Field & temperature scales in charge-ordered $YBa_2Cu_3O_y$

Marc-Henri Julien

LABORATOIRE NATIONAL DES CHAMPS MAGNETIQUES INTENSES, GRENOBLE

LNCMI

Collège de France, March 2015

Acknowledgements

T. Wu
M. Hirata
R. Zhou
I. Vinograd
H. Mayaffre
S. Krämer
M. Horvatic
C. Berthier
LNCMI Grenoble

C. Proust
B. Vignolle
D. Vignolles
D. LeBoeuf
LNCMI Toulouse

P.L. Kuhns
A.P. Reyes
NHMFL Tallahassee

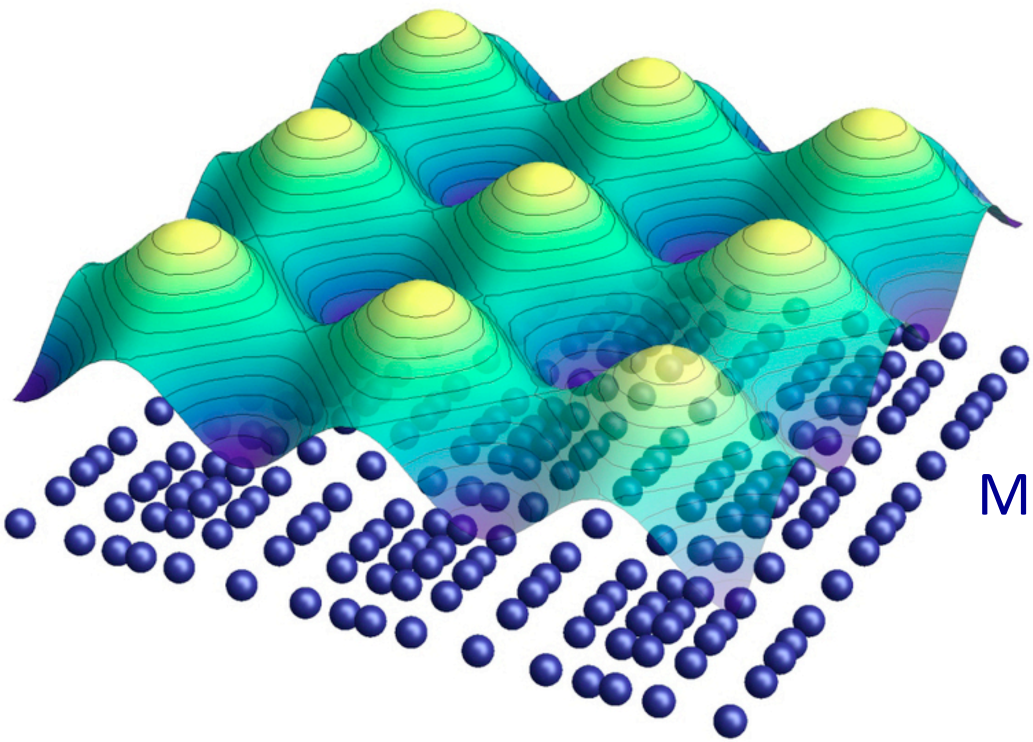
W.N. Hardy
R. Liang
D.A. Bonn
UBC Vancouver

C.T. Lin
T. Loew
D. Haug
V. Hinkov
B. Keimer
MPI-FKF Stuttgart

M. K. Chan
C.J. Dorow
N. Barisic
M. Greven
U. Minnesota, Minneapolis

Support from

Charge (density wave) order, « CDW »



Modulated charge density

Modulated lattice positions

Picture from Keimer group
MPI-FKF Stuttgart

Evidence for stripe correlations of spins and holes in copper oxide superconductors

J. M. Tranquada*, B. J. Sternlieb†, J. D. Axe*, Y. Nakamura† & S. Uchida†

* Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA
† Superconductivity Research Course, The University of Tokyo, Yayoi 2-11-16, Bunkyo-ku, Tokyo 113, Japan

One of the long-standing mysteries associated with the high-temperature copper oxide superconductors concerns the anomalous suppression[1] of superconductivity in $La_{2-x}Ba_xCuO_4$ (and certain related compounds) when the hole concentration x is near $\frac{1}{8}$. Here we examine the possibility that this effect is related to dynamical two-dimensional spin correlations, incommensurate with the crystal lattice, that have been observed in $La_{2-x}Sr_xCuO_4$ by neutron scattering[2–4]. A possible explanation for the incommensurability involves a coupled, dynamical modulation of spin and charge in which antiferromagnetic 'stripes' of copper spins are separated by periodically spaced domain walls to which the holes segregate[5–9]. An ordered stripe phase of this type has recently been observed in hole-doped La_2NiO_4 (refs 10–12). We present evidence from neutron diffraction that in the copper oxide material $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$, with $x = 0.12$, a static analogue of the dynamical stripe phase is present, and is associated with an anomalous suppression of superconductivity[13,14]. Our results thus provide an explanation of the '$\frac{1}{8}$' conundrum, and also support the suggestion[15] that spatial modulations of spin and charge density are related to superconductivity in the copper oxides.

