Recent experiments relevant to PDW and CDW orders in LBCO and LSCO

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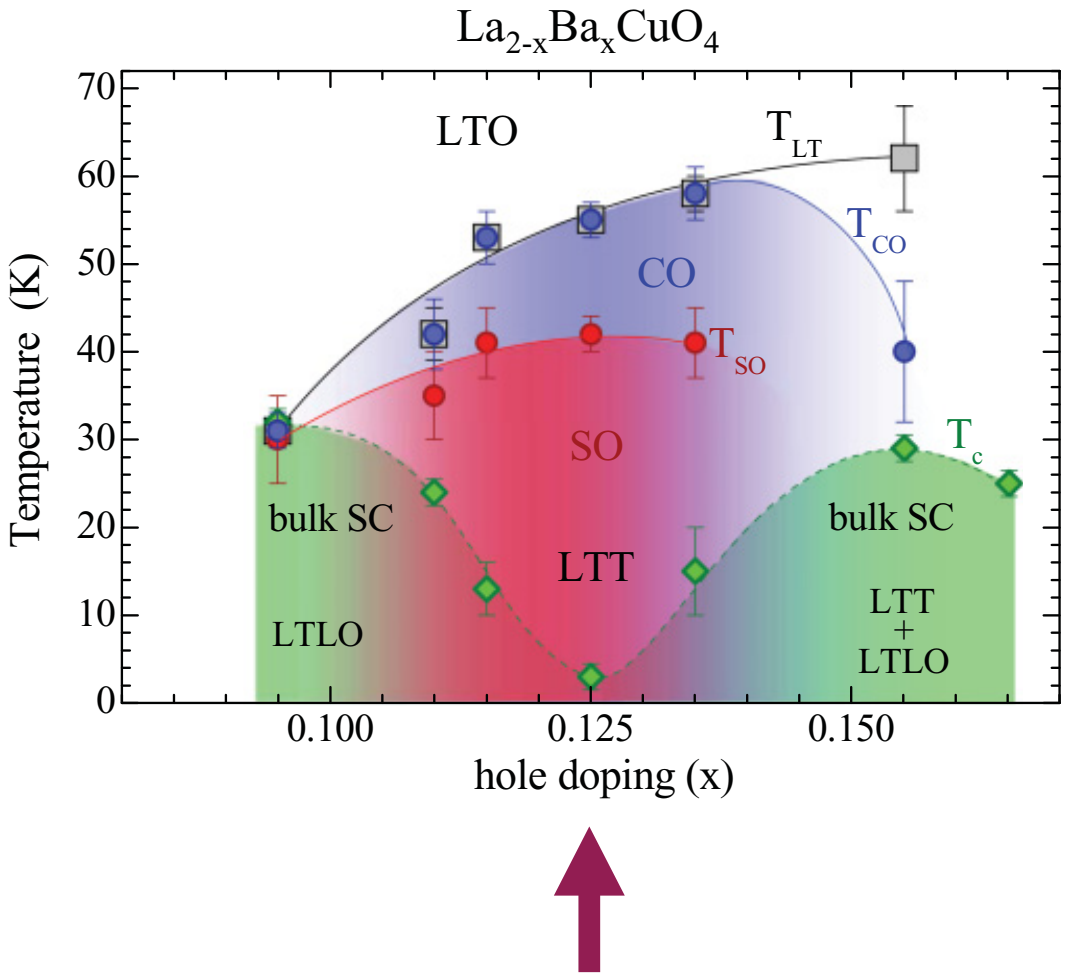
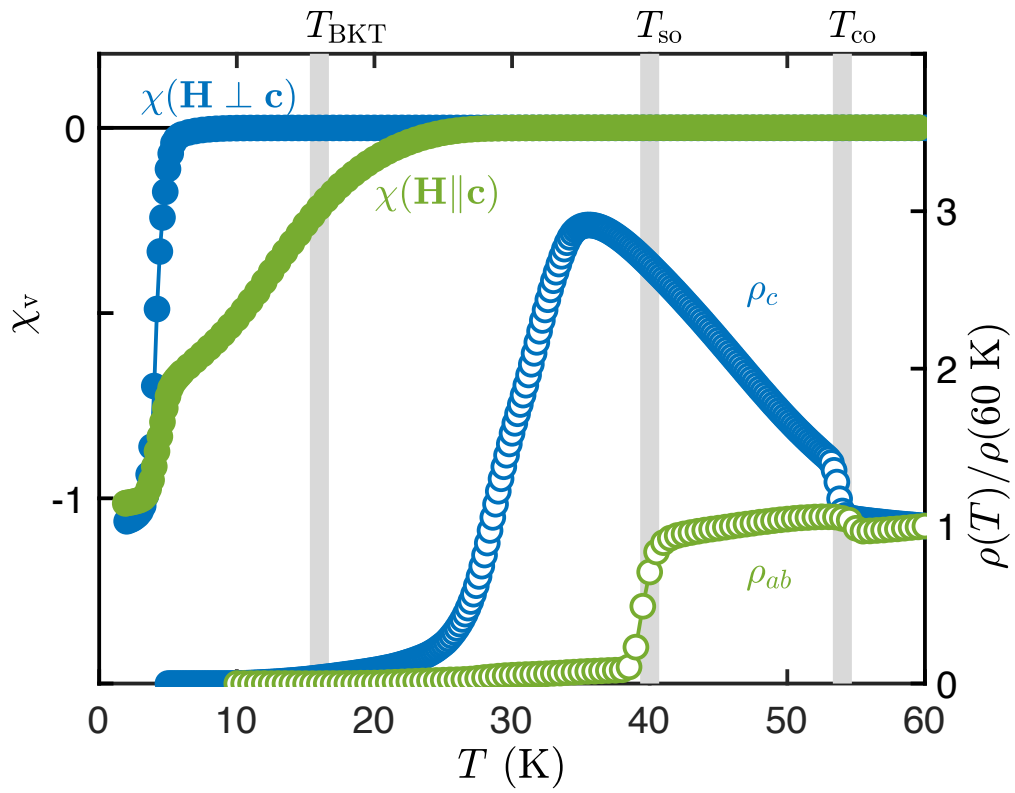
Outline

- LBCO x=1/8, stripe order, and 2D superconductivity: motivation for PDW order
- Testing for PDW order with an in-plane magnetic field
- Transforming from 2D to 3D SC with uniaxial stress: LBCO x=0.115
- Field-induced transition from 3D to 2D SC
- Zn-induced 2D SC in LBCO x=0.095
- 1Q peak, signature of PDW, not seen in RSXS
- Impact of lattice symmetry on charge stripes in LSCO
- Challenge of comparing dynamic spin and charge stripes with theory

