

Making sense of stripes, pseudogaps, and superconductivity in cuprates

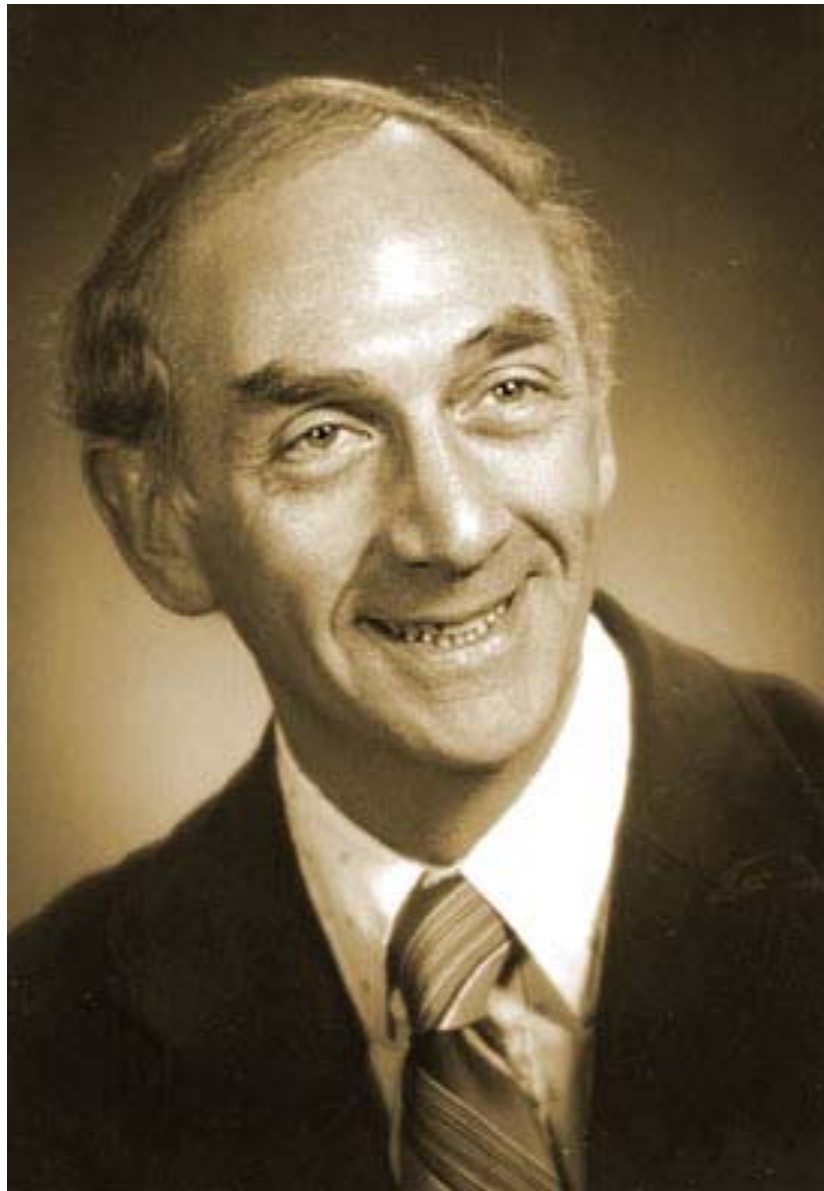
John Tranquada

ECRYS 2022

August 12, 2022

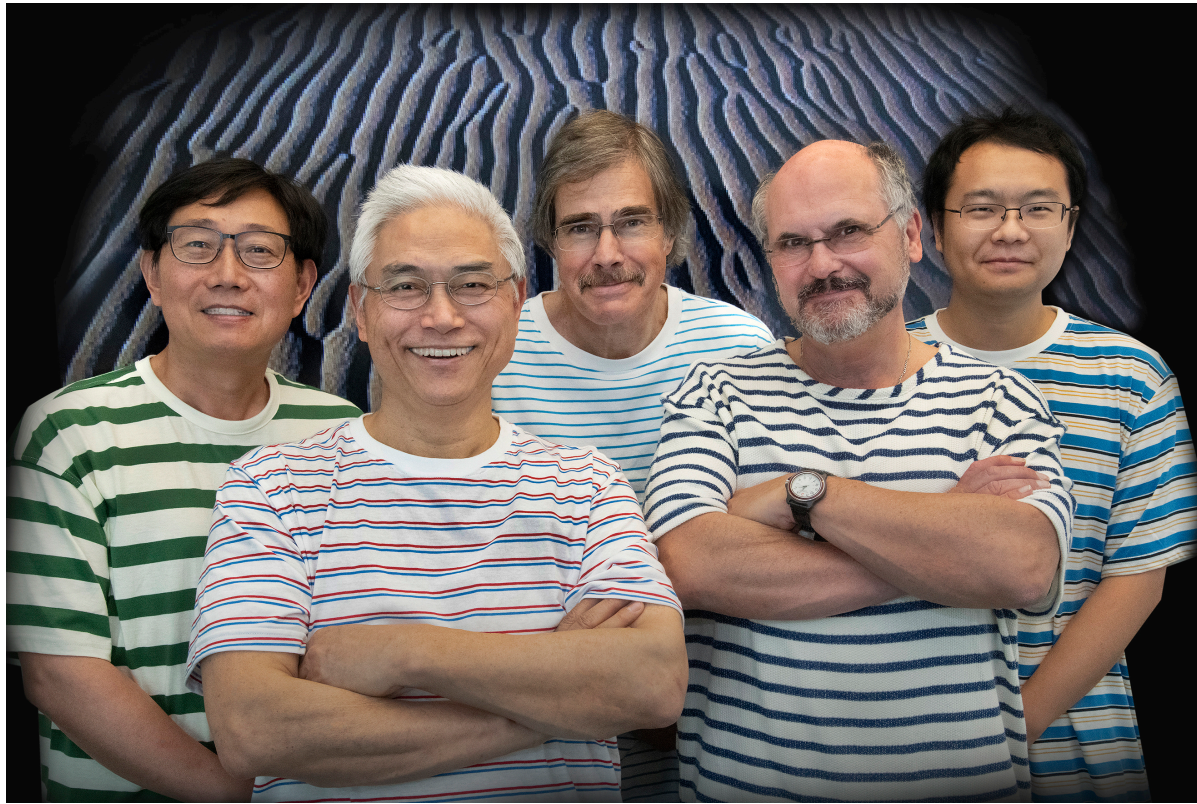


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Vic Emery

Recent collaborators



