# What Stripes Tell Us about Superconductivity in Cuprates

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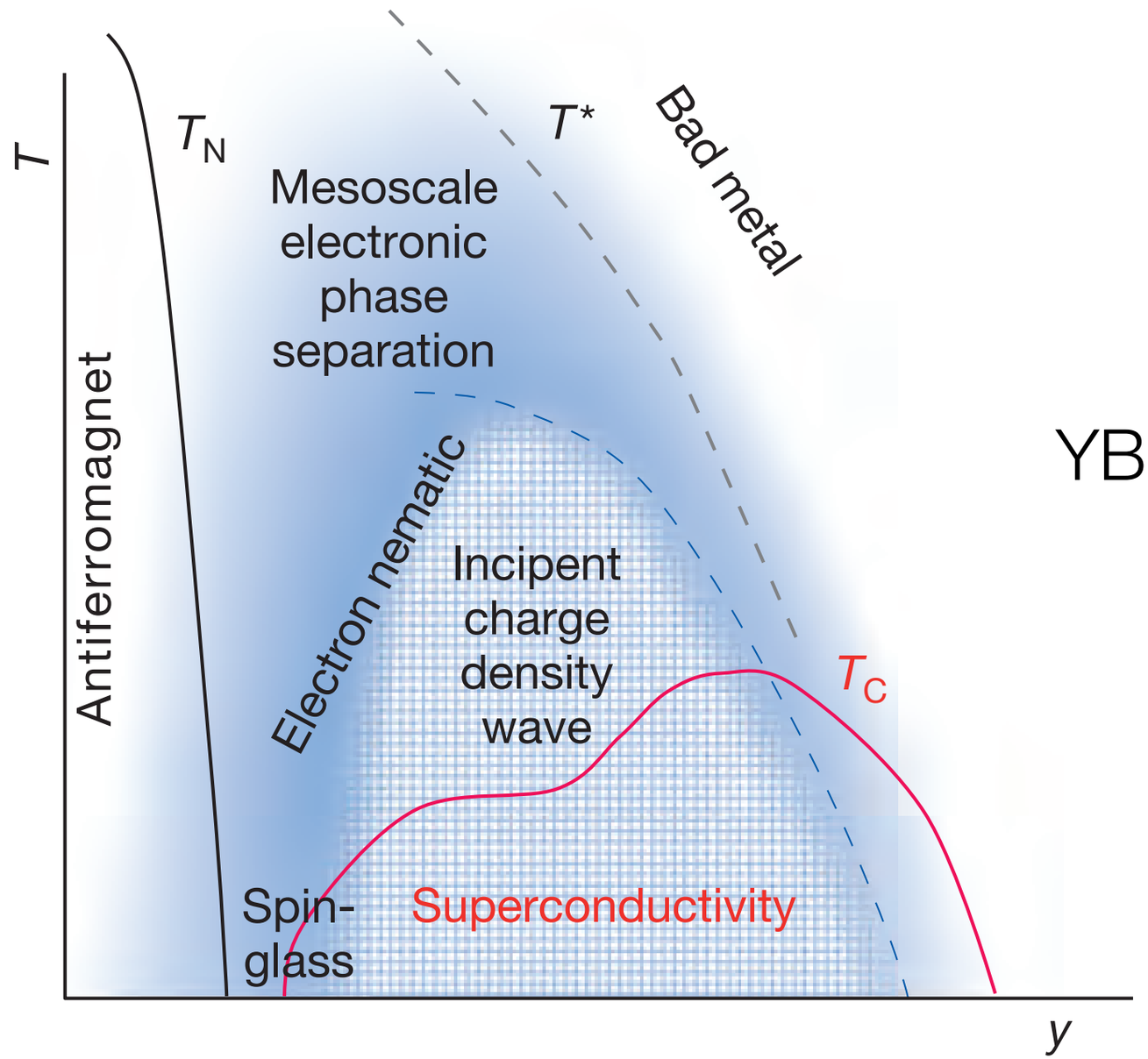
U.S. DEPARTMENT OF ENERGY | Office of Science

CES center for emergent superconductivity

# Ineluctable complexity




$YBa_2Cu_3O_{6+y}$

Fradkin + Kivelson, Nat. Phys. **8**, 864 (2012)

CDW order usually occurs due to
strong electron-phonon coupling.

What if, instead, it is caused by
spin-charge segregation and pairing?

# Cuprate Case

- Charge stripes
  - Compete with 3D superconductivity
  - Coexist with 2D superconductivity
    - Possible through Pair Density Wave state

- General case
  - Stripes of pairs
  - Josephson coupling between stripes yields SC
  - Anti-phase coupling + static stripes → PDW
  - In-phase coupling + fluctuating stripes → uniform d-wave SC

# Collaborators

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NCNR

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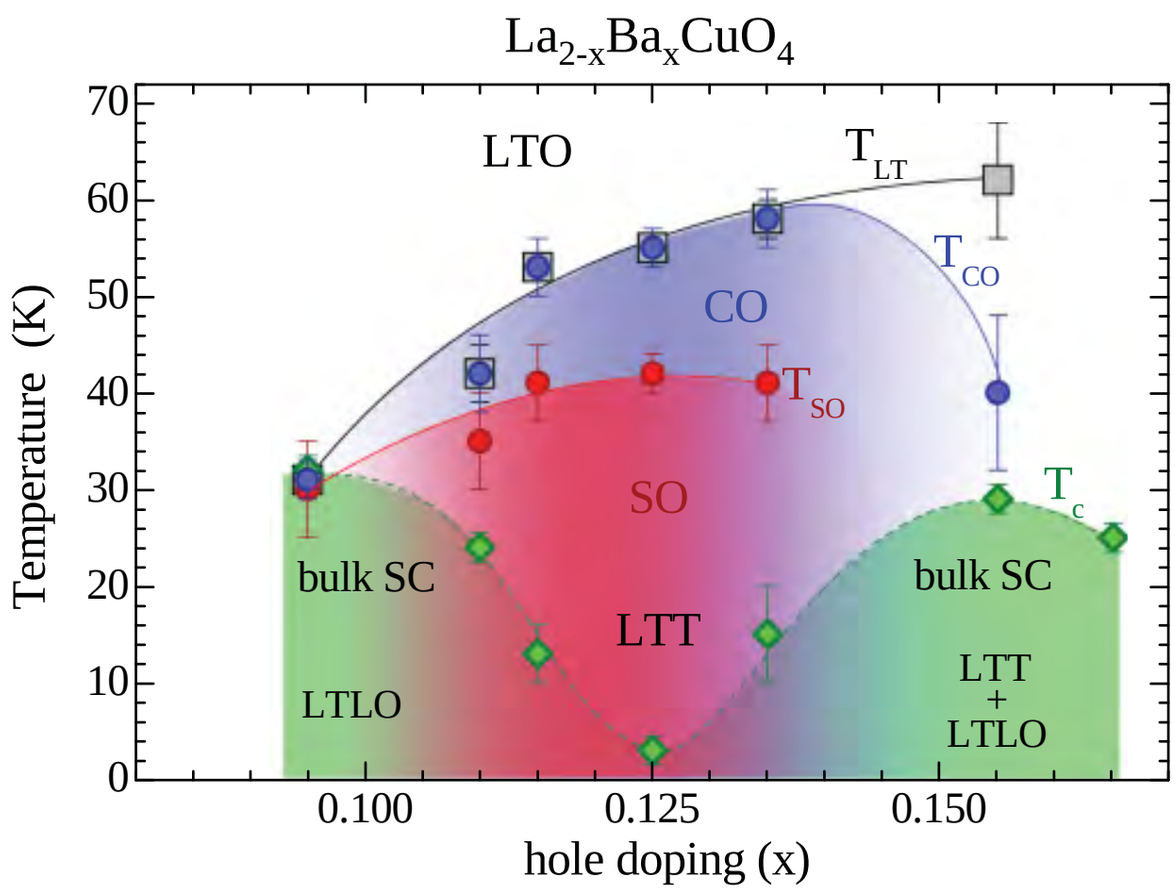
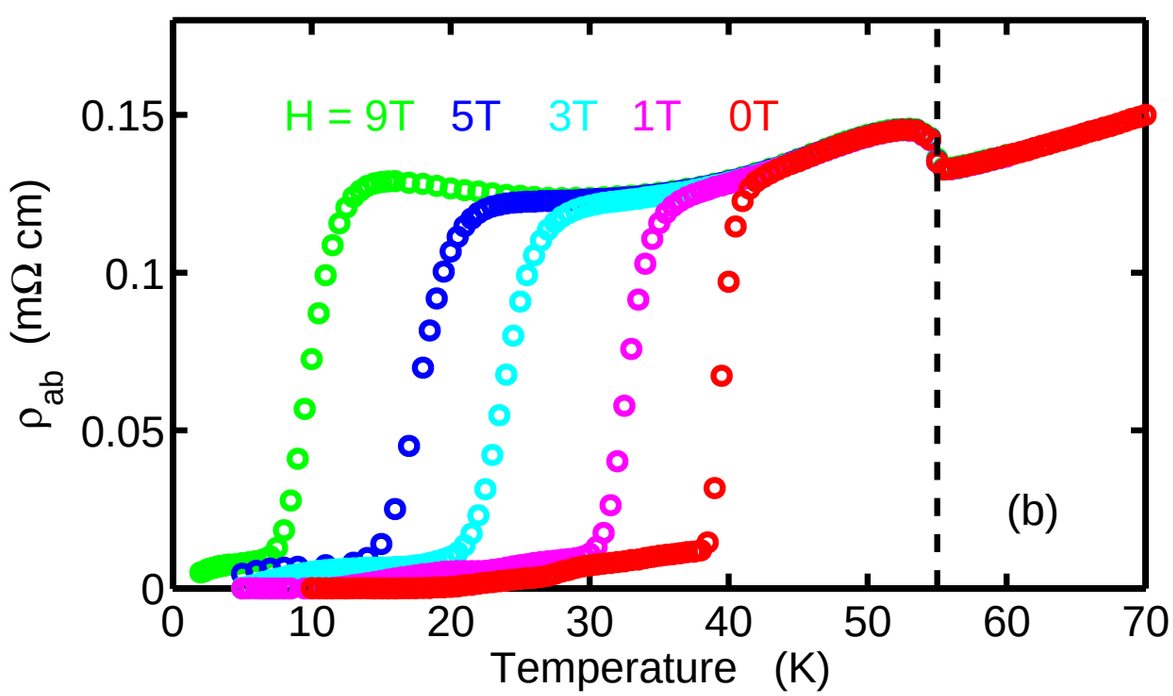
Martin von Zimmermann

# Competition between CDW and 3D SC

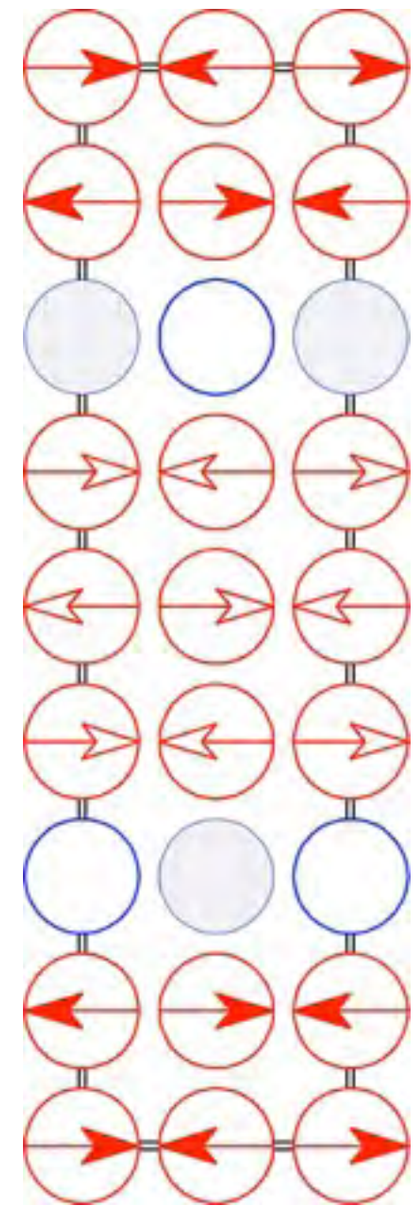



Hücker *et al.*, PRB (2011)

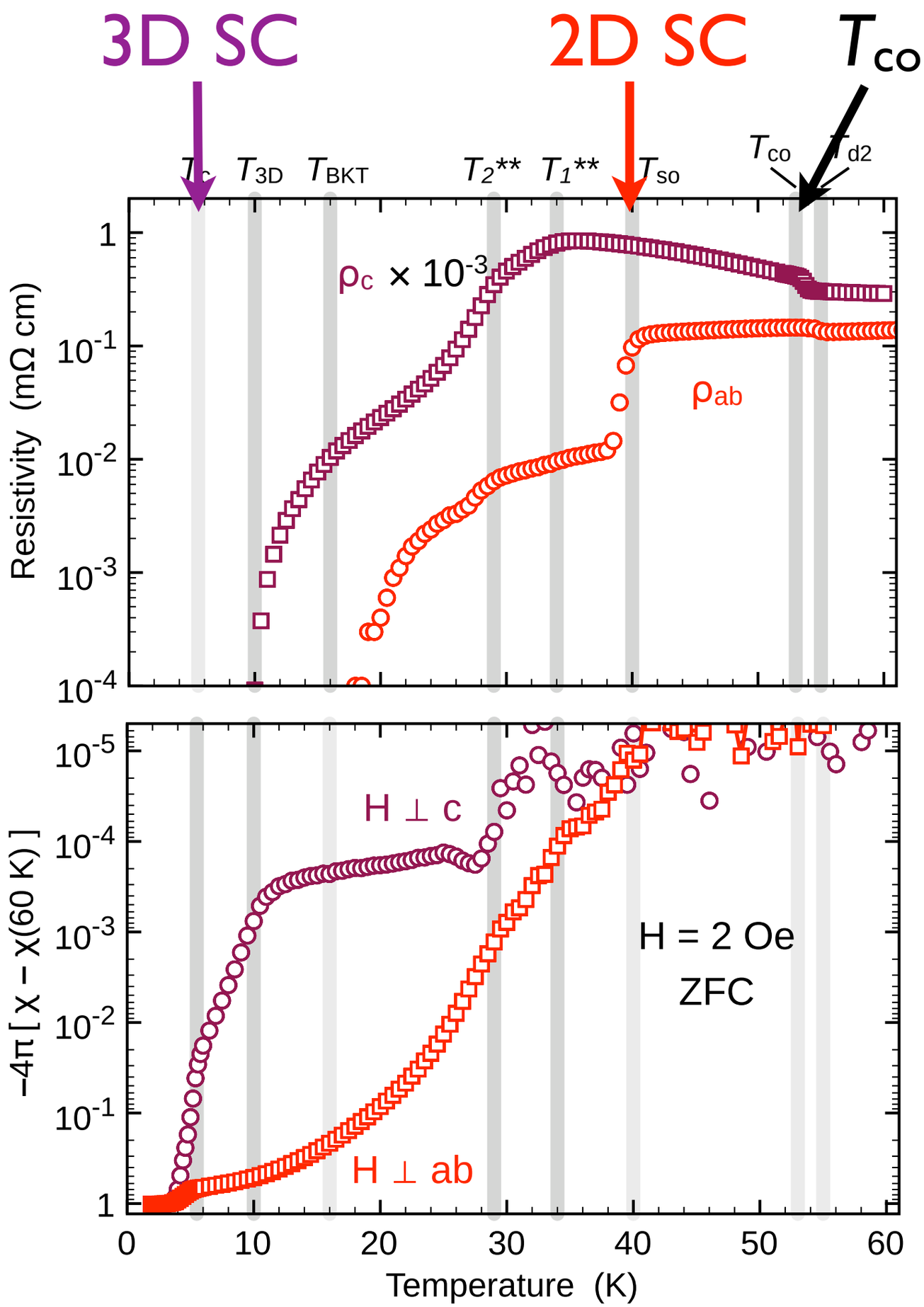



x = 1/8

Q. Li *et al.*, PRL (2007)



# LBCO x=1/8




Stripe order:

compatible with 2D SC at 40 K

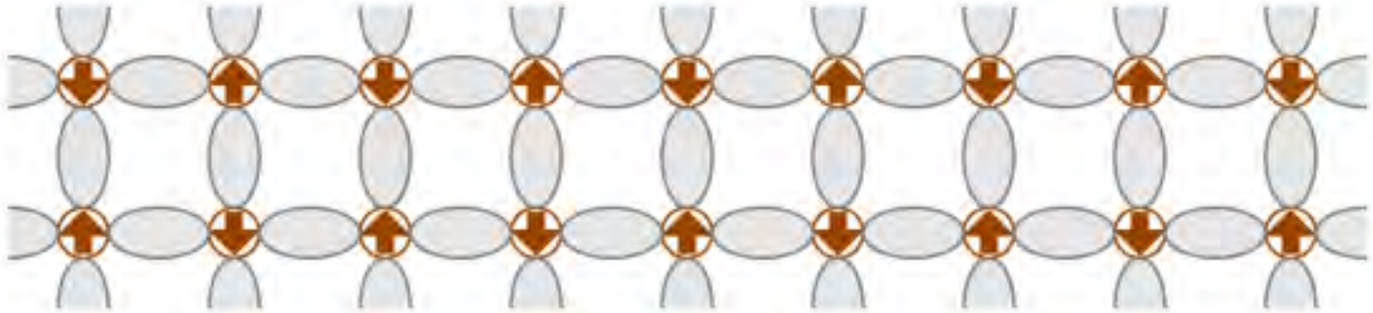
*frustrates* interlayer Josephson coupling

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

# Intertwined orders

(a)

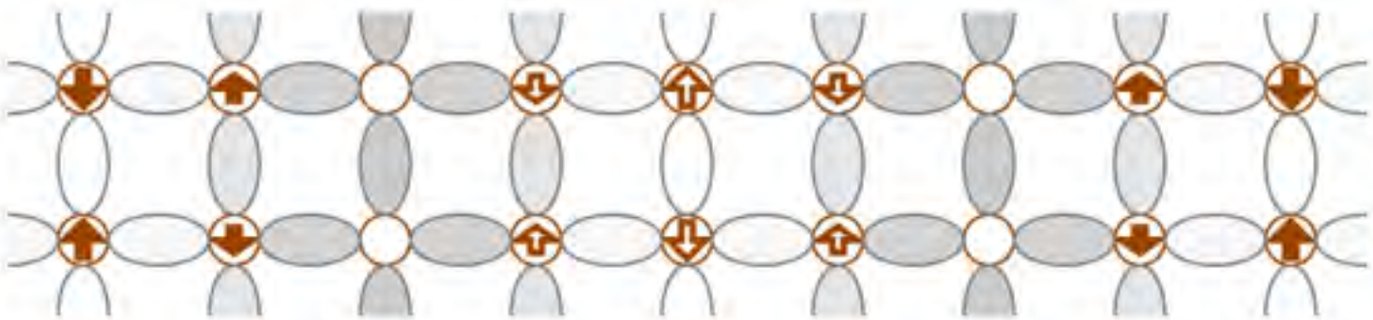
$La_2CuO_4$



AF order

(b)

