Charge Density Waves in High Temperature Superconductors

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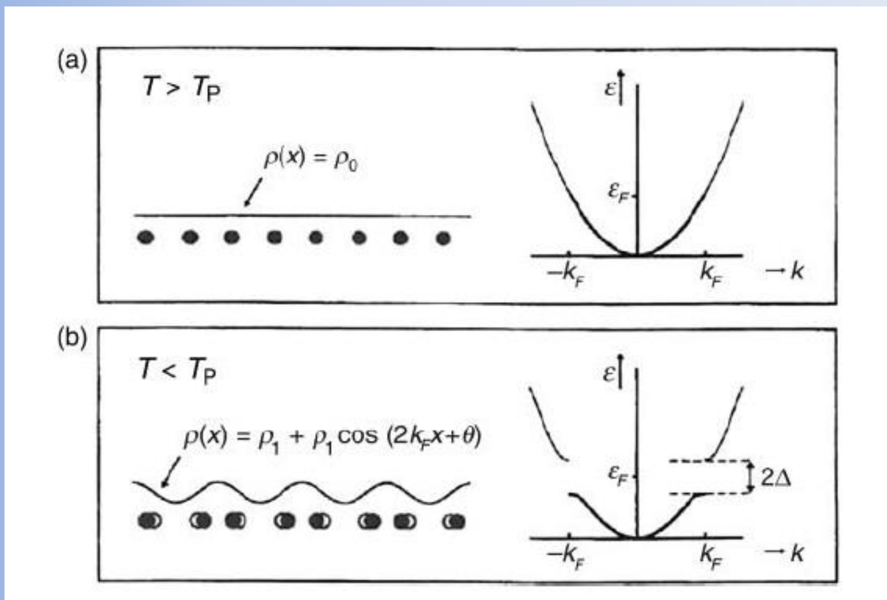
CDWs

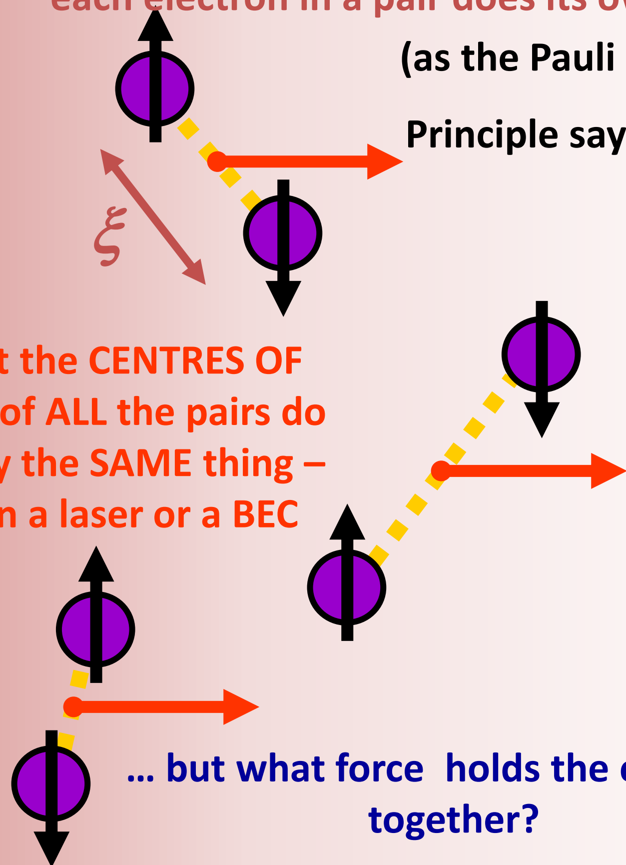


Monceau, Advances in Physics **61**, 325 (2012).

Superconductors

each electron in a pair does its own thing …

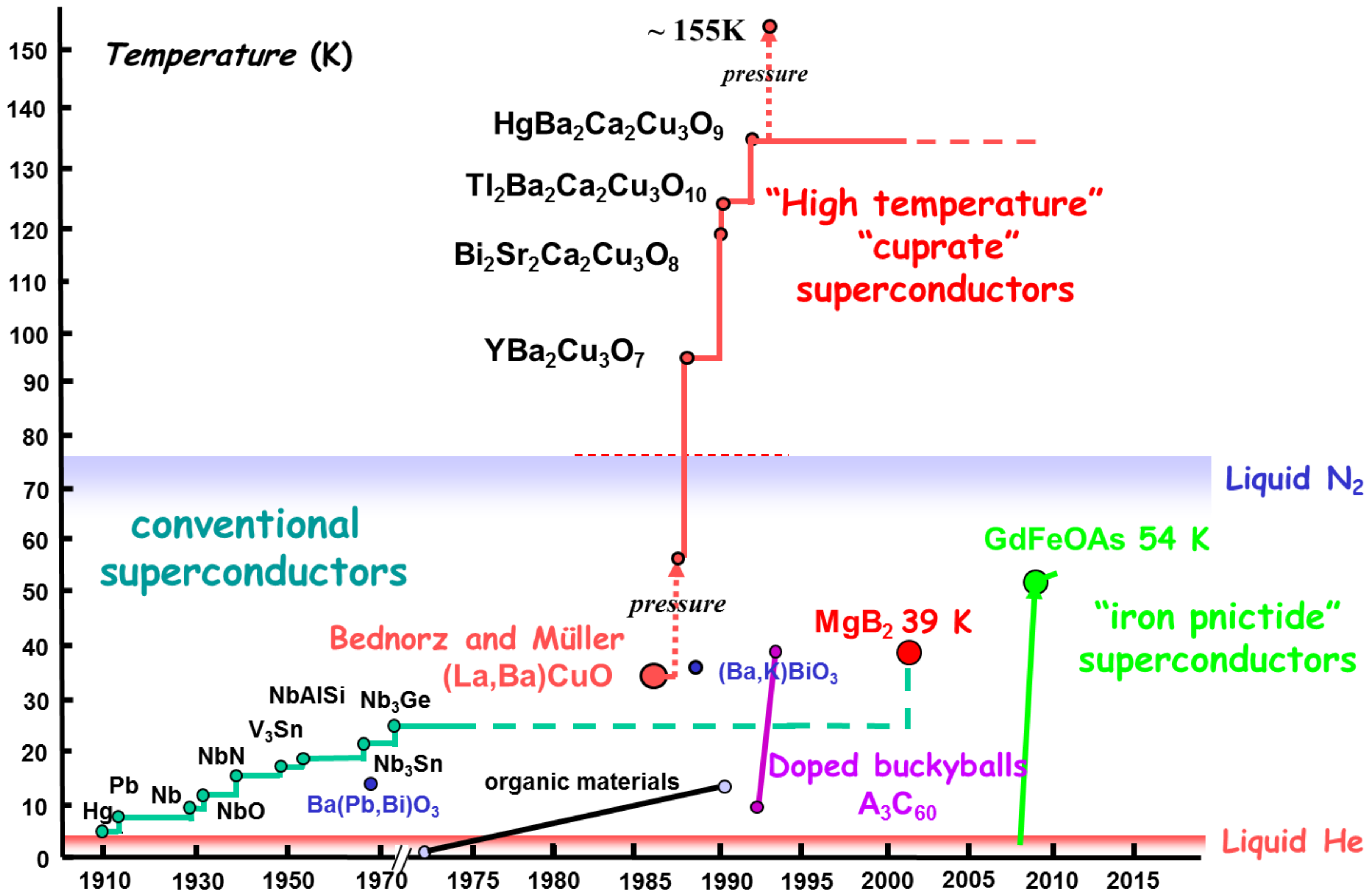
(as the Pauli Exclusion Principle says it must)



… but the CENTRES OF MASS of ALL the pairs do exactly the SAME thing – like in a laser or a BEC

… but what force holds the electrons together?

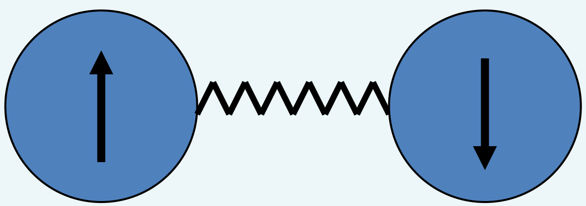
(~ a "coherence length" ξ apart)


Temperature (K)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
~ 155K
pressure
HgBa2Ca2Cu3O9
Tl2Ba2Ca2Cu3O10
Bi2Sr2Ca2Cu3O8
YBa2Cu3O7
"High temperature"
"cuprate"
superconductors
Liquid N2
conventional
superconductors
GdFeOAs 54 K
pressure
MgB2 39 K
"iron pnictide"
superconductors
Bednorz and Müller
(La,Ba)CuO
(Ba,K)BiO3
NbAlSi
Nb3Ge
V3Sn
NbN
Nb3Sn
Pb
Nb
Hg
NbO
Ba(Pb,Bi)O3
organic materials
Doped buckyballs
A3C60
Liquid He
1910
1930
1950
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015

Cooper pairs in superconductors

Conventional '*s*-wave'

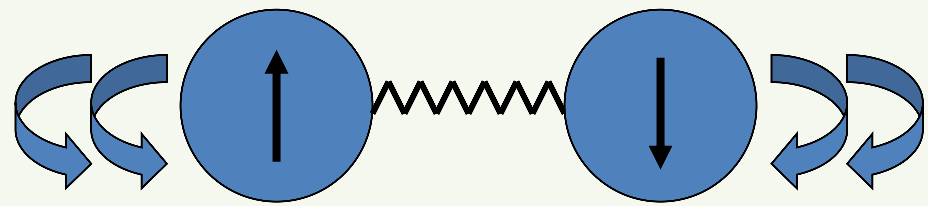
electron pairs



not circulating …

Unconventional '*d*-wave'

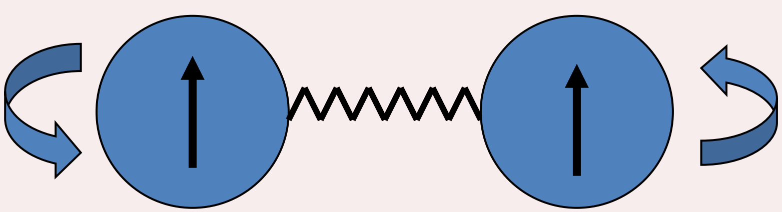
e.g. High-Tc , $CeCoIn_5$



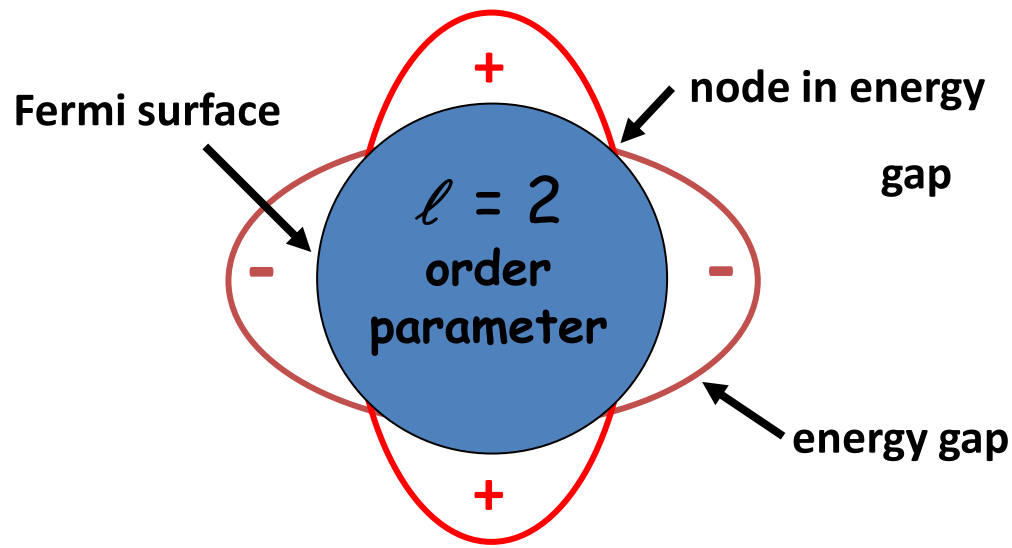
circulating *both* ways - $\ell = 2$

Unconventional: '*p*-wave'

e.g. Sr_2RuO_4



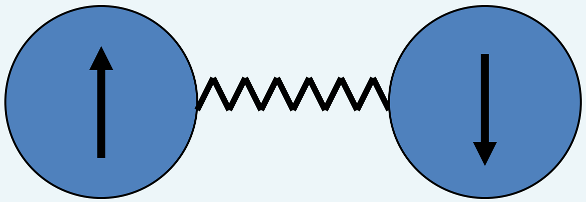
circulating: $\ell = 1$



Cooper pairs in superconductors

Conventional '*s*-wave'

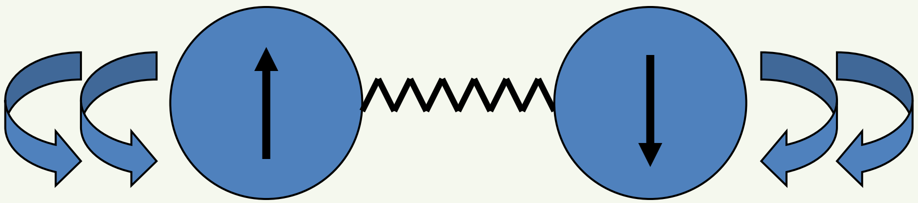
electron pairs



not circulating …

Unconventional '*d*-wave'

e.g. High-Tc , $CeCoIn_5$



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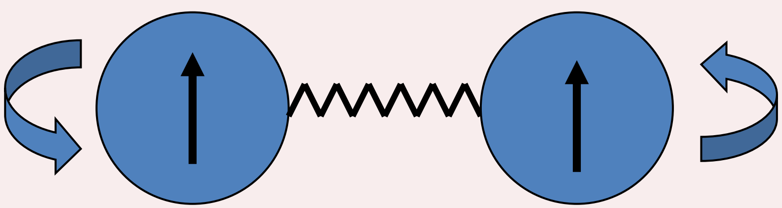
Unconventional: '*p*-wave'

e.g. Sr_2RuO_4

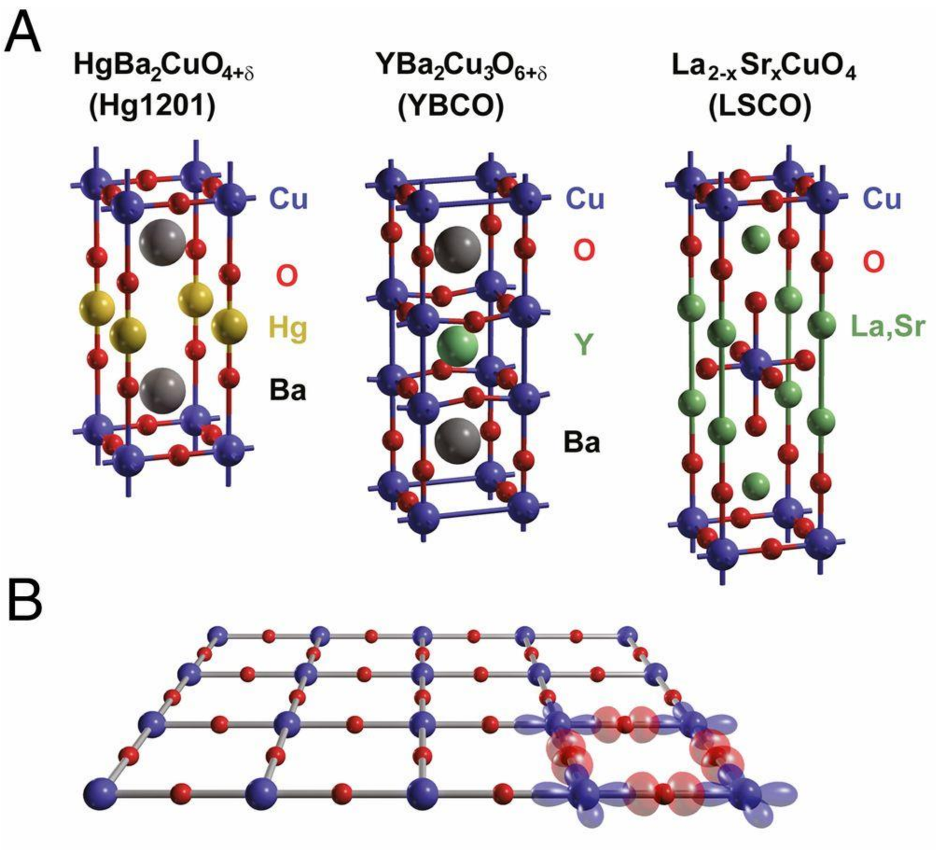


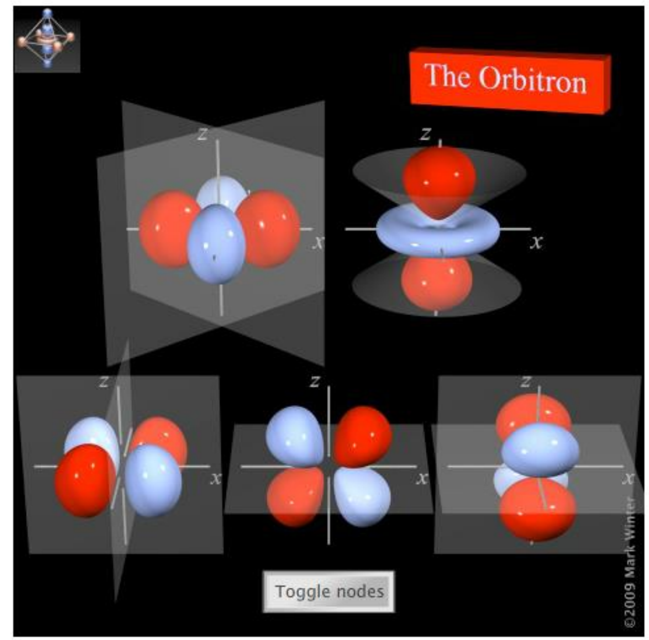
circulating: $\ell = 1$

The type of pairing controls the symmetry of the superconducting gap function, which, amongst other things, affects flux line and Josephson tunnelling properties

How does the pairing arise??

The Copper-Oxygen Planes



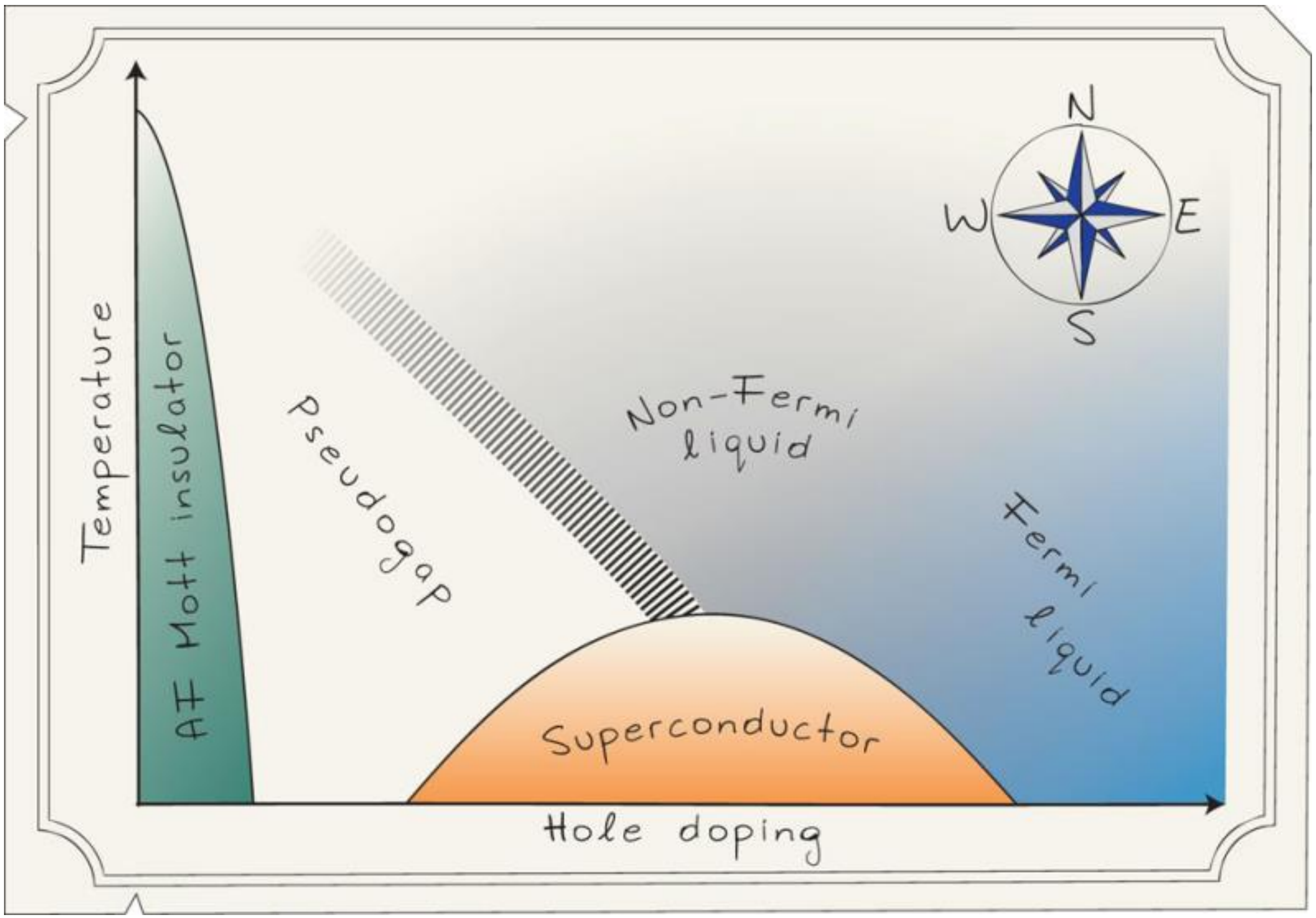


The shape of the five 3d orbitals. *From left to right: (top row) $3d_{x^2-y^2}$ and $3d_{z^2}$ (bottom row) $3d_{xy}$, $3d_{xz}$, and $3d_{yz}$. For each, the yellow zones are where the wave functions have negative values and the blue zones denote positive values.*

Barisic *et al.,* PNAS **110**, 12235 (2013)

Mark Winter,
http://www.shef.ac.uk/chemistry/orbitron/

The cuprate superconductor phase diagram

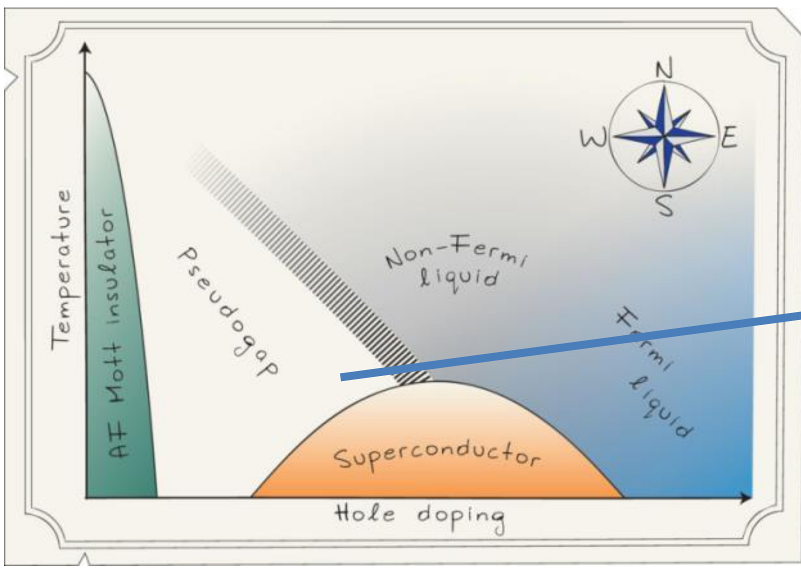


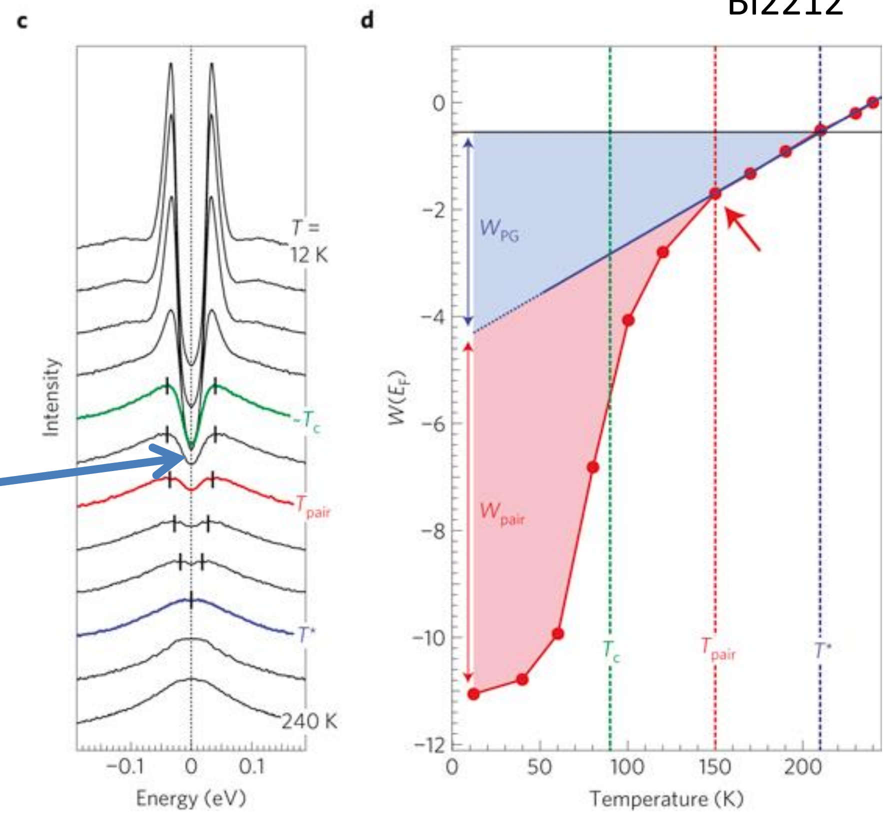
Wahl , Nature Physics (2012)

The pseudogap – loss of DOS at Fermi Level, well above T_c

- Pre-formed pairs?
- Competing order?