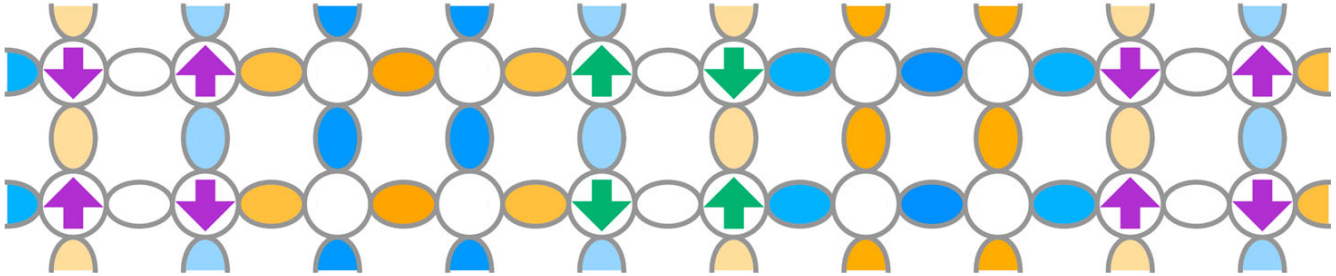
2D superconductivity with stripe order

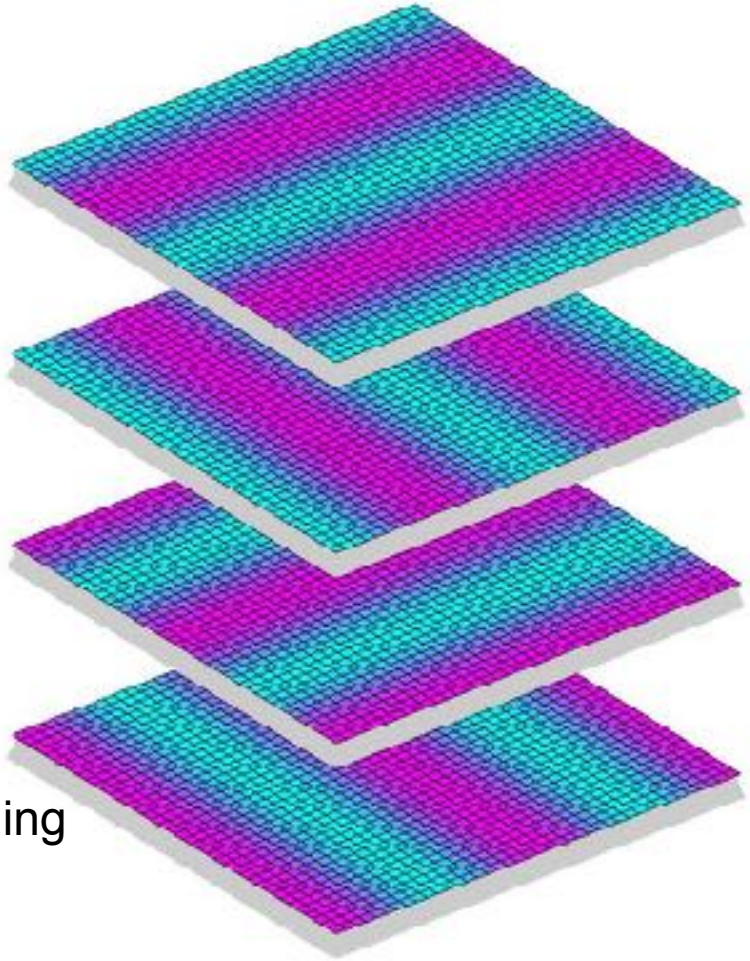




Q. Li *et al.*, PRL **99**, 067001 (2007)
Agterberg *et al.*, ARCMP **11**, 231 (2020)

Explained by Pair-Density-Wave order

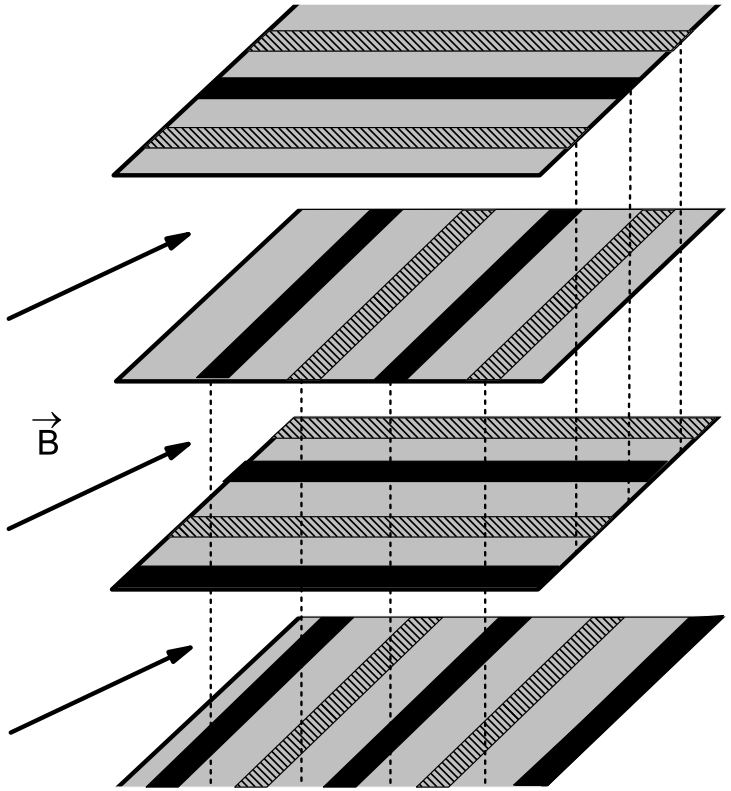




Interlayer Josephson coupling is frustrated.

Berg *et al*., PRL **99**, 127003 (2007)
Agterberg *et al*., ARCMP **11**, 231 (2020)

Proposed phase-sensitive test of stacked PDW

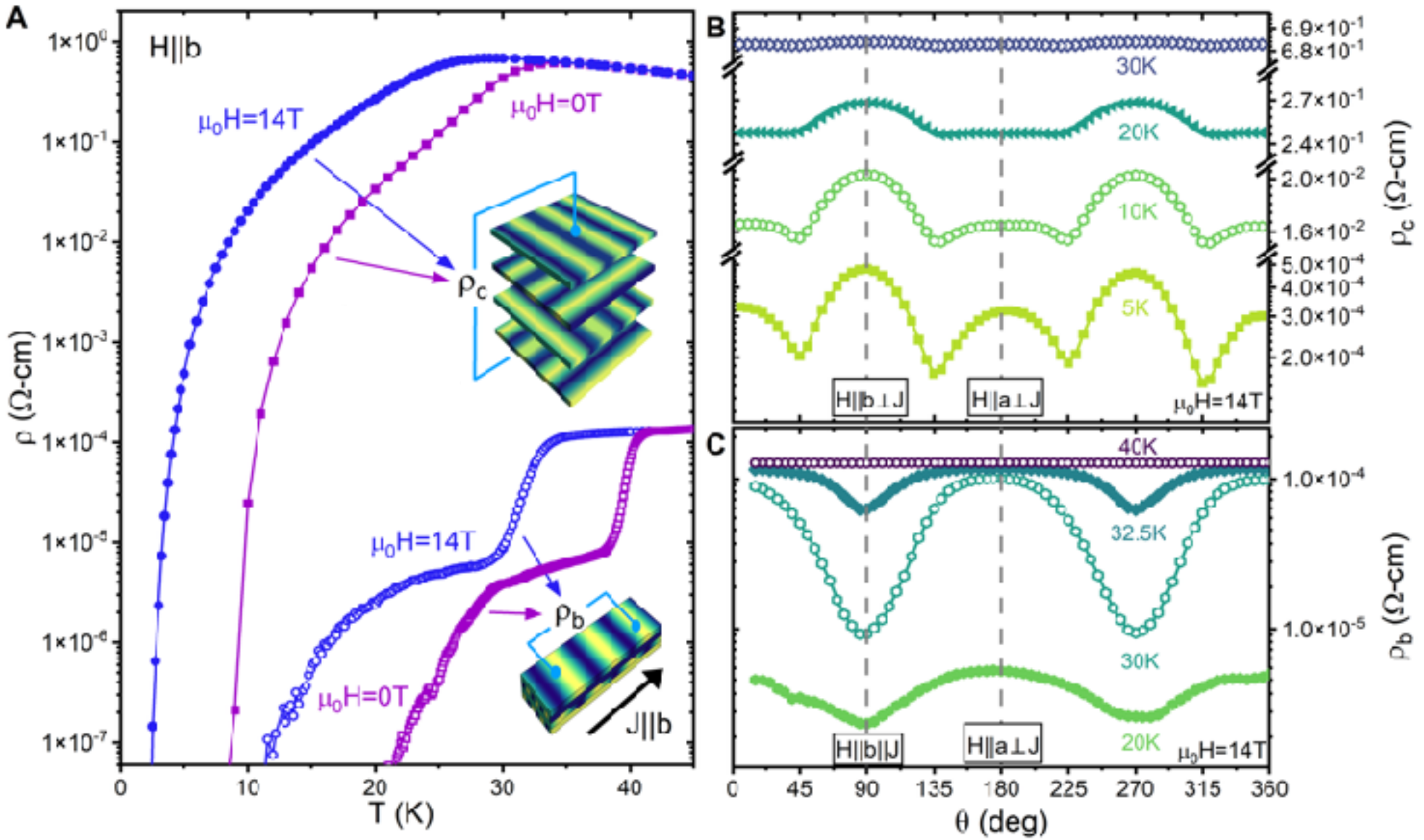


Prediction:

In-plane field B ~ 1000 T
at 45° to PDW should restore
the interlayer Josephson coupling

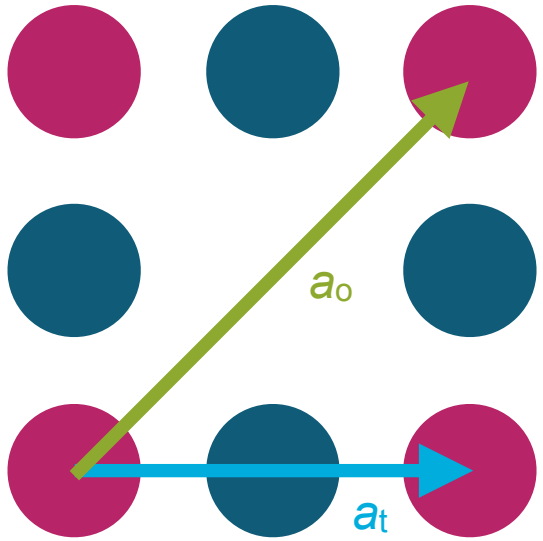
K. Yang, J. Supercond. Nov. Magn. **26**, 2741 (2013)
K. Yang and D.F. Agterberg, PRL **84**, 4970 (2000)