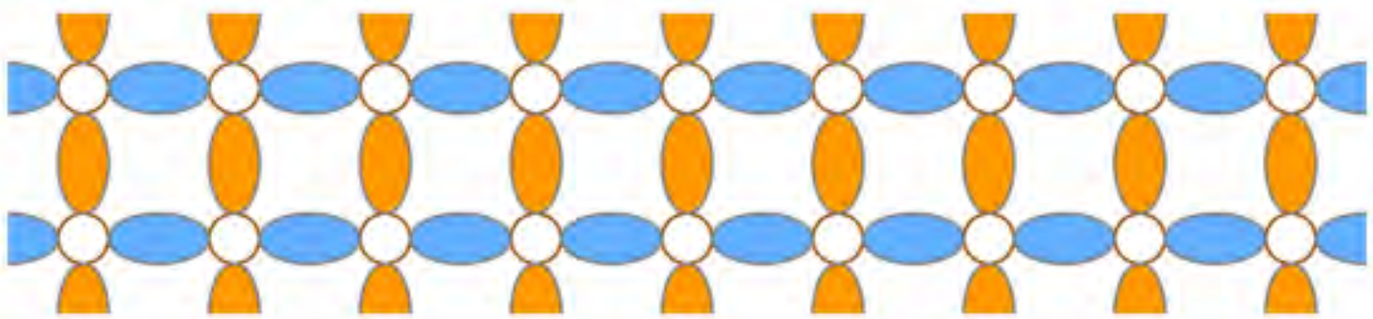
$La_{1.875}Ba_{0.125}CuO_4$



SDW+CDW

(c)

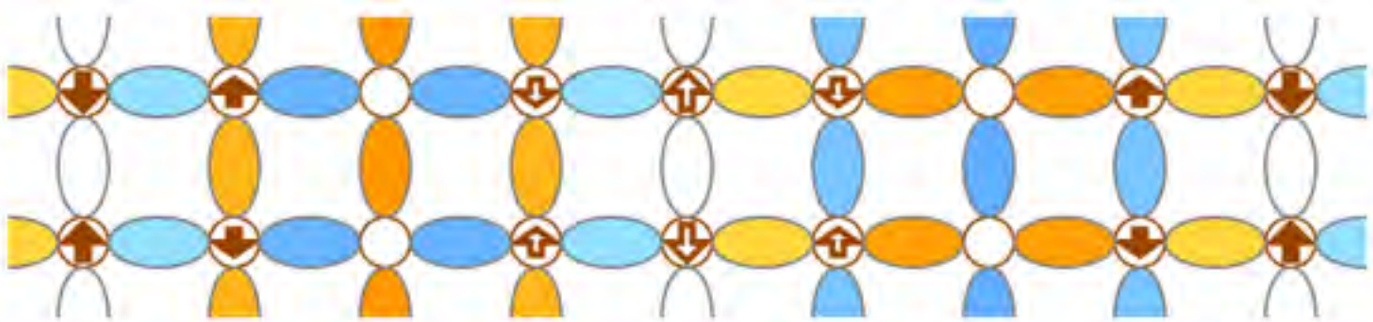
$La_{1.84}Sr_{0.16}CuO_4$



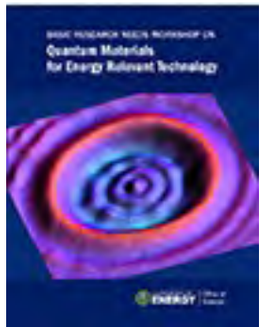
d-wave SC

(d)

$La_{1.875}Ba_{0.125}CuO_4$



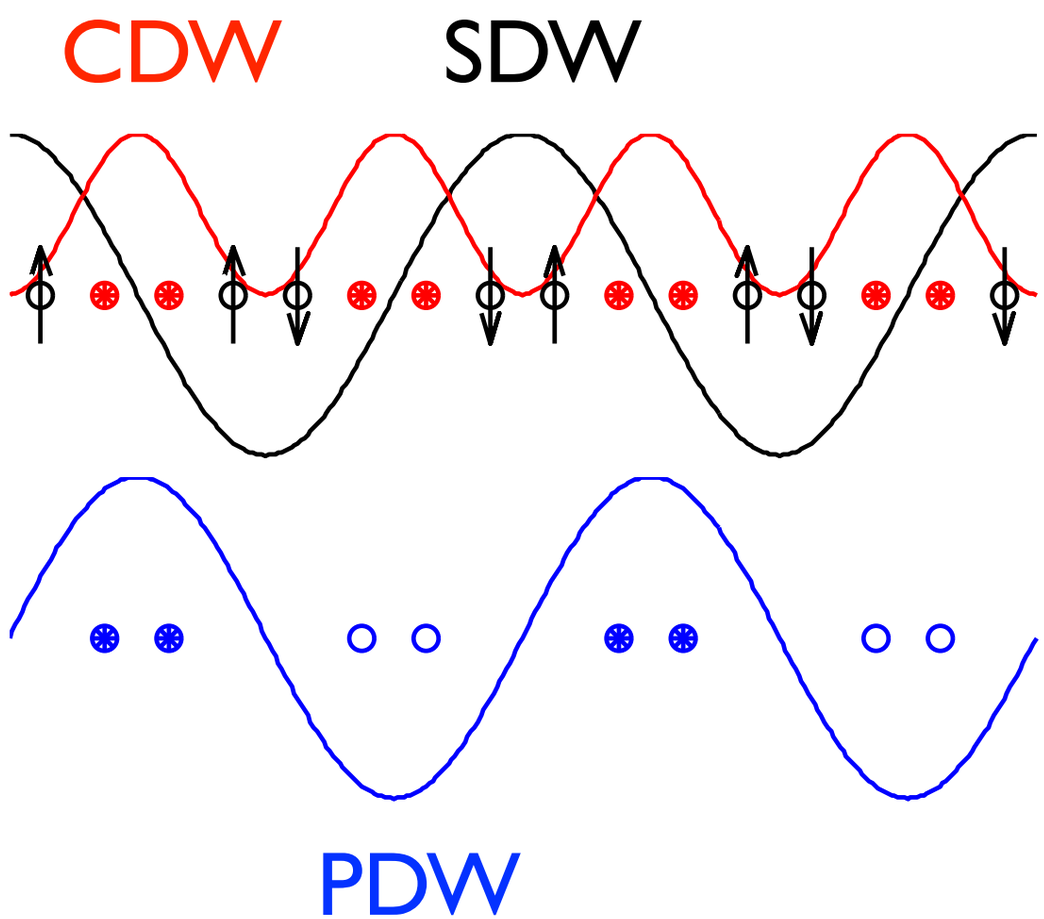
Pair density wave
+SDW+CDW

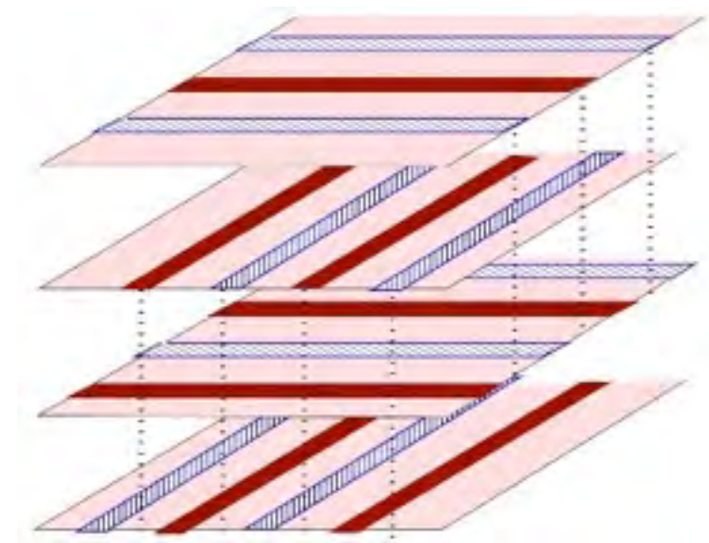



DOE/BES
Quantum Materials Rpt.

Fradkin et al., RMP (2015)

# 2D SC and Pair-Density-Wave Superconductor



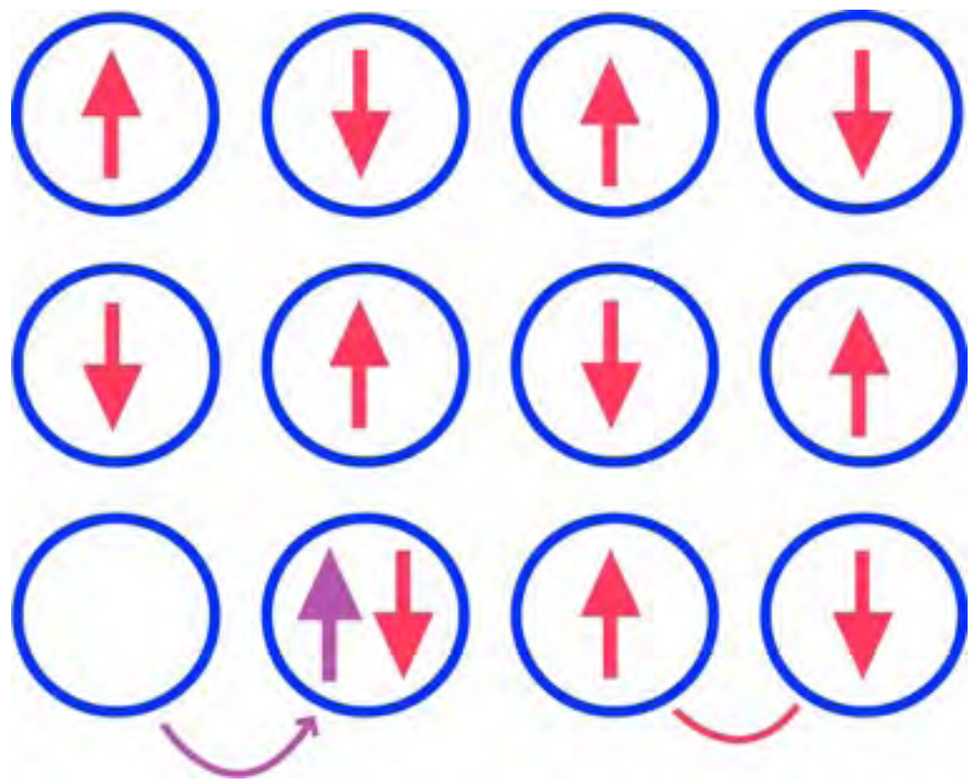
*Frustration of interlayer coupling*:
Himeda *et al.*, PRL (2002)
Berg *et al.*, PRL (2007)

P.A. Lee, PRX (2014)

Intertwined superconductivity
and antiferromagnetism

# Context

# Antiferromagnetic Insulator



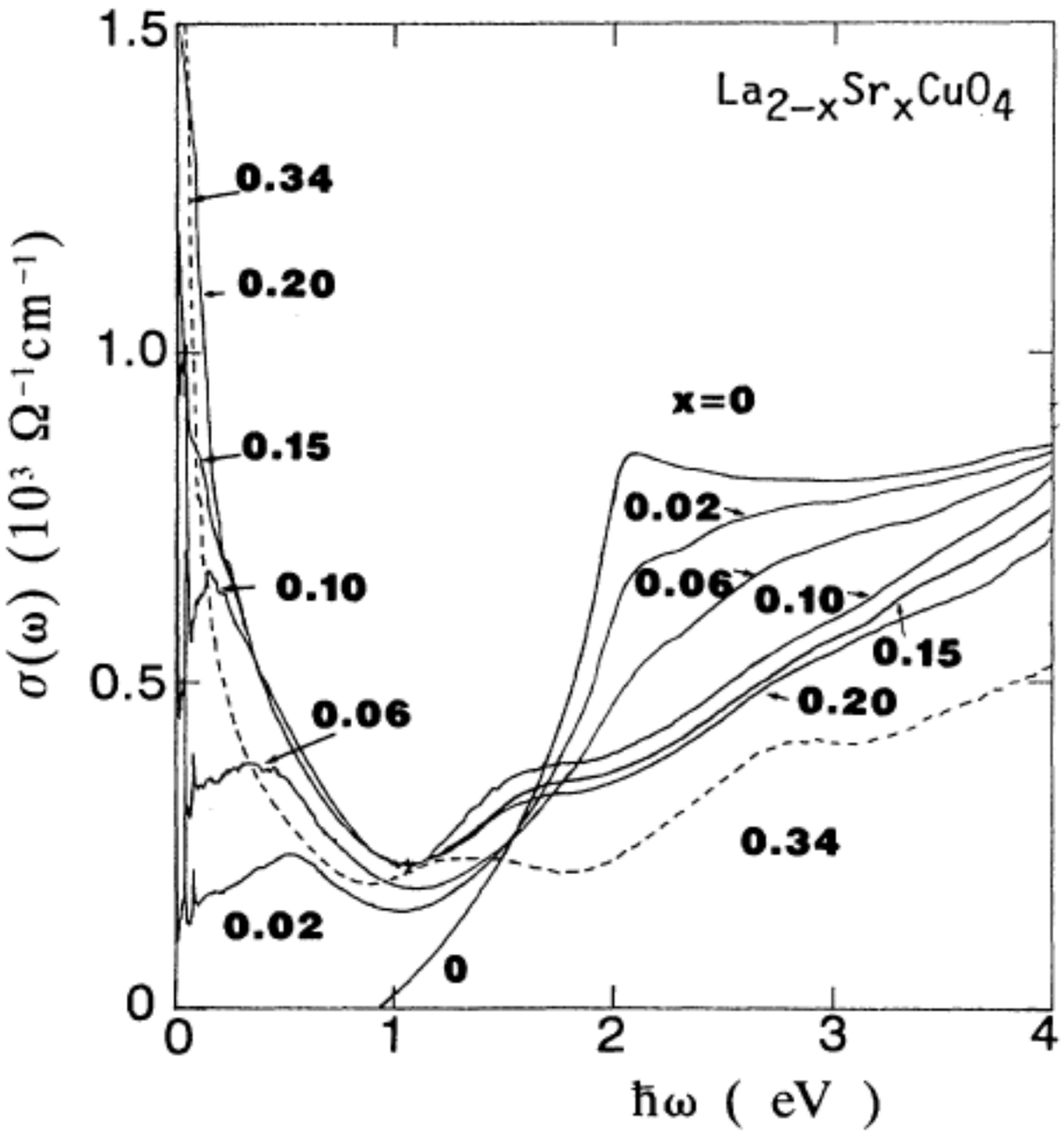
$-t$ $U$ $J = 4t^2/U$

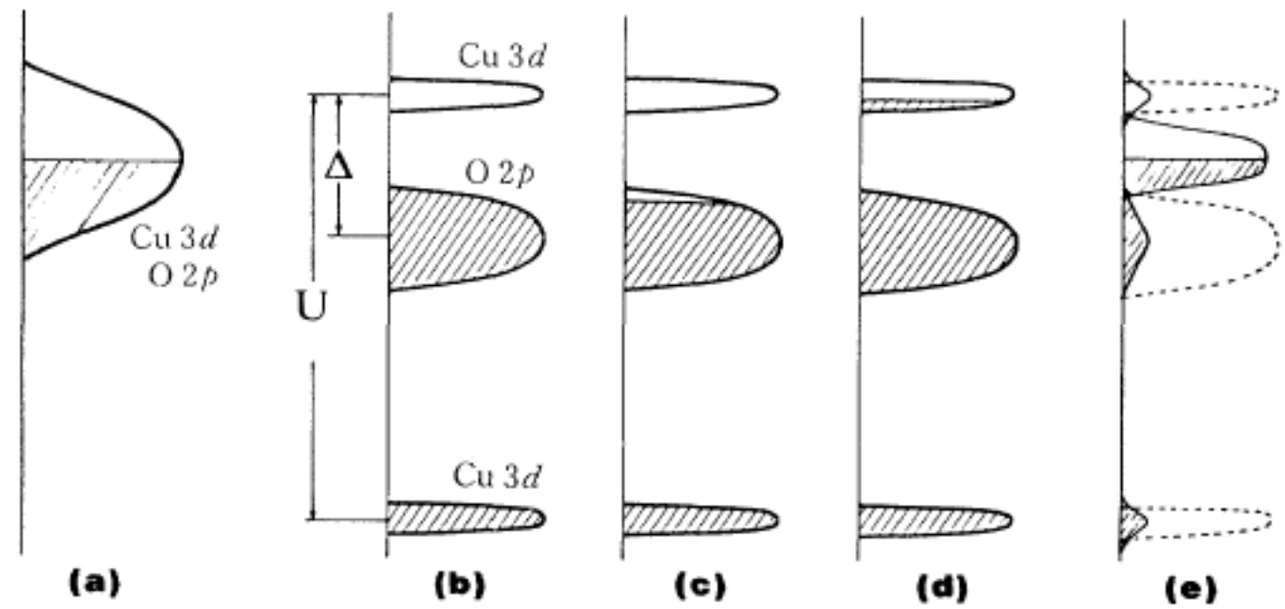
large U → localized electrons

t + Pauli excl. → AF spin alignment

superexchange: P.W. Anderson (1959)

# In-plane optical conductivity for $La_{2-x}Sr_xCuO_4$

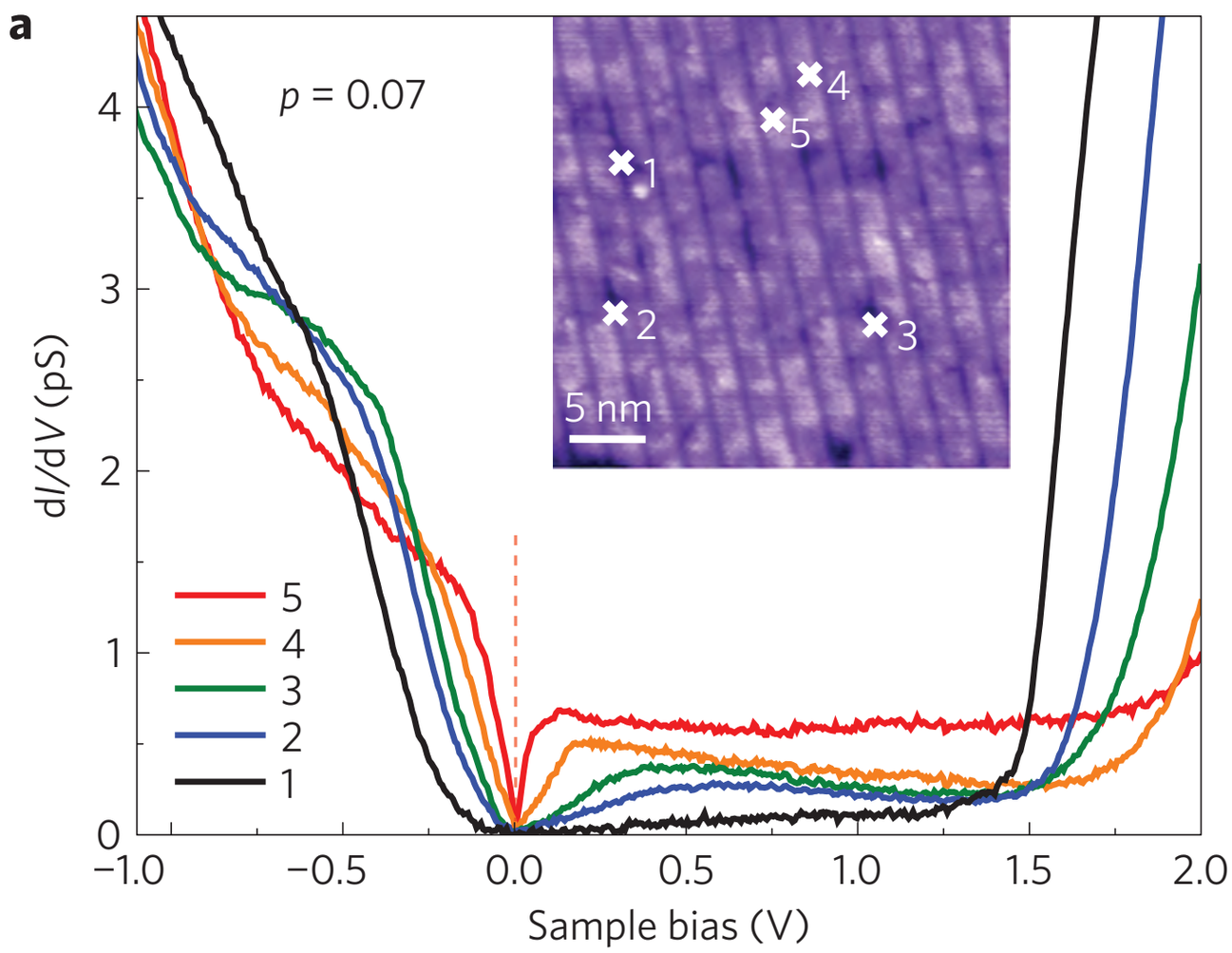


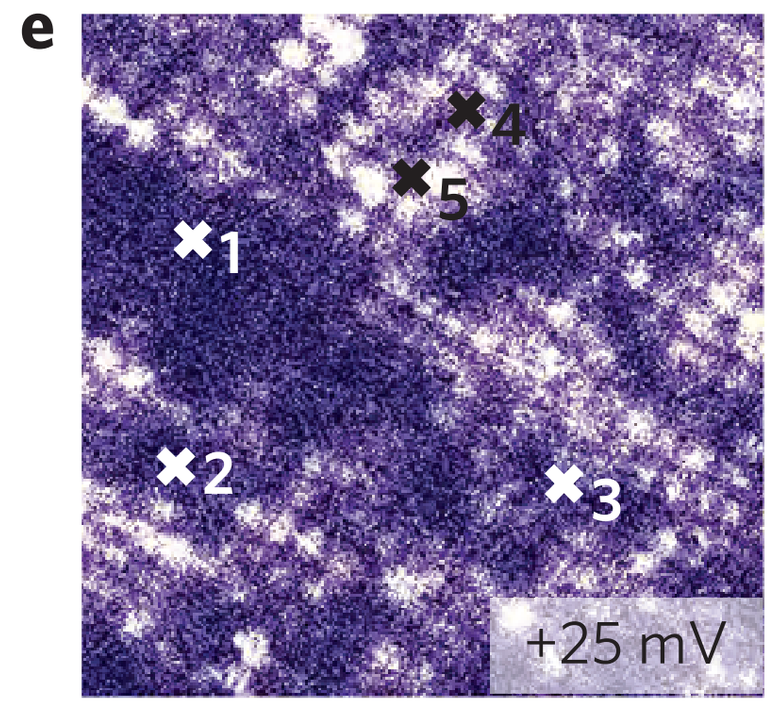




Uchida *et al.*, PRB (1991)

