Stripe order and pairing in the Cuprate Superconductors

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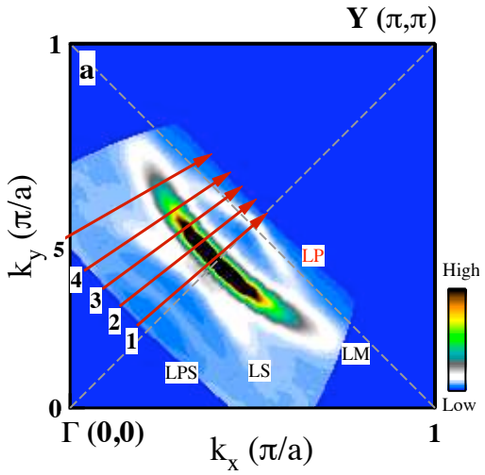
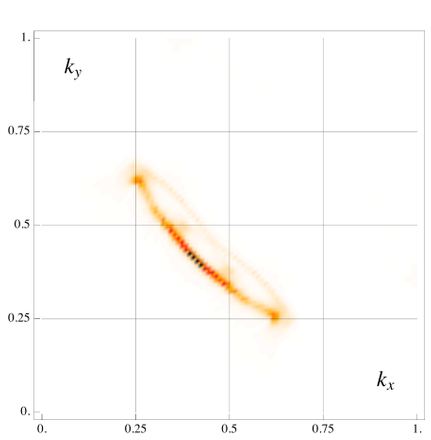
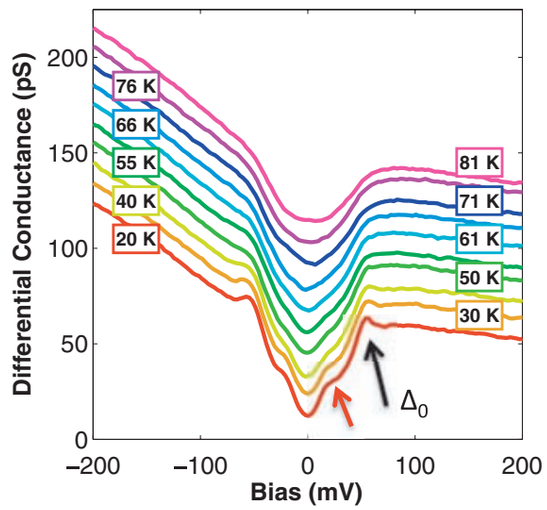
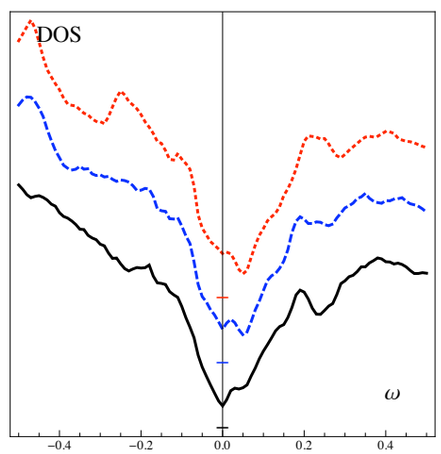
February 17, 2011.





J. Meng et al, Nature 2009



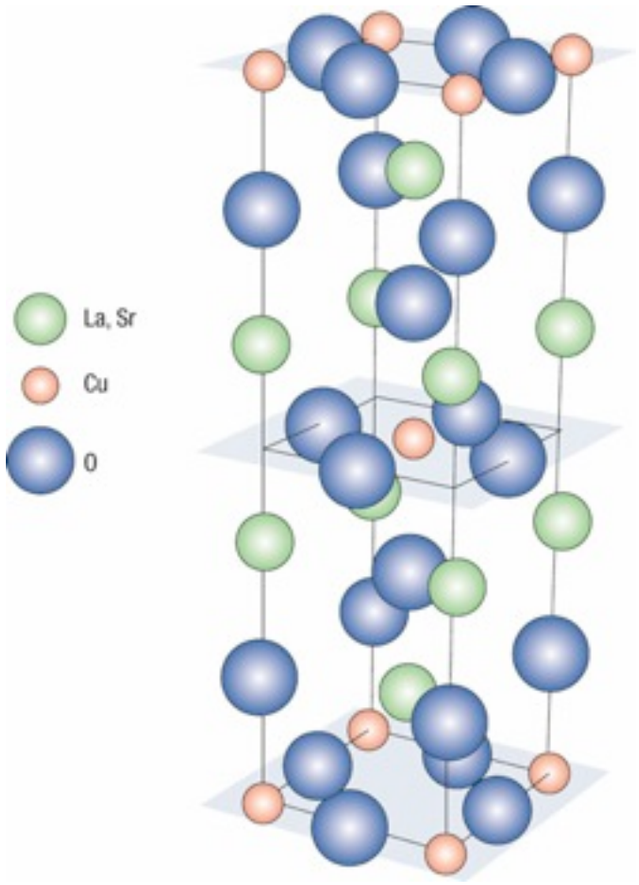


Pushp et al, Science 2009.

Content

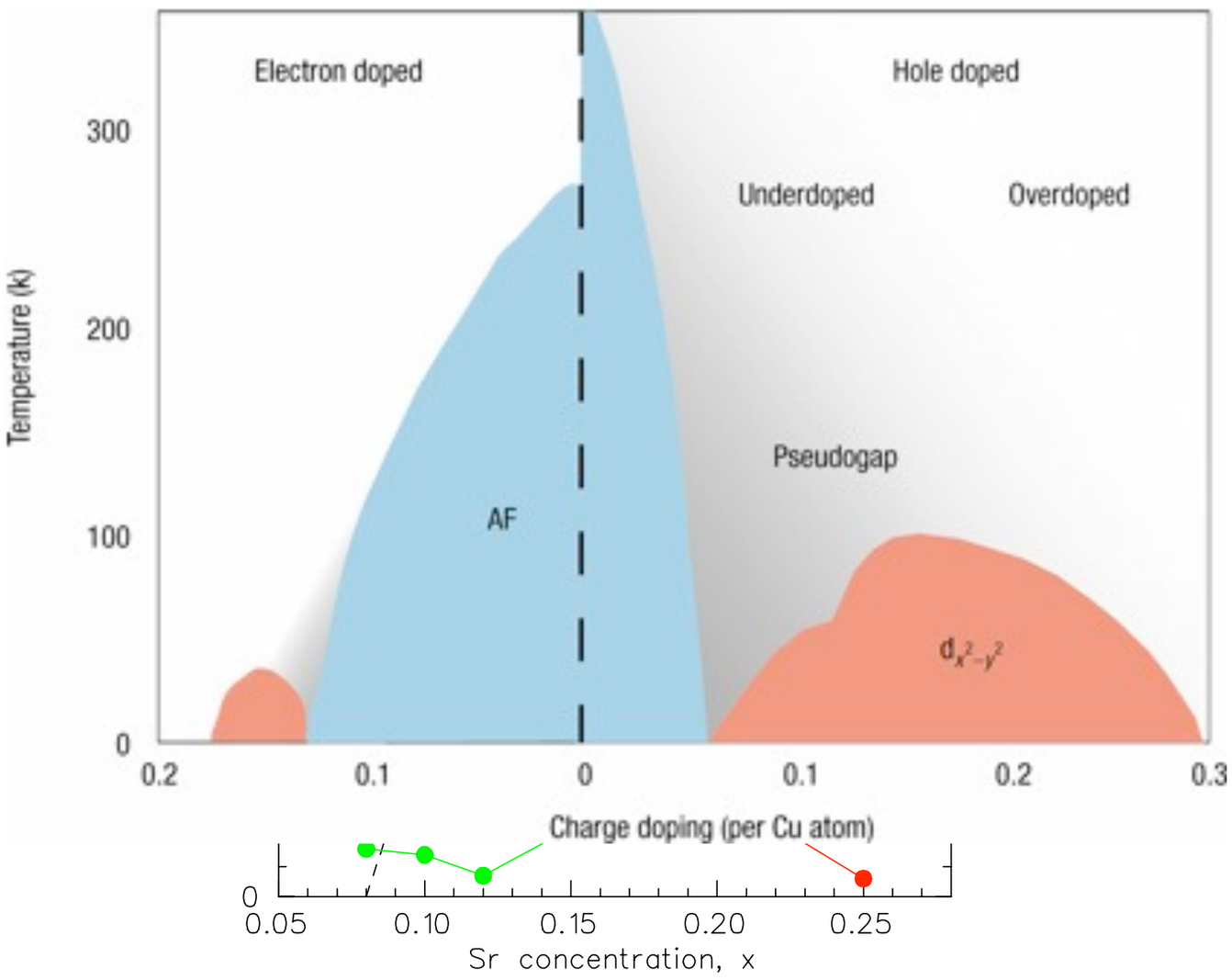
- Introduction to the cuprate high-T_c superconductors.
- The pseudogap.
- Attraction from repulsion.
- Stripes, coupled spin and charge density wave order.
- Pseudogap from pairing on stripes?