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Genda
GU

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LI



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HUCKER



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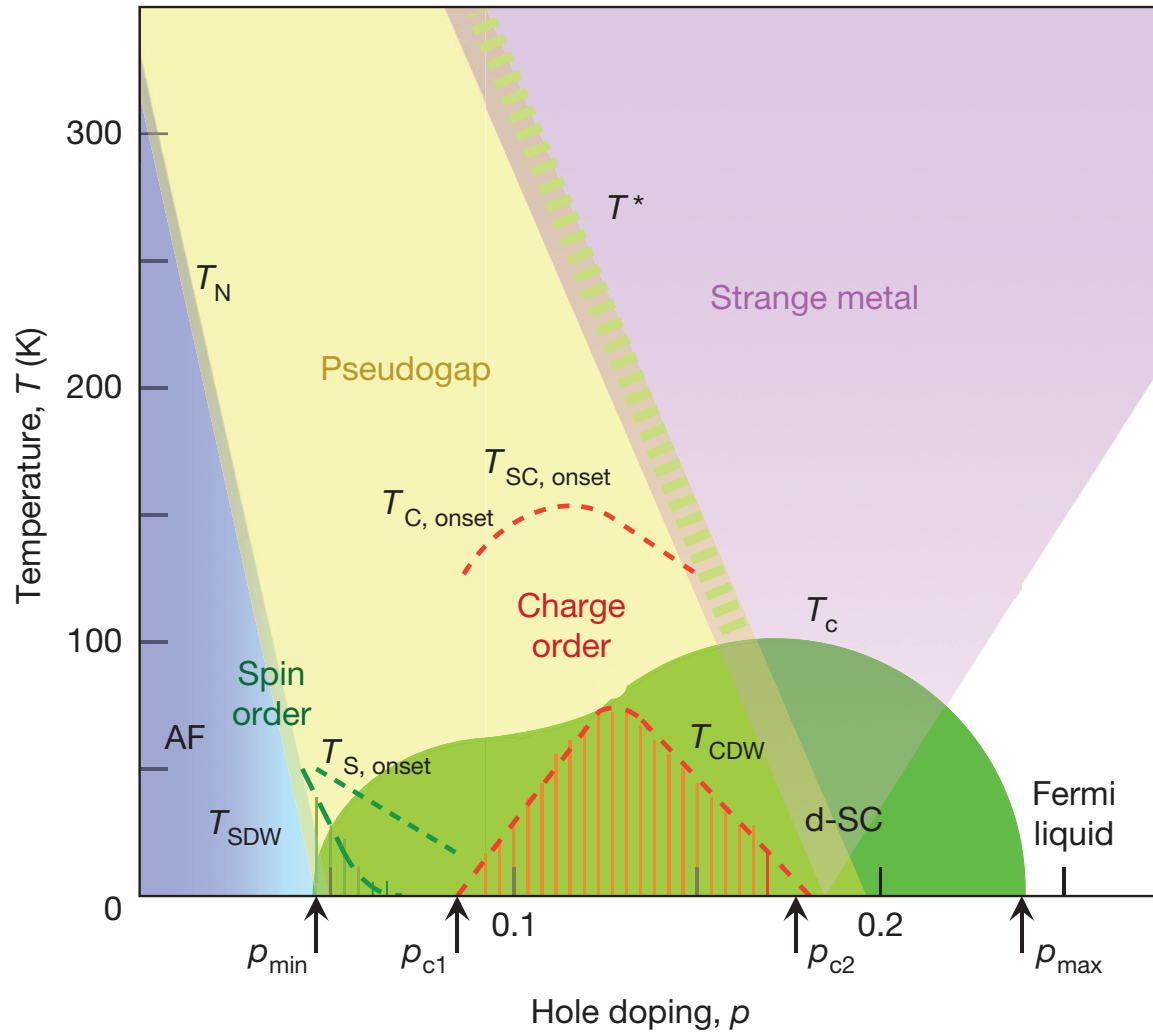