# STM on underdoped $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

p = 0.07, insulating

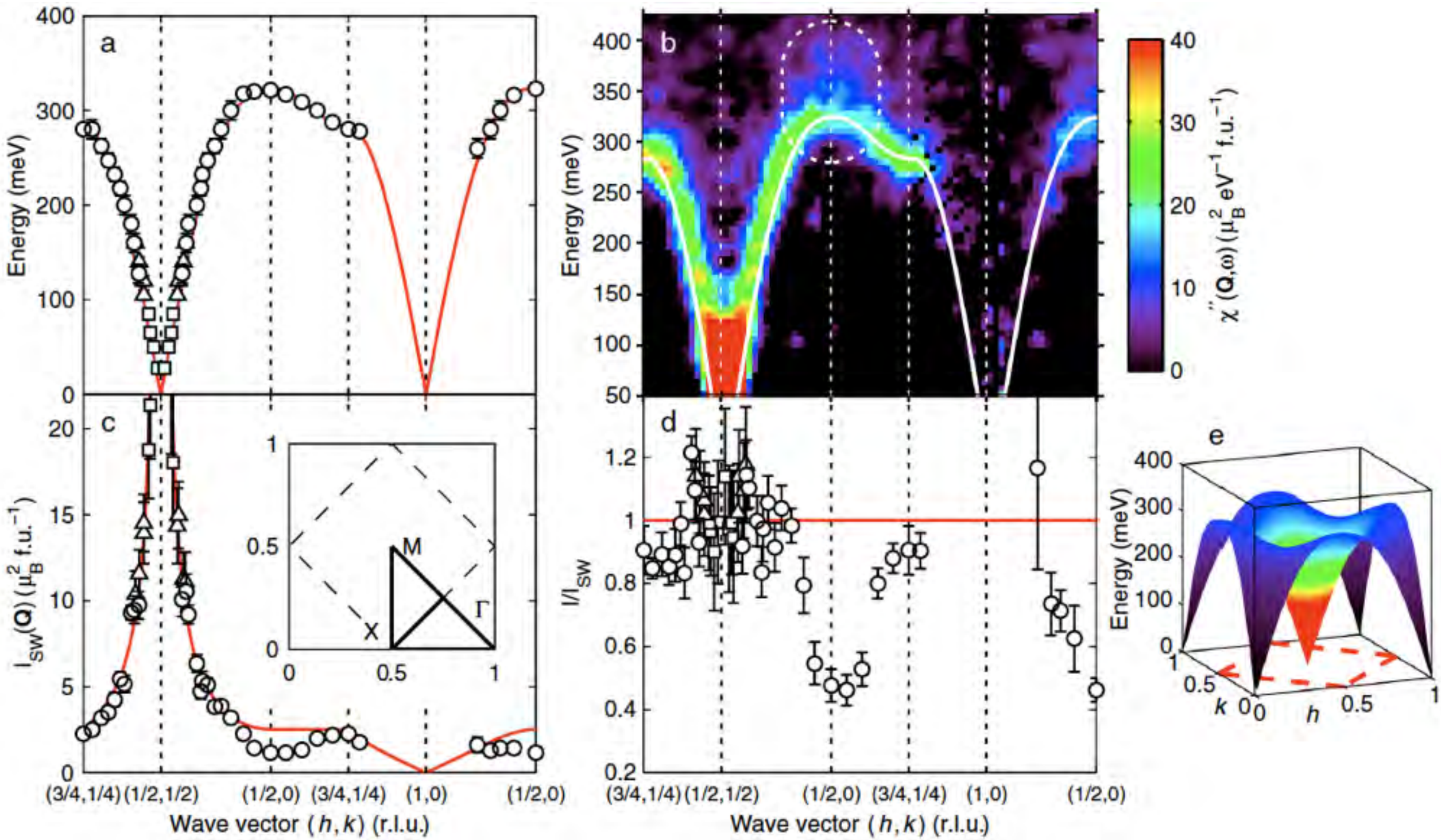



P. Cai *et al*., Nat. Phys. **12**, 1047 (2016)

# Spin waves in $La_2CuO_4$

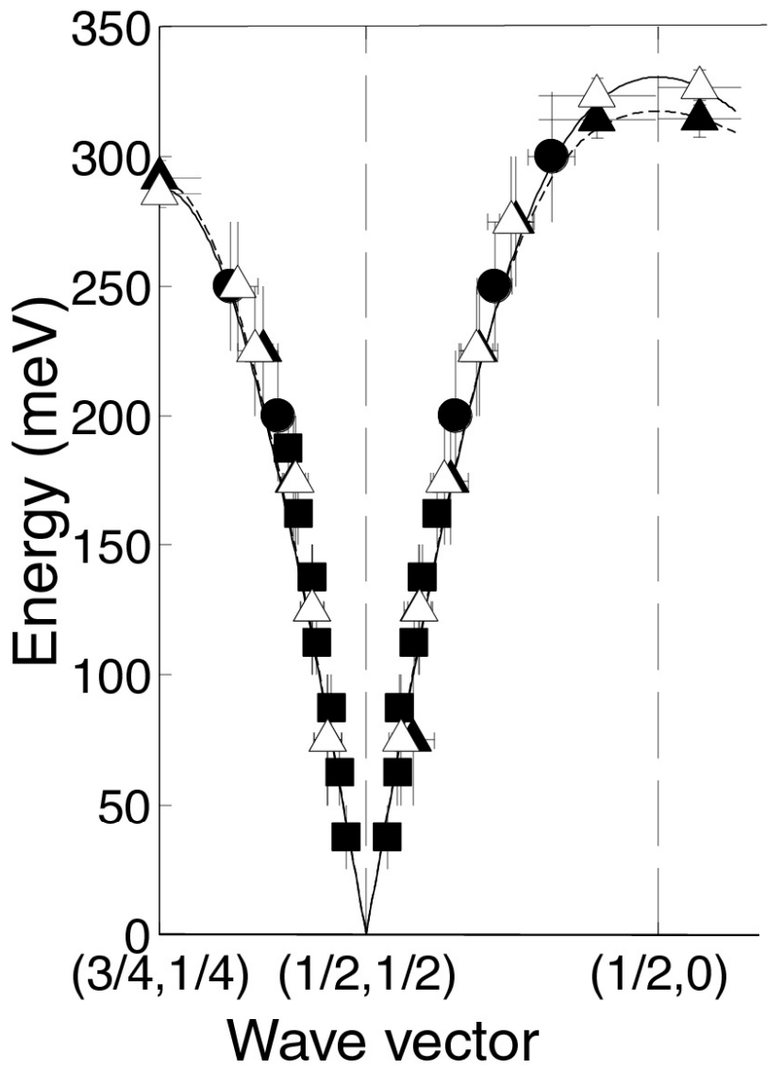
J = 145 meV




Headings *et al.*, PRL (2010)

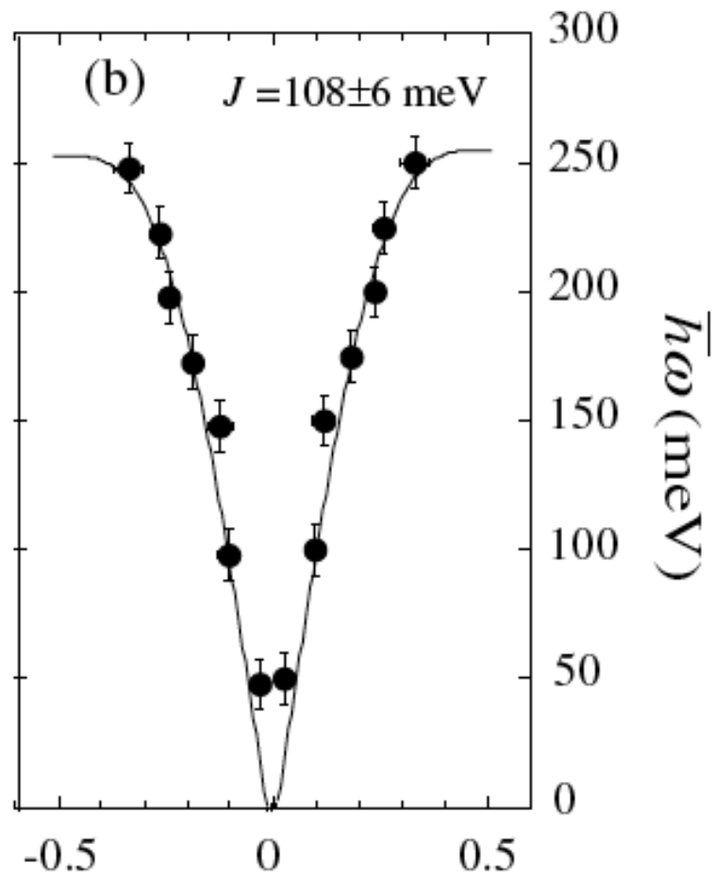
# Magnetic spectrum in $La_{2-x}(Sr,Ba)_xCuO_4$

x = 0



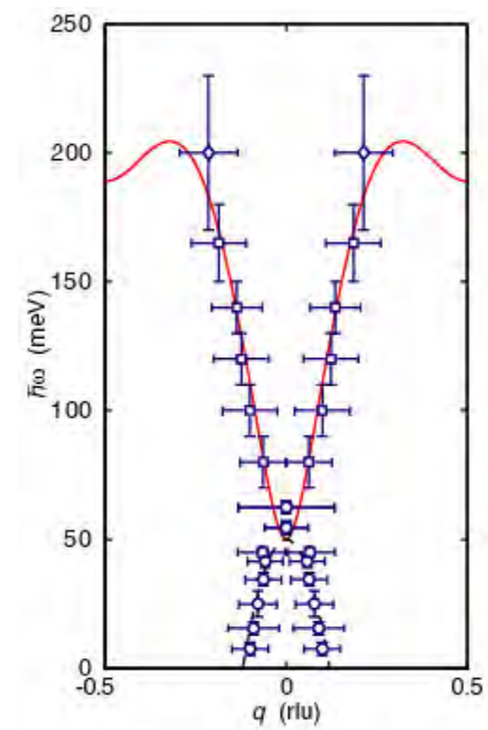

Coldea *et al.*, PRL (2001)

x = 0.05



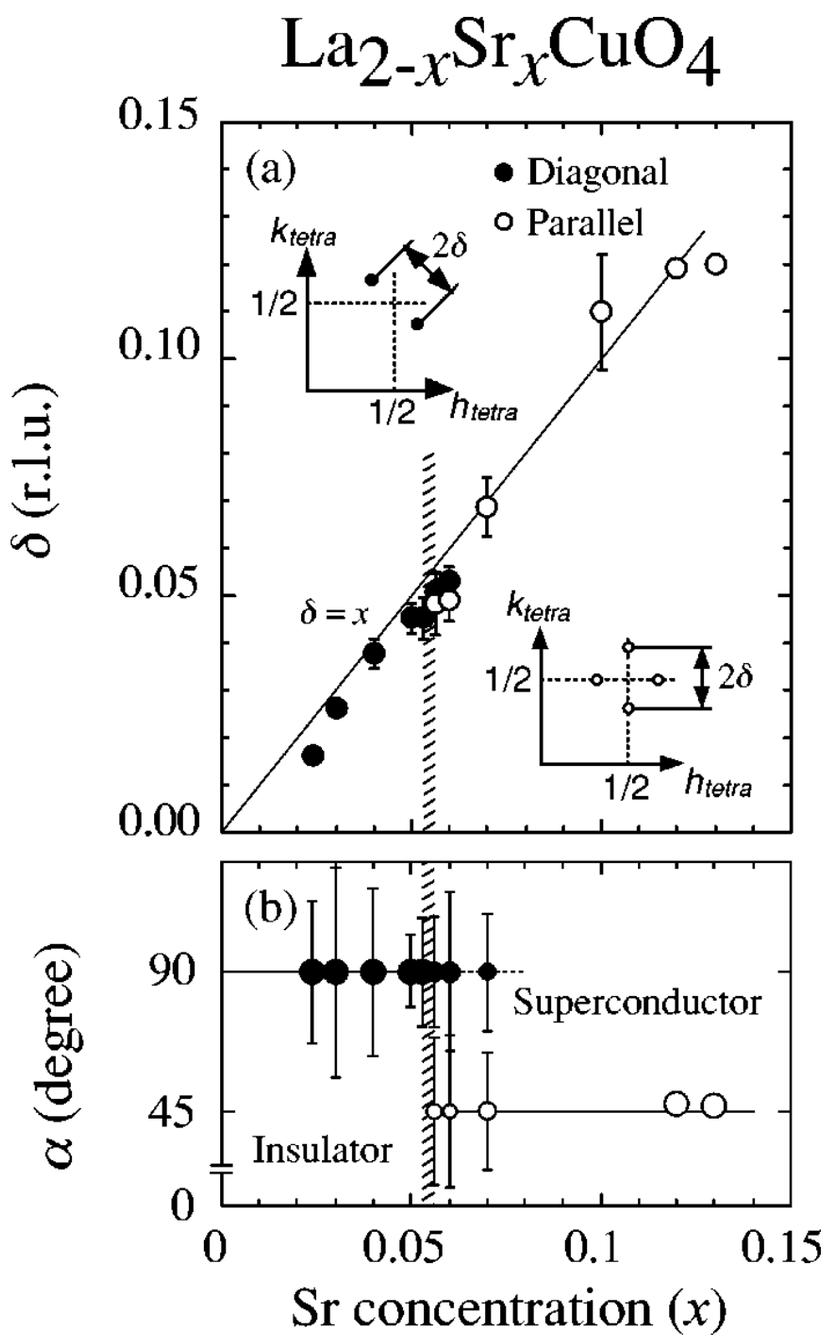

Goka *et al.*, Physica C (2003)

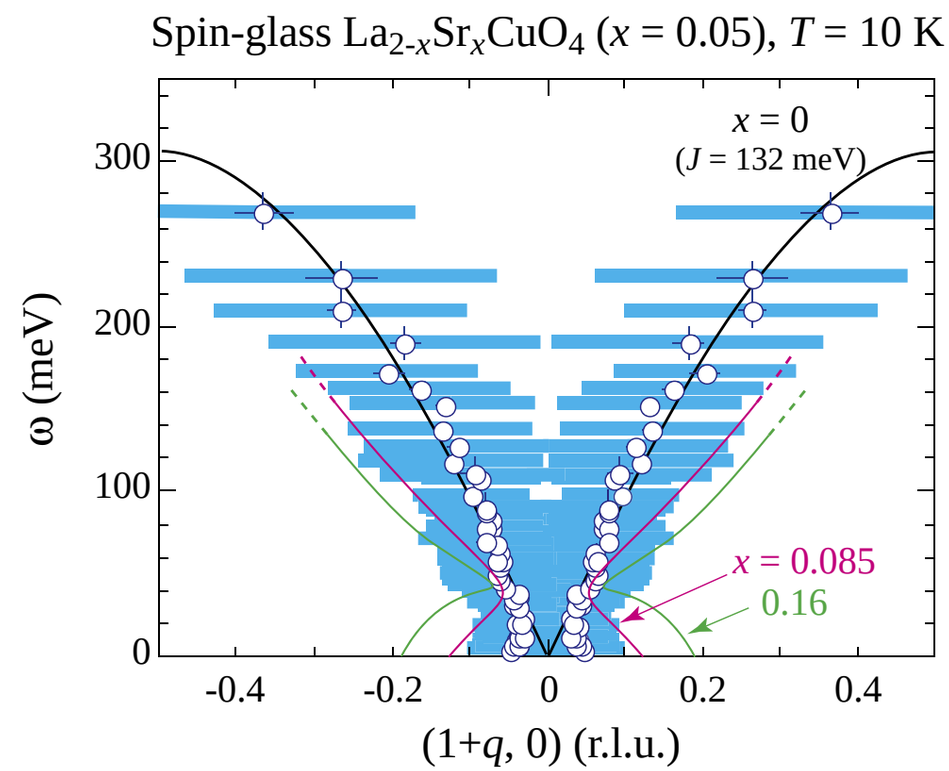
x = 0.125

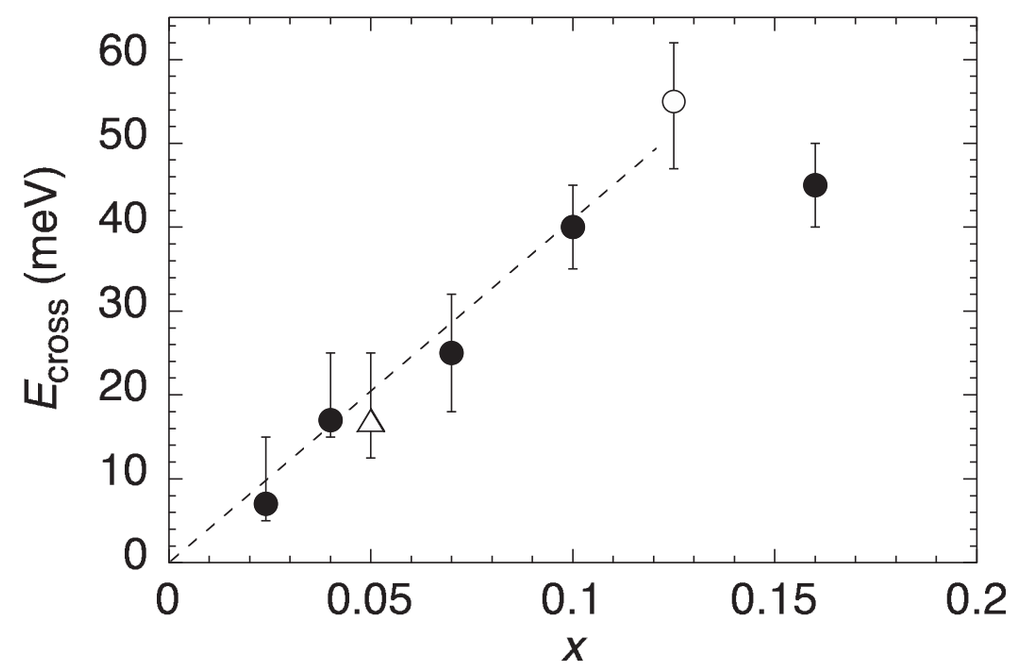



JMT *et al.*, Nature (2004)