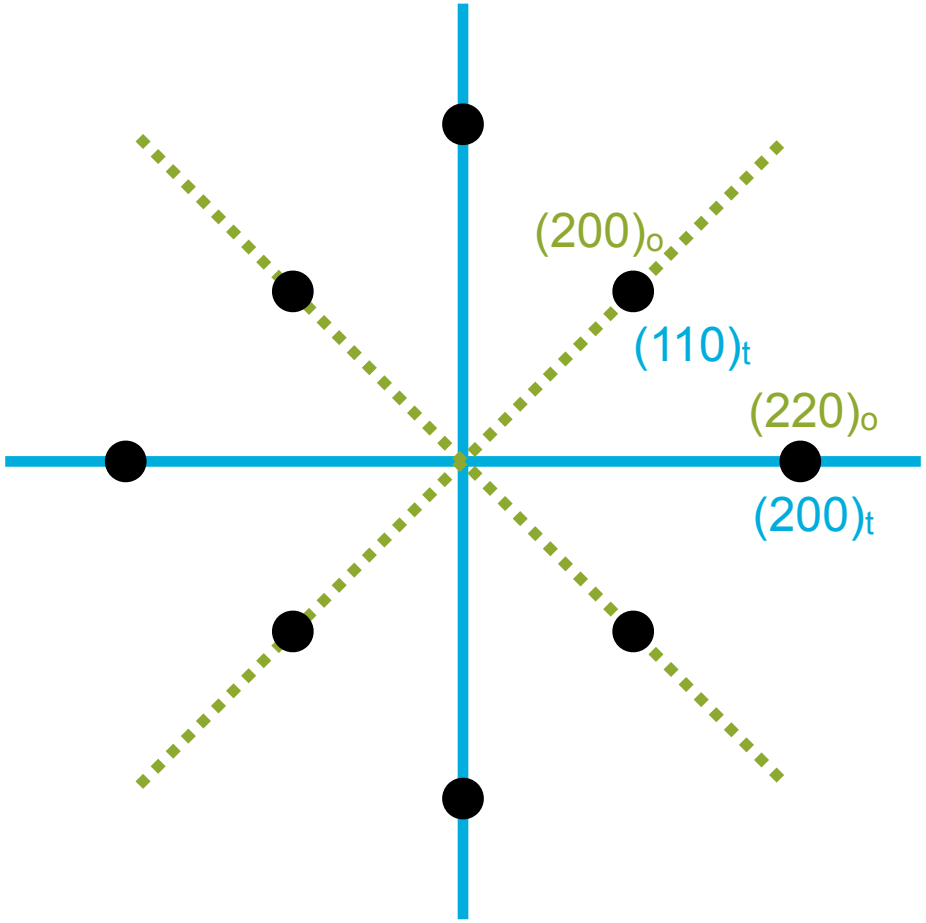
Test of PDW order in LBCO x = 1/8



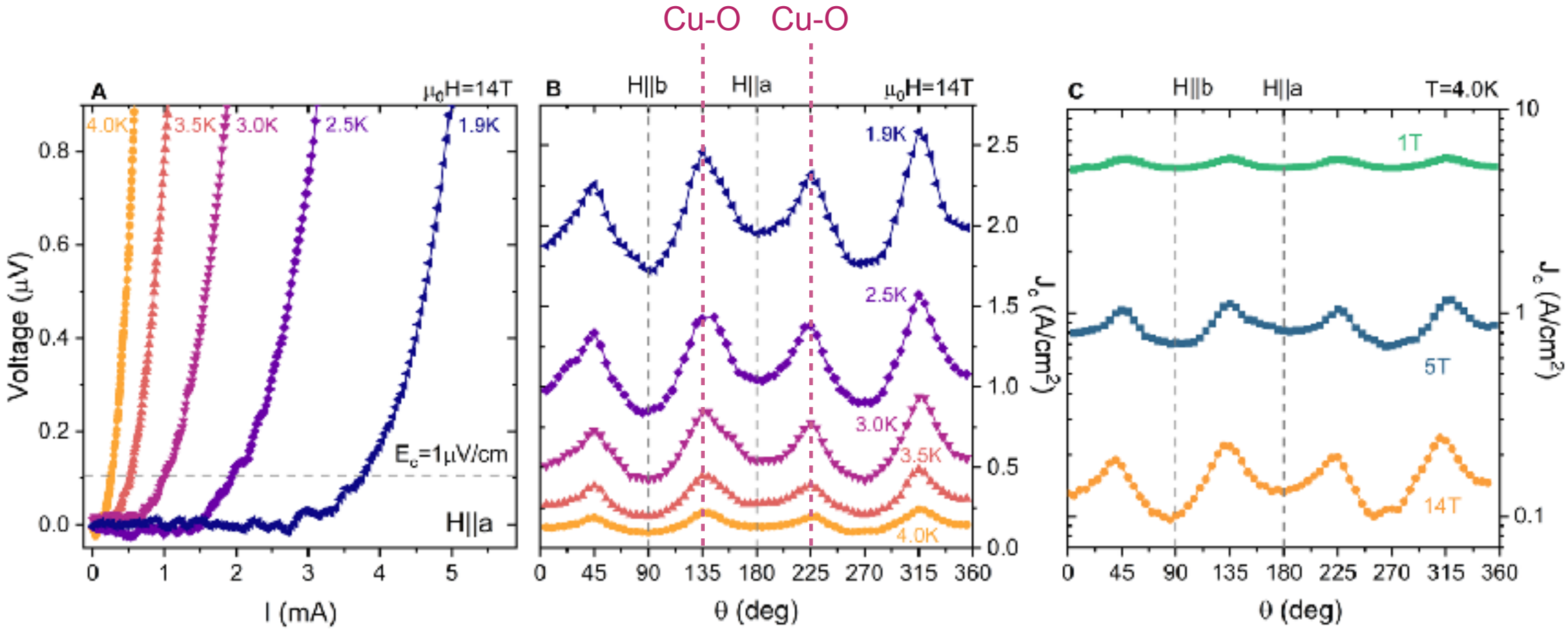
P.M. Lozano
Qiang Li

Which *a* and *b*?





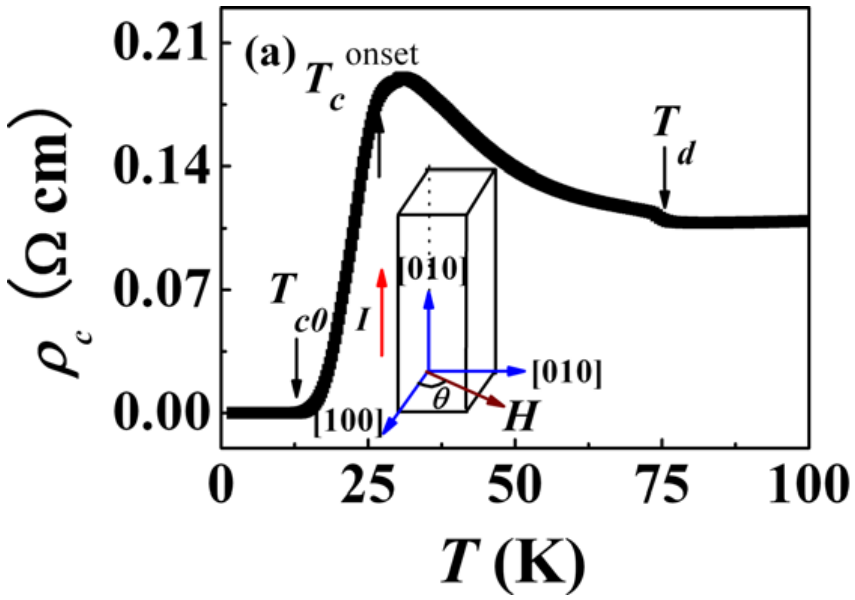
J_c maxima for H along Cu-O bonds

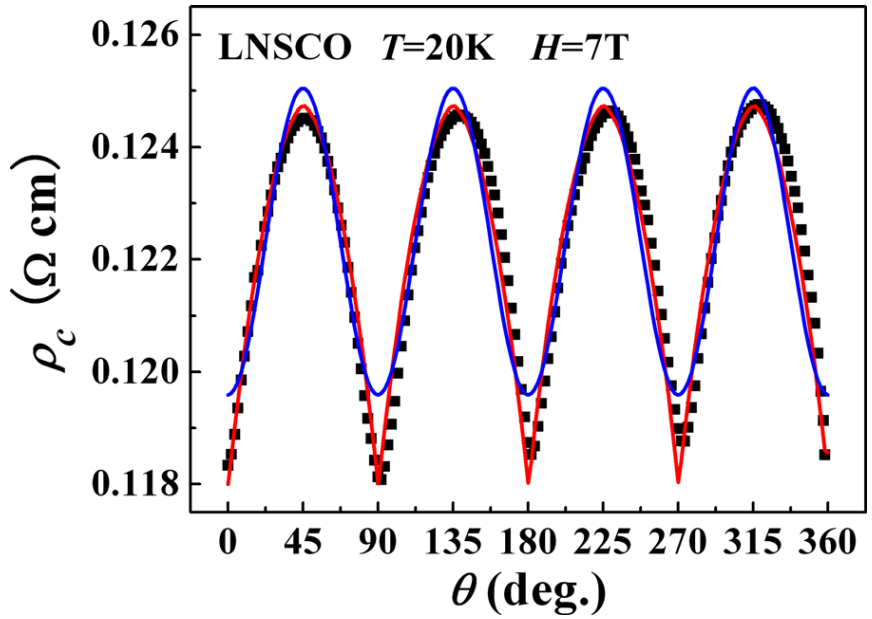


Not consistent with Kun Yang's proposal

$La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ shows similar field dependence

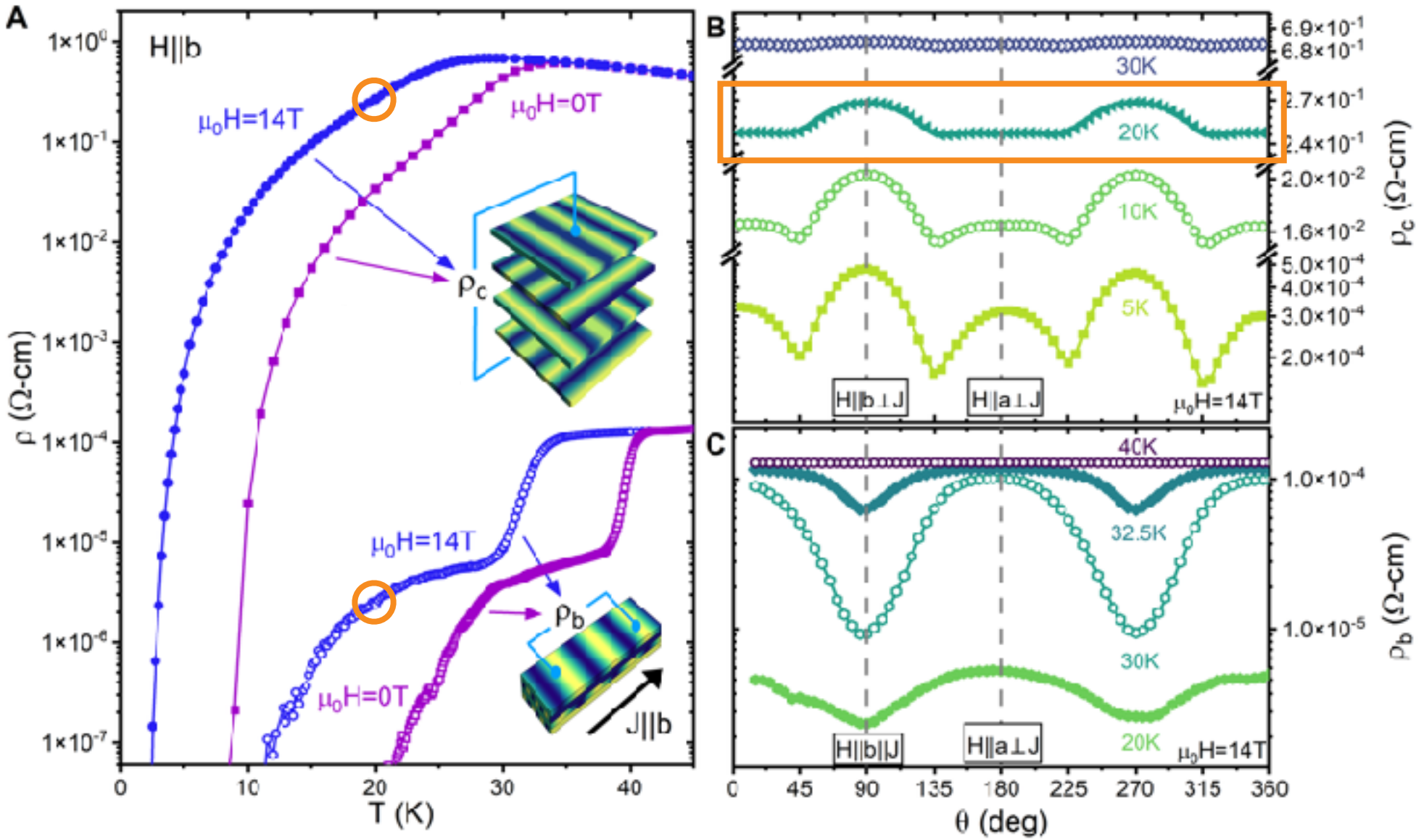
M.L. Teng *et al.*, J. Appl. Phys. **113**, 053912 (2013)





Interpreted in terms of magnetic flux pinning;
but this cannot explain all of the LBCO results!