The cuprate superconductors



figure, D. Bonn

$La_{2-x}Sr_xCuO_4$

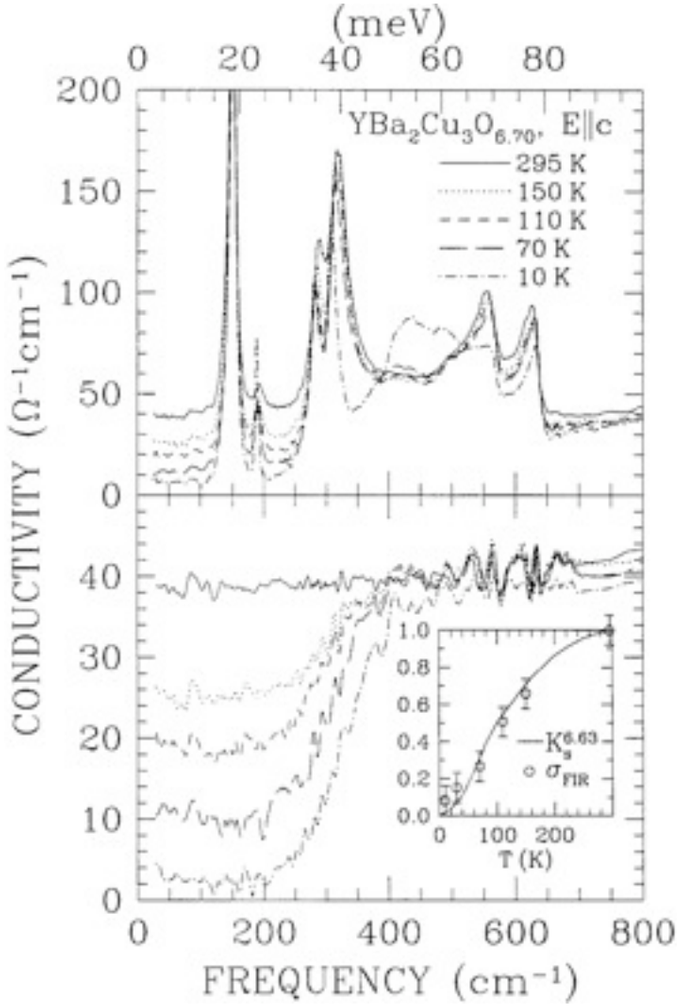


Ichikawa et al, PRL 2001

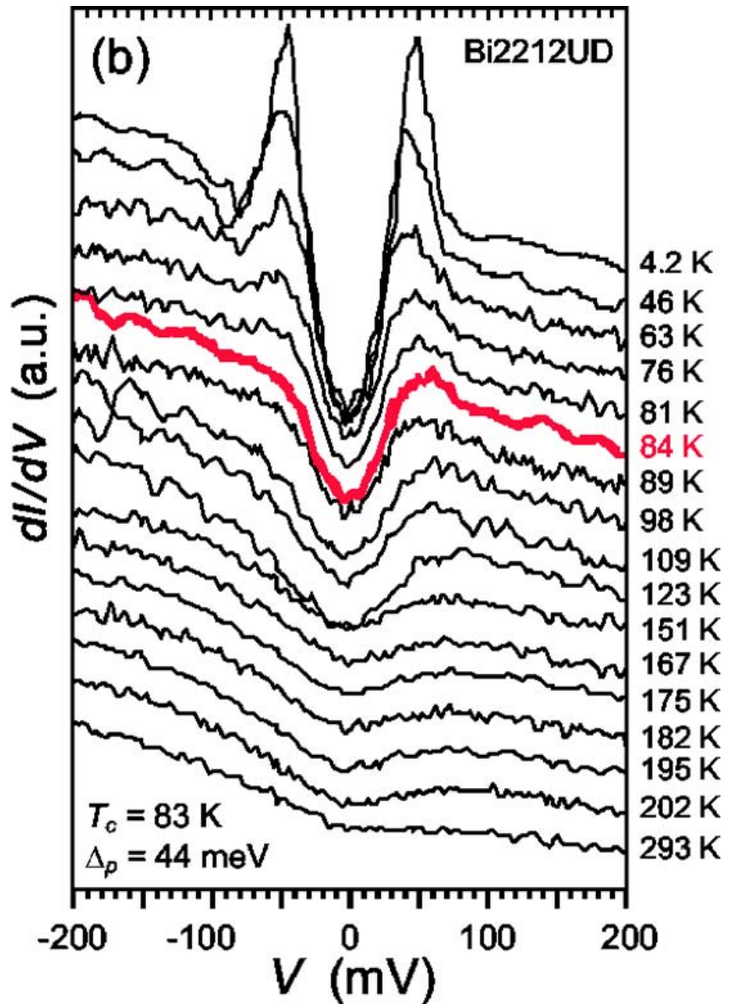
The Pseudogap

NMR, optical conductivity, Raman, tunneling, photoemission,...

Early on it was suggested to be due
to spin pairing above Tc,
(e.g. NMR by Warren et al PRL 1993)



Homes et al, PRL 1994



Renner et al, PRL 1998

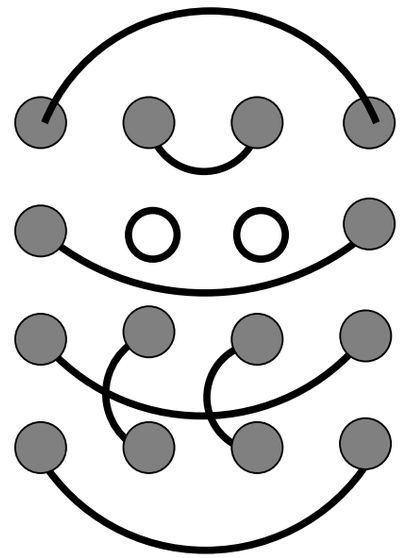
conventional superconductor, Nb

Pairing from strong singlet correlations

Spin liquid or Resonating Valence Bond(RVB)

P.W. Anderson Science 1987

Doping a Spin liquid



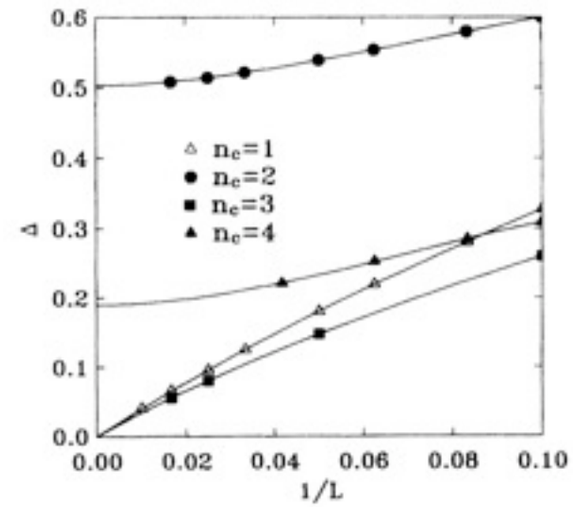
Hard to find in 2D, generally broken spin rotation invariance and gapless spin excitations

Heisenberg model in 2D has Antiferromagnetic order, no spin gap.
Undoped cuprates are Antiferromagnetic.

Spin liquid in one dimension, spin ladder

Haldane 1983; Rice at al. 1993

$$H = J \sum_{<i,j>} (\vec{S}_i \cdot \vec{S}_j - \frac{1}{4}) = -J \sum_{<i,j>} P^0_{i,j}$$

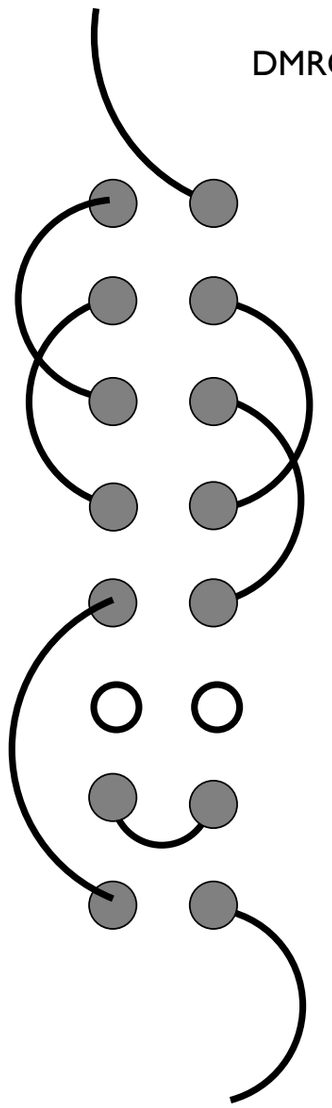


DMRG, White et al PRL 1994

Even leg Heisenberg ladders has gap that decrases exponentially with the number of legs

$$\Delta \sim J e^{-.68 n_{leg}}$$

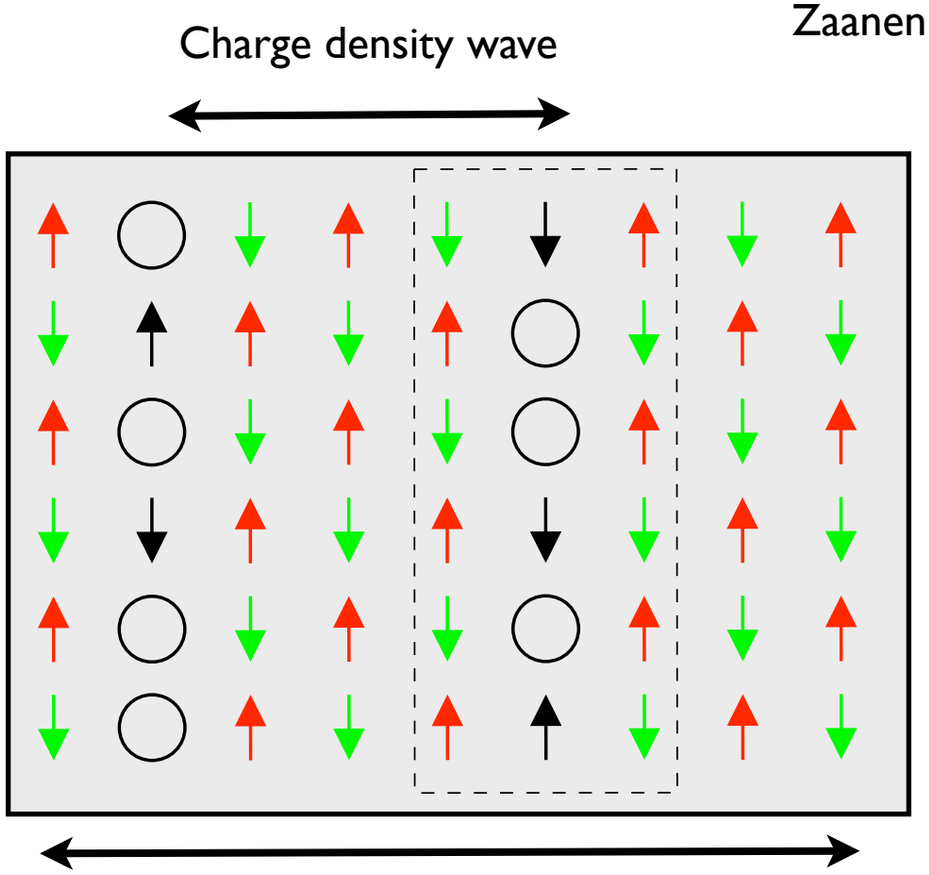
S. Chakravarty, PRL 1996

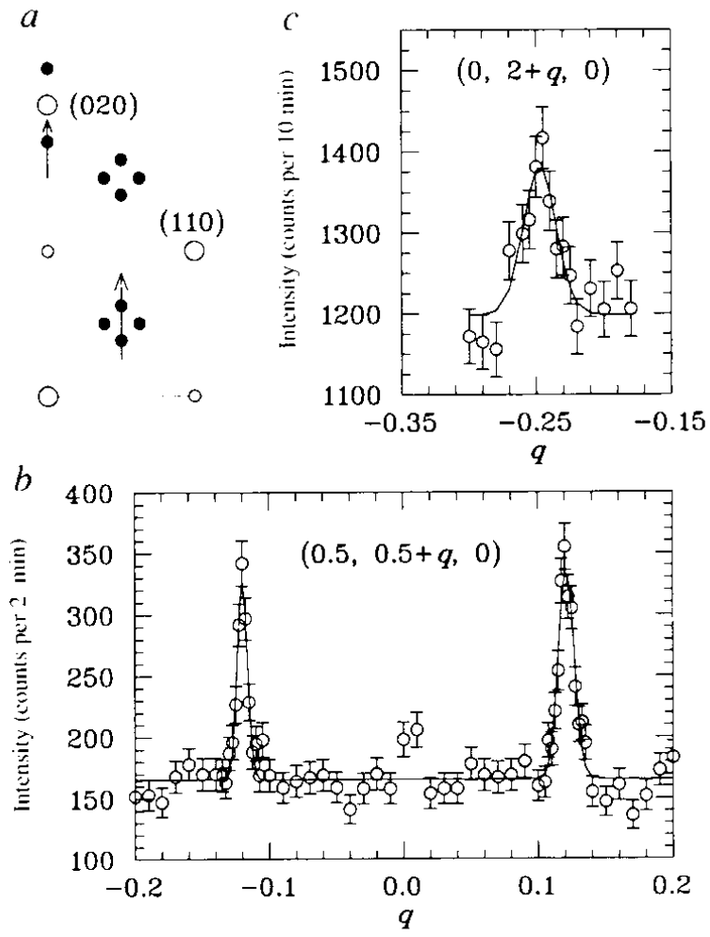


But the cuprates are 2D not 1D?