# Doping dependence of IC and $E_{cross}$




M. Fujita *et al*., PRB **65**, 064505 (2002)

M. Fujita *et al*., JPSJ **81**, 011007 (2012)

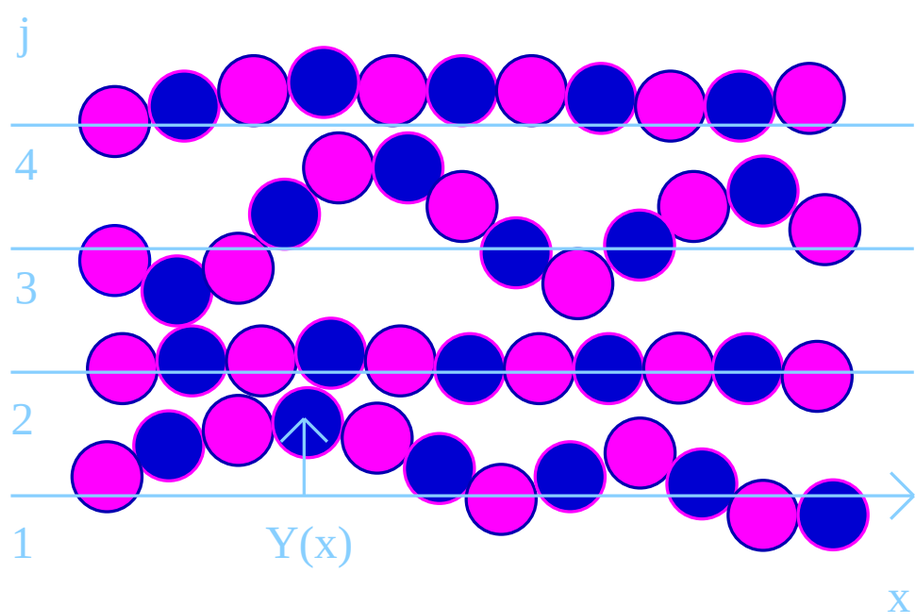
# Stripes and Superconductivity

# Charge Stripes: Superconductivity vs. CDW Order

- ✤ Treat each charge stripe as a 1D electron gas
- ✤ Interaction with the AF environment leads to pairing
- ✤ Josephson coupling between stripes gives SC order

Emery, Kivelson, Zachar, PRB **56**, 6120 (1997)

✤ 1D electron gas: CDW competes with pairing

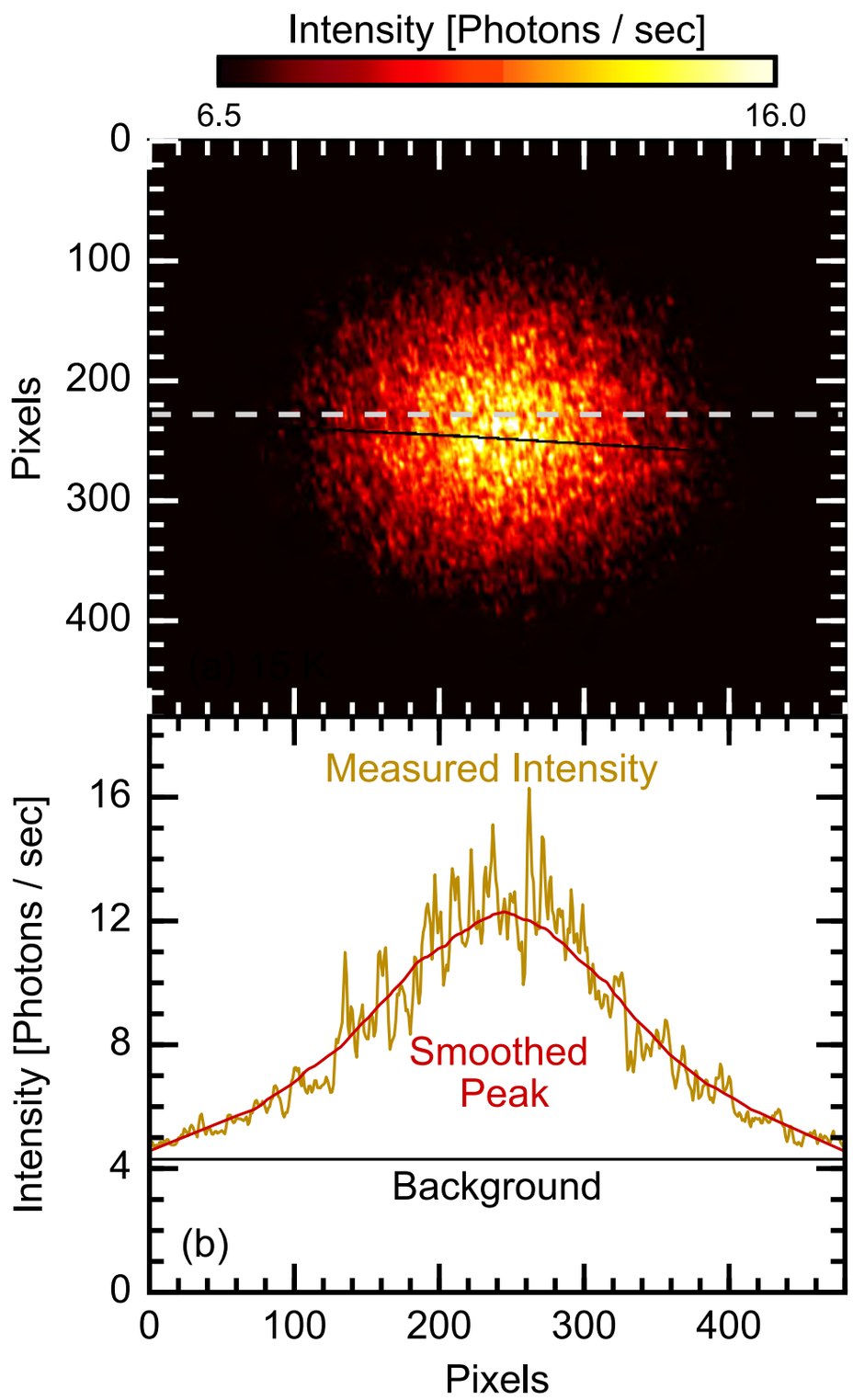



Electronic liquid crystal phases:

fluctuations suppress CDW order

Kivelson, Fradkin, Emery, Nature **393**, 550 (1998)

# Charge stripes in LBCO do not fluctuate




LBCO x=1/8

Coherent soft-x-ray scattering resonant at Cu $L_3$ edge

Speckle pattern does not change with time

X. Chen *et al.*, PRL **117**, 167001 (2016)

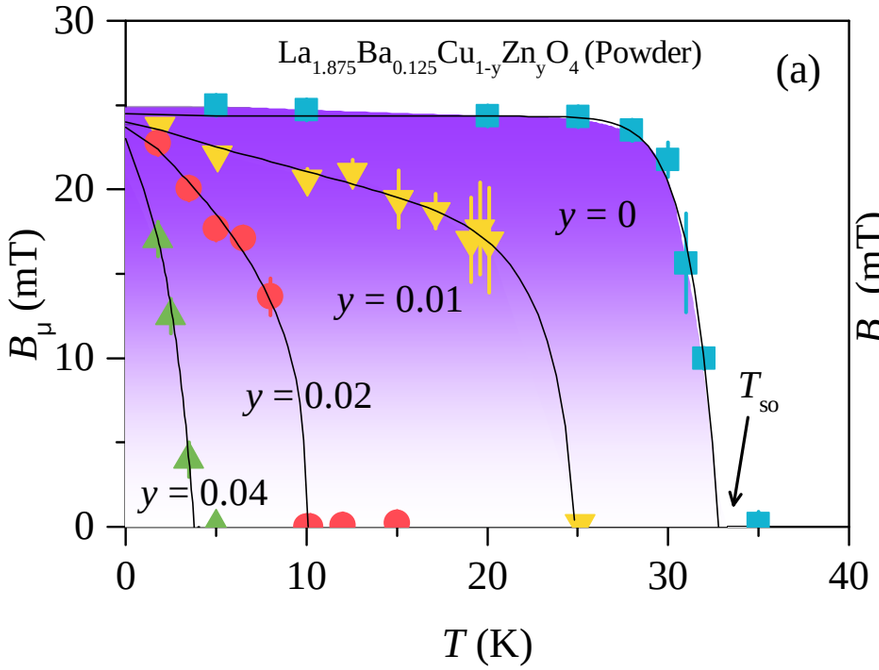
LBCO x = 0.11, $T_c$ = 22 K
measurements down to 10 K