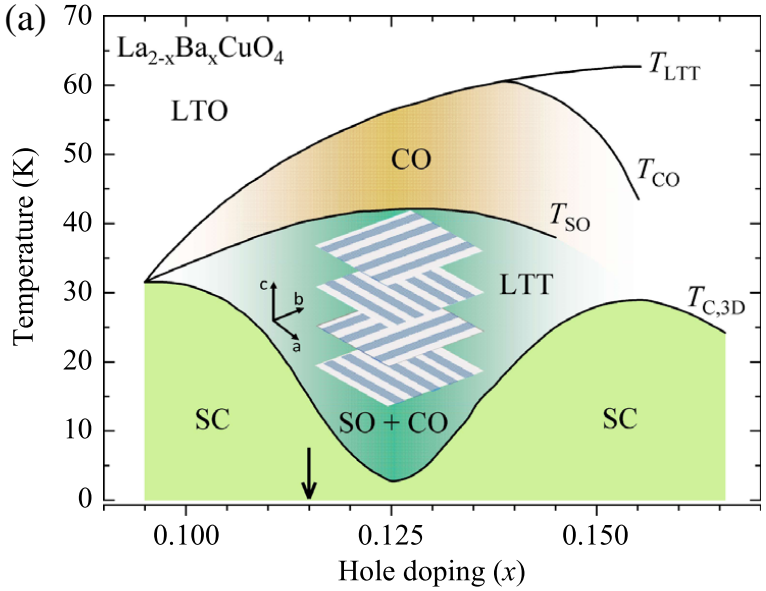
Anisotropy even in the absence of 2D phase order

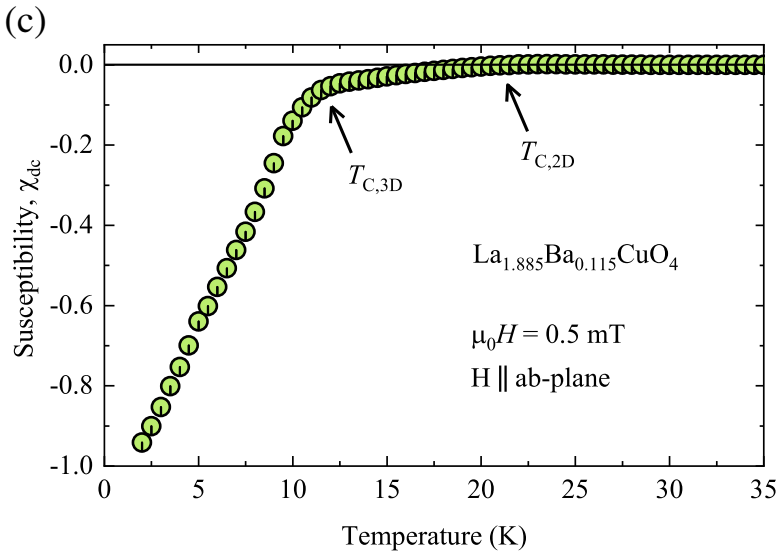


P.M. Lozano
Qiang Li

How can we understand the observed dependence of J_c and ρ_c on in-plane H?

Recovering interlayer Josephson coupling with stress





Uniaxial stress at 30° to Cu-O bonds
Stress device from Cliff Hicks, MPI Dresden

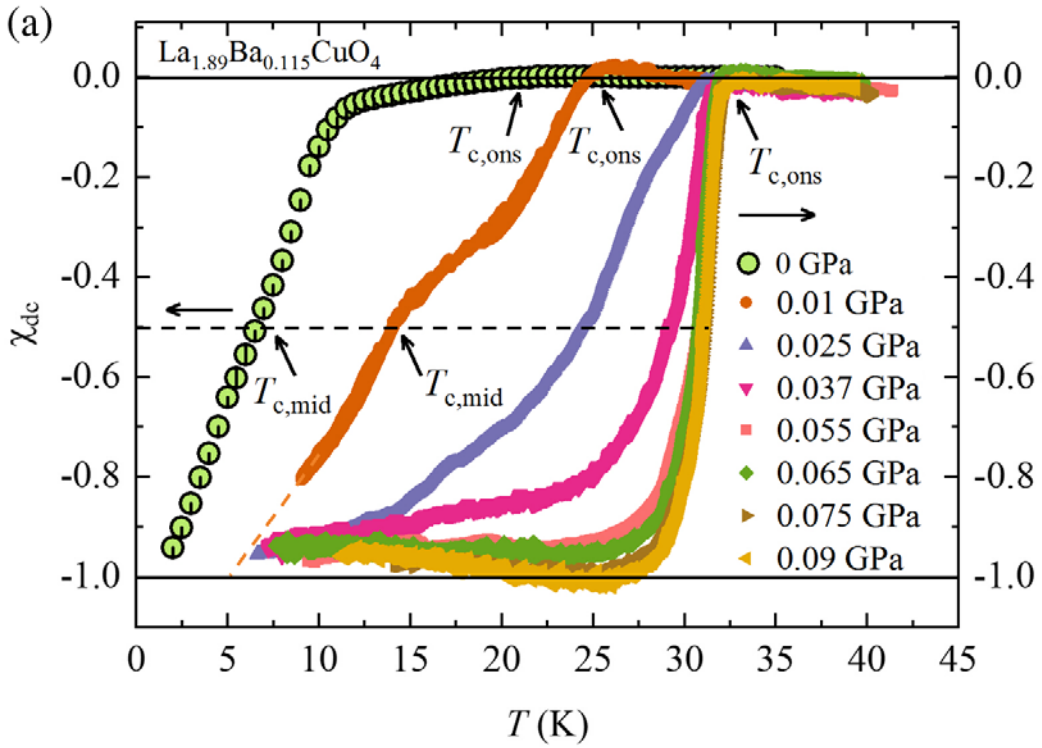
Spin order probed by zero-field μSR at PSI

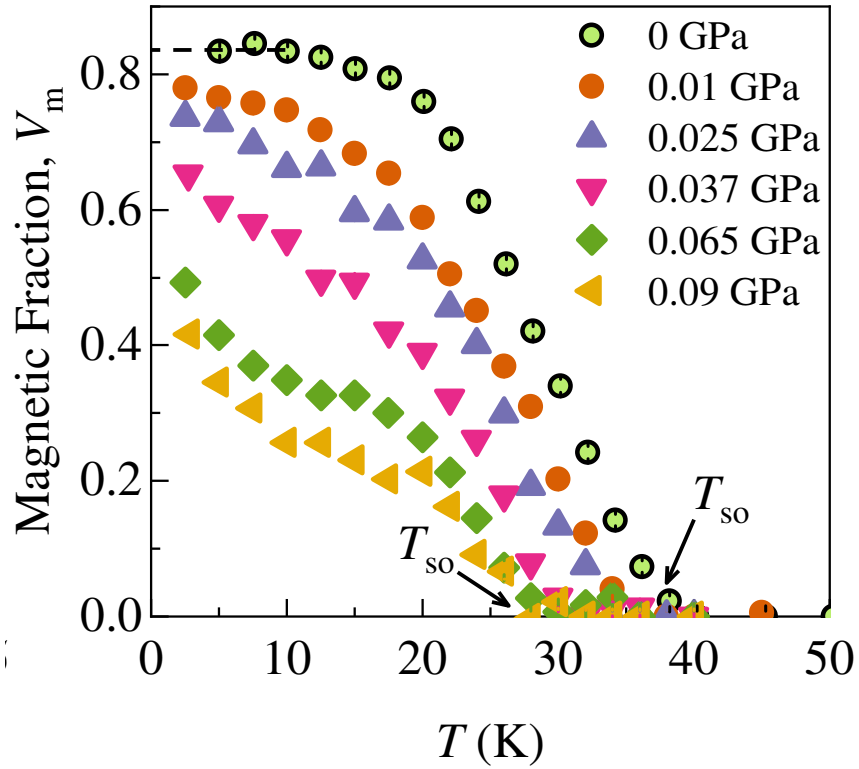
In situ ac susceptibility to measure SC response

Z. Guguchia *et al.*, PRL **125**, 097005 (2020)

Structure vs. stress with 100-keV XRD at PETRA-III
(Unpublished)

