

Intertwined Orders in High Temperature Superconductors

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Outline

- Context
 - ▶ Competing vs Intertwined orders
- Stripes in $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$
 - ▶ Evidence for Pair-Density-Wave (PDW) superconductivity
- Charge order in $\text{YBa}_2\text{Cu}_3\text{O}_{6+y}$
 - ▶ Occurs on electron nematic background (?)



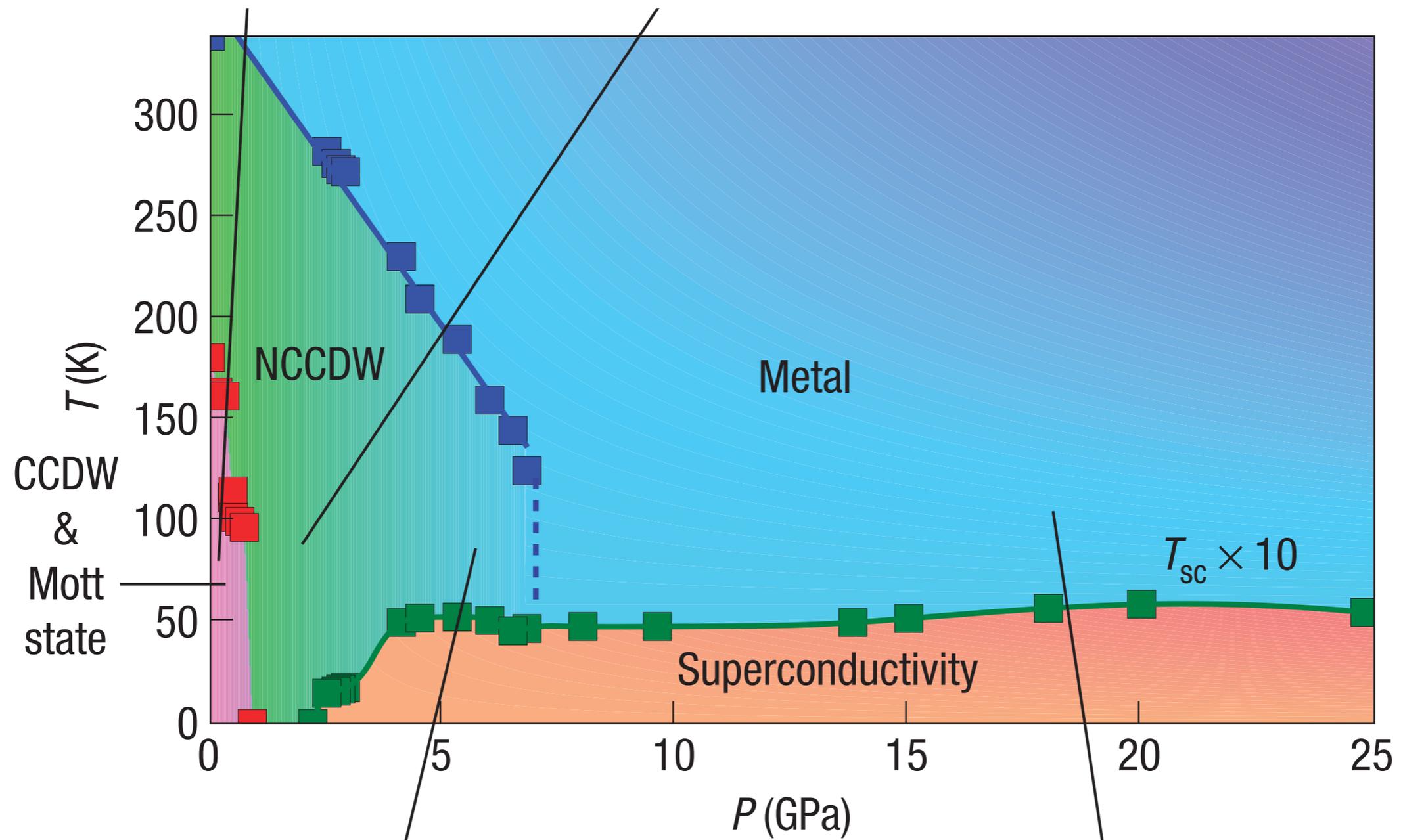
Eduardo Fradkin



Steve Kivelson

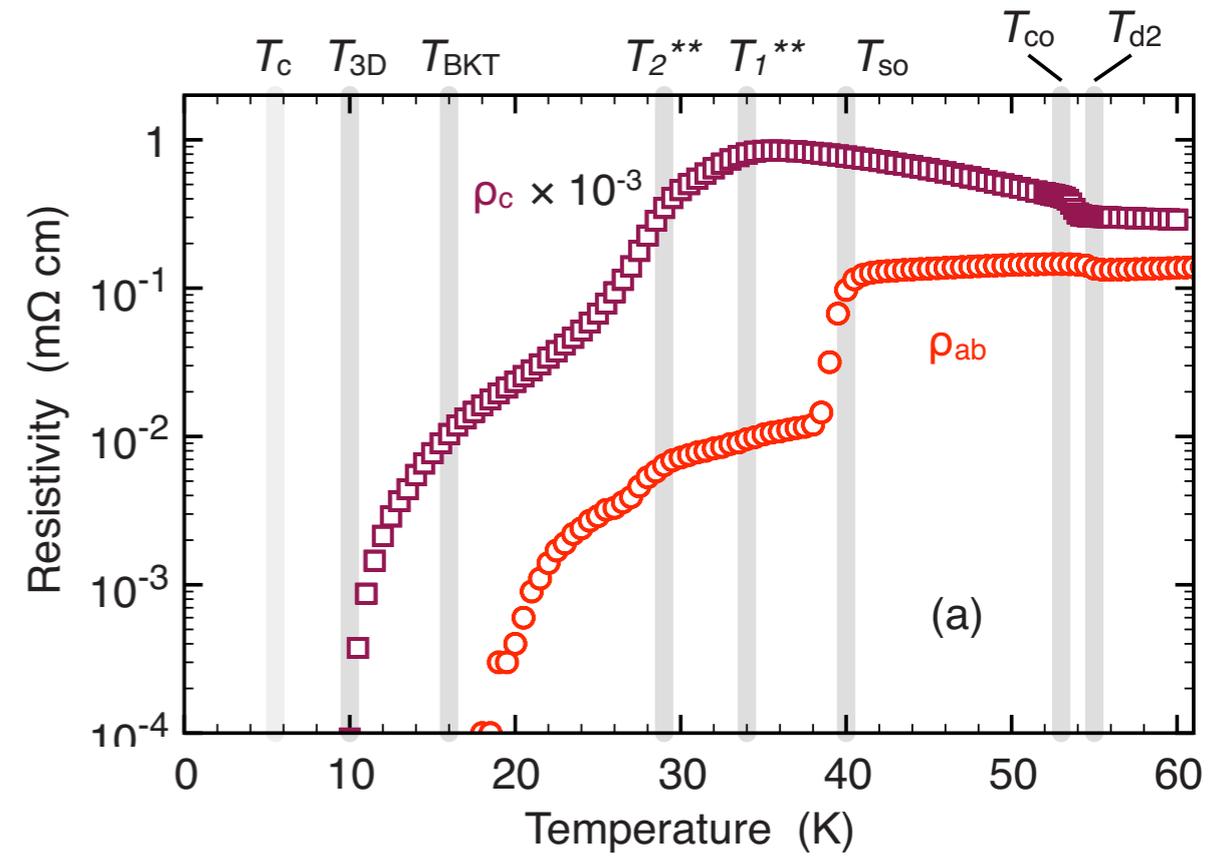
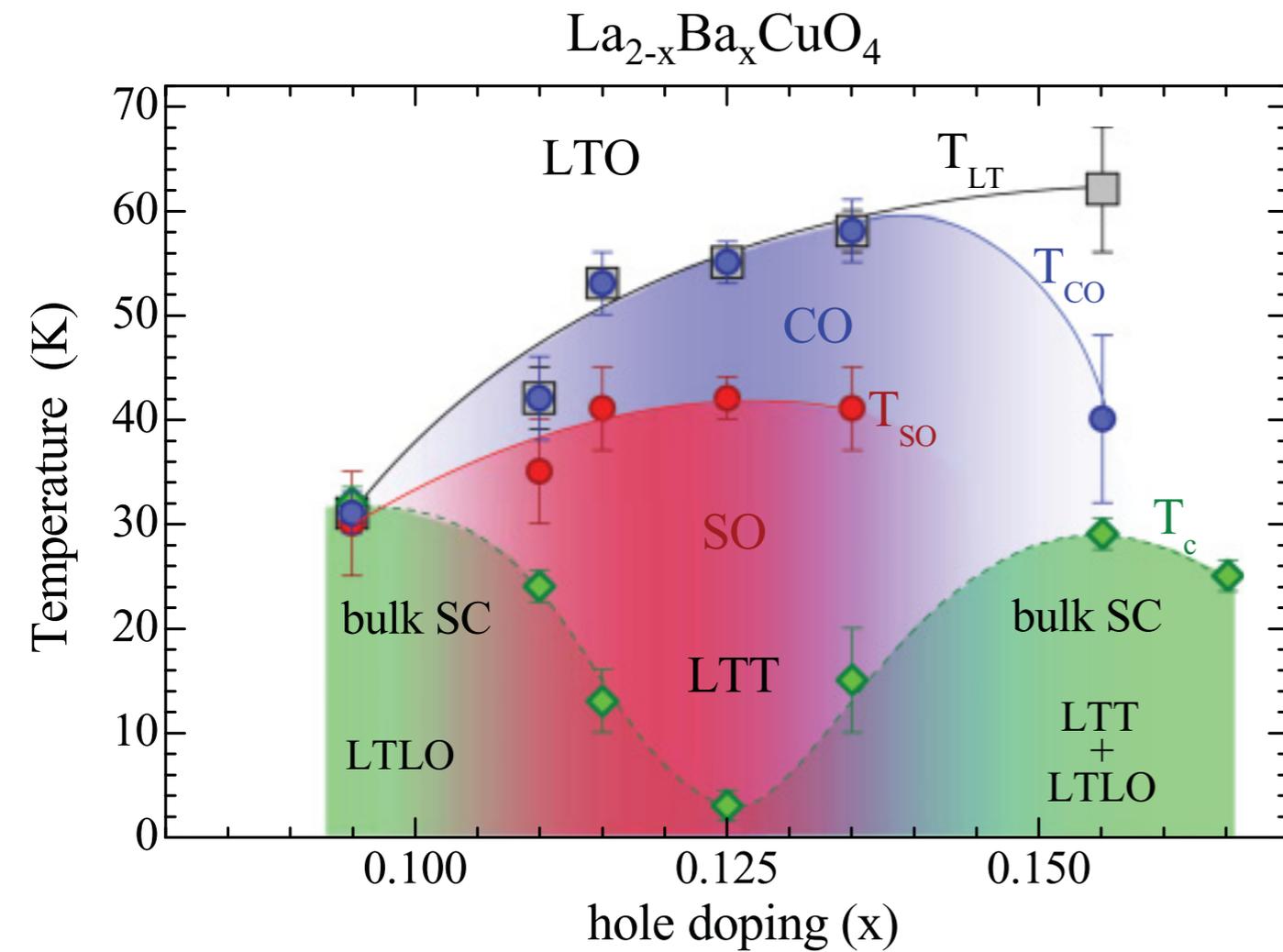
Theory of Intertwined Orders in High Temperature Superconductors
arXiv:1407.4480

1T-TaS₂: Example of competing order

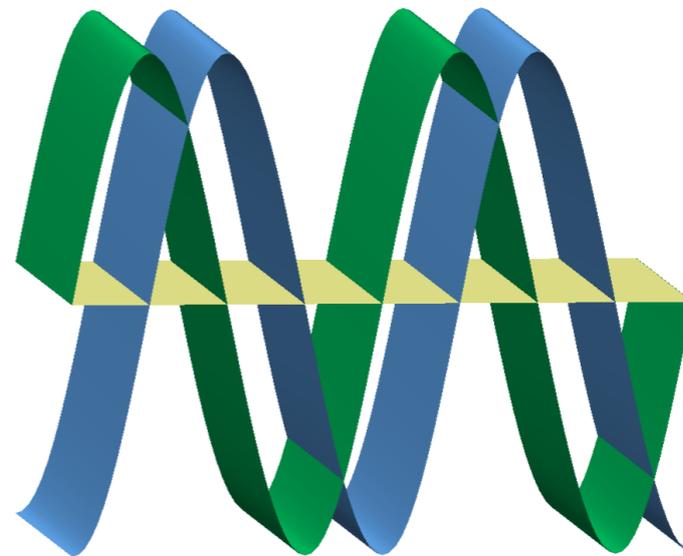


$T_{cdw} \sim 300$ K
 $T_{sc} \sim 5$ K

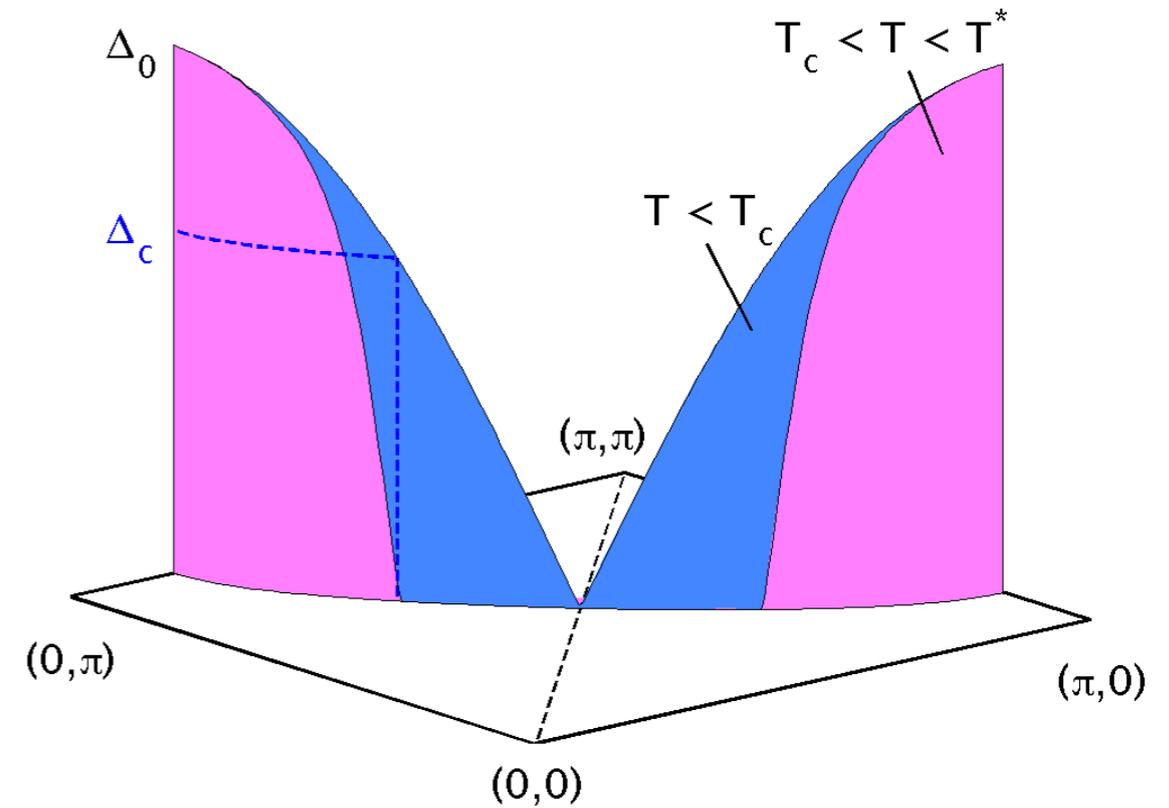
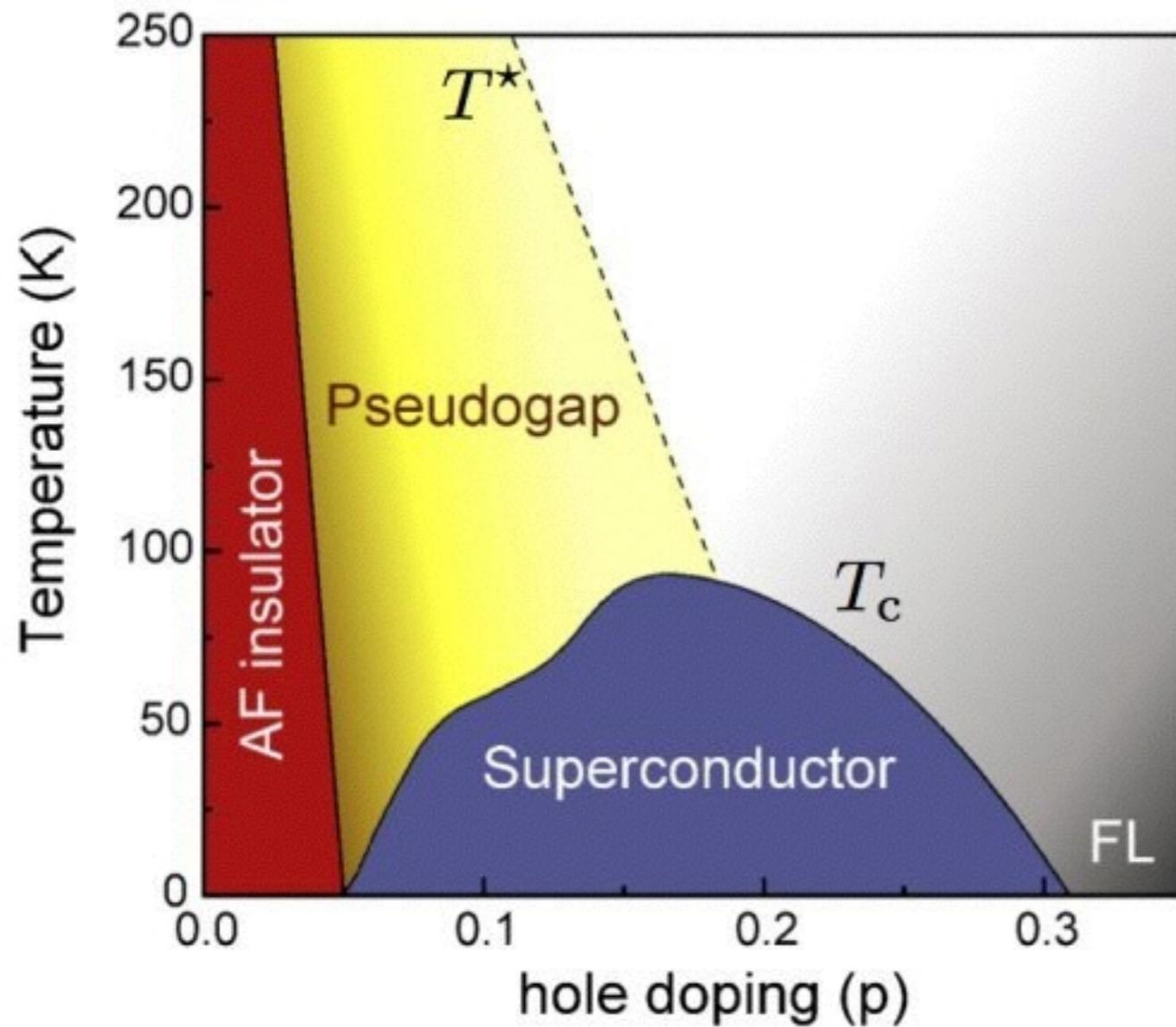
La_{2-x}Ba_xCuO₄: Example of intertwined orders



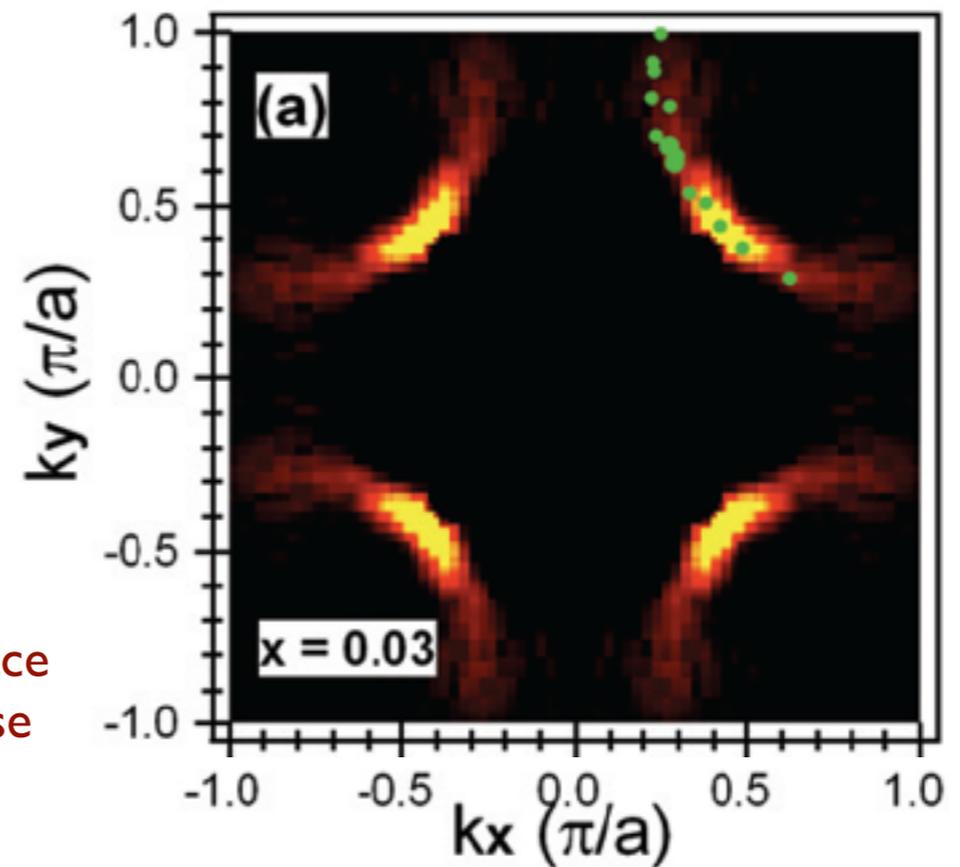
Intertwined
antiferromagnetism
and
superconductivity



