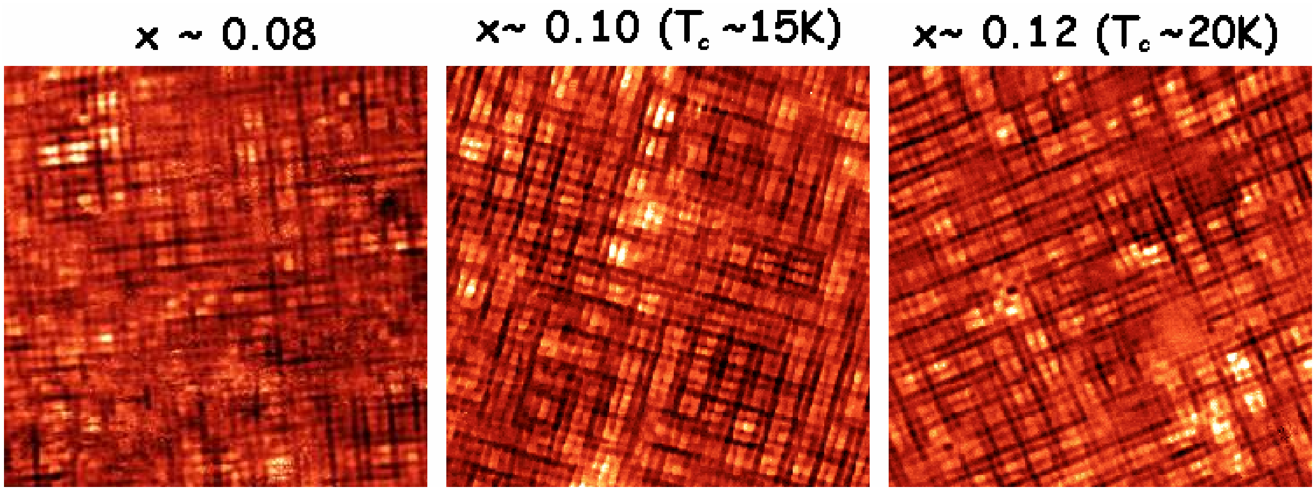






Nodal quasiparticle excitations coexists with charge order. Clearly, we do not have a simple charge insulator.