V. Thampy *et al.*, PRB **95**, 241111(R) (2017)

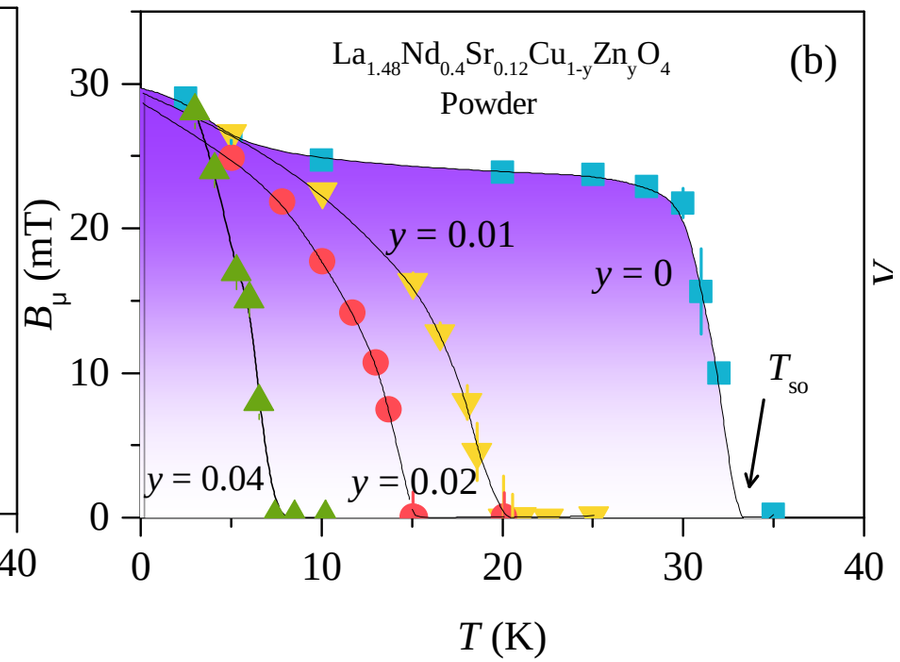
Measured on CSX beam line at NSLS II

# Same sensitivity of spin and SC orders to Zn

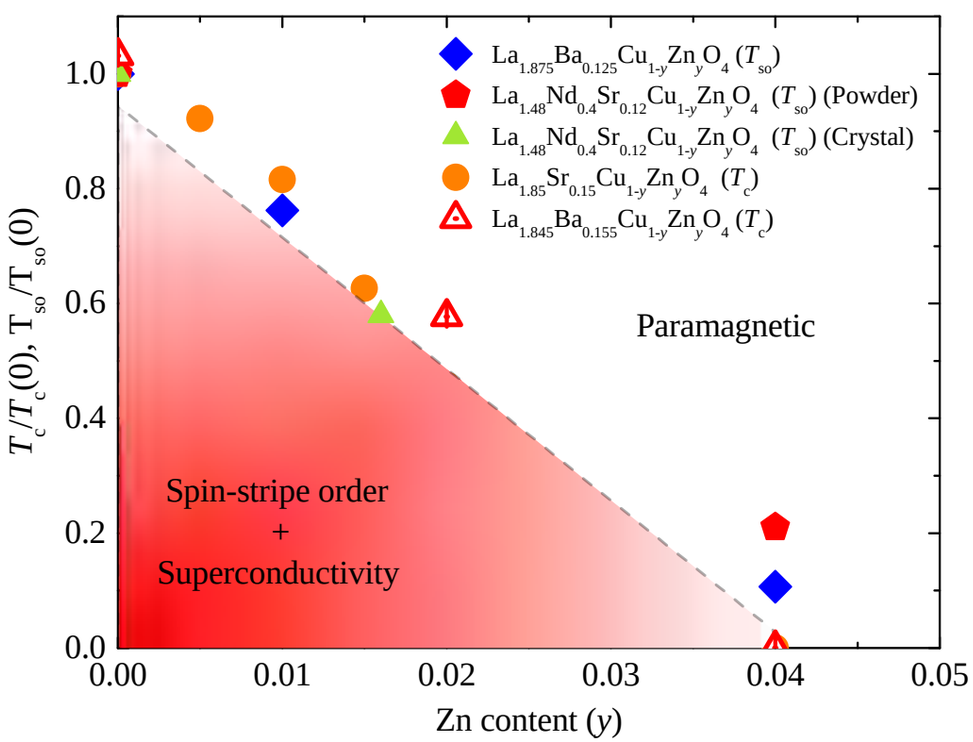
LBCO x=1/8 + Zn




LNSCO x=1/8 + Zn

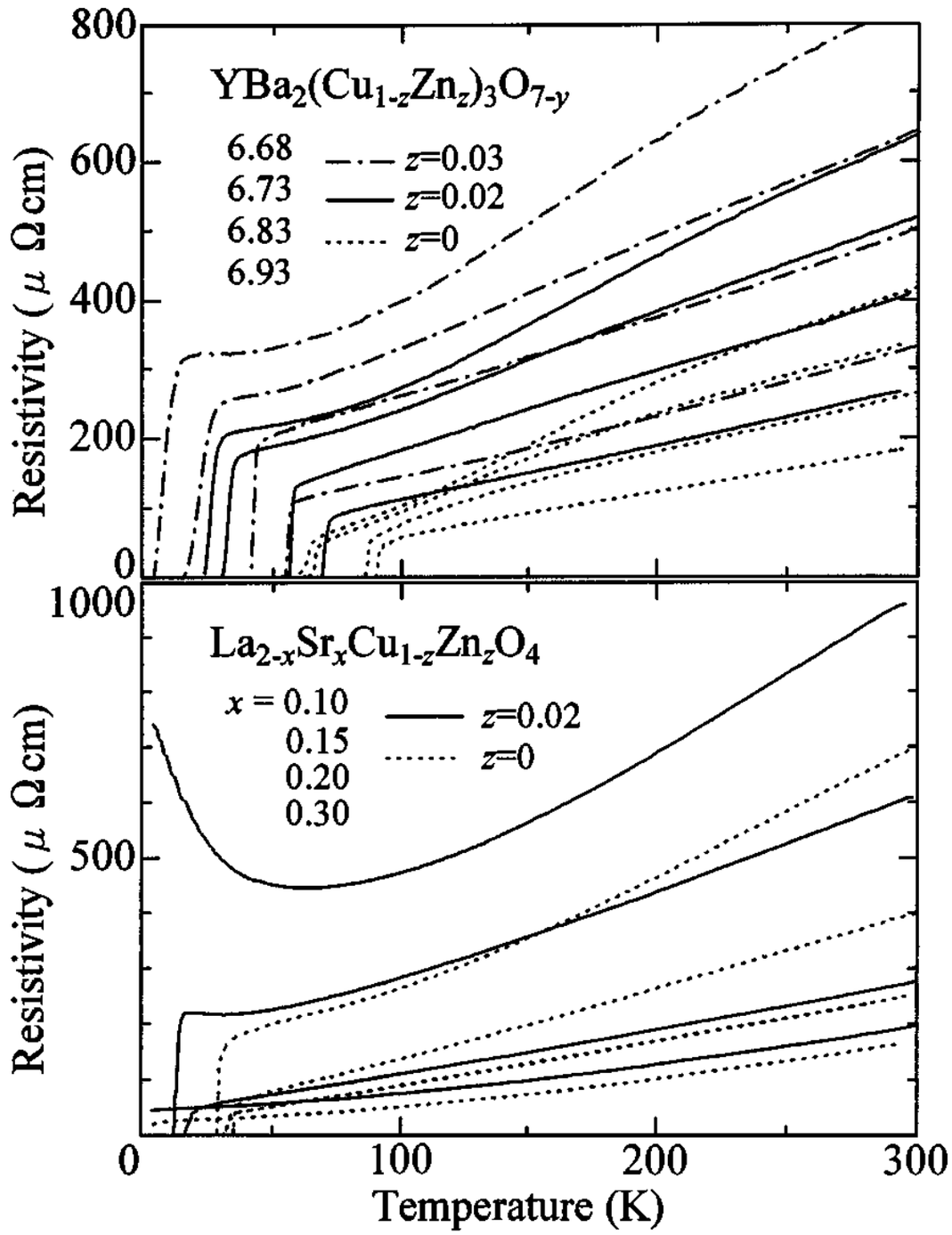



Internal field measured by μSR

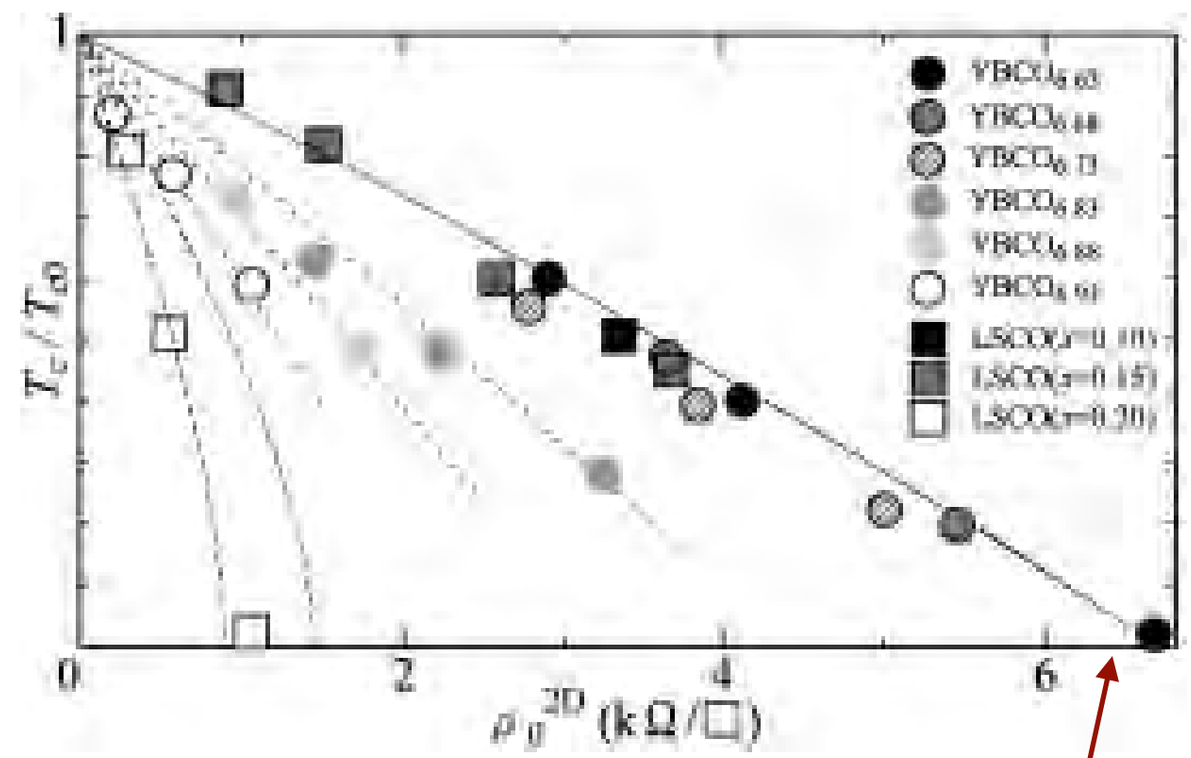



Z. Guguchia *et al.*, PRL (2017)

# Zn-doping localizes pairs




Localization, not breaking, of pairs



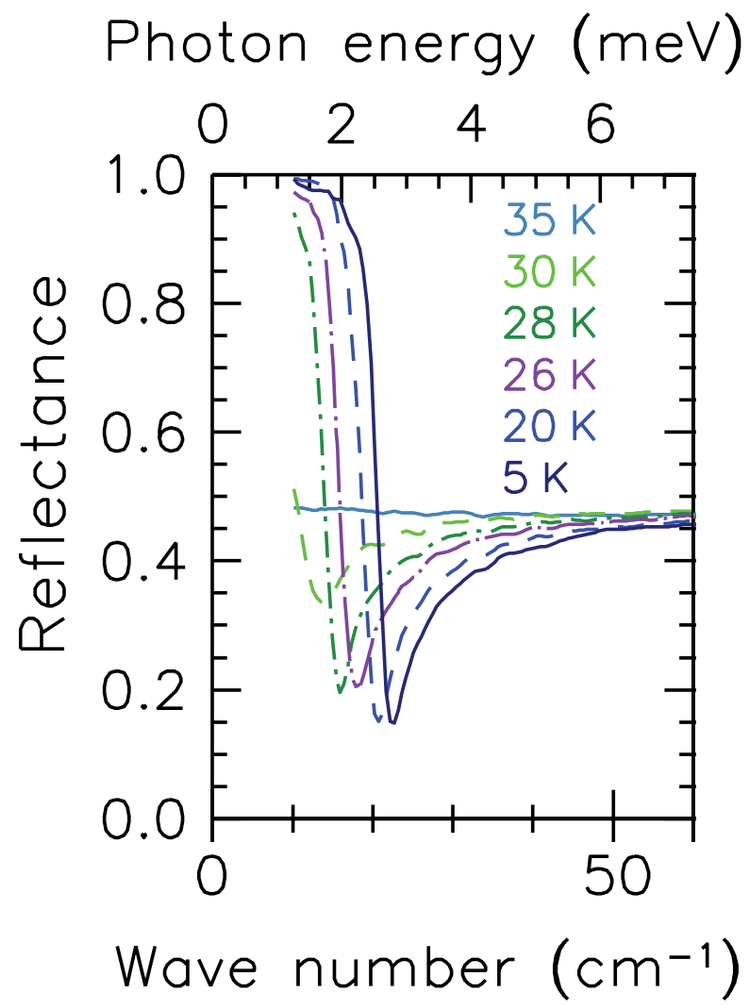

h/4e$^2$
quantum of resistance
for electron pairs

Y. Fukuzumi *et al*., PRL **76**, 684 (1996)

# Evidence for Josephson coupling between stripes?

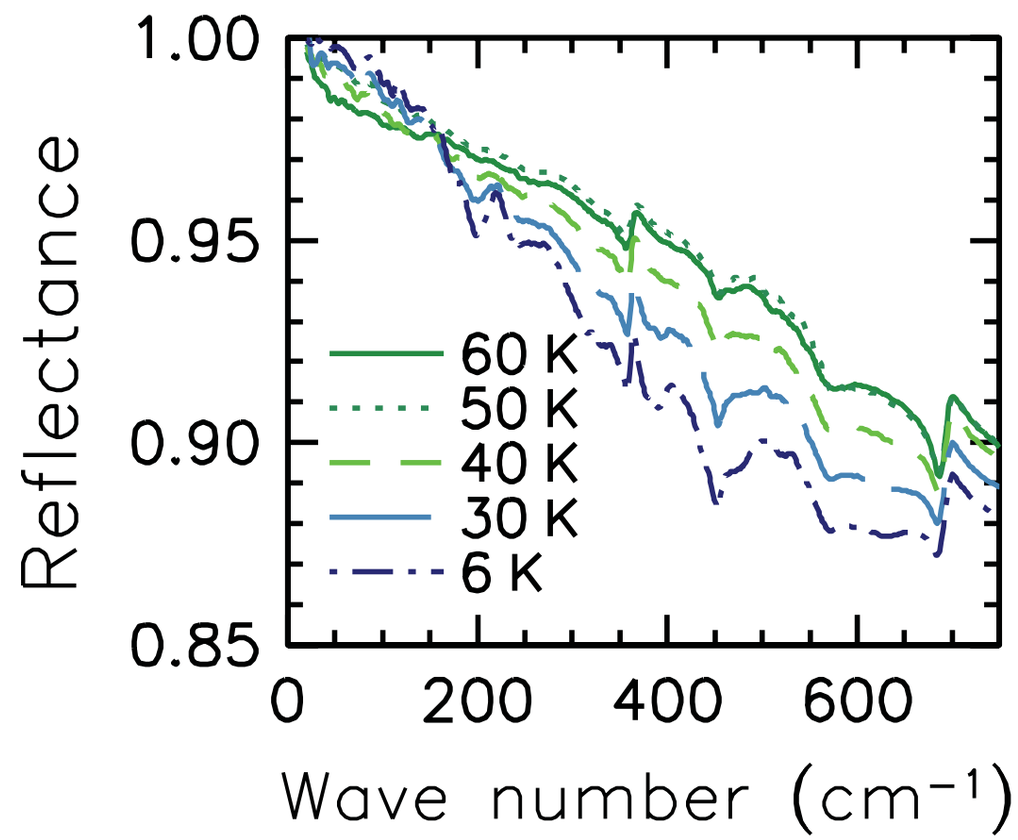
# Josephson plasma resonance

LBCO x = 0.095
c-axis reflectance




Evidence for pair transport between planes

LBCO x = 0.125
in-plane reflectance

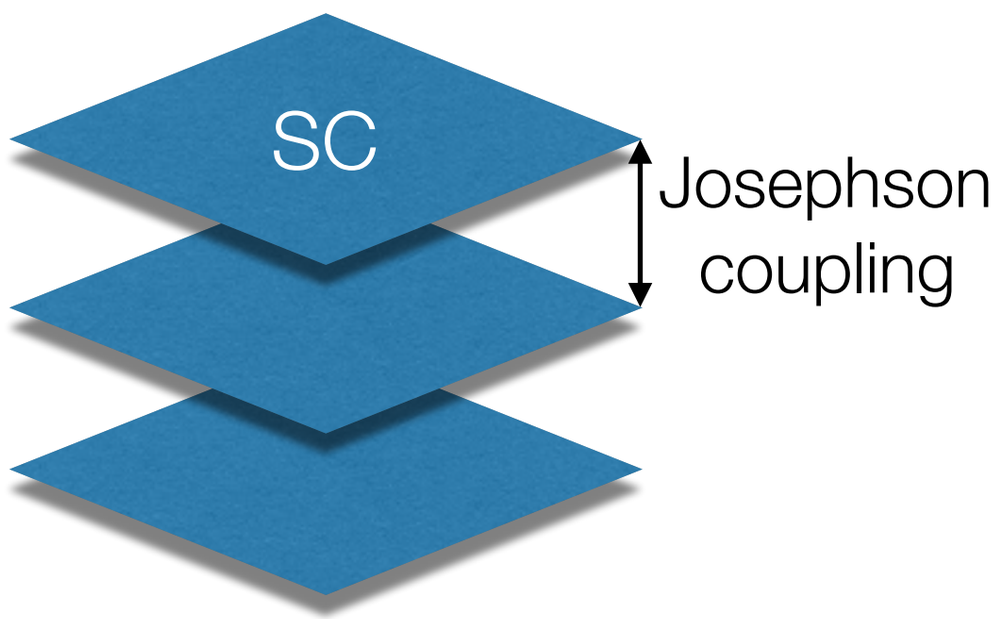



Evidence for pair transport between charge stripes

Homes *et al.*, PRB (2012)

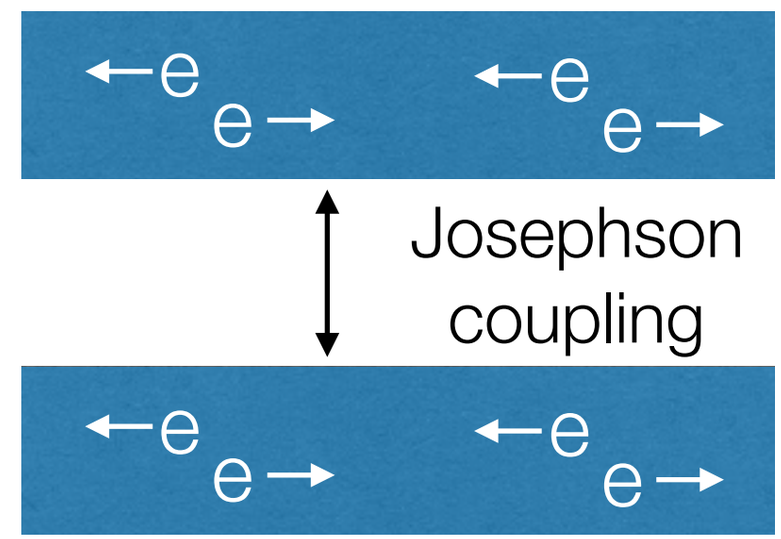
# Analogous models

3D




Josephson coupling
provides SC phase order

2D

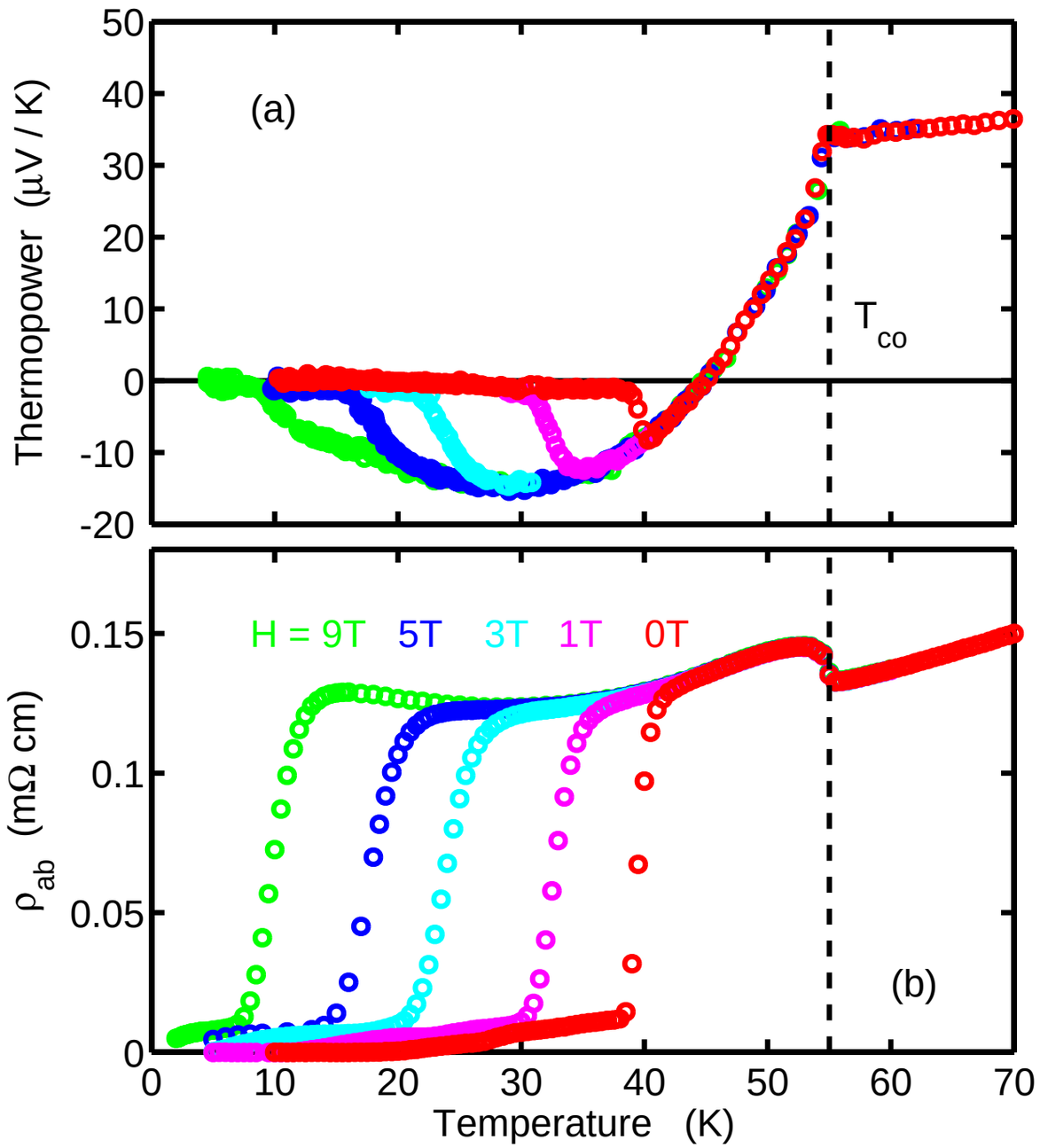


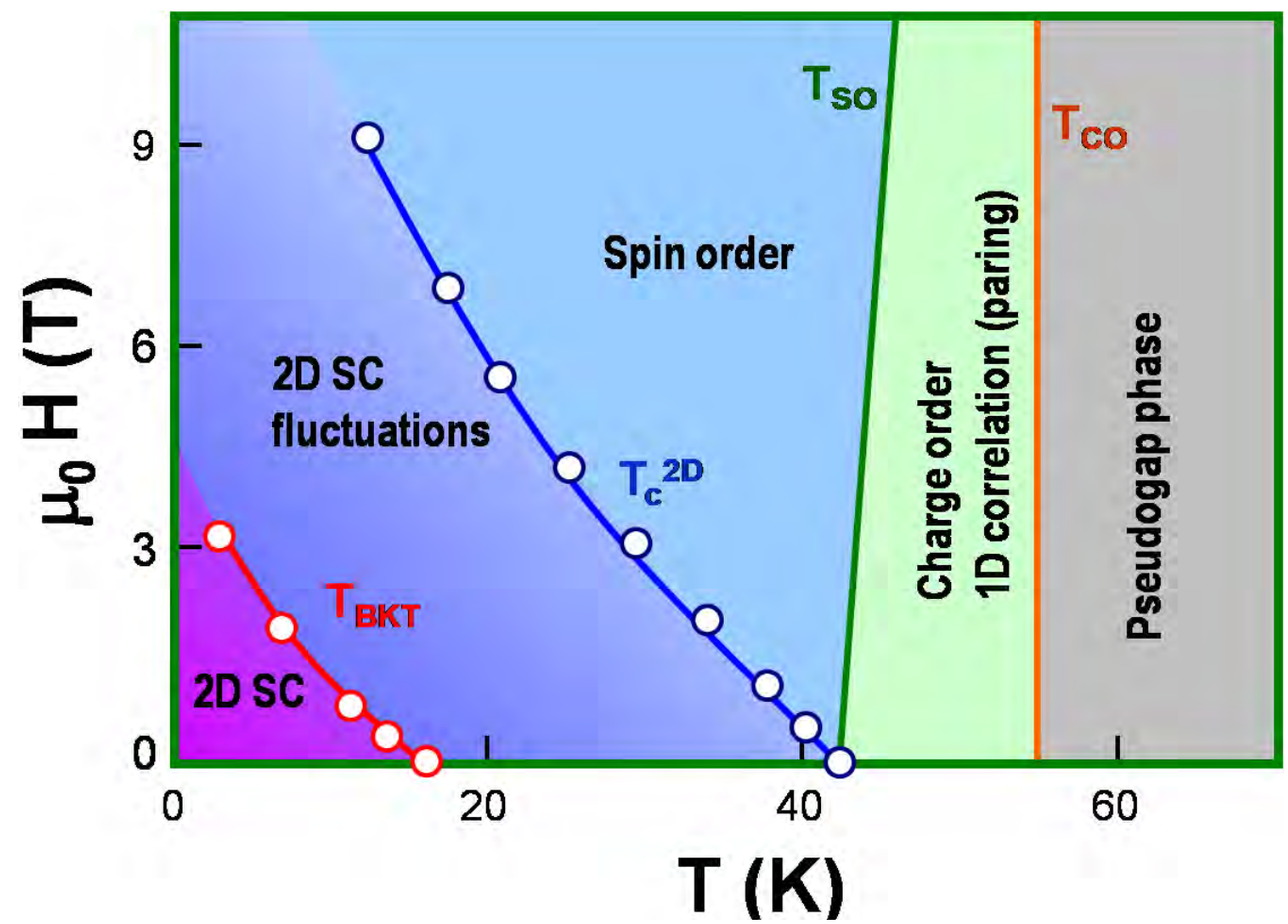

with coupling: PDW

without coupling: CDW
(of incoherent Cooper pairs)

CDW and PDW
compete with uniform SC

# LBCO x = 1/8



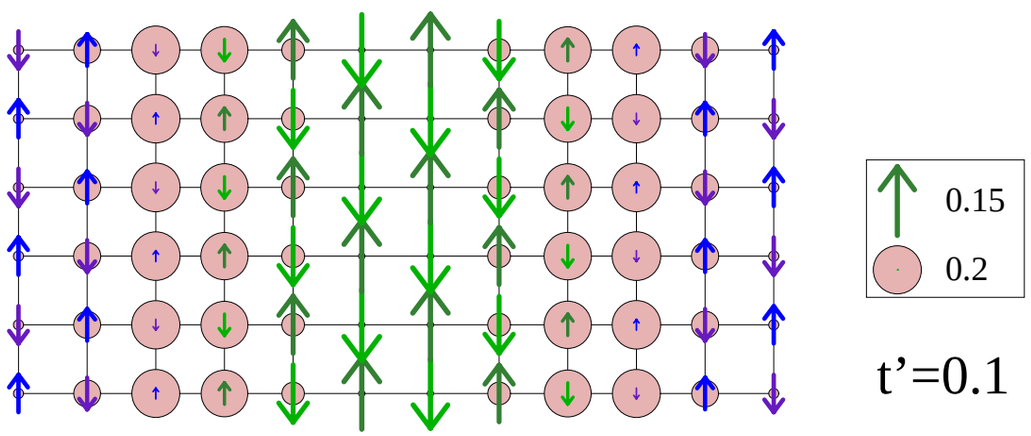




Q. Li *et al.*, PRL (2007)

Do numerical calculations support superconducting stripes?