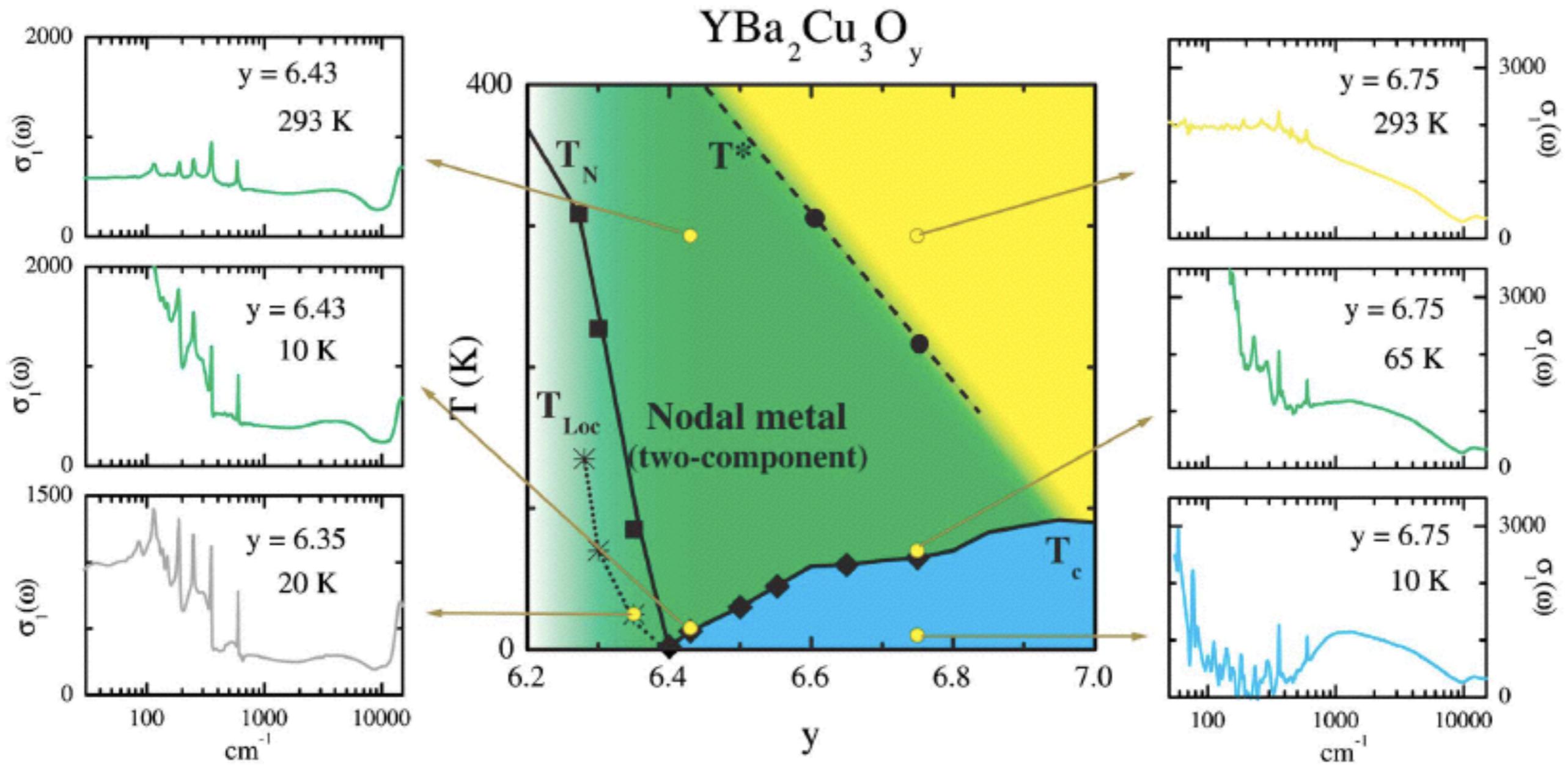
Cuprates: Superconductivity and Pseudogap



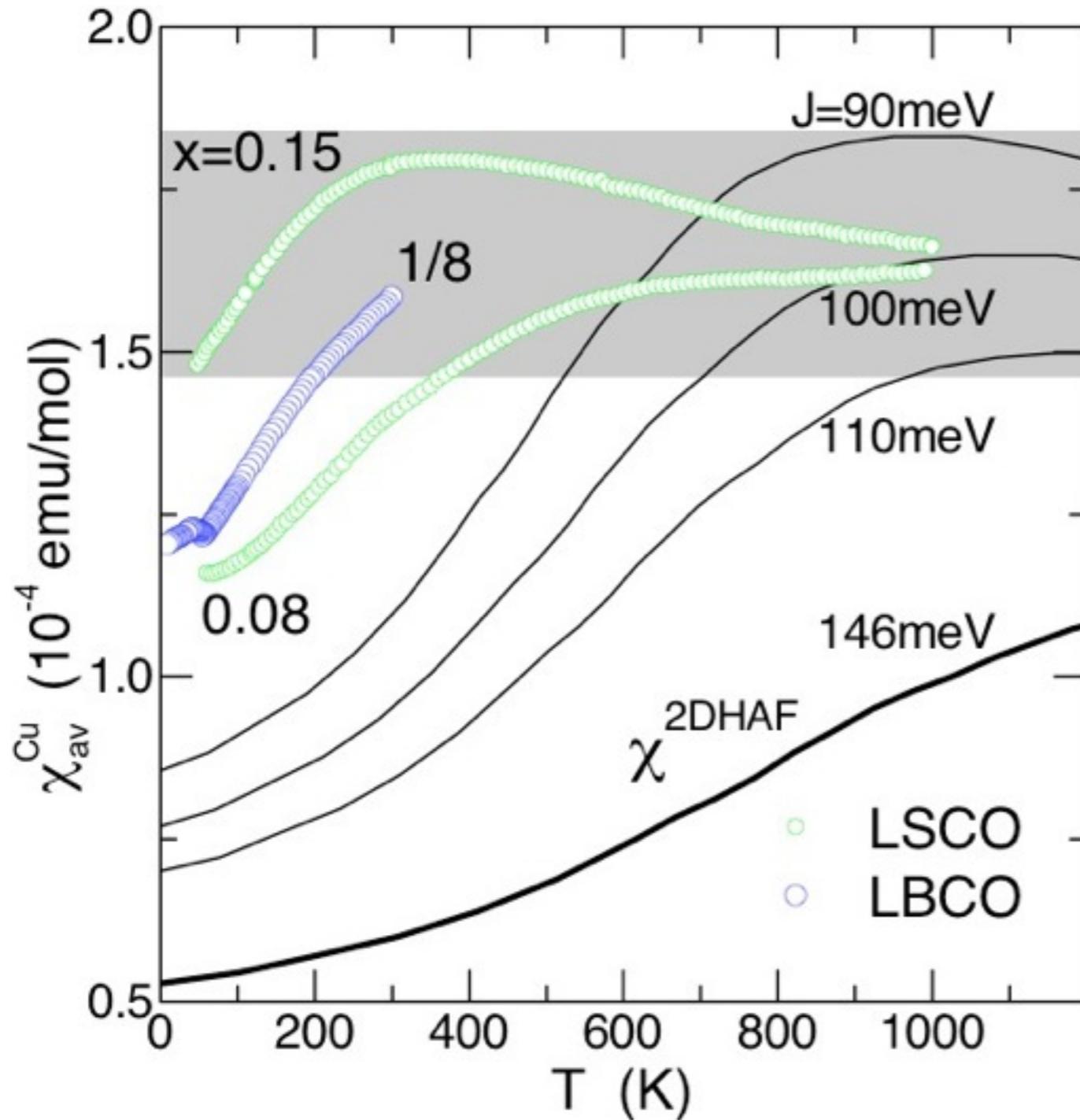
ARPES Fermi surface in pseudogap phase



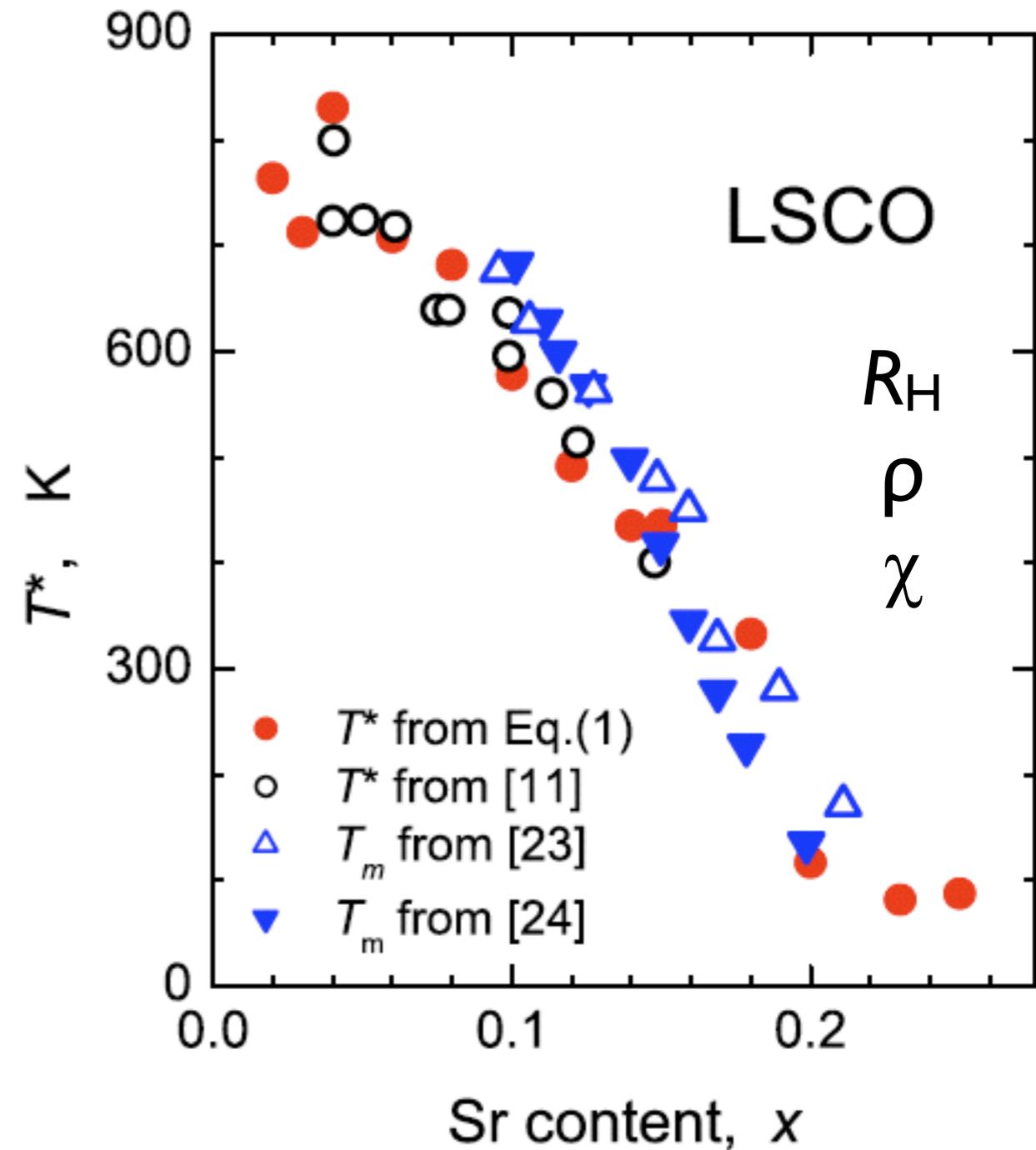
Incoherent \rightarrow nodal metal on cooling



AF domains and nodal metal evolve cooperatively



Hücker *et al.*, PRB (2008)



Gor'kov+Teitel'baum, PRL (2006)

- Correlations in pseudogap phase develop from incoherent metal
- No general theory for such correlations
- Consider LBCO, where a specific kind of ordering occurs

Collaborators

Brookhaven

Genda Gu

Markus Hücker

Guangyong Xu

Jinsheng Wen (→Nanjing)

Zhijun Xu (→LBNL)

Qiang Li

Chris Homes

Alexei Tselik

IMR/Tohoku U.

Masaki Fujita

Kazu Yamada (→KEK)

Stanford

Steve Kivelson

U. Illinois

Eduardo Fradkin

NHMFL, FSU

Greg Boebinger

Zach Stegen

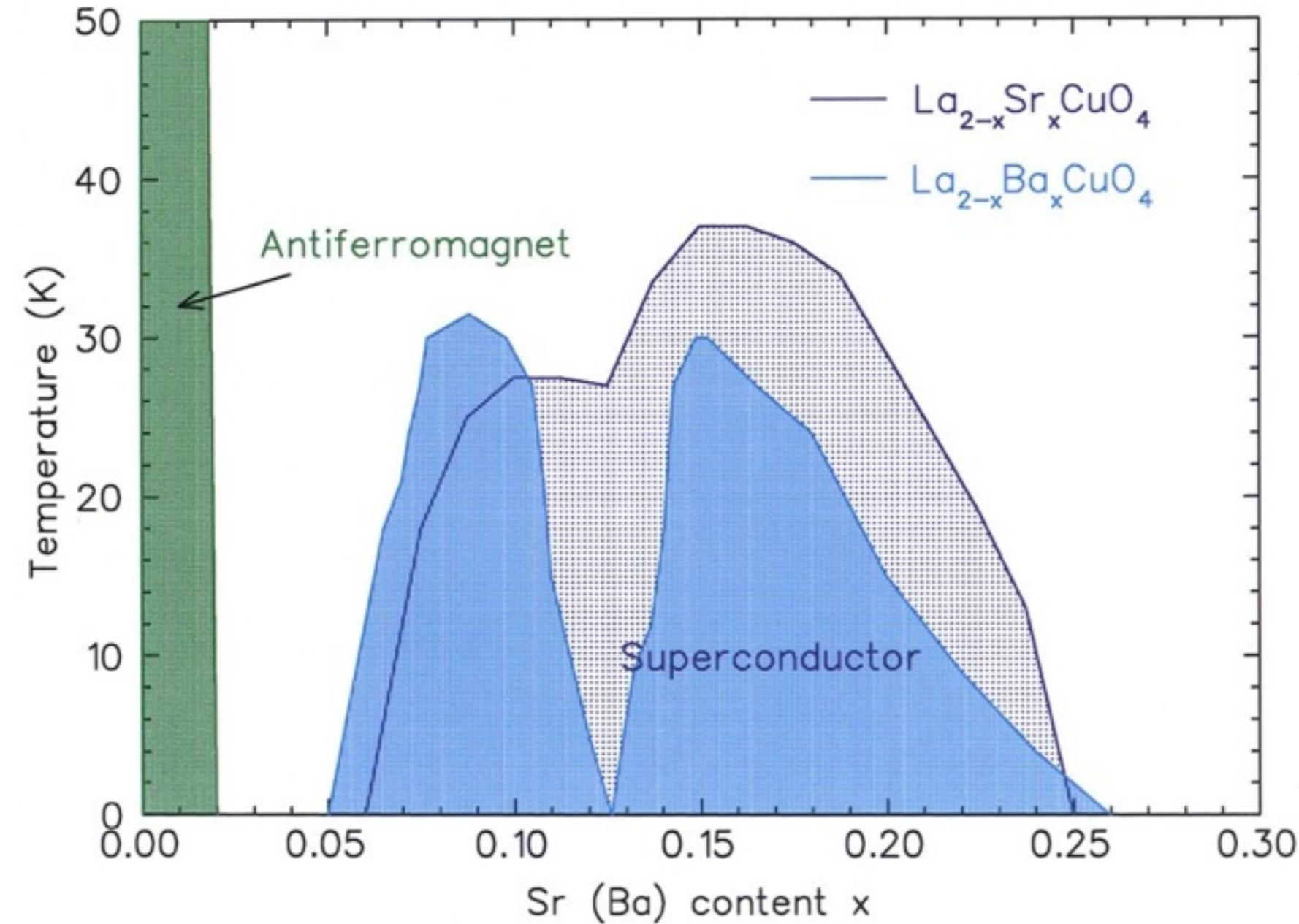
NIST

Chris Stock (→Edinburgh)

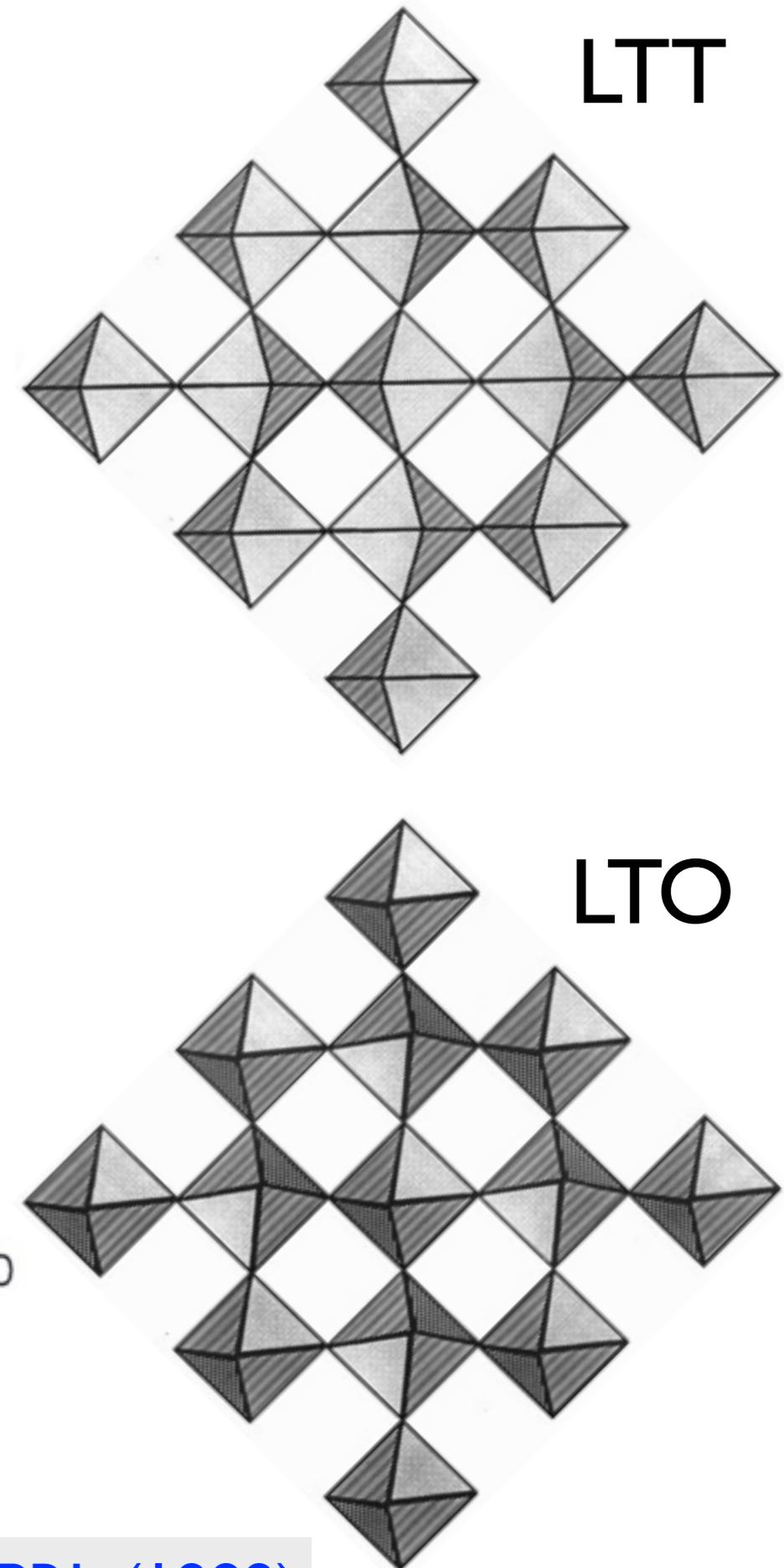
ORNL

Alexander Kolesnikov

1/8 problem

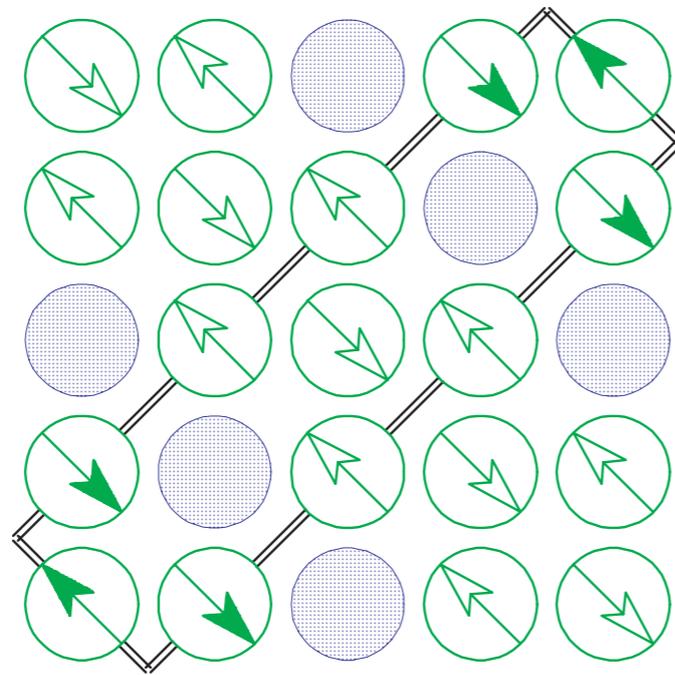
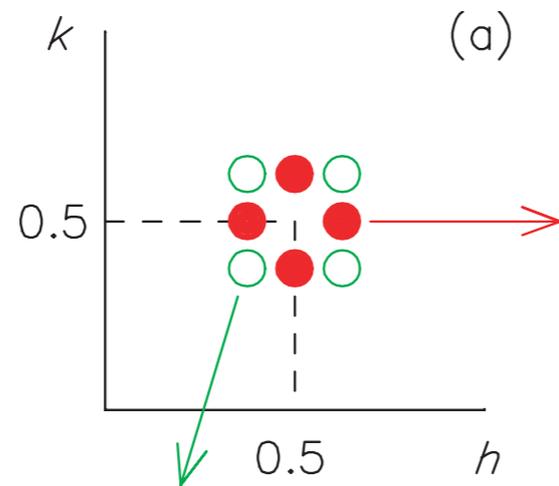


Moodenbaugh *et al.*, PRB (1988)

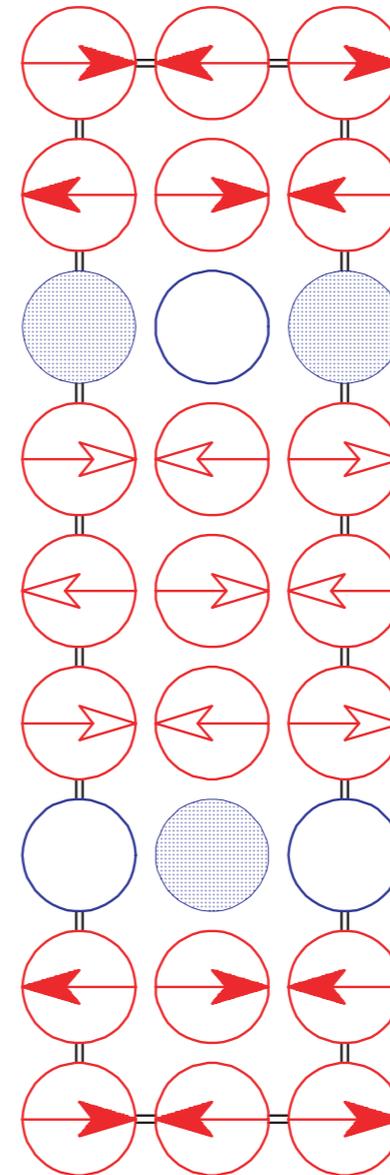


Axe *et al.*, PRL (1989)