Enter Stripes

Zaanen and Gunnarsson, Machida, 1989

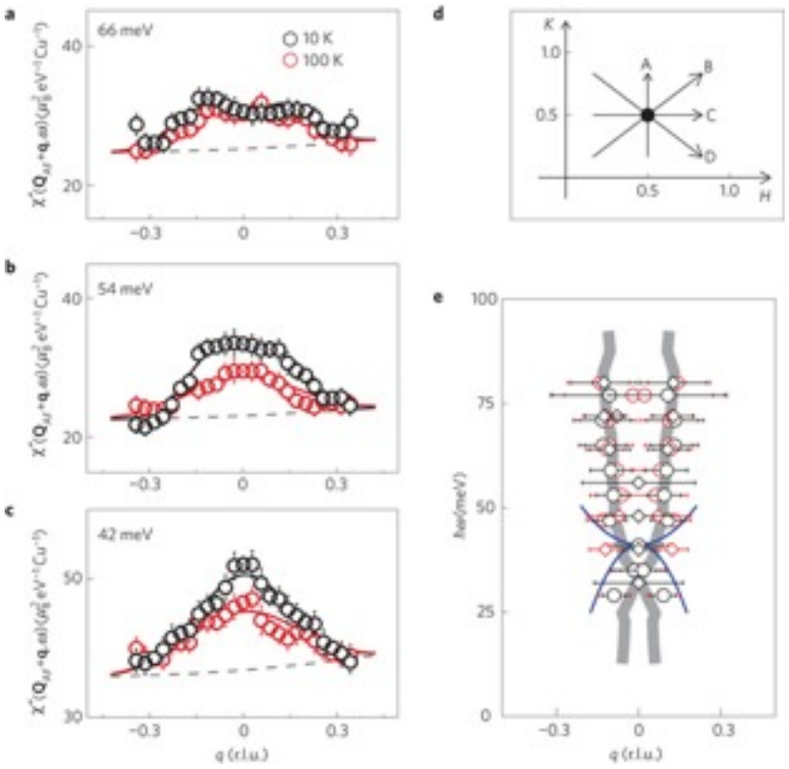




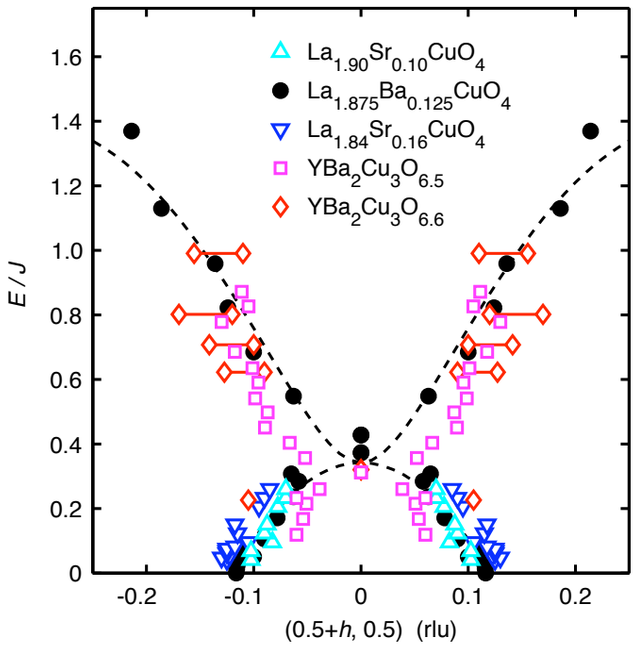
Tranquada et al, Nature 1995

Emery and Kivelson 1993, pairing from spin gap (RVB state) on stripes.

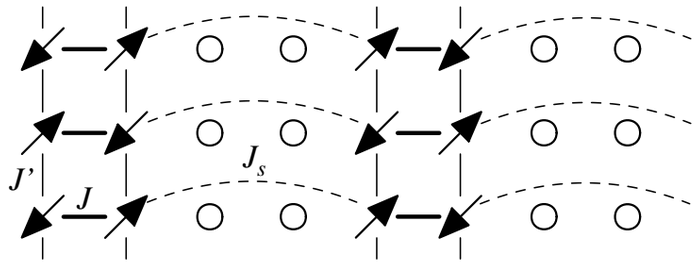
Universal Spin Correlations, hourglass spectrum



Xu et al, Nature Physics 2009, BSCCO



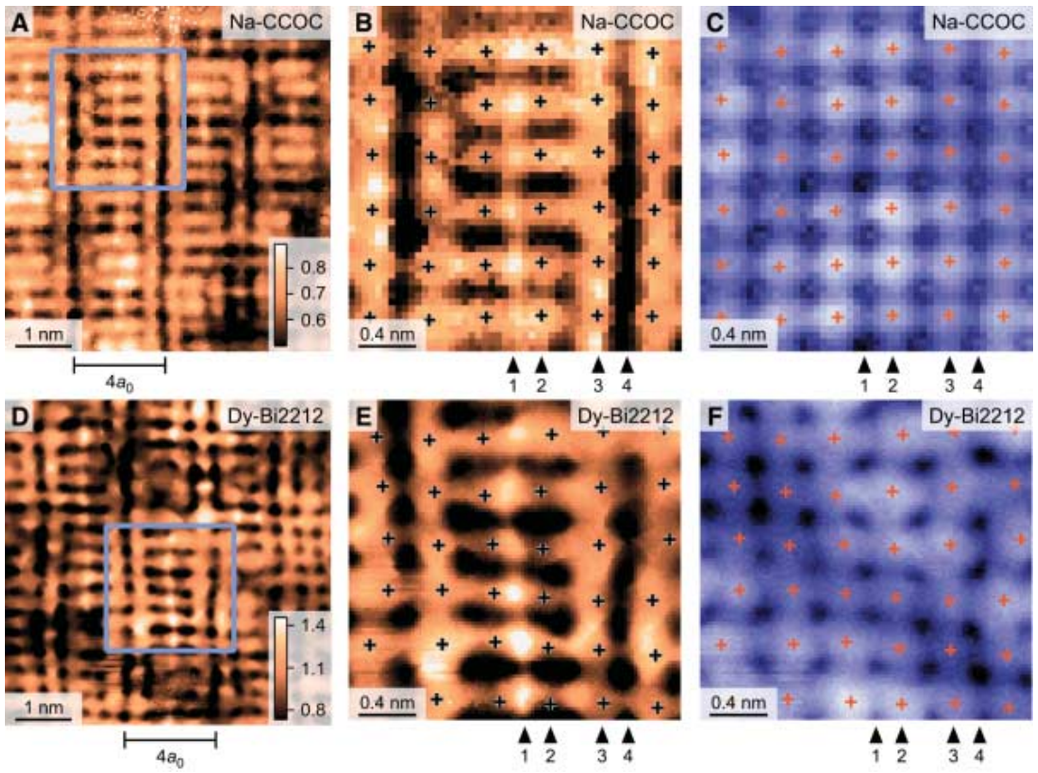
Christensen et al PRL 2004, Stock et al PRB 2005,
Hayden et al Nature 2004, Tranquada et al Nature 2004



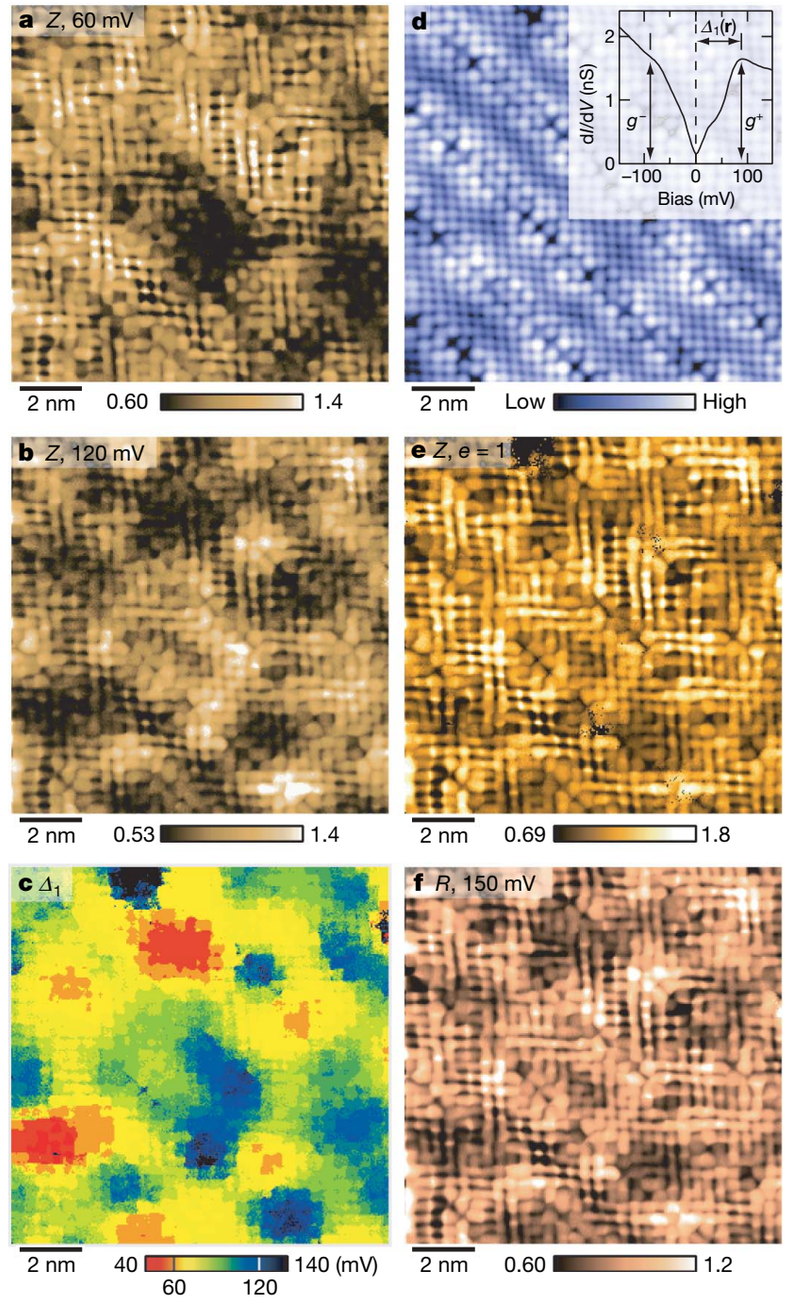
M. Vojta and Ulbricht, PRL 2004,
Seibold and Lorenzana PRL 2005,
Yao et al PRL 2006

low energy, spin waves
high energy, spin ladder magnons

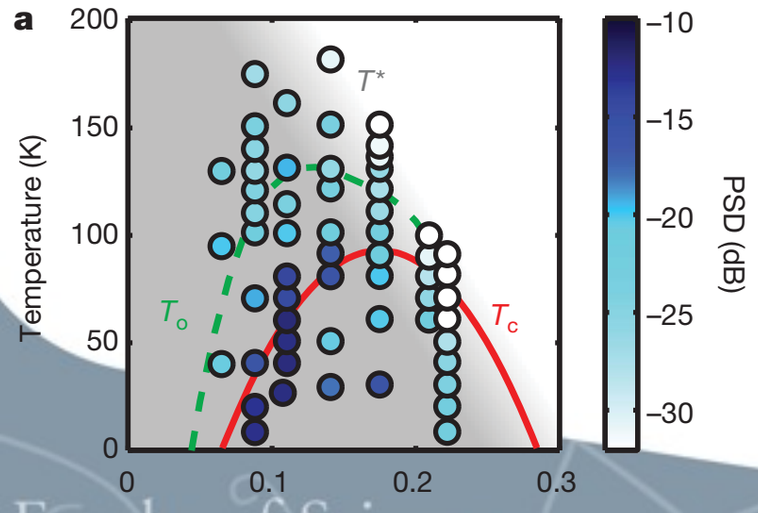
Stripe Glass seen by Scanning tunneling Spectroscopy



Kohsaka et al, Science 2007.