Steven
KIVELSON



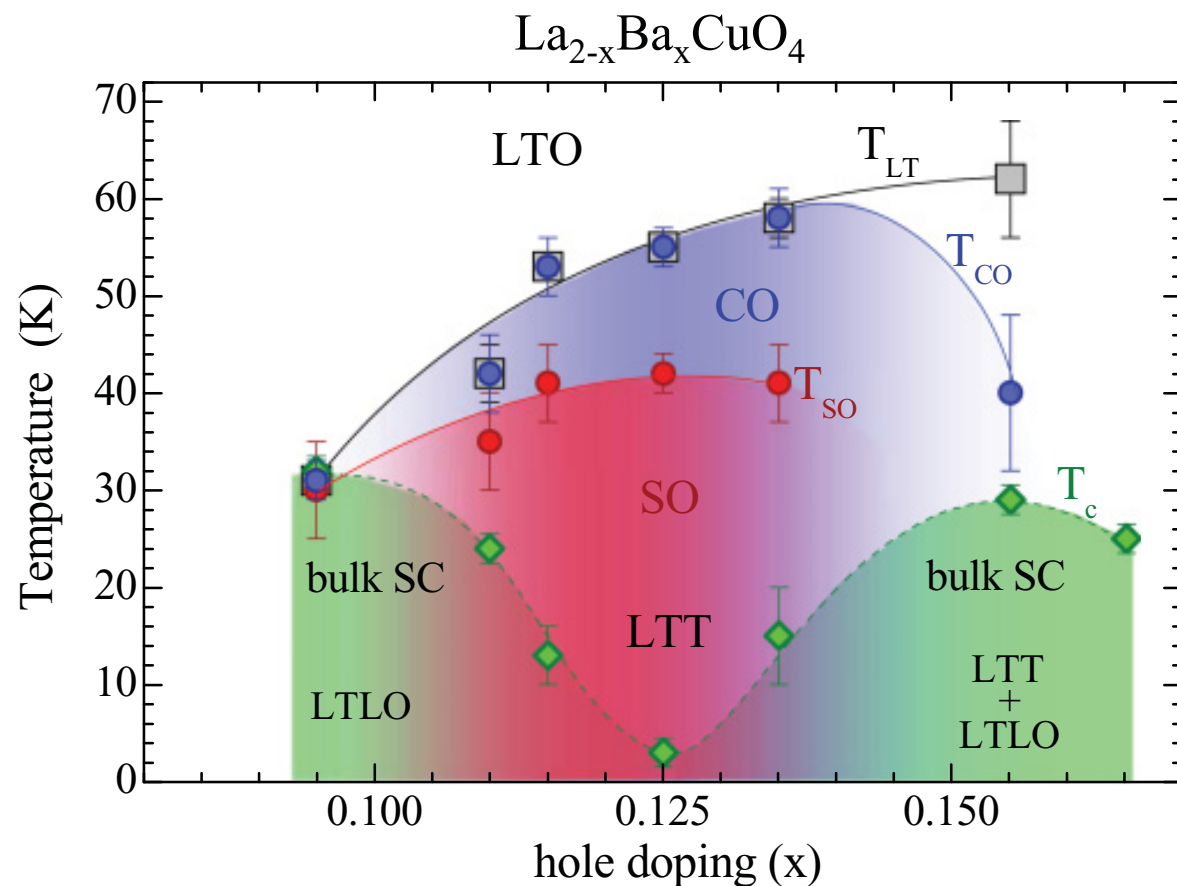
Eduardo
FRADKIN

Cuprate phase diagram

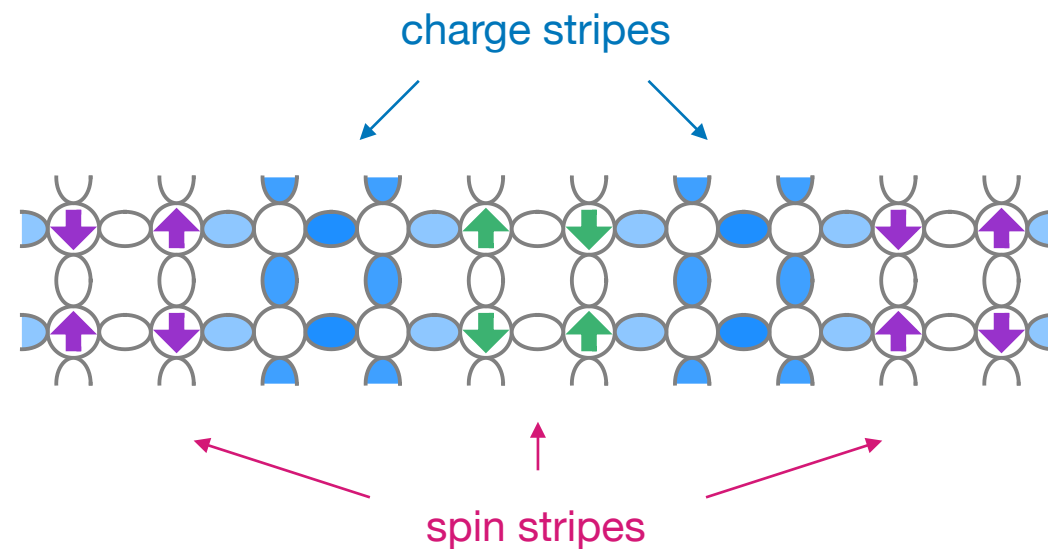