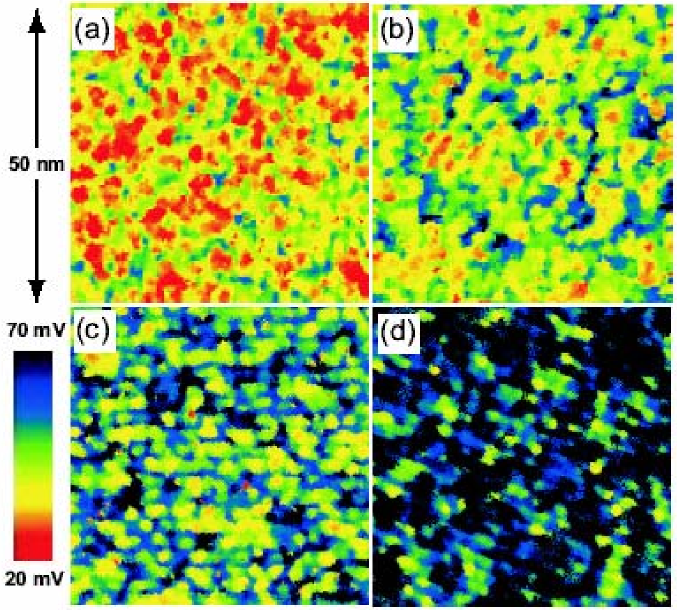
Hanaguri *et al*

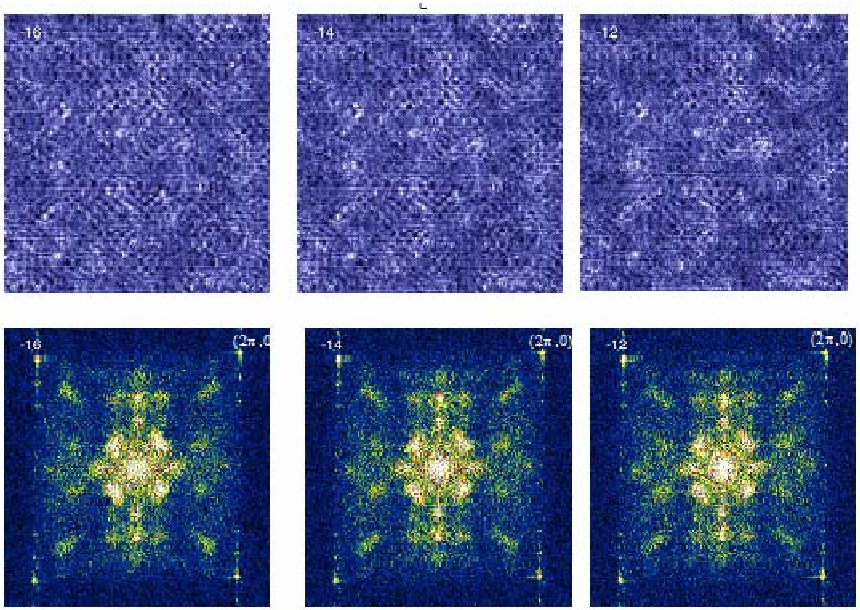


The same periodic pattern is seen for a range of doping
→ lattice pinning plays an important role.