Bi2212

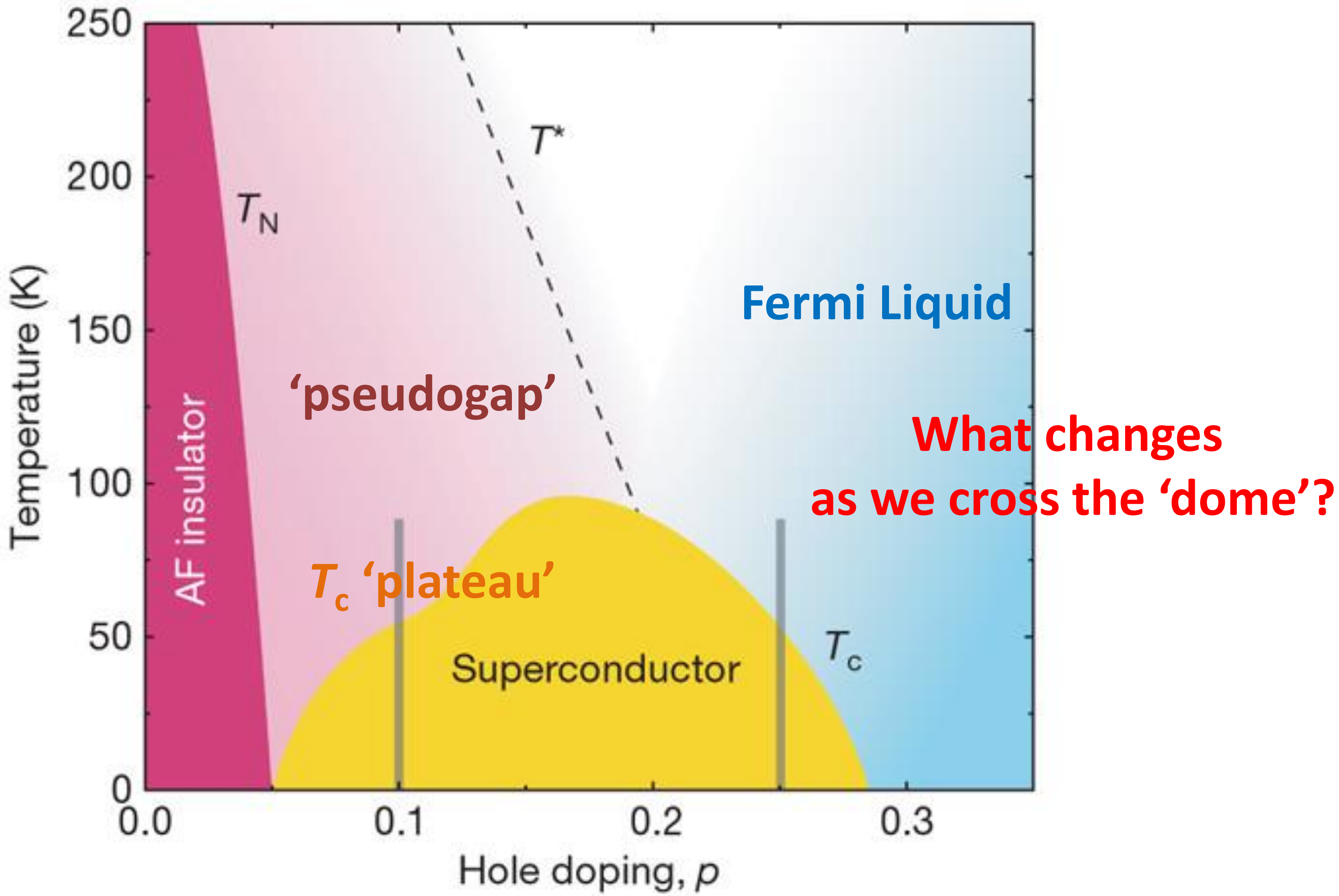




Wahl , Nature Physics (2012)

Kondo *et al.*, Nature Physics (2011)

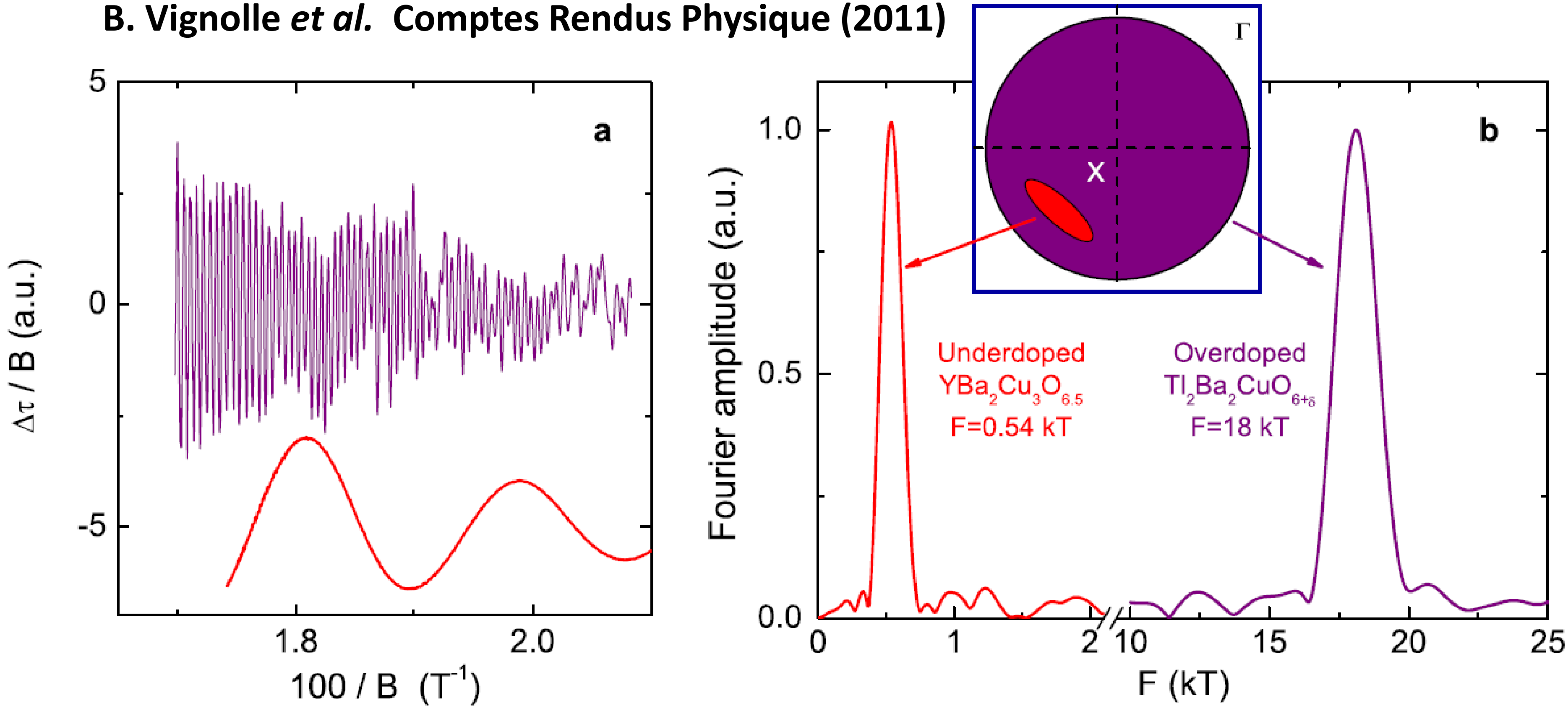
Phase diagram of $YBa_2Cu_3O_{7-x}$ versus doping



The Fermi surface – quantum oscillation data

Overdoped – all holes visible - obeys Luttinger theorem

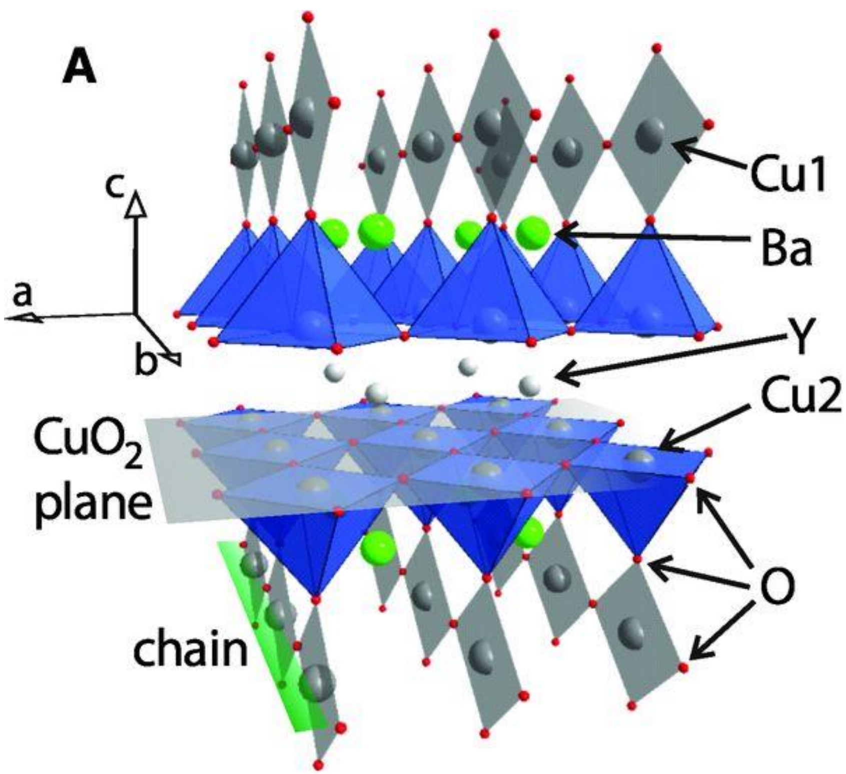
B. Vignolle *et al.* Comptes Rendus Physique (2011)



Underdoped – tiny number of *electrons* not holes

N.B. QOs give the *area* of the electron pocket

Superconductivity in YBCO$_{6+x}$

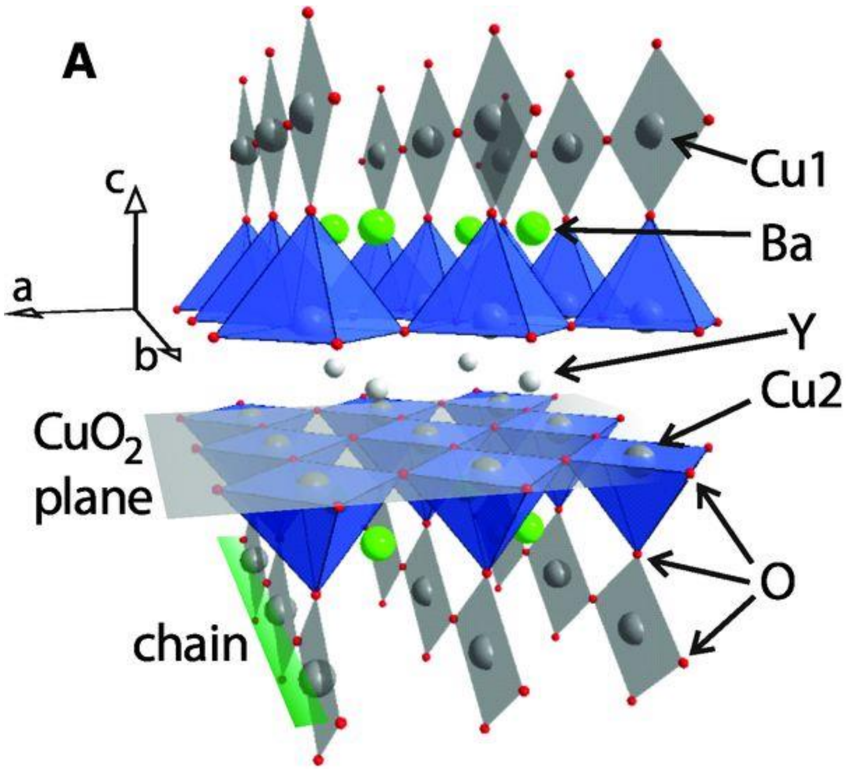


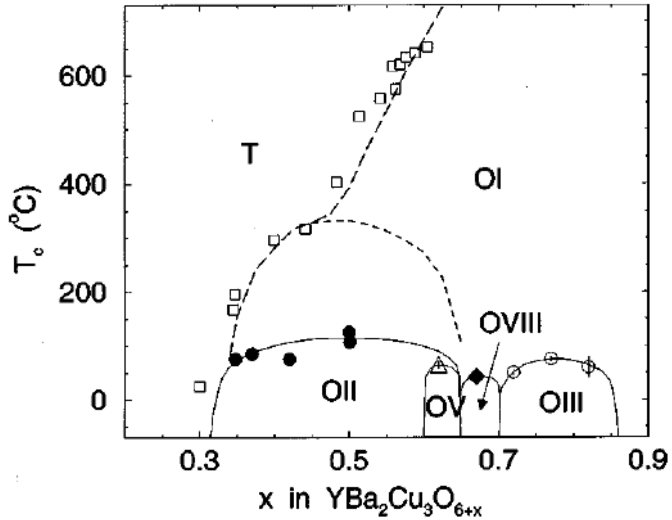
Ghiringhelli *et al.,* Science (2012)
Andersen *et al.,* Physica C (1999)
v. Zimmerman *et al.,* Phys.Rev.B (2003)

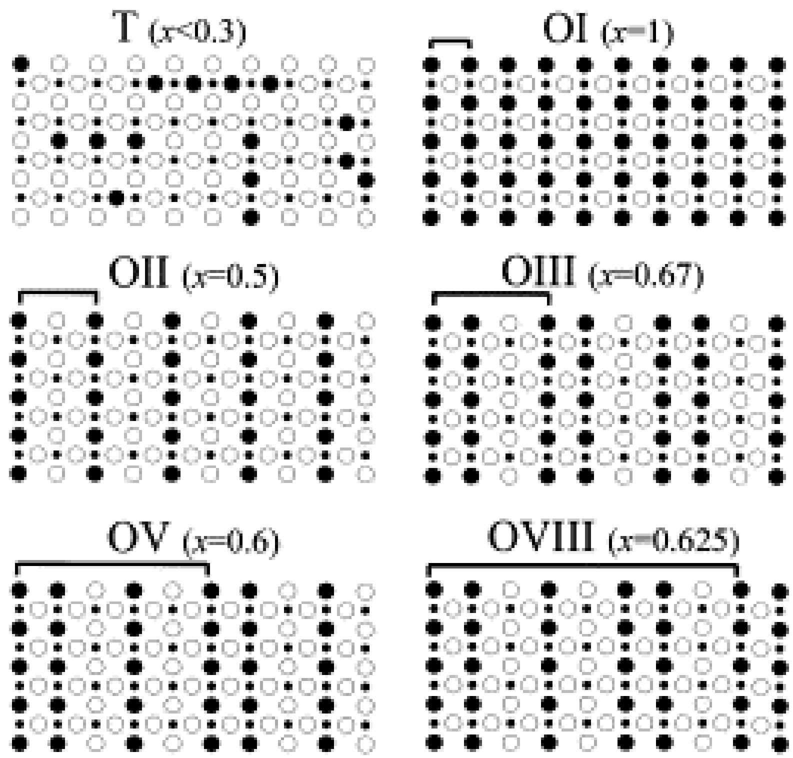
Superconductivity mainly resides in the CuO_2 bi-layered planes

Oxygen content is varied from O_7 to O_6 by removing O from the chains running along ***b***

Oxygen ordering in YBCO$_{6+x}$







Ghiringhelli *et al.,* Science (2012)
Andersen *et al.,* Physica C (1999)
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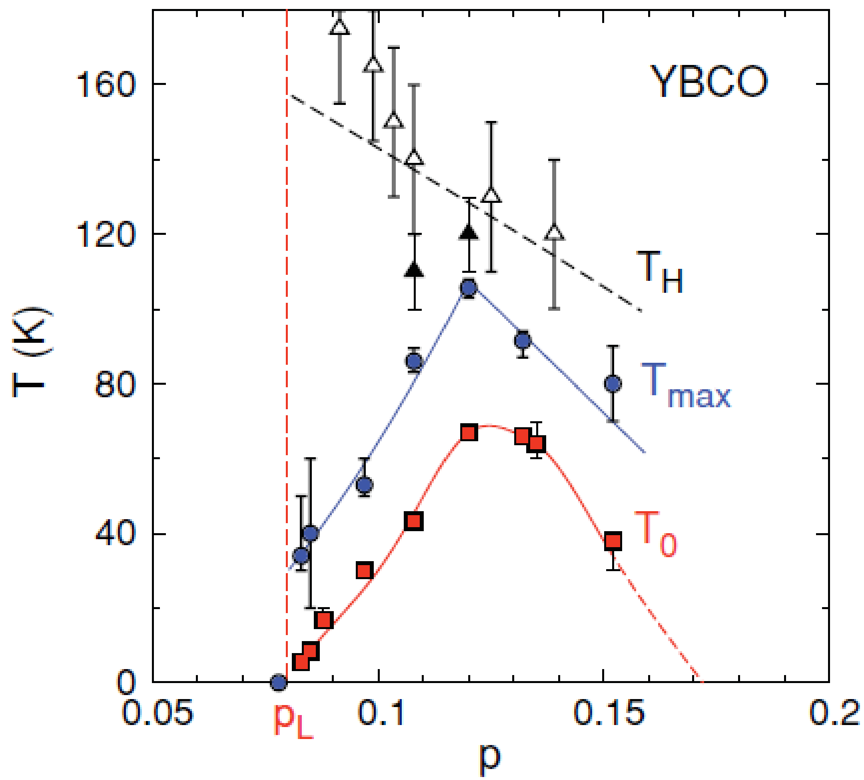
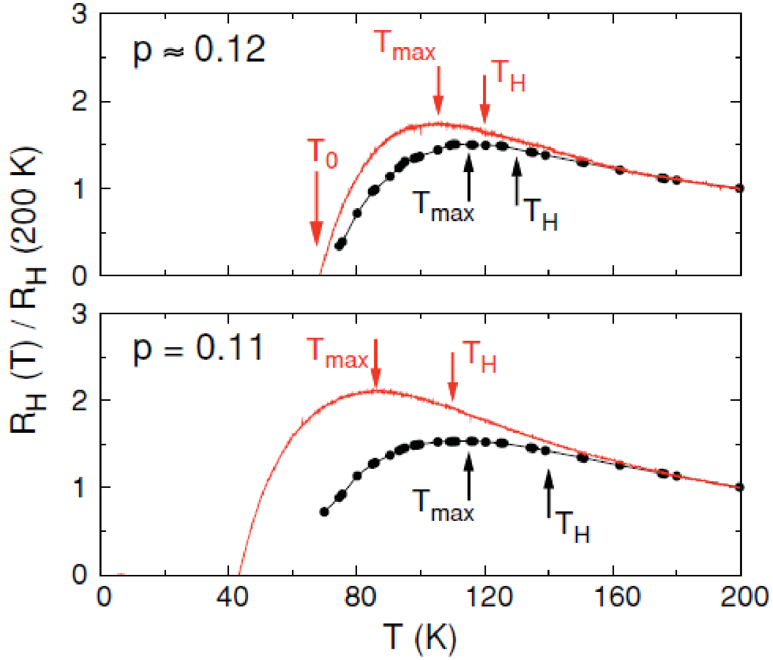
Signs of something changing inside the PG region

- Transport measurements

Hall effect





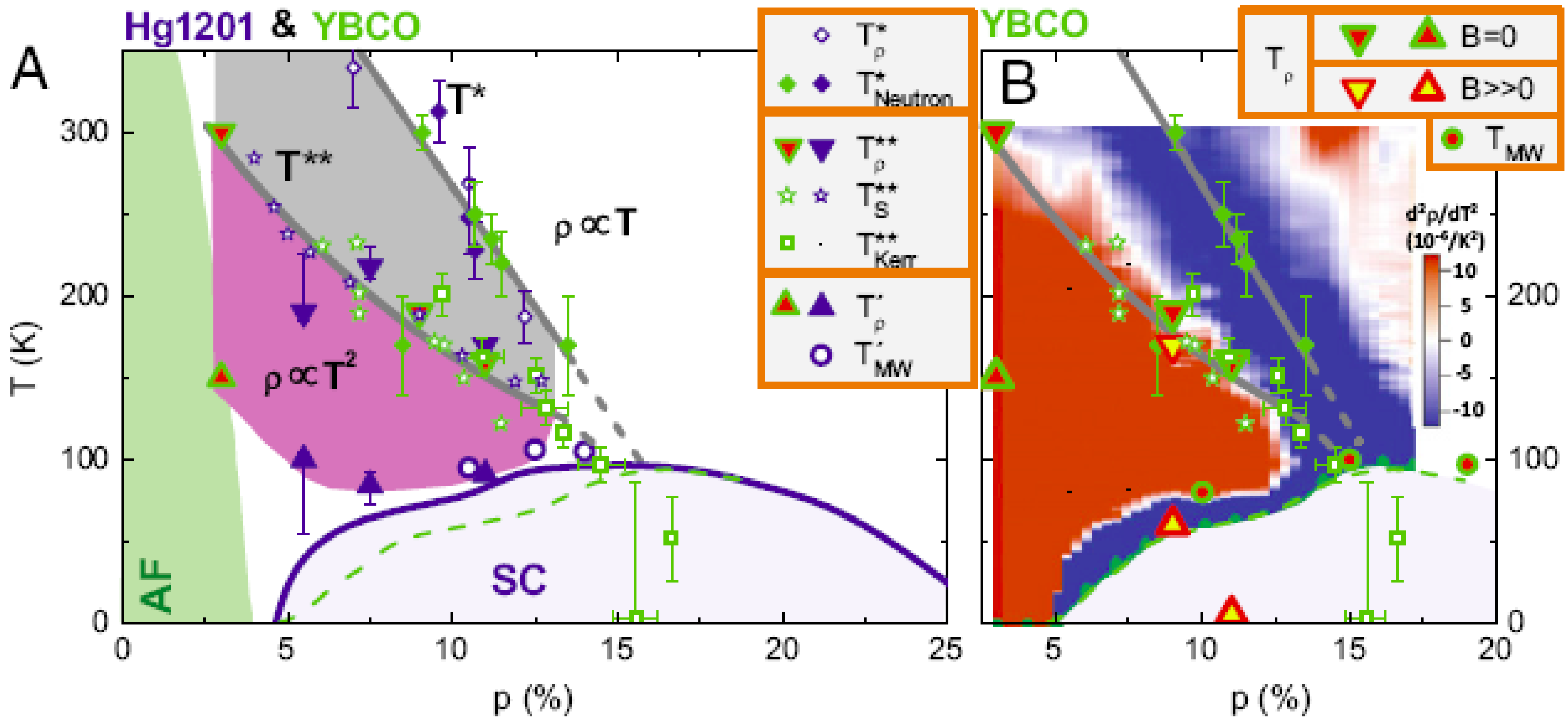
LeBoeuf *et al.*, Nature (2007), Phys. Rev. B (2011)