Charge and spin stripe order

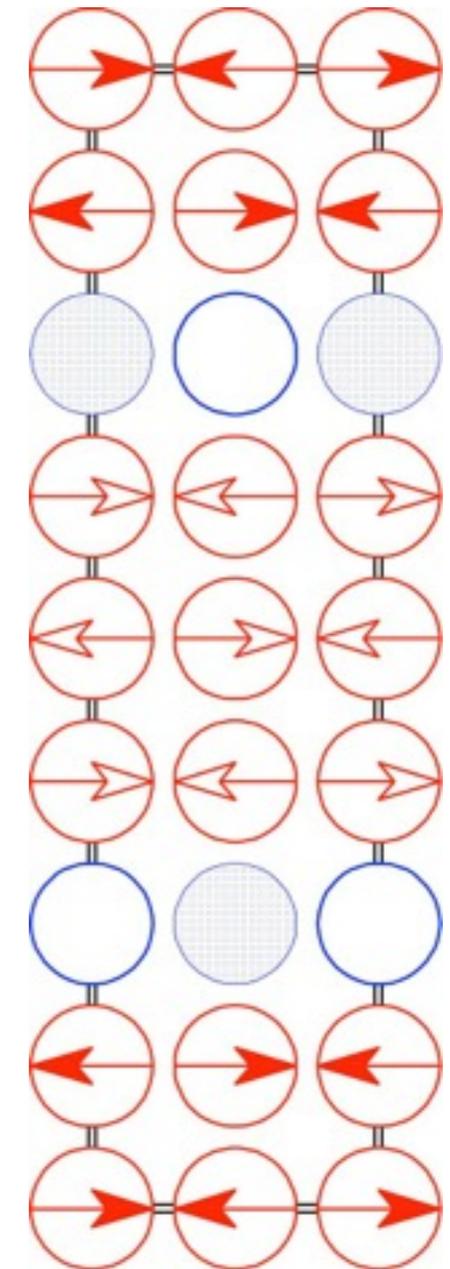
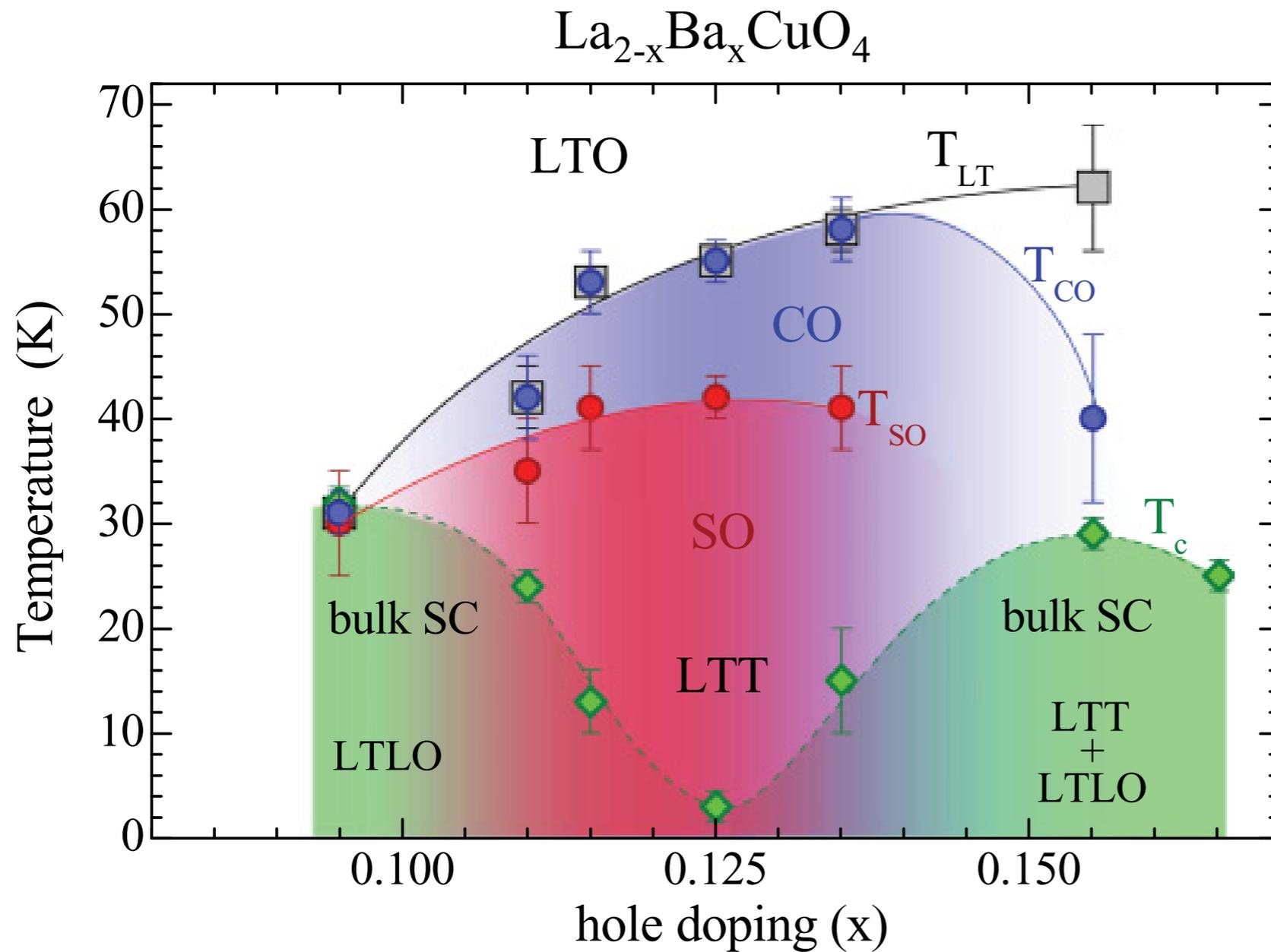


(b) NiO_2 : $n_h = 0.25$



(c) CuO_2 : $n_h = 0.125$

La_{2-x}Ba_xCuO₄



Hücker *et al.*, PRB (2011)

Stripe predictions

Hartree-Fock solution of Hubbard model

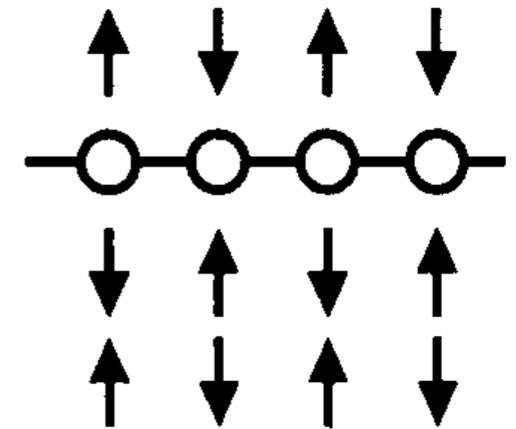
J. Zaanen and O. Gunnarsson, PRB (1989)

K. Machida, Physica C (1989)

D. Poilblanc and T.M. Rice, PRB (1989)

etc.

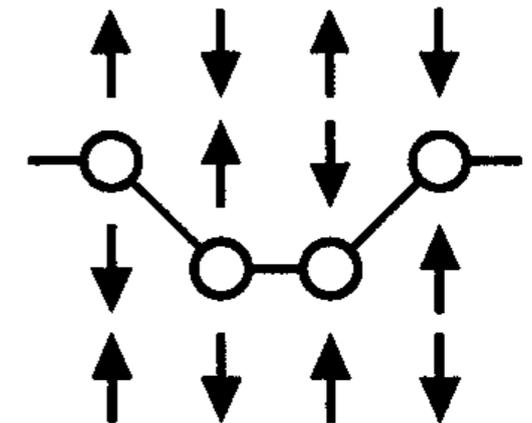
Insulating stripes
1 hole/site



Fluctuating charge stripes

J. Zaanen, M.L. Horbach, & W. van Saarloos,
PRB (1996)

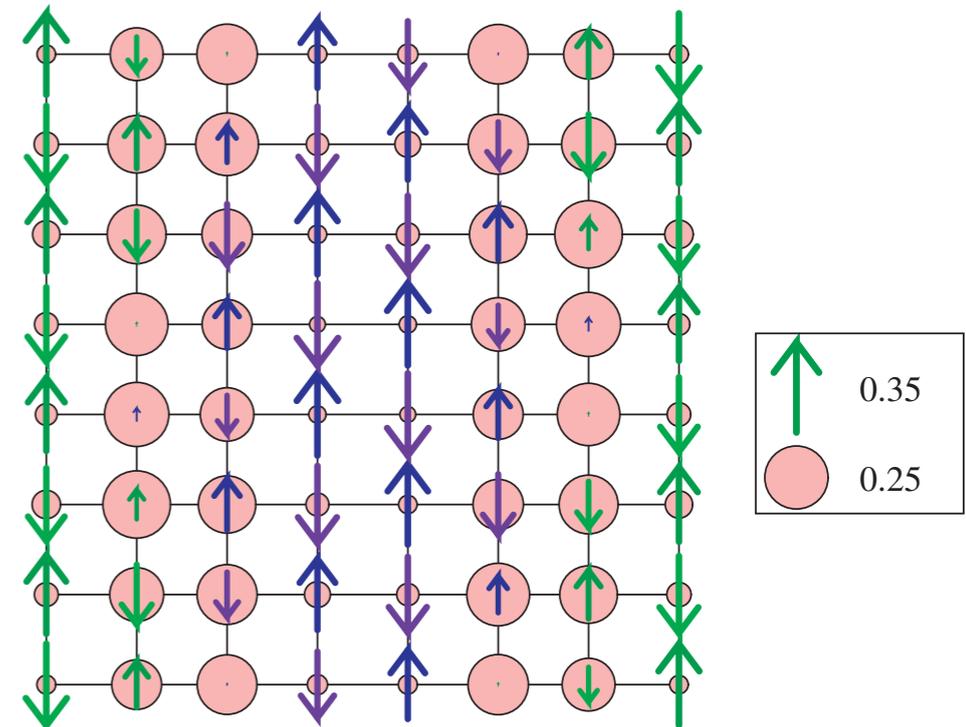
etc.



Competing kinetic and exchange energies

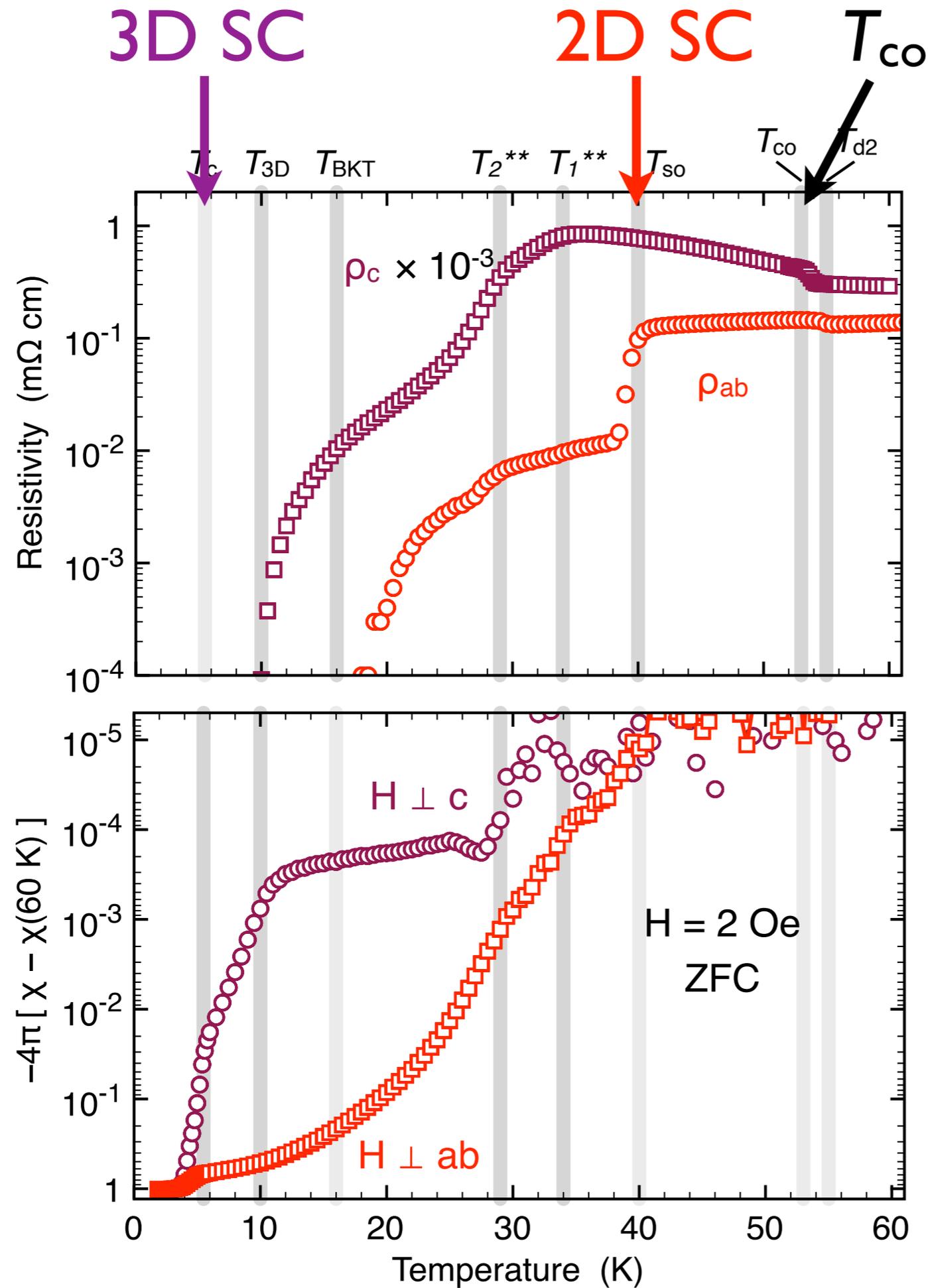
DMRG calculations on t-J model

S.R. White and D.J. Scalapino, PRL (1998)
PRB (1999)



Find ~ 0.5 hole/site; consistent with experiment

LBCO $x=1/8$



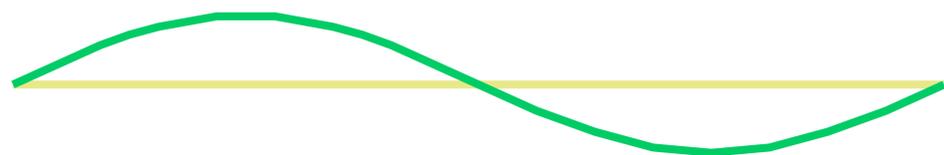
Stripe order:

- compatible with 2D SC at 40 K
- frustrates interlayer Josephson coupling

Q. Li *et al.*, PRL (2007)
JMT *et al.*, PRB (2008)

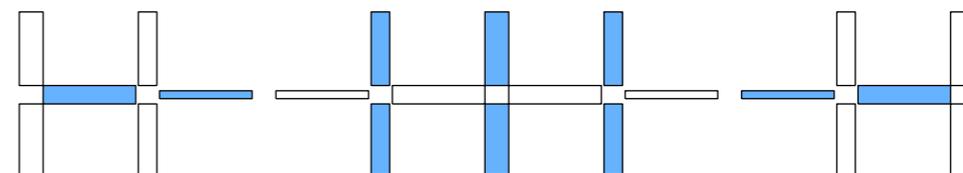
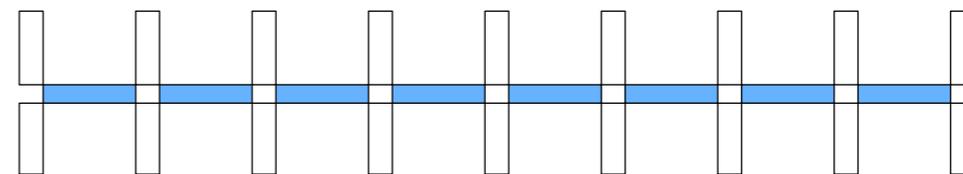
Intertwined Orders

Antiferromagnetism

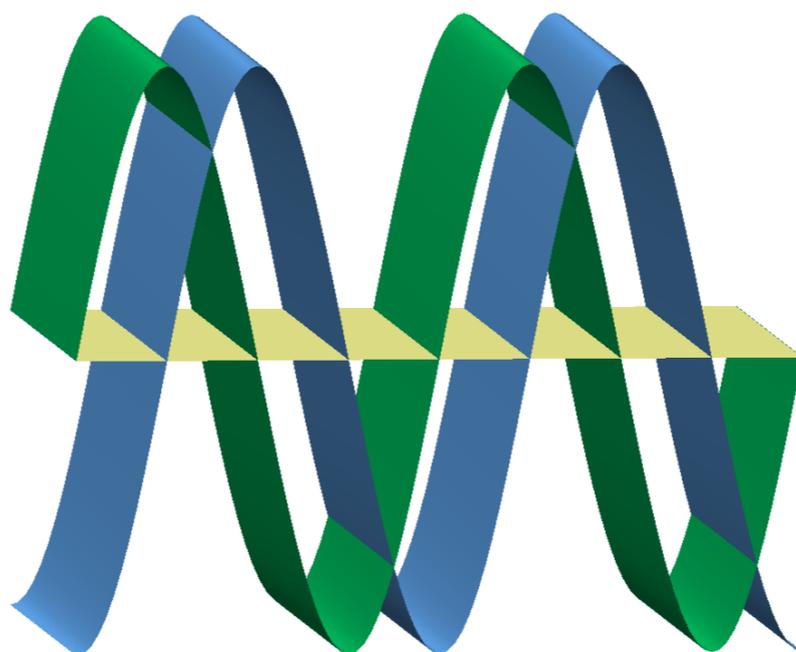


Spin Stripes

Uniform d-wave Superconductor

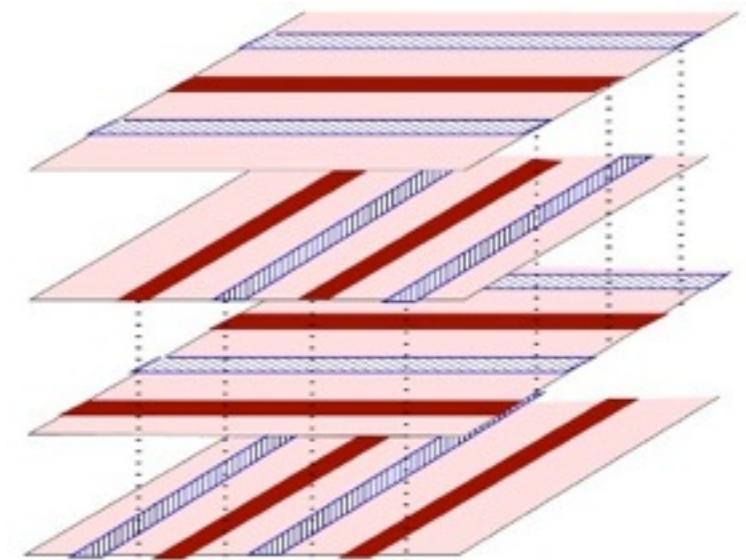
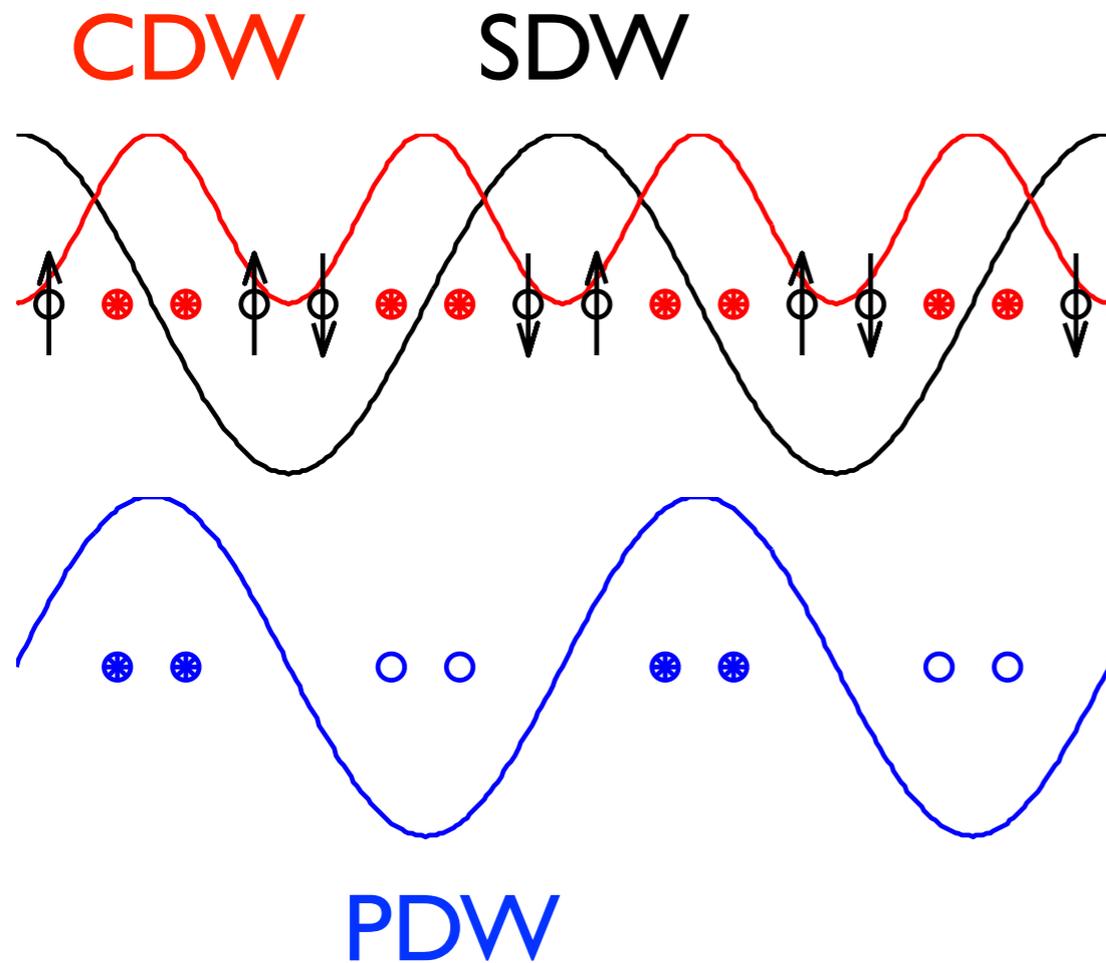