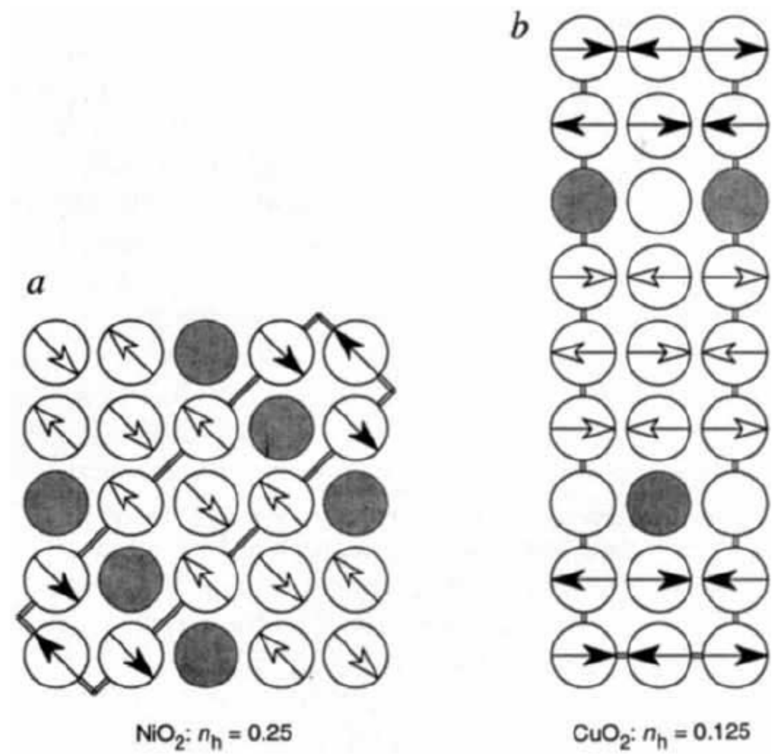
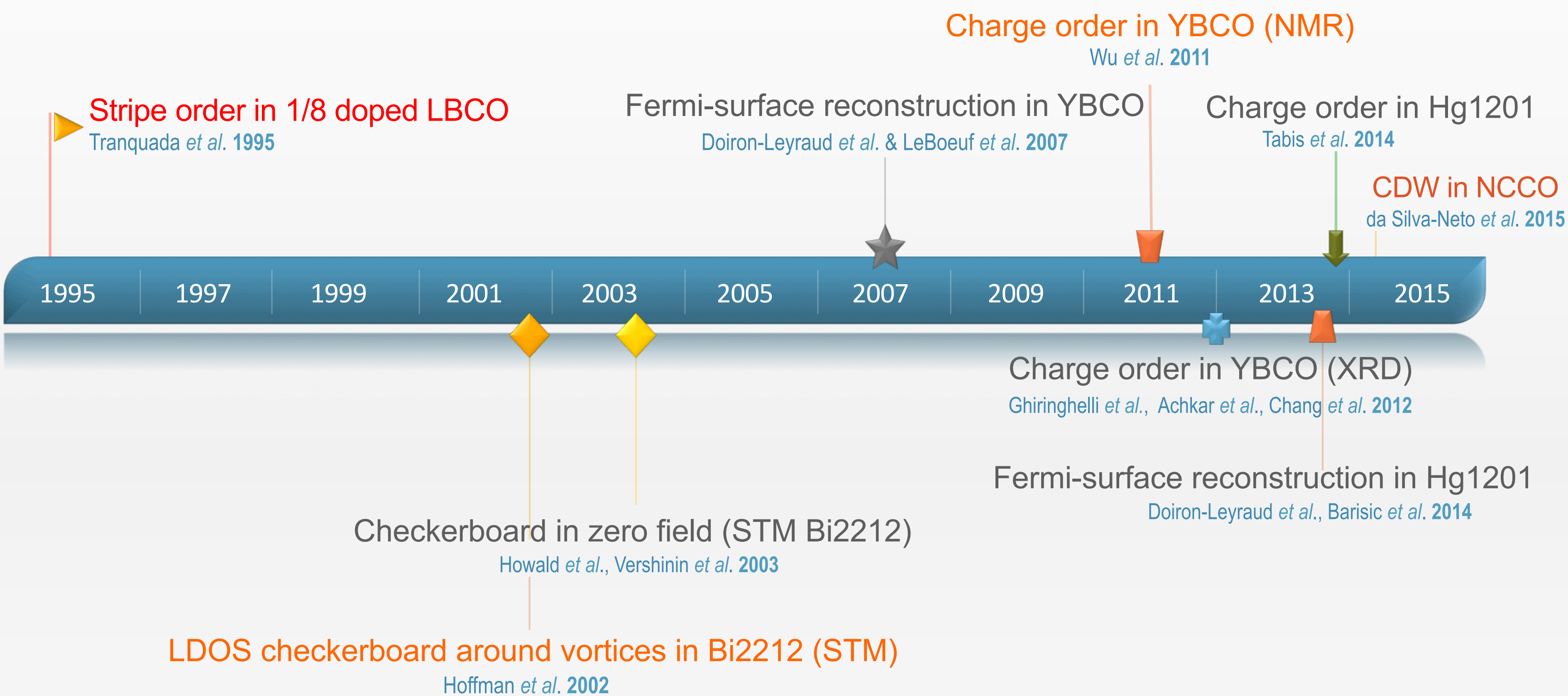


FIG. 1 *a*, Idealized diagram of the spin and charge stripe pattern within a NiO_2 plane observed in hole-doped La_2NiO_4 with a hole density of $n_h = \frac{1}{4}$. *b*, Hypothesized stripe pattern in a CuO_2 plane of hole-doped La_2CuO_4 with $n_h = \frac{1}{8}$. In both, only the metal atoms are represented; the oxygen atoms, which surround the metal sites in a square planar array (as shown in Fig. 2), have been omitted. Arrows indicate the orientation of magnetic moments on metal atoms, which are locally antiparallel; the spin direction rotates by 180° (relative to a simple antiferromagnetic structure) on crossing a domain wall, as emphasized by the change in

Received 1 March; accepted 19 May 1995.