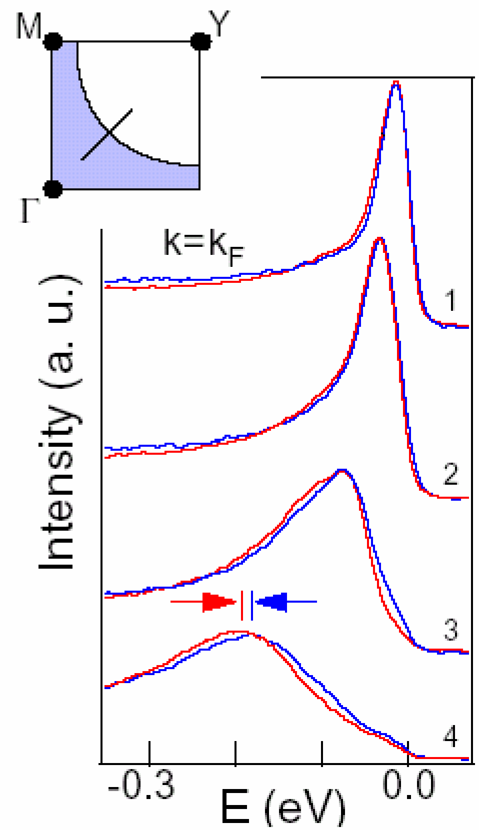
Summary

Effect of (oxygen dopant) disorder

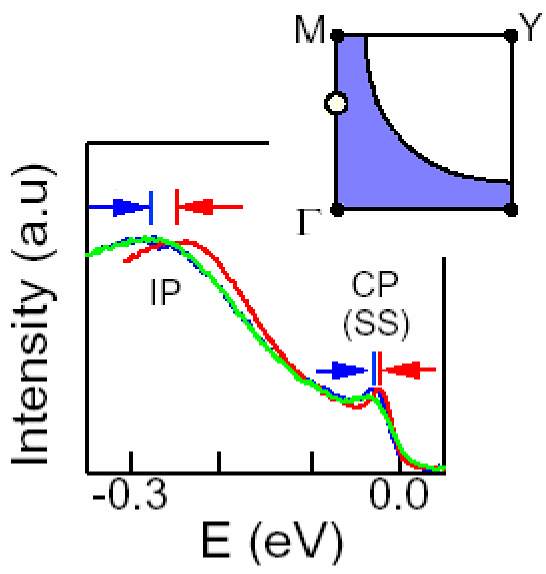




Effect of lattice vibration

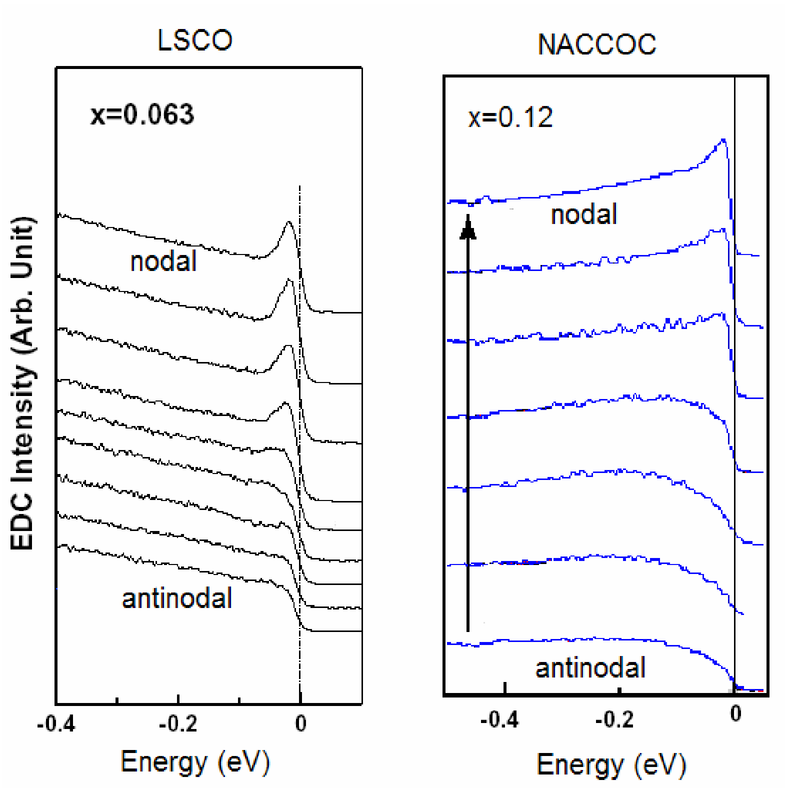


Nodal direction

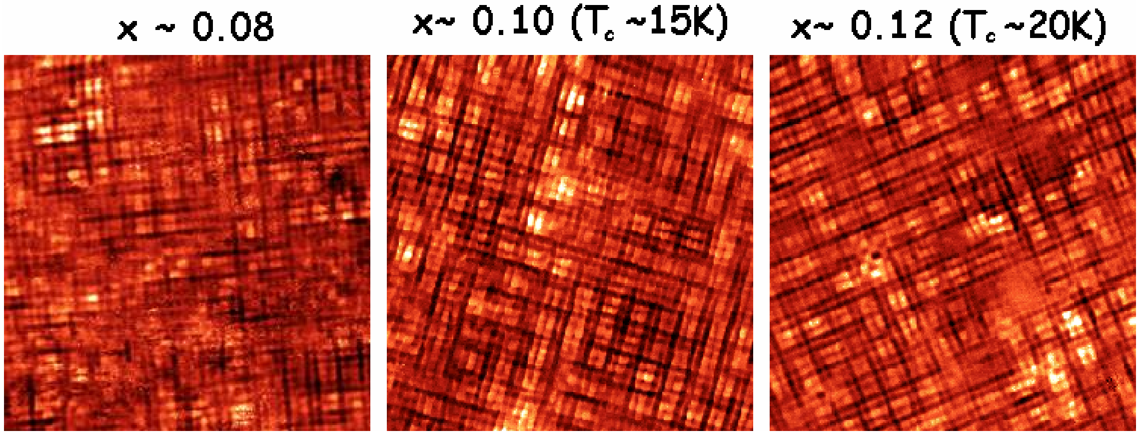


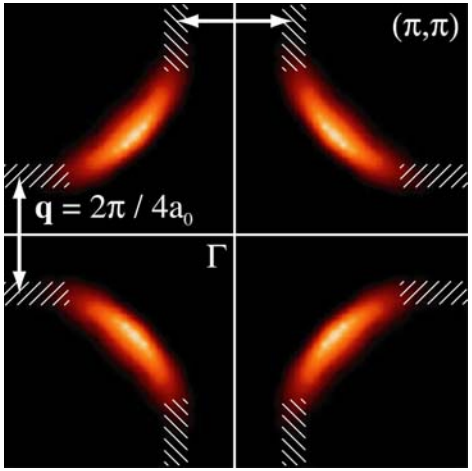
Near the antinode

The nodal-antinodal dichotomy in ARPES spectra.