Kohsaka et al, Nature 2008.

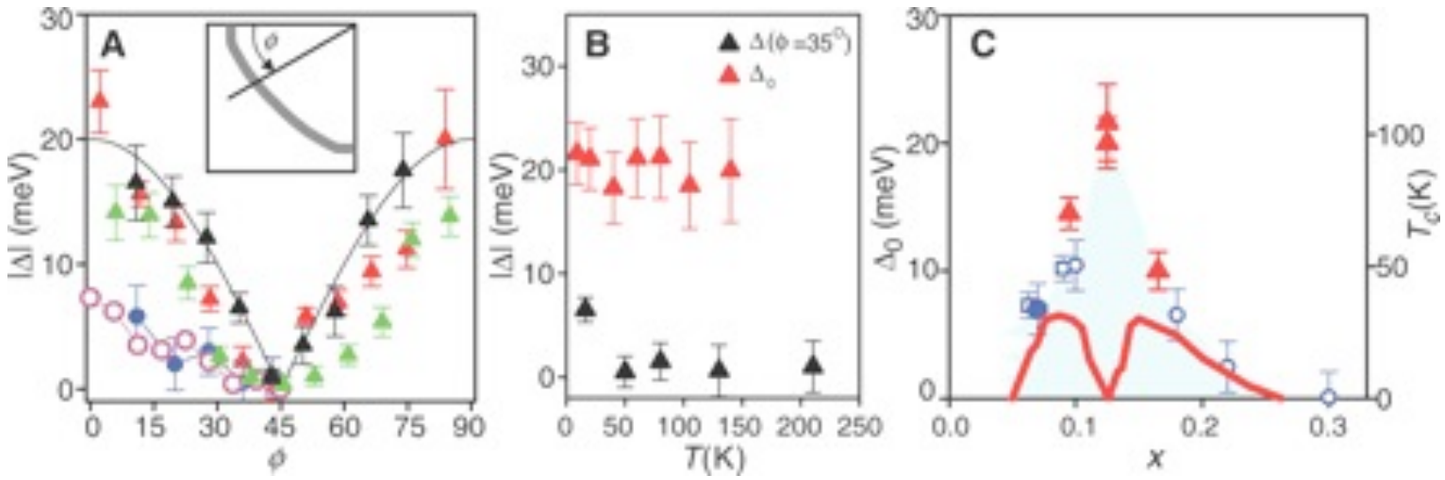


Charge order correlated with the pseudogap

Parker et al, Nature 2010

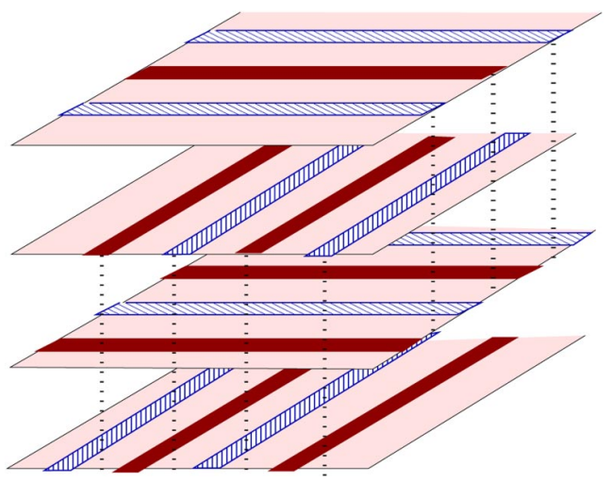
Competition or cooperation, are stripes good or bad for superconductivity?

In LBCO at x=1/8, static stripes and sc coexist.
Evidence for 2D superconductivity at high temperature.

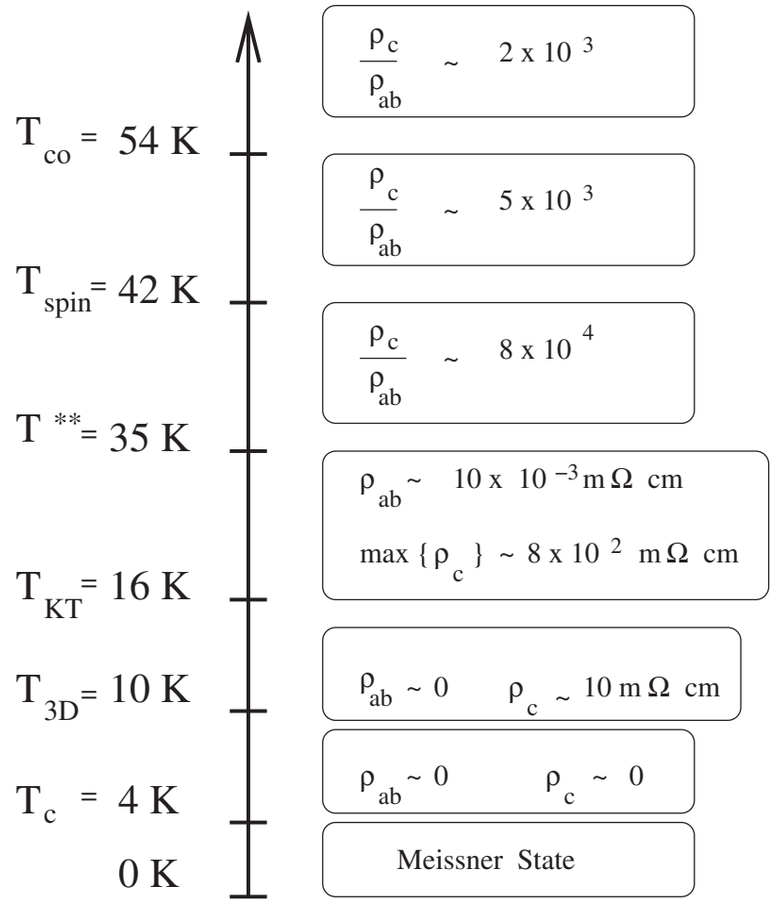


Valla et al Science 2006

Maximal pseudogap at x=1/8 where stripe order is most prominent.



Original high-Tc compound



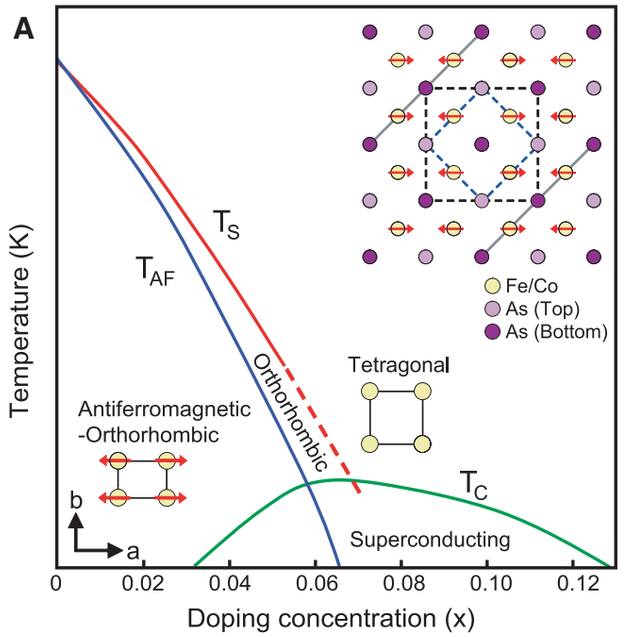
Li et al PRL 2007, Figure: Berg et al PRL 2007

In plane resistivity drops dramatically (to 0?) with stripe ordering!

Stripes in pnictides?

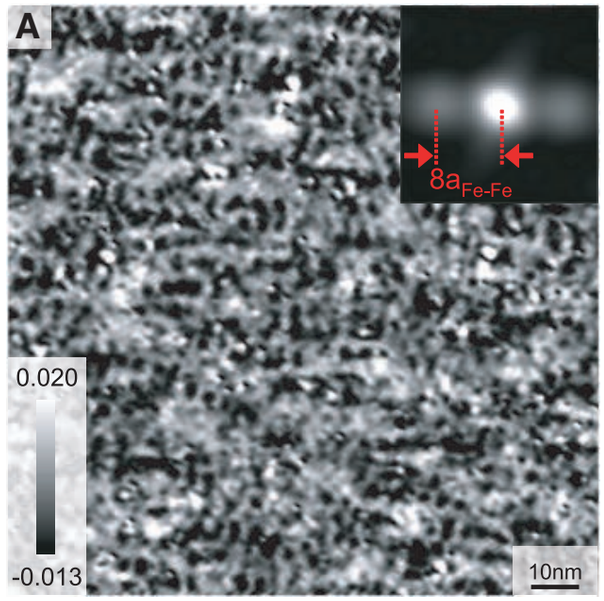
New (2008) Iron based high-T_c superconductors

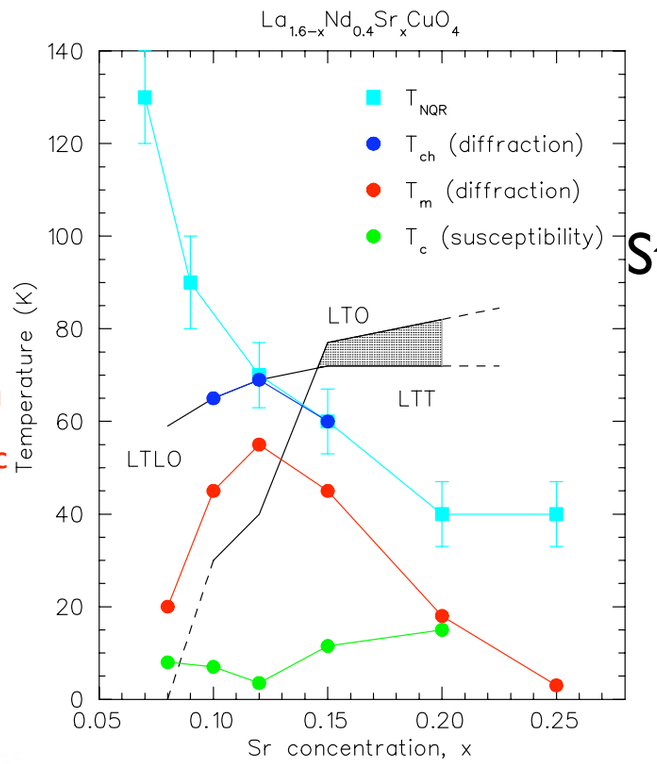
Chuang et al, Science 2010



Tetragonal to orthorhombic transition is common to the two types of high-T_c superconductor