Pair Density Wave



Intertwined
antiferromagnetism
and
superconductivity

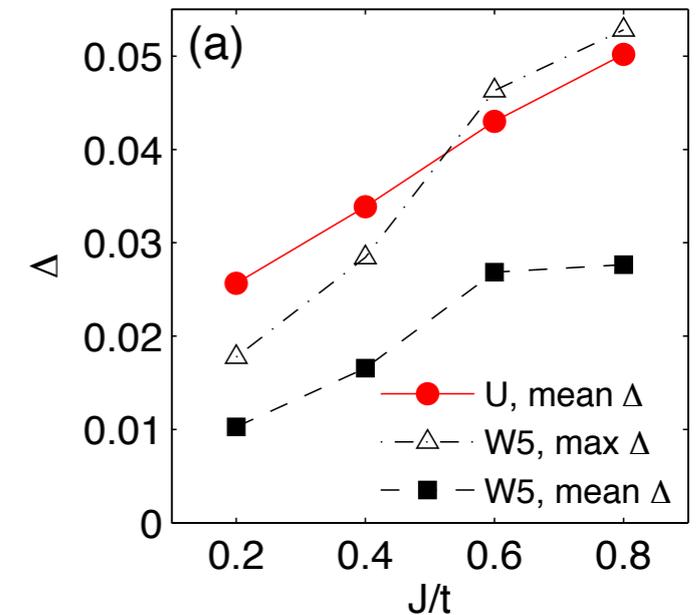
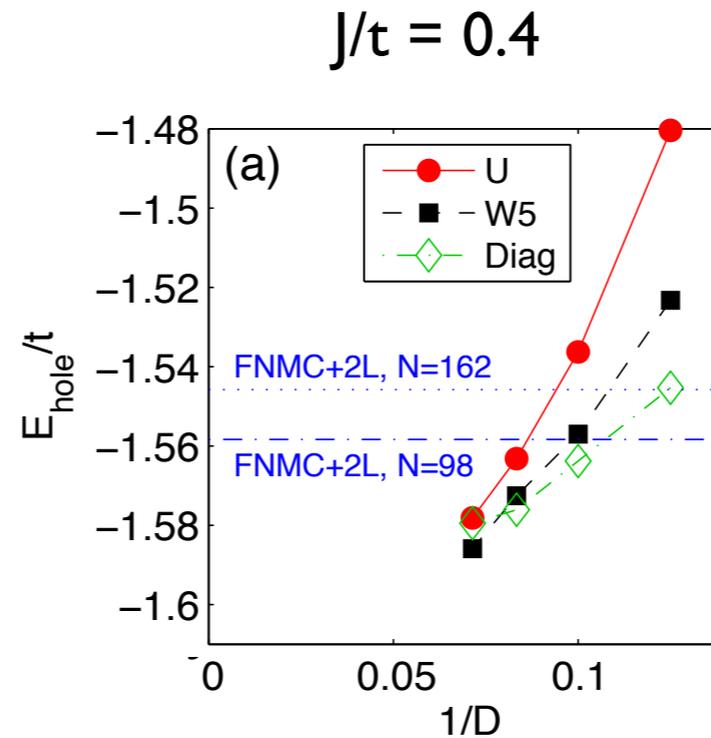
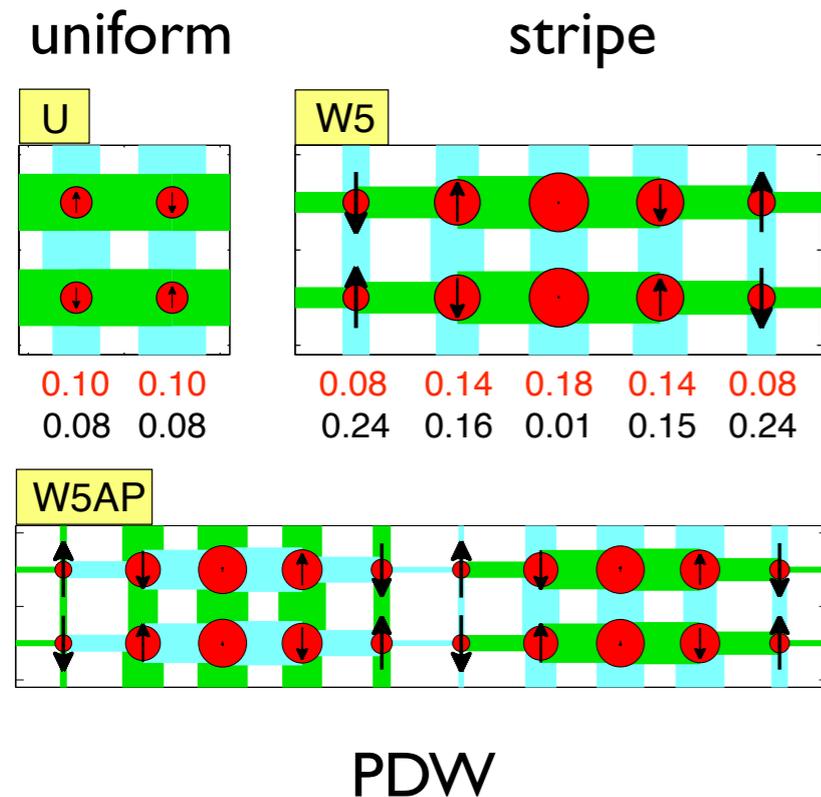
2D SC and Pair-Density-Wave Superconductor



Frustration of interlayer coupling:
Himeda *et al.*, PRL (2002)
Berg *et al.*, PRL (2007)

Intertwined **superconductivity**
and **antiferromagnetism**

Competing superconducting states in t-J model



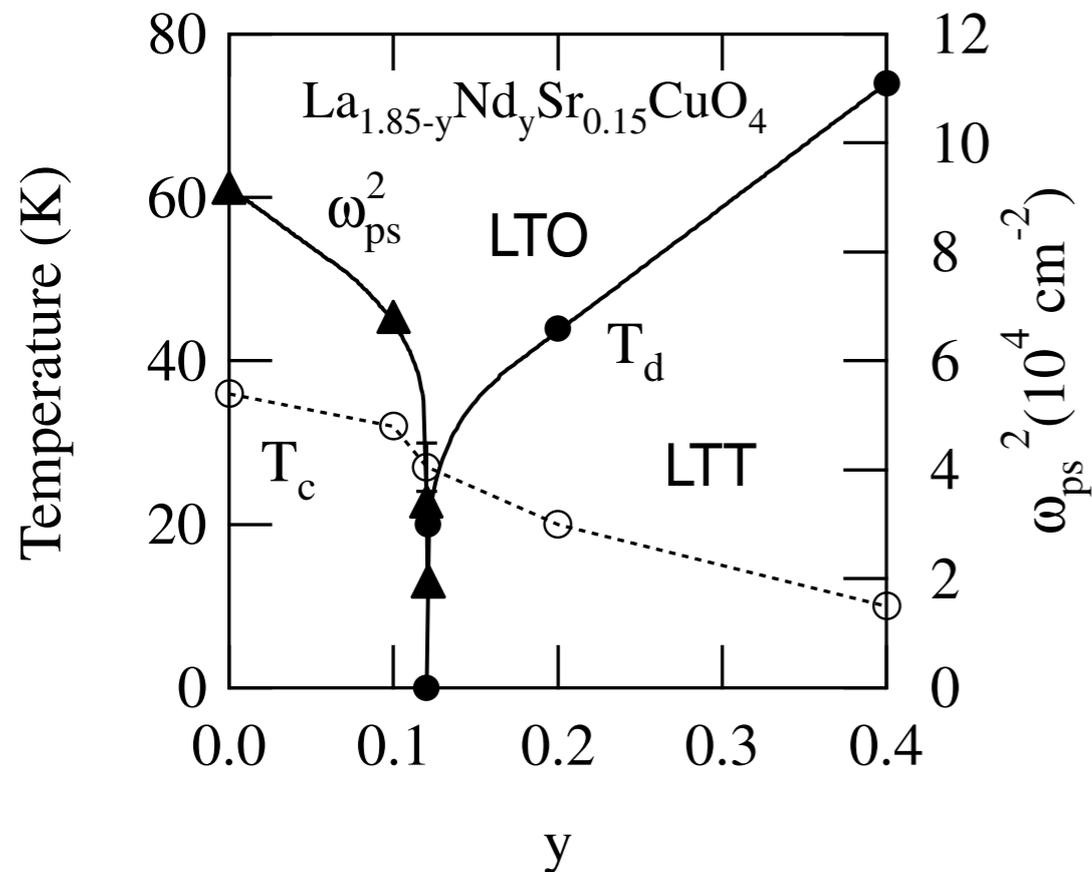
variational studies using infinite projected-entangled pair states (iPEPS)

P. Corboz, T.M. Rice, & M. Troyer, PRL (2014)

PDW very close in energy to SC stripes;
Both are lower in energy than uniform SC

P.A. Lee, "Amperean Pairing", PRX (2014)

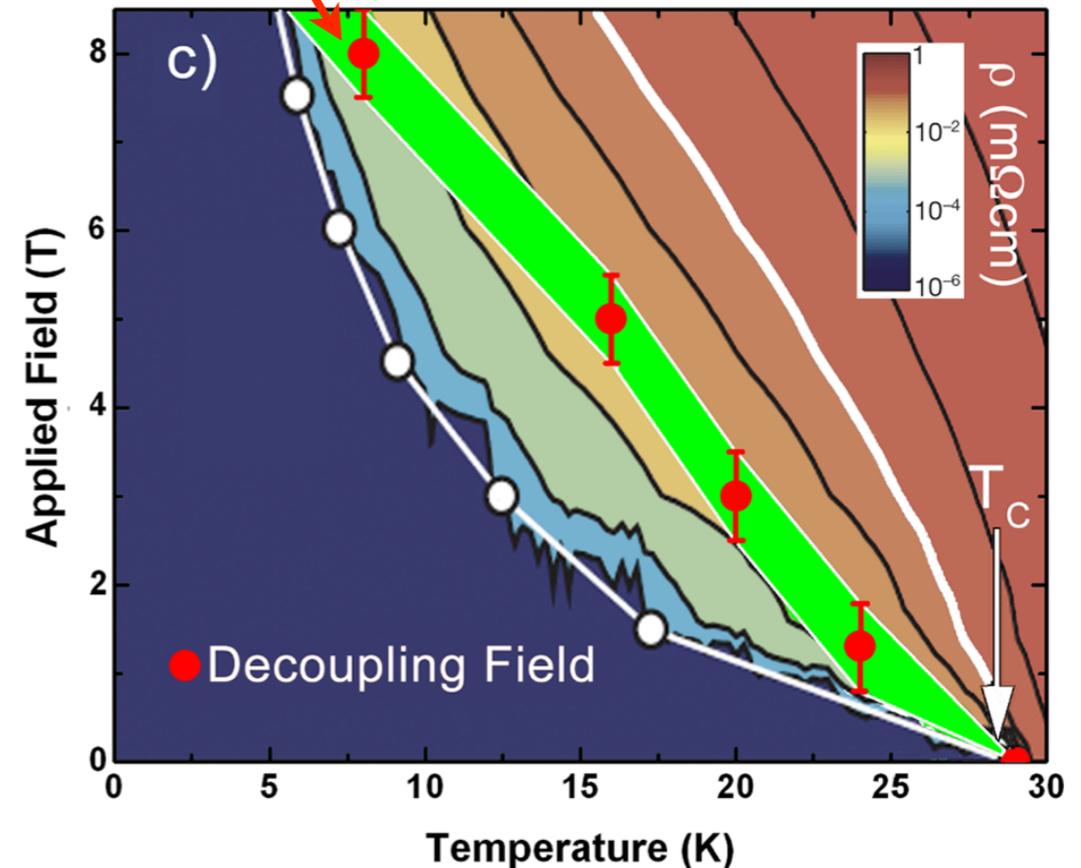
Decoupling evidence: c-axis optical conductivity



S. Tajima *et al.*, PRL (2001)



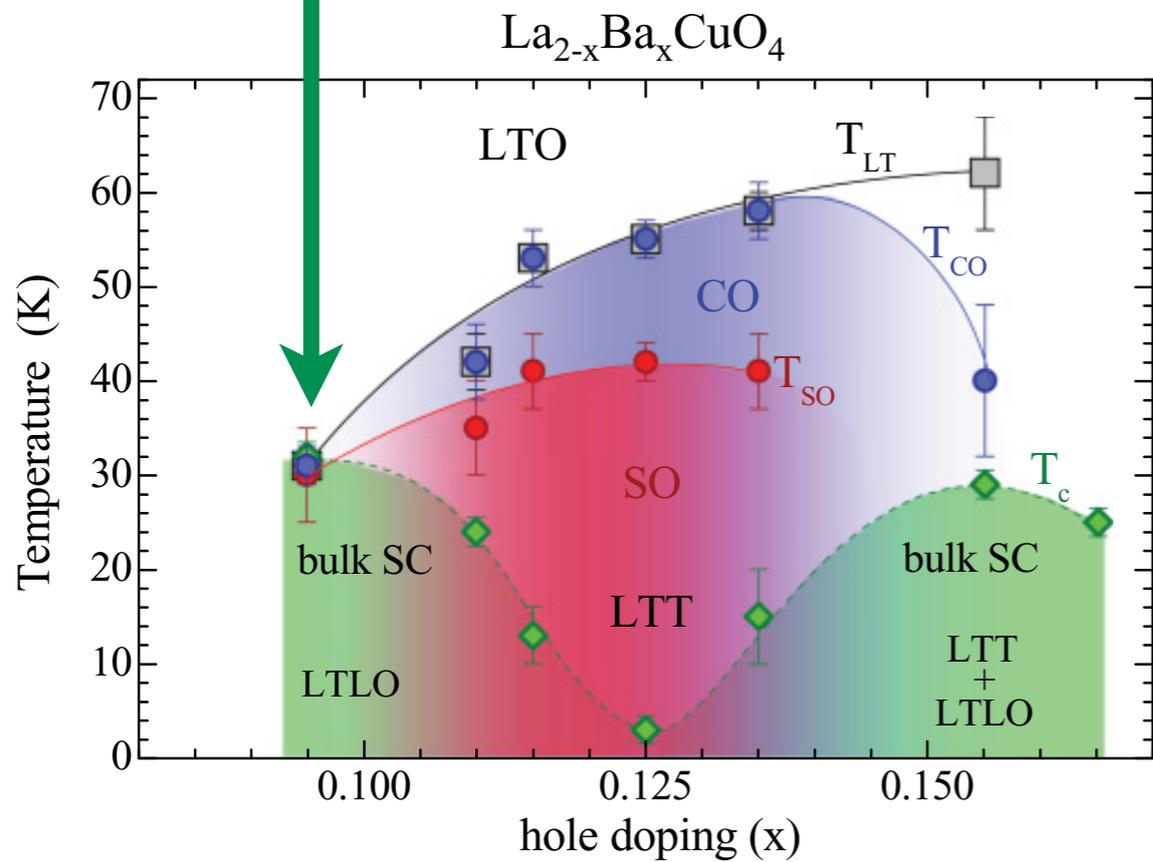
Josephson coupling disappears here but still have in-plane ρ_s



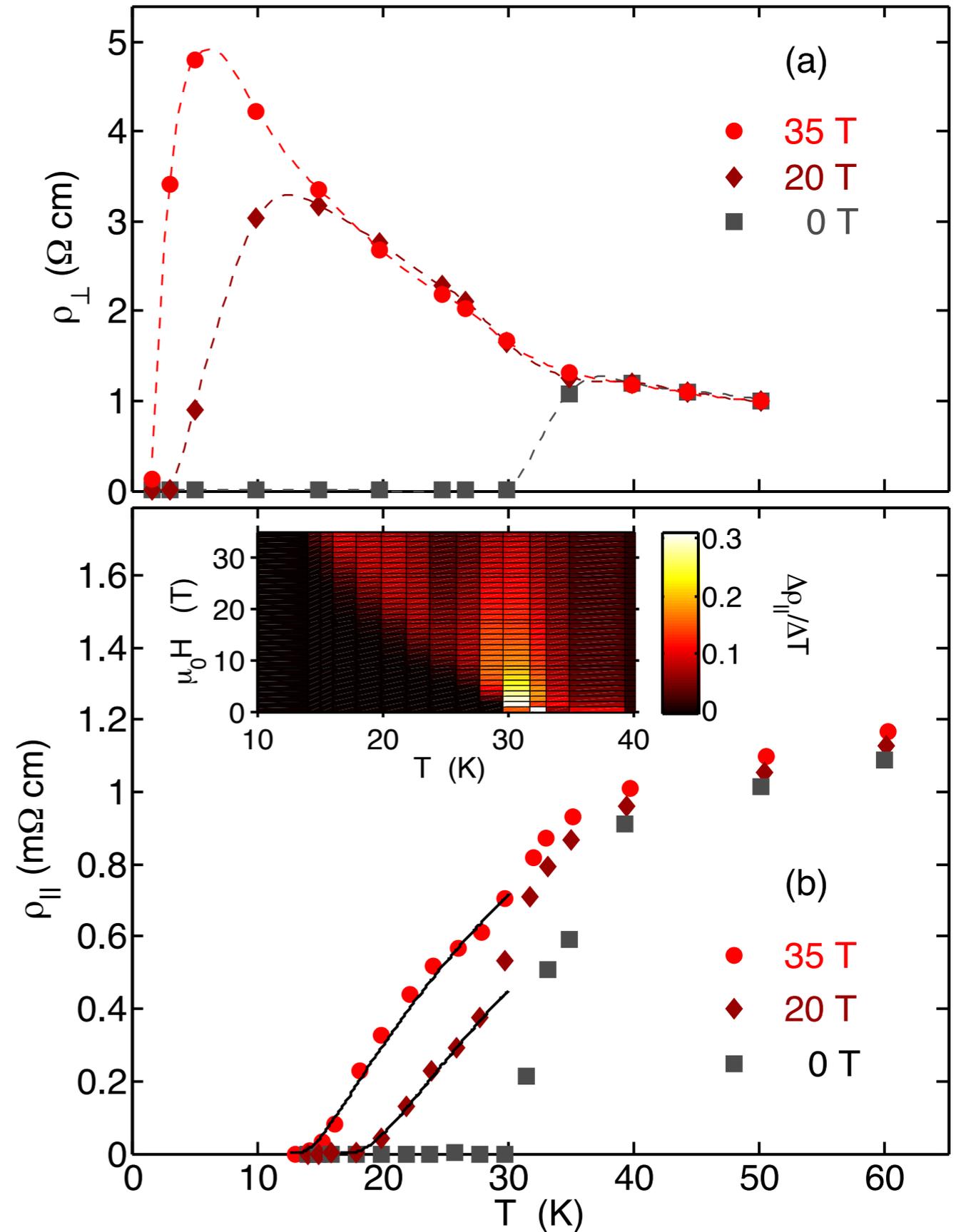
A.A. Schafgans *et al.*, PRL (2010)
PRB (2010)

La_{1.905}Ba_{0.095}CuO₄: Resistivity vs. T at high field

$x = 0.095$
 $T_c = 32$ K



Stegen *et al.*, PRB (2013)