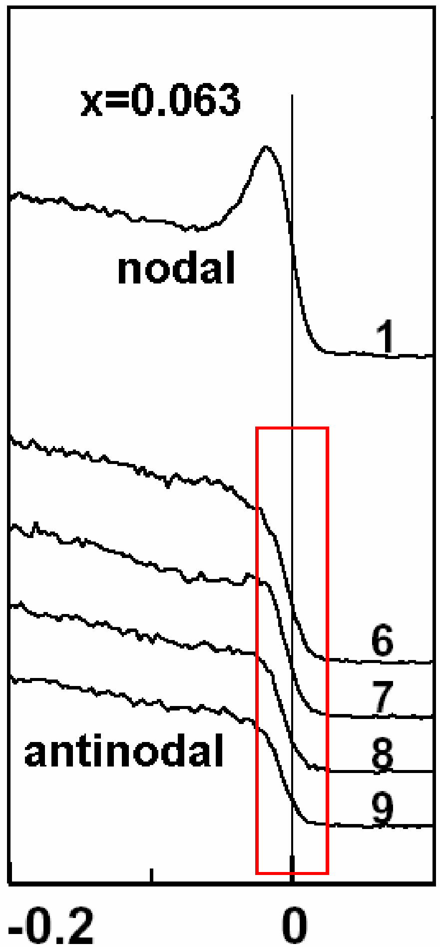
Coupling to charge order





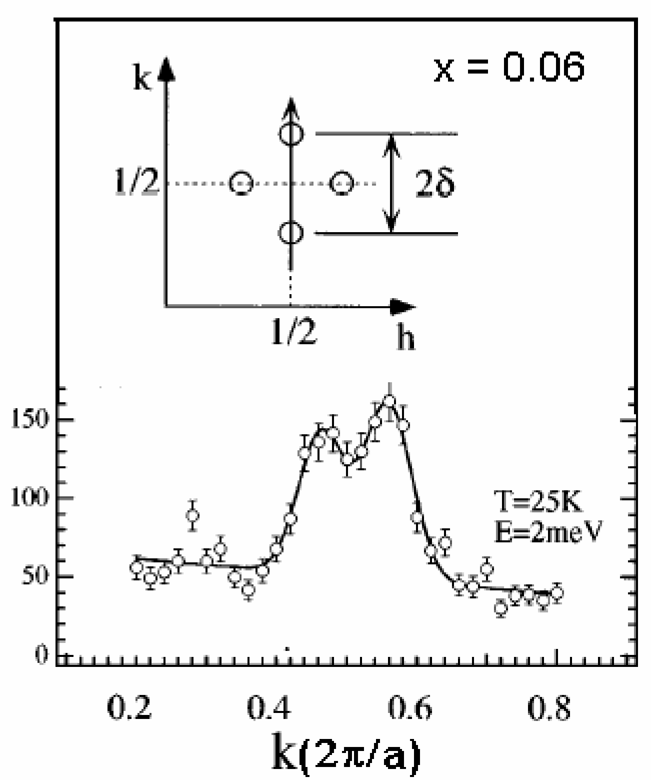
Theoretical discussions

What causes the antinodal decoherence ?
Why is the pseudogap so small ?



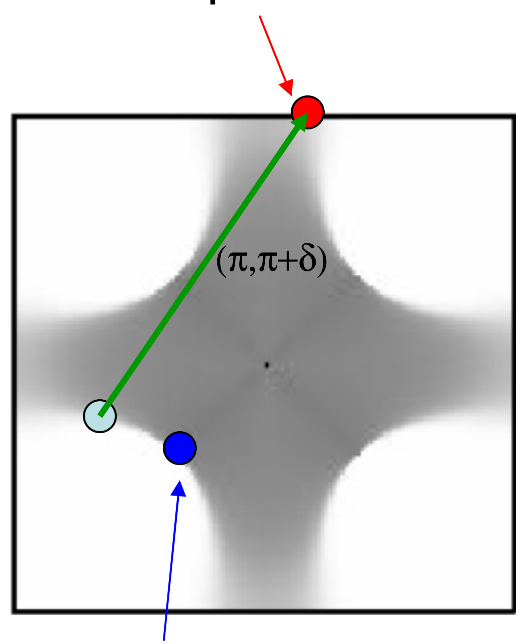
The cause of antinodal (single-particle) decoherence

The existence of low-energy incommensurate spin excitations.