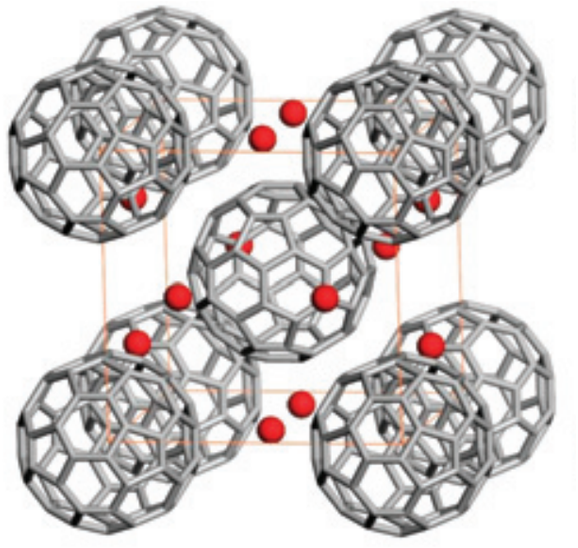
$Ca(Fe_{1-x}Co_x)_2As_2$



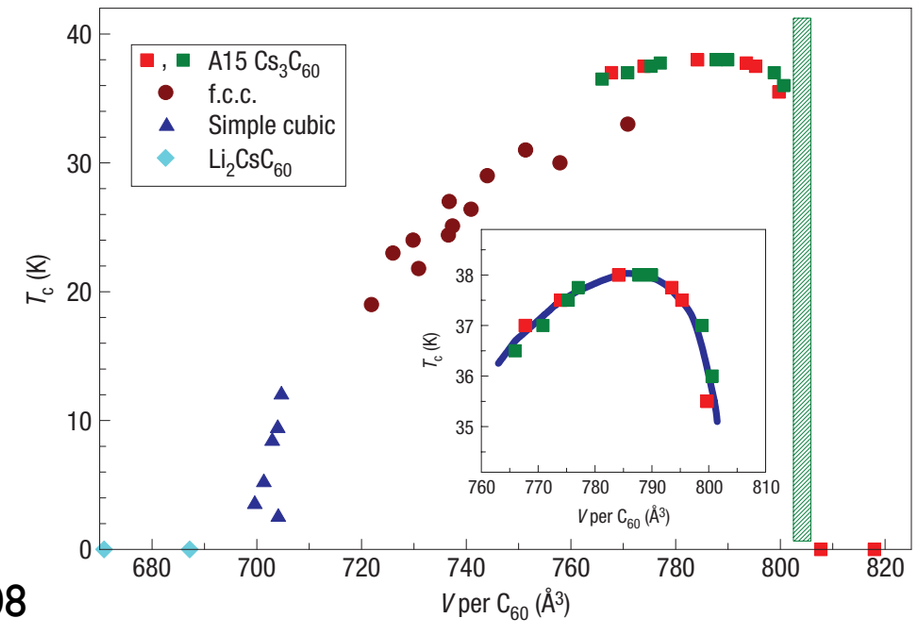


Static charge order with direction tied to orthorombic distortion

Paring on balls instead of stripes in A_3C_{60}?



A.Y. Ganin et al, Nature Materials 2008



- Non-monotonic T_c with lattice spacing (density of states).
- Metal-insulator (Mott insulator) transition.
- Antiferromagnetic order.

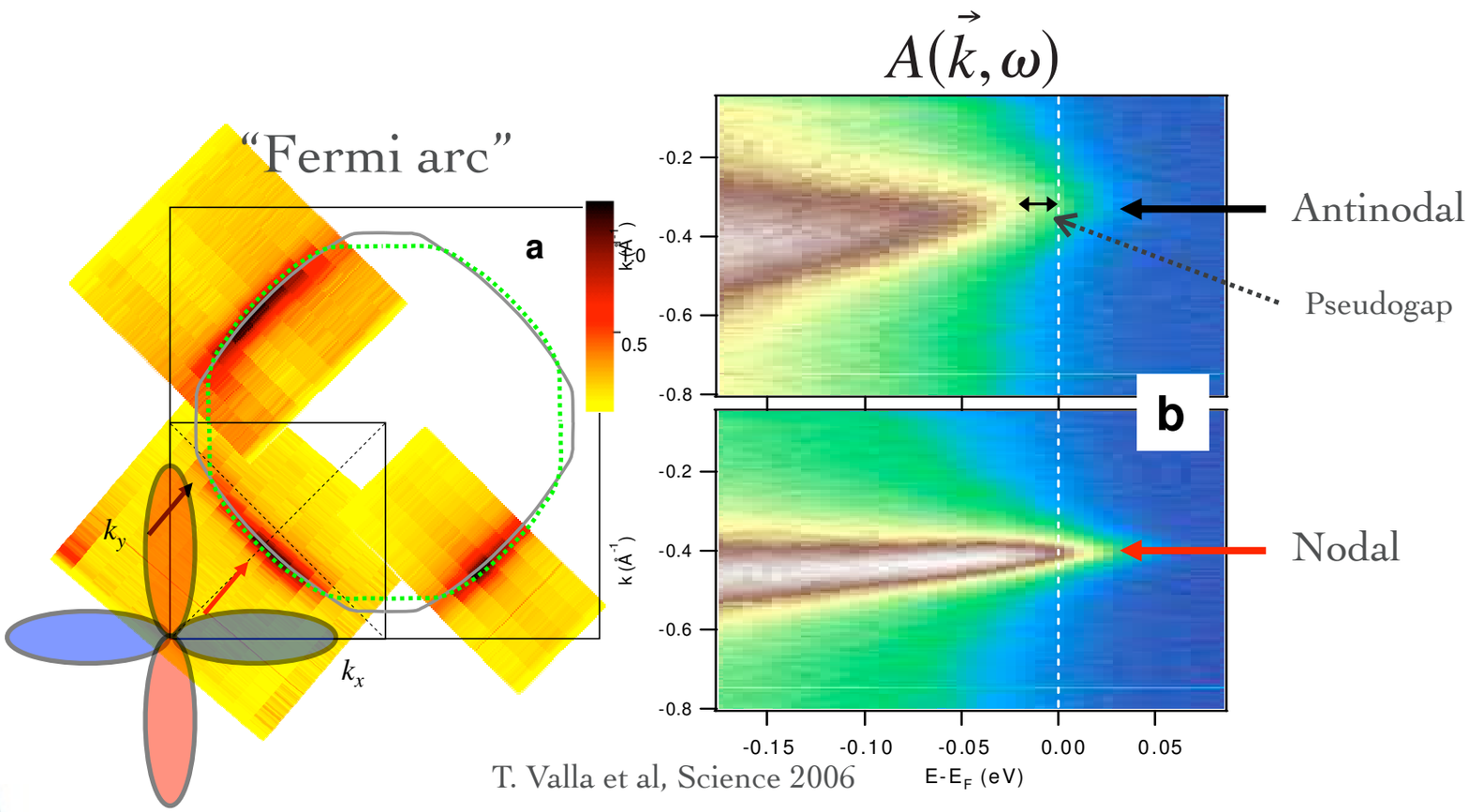
Returning to cuprates

ARPES

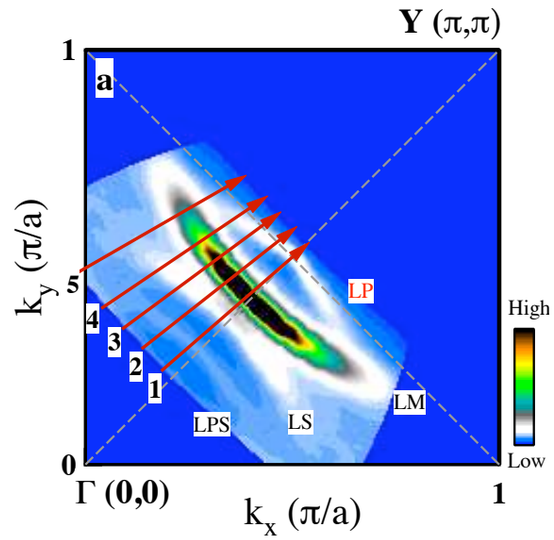
Angle resolved photoemission

Are stripe correlations related to:

- Normal state antinodal pseudogap?
- Normal state Fermi arc?
- Other spectral features?



T. Valla et al, Science 2006



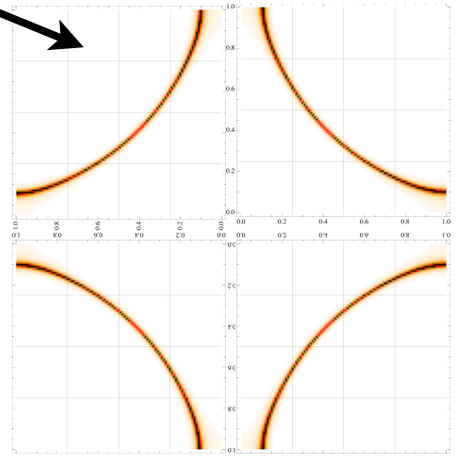
J. Meng et al, Nature 09
La-BSCCO U18

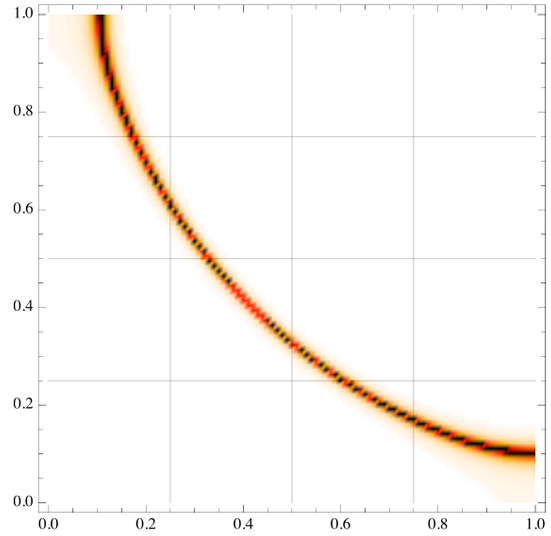
Stripes in mean field

$$H_t = -t \sum_{<rr'>} c^\dagger_{r\sigma} c_{r'\sigma} - t' \sum_{<<rr'>>} c^\dagger_{r\sigma} c_{r'\sigma}$$

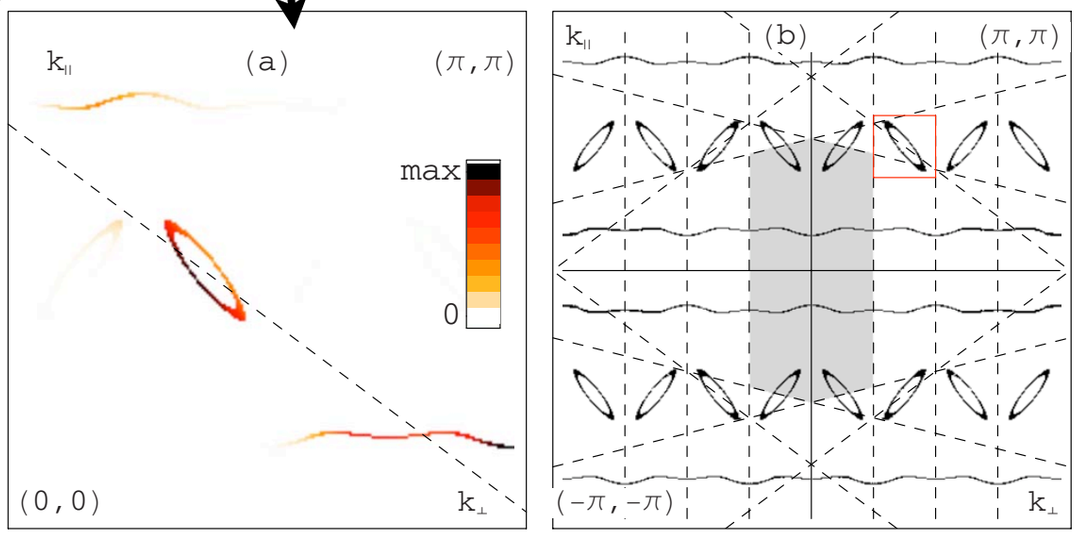
$$\begin{aligned} H_{SDW} &= m\sigma \sum_{x,y} (-1)^y V(x) n_{x,y,\sigma} \\ &= m\sigma \sum_{k_x,k_y,q} V_q c^\dagger_{k_x,k_y,\sigma} c_{k_x-q,k_y-\pi,\sigma} \, . \end{aligned}$$