20 years of charge order in cuprates



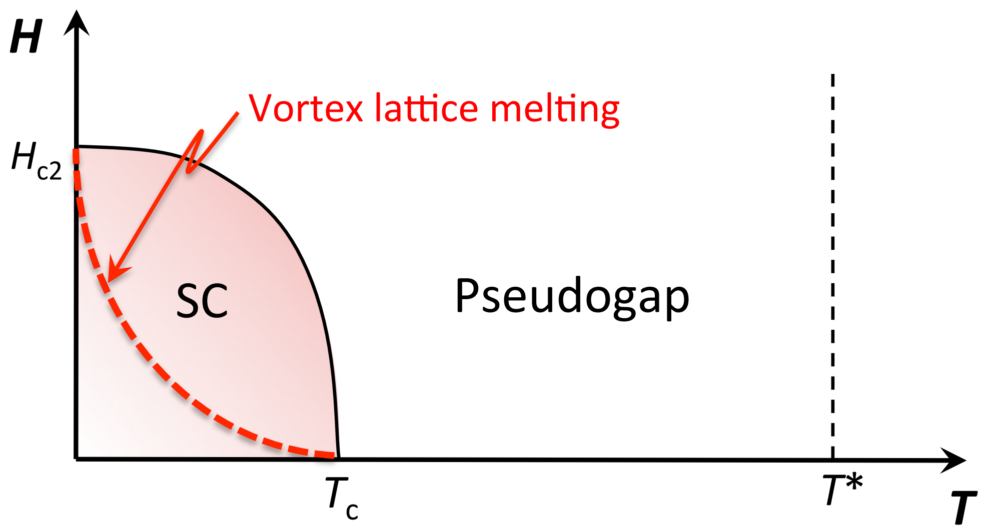
20 years of charge order in cuprates

High field NMR in YBCO
(unsuccessful)

MHJ et al. unpublished

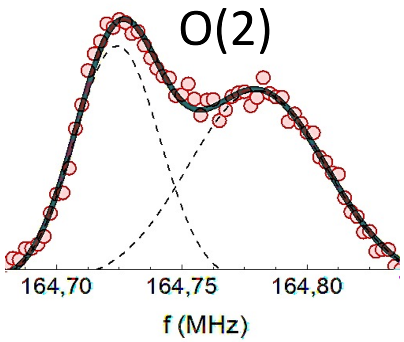
1995 | 1997 | 1999 | 2001 | 2003 | 2005 | 2007 | 2009 | 2011 | 2013 | 2015

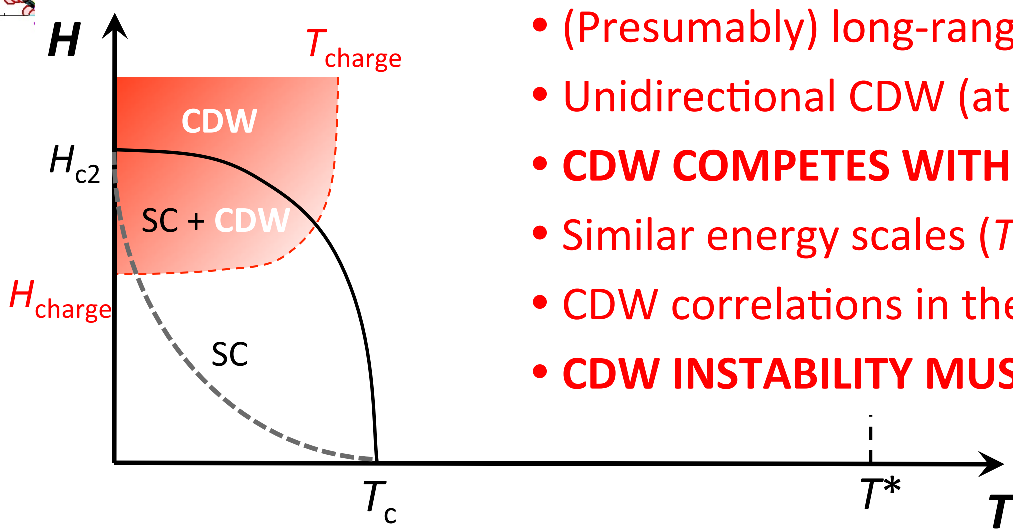
H – *T* phase diagram



Charge order phase diagram ($YBa_2Cu_3O_{6.5\text{-}6.7}$)