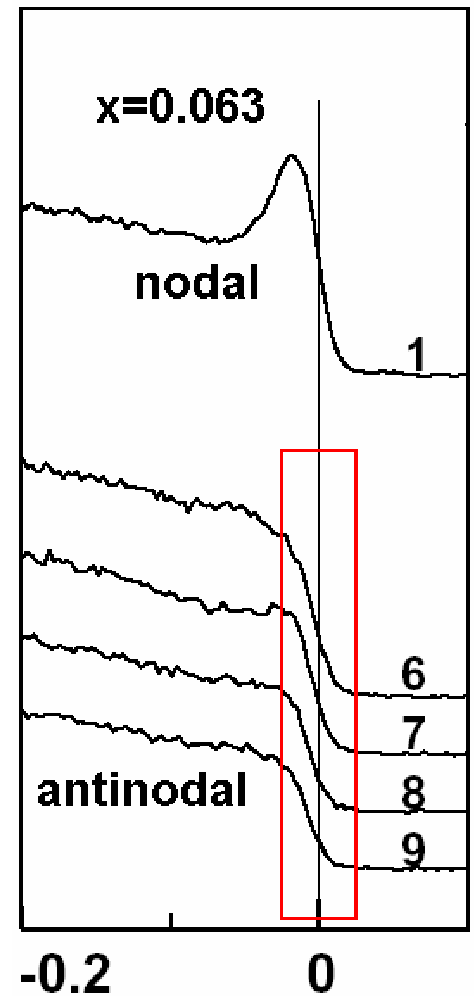


K. Yamada et al, PRB (98)

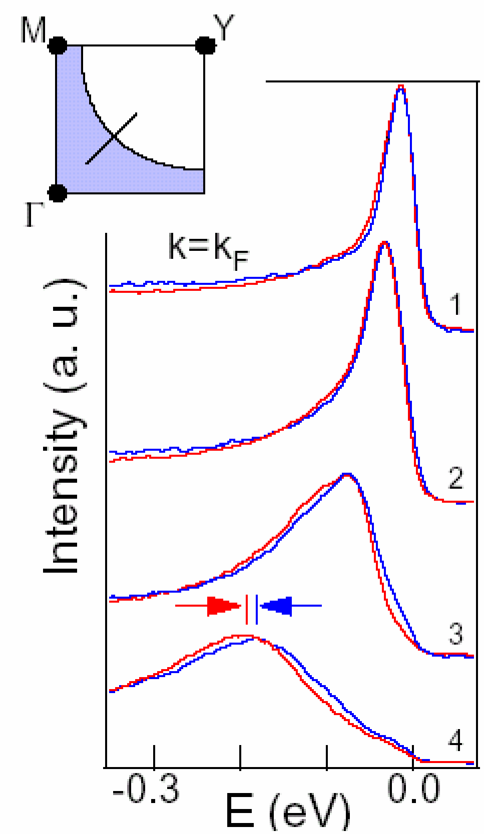
Lowest E excitation is Multi-particle-like



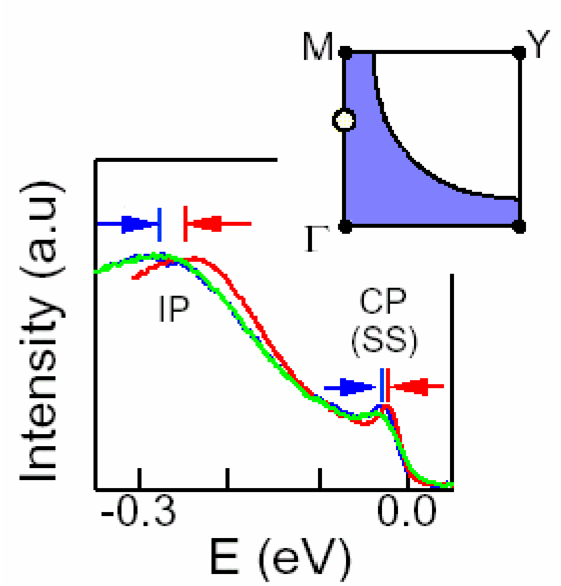
Lowest E excitation = quasiparticle



Why is the electron-phonon coupling stronger for antinodal excitations ?



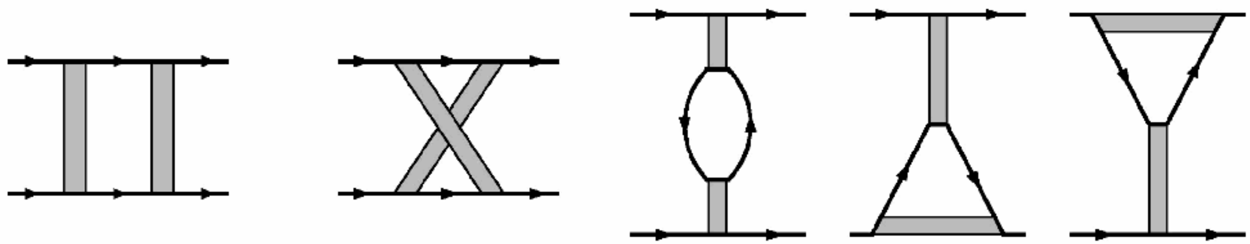
Nodal direction

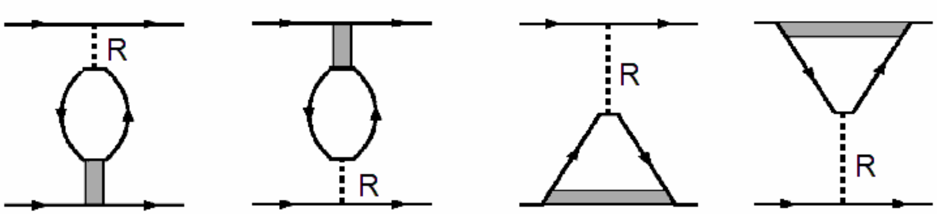


Near the antinode

One-Loop renormalization group study

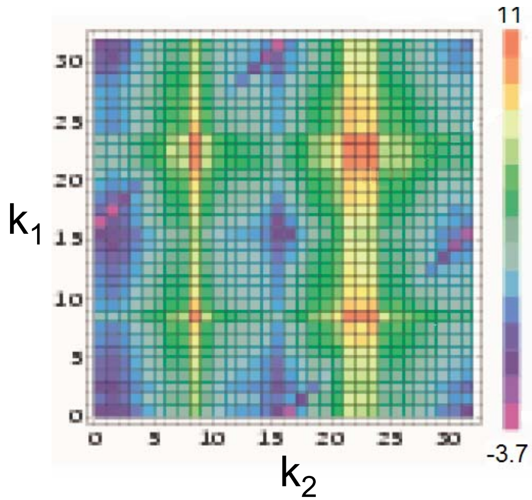
$$H = \sum_{ij\sigma} t_{ij}[c^{+}_{i\sigma} c_{j\sigma} + h.c.] + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$ + coupling to phonons