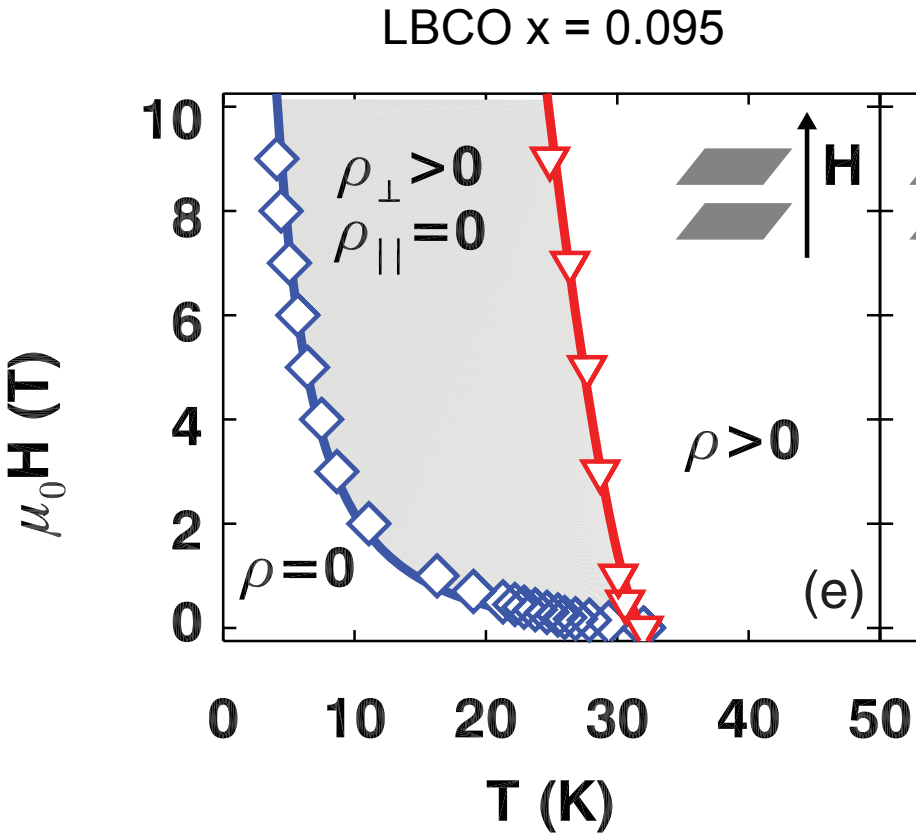
LBCO x = 0.115 under uniaxial stress



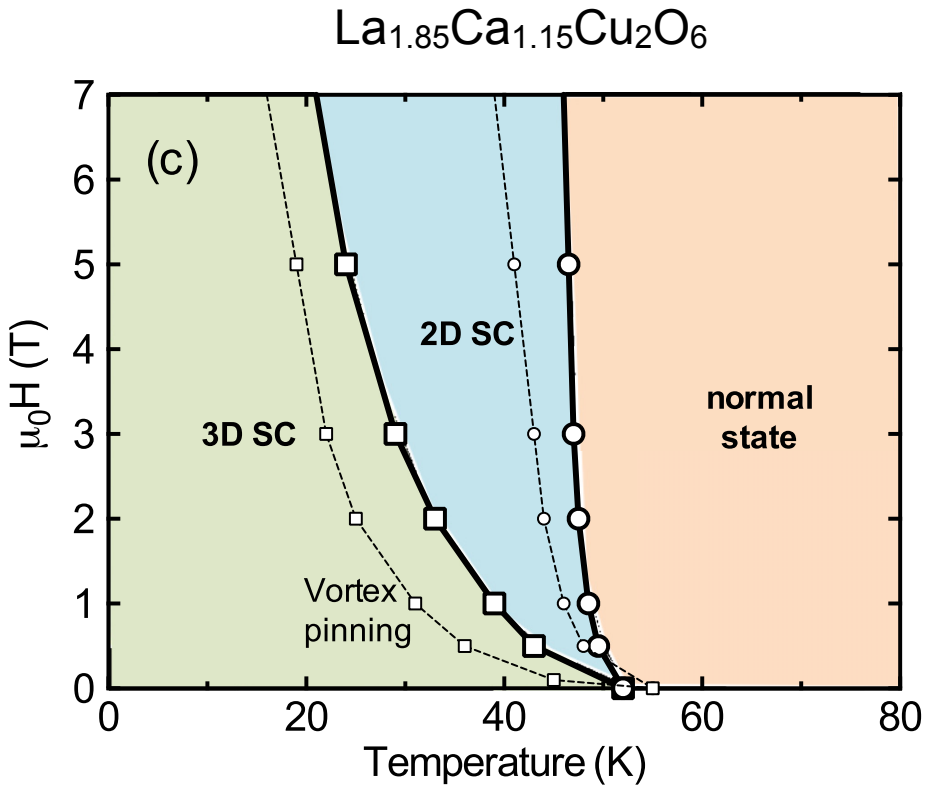


Z. Guguchia *et al.*, PRL **125**, 097005 (2020)

Field-induced transition from 3D to 2D SC



Wen *et al.*, PRB **85**, 134513 (2012)

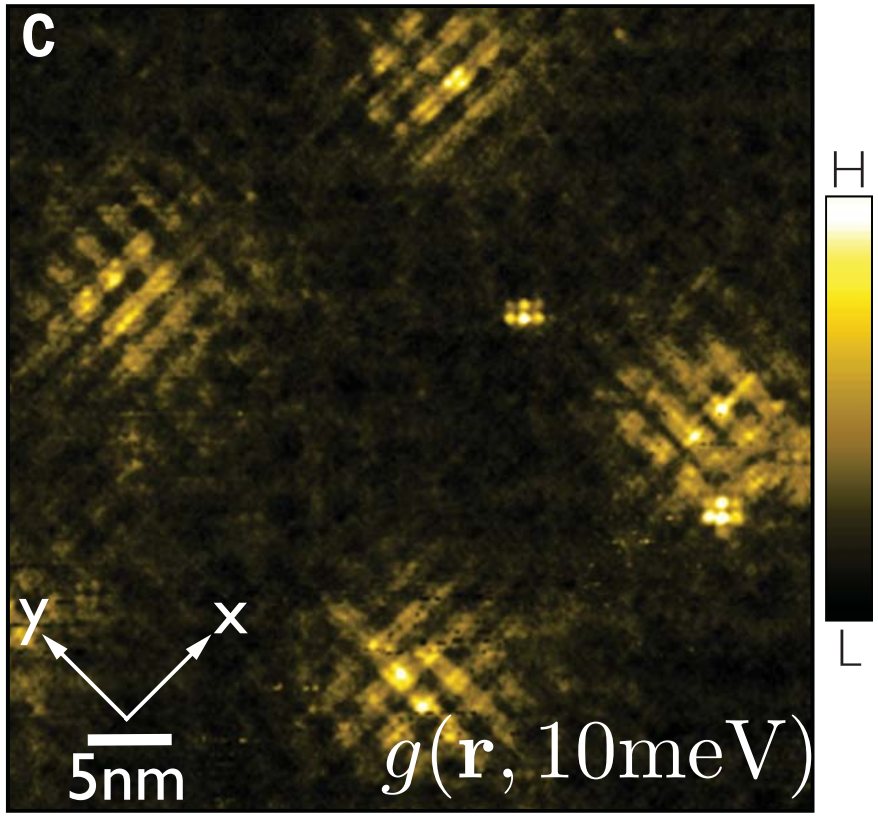


Zhong *et al.*, PRB **97**, 134520 (2018)

Local perturbations

PDW order in vortex halos

dI/dV: difference between B = 8.25 T and 0 T



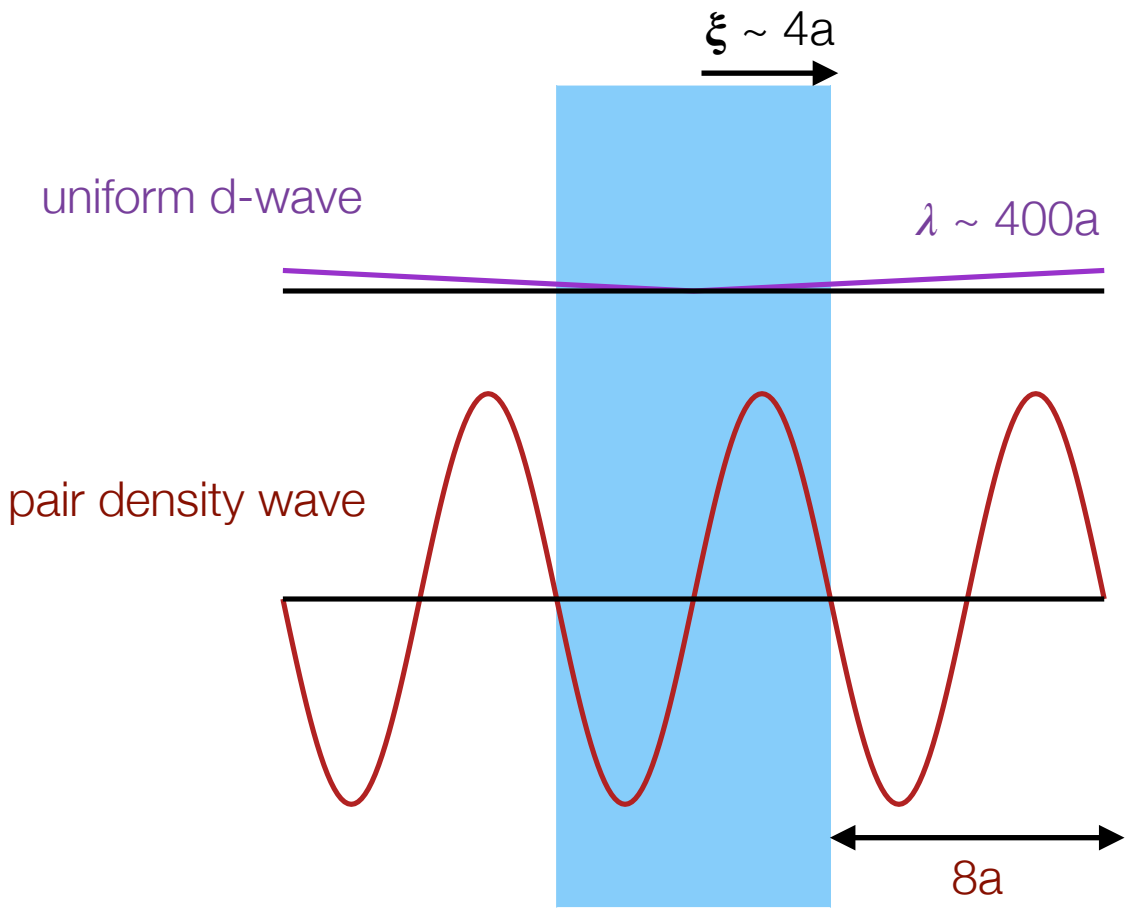
Charge stripes around vortices

J.E. Hoffman et al., Science 295, 466 (2002)

PDW order around vortices

S.D. Edkins et al., Science 364, 976 (2019)