From Nuclear Magnetic Resonance



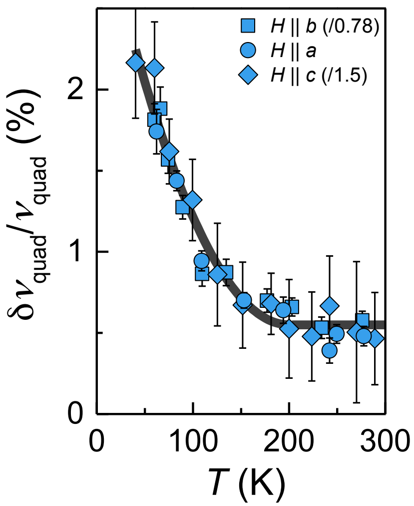


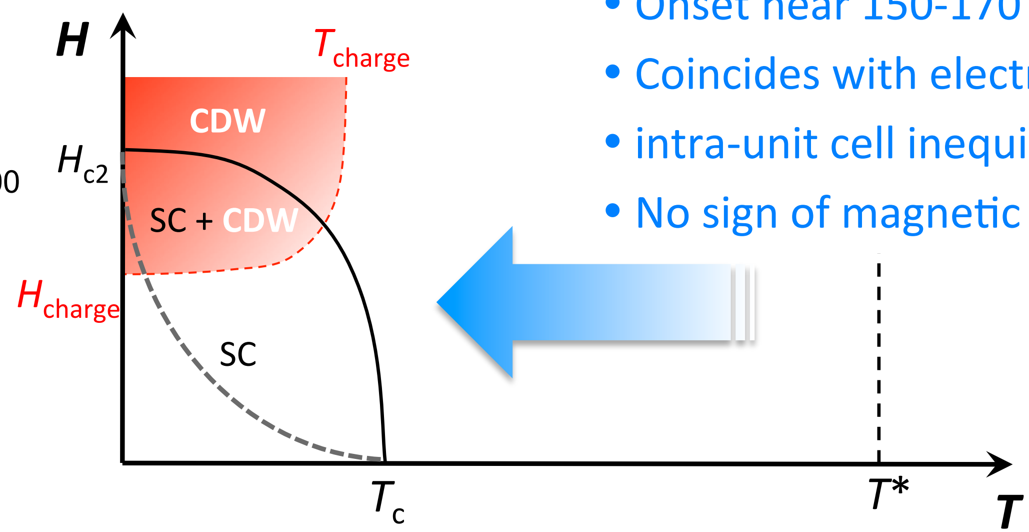
- **CHARGE (CDW) ORDER**
- No spin order
- CDW must reconstruct Fermi surface
- Looks like a phase transition
- (Presumably) long-range CDW order
- Unidirectional CDW (at least in O-II)
- **CDW COMPETES WITH SC**
- Similar energy scales ($T_{charge} \approx T_c$)
- CDW correlations in the normal state
- **CDW INSTABILITY MUST BE GENERIC**

Wu *et al.* Nature 477, 191 (2011)
Wu *et al.* Nature Commun. 4, 2113 (2013)

Charge order phase diagram ($YBa_2Cu_3O_{6.5-6.7}$)

From Nuclear Magnetic Resonance





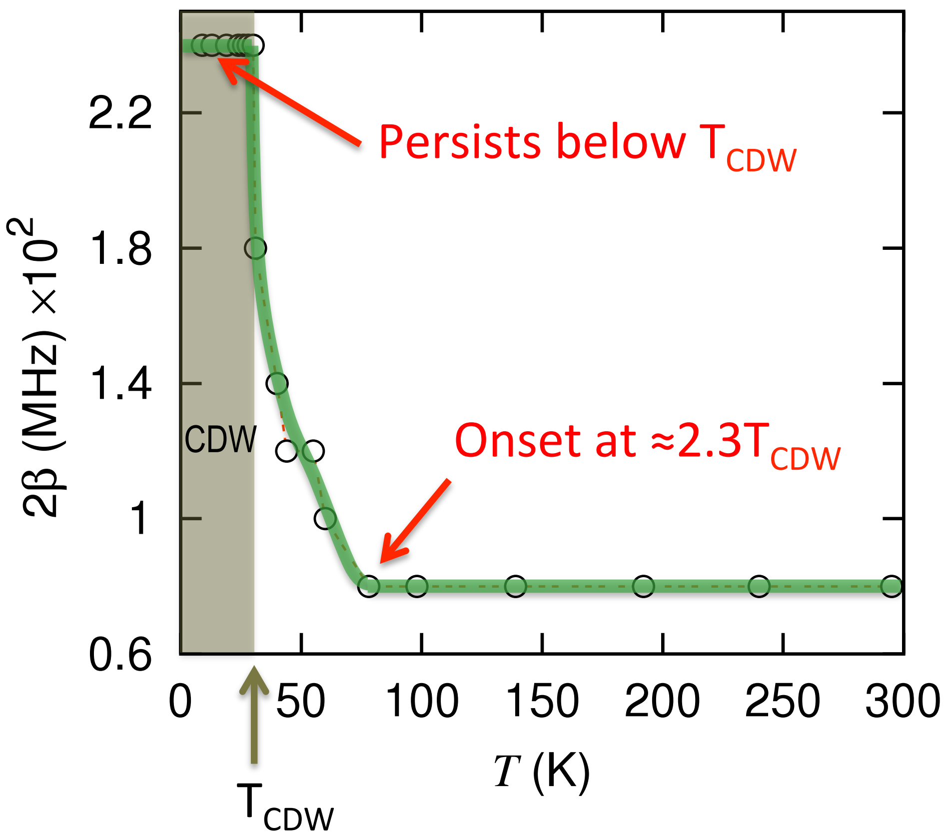
- **PRECURSOR LINE BROADENING**
- « Weaker » charge modulation
- Really static (timescale 0.1 ms)
- Onset near 150-170 K
- Coincides with electronic anomalies
- intra-unit cell inequivalence (nematic)
- No sign of magnetic order

Wu *et al.* Nature Commun. 6, 6438 (2015)

Lessons from $NbSe_2$

Archetypal 2D CDW system

Berthier *et al.* J. Phys.: Solid State Phys. (1978)
Ghoshray *et al.* J. Phys.: Condens. Matter (2009)