# Charge stripes found in numerical calculations

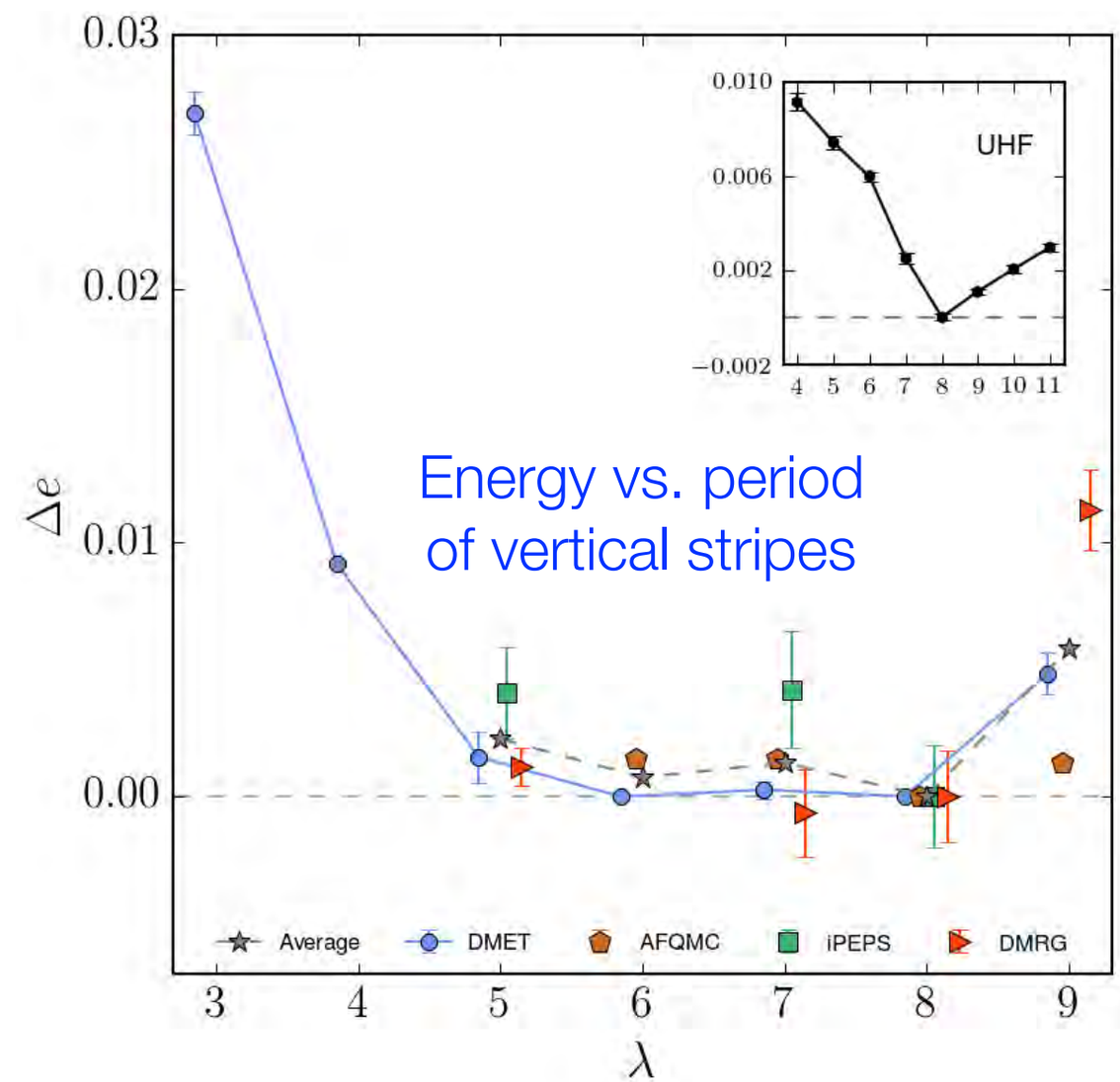
Density Matrix Renormalization Group




t-t'-J model, J/t = 0.5, 8 holes
half-filled stripes

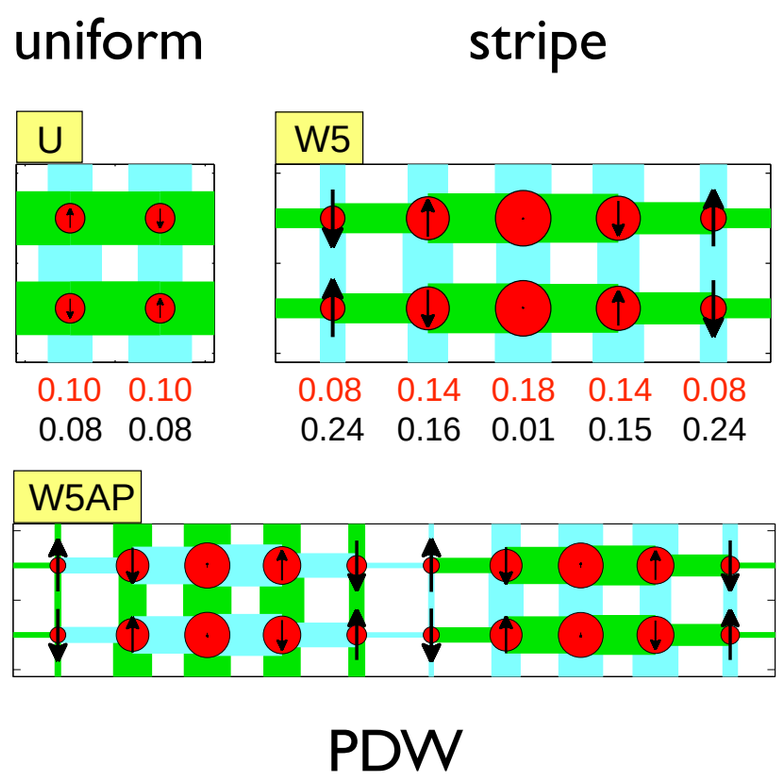
White+Scalapino, PRB (1999)

Comparison of 4 techniques
on the Hubbard model
with U/t = 8




B.X. Zheng *et al.*, arXiv:1701:00054

# In t-J model, charge stripes show SC



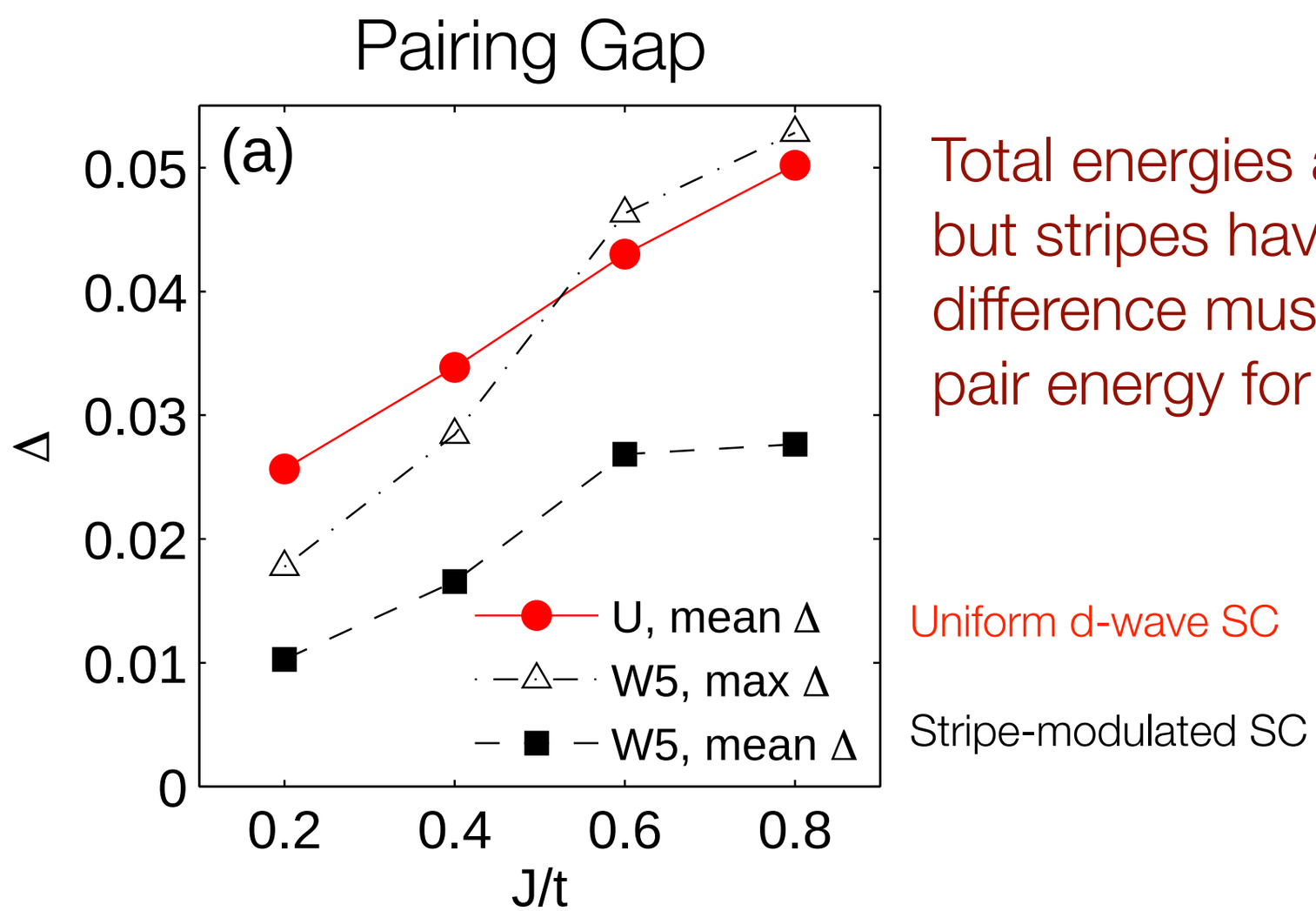

All of these states have very similar energies

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

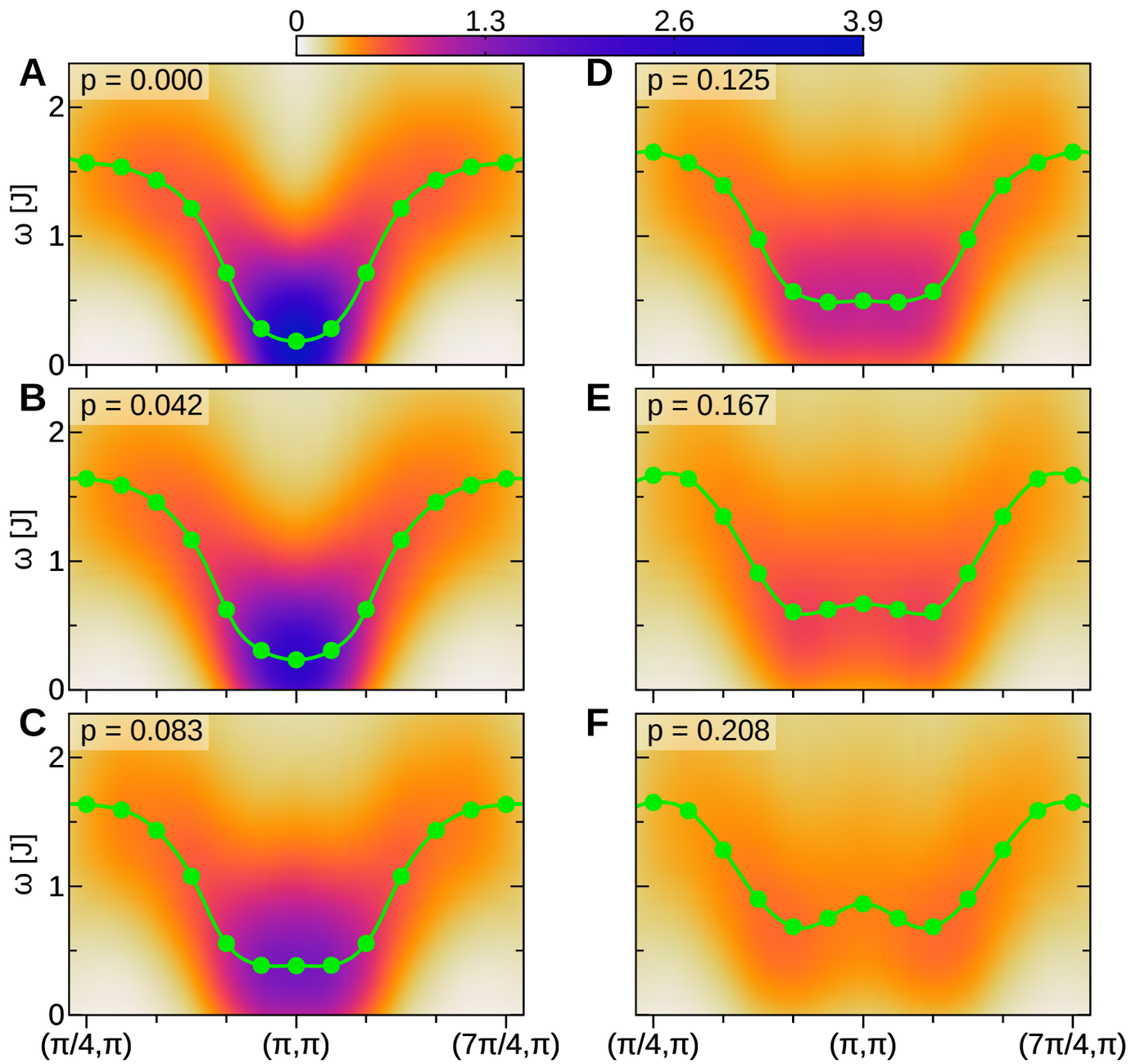
# Equivalence of spin and pairing energies




Total energies are ~ the same,
but stripes have lower average pair energy;
difference must come from trading
pair energy for exchange energy

Corboz *et al.*, PRL (2014)

# Spin dynamics in 3-band Hubbard model




Determinant QMC calculations

T ~ 1000 K

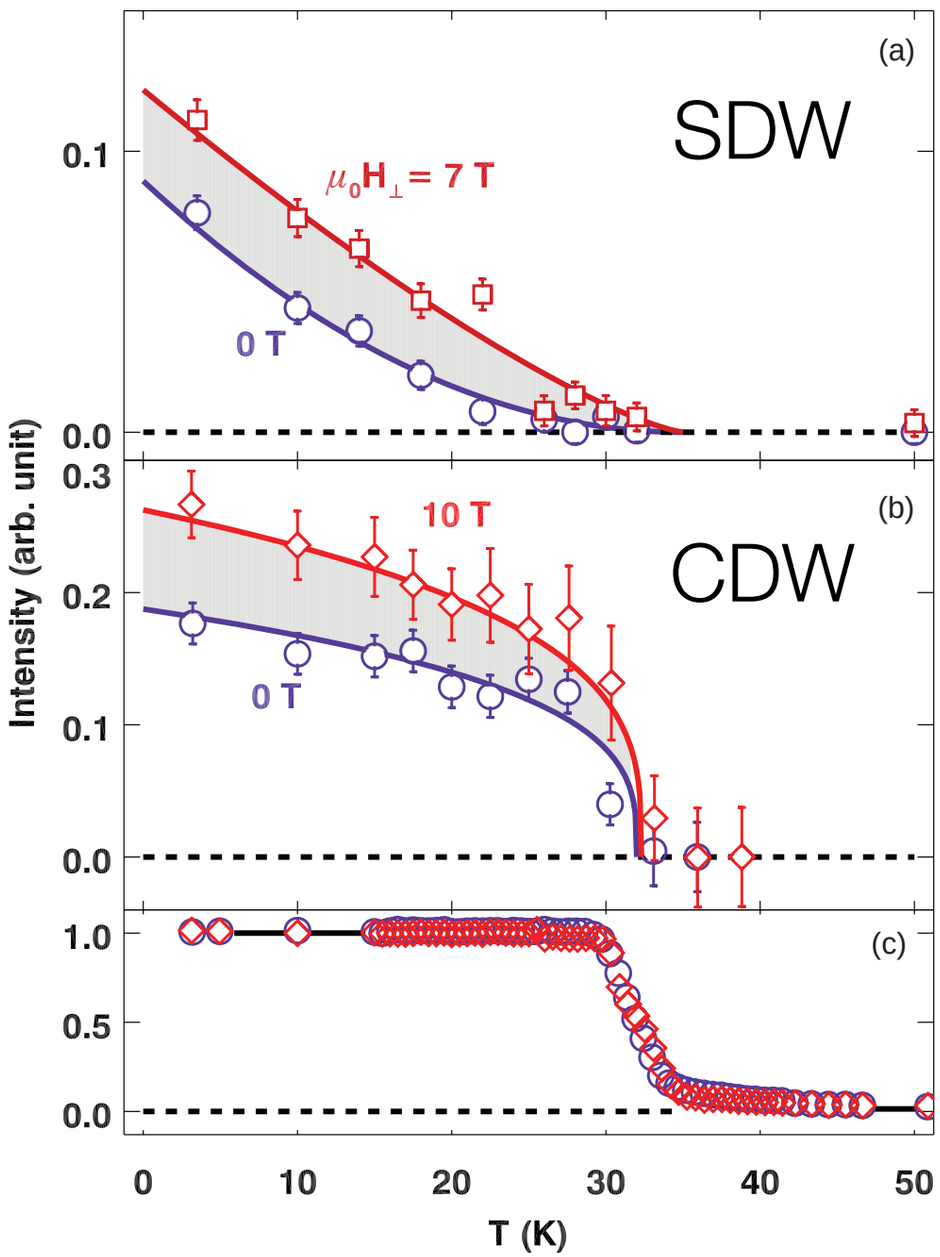
(limited by sign problem)