LBCO $x=0.095$ in zero field

inelastic neutron scattering

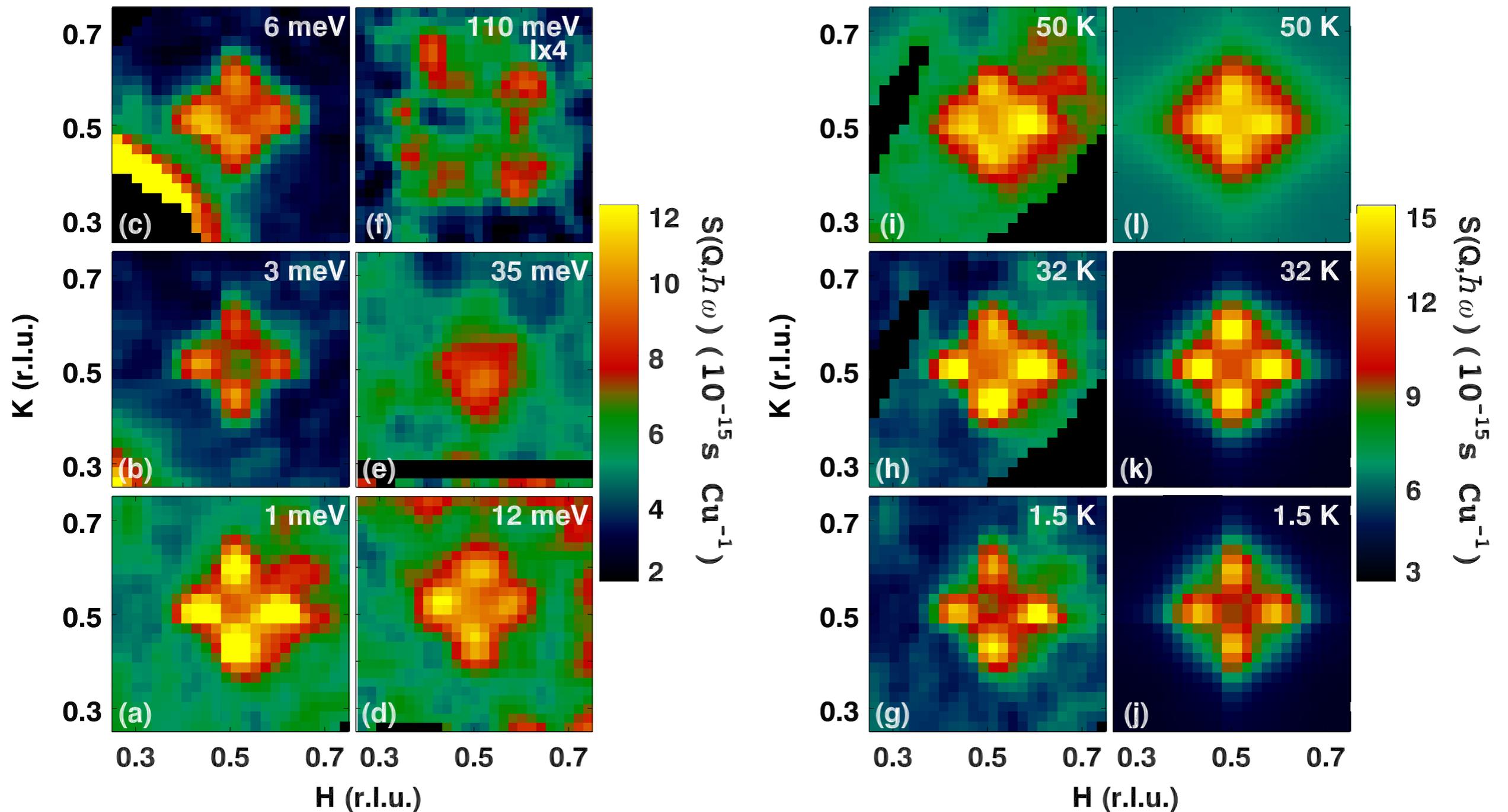
MACS

SEQUOIA

$\Delta E = 1 \text{ meV}$

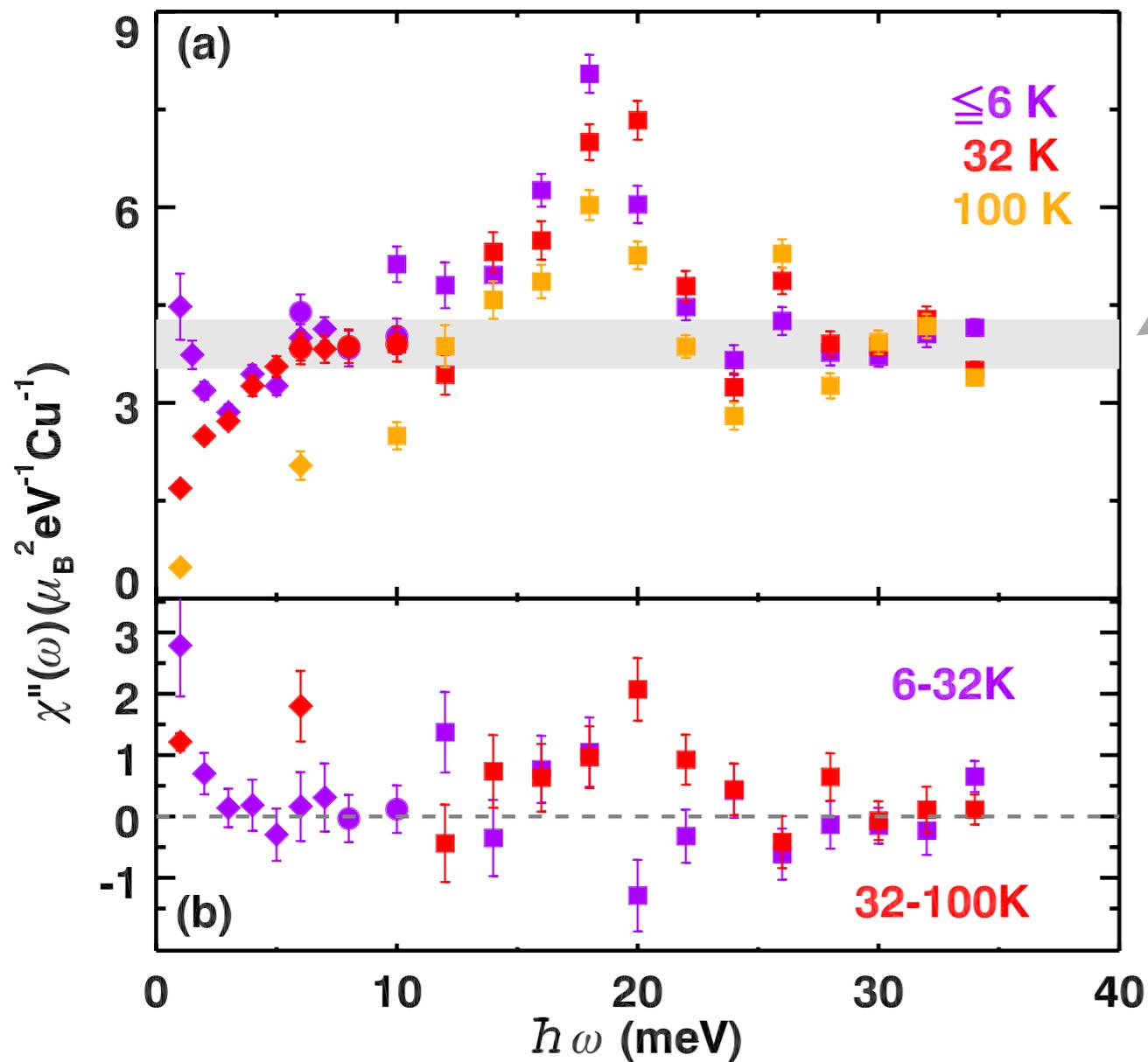
Data

Fit



No resonance or spin gap

LBCO $x = 0.095$

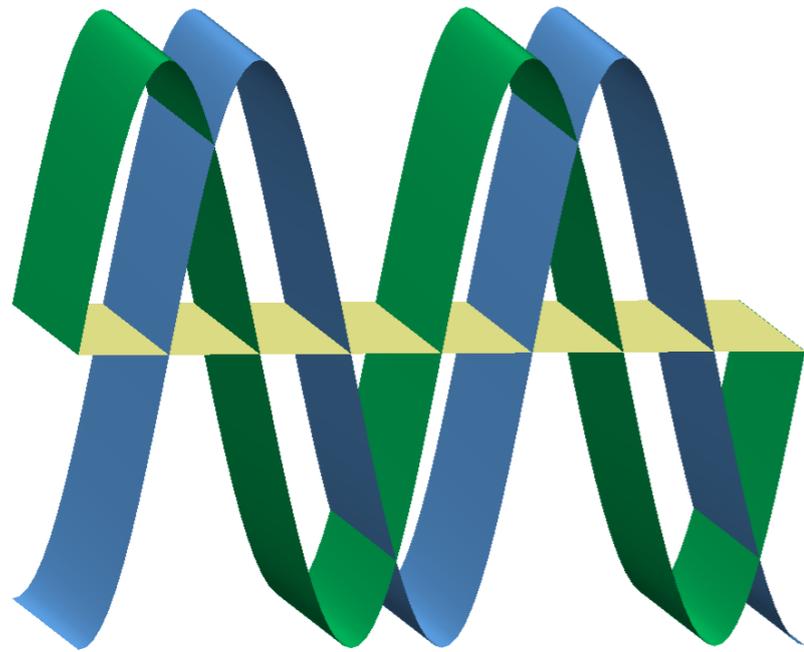


strength of spin waves in La_2CuO_4

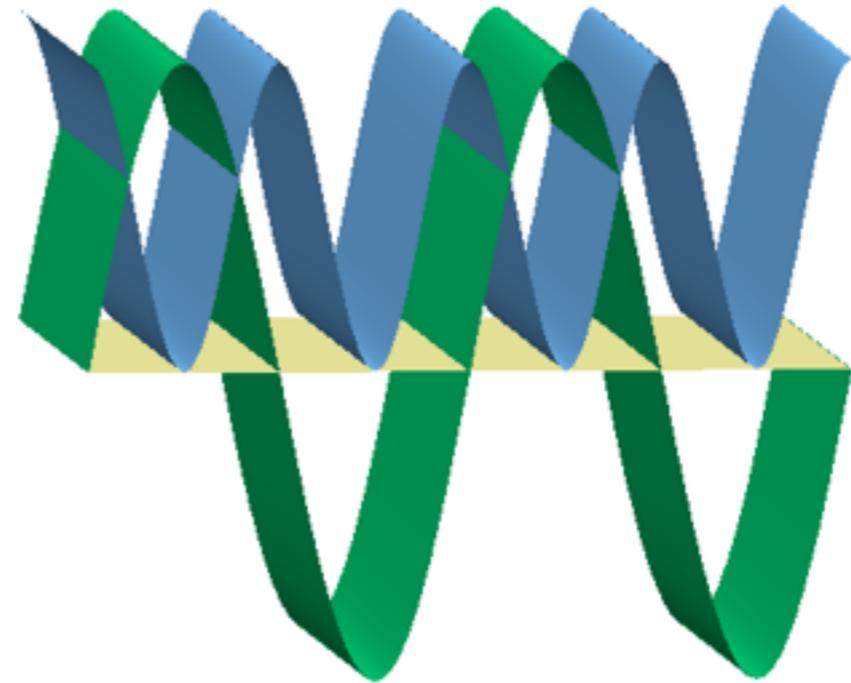
Strong gapless spin fluctuations
 \Rightarrow all parts of sample must contribute

Appropriate bulk ρ_s from $\sigma(\omega)$
 \Rightarrow gapless spin fluct. and SC must coexist

Intertwined states



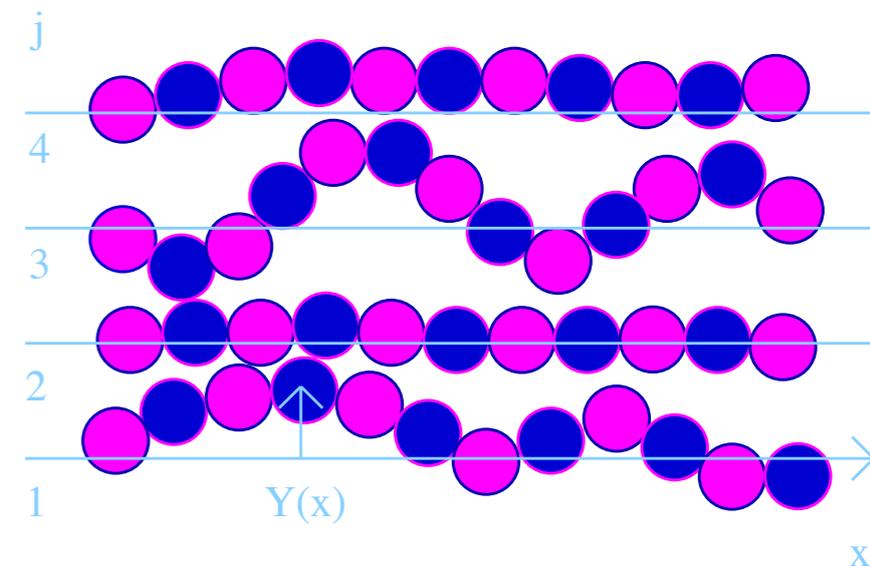
Pair density wave



In-phase striped superconductor

Add stronger fluctuations: get nematic phase

S.A. Kivelson, E. Fradkin, & V.J. Emery, Nature (1998)

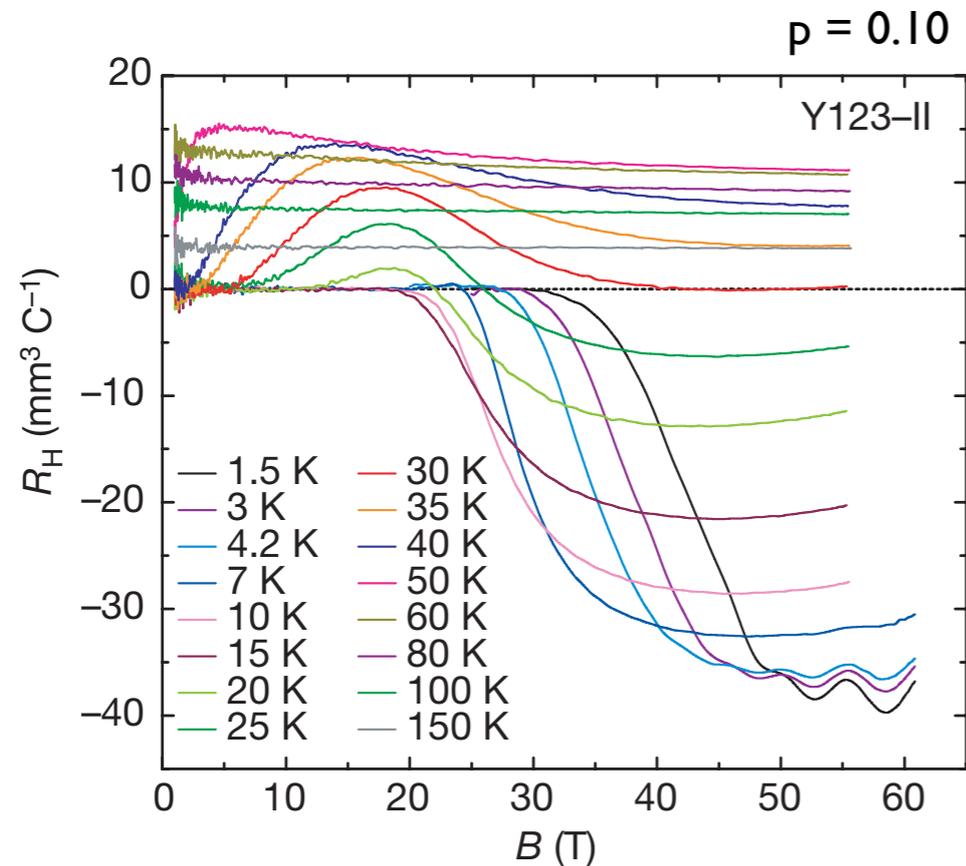


**Lesson from LBCO:
Even ordered stripes can be superconducting**

Charge order in YBCO

Quantum Oscillations in $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$

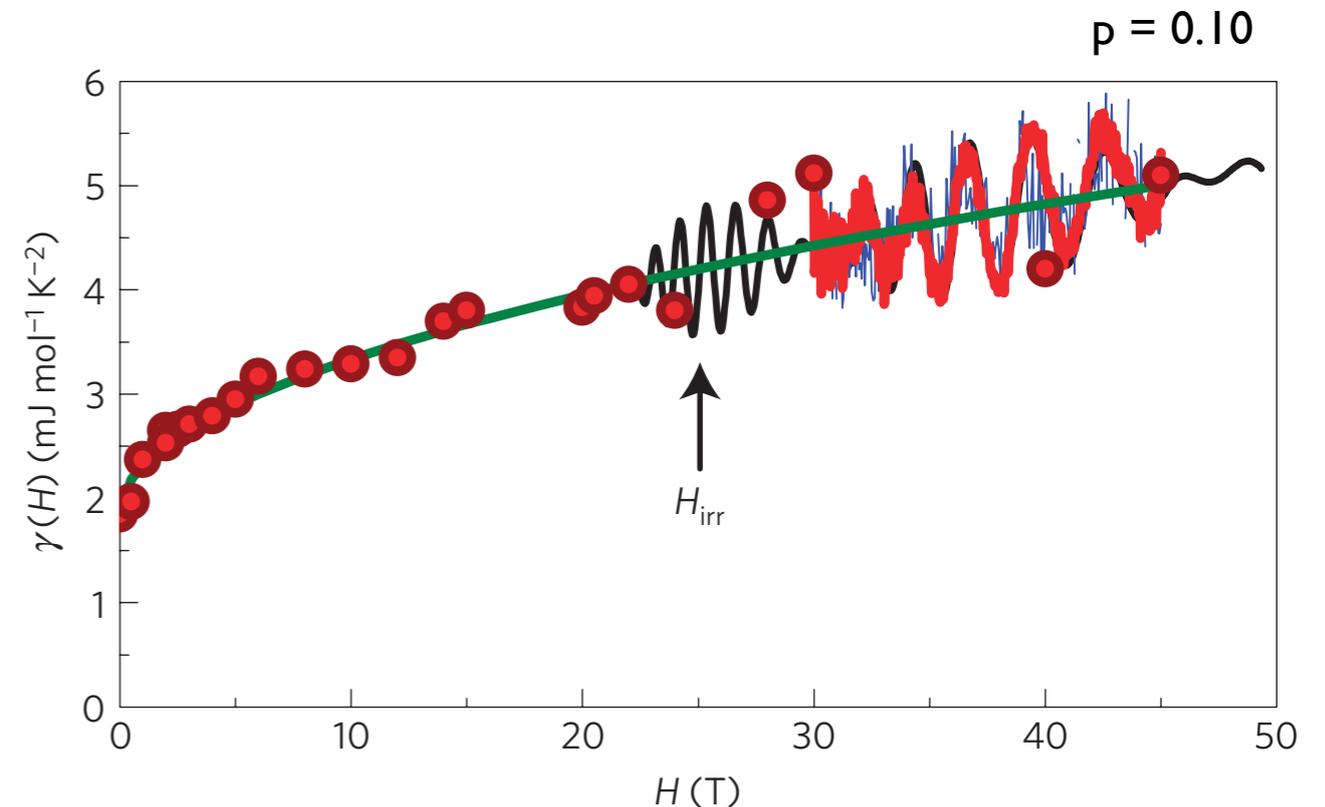
electron pockets
above H_{c2} ?



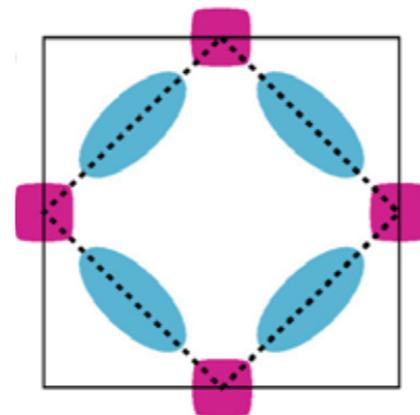
LeBoeuf *et al.*, Nature (2007)
Doiron-Leyraud *et al.*, Nature (2007)

Sebastian *et al.*, Nature (2008)

specific heat: $C(T)/T$
mixed state?



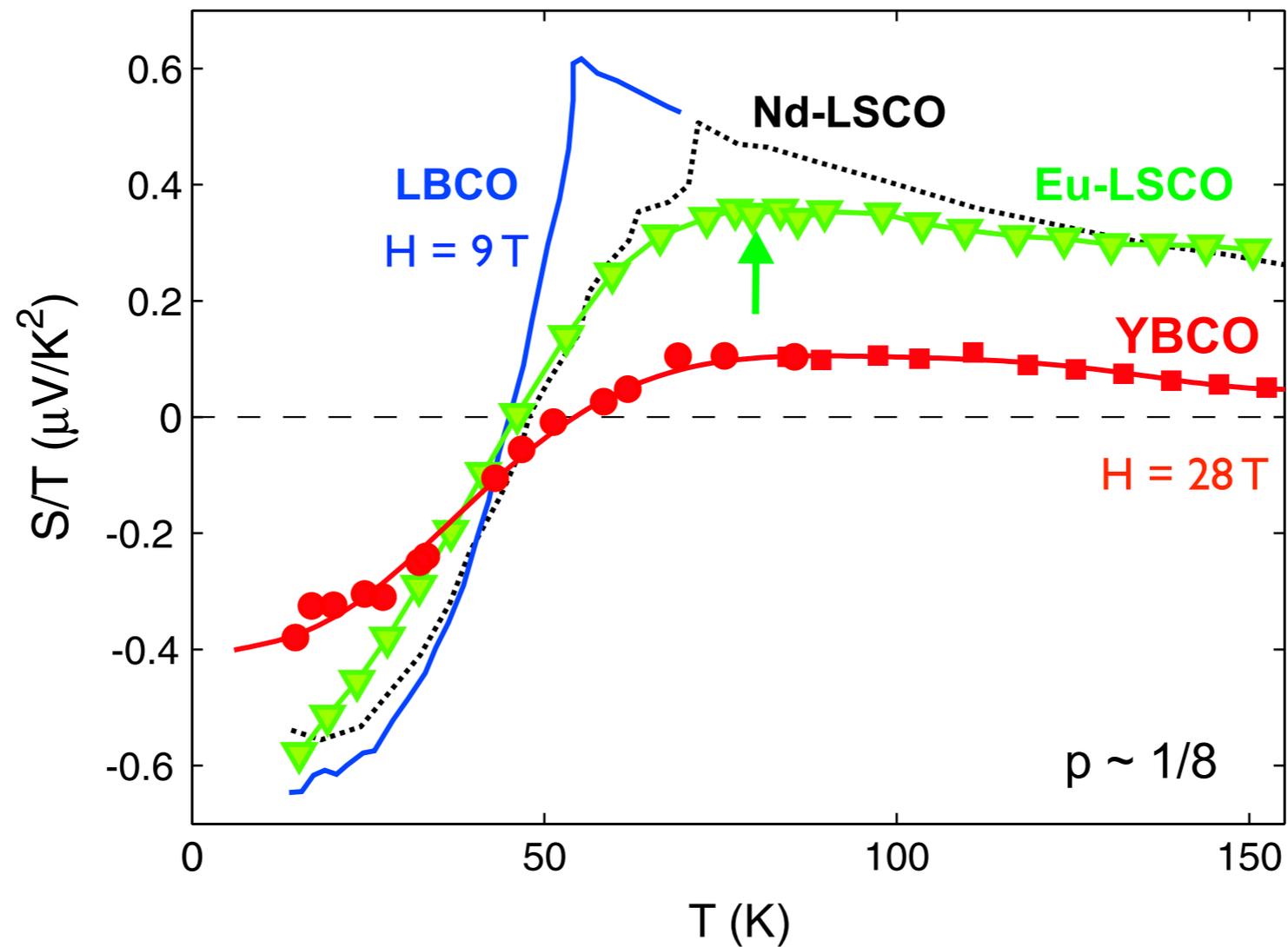
Riggs *et al.*, Nat. Phys. (2011)



Fermi surface
reconstruction?