Comparison: vortex core and Zn impurity



Zn site

Locally depresses superfluid

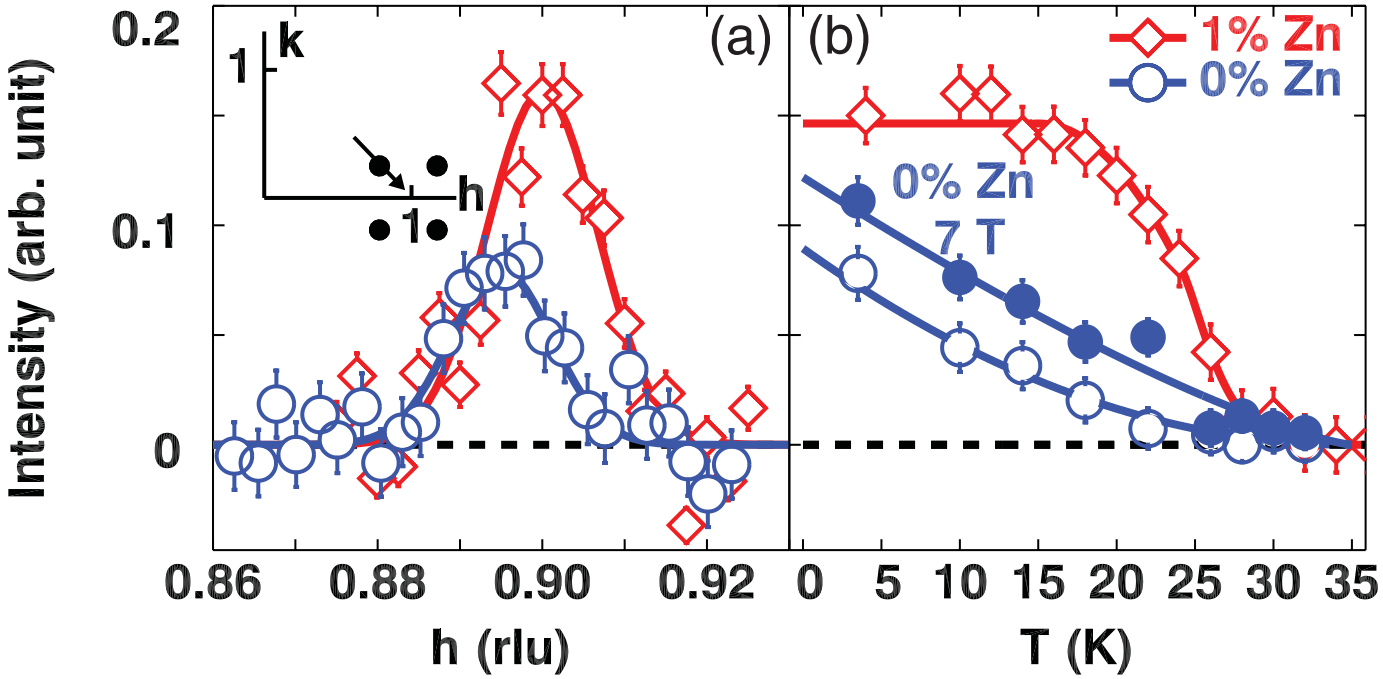
Should have similar impact on superconducting wave function

In LBCO, enhanced PDW should frustrate 3D SC order

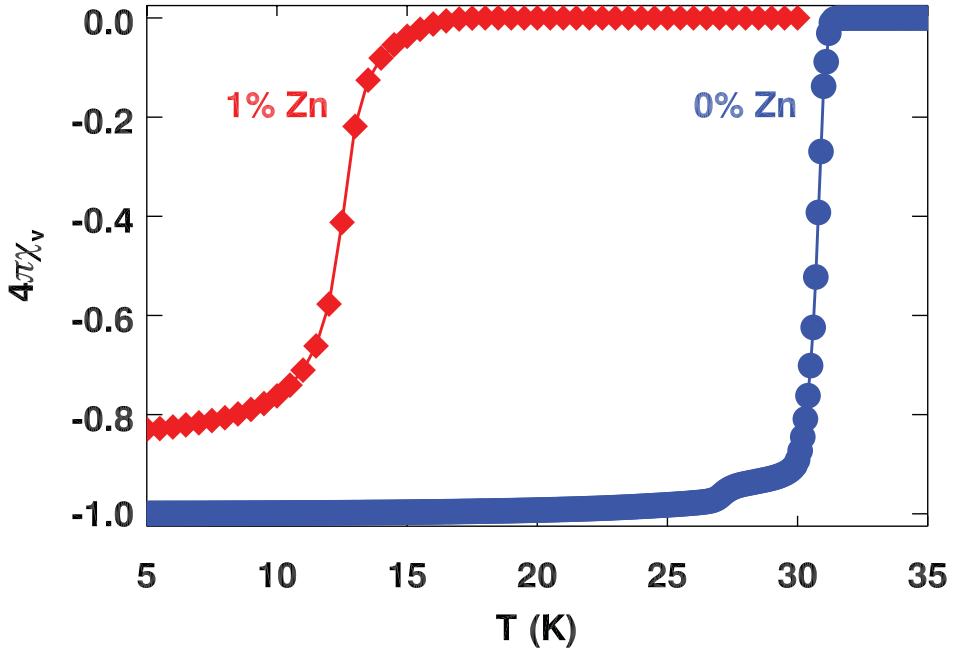
S. Kivelson: “Does Zn induce 2D SC?”

LBCO x = 0.095 + 1% Zn

Zn enhances spin stripe order …

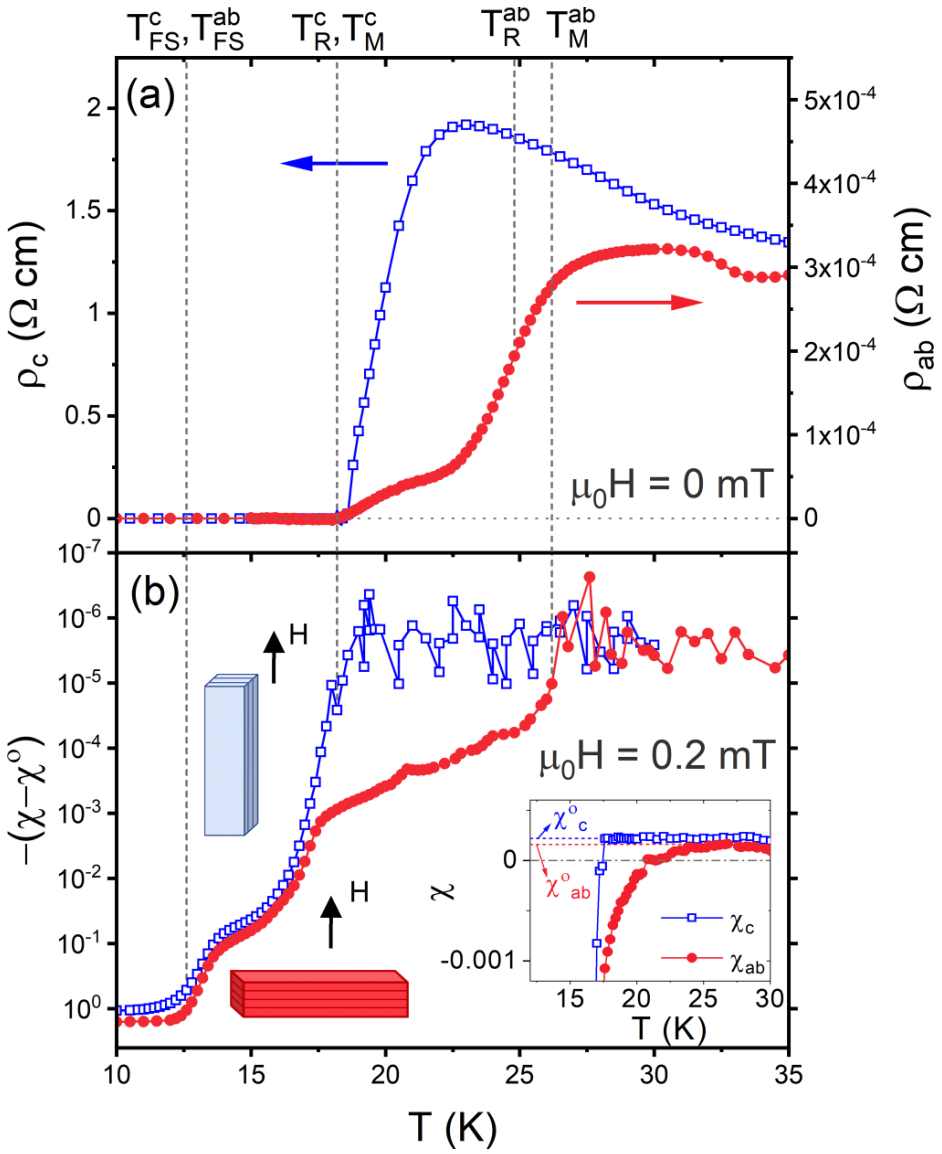


and reduces the bulk T_c



J.S. Wen et al., PRB **85**, 134512 (2012)

LBCO x = 0.095 + 1% Zn



Yes!

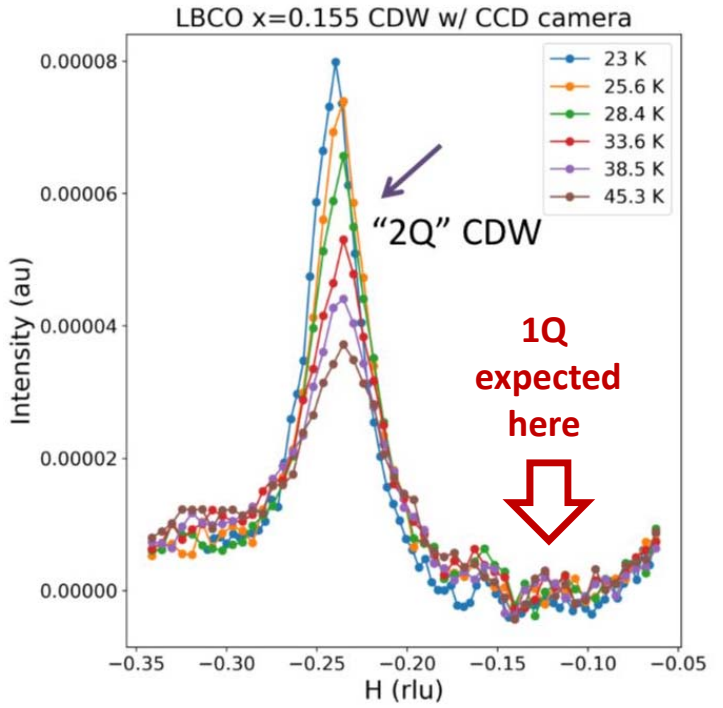
Zn induces 2D SC

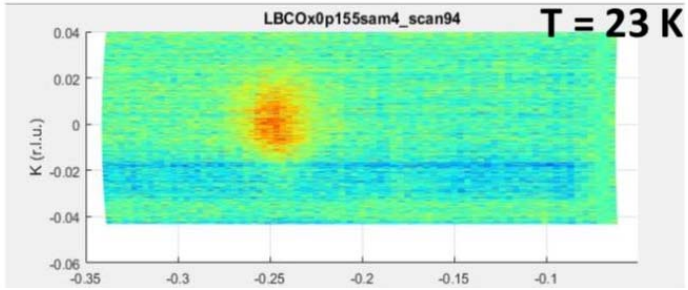
We infer PDW order

P.M. Lozano *et al.*, PRB **103**, L020502 (2021)