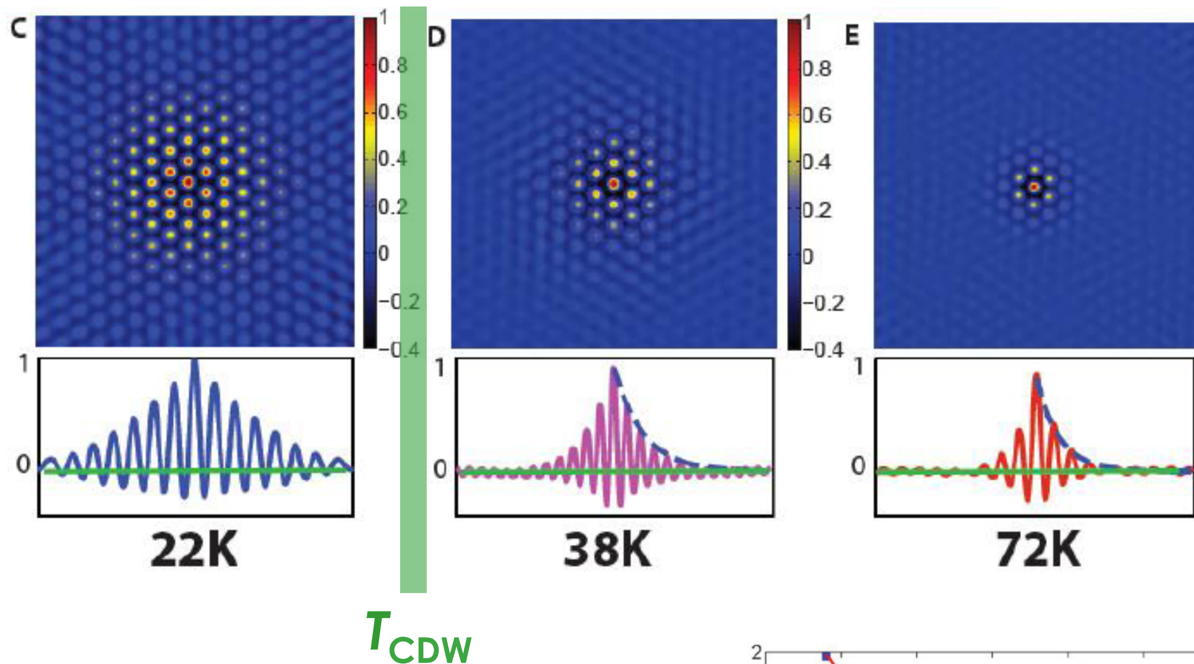


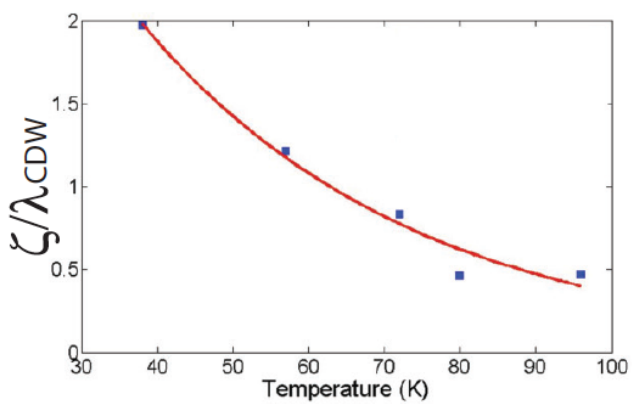
Pre-transitional NMR broadening from
short-range CDW around defects

Lessons from $NbSe_2$

Recent STM experiments provide real-space images of Friedel oscillations with CDW period

Arguello *et al.* Phys. Rev. B 89, 235115 (2014)
Chatterjee *et al.* Nature Commun. 6, 6313 (2015)

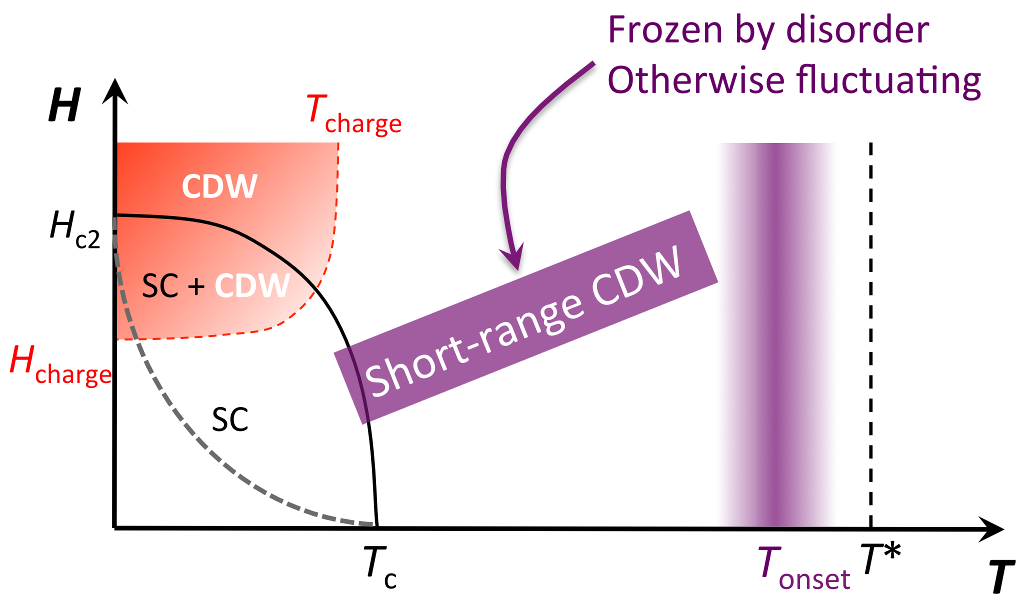




Charge order phase diagram ($YBa_2Cu_3O_{6.5\text{-}6.7}$)

From NMR

Striking analogy with $NbSe_2$ suggests:

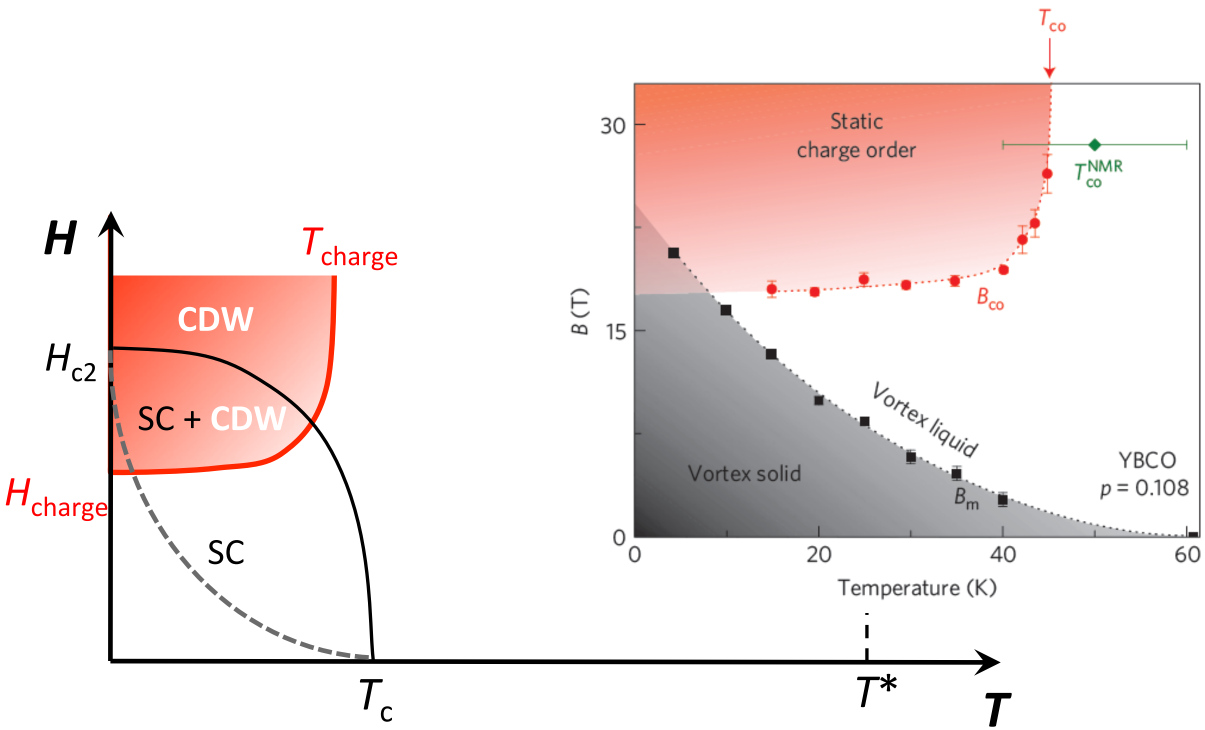


Wu *et al.* Nature Commun. 6, 6438 (2015)

Charge order phase diagram ($YBa_2Cu_3O_{6.5\text{-}6.7}$)

From sound velocity

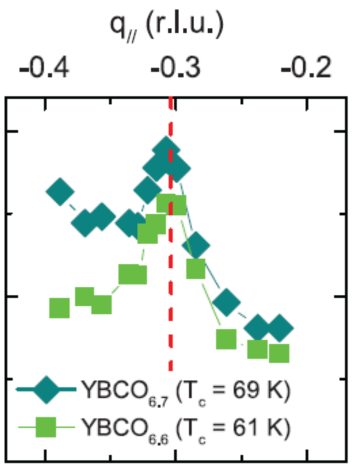
- Thermodynamic evidence of phase transition



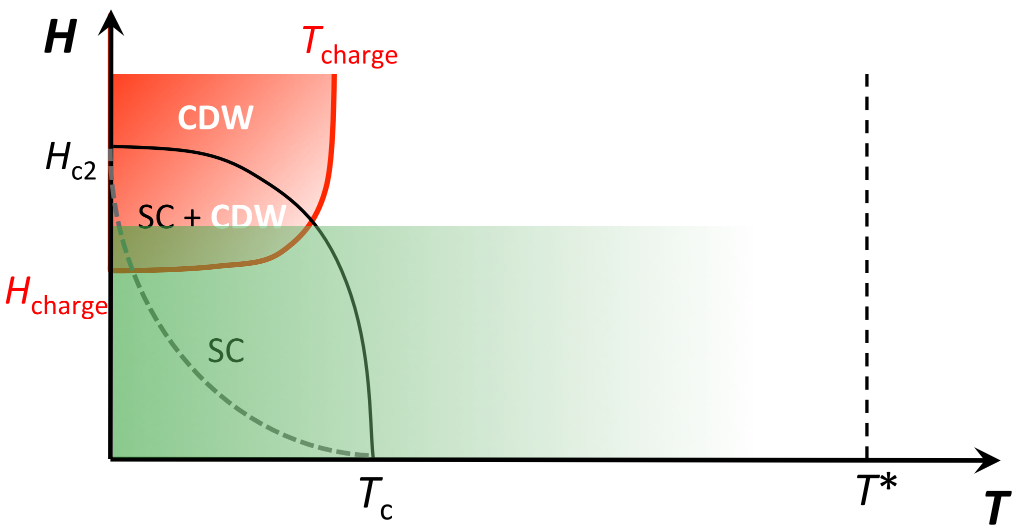
LeBoeuf *et al.* Nature Phys. 9, 79 (2013)

Charge order phase diagram ($YBa_2Cu_3O_{6.5\text{-}6.7}$)

From (hard & soft) X-ray scattering



- Incommensurate period λ ~ 3.2 *b*
- **Correlation length (*H*=0) ~ 20 *b* ~ 6 λ**
- And much more… (following talks)



Ghiringhelli *et al.* Science 337, 821 (2012)
Chang *et al.* Nature Phys. 8, 871 (2012)
Achkar *et al.* PRL 109, 167001 (2012)
Blackburn *et al.* PRL 110, 137004 (2013)
Blanco-Canosa *et al.* PRL 110, 187001 (2013)

Should we call this « CDW order »?