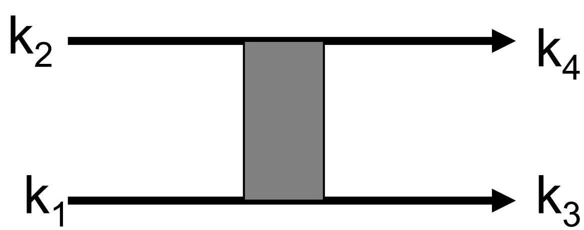


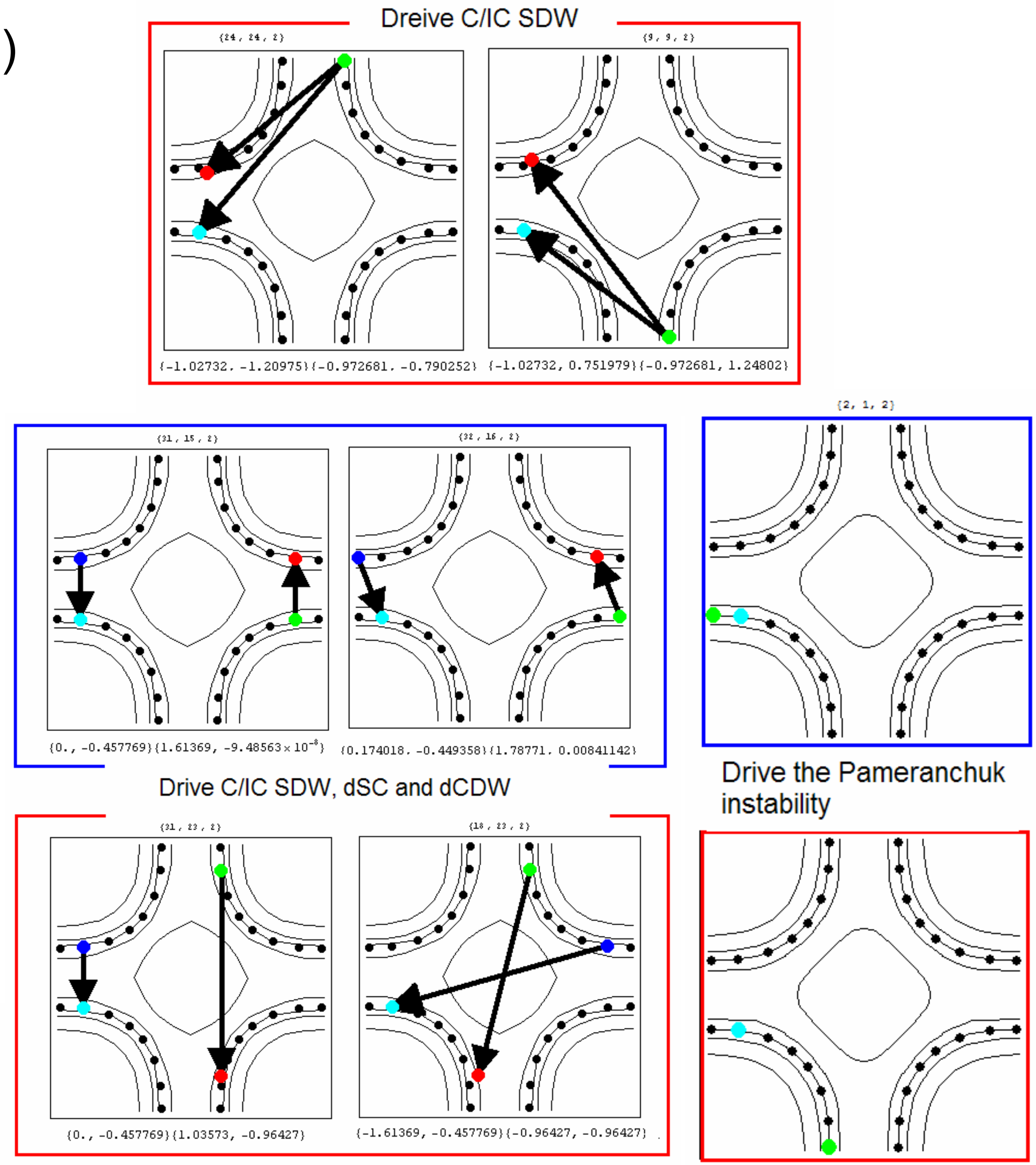


Electron-electron interaction

Honerkamp *et al*, *PRB* (2003)