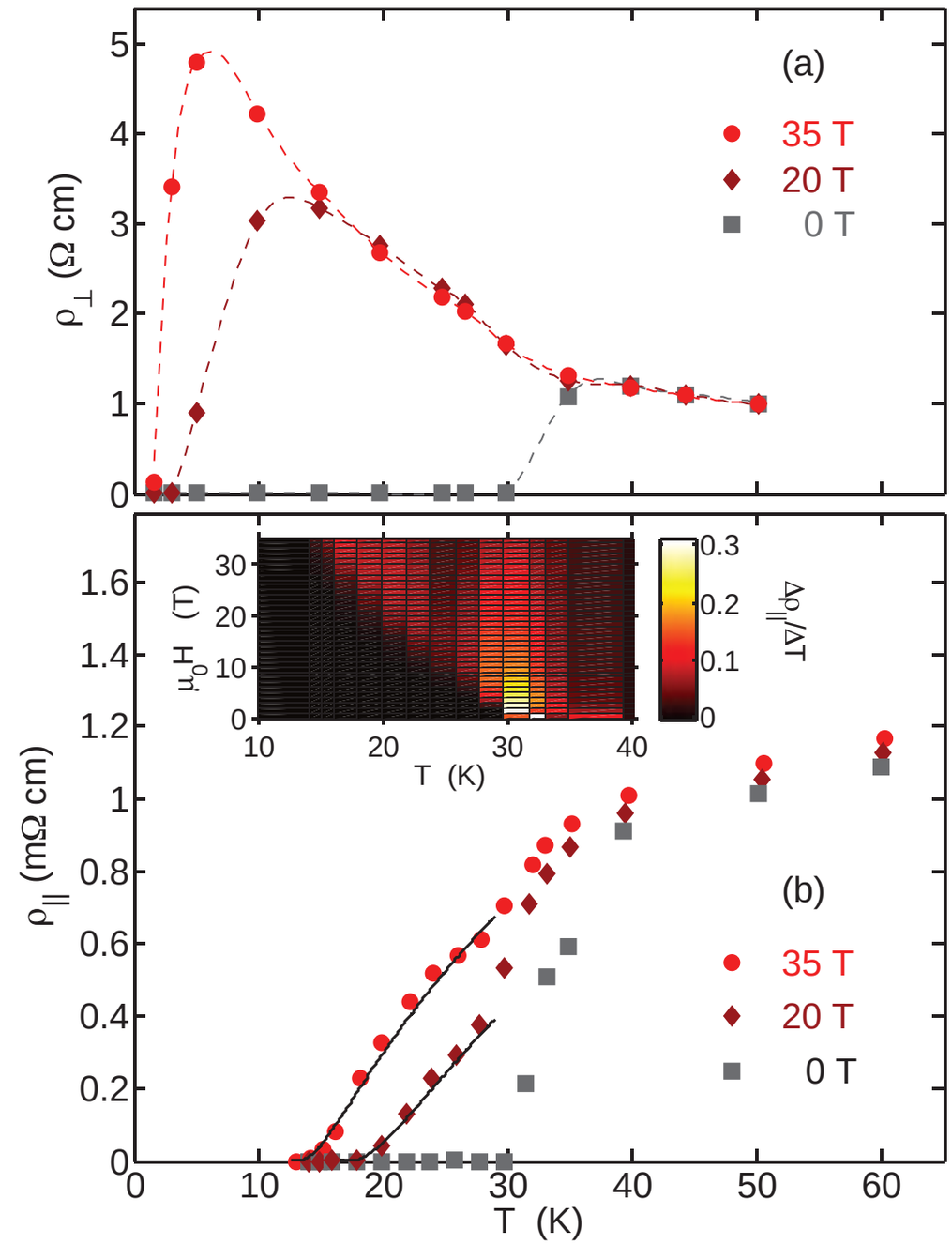
Huang *et al.*, arXiv:1612.05211

# Does the PDW exist away from $x = 1/8$?

# Related behavior in LBCO x = 0.095

H || c enhances CDW, decouples layers, but 2D SC survives



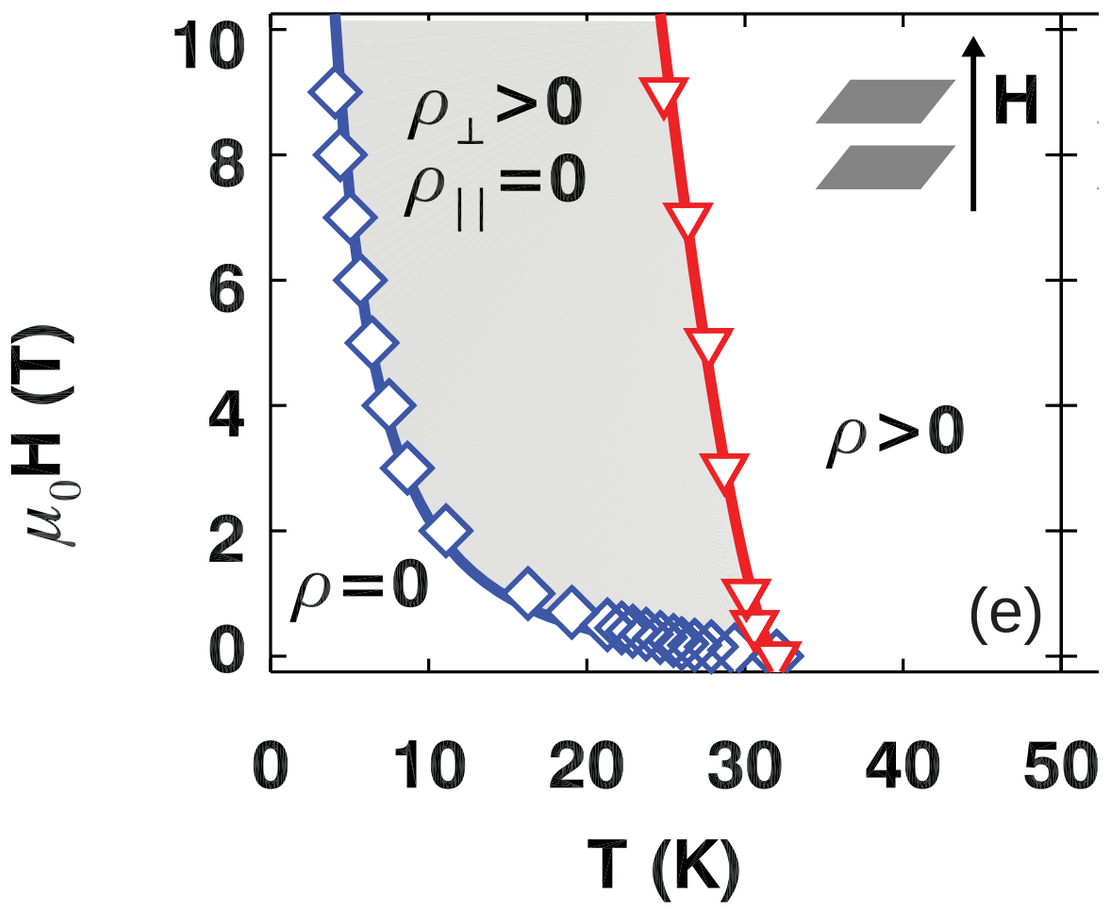

Wen *et al.*, PRB (2012)

Stegen *et al.*, PRB (2013)

# Superconducting planes decoupled by H || c

LBCO x = 0.095

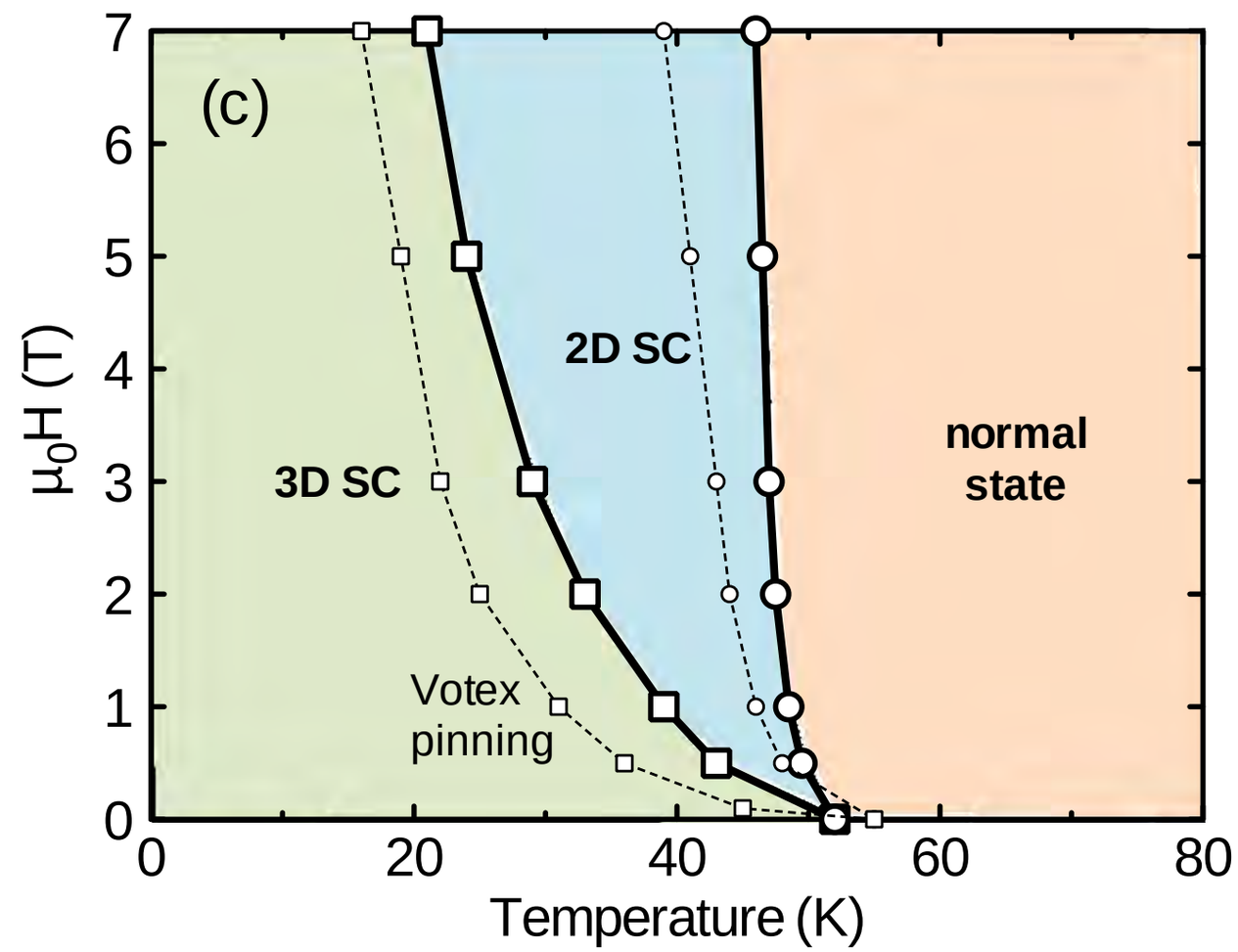
$T_c$ = 32 K




Wen *et al*., PRB (2012)

$La_{1.9}Ca_{1.1}Cu_2O_6$

$T_c$ = 54 K

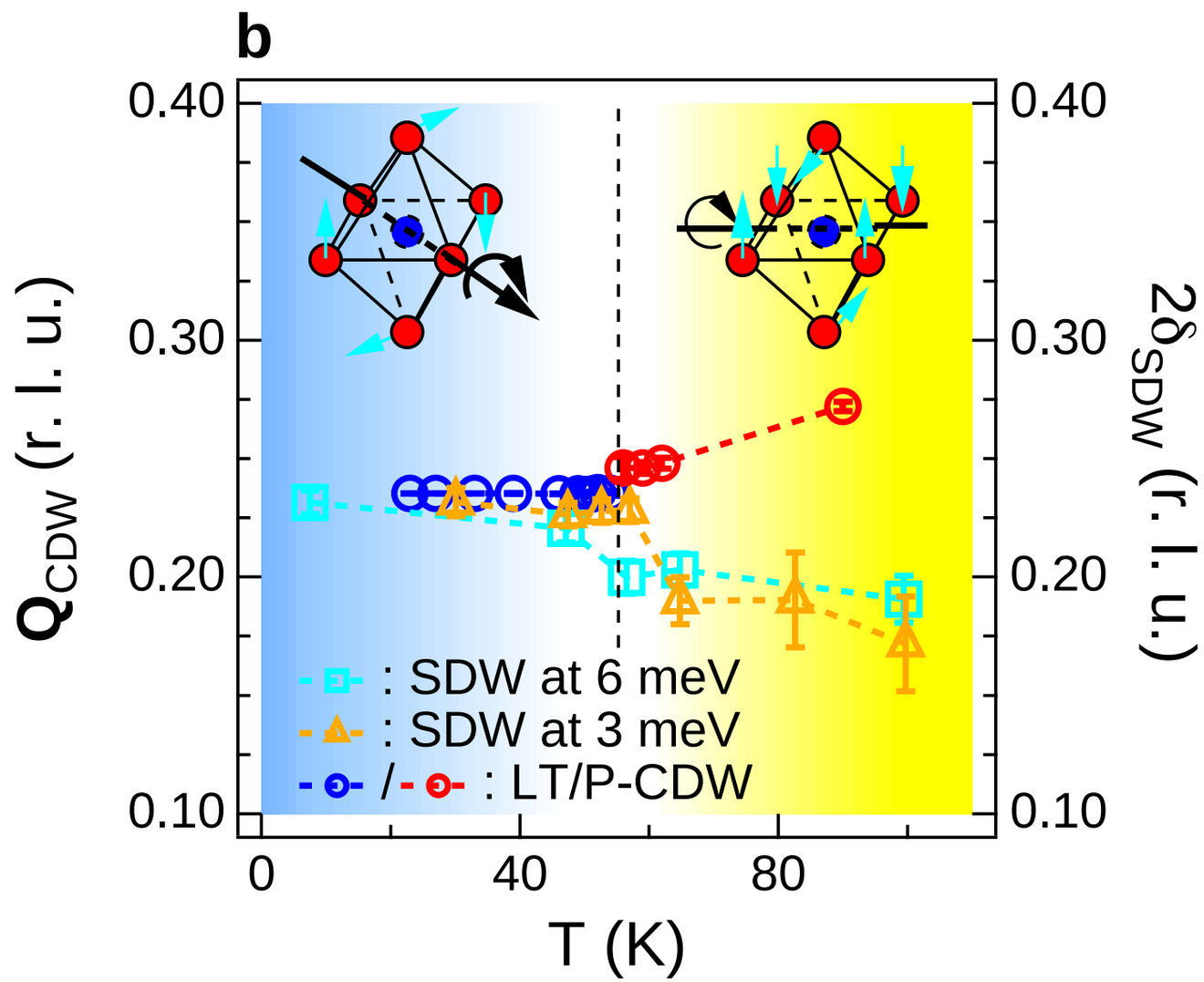



R. Zhong *et al*., unpublished

Are the CDW and SDW wave vectors always locked at $Q_{CDW} = 2Q_{SDW}$ ?

# LBCO: Fluctuating CDW and SDW

LBCO x = 1/8

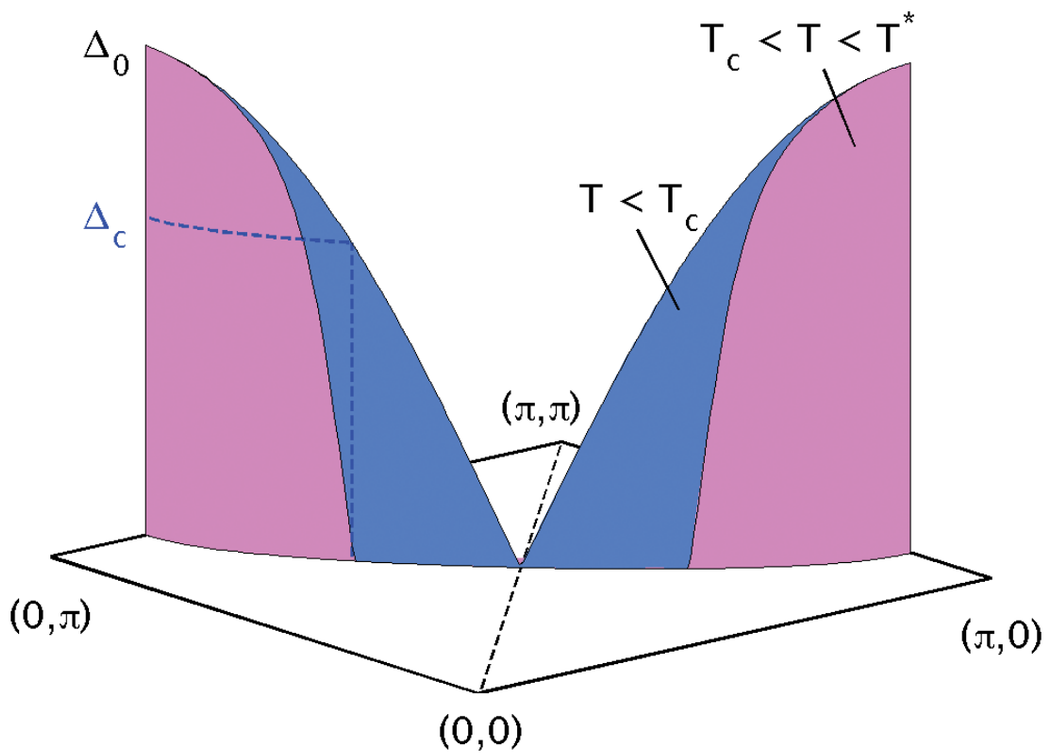



CDW correlations measured on ERIXS at ESRF

H. Miao *et al.*, arXiv:1701.00022

# Can the PDW gap be detected?

# PDW vs. d-wave SC gap

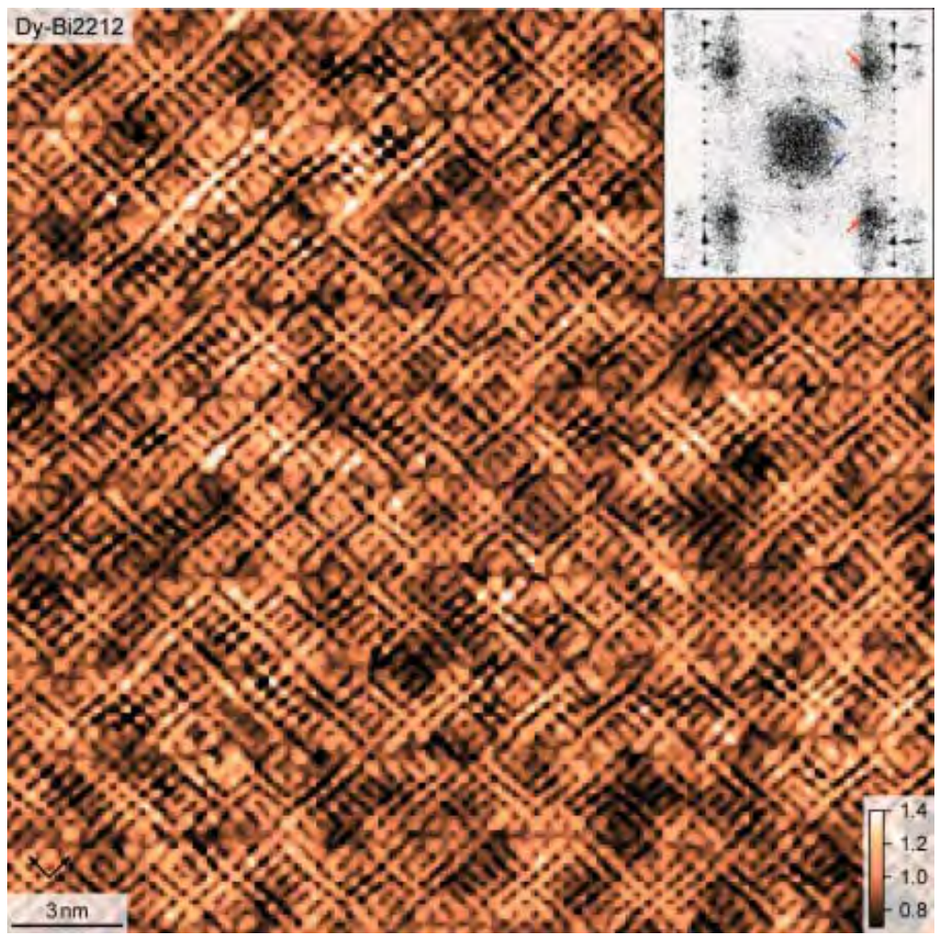



Angle-resolved photoemission spectroscopy always finds d-wave gap for $T < T_c$

even in LBCO x = 1/8 !?