Keimer, Kivelson, Norman,
Uchida & Zaanen,
Nature **518**, 179 (2015)

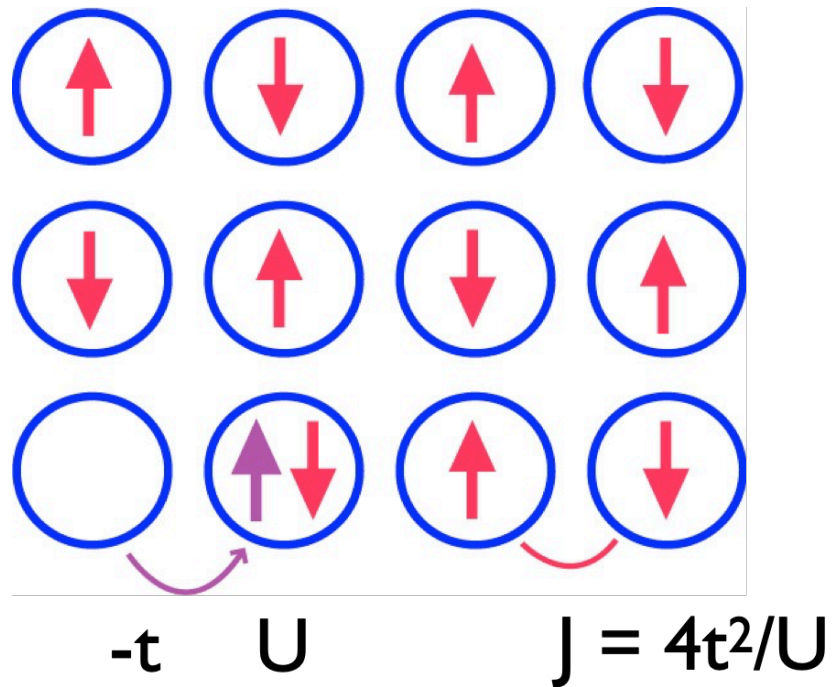
Finding the answer in an unexpected place