Similarities between YBCO and LBCO

thermopower/temperature

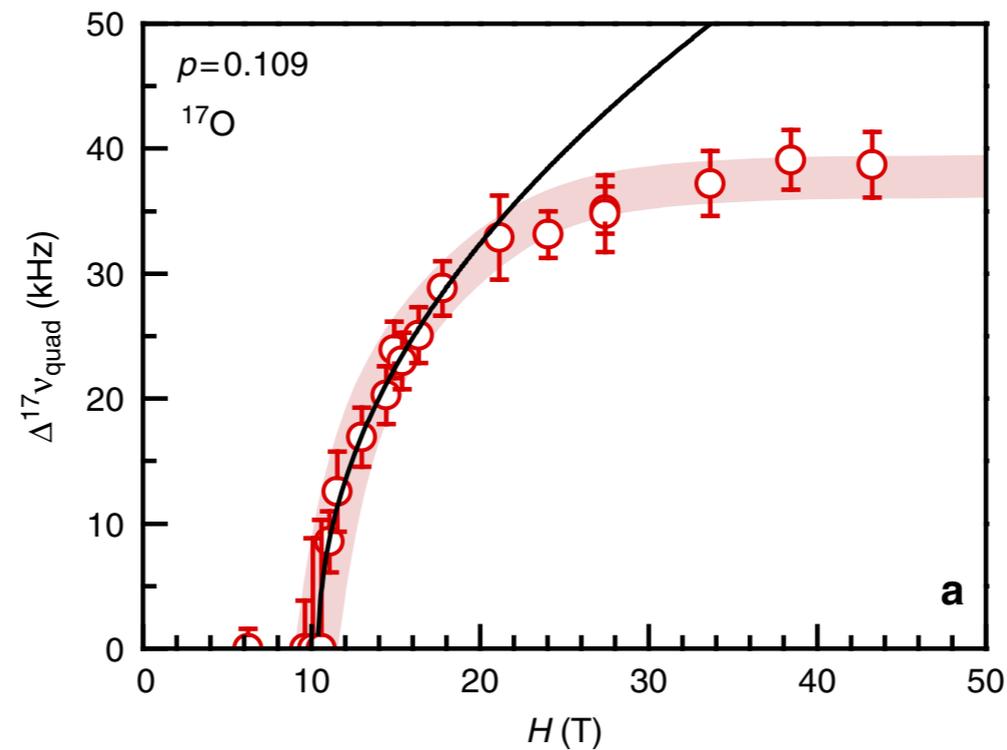
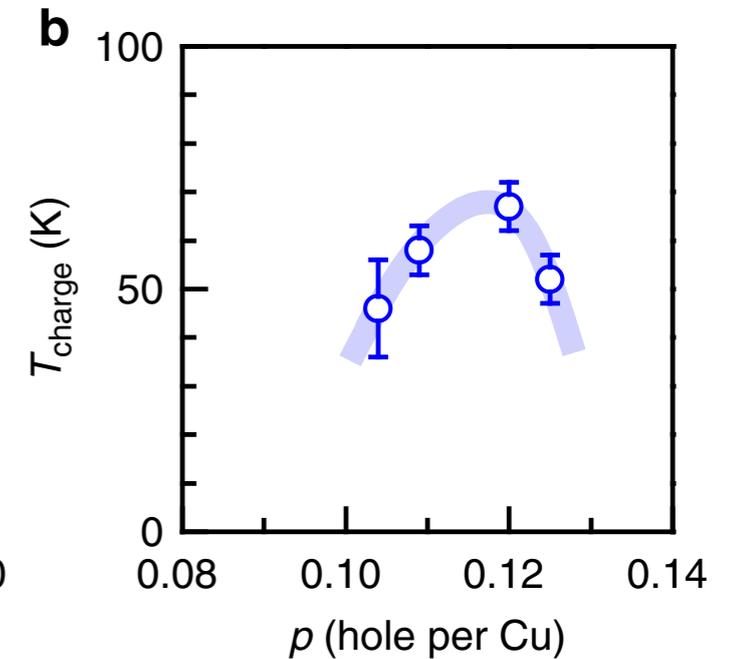
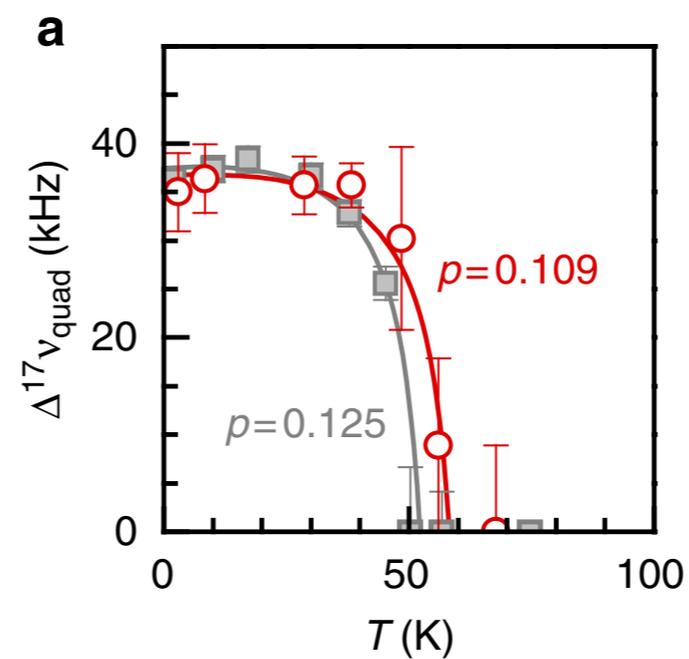
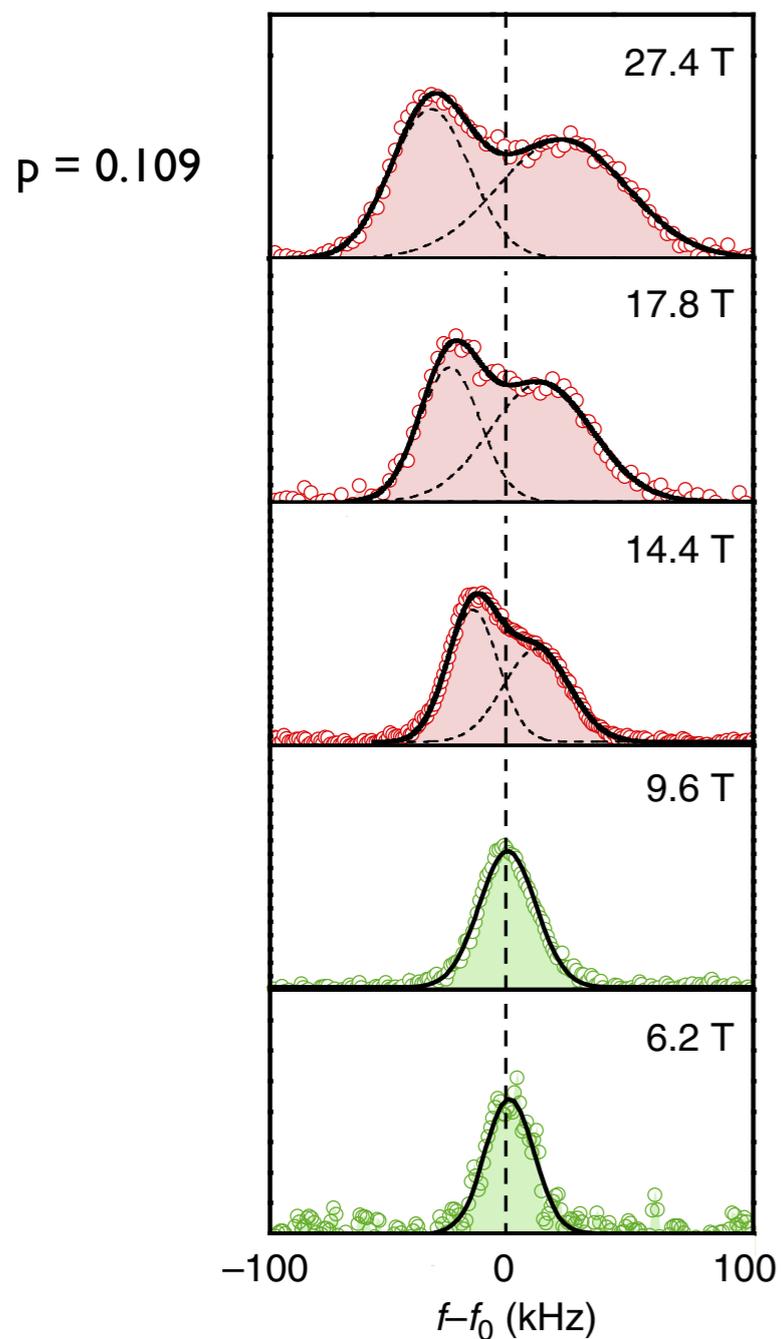


Chang *et al.*, PRL (2010)

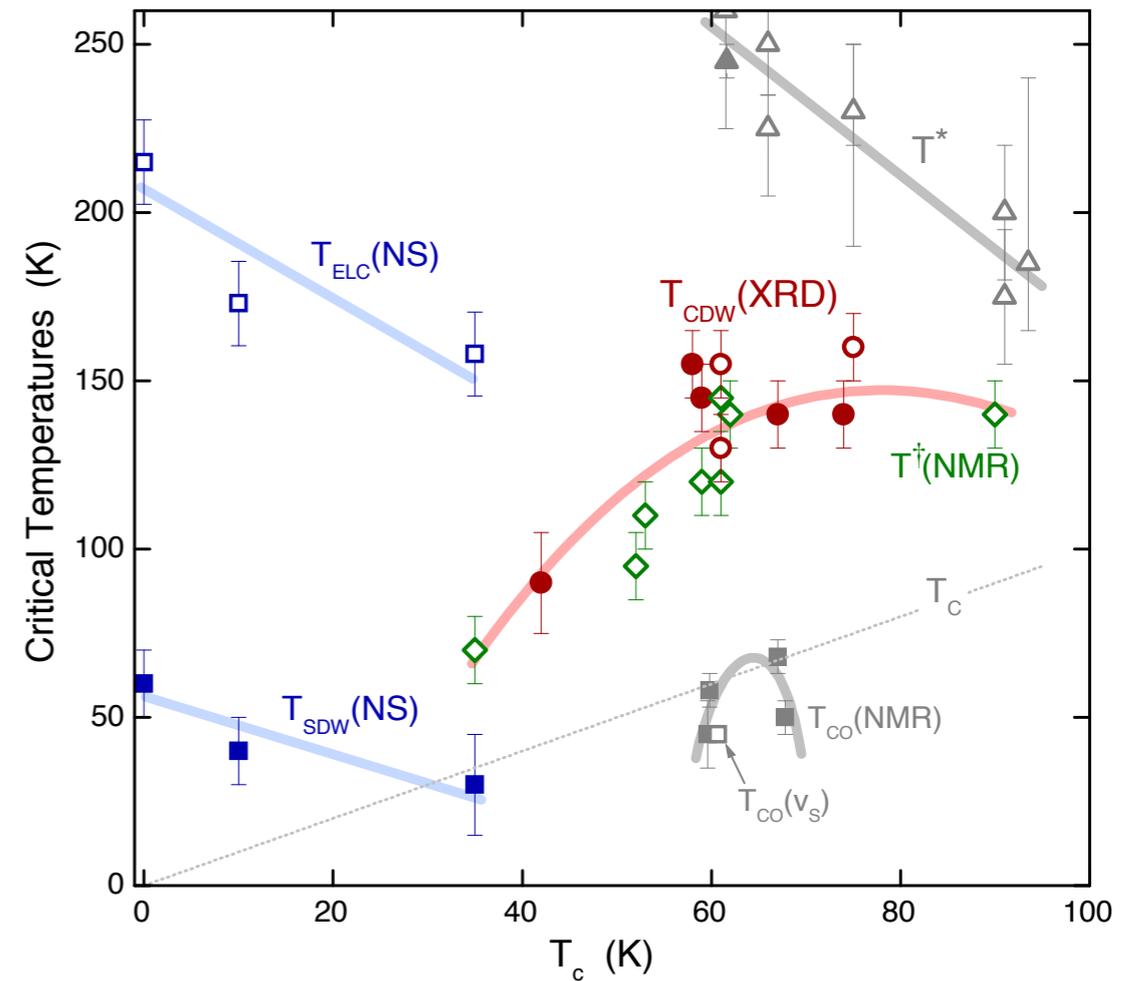
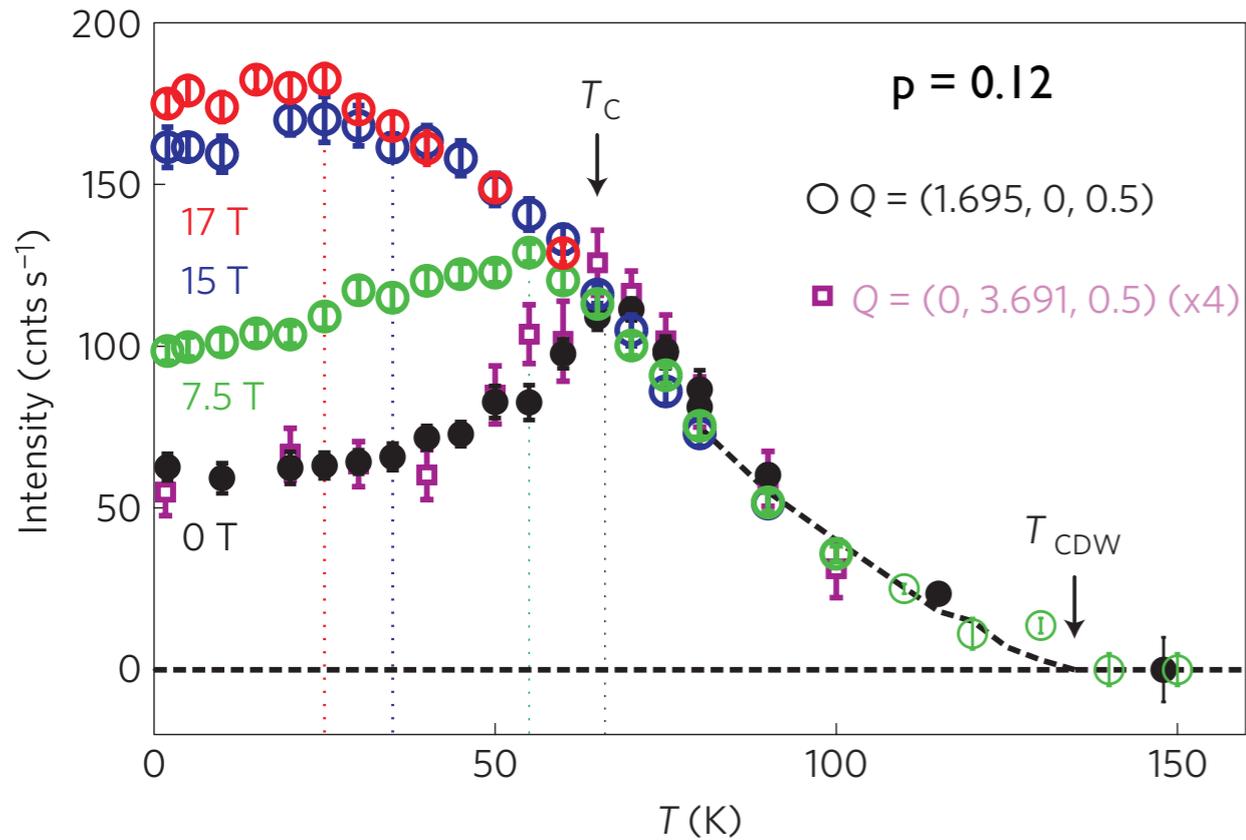
NMR: Charge order in YBCO

Wu *et al.*, Nature (2011)
Wu *et al.*, Nat. Comm. (2013)

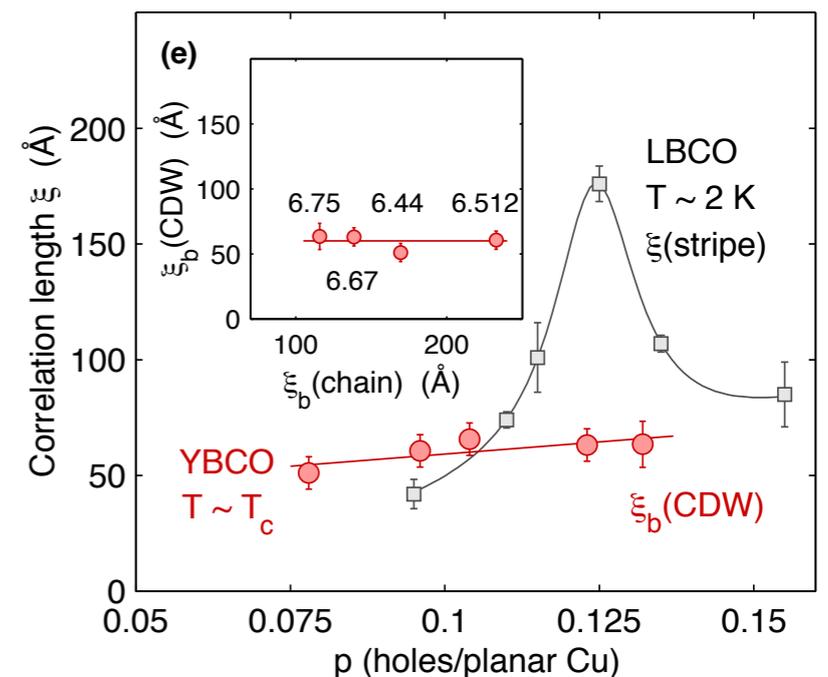
in-plane a-axis O site
 ^{17}O NMR



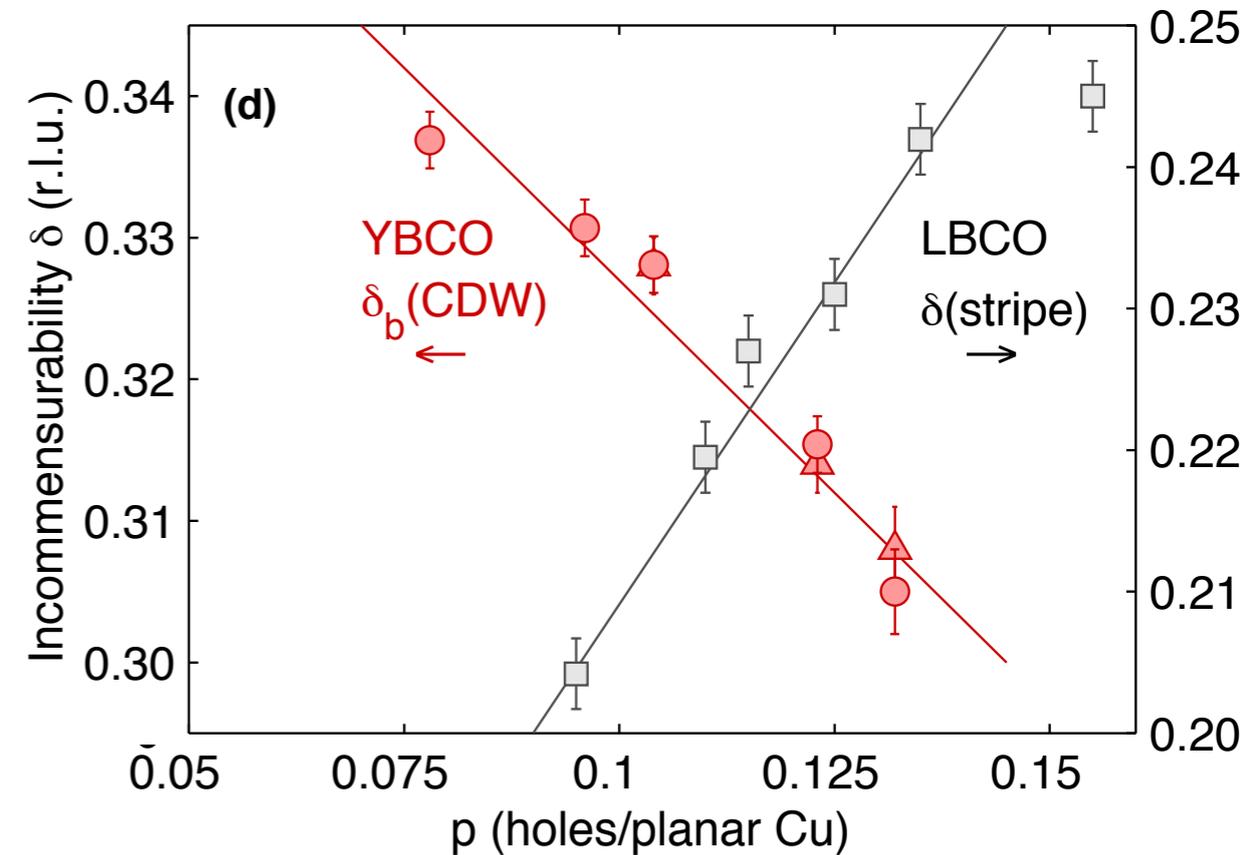
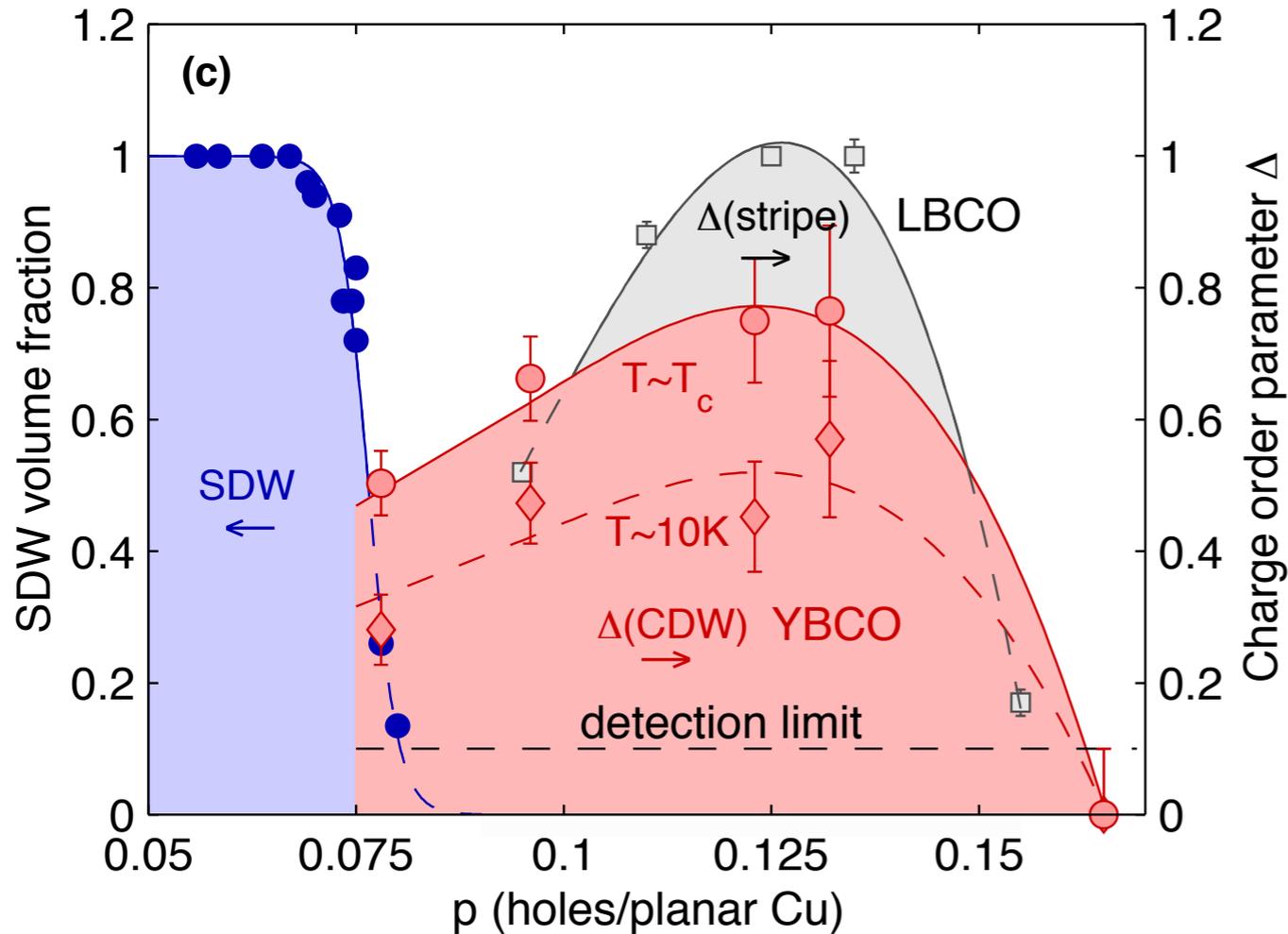
X-Rays: short-range CDW