This suggests that the Fermi surface changes topology below T_{Hall}

Signs of something changing inside the PG region

- Transport measurements

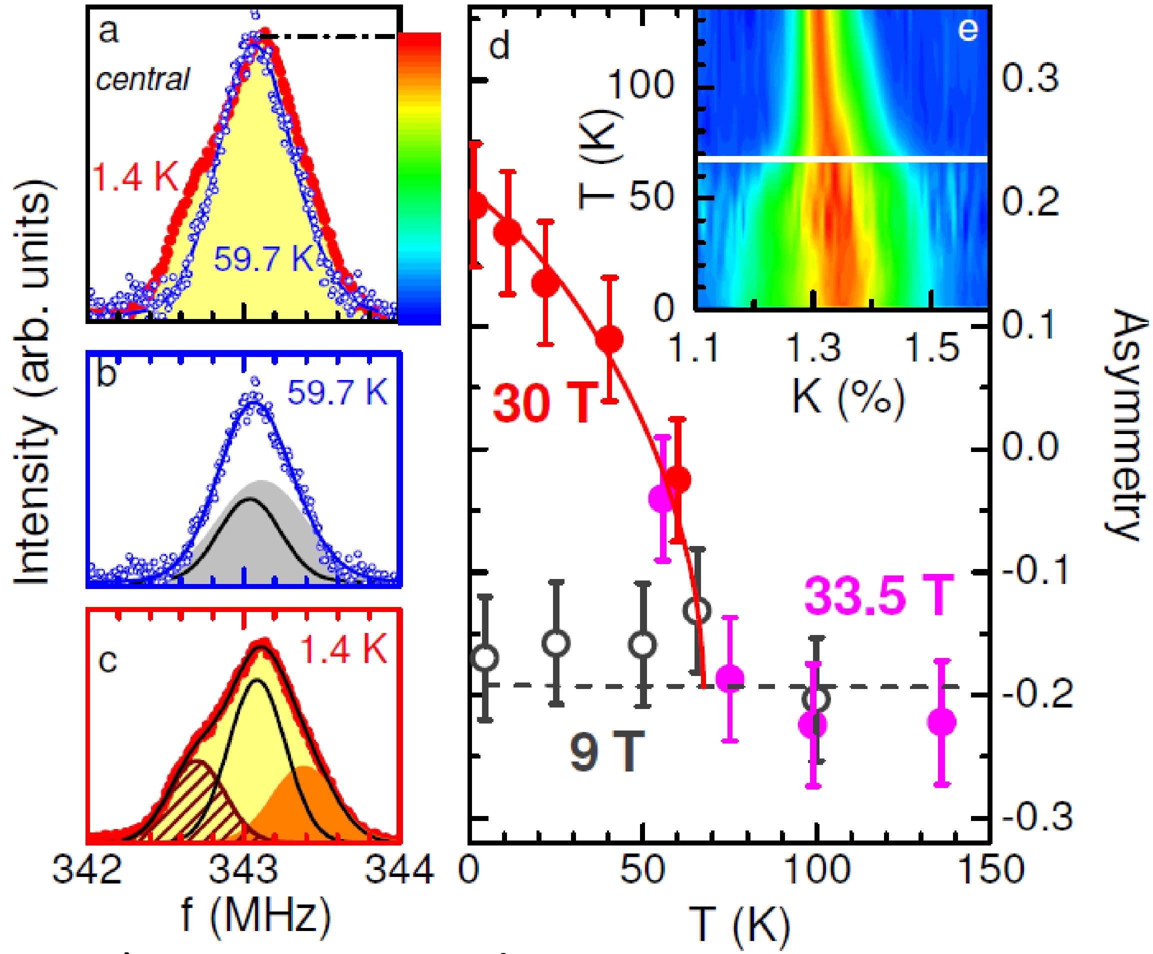
Sheet resistance



Barisic *et al.*, PNAS **110**, 12235 (2013)

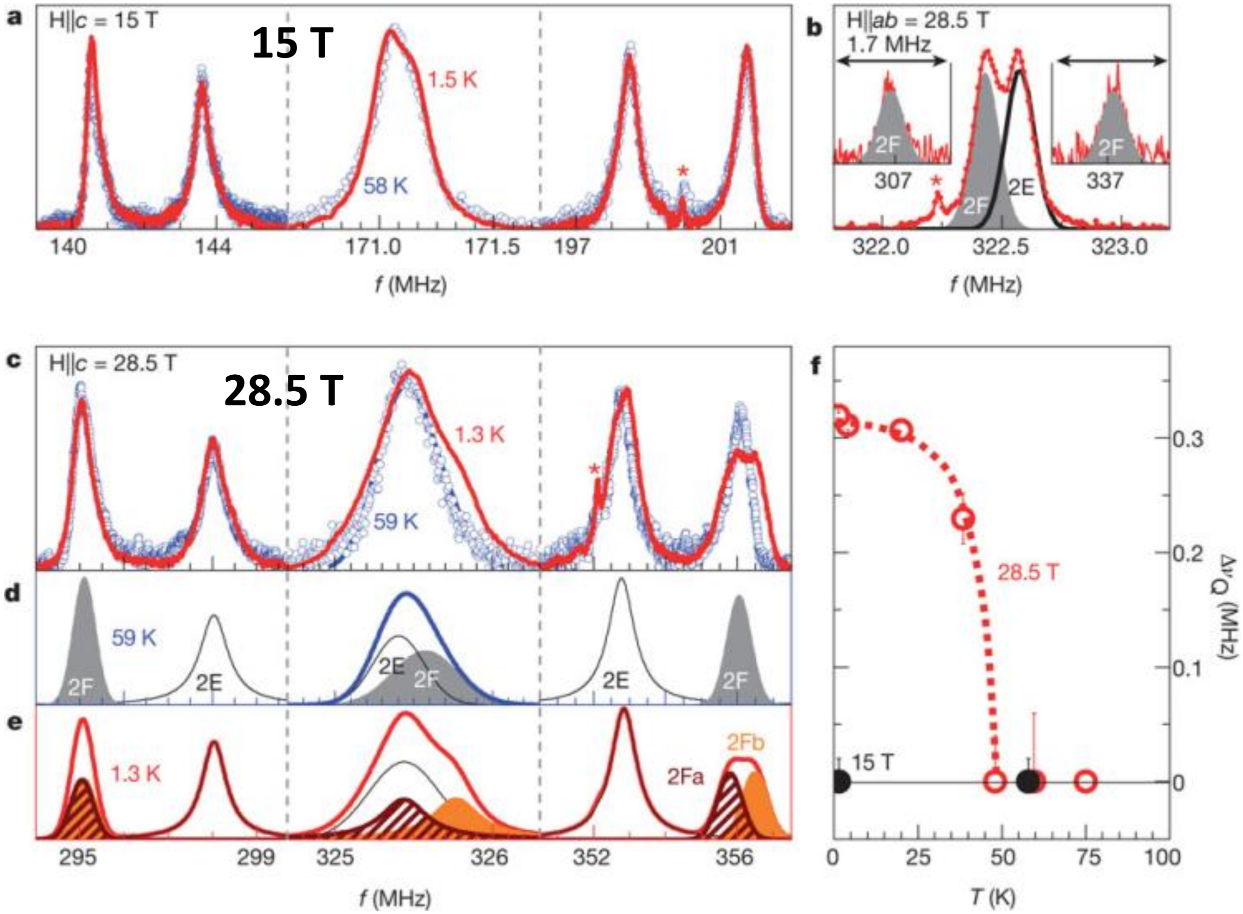
Signs of something changing inside the PG region

- Transport measurements
- NMR/NQR



Wu *et al.,* Nature **477**, 7363 (2011) – picture is ortho-VIII.

^{63}Cu NQR shows signs of charge order in o-II YBCO



Wu *et al.*, Nature (2011)

(& Nature Comms .2013)

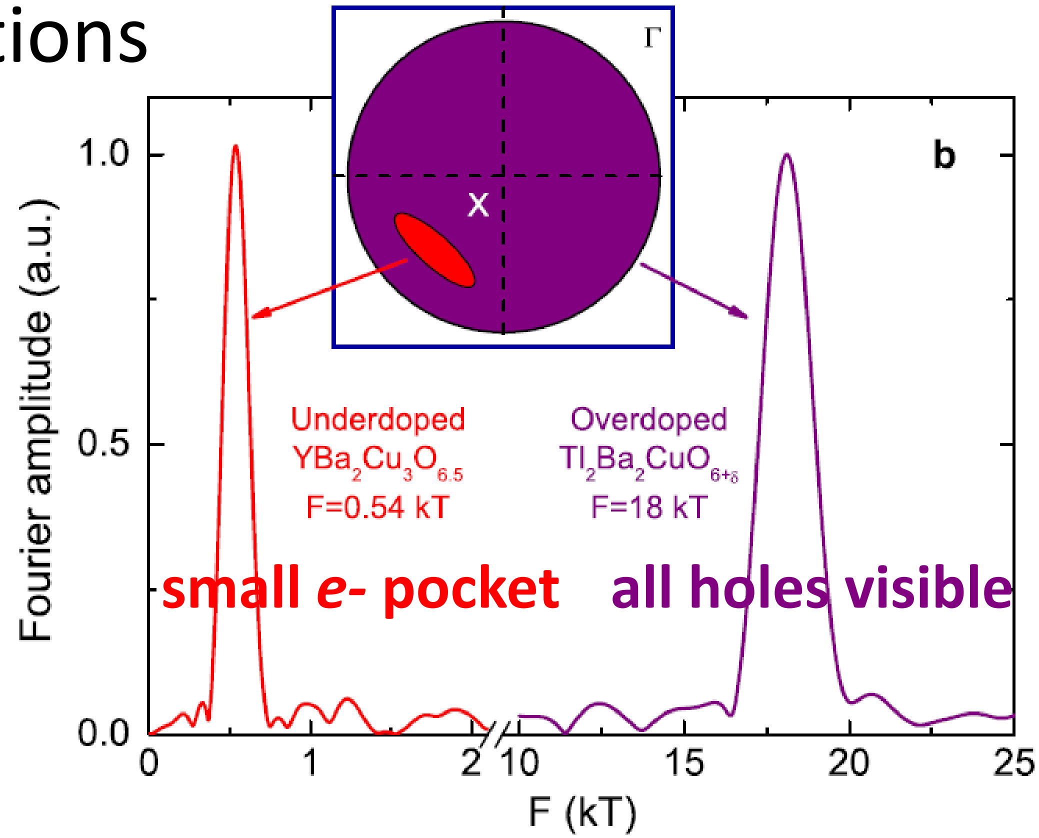
Splitting in a Cu line appears at high field and low temperature.

They suggested a charge modulation along ***a*** with period 4*a*…

… beware: NMR/NQR is a ‘local’ probe

Signs of something changing inside the PG region

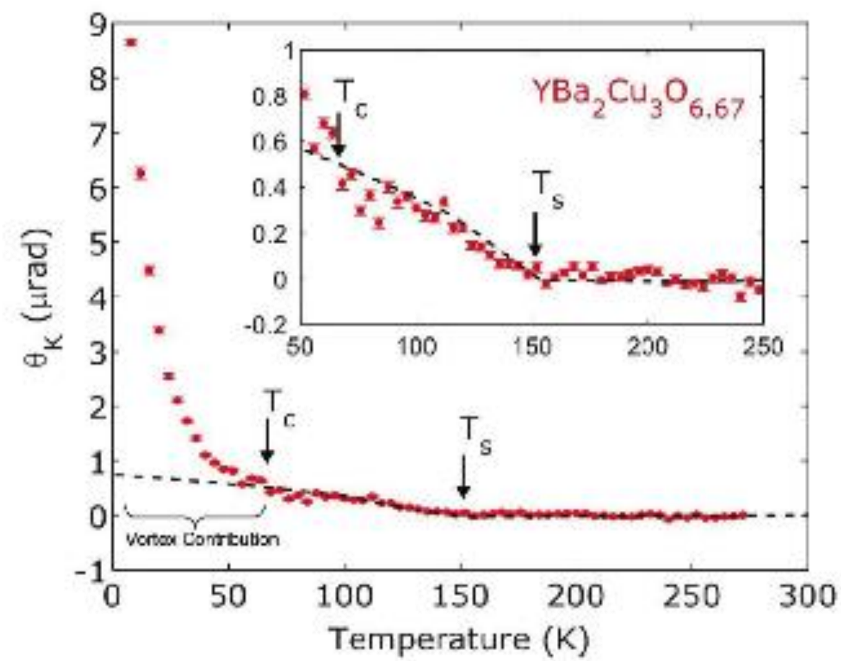
- Transport measurements
- NMR/NQR
- Quantum oscillations



Signs of something changing inside the PG region

- Transport measurements
- NMR/NQR
- Quantum oscillations
- Kerr effect

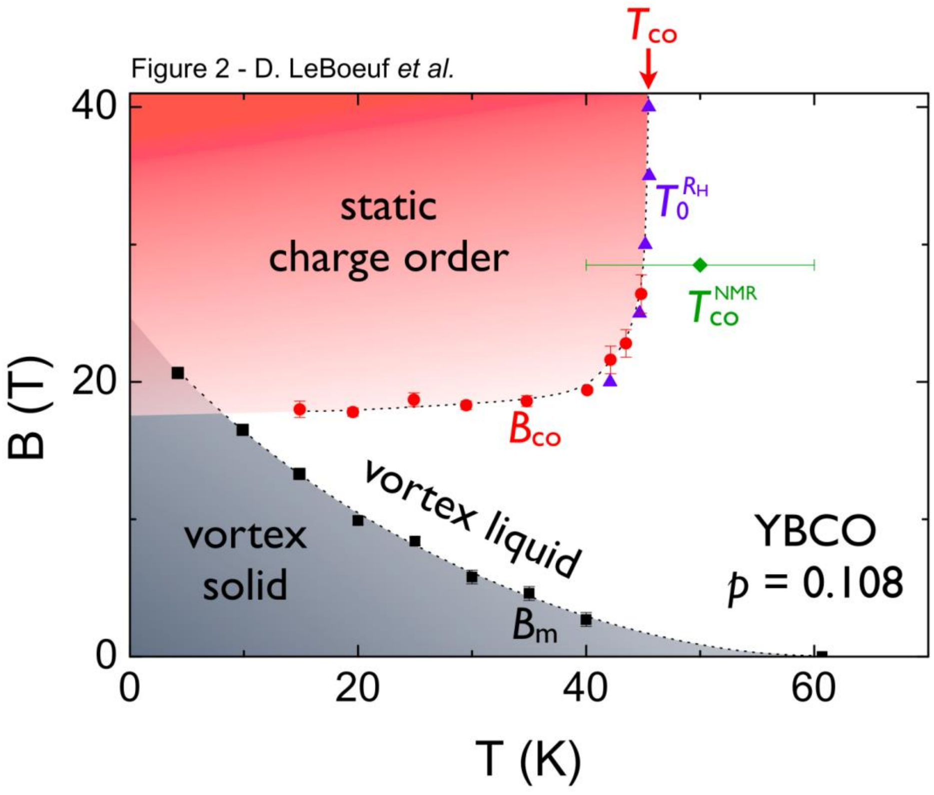
FIG. 2 (color online). The Kerr effect of $YBa_2Cu_3O_{6.67}$ crystal. The sample was first cooled to 4.2 K in a +4 T field. The field was turned off at 4.2 K, and measurements were taken while warming the sample. Note the large vortex contribution that disappears just before $T_c = 65$ K. The inset shows the region above T_c with its zero baseline, indicating a finite Kerr signal that disappears at $T_s = 155$ K. Dashed lines are guides to the eye.



Xia *et al.*, Phys. Rev. Lett. **100**, 127002 (2008).

Signs of something changing inside the PG region

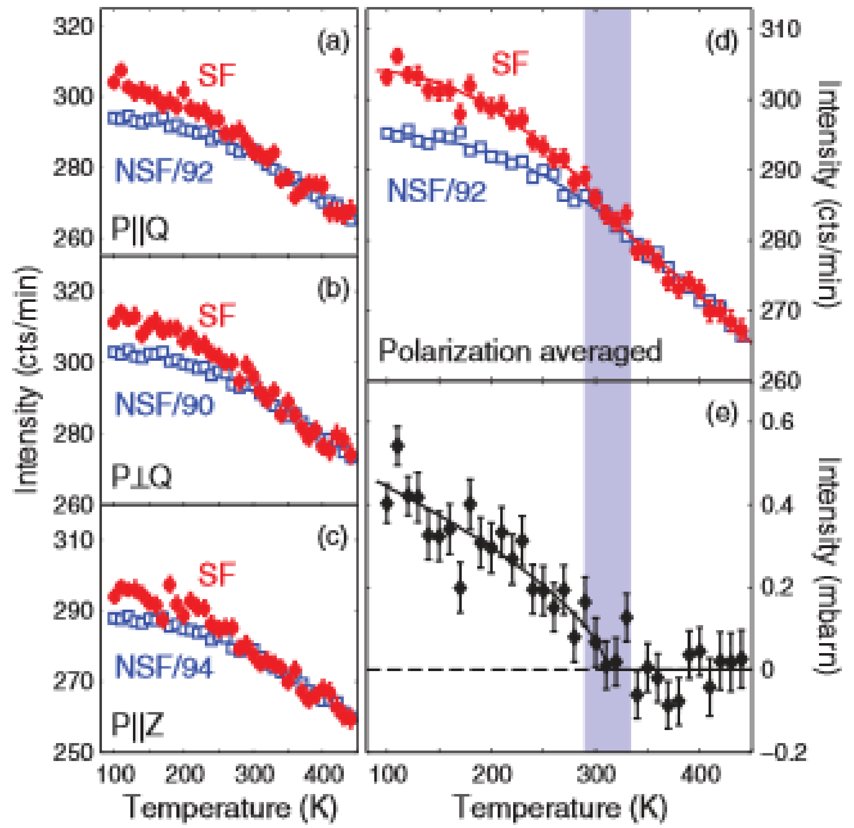
- Transport measurements
- NMR/NQR
- Quantum oscillations
- Kerr effect
- Ultrasound



LeBoeuf *et al.*, Nat. Phys. **9**, 79 (2012).

Signs of something changing inside the PG region

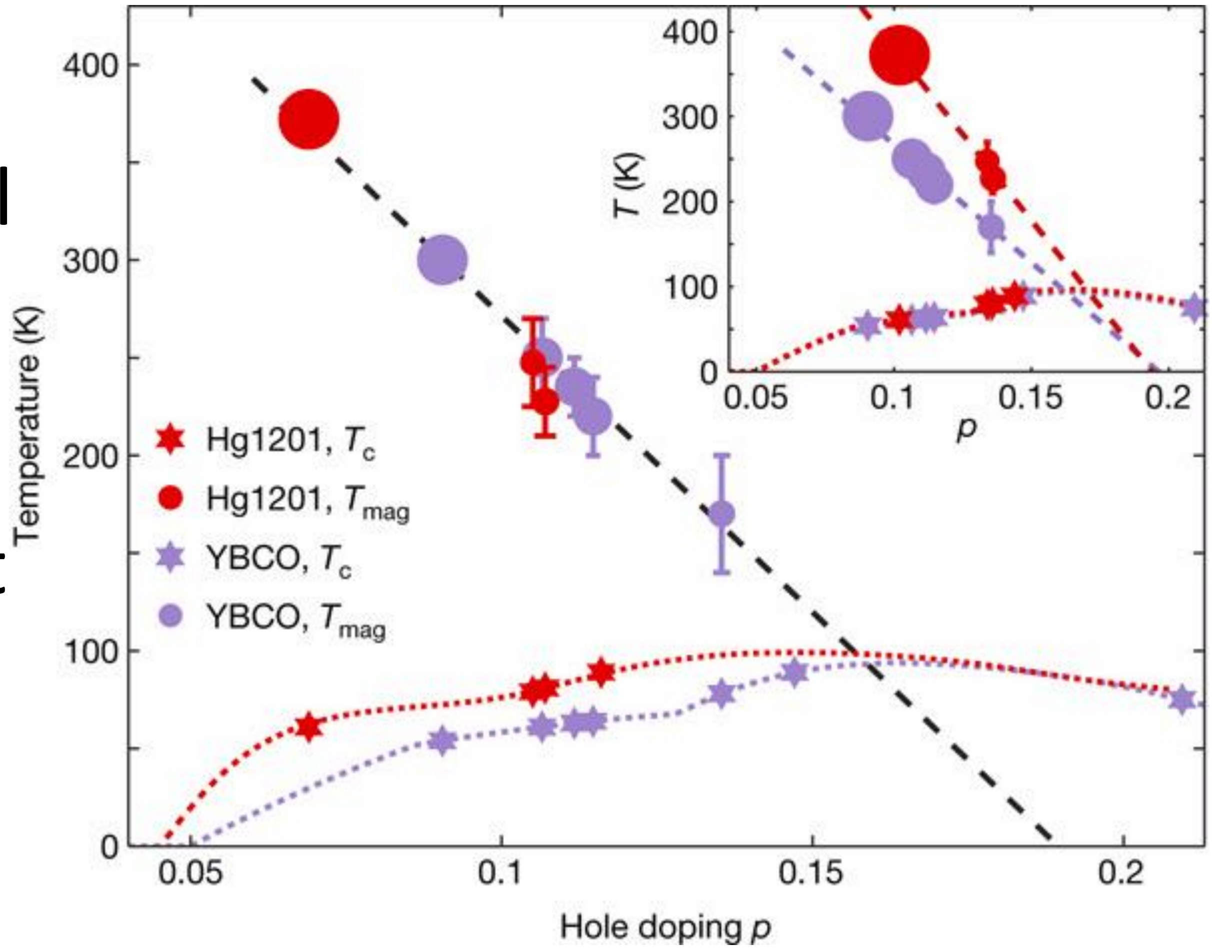
- Transport measurements
- NMR/NQR
- Quantum oscillations
- Kerr effect
- Ultrasound
- Polarized neutron diffra



HgBCO - Li *et al.*, Phys. Rev. B **84**, 224508 (2011).

Signs of something changing inside the PG region

- Transport measurements
- NMR/NQR
- Quantum oscil
- Kerr effect
- Ultrasound
- Polarized neut



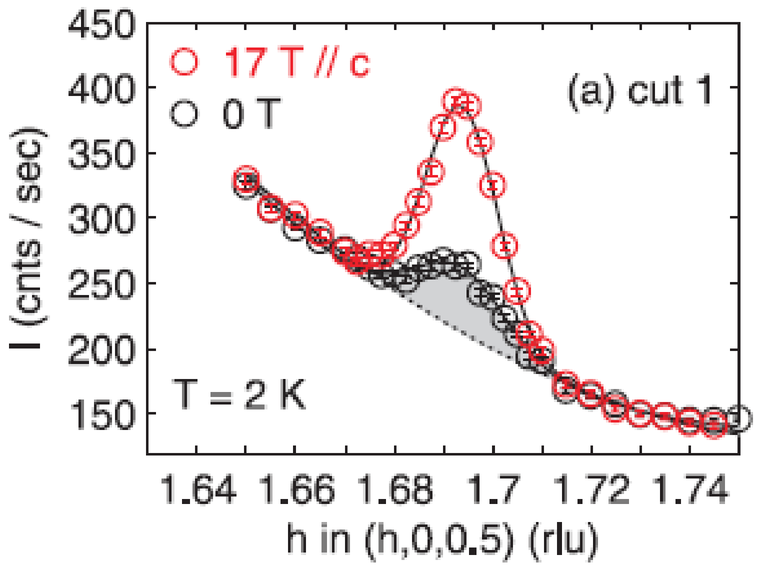
Li *et al.*, Nature **455**, 372 (2008).