Bare Fermi surface





Band folding due to spin density wave order



M.G. PRB 2008

In mean field, stripes give antinodal spectral weight ("stripe bands")

SDW/CDW order cannot explain pseudogap

Include on-stripe pair correlations ("RVB stripes")

M.G. and B.M. Andersen, PRB 2010

Single particle caricature of the correlated system with spin gap on charge stripes:

$$H_t = -t \sum_{<rr'>} c^\dagger_{r\sigma} c_{r'\sigma} - t' \sum_{<<rr'>>} c^\dagger_{r\sigma} c_{r'\sigma}$$

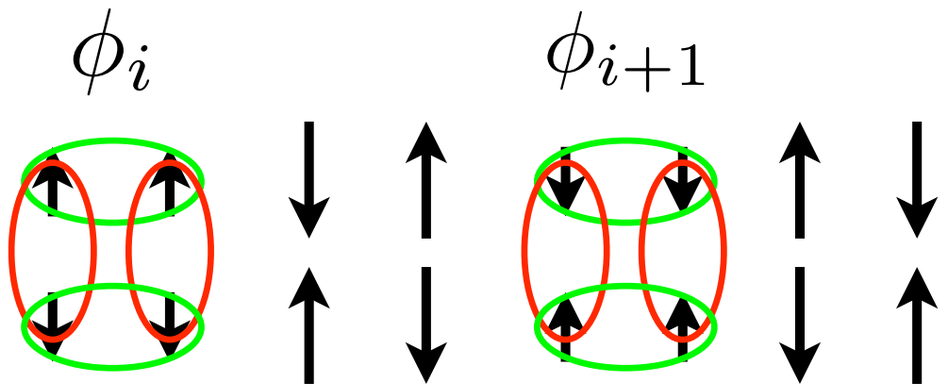
$$H_{SDW} = m\sigma \sum_{x,y} (-1)^y V(x) n_{x,y,\sigma}$$

$$= m\sigma \sum_{k_x,k_y,q} V_q c^\dagger_{k_x,k_y,\sigma} c_{k_x-q,k_y-\pi,\sigma} \, .$$

$$H_{BCS,d} = \Delta_d \sum_{i,y,\sigma} e^{i\phi_i} \Big(c^\dagger_{x_{1,i},y,\sigma} c^\dagger_{x_{2,i},y,-\sigma} - \quad (2)$$

$$(c^\dagger_{x_{1,i},y,\sigma} c^\dagger_{x_{1,i},y+1,-\sigma} + c^\dagger_{x_{2,i},y,\sigma} c^\dagger_{x_{2,i},y+1,-\sigma}) \Big) + H.C.$$

$$H_{BCS,s} = \Delta_s \sum_{i,y,j=1,2;\sigma} (e^{i\phi_i} c^\dagger_{x_{j,i},y,\sigma} c^\dagger_{x_{j,i},y,-\sigma}) + H.C.$$