Ghiringhelli *et al.*, Science (2012)
 Chang *et al.*, Nat. Phys. (2012)
 Achkar *et al.*, PRL (2012)
 Blackburn *et al.*, PRL (2013)
 Blanco-Canosa *et al.*, PRL (2013)
 Hücker *et al.*, arXiv:1405.7001
 Blanco-Canosa *et al.*, arXiv:1406.1595



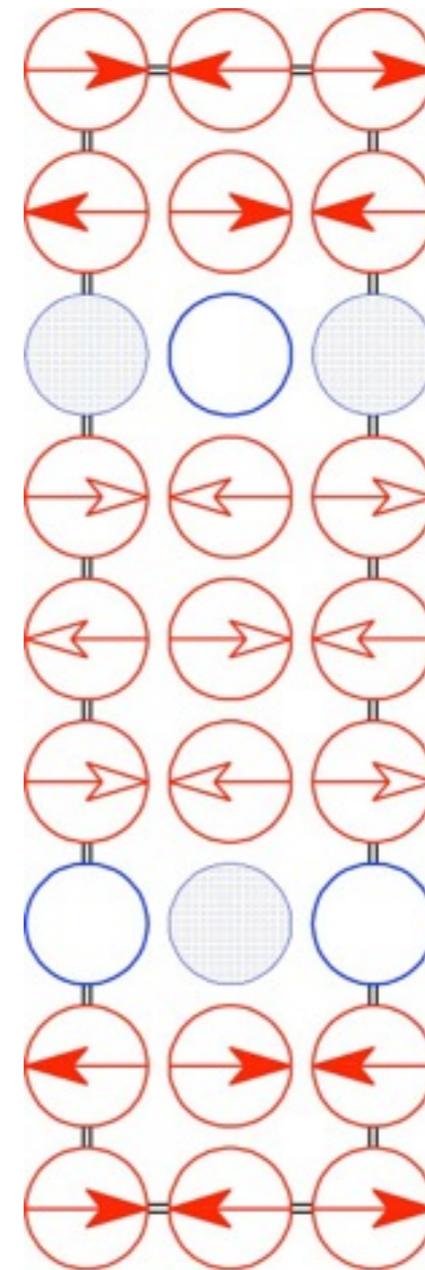
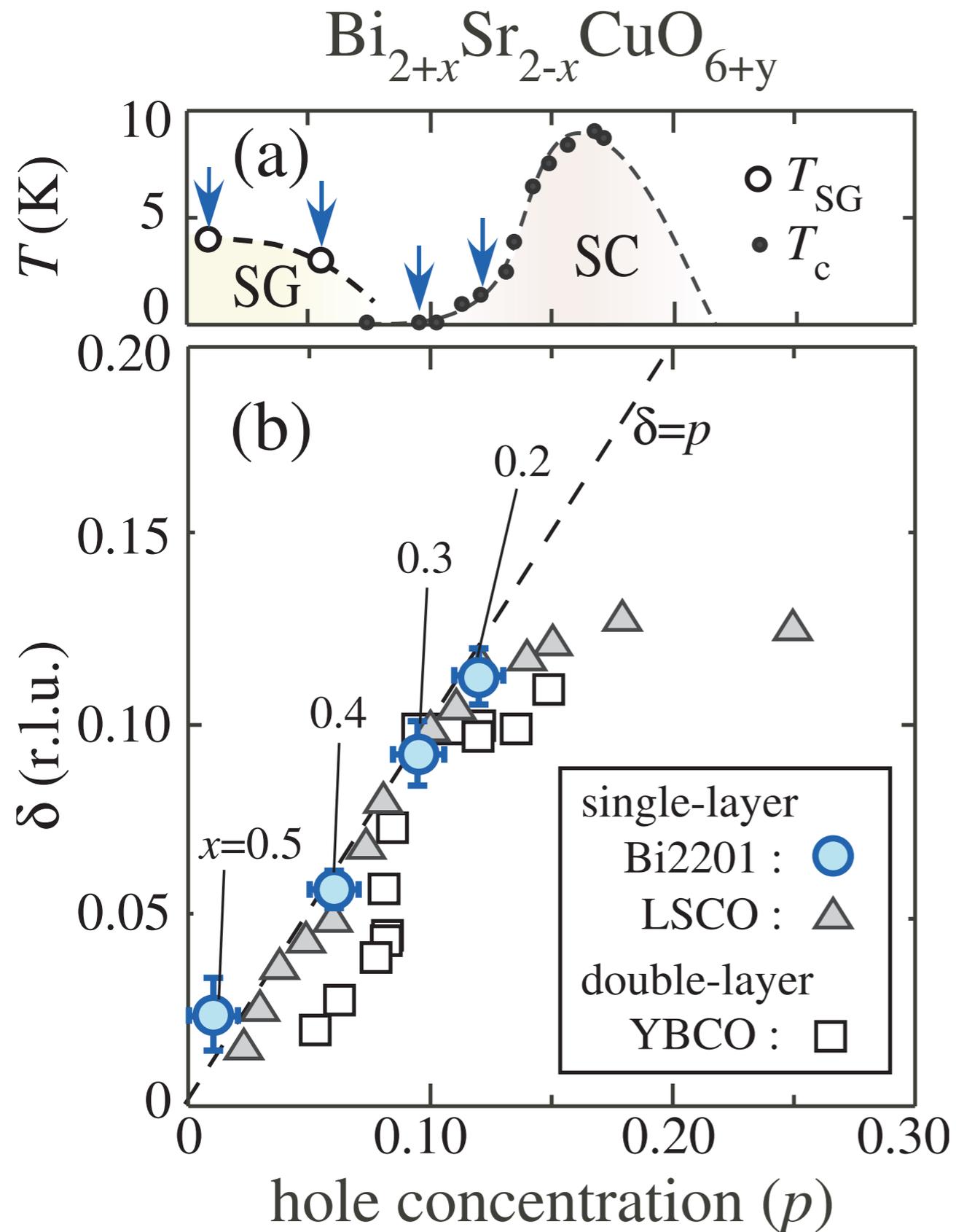
CDW order in $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$



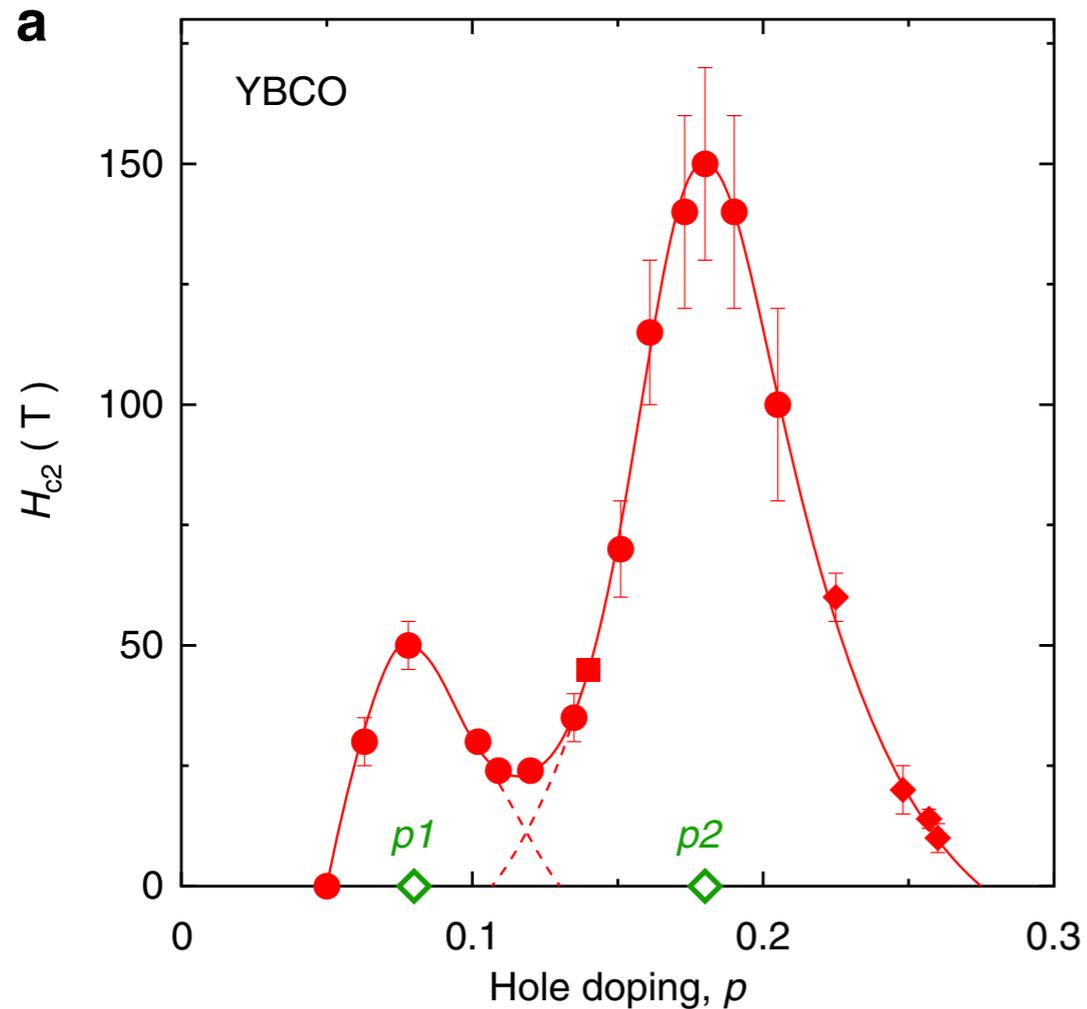
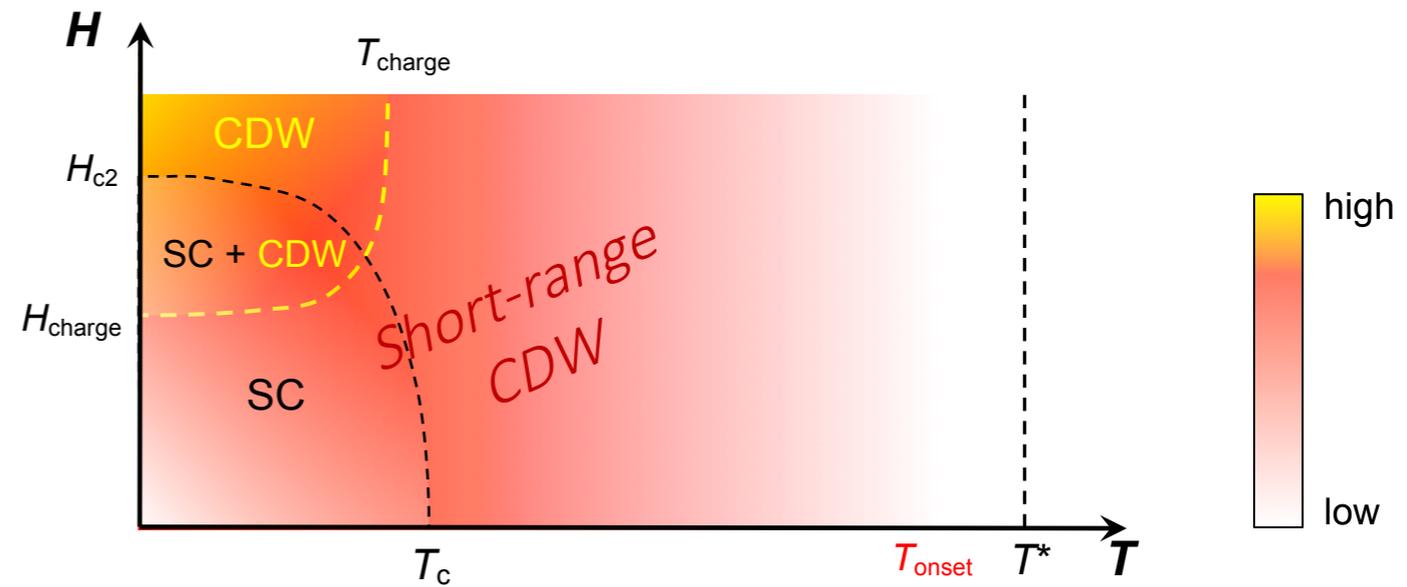
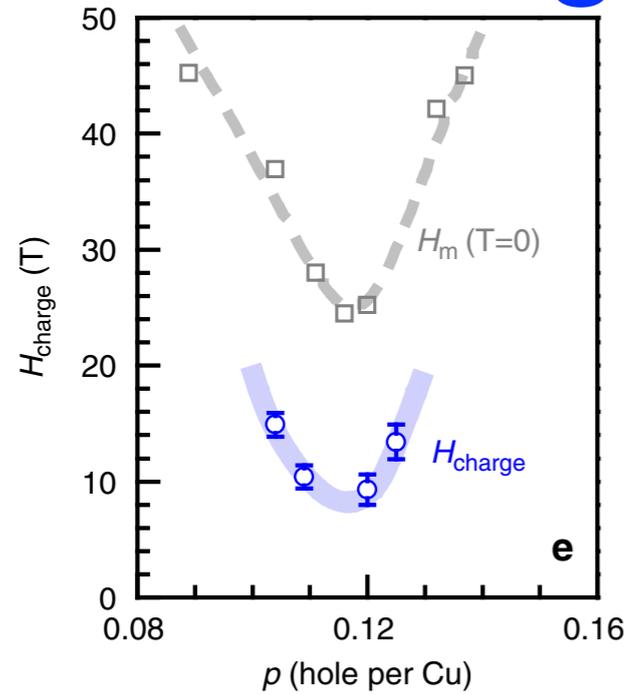
Hücker, Christensen, Holmes, Blackburn, Forgan, Liang, Hardy,
Gutwoski, Zimmermann, Hayden, & Chang, arXiv:1405.7001

Blanco-Canosa, Frano, Schierle, Porras, Loew, Minola, Bluschke, Weschke,
Keimer, & Le Tacon, arXiv:1406.1595

Universal behavior: spin stripe density vs. doping



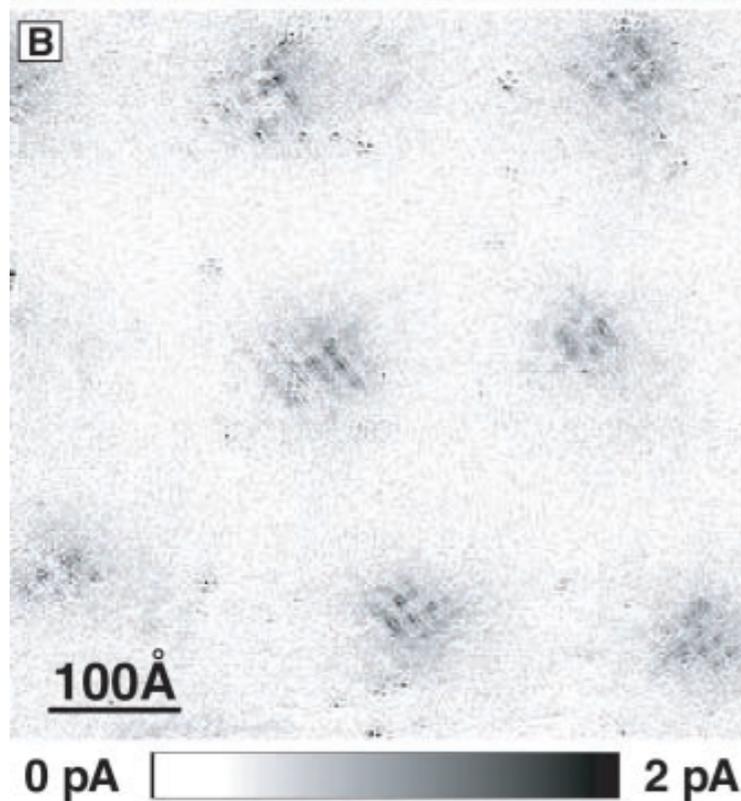
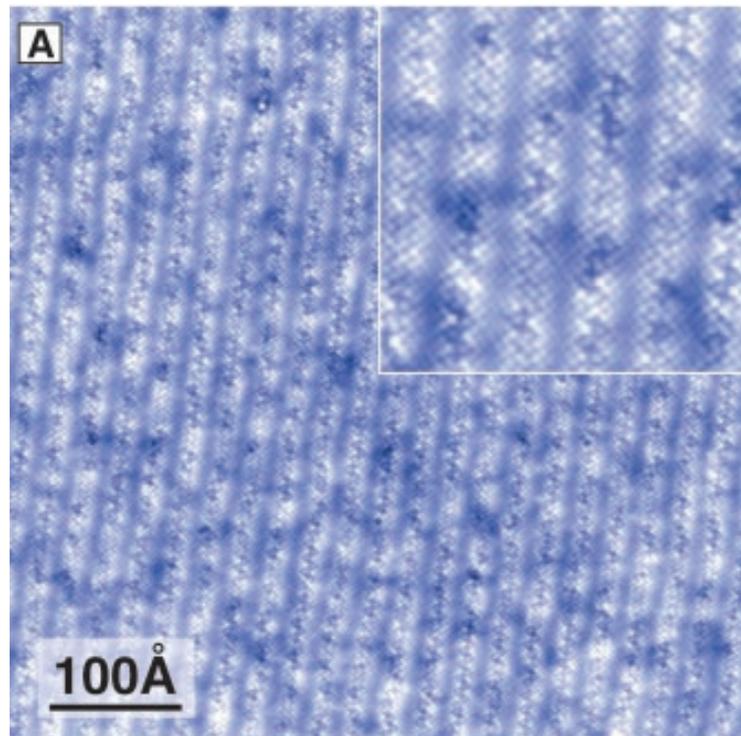
High- vs. low-field CDW



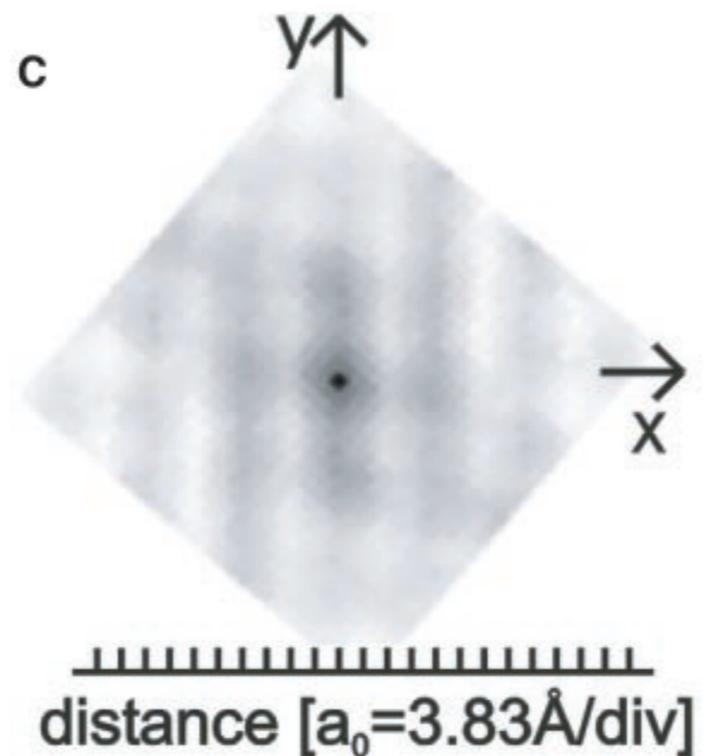
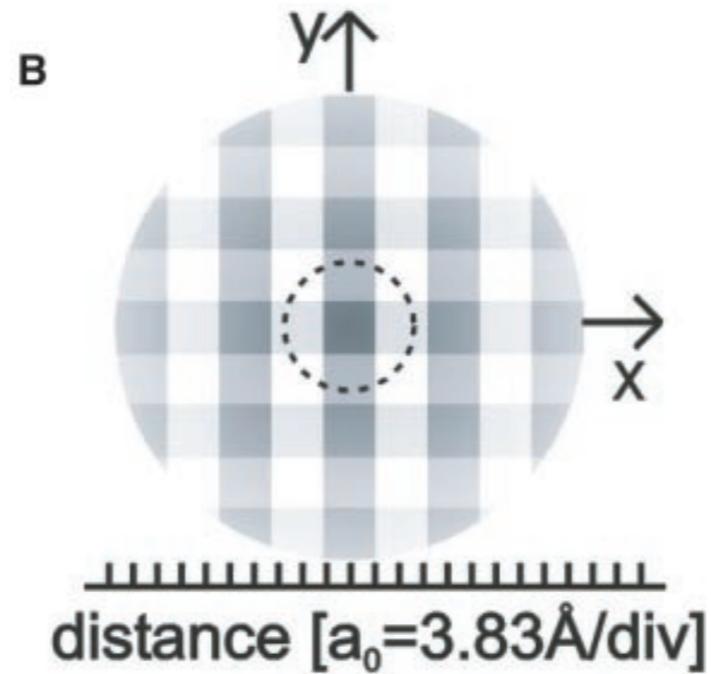
Wu et al., arXiv:1404.1617

Grisonnanche et al., Nat. Commun. (2014)