Hücker *et al.*, PRB **83**, 104506 (2011)

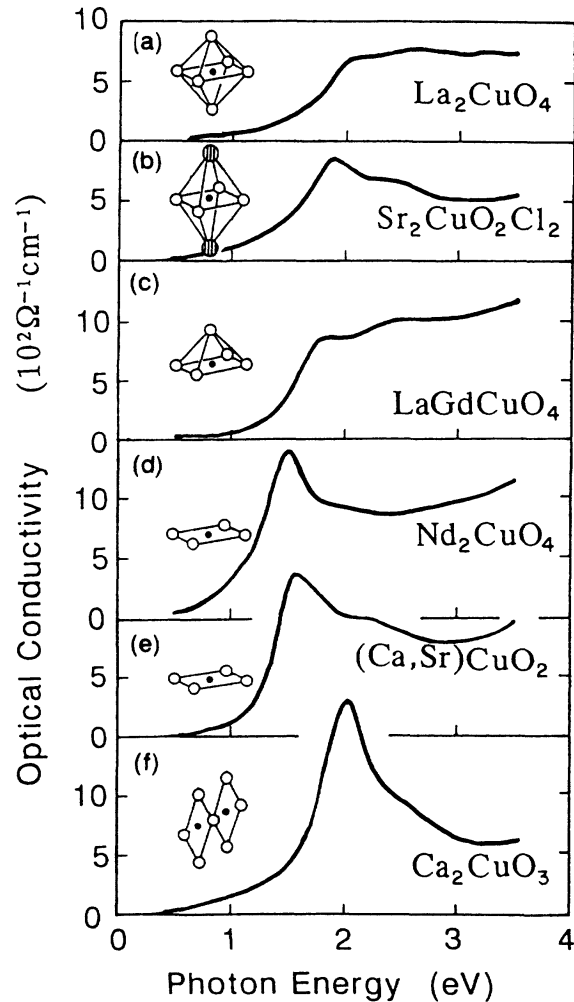


Antiferromagnetic insulator

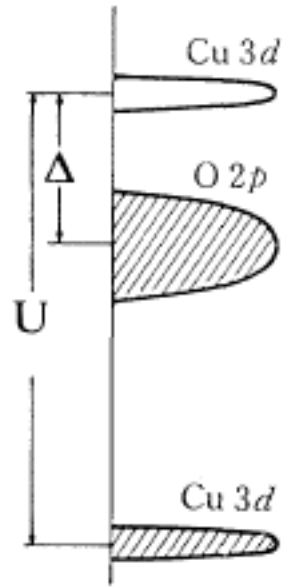


large $U \rightarrow$ localized electrons
 $t +$ Pauli excl. \rightarrow AF spin alignment
superexchange: P.W. Anderson (1959)