Signs of something changing inside the PG region

- Transport measurements
- NMR/NQR
- Quantum oscillations
- Kerr effect
- Ultrasound
- Polarized neutron diffraction

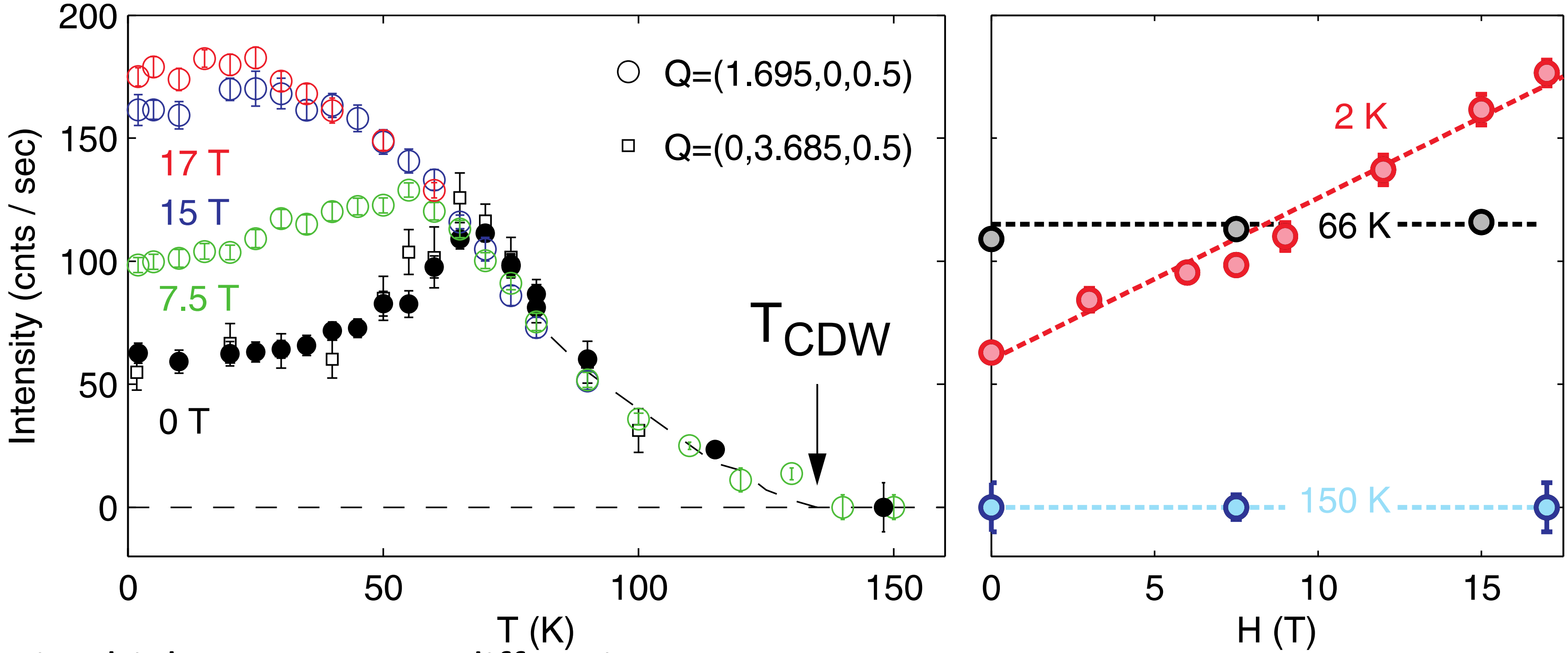
What is changing?

The $YBa_2Cu_3O_y$ family shows charge density wave order which competes with superconductivity



What is changing?

The $YBa_2Cu_3O_y$ family shows charge density wave order which competes with superconductivity



– Using high energy x-ray diffraction
  - Chang *et al.*, Nature Physics (2012)
  - Blackburn *et al.*, Phys. Rev. Lett. (2013)

– Using soft x-ray resonant scattering
  - Ghiringhelli *et al.*, Science (2012)
  - Achkar *et al.*, Phys. Rev. Lett. (2012)

Direct Observations of CDWs - two techniques:

Our Collaboration: 'Hard' X-ray (100 keV) diffraction up to B = 17 T

Diffraction signal arises from displacements of *all* atoms in the unit cell…

Large volume of ***Q***-space accessible – extra info.

Chang *et al.,* Nat. Phys. **8**, 871 (2012).
- o-VIII

Blackburn *et al.,* PRL **110**, 137004 (2013).
- o-II and o-III

Resonant Elastic X-ray Scattering: mainly 930 eV Cu L_3 edge

Diffraction signal arises from spatial variation of Cu *L*-resonance energy

Small volume of ***Q***-space accessible – but site-specific

Ghiringhelli *et al.,* Science **337,** 821 (2012).

Achkar *et al.,* PRL **109**, 167001 (2012).
- o-III + origin of contrast discussion

Blanco-Canosa *et al.*, PRL **110**, 187001 (2013).
- o-II

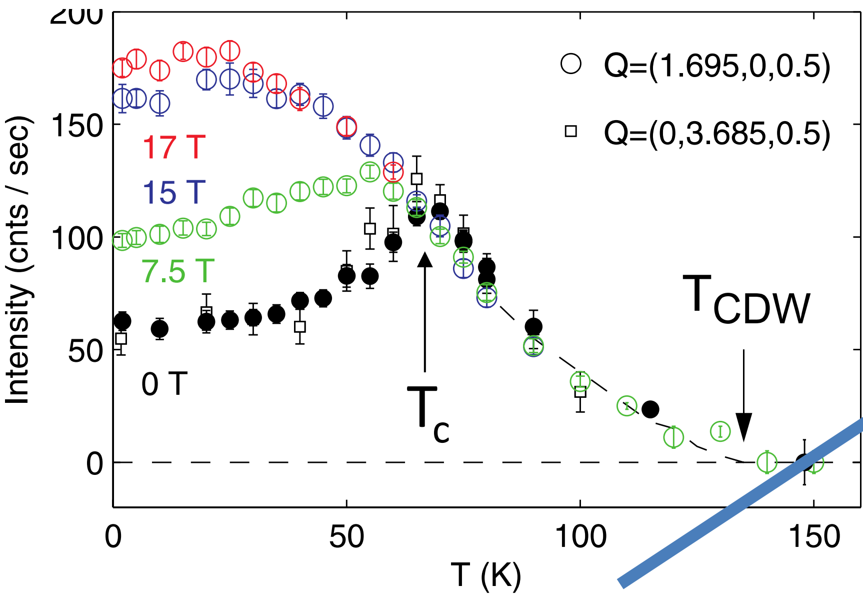
Similar results seen over a range of (under) dopings and for different Cu-O chain orderings (ortho-II, -III & -VIII)

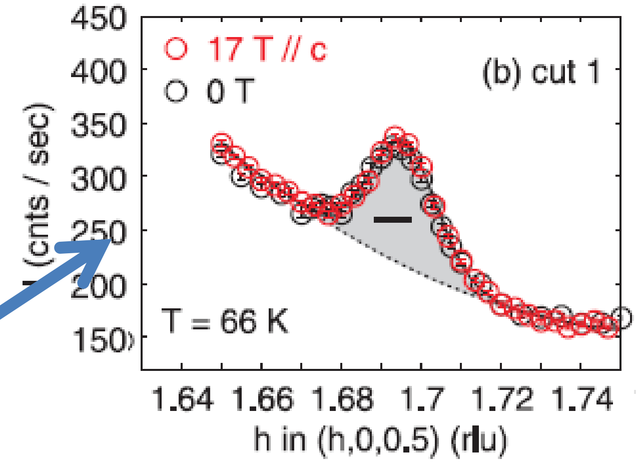
CDWs (and other lattice instabilities) are also seen in other cuprates!

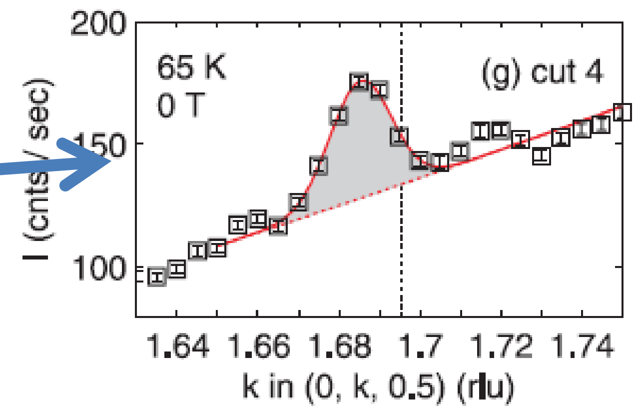
- YBCO
- Bi2201 – Comin *et al.,* Science **343**, 390 (2014).
- Hg1201 – Tabis *et al.*, arXiv 1404.7658 (2014).
- Eu-LSCO – Ghiringhelli *et al.,* Science **337**, 821 (2012)
- LSCO – Christensen *et al.,* arXiv 1404.3192 (2014)
- ….

A general feature of the underdoped cuprates
- can we link it to the other observations?

Let's start with one compound, YBCO o-VIII







In $YBCO_{6.67}$ $\boldsymbol{q_1} = (0.305, 0, 0.5)$

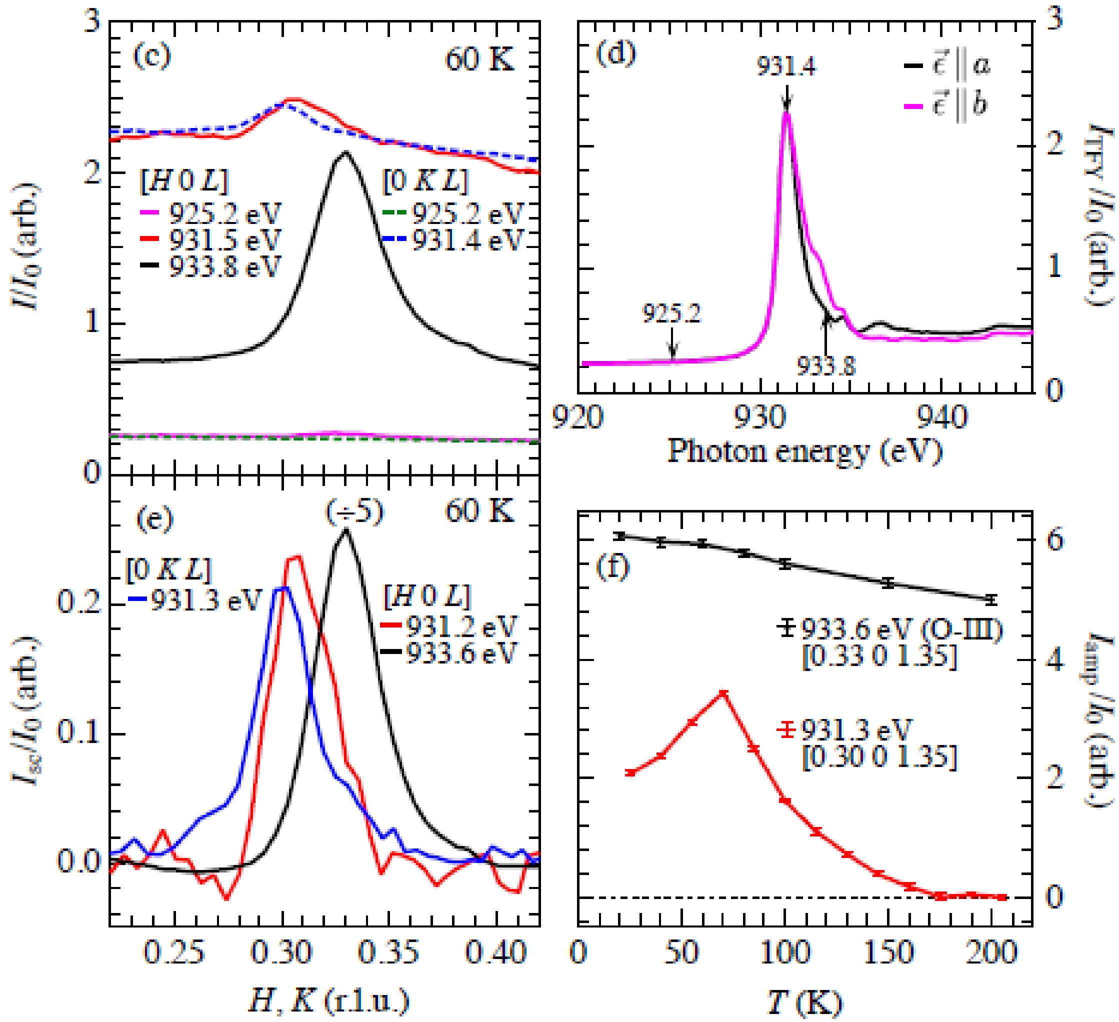
$\boldsymbol{q_2} = (0, 0.314, 0.5)$

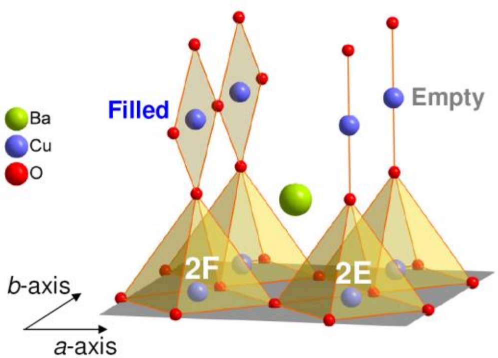
Similar but unequal ***q***-vectors along the ***a*** & ***b*** directions

Adjacent cells along ***c*** in antiphase

J. Chang et al., Nature Physics (2012)

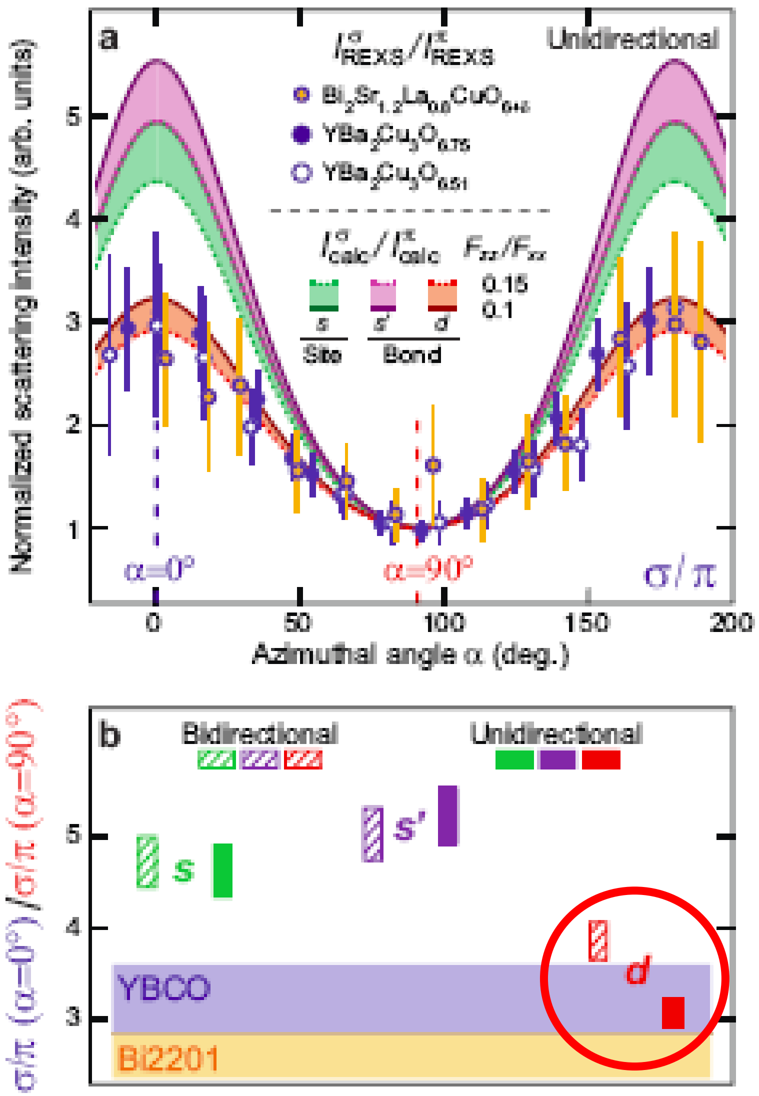
Energy dependence in ortho-III YBCO

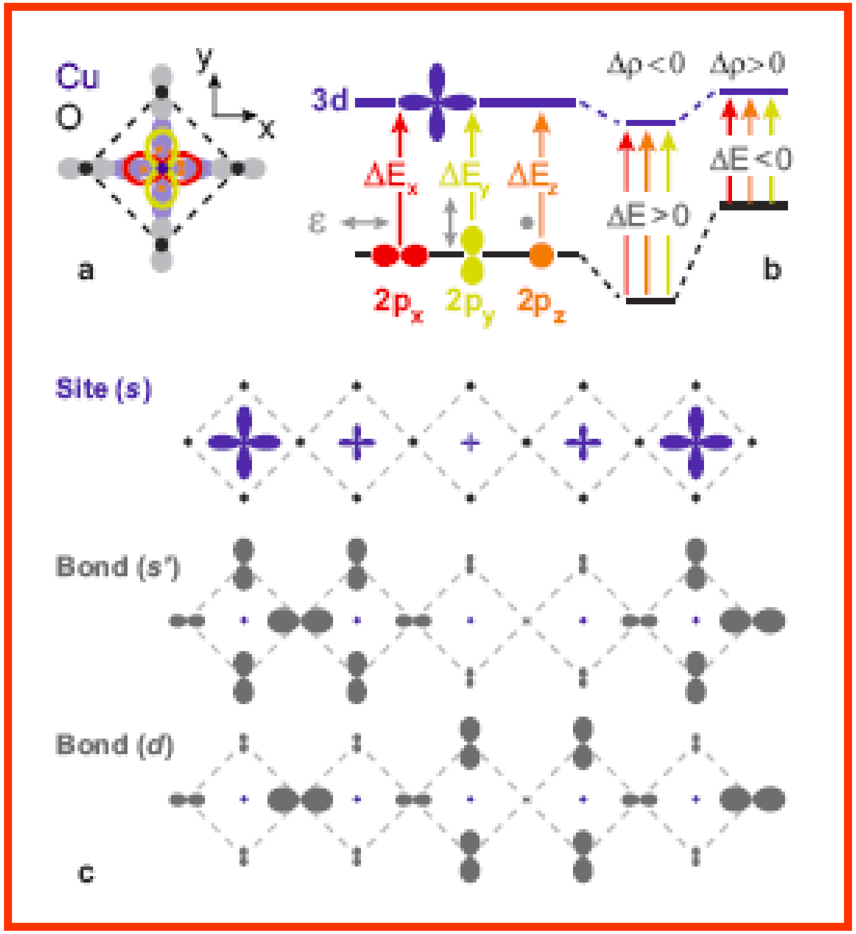




Achkar *et al.*,Phys. Rev. Lett. (2012).

A bond density wave?

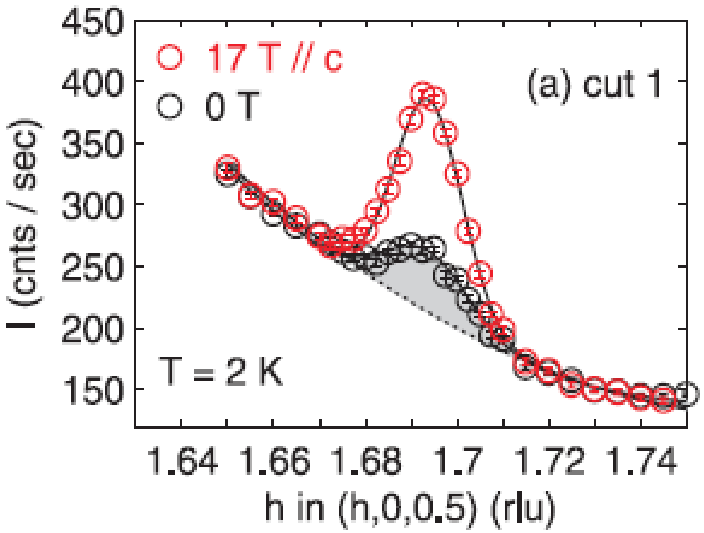


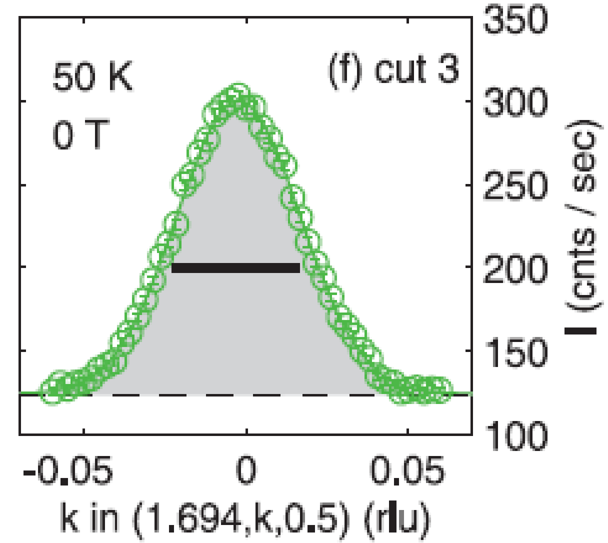


O-2*p* charge modulations

Comin *et al.*, arXiv 1402.5415 (2014)

Ortho-VIII example





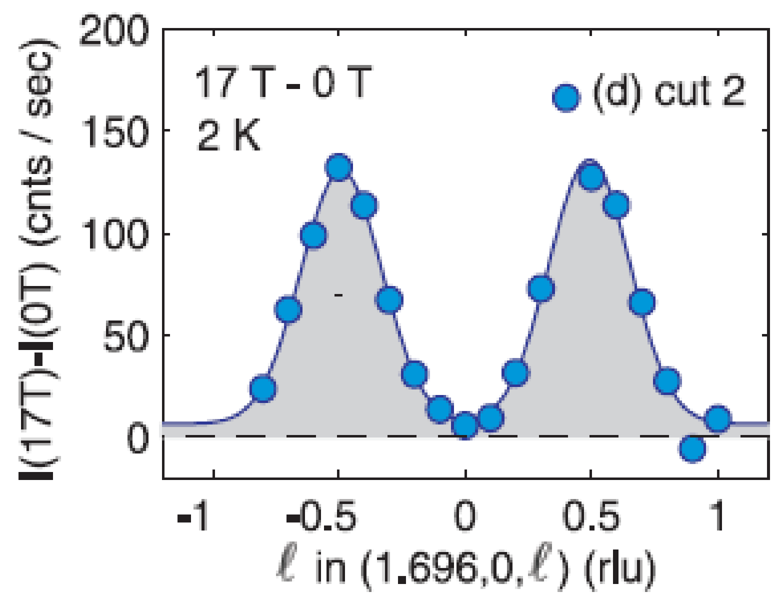
J. Chang et al., Nature Physics (2012)

Correlation lengths:

ξ_a = 95±5 Å

$\xi_c \approx$ 0.6 c

(Gaussian sigmas)



Lattice parameters:
a = 3.81 Å, b = 3.87 Å, c = 11.72 Å

Origin of this scattering

atomic displacements *vs* charge modulation

$$\rho^u(x) = \frac{Ze}{a}\left[1 + uq\cos(qx)\right]$$

$$\rho^v(x) = \frac{2e}{a}\left[1 + \Sigma_{CDW} N(\varepsilon_F)\cos(qx)\right],$$

$$\frac{I^u}{I^v} = \left(\frac{Zuq}{2\Sigma_{CDW} N(\varepsilon_F)}\right)^2 \approx 600.$$

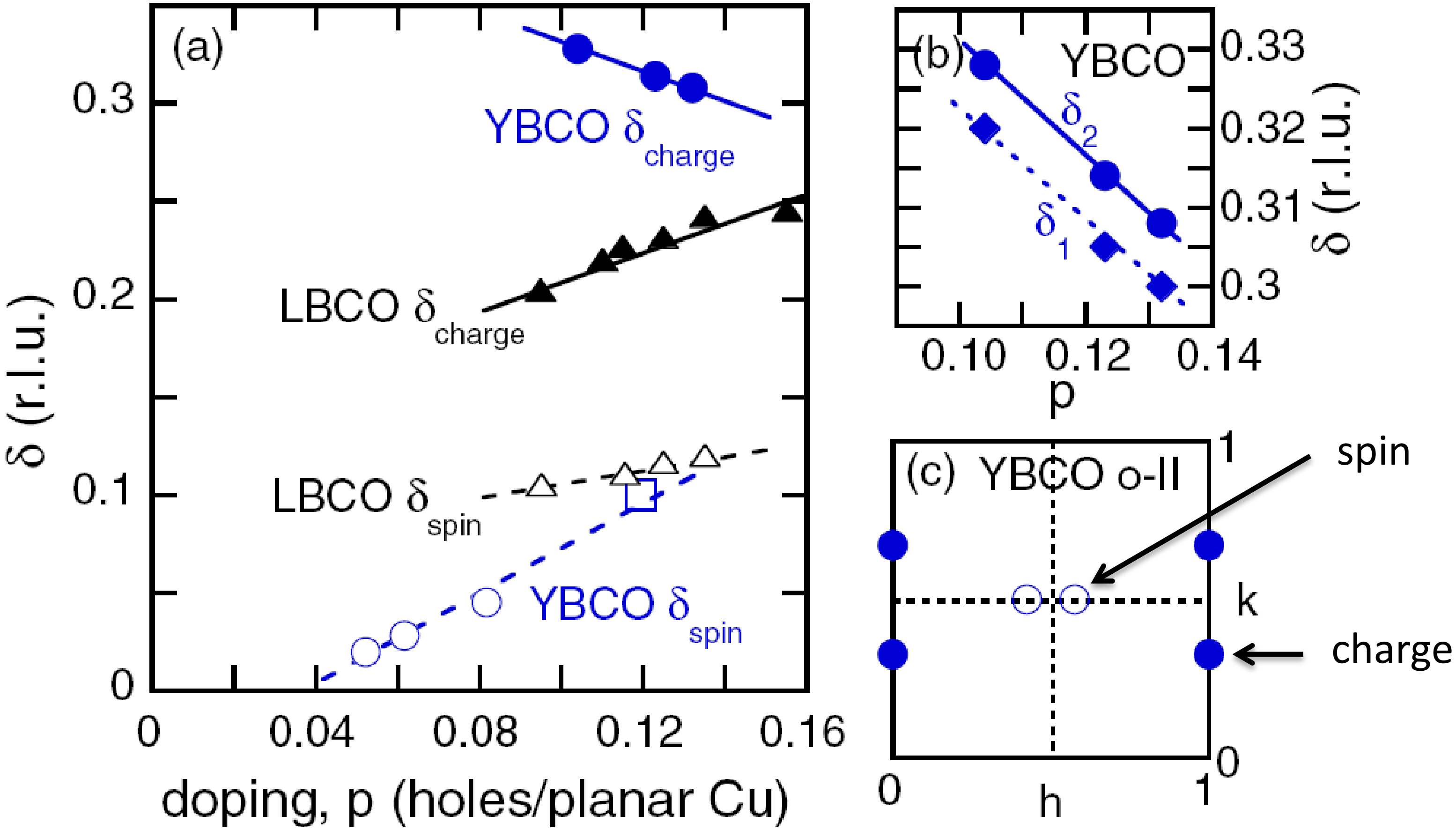
estimated: *u/a* ~ 8 x 10^{-4}

measured *u/a* ~ 7 x 10^{-4}

$$u = \left(\Sigma_{CDW}^2 N(\varepsilon_F)/M\omega_q^2\right)^{1/2} \approx 0.003\ \text{Å}.$$

net charge / unit cell (CDW amplitude) is ~ 10^{-3} *e*, => not a Cu valence modulation