4a CDW in vortex halos: STM on Bi2212



$B = 5 T$



Autocorrelation about one vortex core

$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

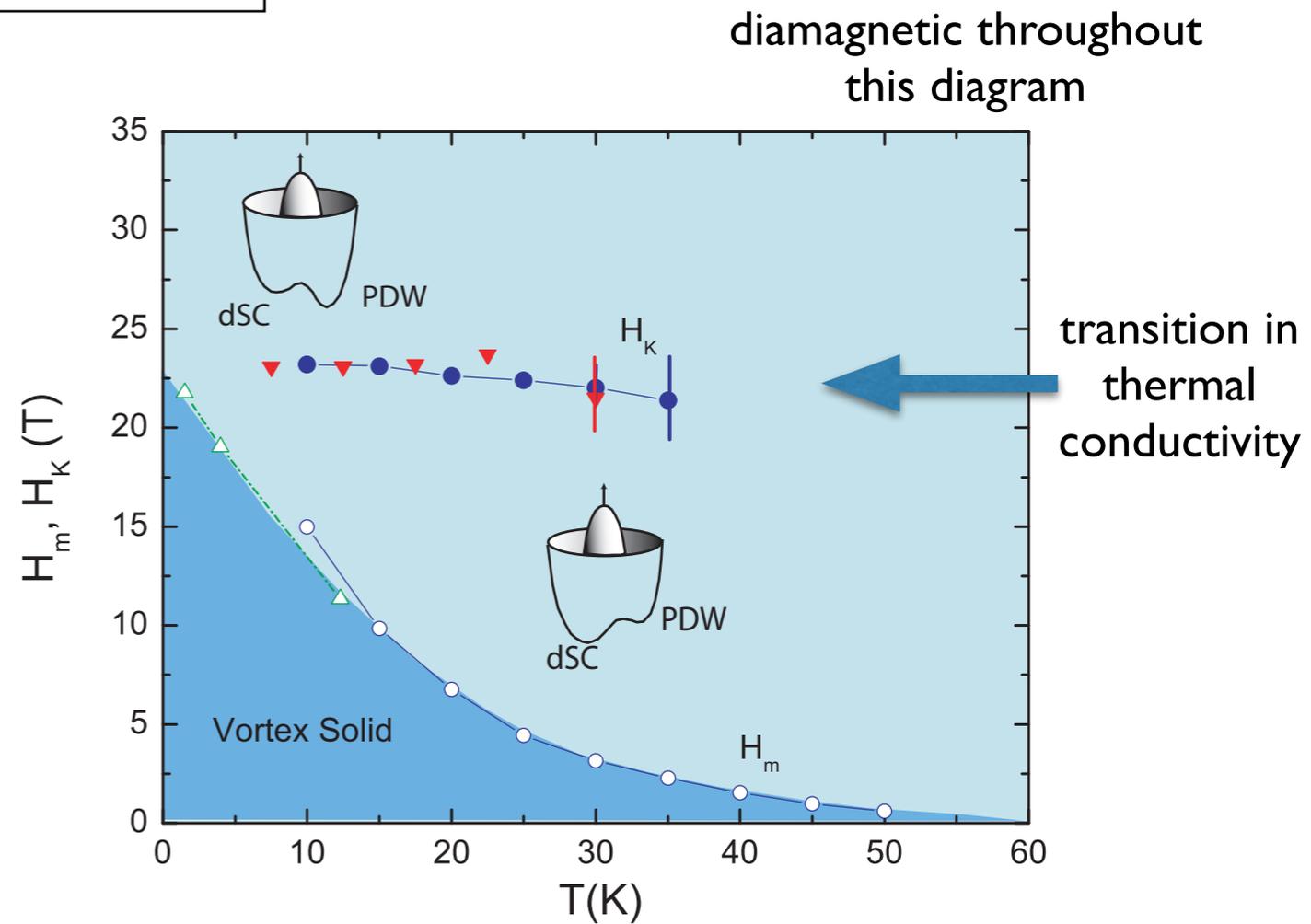
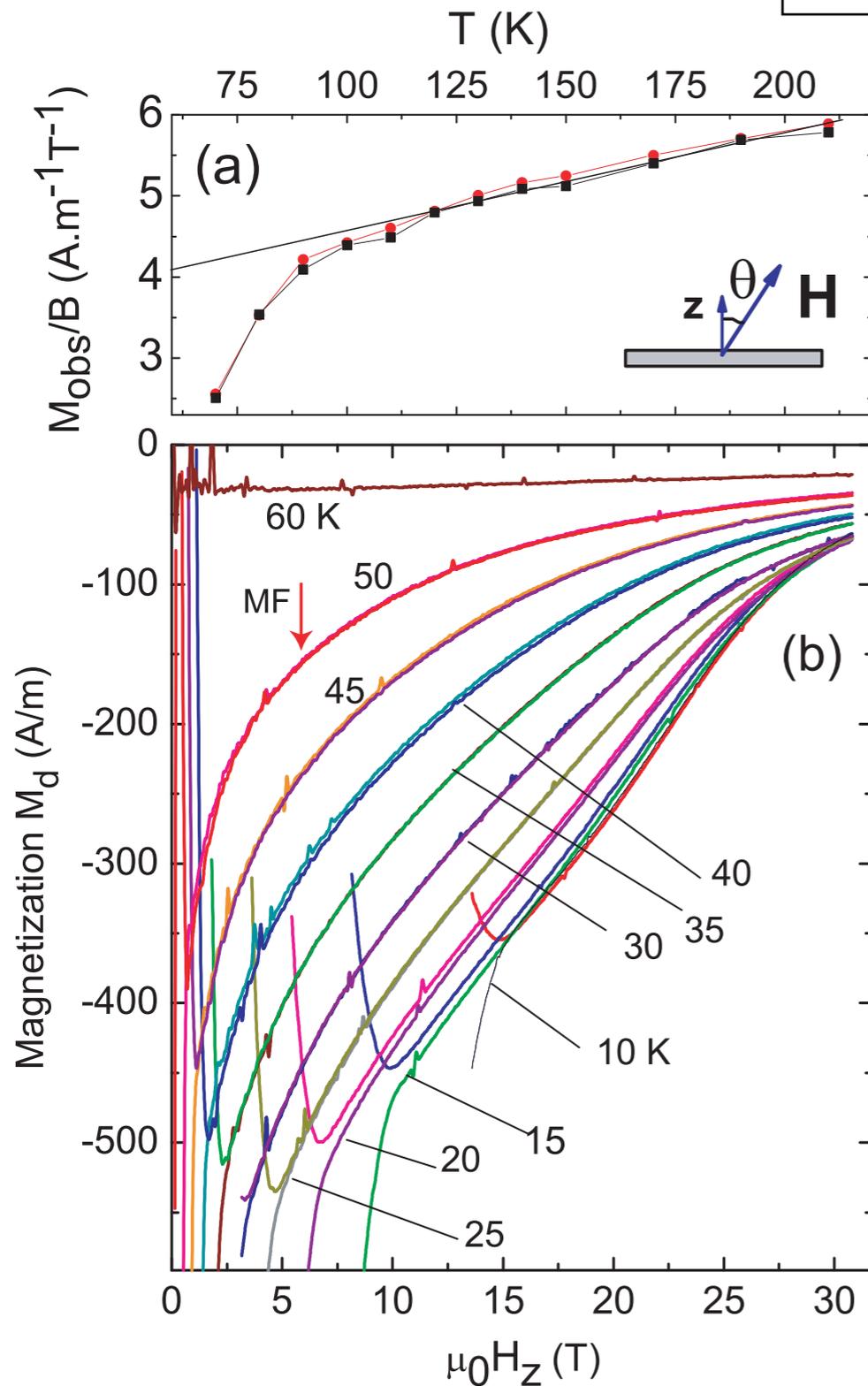
$T_c = 89 \text{ K}$

imaged with
in-gap states:
1-12 meV

Hoffman *et al.*,
Science (2002)

Diamagnetism + CDW \rightarrow PDW (?)

YBCO $\rho = 0.11$



Yu et al., arXiv:1402.7371

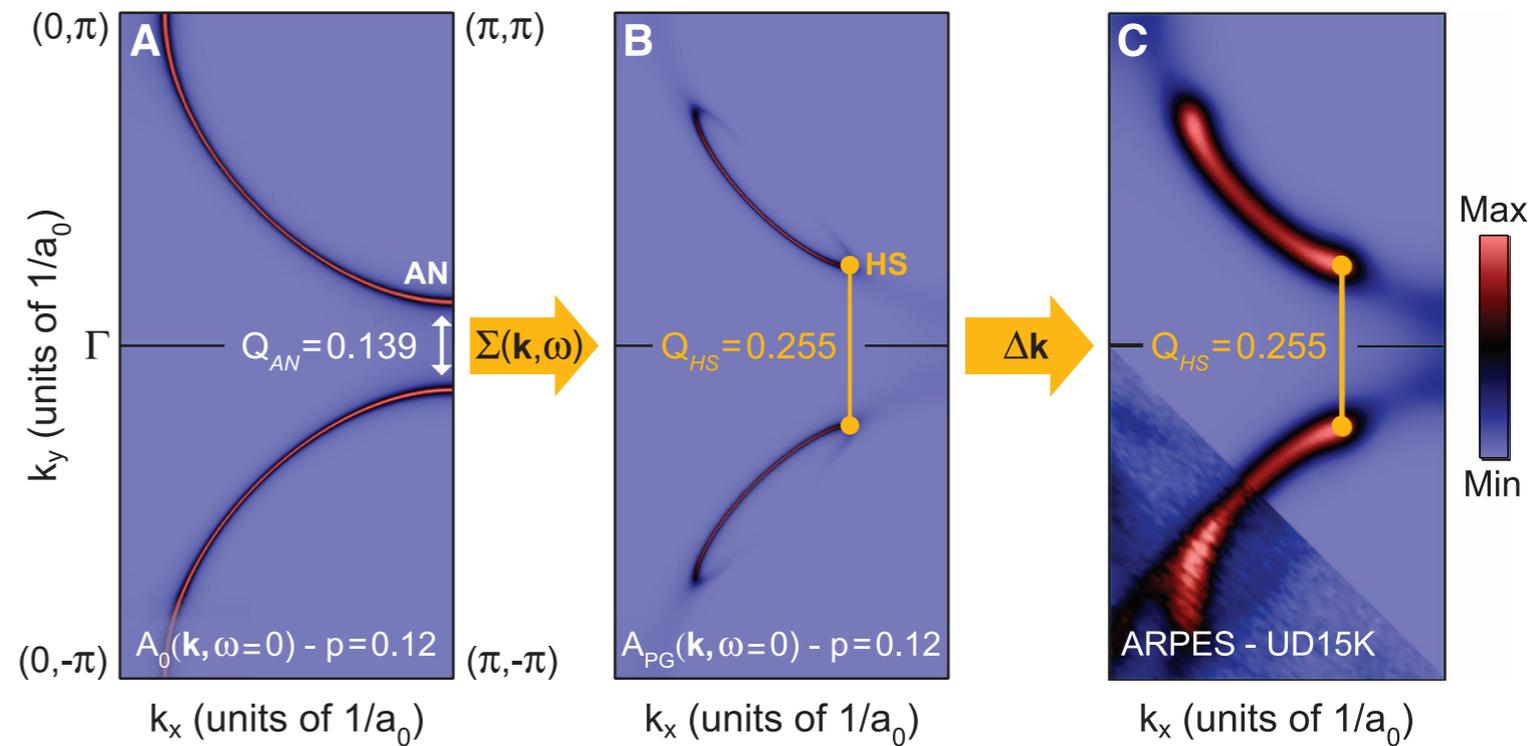
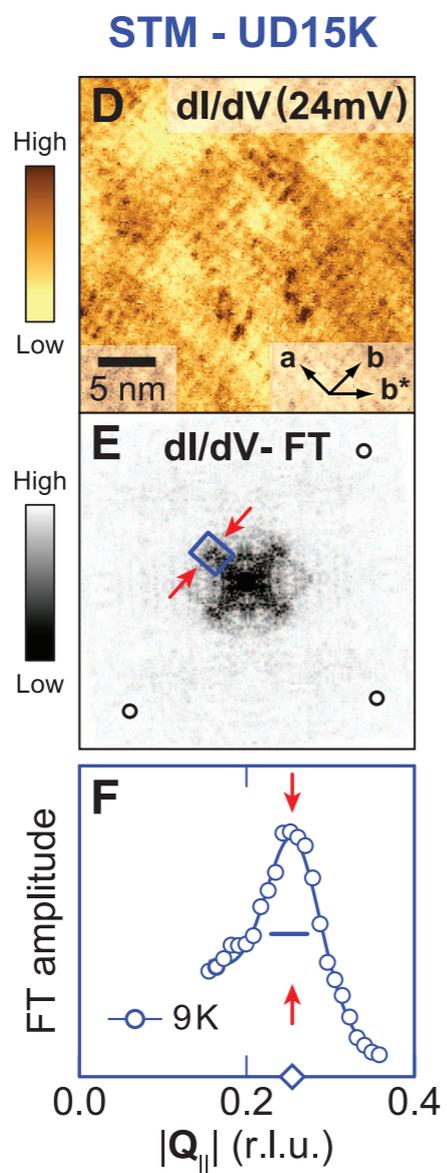
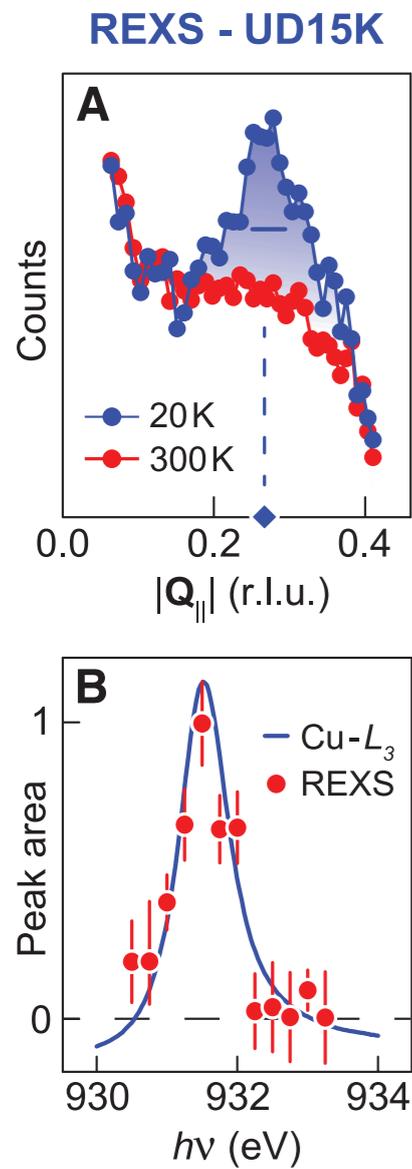
Charge order in Bi2201

REXS

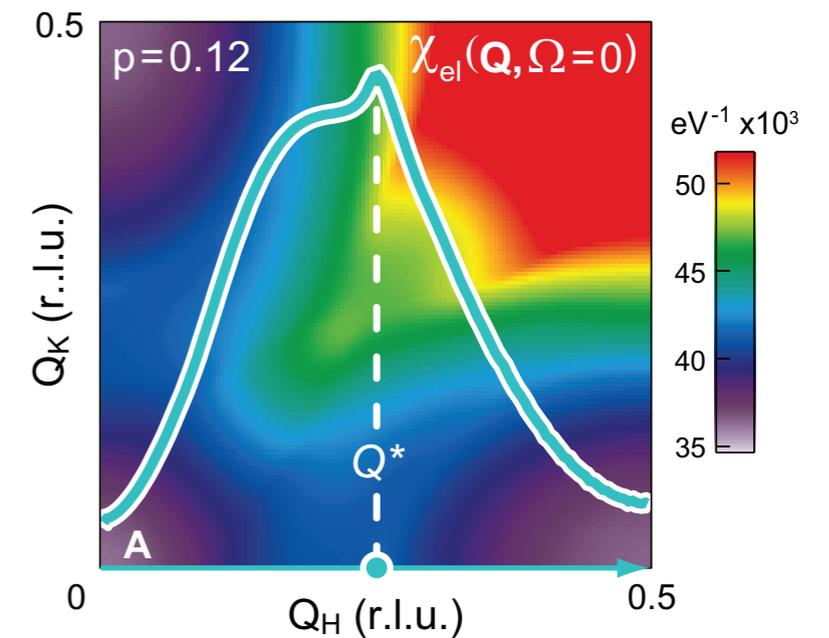
STM

model Fermi surface

ARPES

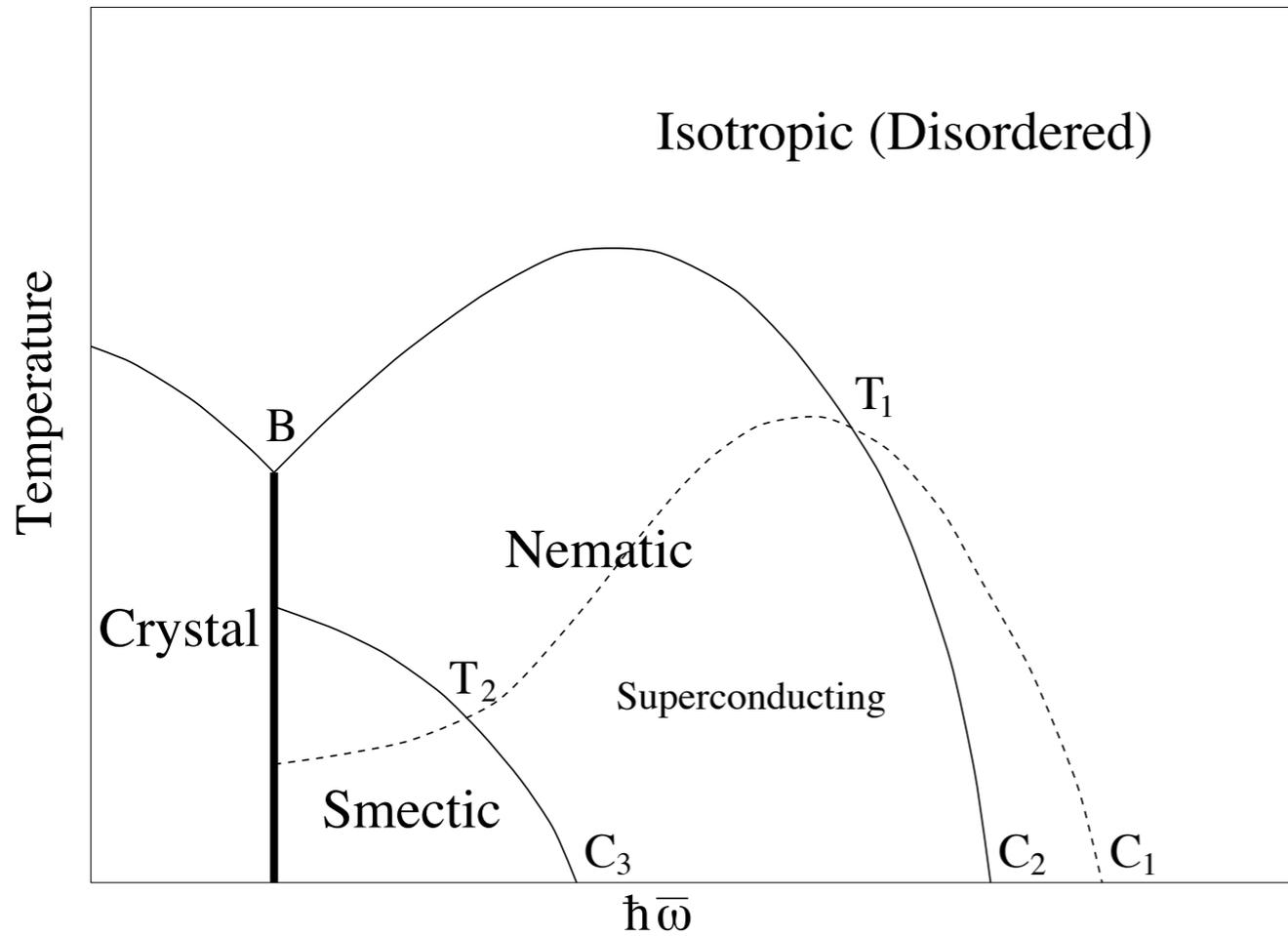


charge
susceptibility



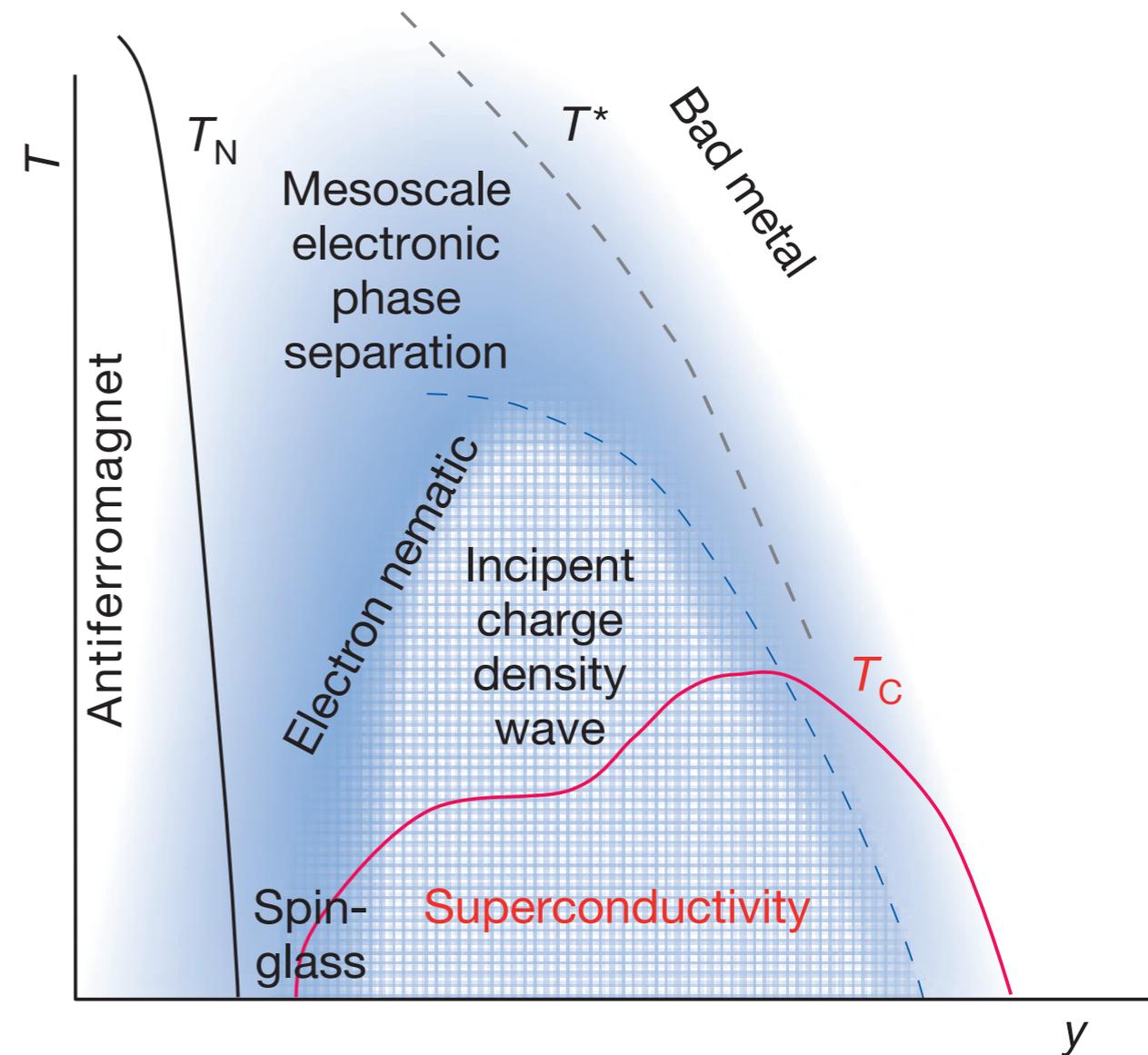
Comin *et al.*, Science (2014)

Electronic liquid crystal phases



Kivelson, Fradkin, & Emery, Nature (1998)

Ineluctable complexity



Fradkin & Kivelson, Nat. Phys. (2012)

Conclusions

- Spatial inhomogeneity allows coexistence of AF spin correlations and mobile holes
- Ordered stripes can be superconducting (LBCO)
- Fluctuating stripes (nematic phase) may underlie the CDW order in YBCO
- Typical ordering temperature for SDW, CDW, SC are all quite similar \Rightarrow intertwined orders