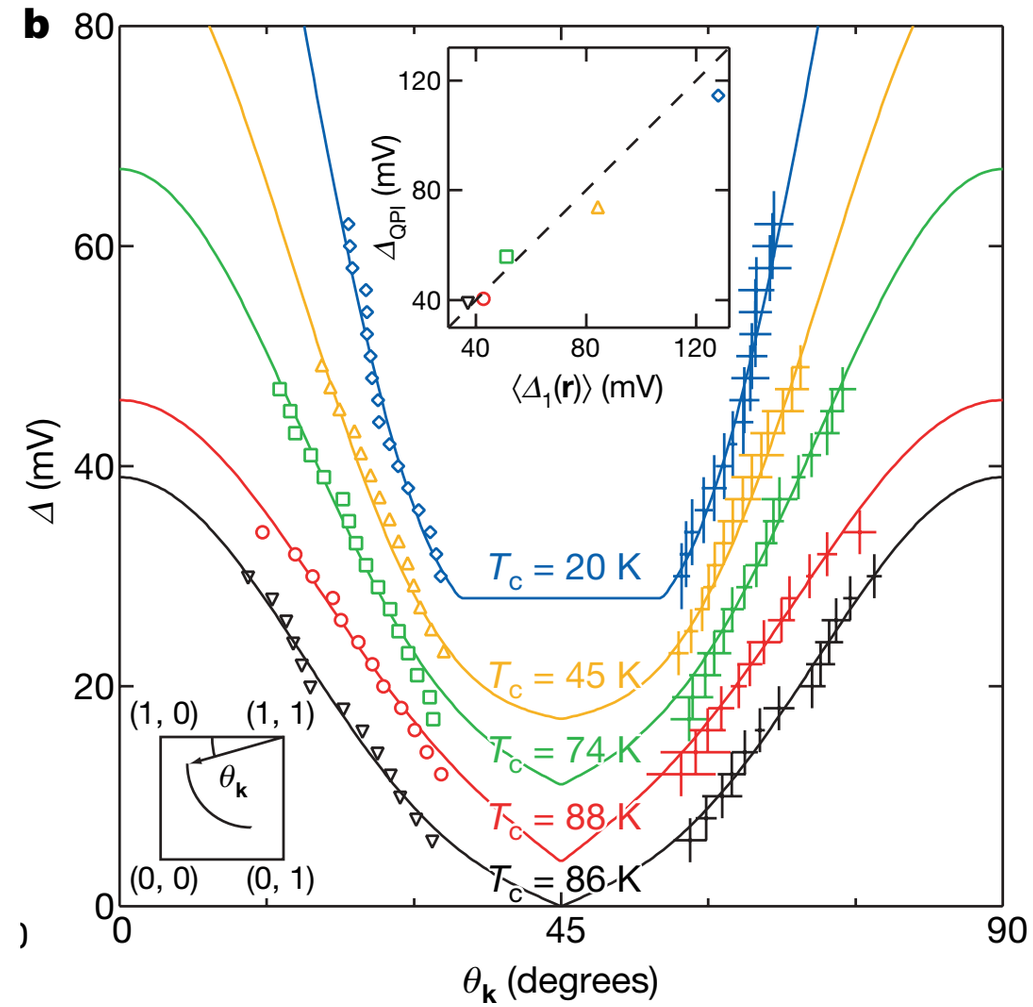
# STM may see PDW gap

R map, 150 meV




Kohsaka *et al*., Science (2007)

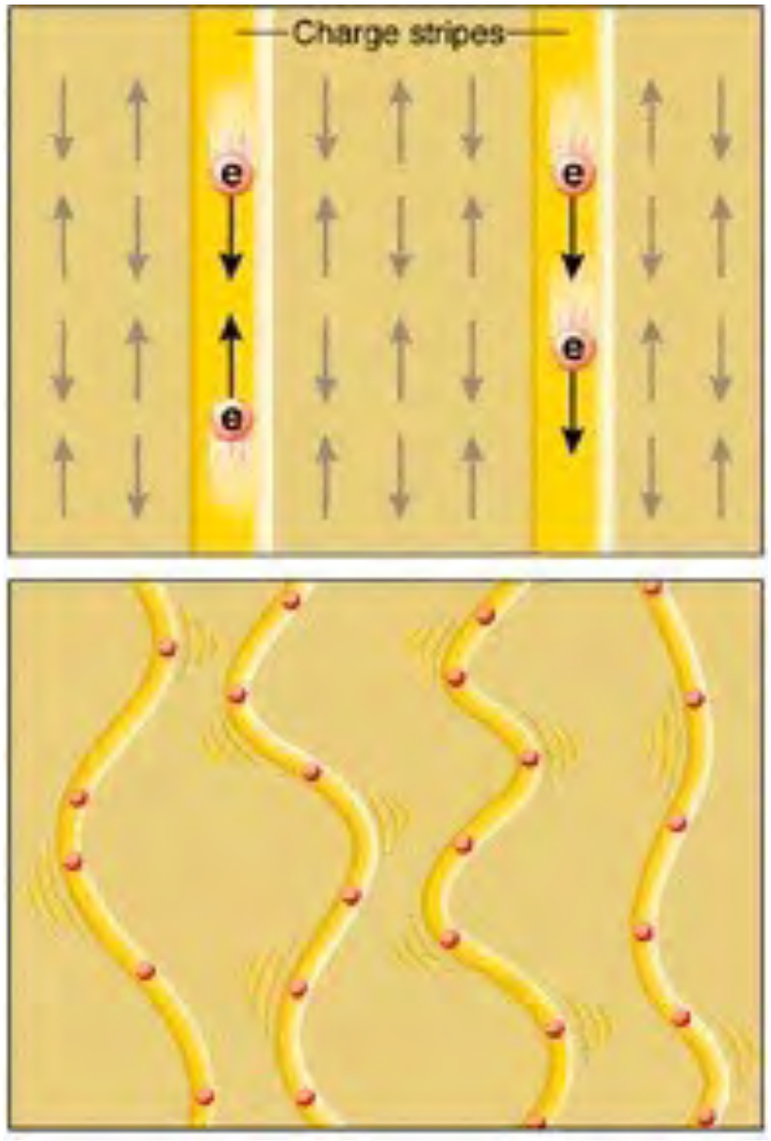
SC gap determined from analysis of quasiparticle inteference




Kohsaka *et al*., Nature (2008)

# How do we get uniform d-wave SC from stripes?

# Gap the spins

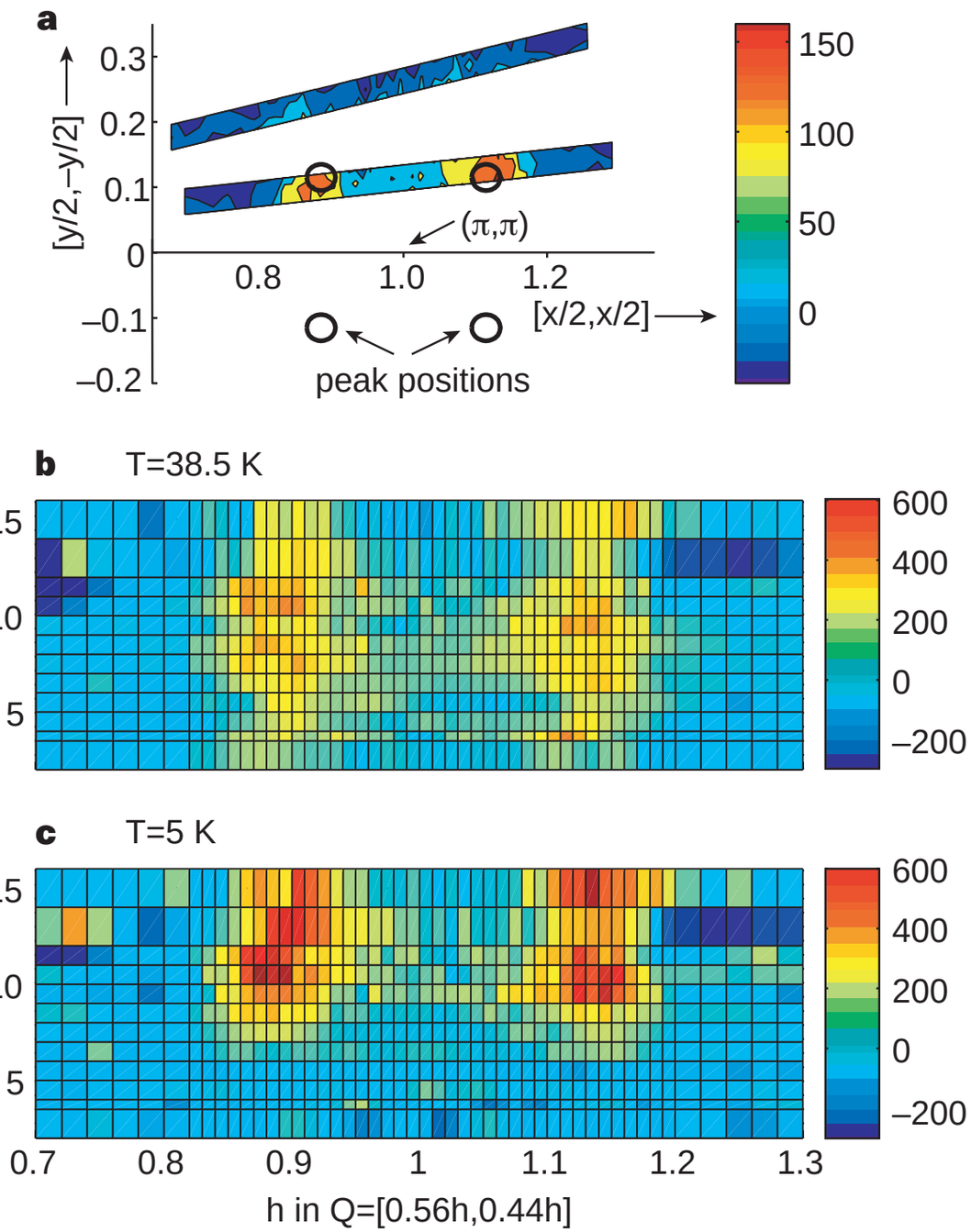



With spin-stripe order, anti-phase coupling between charge stripes yields PDW

For in-phase coupling, the system must gap the intervening spin correlations.

# Uniform d-wave superconductor

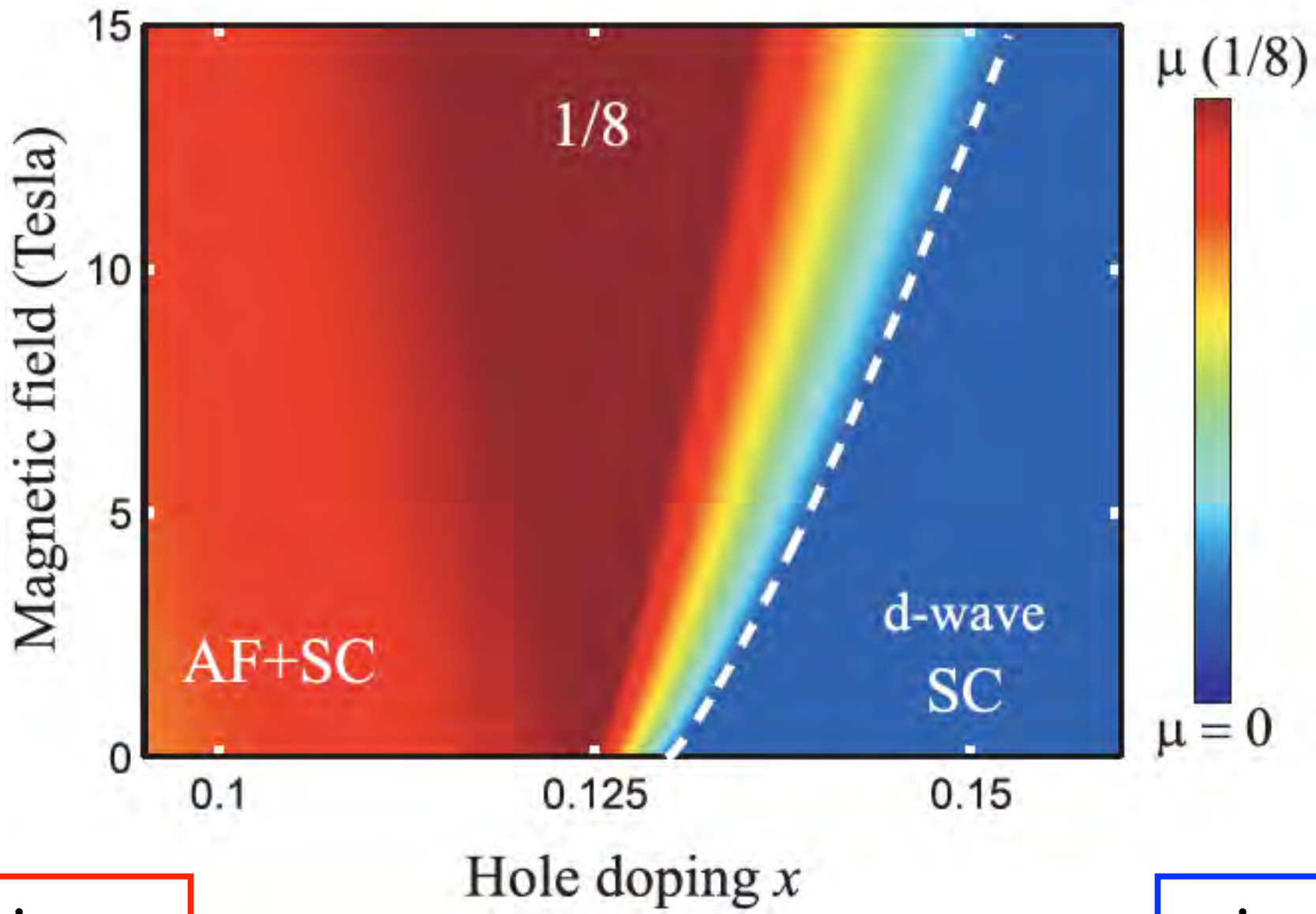
LSCO x = 0.16
$T_c$ = 38.5 K




Low-energy
spin fluctuations
gapped out for $T < T_c$

Lake, Aeppli,…, Hayden, Nature (1999)

# Field-induced stripe order in LSCO

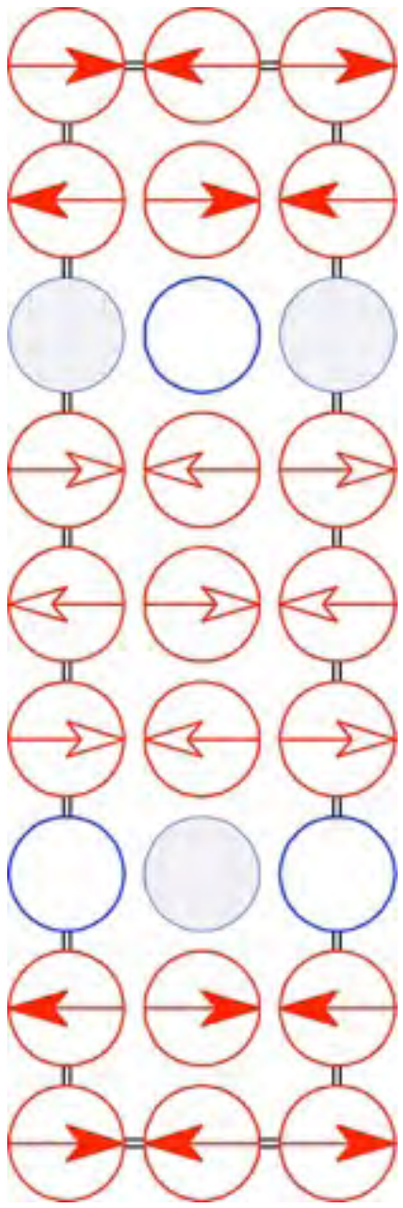


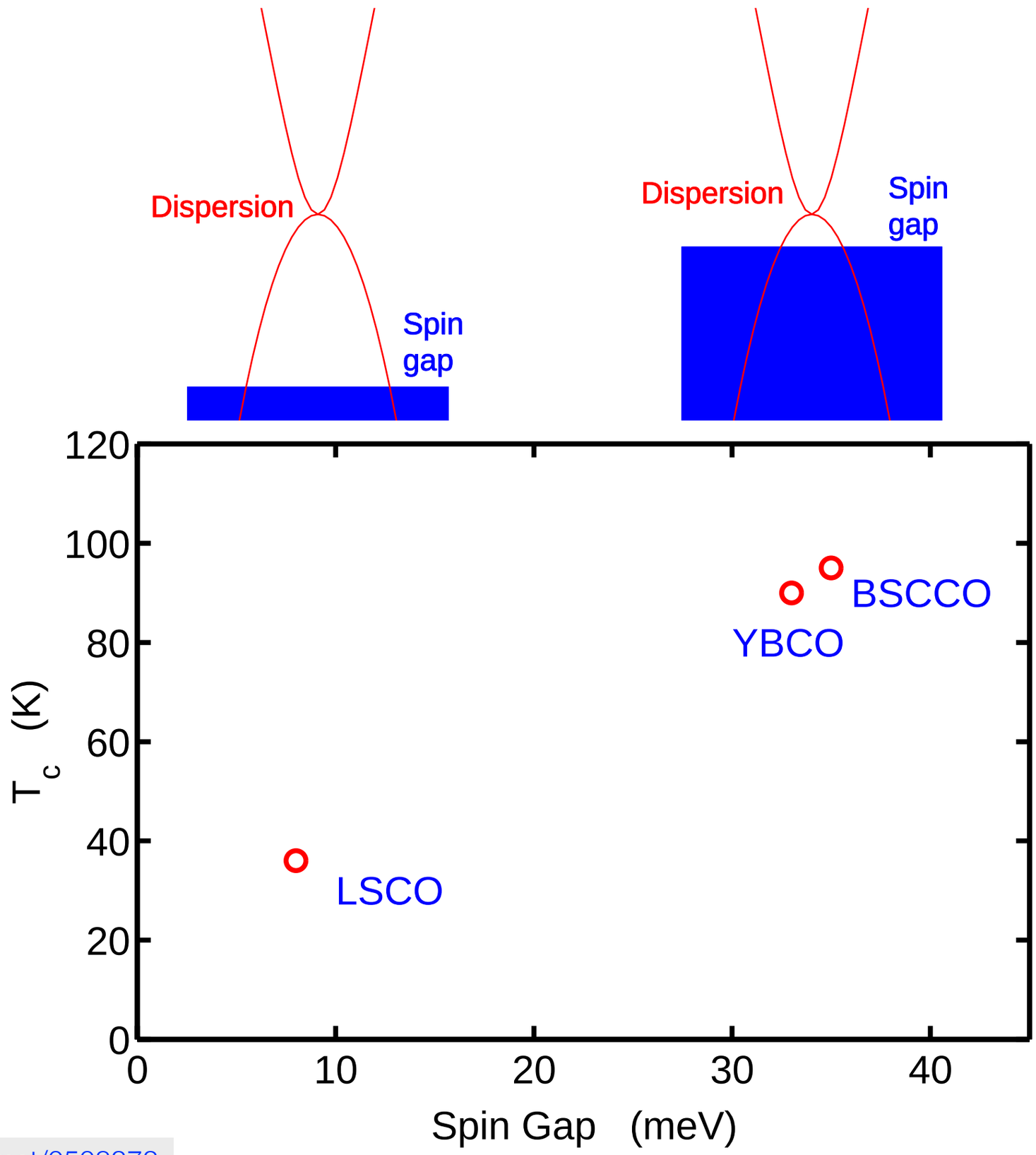

no spin gap

spin gap

J. Chang *et al.*, PRB (2008)

# Trade off: AF spin correlations vs. SC phase coherence






JMT, Proc SPIE **5932**, 59320C (2005); cond-mat/0508272

# Conclusions

- Competition between KE of holes and J between spins leads to inhomogeneity
  - Which can take the form of stripes

- Charge stripes may contain strong pairing correlations
  - Josephson coupling between stripes gives SC

- SC phase coherence
  - Spin order survives — Pair-density-wave SC
  - Spin fluct. develop gap — uniform d-wave SC