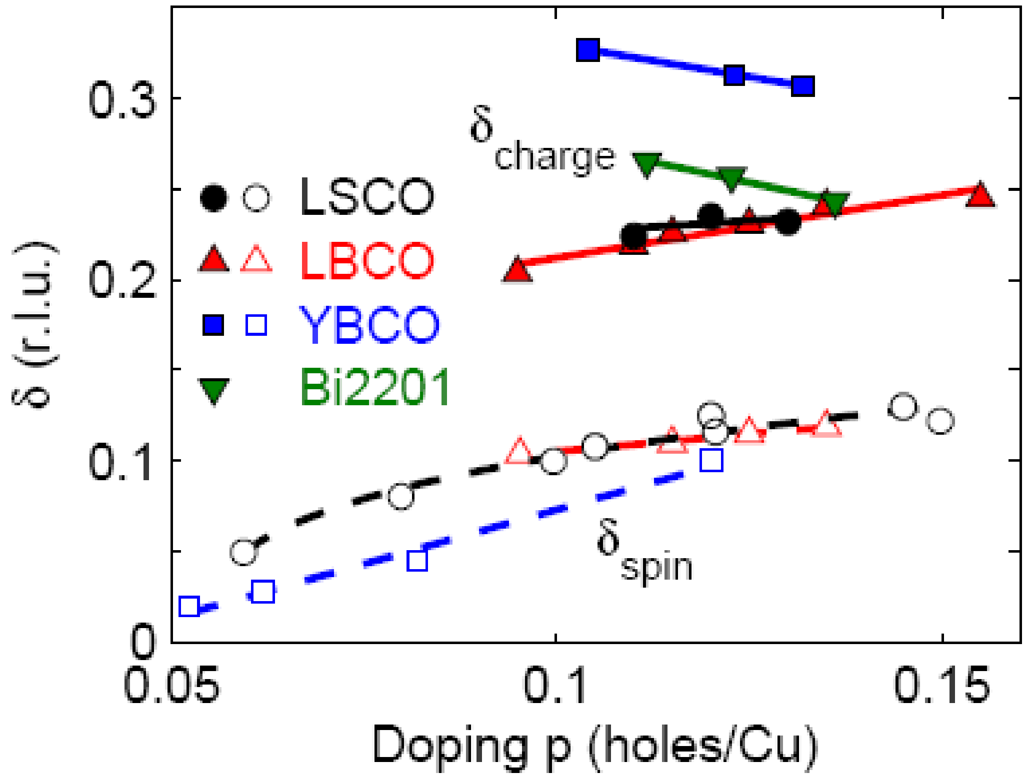
Spin and charge wavevectors



$$\delta_{\text{charge}} \neq 2\delta_{\text{spin}}$$

Blackburn *et al*, PRL (2013).

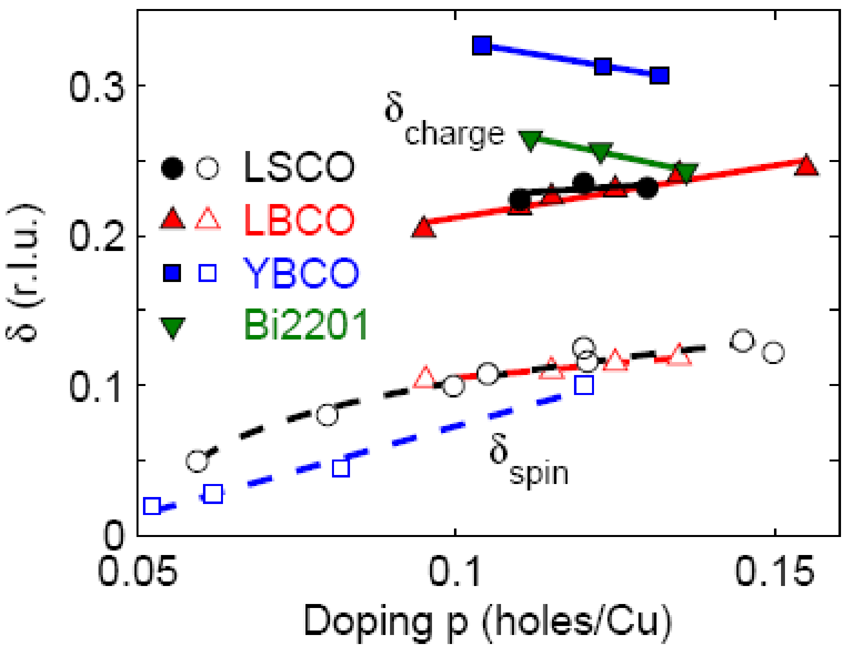
Spin and charge wavevectors – updated a little…

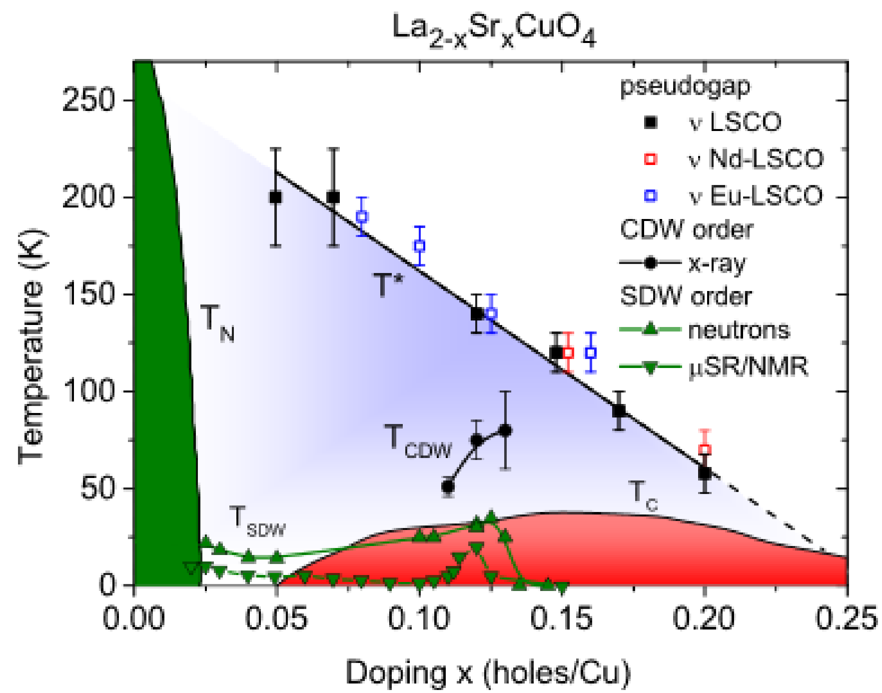


Open points: spin order or strong spin fluctuations at (½ + δ_{spin}, ½)
Closed points: CDW peaks at (δ_{charge},0)

T. P. Croft *et al*, Phys Rev B **89**, 224513 (2014).

Spin and charge wavevectors – updated a little…



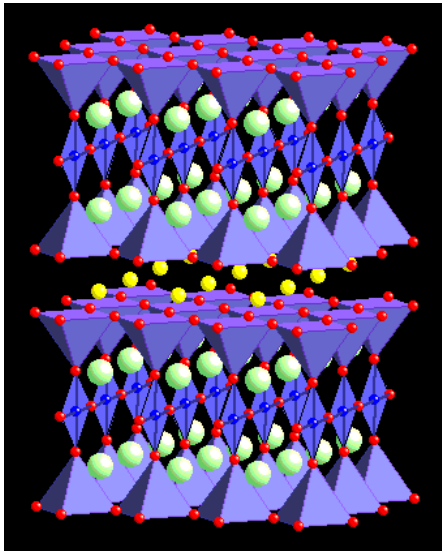


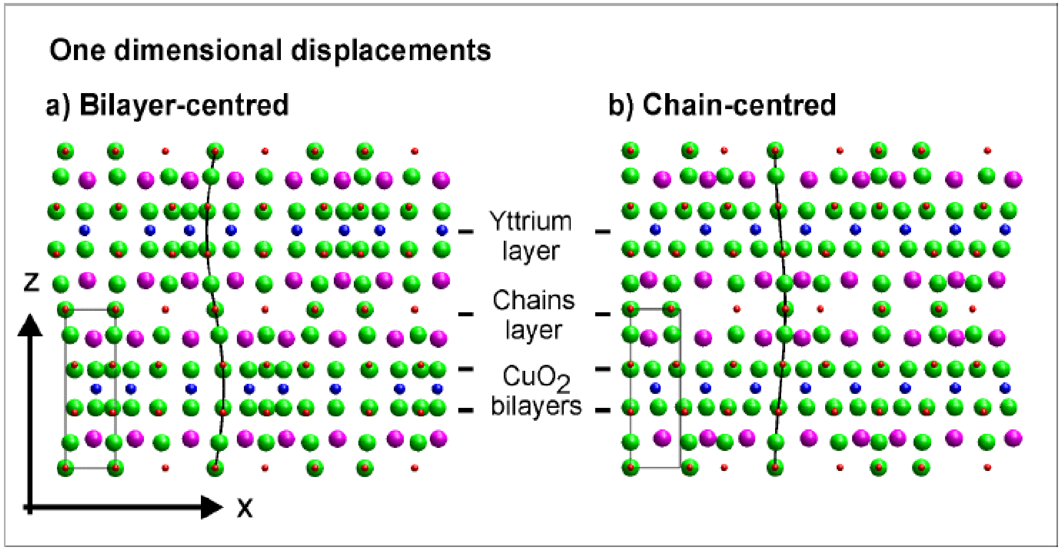
Open points: spin order or strong spin fluctuations at (½ + δ_{spin}, ½)

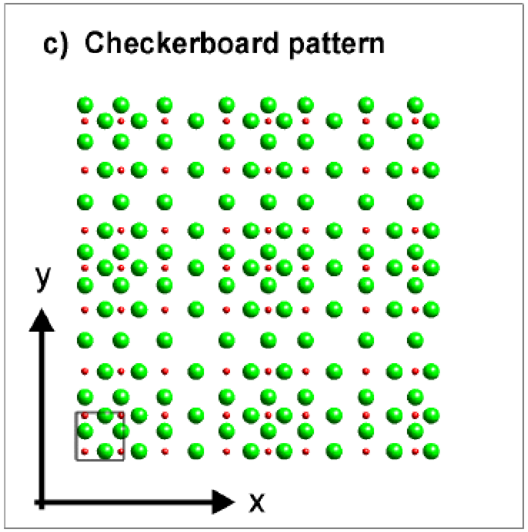
Closed points: CDW peaks at (δ_{charge},0)

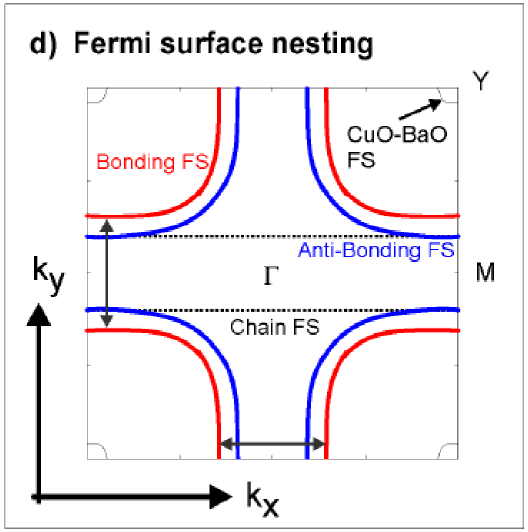
T. P. Croft *et al*, Phys Rev B **89**, 224513 (2014).

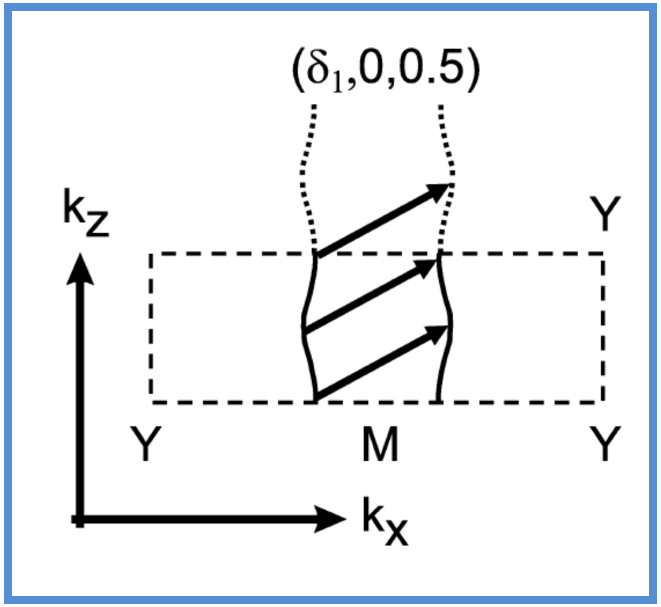
Modelling the CDW



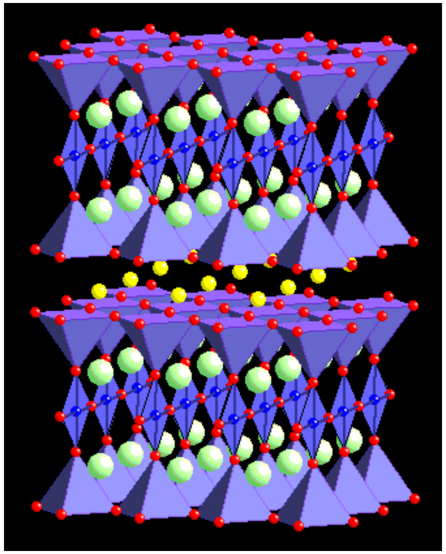


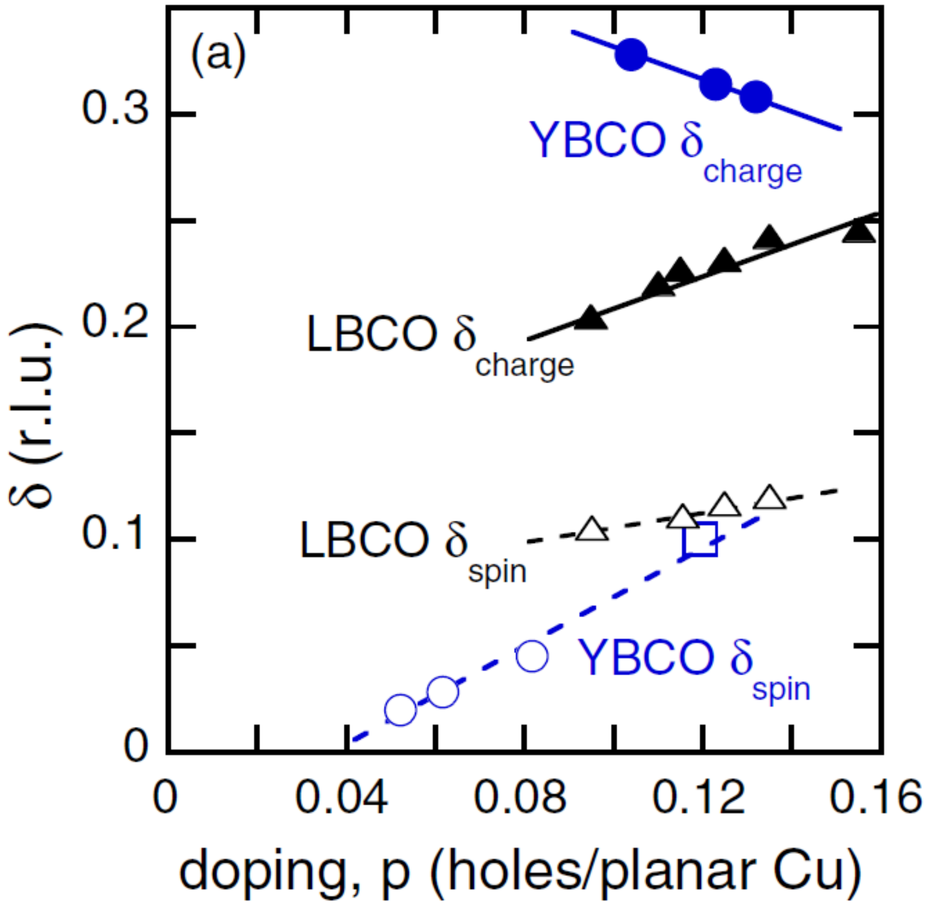


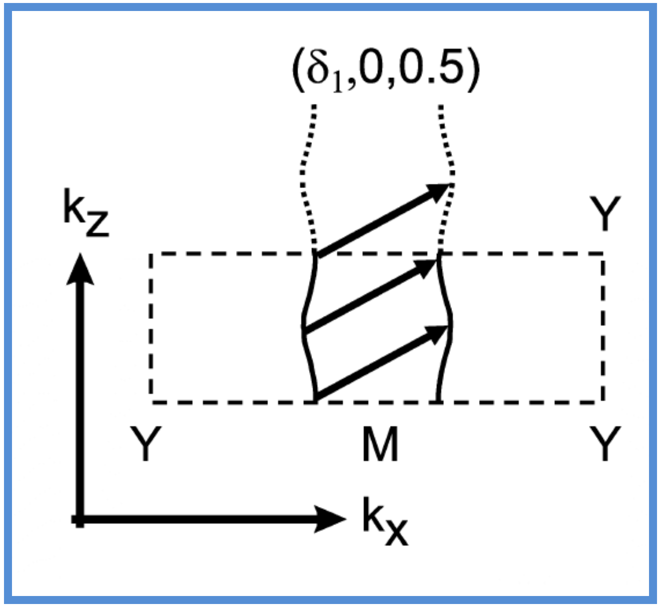




Modelling the CDW

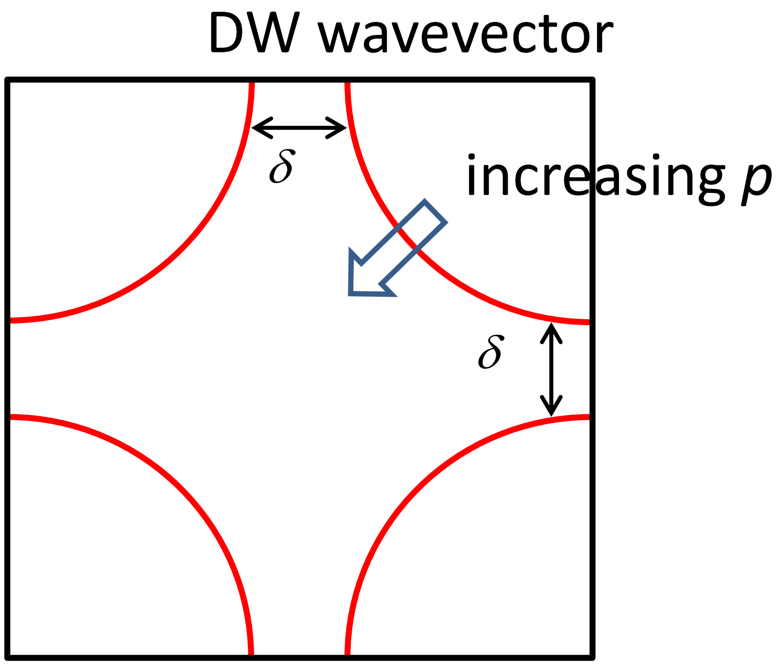




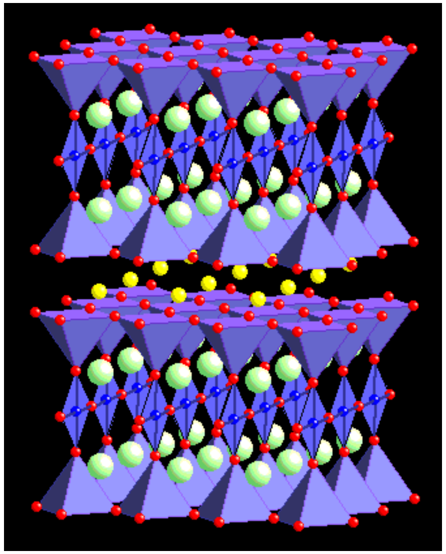


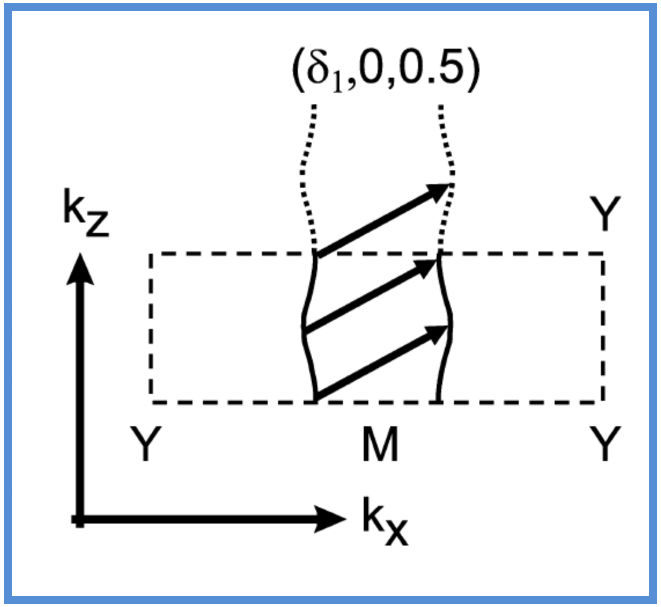
Blackburn *et al.*, Phys. Rev. Lett. (2013)

Modelling the CDW



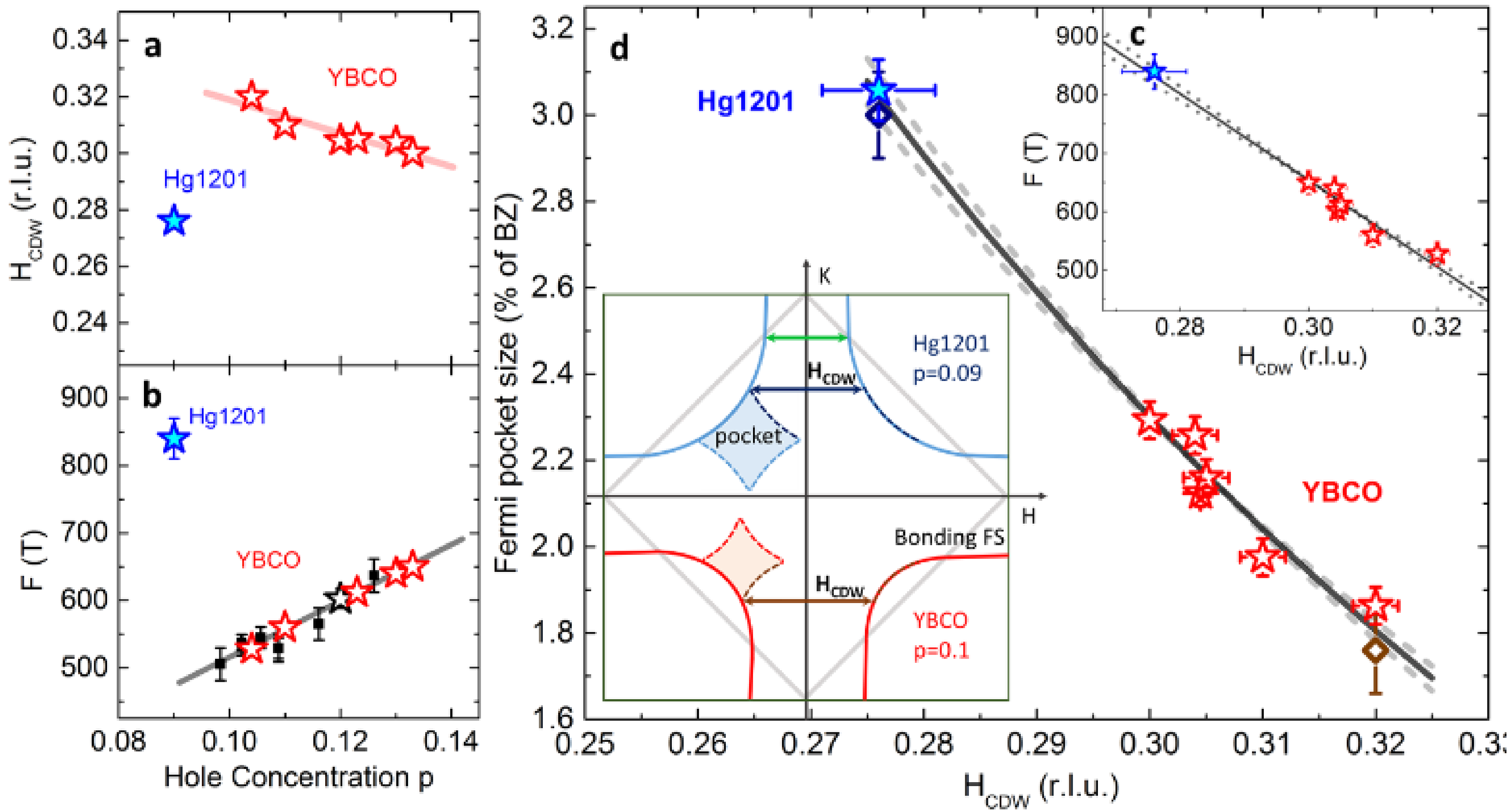
→Fermi surface effects





Blackburn *et al.*, Phys. Rev. Lett. (2013)