Charge transfer gap and doping

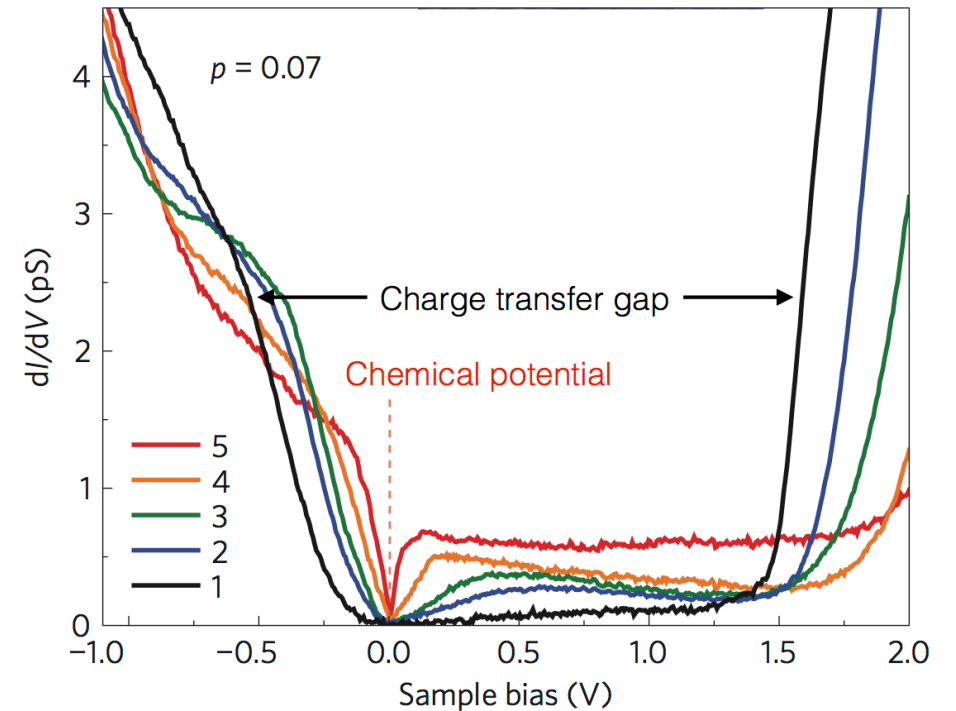


Tokura *et al.*, PRB **41**, R11657 (1990)



Uchida *et al.*,
PRB **43**, 7942 (1991)

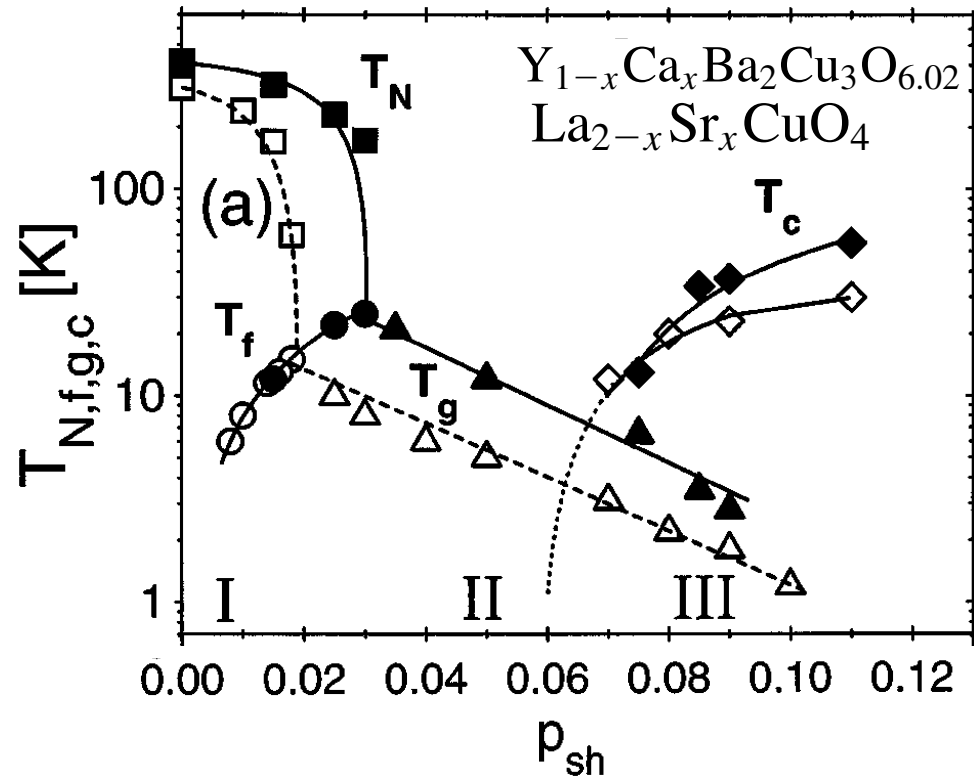
STM on underdoped
 $\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$