What does $\xi_{CDW} \approx 6\,\lambda$ mean?

Is this a CDW?	No	Yes
ξ_{CDW}	Small	Half as long as in LBCO (1/8)
If disorder were absent	Fluctuating CDW	Long-ranged CDW
Effect of disorder	Freezes fluctuations	Breaks into domains
High-field transition	« The » CDW transition	Subsidiary transition
Vocabulary	« Embryonic » CDW	« Vestigial » CDW

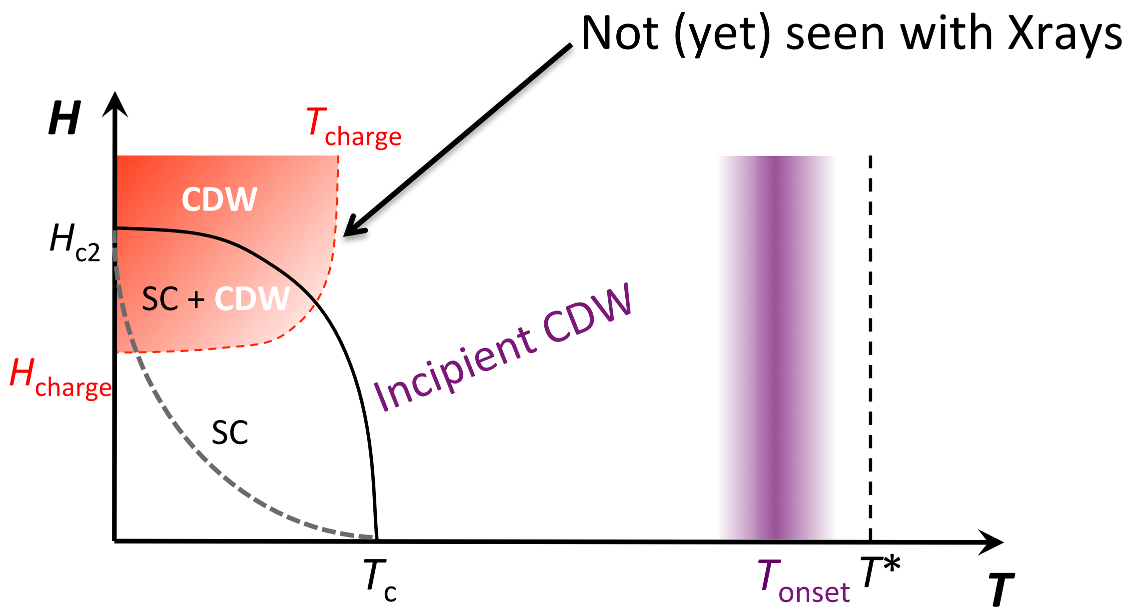
Nie, Tarjus, Kivelson, PNAS 111, 7980 (2014)

In any event: « Incipient CDW » pinned by native defects
Disorder does play a role, even in super-clean O-II YBCO

NB: disorder pinning affects CDW « texture »

Del Maestro *et al.*, Phys. Rev. B 74, 024520 (2006)
Robertson *et al.*, Phys. Rev. B 74, 134507 (2006)

Charge order phase diagram ($YBa_2Cu_3O_{6.5\text{-}6.7}$)

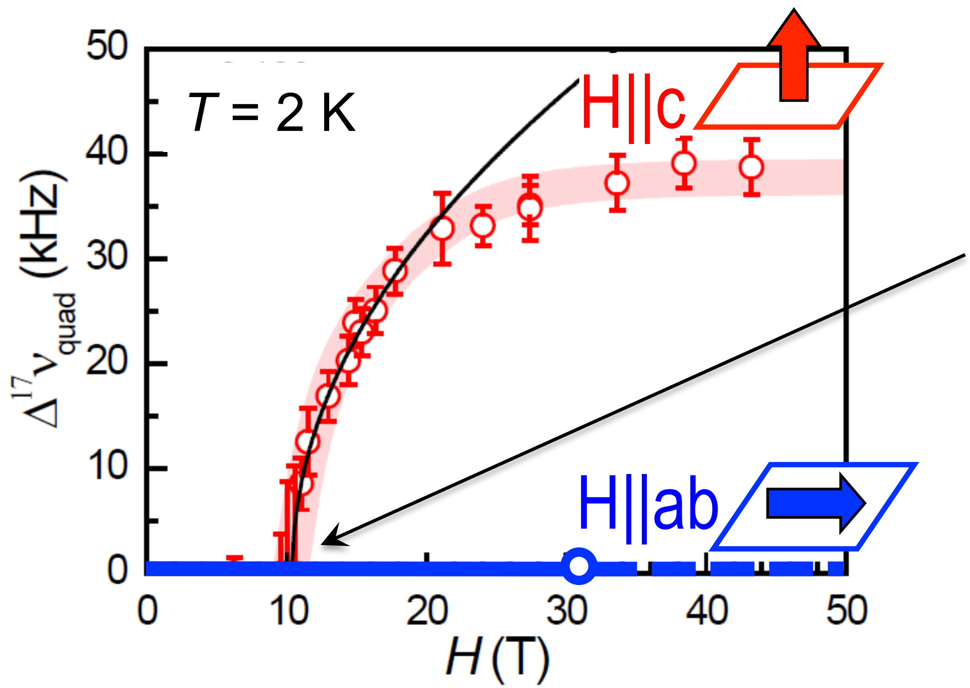


Wu *et al.* Nature Commun. 6, 6438 (2015)

Field dependence

Provides direct evidence of competition: SC impedes CDW

Wu *et al.* Nature Commun. 4, 2113 (2013)