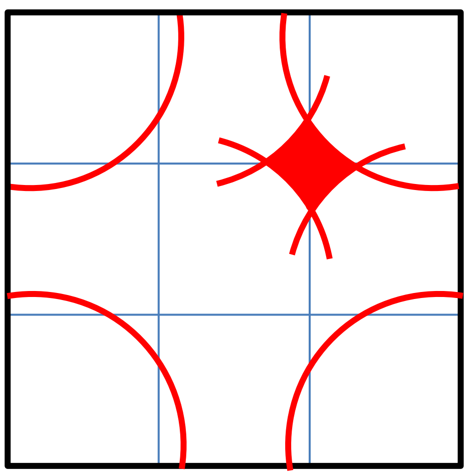
Links to the Fermi surface



Tabis *et al.*, arXiv: 1404.7658

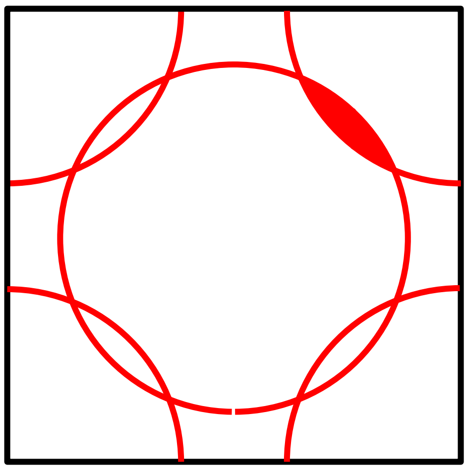
2D suggestions for Fermi surface reconstruction

Charge Density Wave



gives an electron pocket
(N.B. this is a 2d picture of
3d reconstruction by CDW)

"Antiferromagnetic"

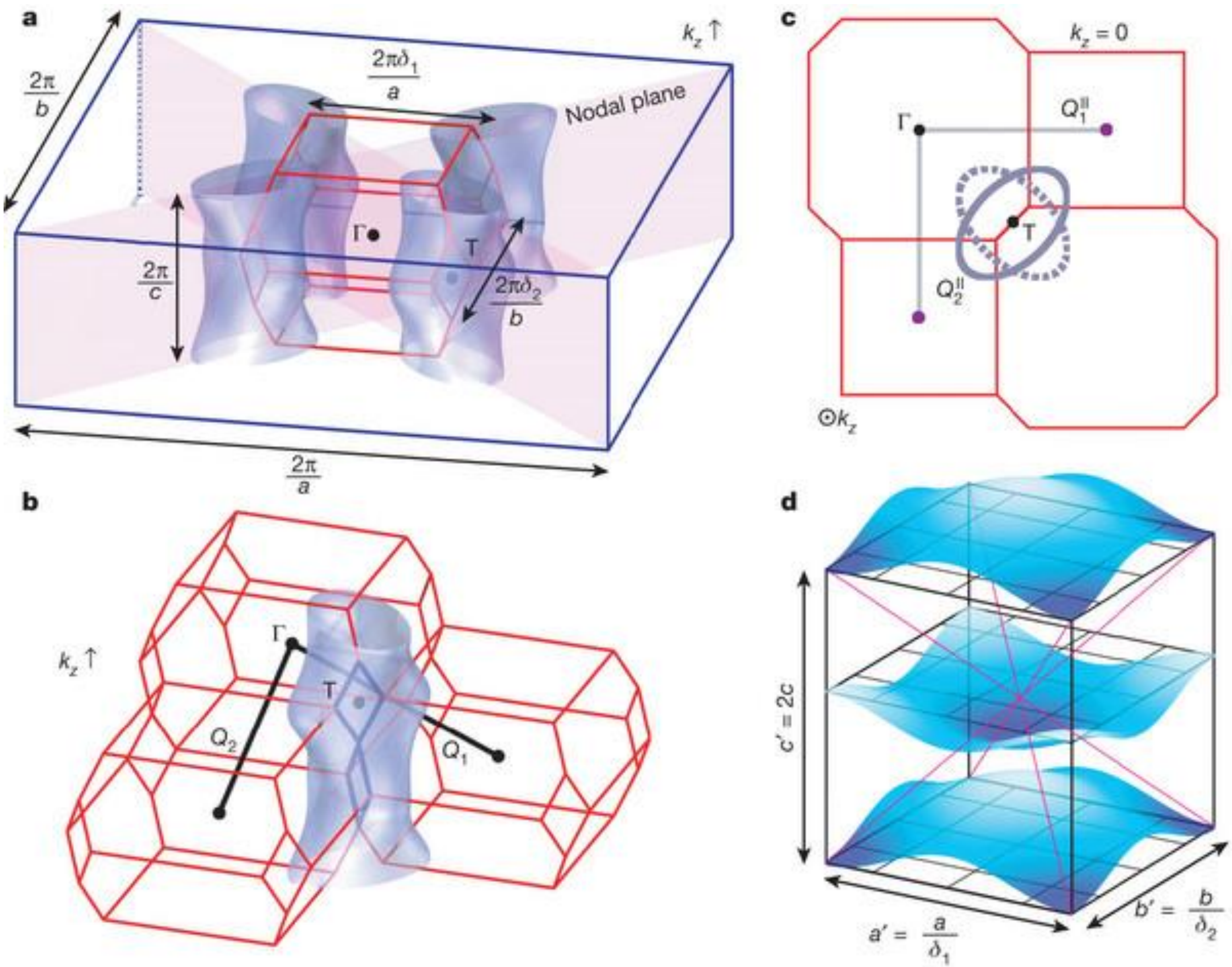


looks a bit like
the ARPES/STM signals

gives a hole pocket –
disagrees with Hall data

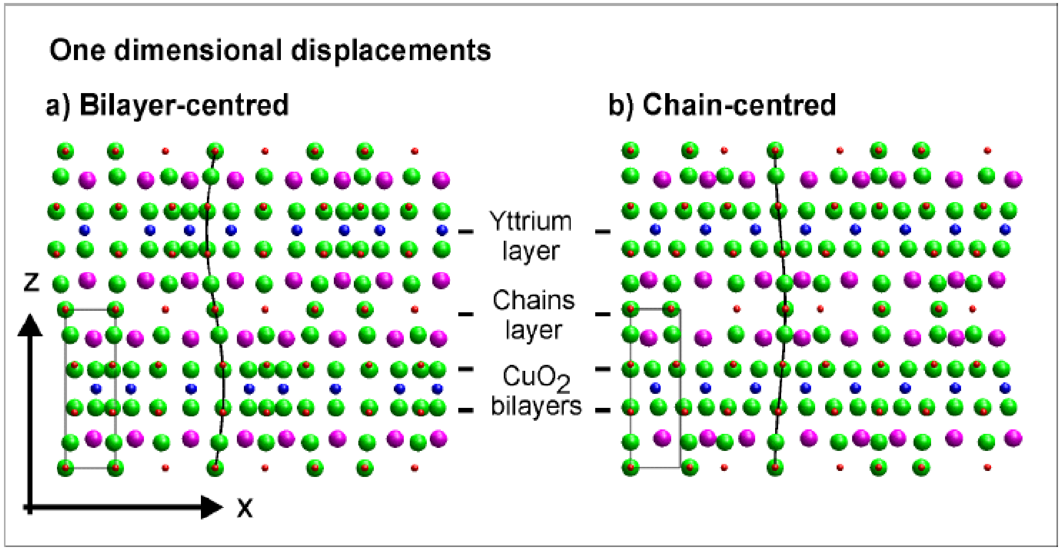
Sachdev *et al.*, J. Phys.: Condens. Matter (2012)

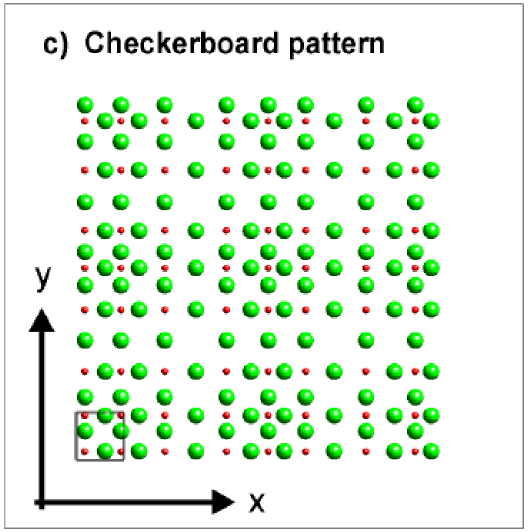
The Fermi surface – quantum oscillation data

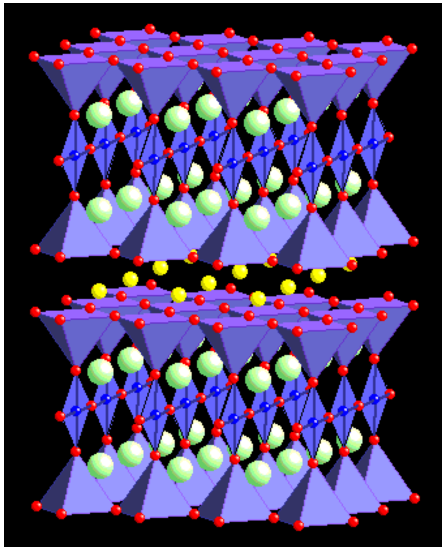


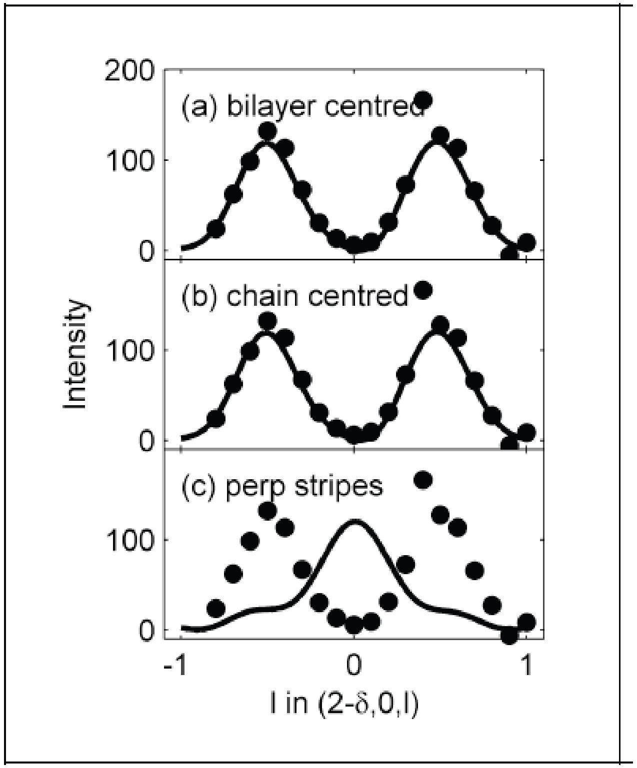
S. E. Sebastian *et al*, Nature (advance online) (2014).

Modelling the CDW





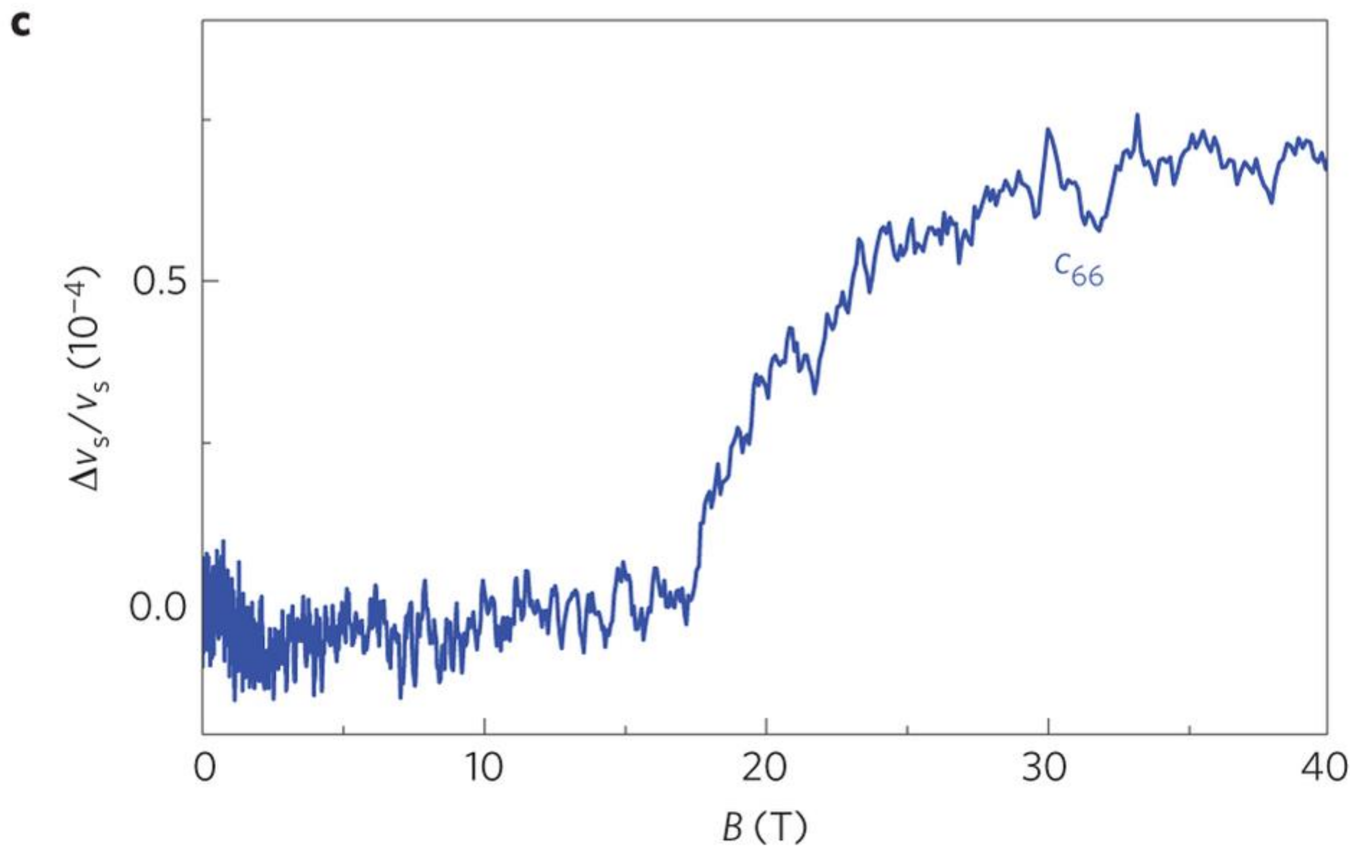




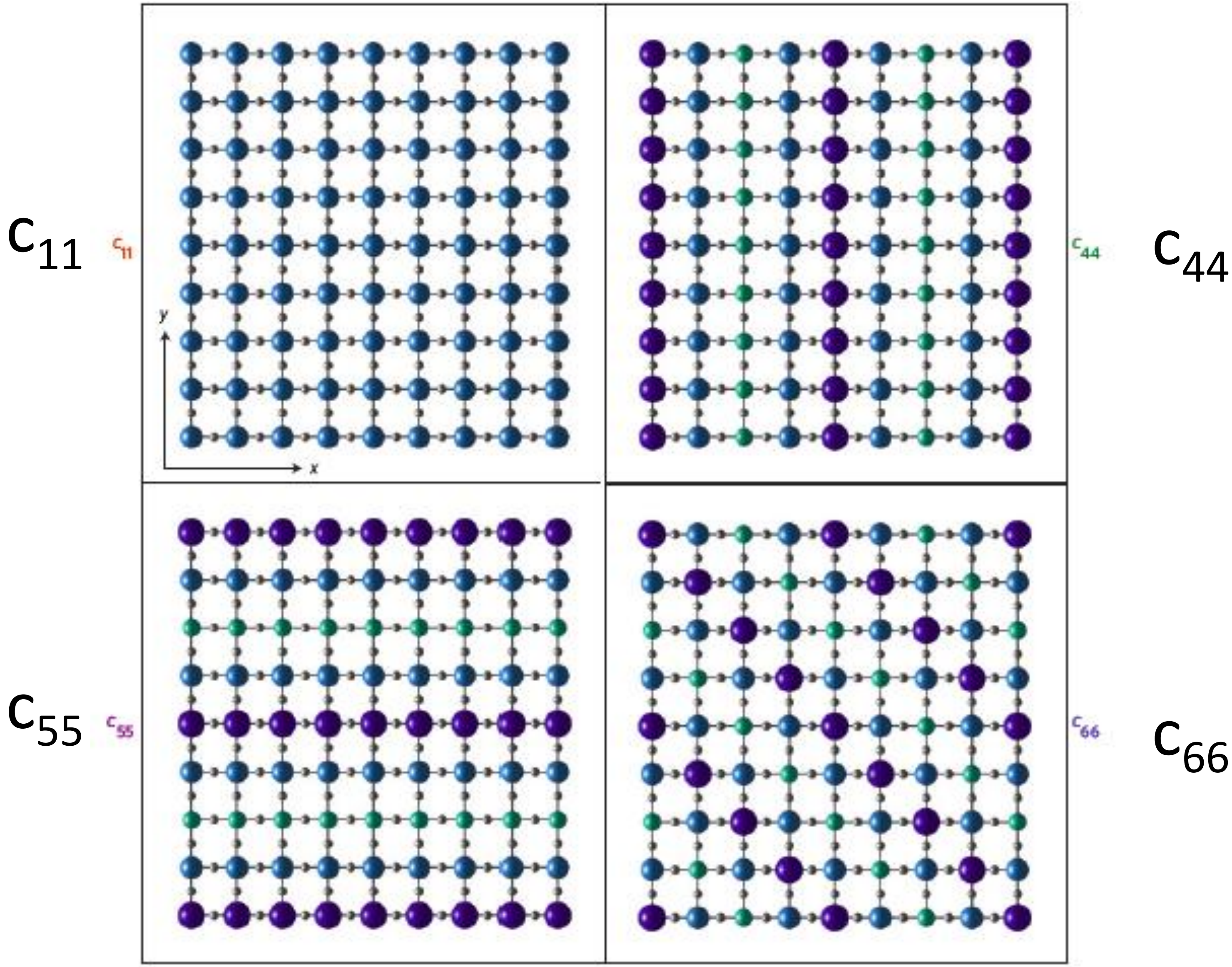
Is it single-**q** or double-**q**?

Ultrasound Studies

ortho-II

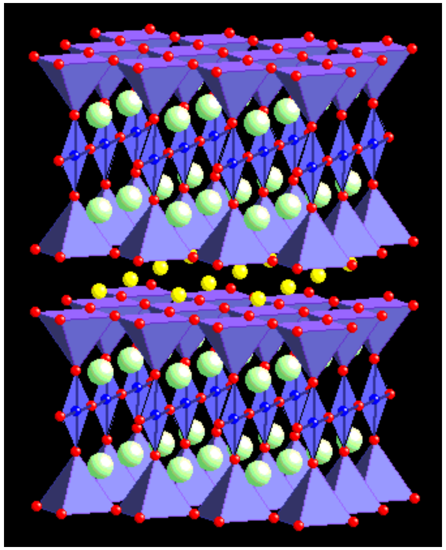


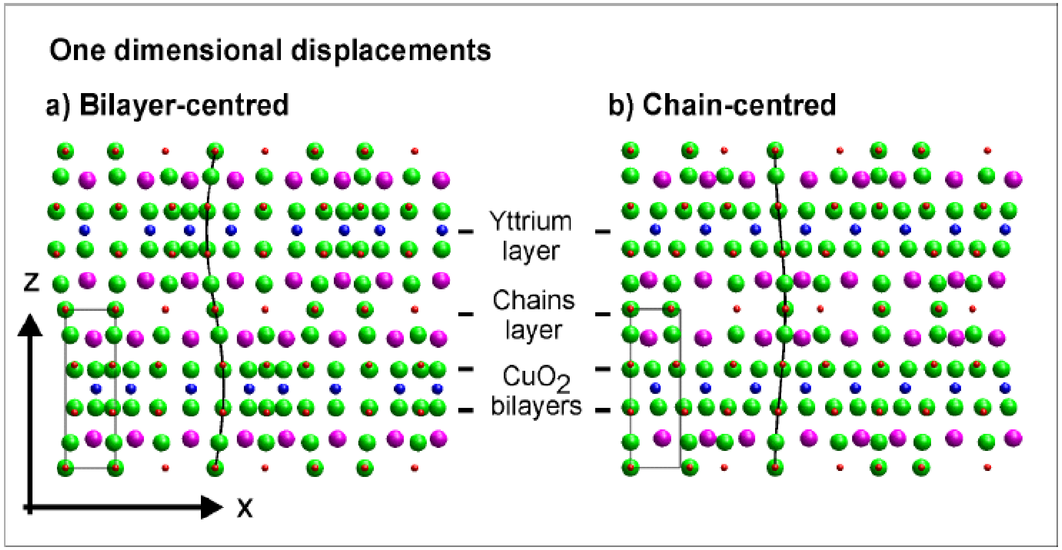
LeBoeuf *et al.*, Nature Physics (2012).

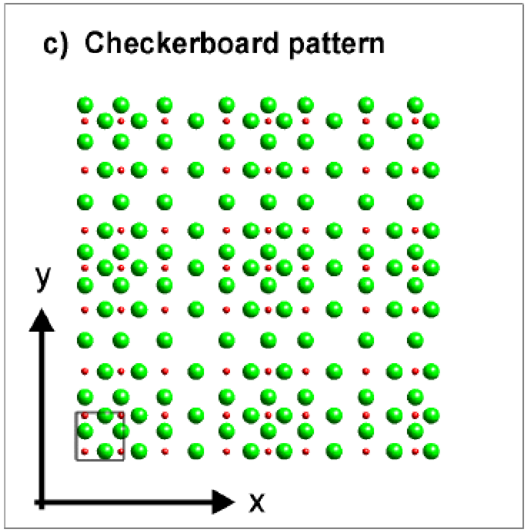


LeBoeuf *et al.,* Nature Physics (2012).