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

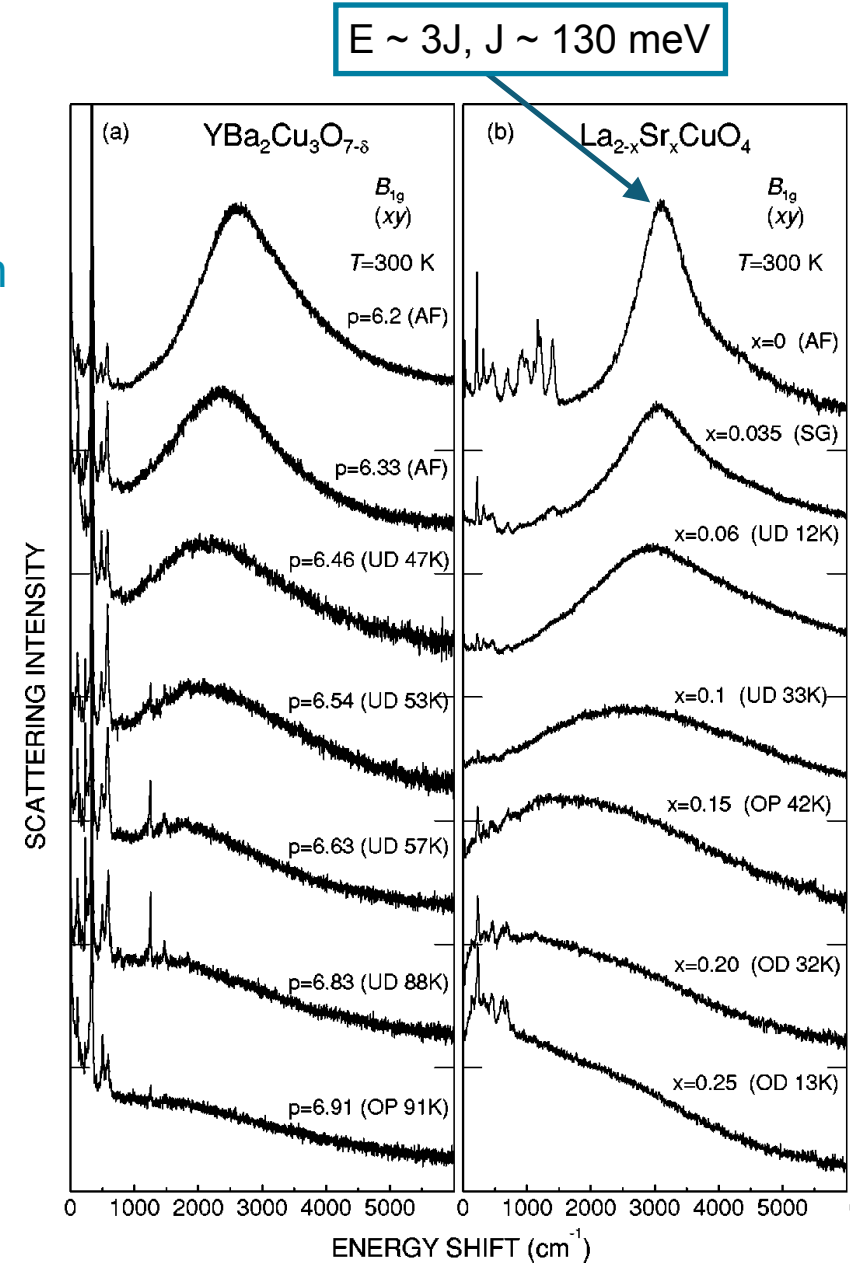
Impact of holes on AF correlations

Muon spin rotation, in zero field



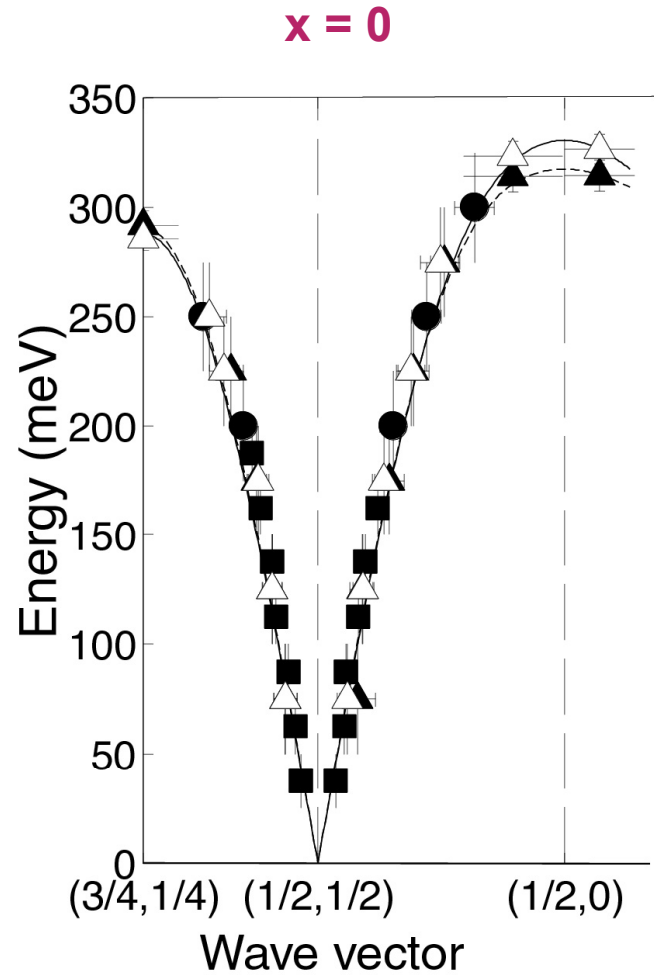
Niedermayer *et al.*, PRL **80**, 3843 (1998)