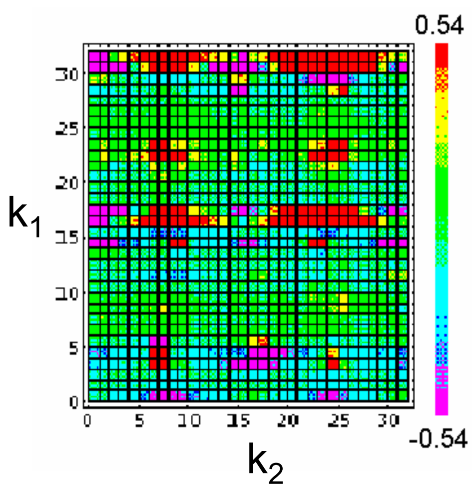


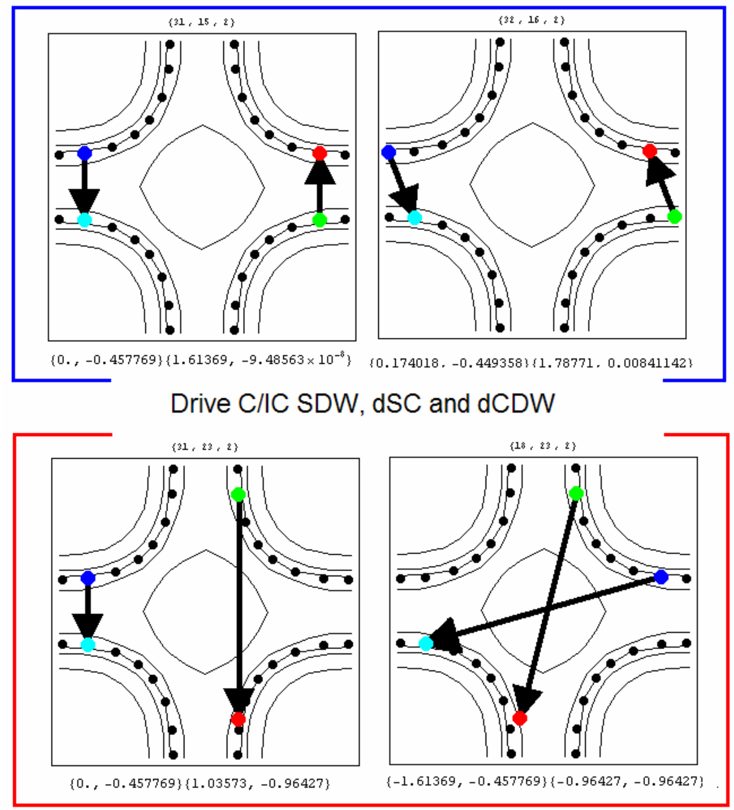
dCDW order parameter

$$\sum_{\mathbf{k}\sigma} (\cos k_x - \cos k_y) c^{+}_{\mathbf{k}+\mathbf{q}\sigma} c_{\mathbf{k}\sigma}$$

Retarded coupling

Fu *et al*, to be submitted





Growing antinodal scattering processes upon RG

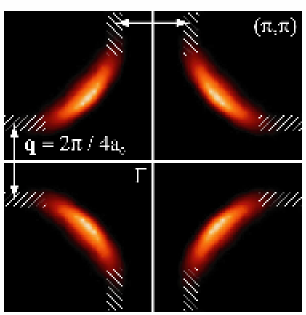
Electronic scattering that drives C/IC SDW ↔ Electronic scattering that drives dSC and dCDW