pairing on charge stripes
incoherent between stripes,
d- or s-like

On-stripe pairing gives pseudogap/nodal pocket

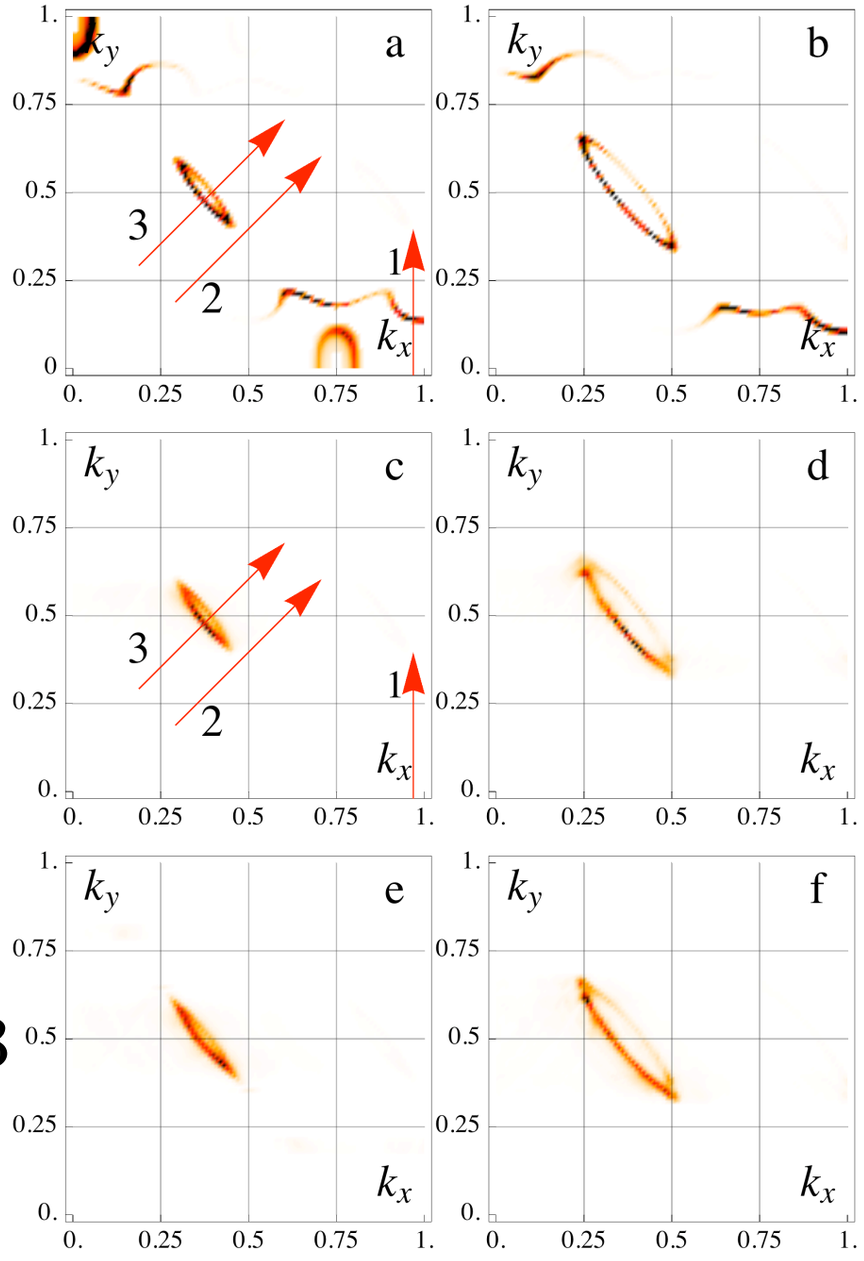
$m = t/3$ $\quad A(k, \omega = 0)$

$n \approx 0.16$ $\quad n \approx 0.20$

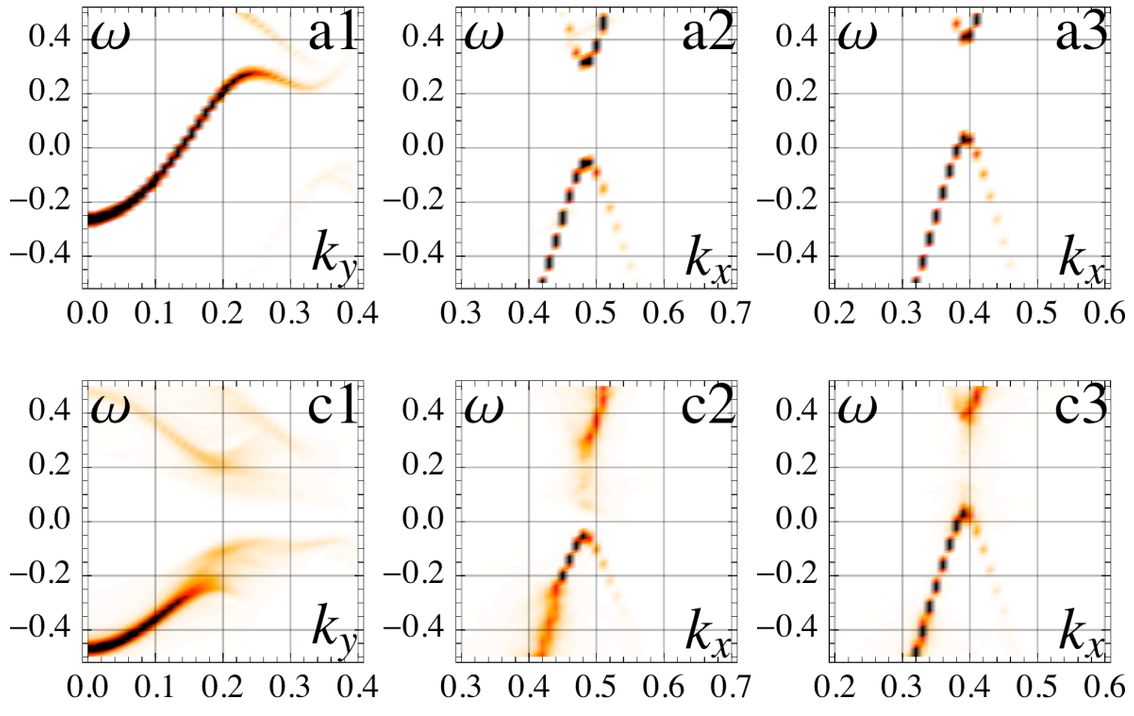
$\Delta = 0$

$\Delta_d = t/4$

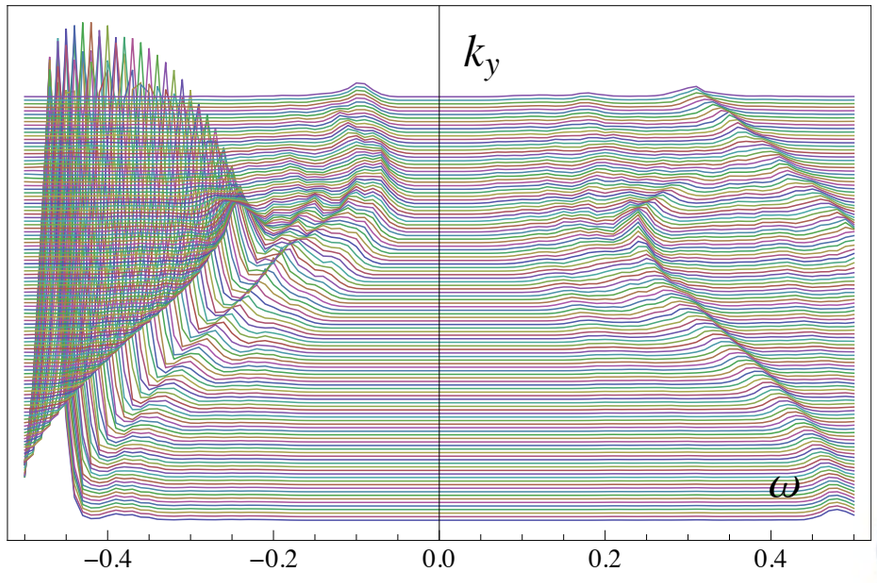
$\Delta_s = t/3$



$A(k, \omega)$



particle-hole symmetric antinodal pseudogap



Faculty of Science

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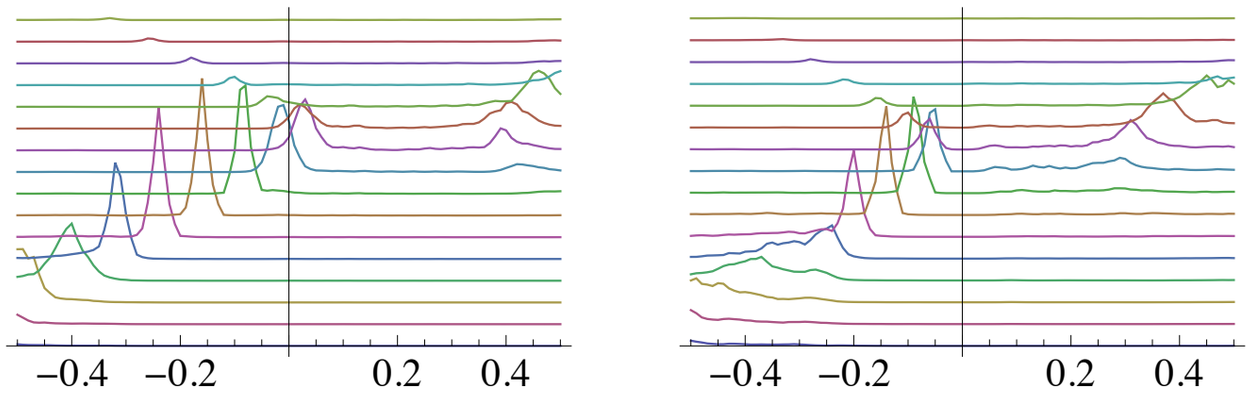
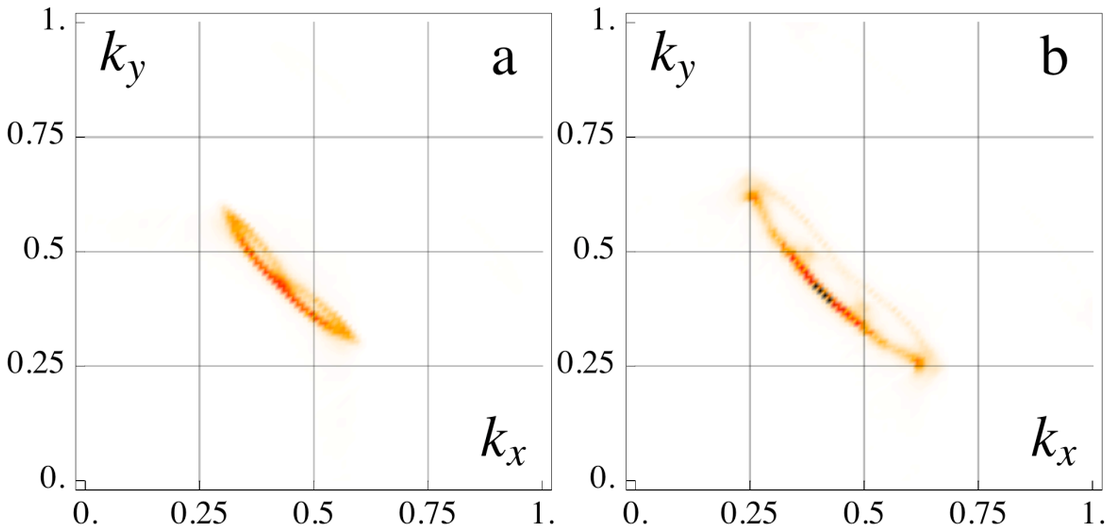
Pocket

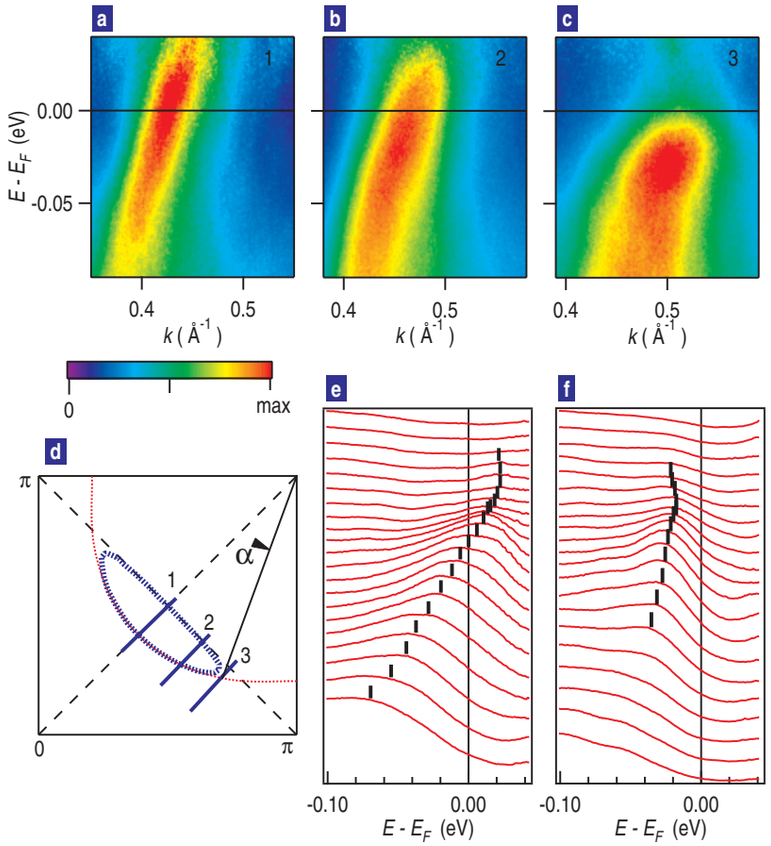
Line cuts, EDCs



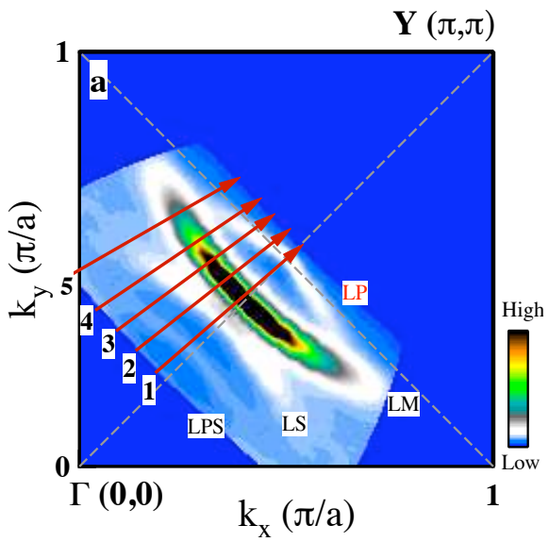
Symmetrized "Fermi surface" w.r.t. stripe orientation:



$n \approx 0.16$ $n \approx 0.20$



Yang et al, Nature 2008



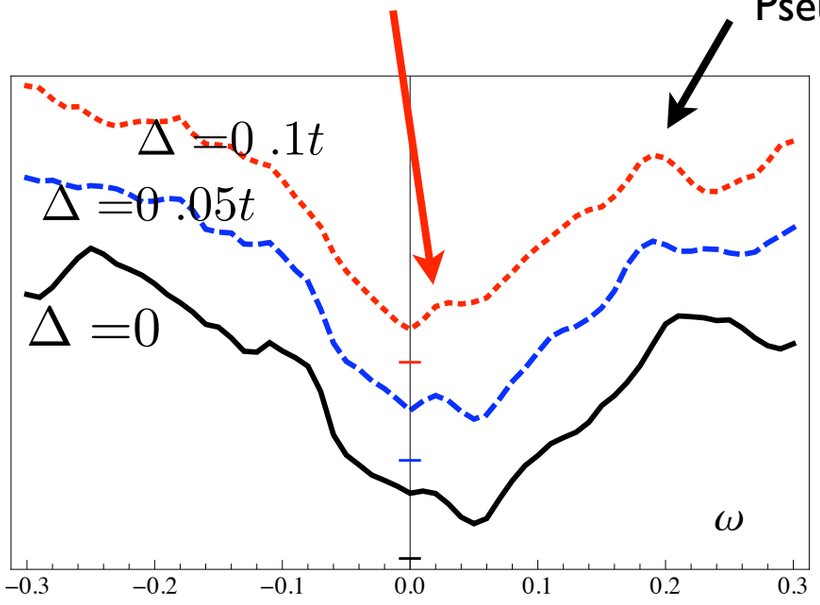
J. Meng et al, Nature 09
La-BSCCO U18

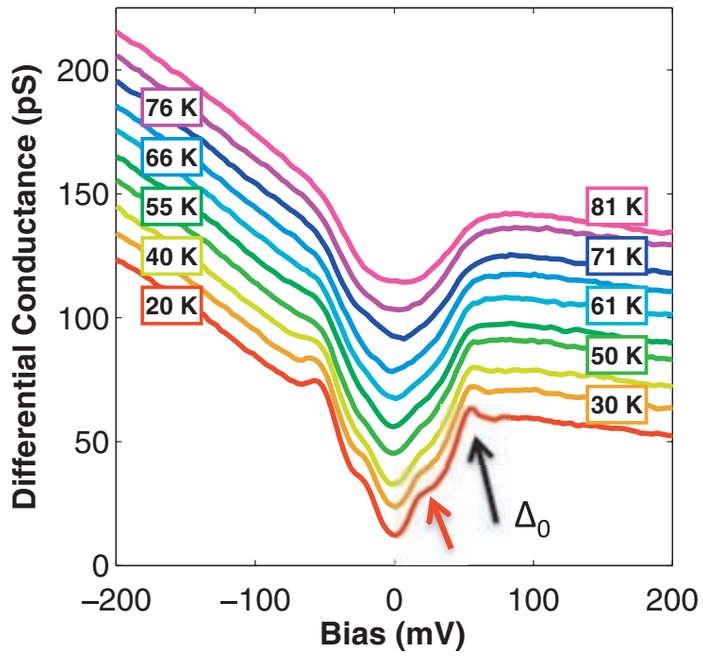
Superconducting state

For a stripe glass state we expect only q=0 pairing to order: $\Delta(\cos k_x - \cos k_y)$