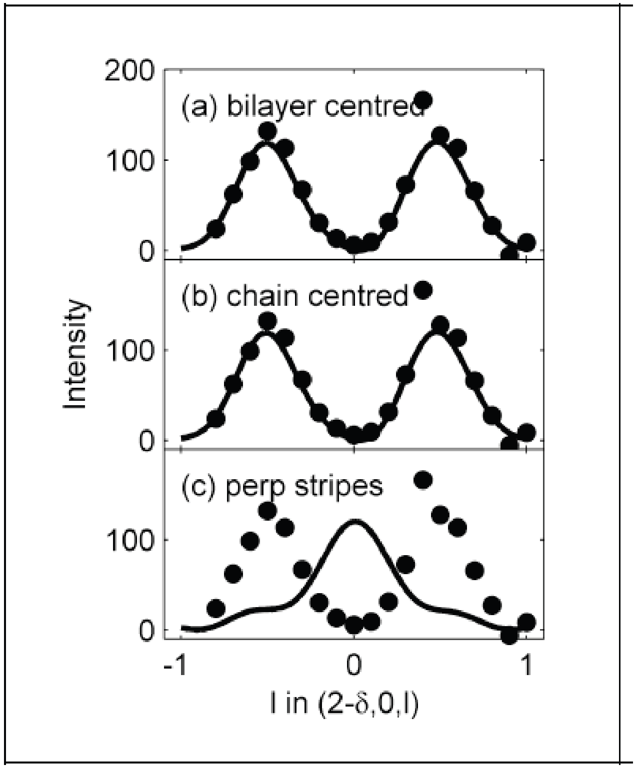
Modelling the CDW



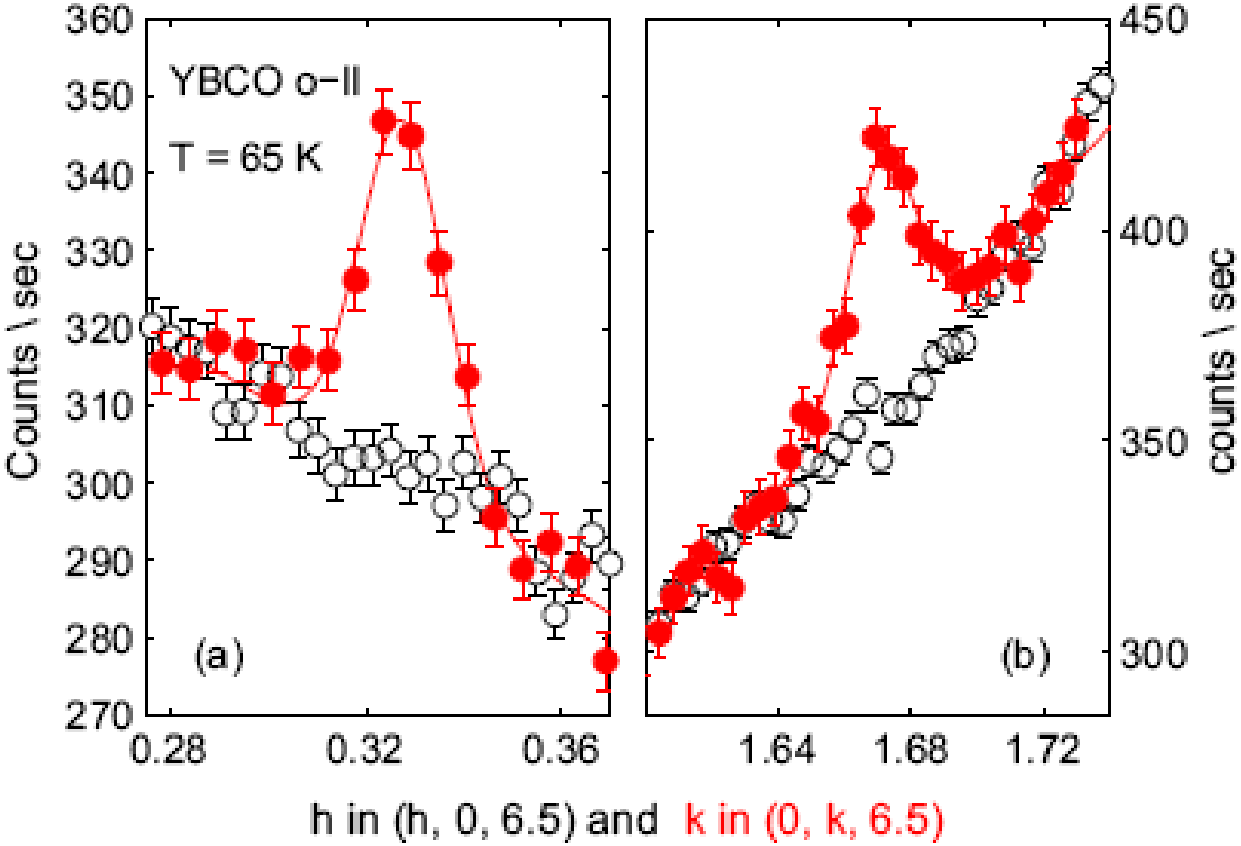




Is it single-**q** or double-**q**?



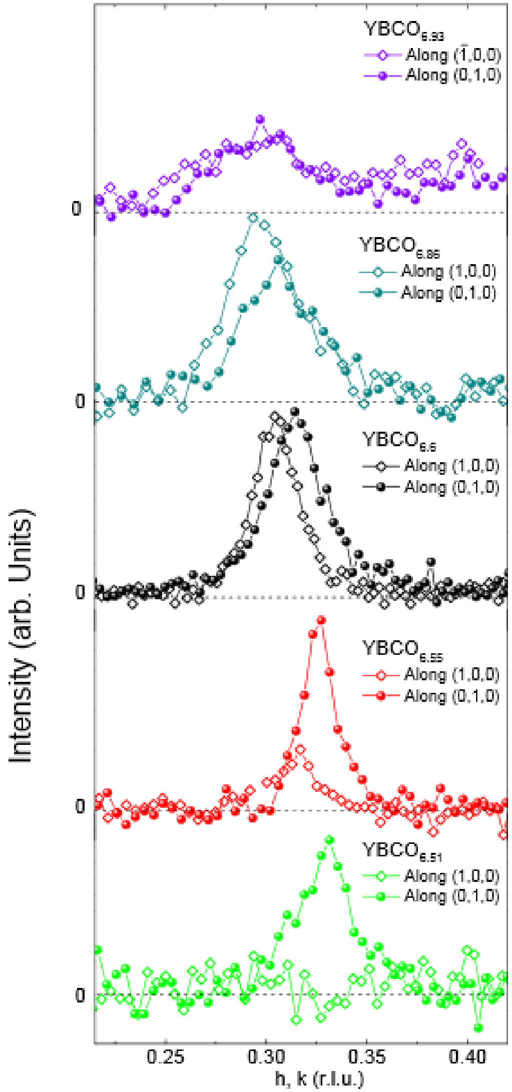
Differences between q_a and q_b



It is therefore likely that the lattice response is driven by the CuO_2 planes, which determine the ***q***.

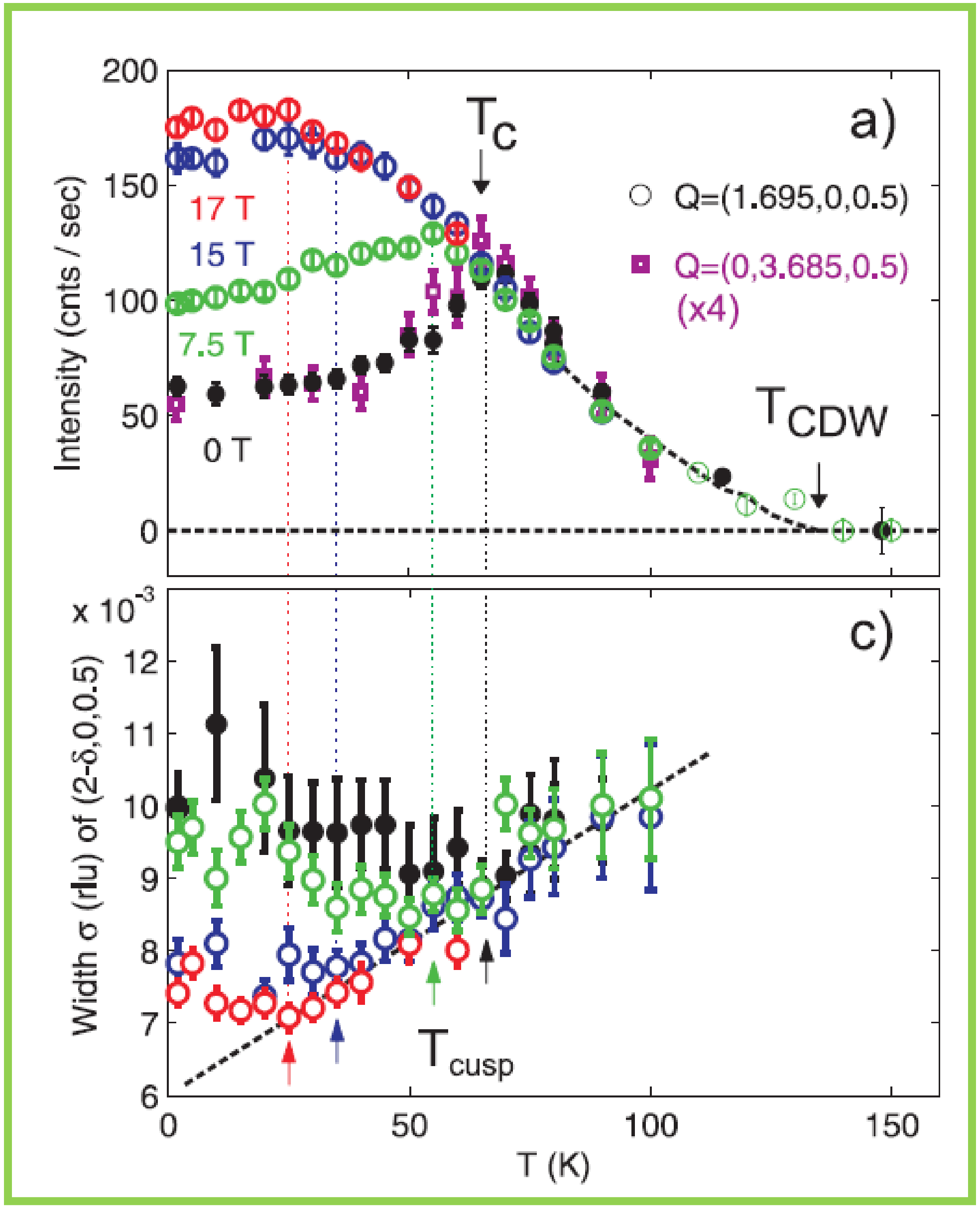
Blackburn *et al*, PRL (2013).

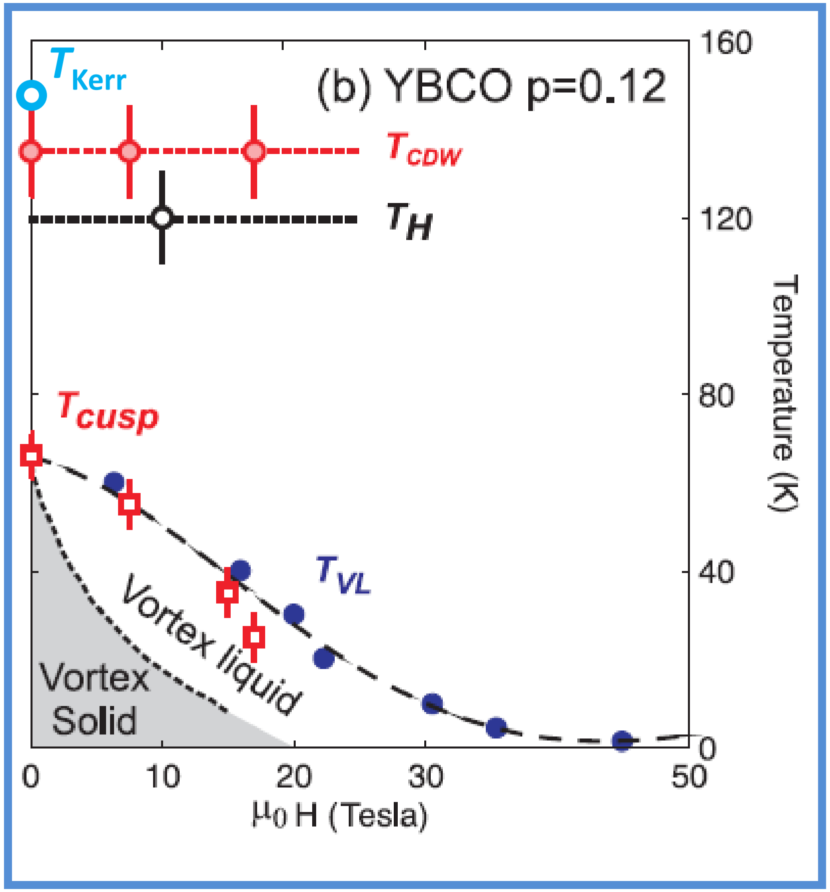
Differences between q_a and q_b



Blanco-Canosa *et al.* arXiv 1406.1595 (2014).

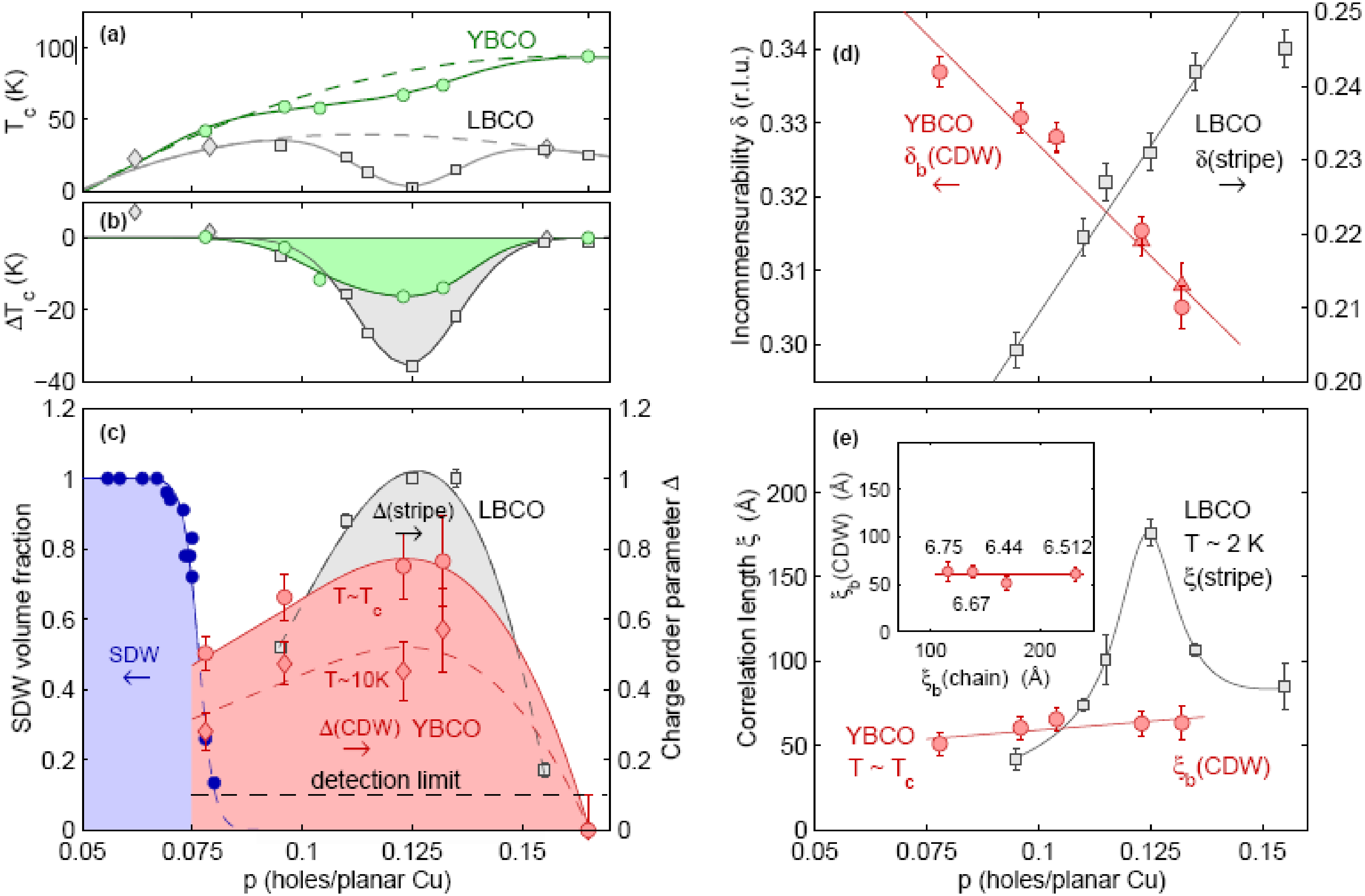
Crossover temperature as f(B)





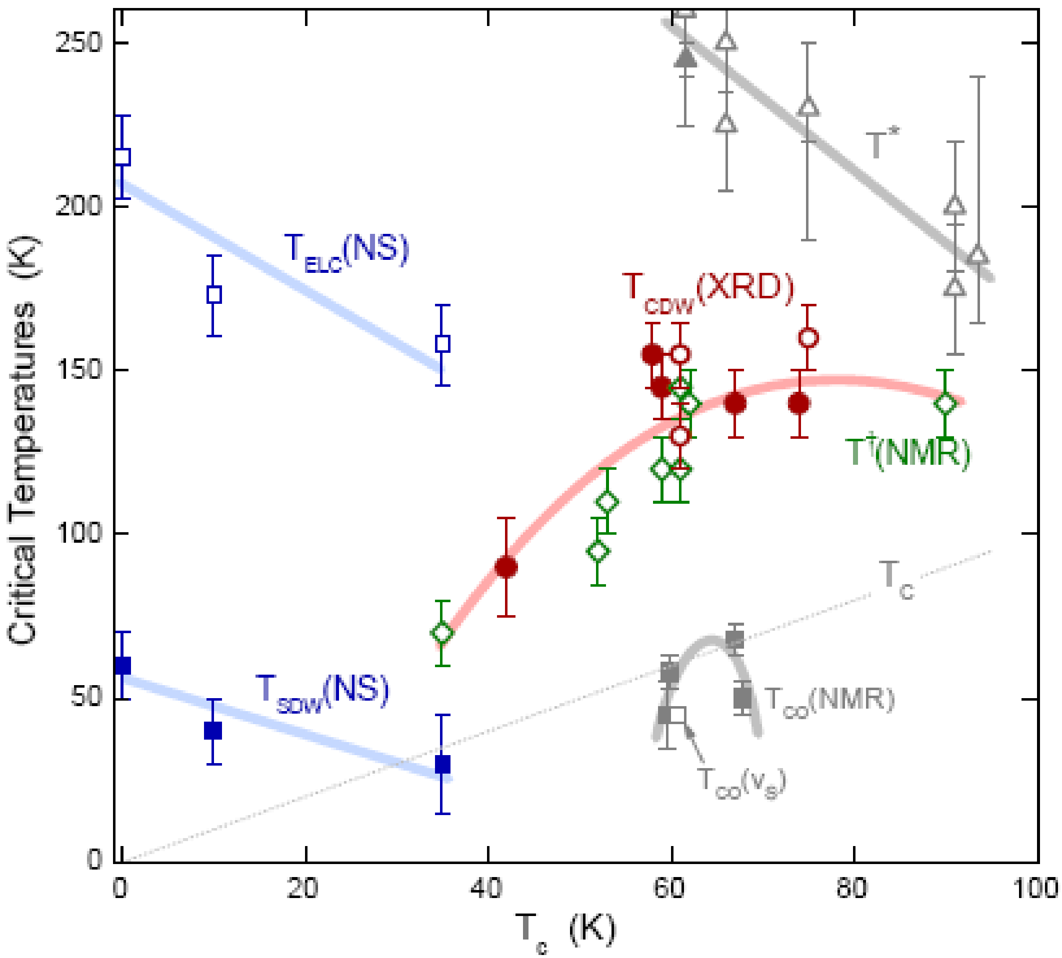
T_{VL} and T_{VS} from
LeBoeuf *et al.*, PRB **83**, 054506 (2011).

Examining the doping dependence



Huecker *et al*, arXiv:1405.7001 (2014).

Examining the doping dependence

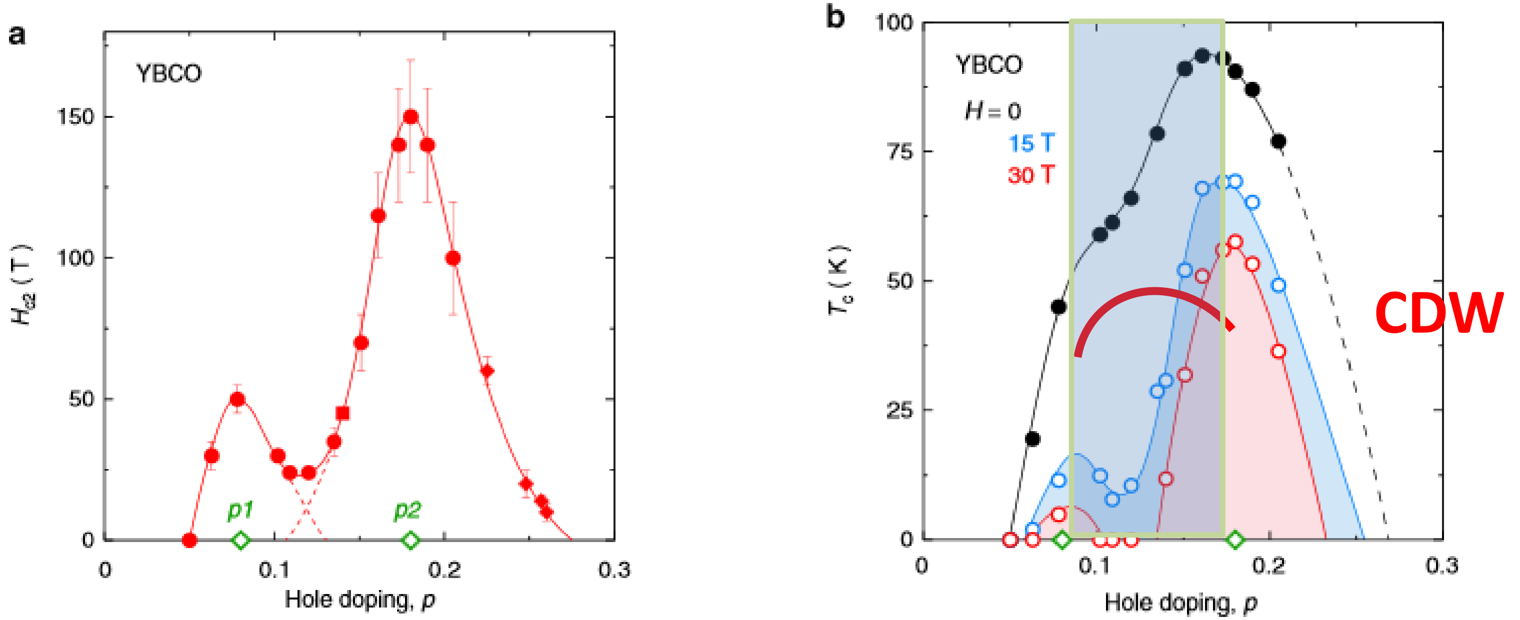


$T^\dagger$ = broad maximum in $1/(T_1T)$ from planar ^{63}Cu NQR/NMR

Huecker *et al*, arXiv:1405.7001 (2014).

Studying the critical field in YBCO

- Two superconducting domes?