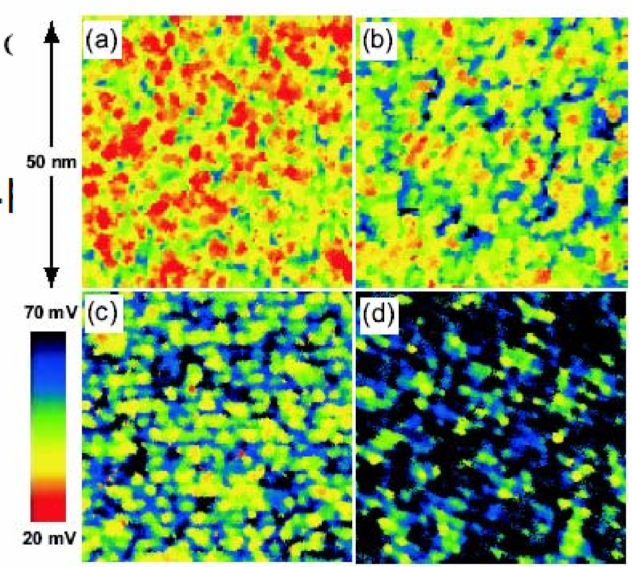
↓

Phono-mediated scattering that drives dSC and dCDW

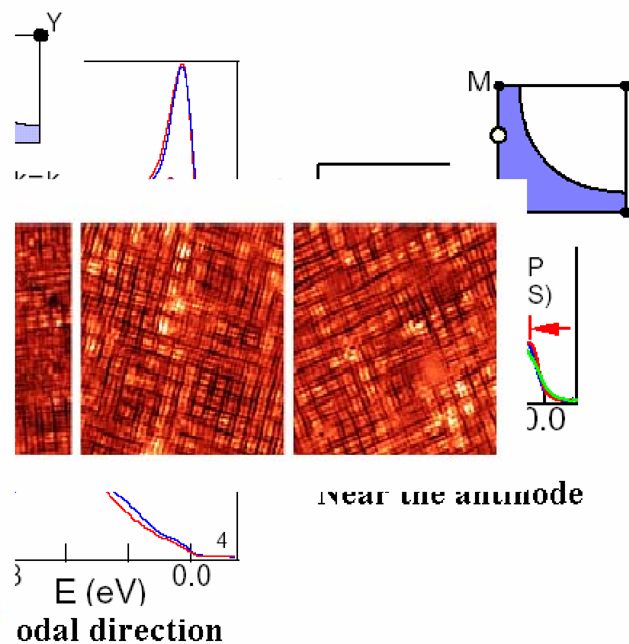
dCDW = $\sum_{k\sigma}(\cos k_x - ($

does not affect nodal q.|

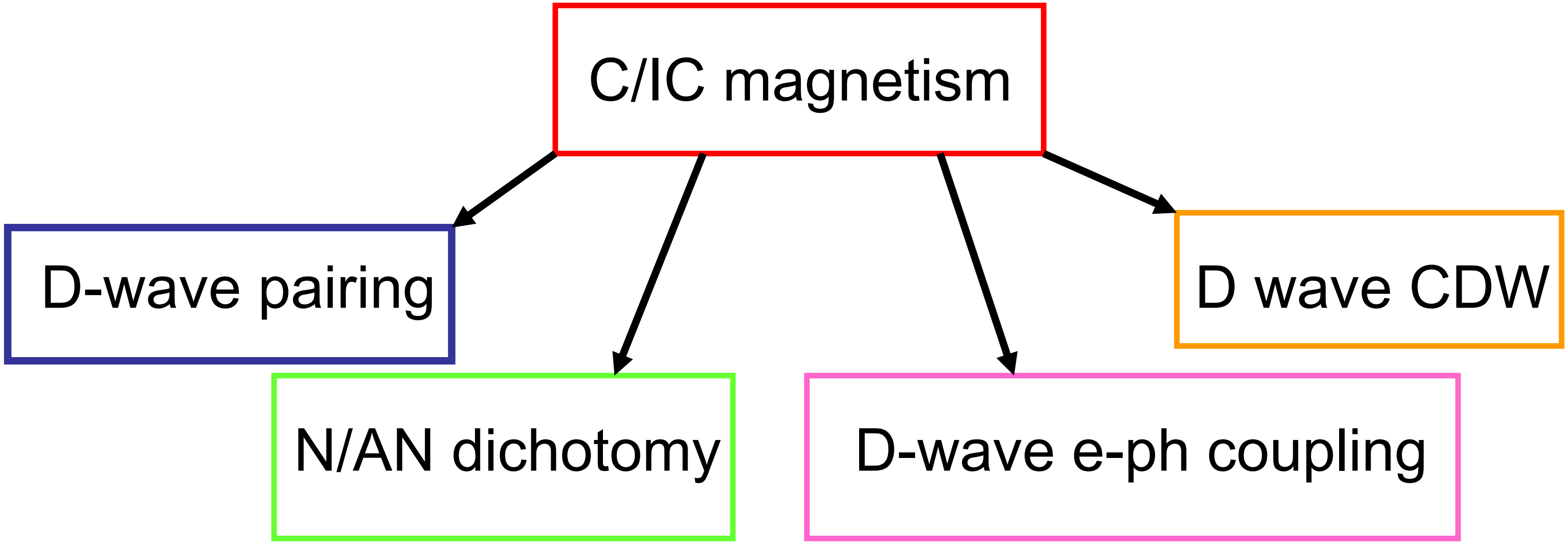




Due to local Lattice distortion ?



Conclusion


C/IC magnetism
D-wave pairing
N/AN dichotomy
D-wave e-ph coupling
D wave CDW