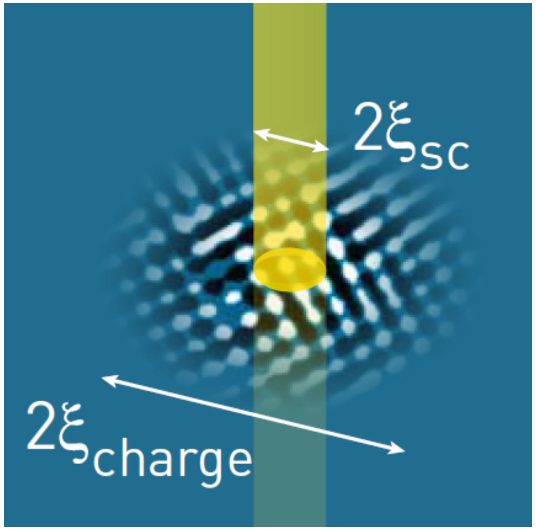
Transition field in vortex state

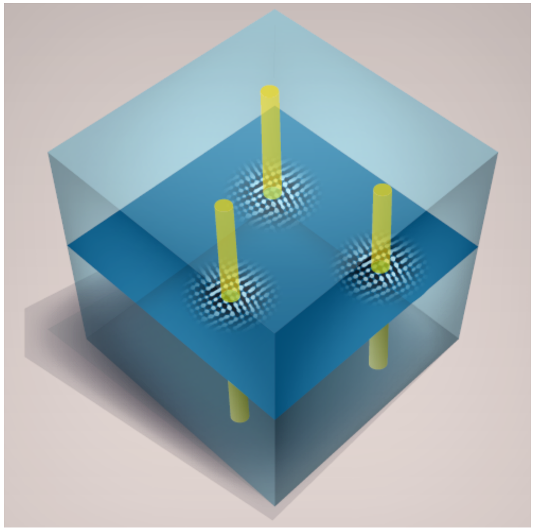
$YBa_2Cu_3O_{6.56}$ ortho-II

CDW in vortex state

Incipient CDW takes refuge in/around vortex cores

Wu *et al.* Nature Commun. 4, 2113 (2013)





Halo of enhanced CDW correlations around each vortex core

Increase field

Long range order when halos overlap?

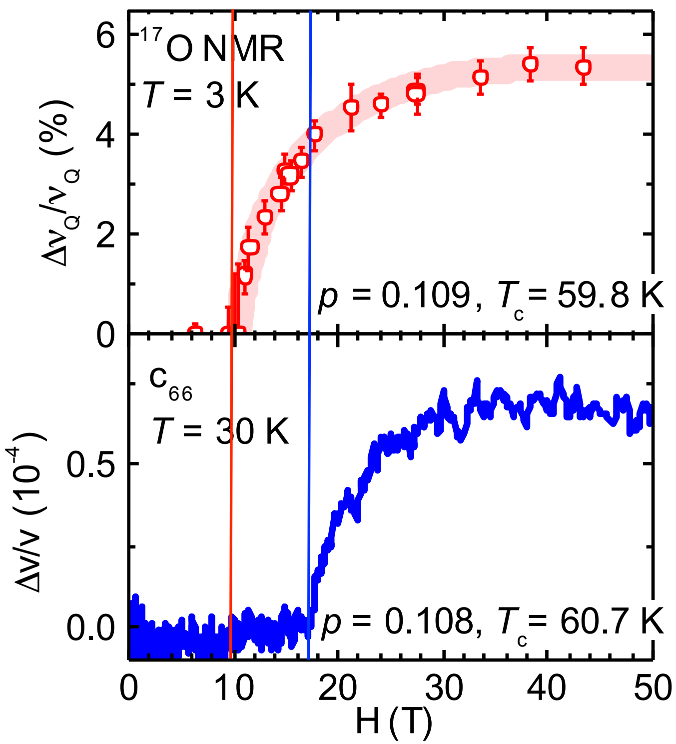
$$H_{charge} = \frac{\Phi_0}{2\pi \xi_{charge}^{\;2}}$$

Hoffman *et al.* Science 295, 466 (2002)

Nature of field-induced transition?

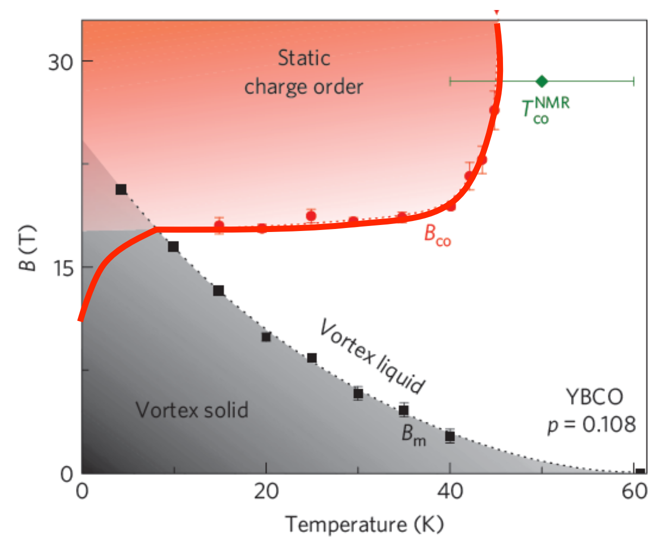
Should we expect 2nd order transition?

Transition fields in NMR and ultrasound are different



Possible explanations:

- Experimental error (ruled out)
- Phase diagram has cusp
- NMR sees *local* order first



Conclusion

CDW is an important piece of the high-T_c puzzle

- Ubiquitous
- Impacts on many electronic properties
- Related to superconductivity in a way or another

Yet, its exact nature remains to be worked out