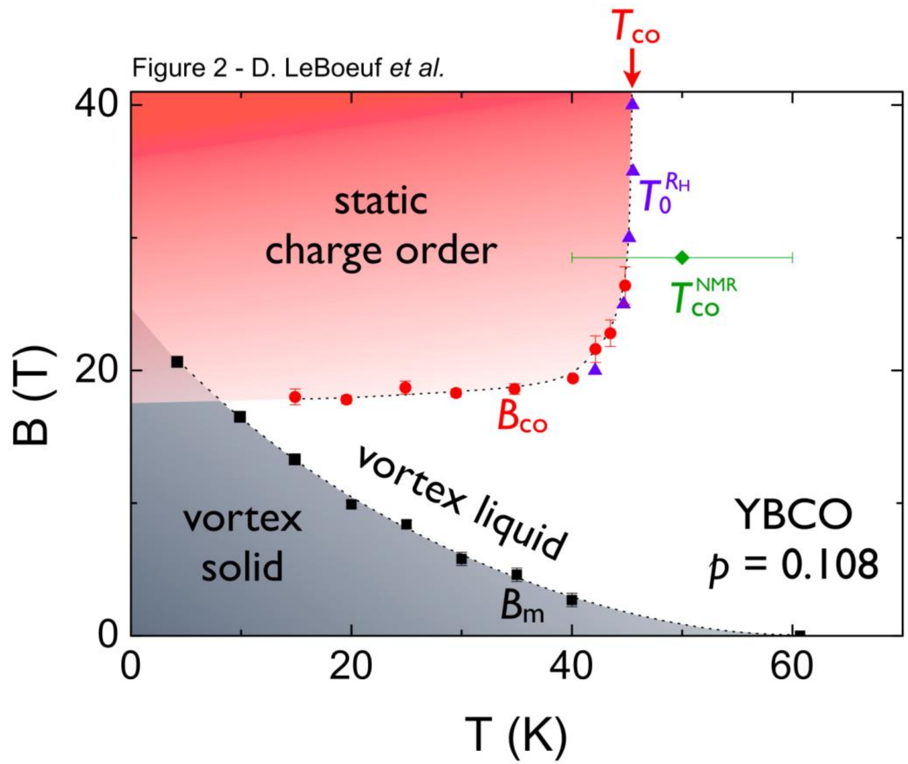
Grissonnanche *et al.*, Nature Comms (2014)

Signs of something changing inside the PG region

- Transport measurements
- NMR/NQR
- Quantum oscillations
- Kerr effect
- Ultrasound
- Polarized neutron diffraction

Time/Energy Scales of CDW

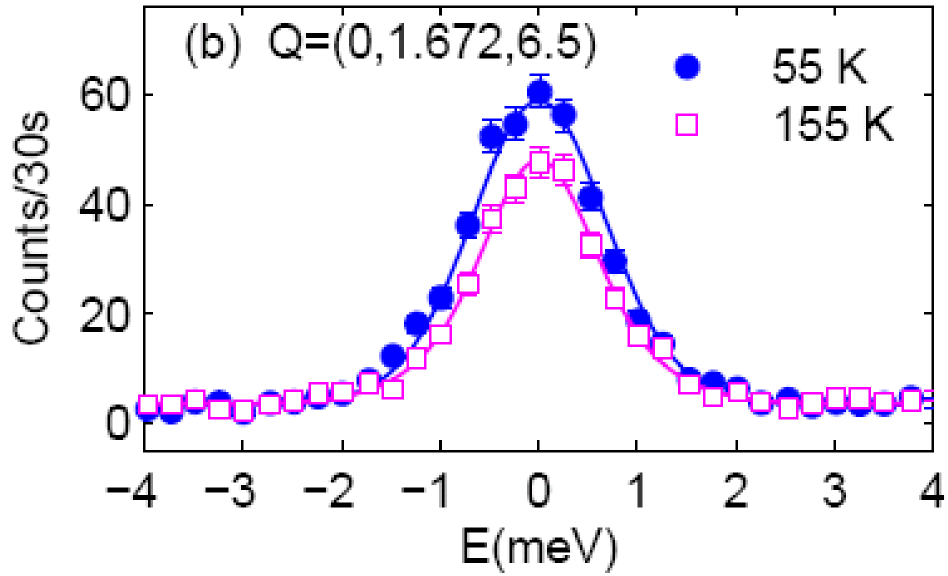
Probe	E_{probe}	T_{CO}(K)	B(T)
NMR[8]	1.5 μeV	50	28.5
ultrasound[10]	0.6 μeV	44.8	26.4
100 keV x-ray diffraction[4]	$\sim$1 keV	155(10)	0
IXS (this work)	1.5 meV	150(40)	0



LeBoeuf *et al.*, Nat. Phys. (2012).

Can we improve these measurements with using inelastic x-ray scattering?

Lifetime



Energy at which the charge response is probed.

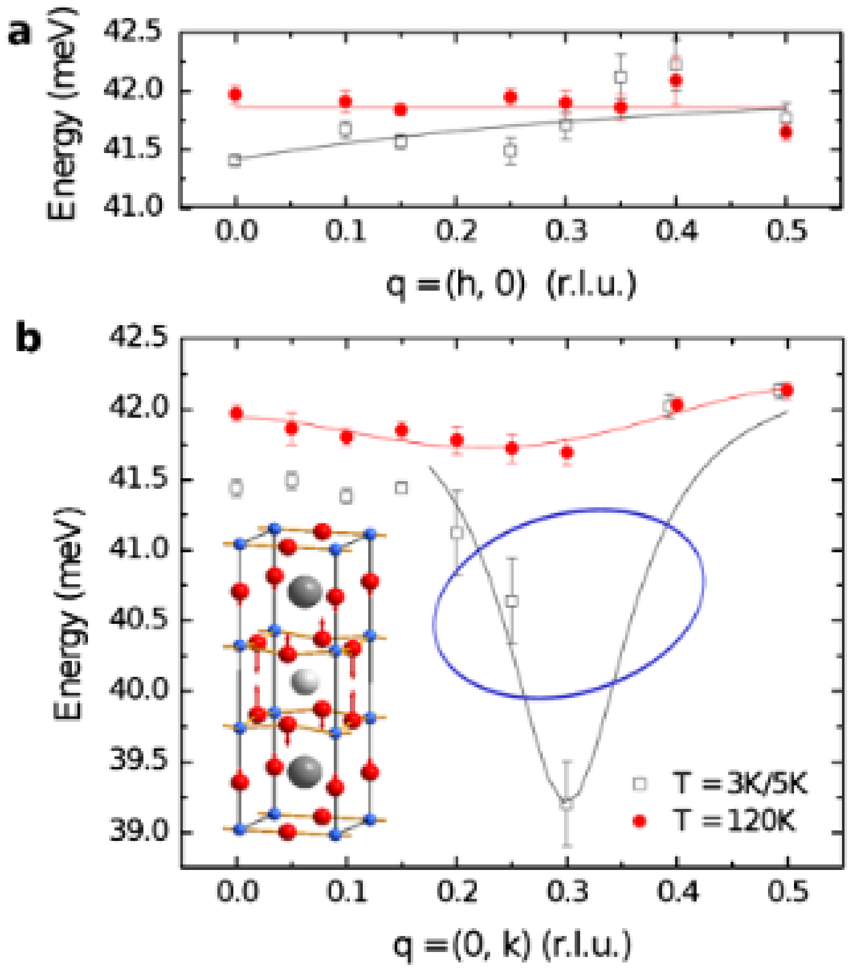
Energy resolution of the instrument.

Probe	E_{probe}	T_{CO}(K)	B(T)
NMR[8]	1.5 μeV	50	28.5
ultrasound[10]	0.6 μeV	44.8	26.4
100 keV x-ray diffraction[4]	~1 keV	155(10)	0
IXS (this work)	1.5 meV	150(40)	0

Blackburn *et al.*, PRB **88**, 054506 (2013).

What about phonons?

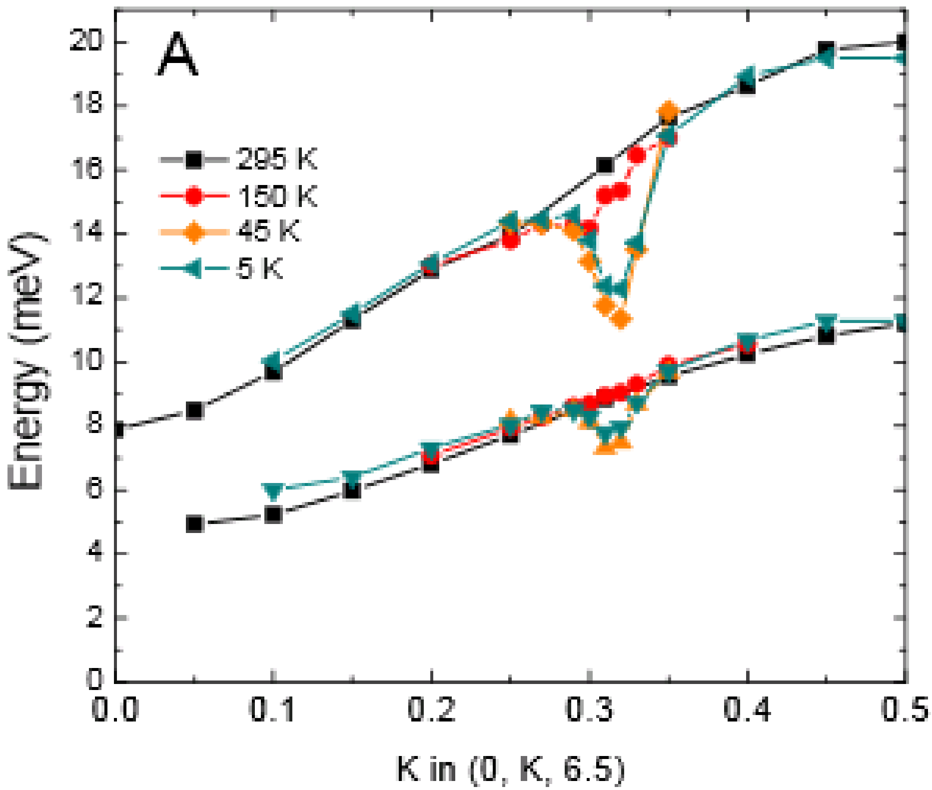
Cu-O bond bending phonon @ ~ 40 meV (YBCO7)



Softens at k = 0.3,
but not at h = 0.3

Raichle *et al.,* Phys. Rev. Lett. **107**, 177004 (2011).

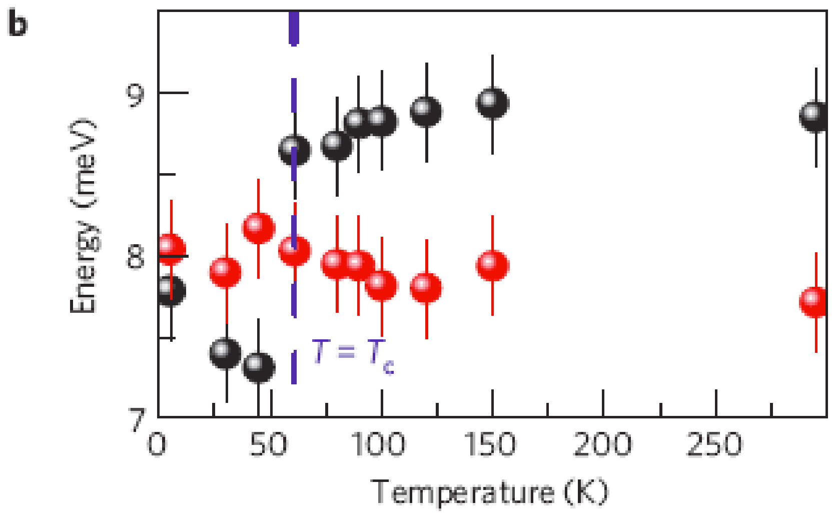
Associated Phonon Anomalies – ortho-VIII



Almost purely transverse acoustic mode

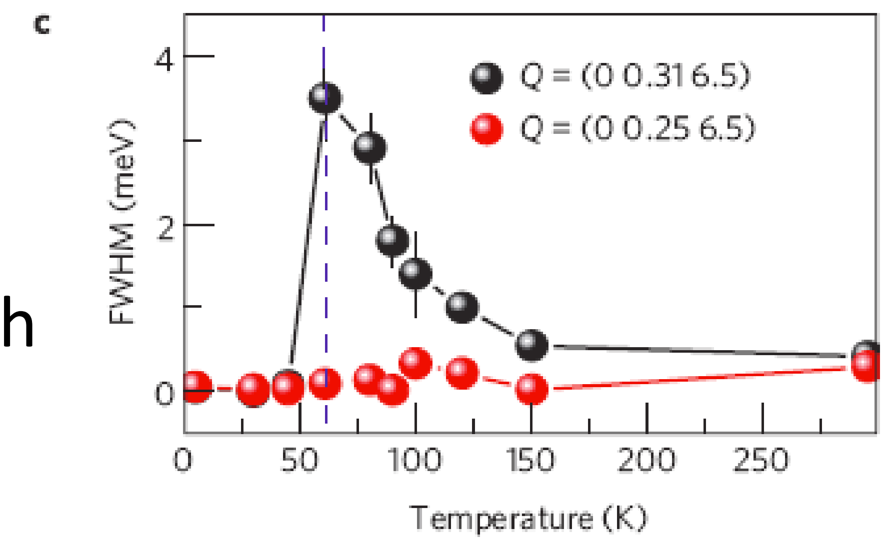
Le Tacon *et al.,* Nature Physics **10**, 52 (2013).

Associated Phonon Anomalies – ortho-VIII



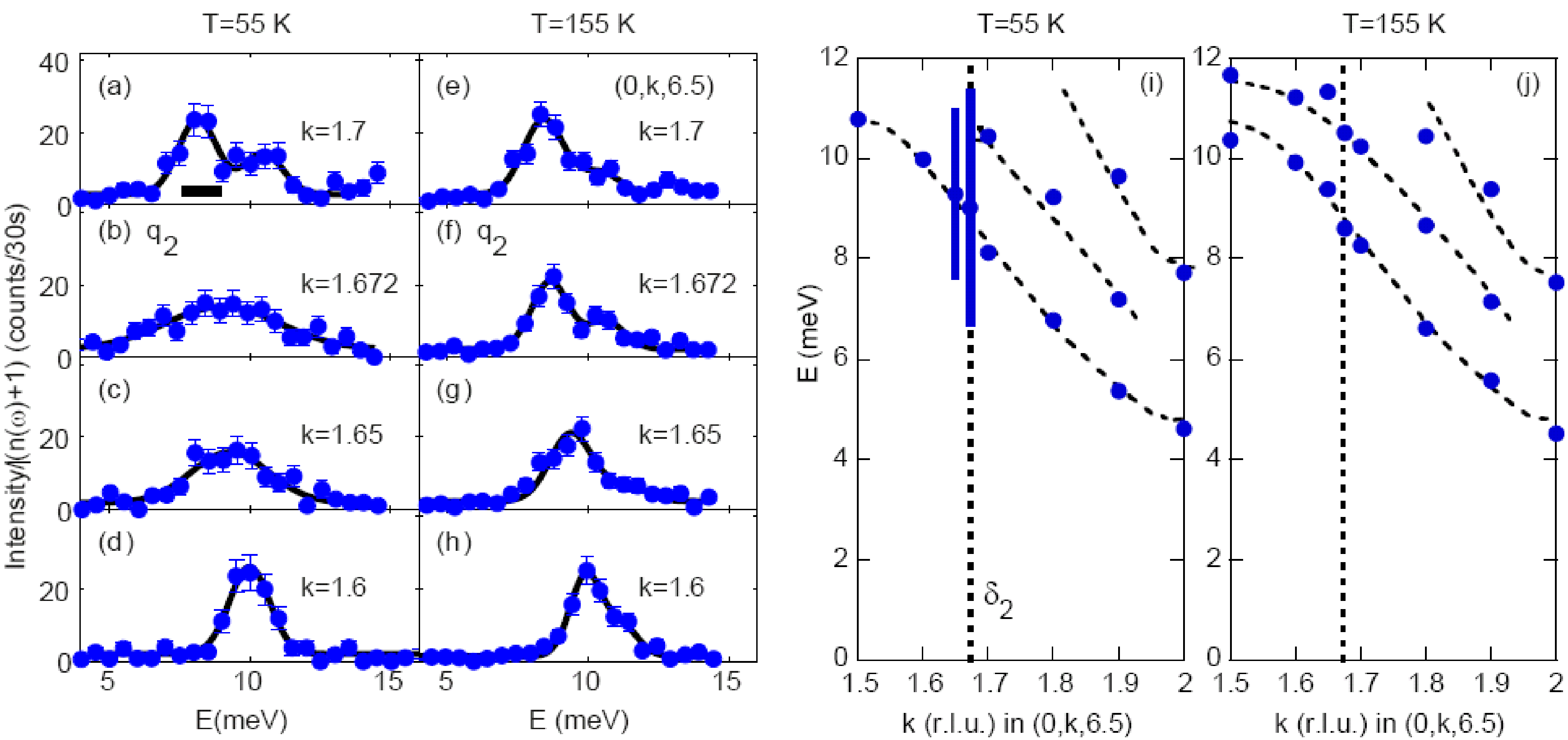
Mode Energy

Phonon Linewidth



Le Tacon *et al.*, Nature Physics **10**, 52 (2013).

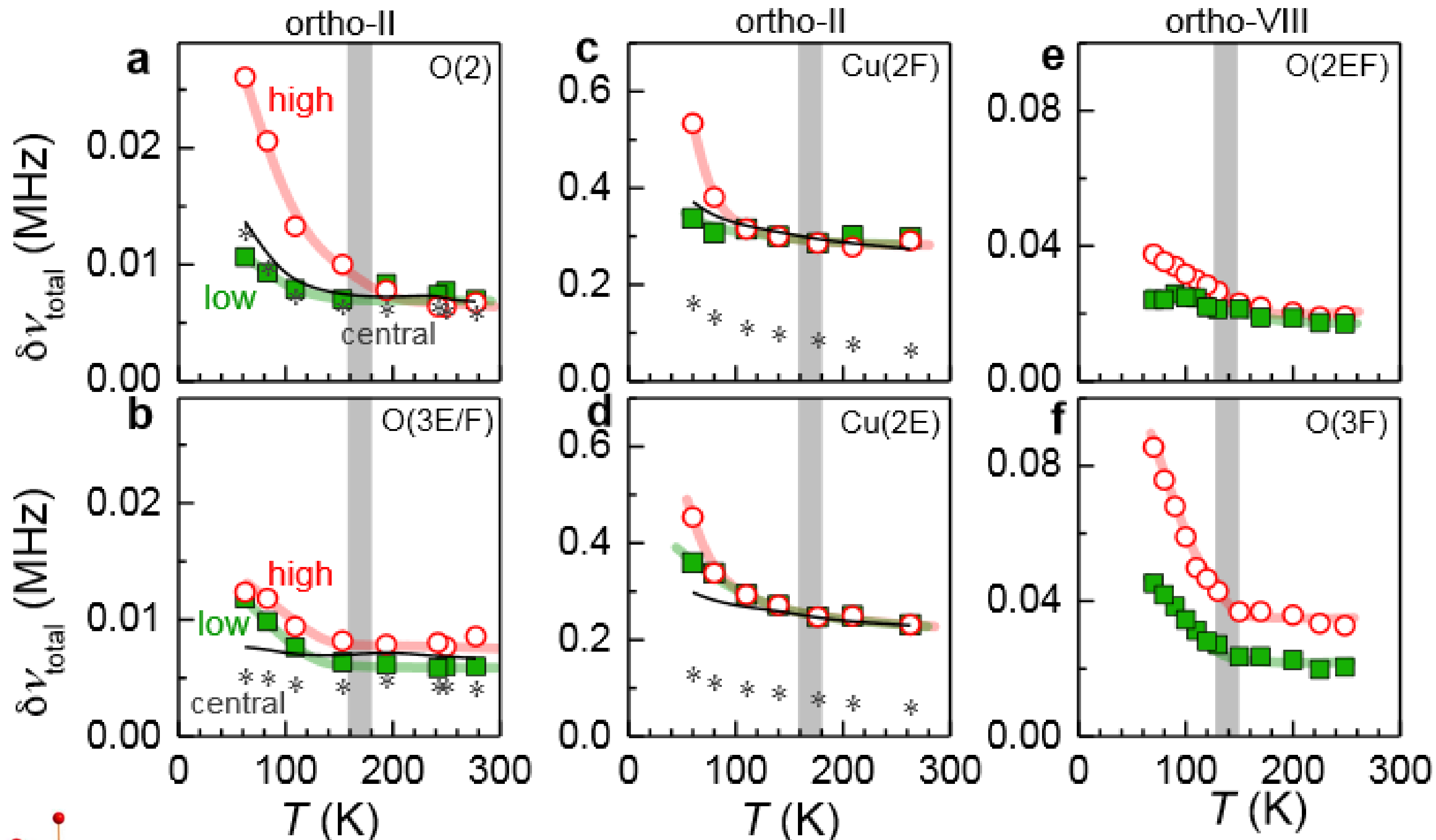
Associated Phonon Anomalies – ortho-II

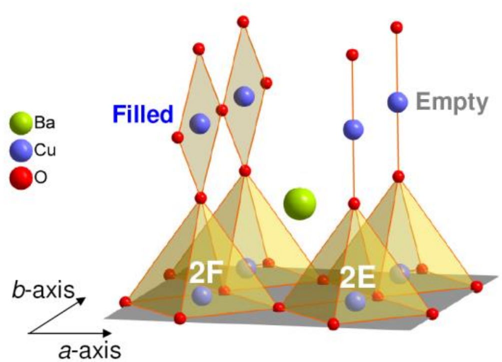


Measured at a mixed mode, thought to be primarily transverse acoustic

Blackburn *et al.,* Phys. Rev. B **88**, 054506 (2013).

BUT – does this match the NMR data?





Evidence of static charge order in the pseudogap state.

T. Wu *et al.*, arXiv:1404.1617 (2014).

BUT – does this match the NMR data?

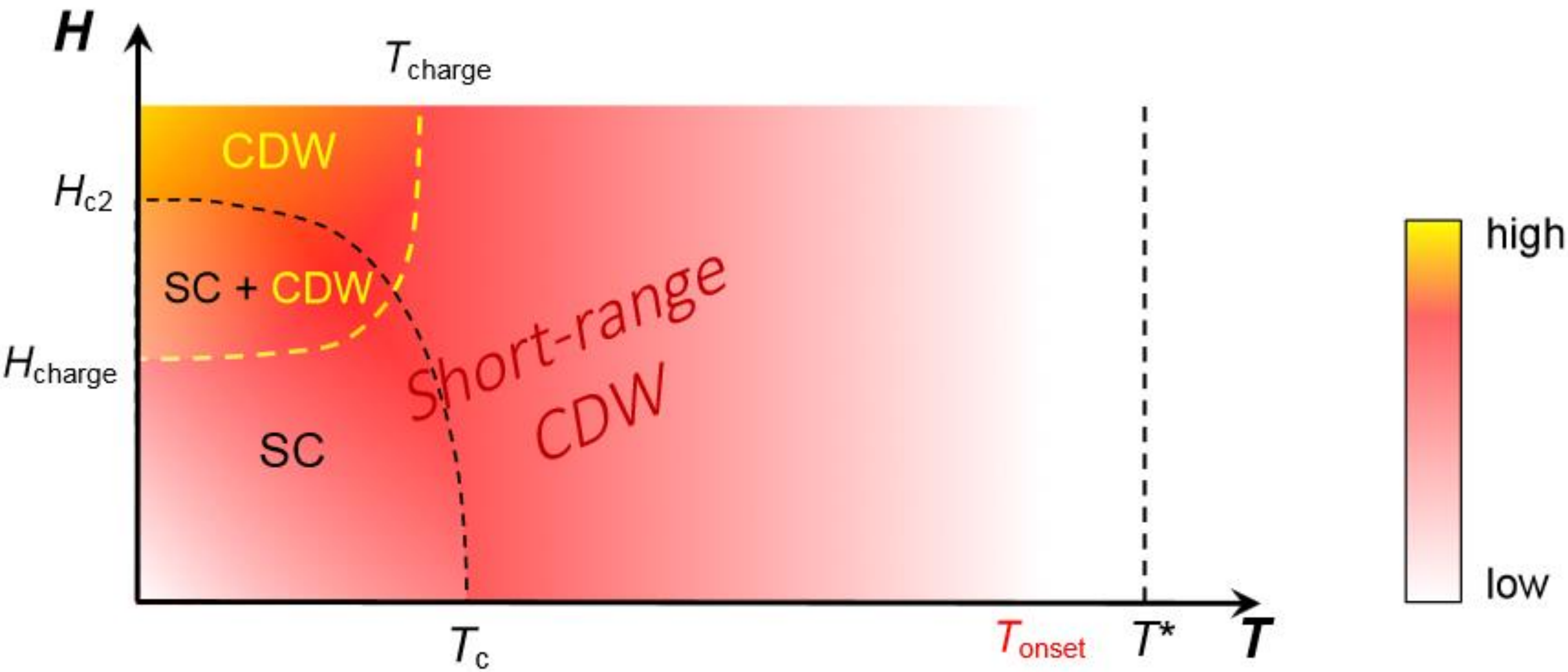
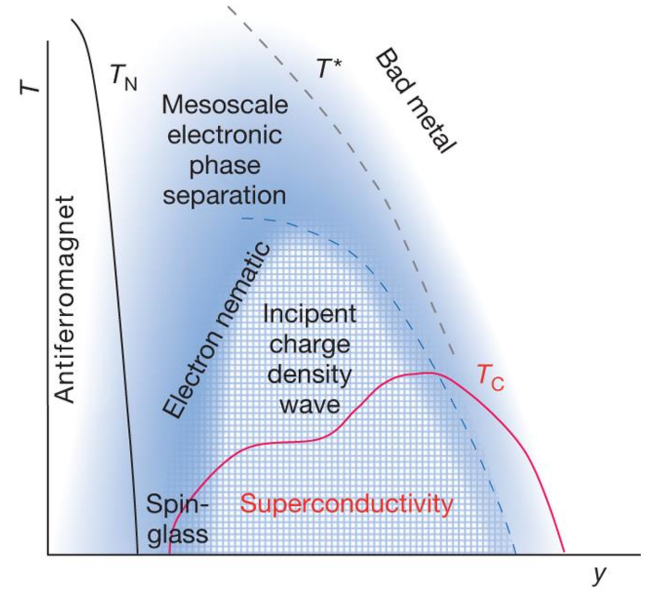


Figure 4 | *H–T* phase diagram of charge-ordered $YBa_2Cu_3O_y$.

T. Wu *et al.*, arXiv:1404.1617 (2014).

Summary



Fradkin & Kivelson
Nature Physics (2012)

- The CuO_2 planes are prone to an instability before becoming superconducting.
- The CDW appears to be able to motivate the FS reconstruction.
- What does it have to do with the pseudogap?