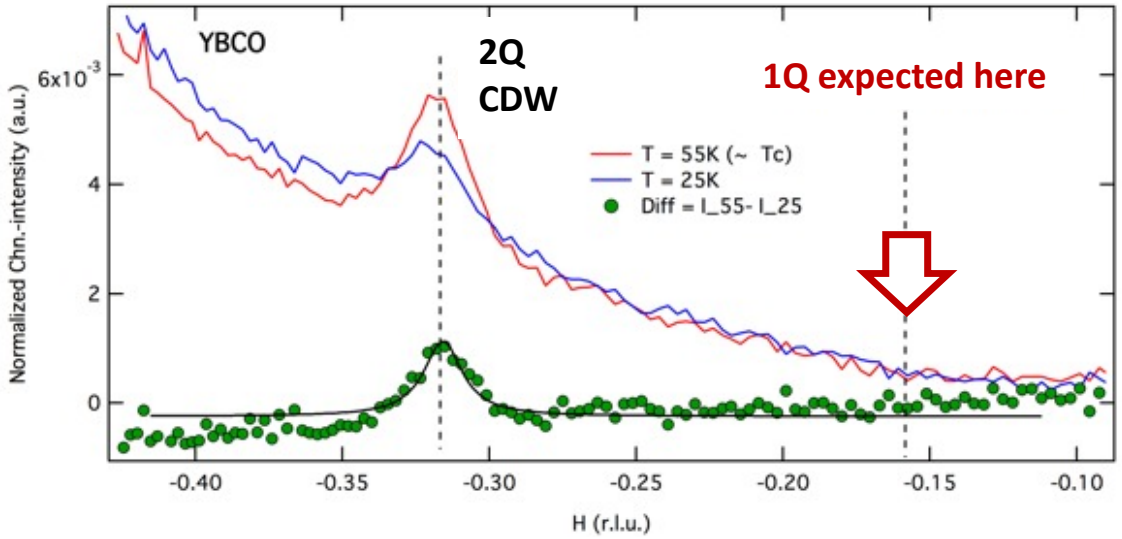
Selected Abbamonte group data on the elusive 1Q peak

LBCO x=0.155 (Tc = 29 K)
CDW measured with CCD camera



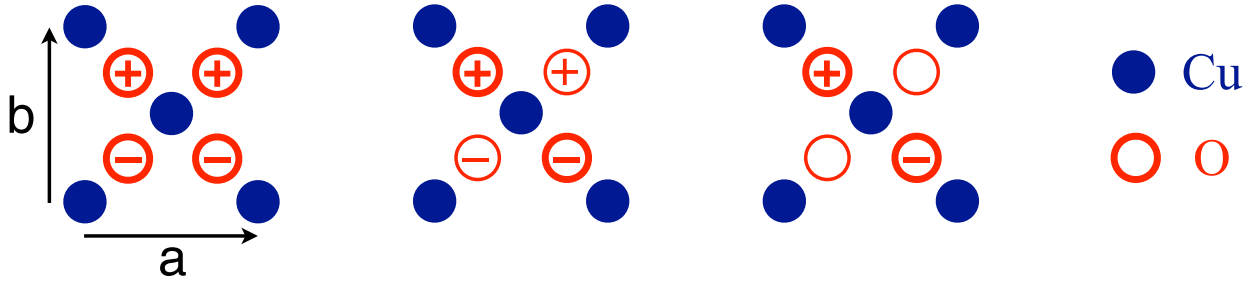


YBCO



- Both samples tuned slightly away from p=1/8 to increase T_{SC}.
- Both measurements done below T_{SC} so $\Delta_0 \neq 0$
- Upper bound on 1Q intensity ~5% that of 2Q.

Pinning charge order in LSCO



LTO
Bmab

LTLO
Pccn

LTT
P4_2/*ncm*

Assumed structure of LSCO

All Cu-O bonds equivalent

No preferred direction for CO

Structure of LBCO

Inequivalent Cu-O bonds at 90°

Preferred direction for CO

Demonstrated structure of LSCO

Slightly inequivalent Cu-O bonds at 90°

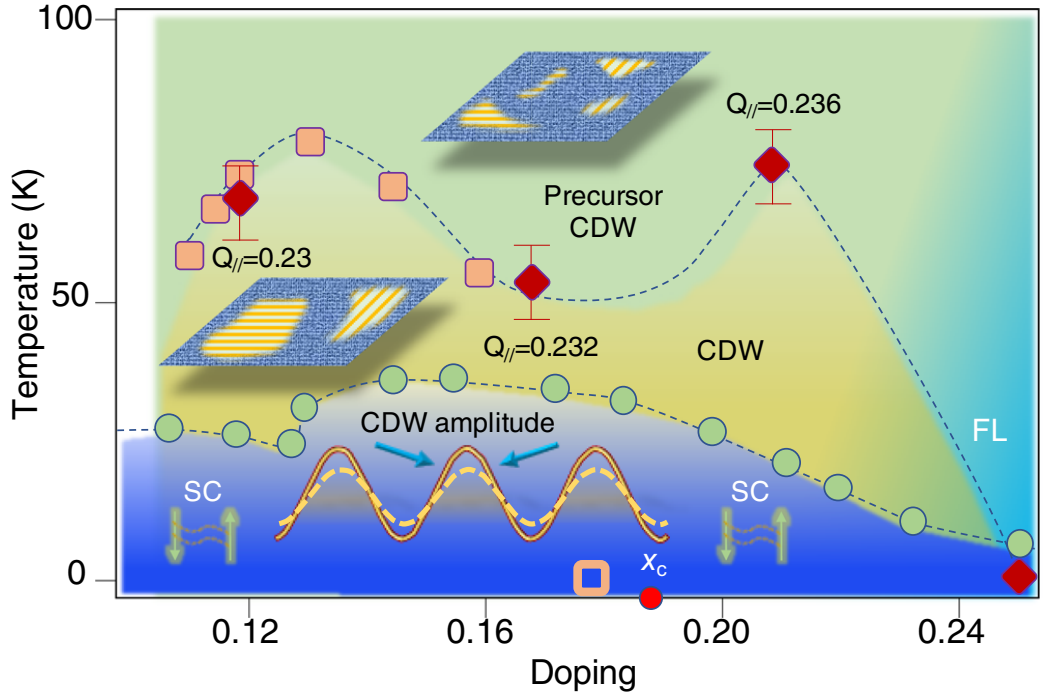
Slightly preferred direction for CO

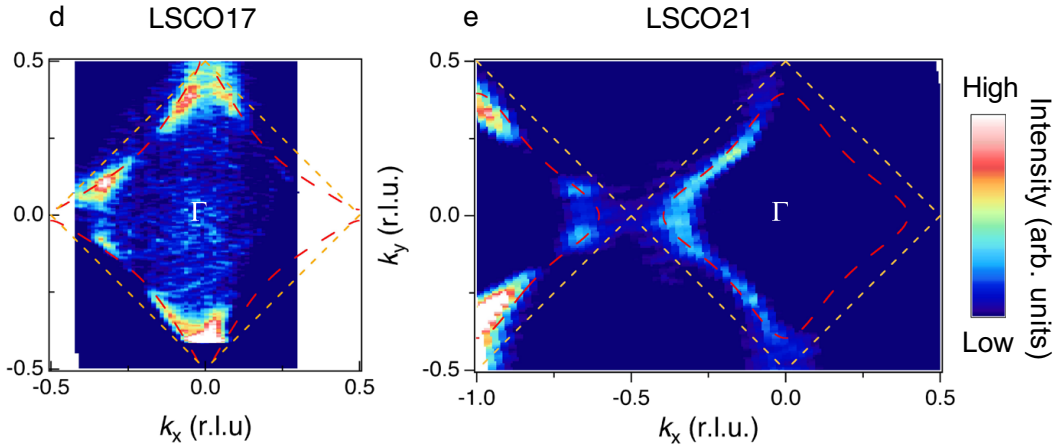
x = 0.07 Jacobsen *et al.*, PRB **92**, 174525 (2015)

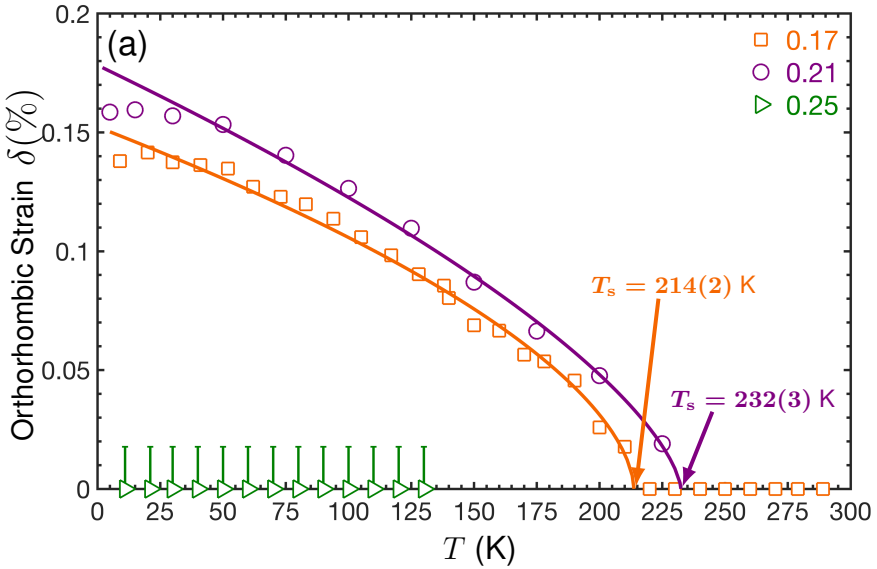
x = 0 Sapkota *et al.*, PRB **104**, 014304 (2021)