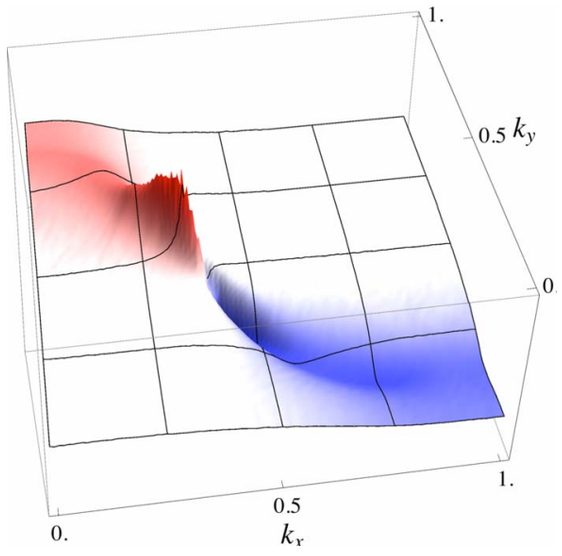
Gapping of the nodal pocket

Pseudogap from on-stripe pairing

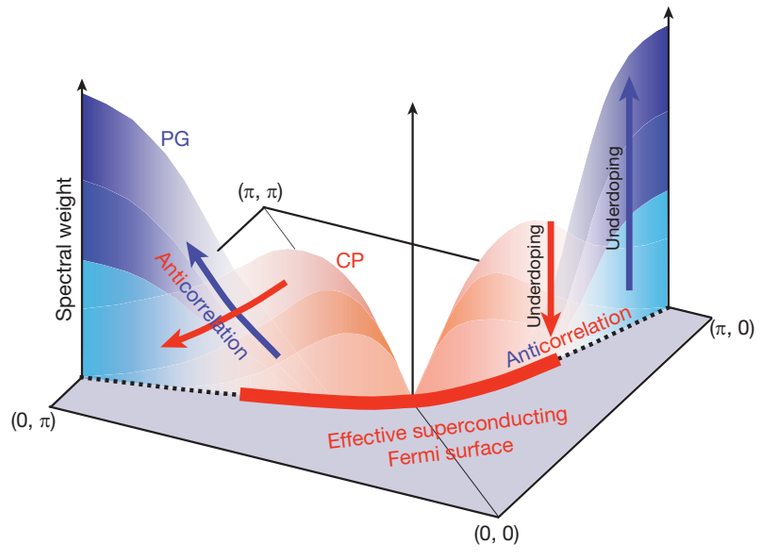




Pushp et al, Science 2009

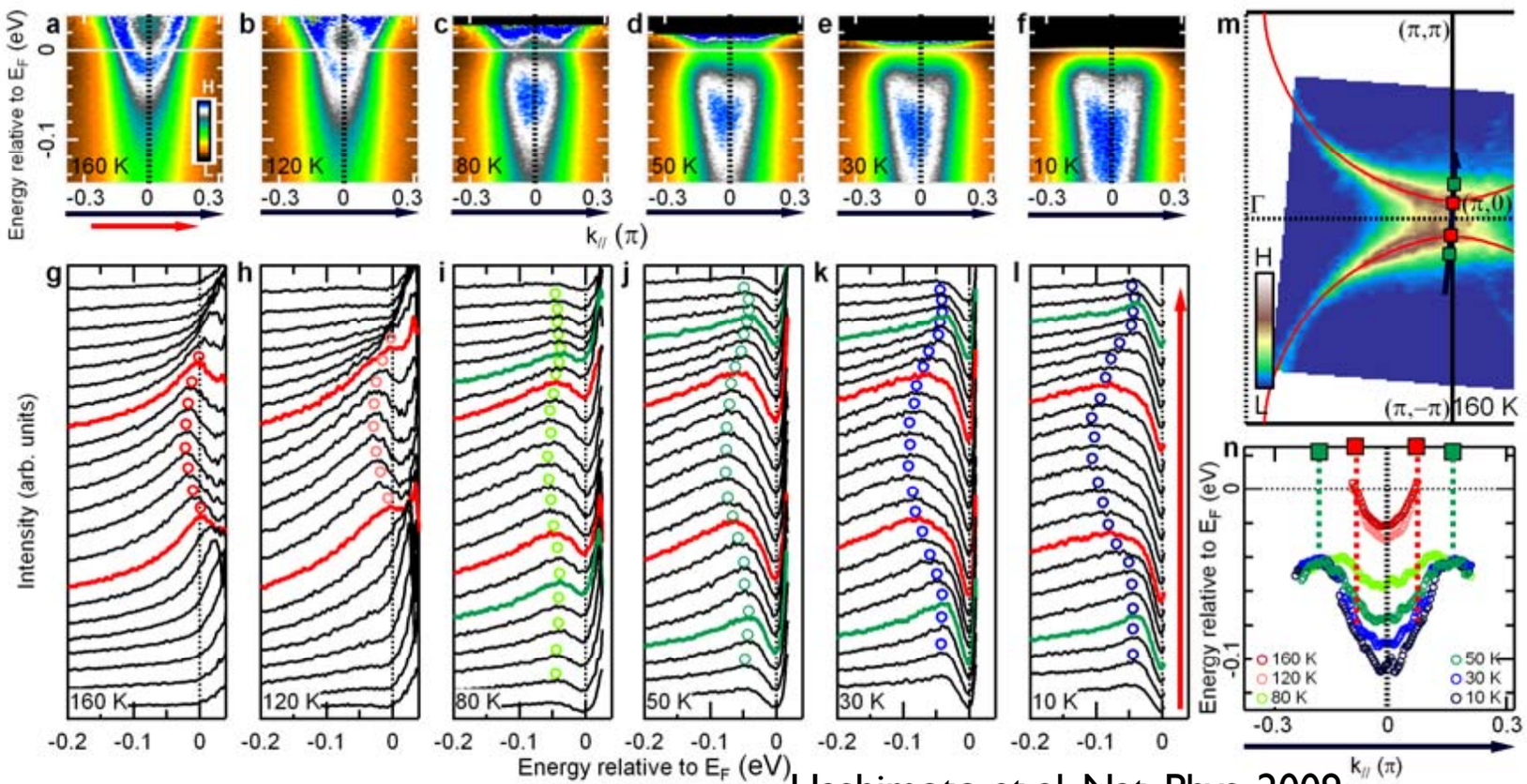


Coherent pair density on (nodal) part of Fermi surface

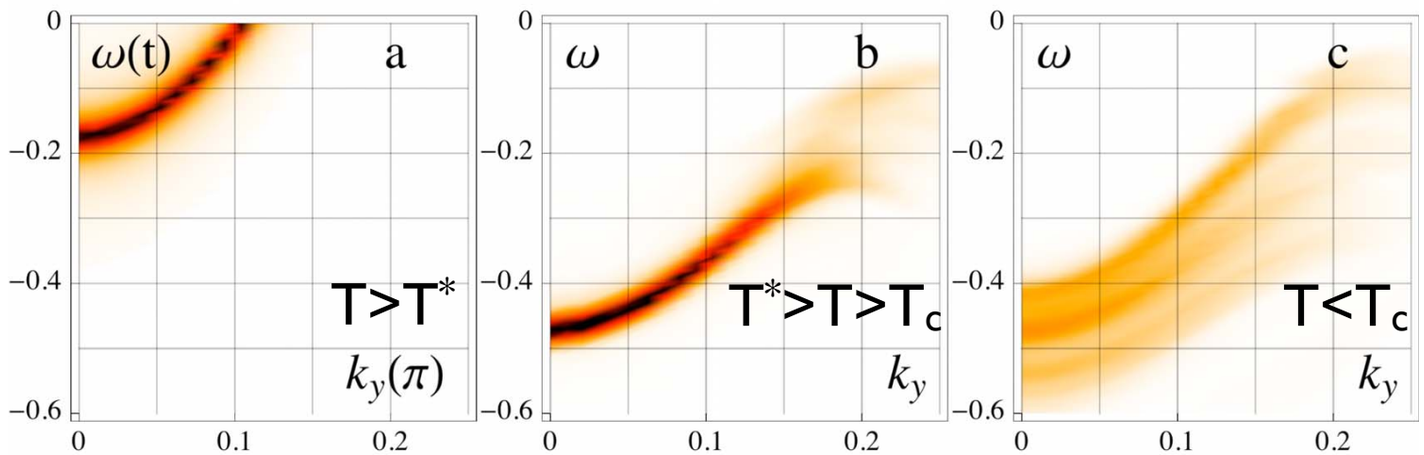


ARPES, Kondo et al. Nat. 2009

Anomalous spectral broadening and shift of k_F

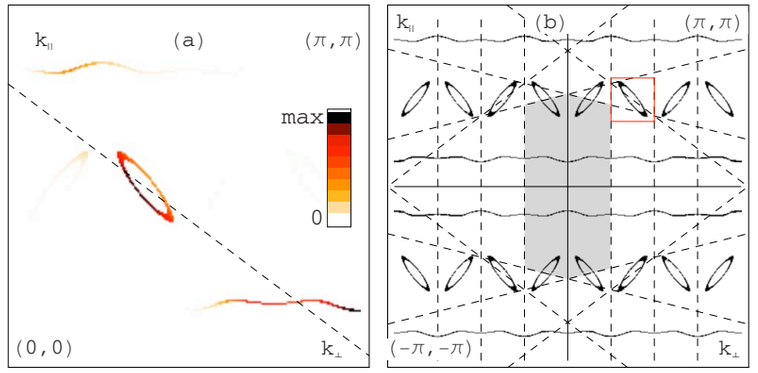


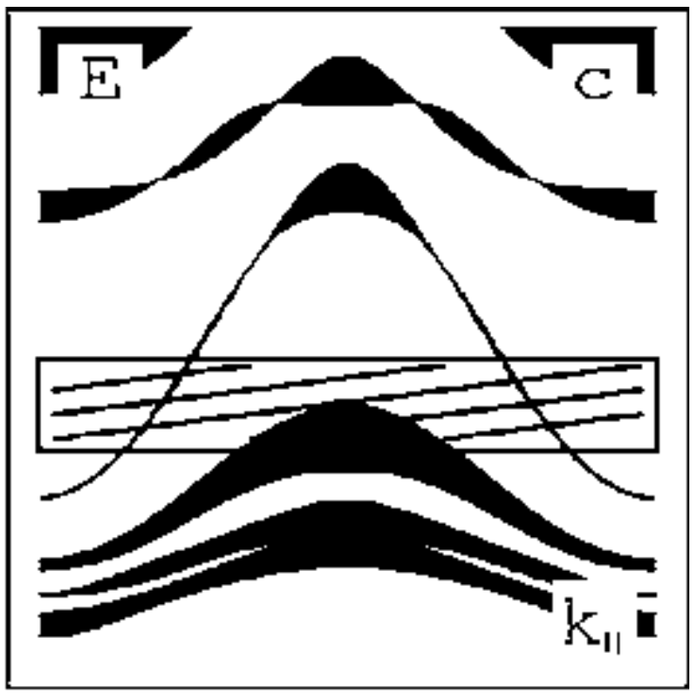
Hashimoto et al, Nat. Phys. 2009



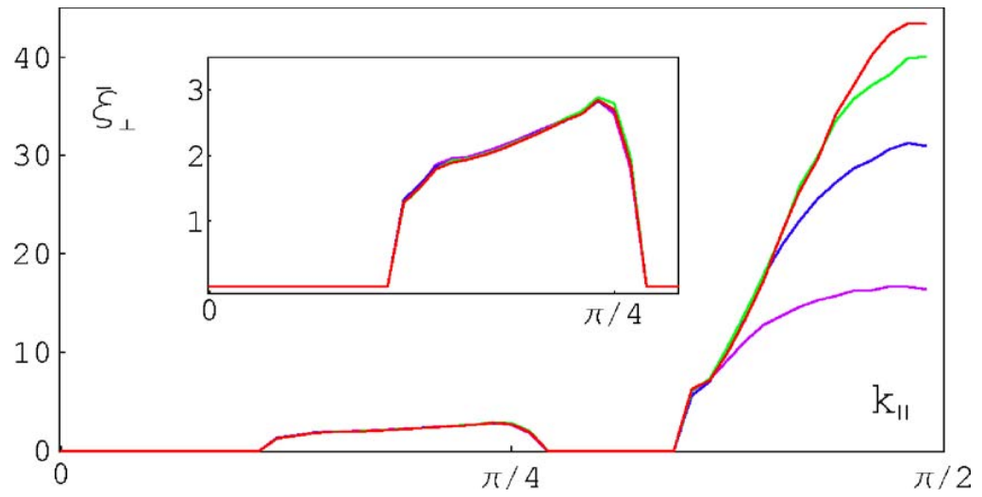
Shift of k_F due to stripe order, broadening due to?

Why antinodal gap?





Localization length with weak potential disorder



M.G. PRB 2006

Band that gives antinodal weight is narrow, "localized" on stripes, thus gapped by local pairing

Summary

- Pseudogap may be RVB stripes (or disordered spin-, charge- and pair-density wave order).
- Number of observed spectroscopic signatures follow.
- Superconductivity from phase coherent pairing on the nodal pocket (Fermi arc)