x = 0.12 Frison *et al.*, arXiv:2201.04858

Charge “order” in LSCO





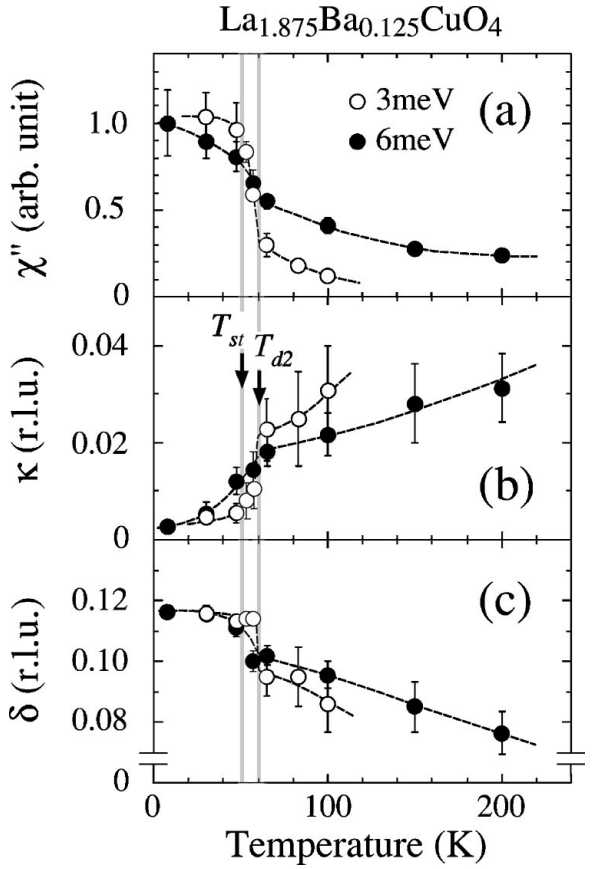


Y. Li *et al.*, arXiv:2205.01702

H. Miao *et al.*, npjQM **6**, 31 (2021)

Thermally disordered spin and charge stripes

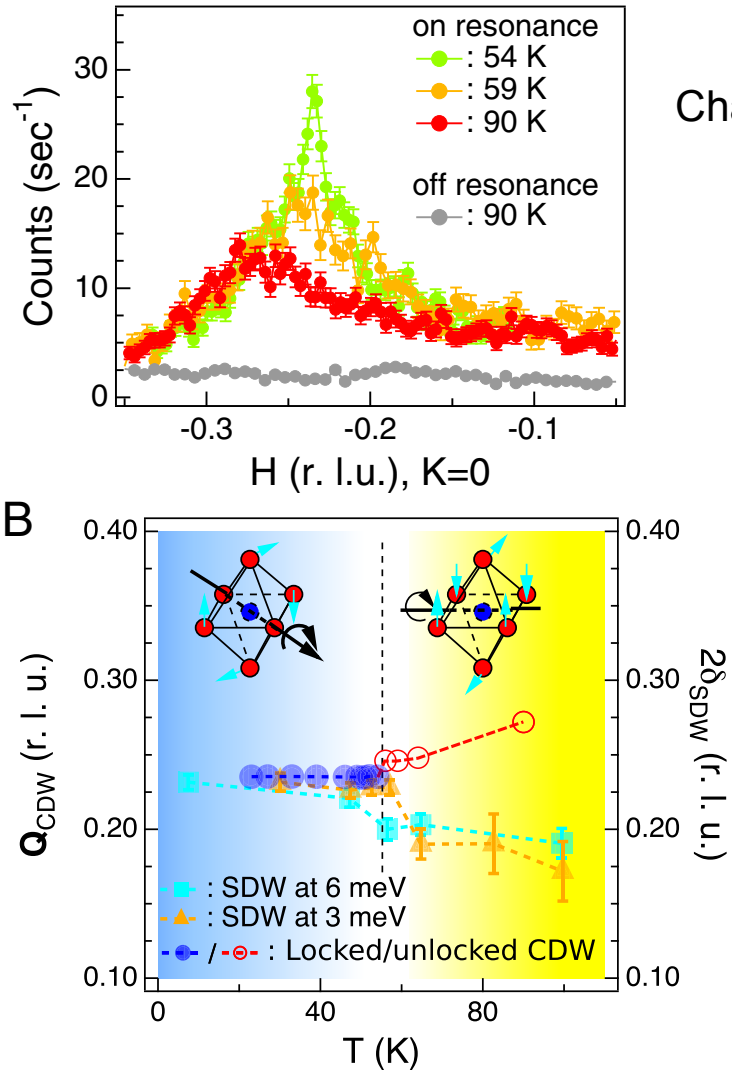
Spin correlations from neutron scattering



M. Fujita *et al.*, PRB **70**, 104517 (2004)

Charge correlations from

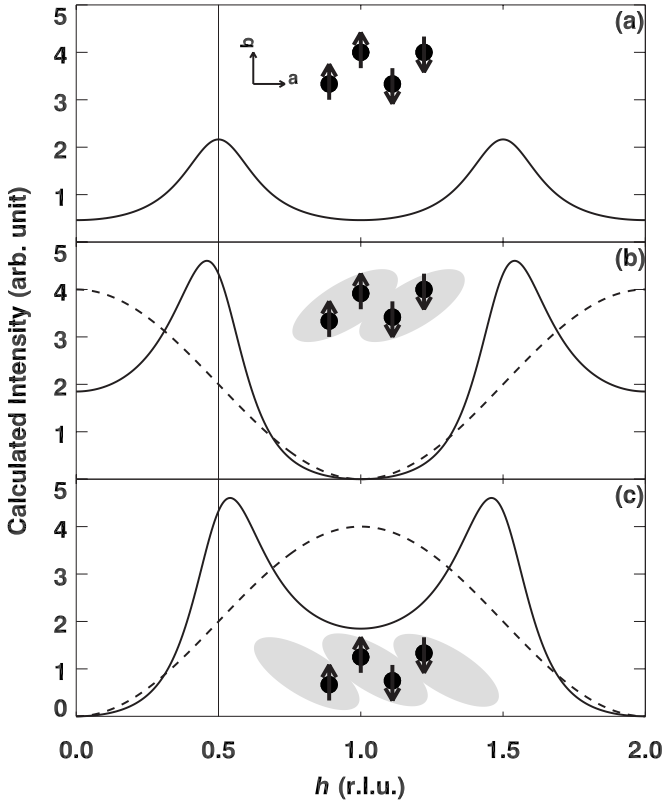
RIXS integrated over ±150 meV



H. Miao *et al.*, PNAS **114**, 12430 (2017)

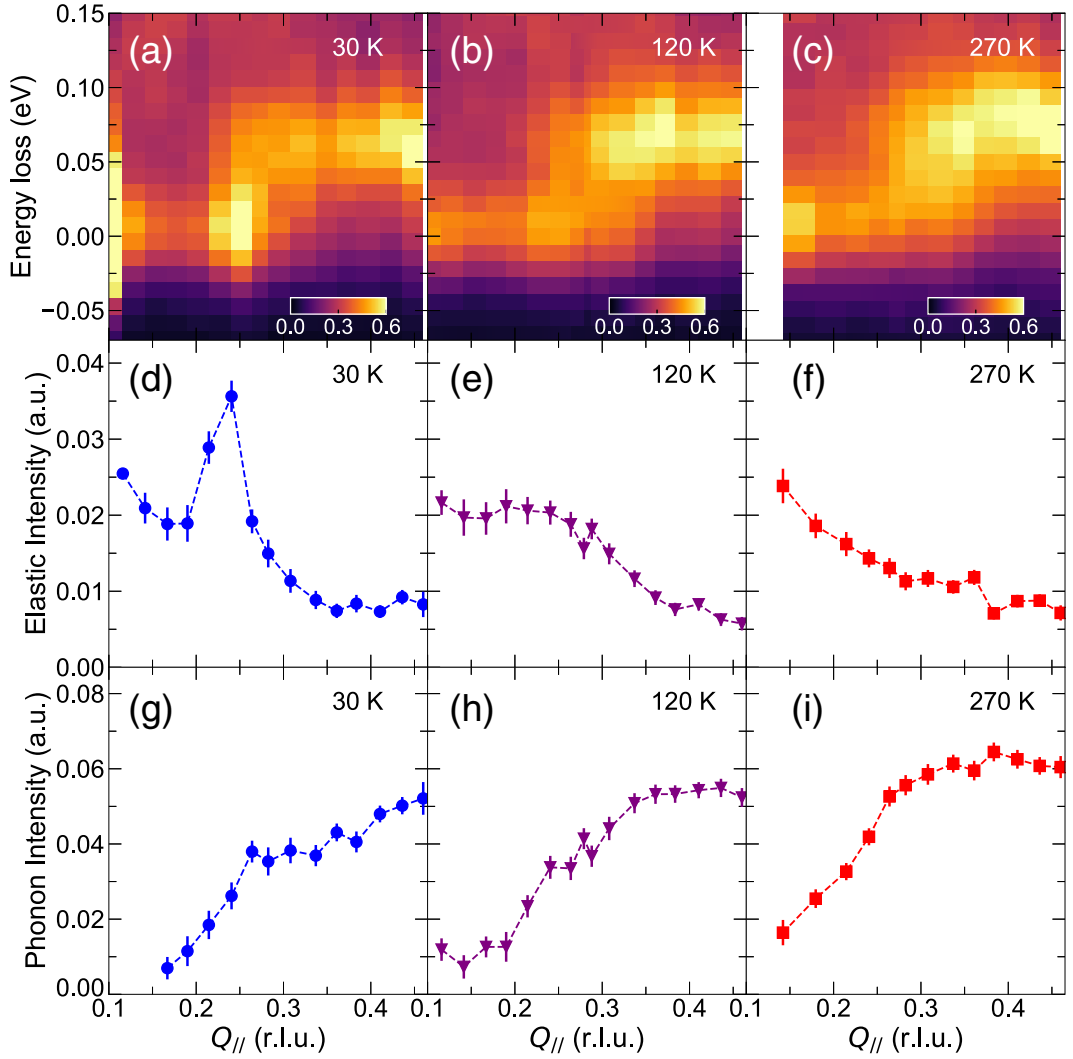
Looks can be deceiving

Model for spin correlations in disordered $Fe_{1+y}Te$



J. Wen *et al.*, PRB **80**, 104506 (2009)

RIXS (ΔE = 55 meV) on LESCO x=0.125



Y.Y. Peng *et al.*, PRL **125**, 097002 (2020)

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