2-magnon Raman scattering

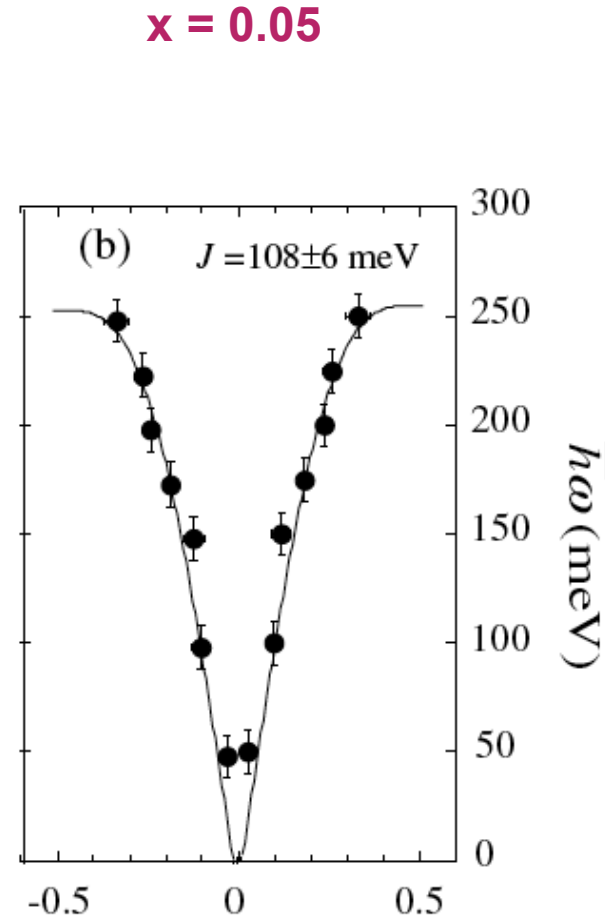


Sugai *et al.*, PRB **68**, 184504 (2003)

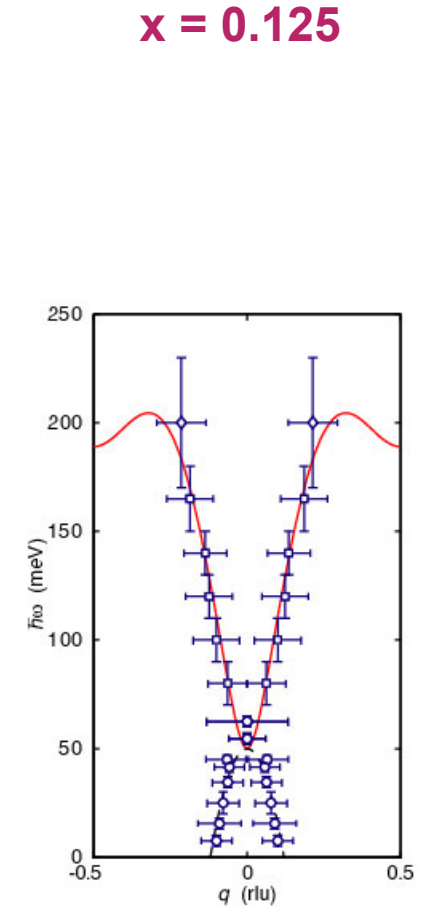
Spin excitations in $\text{La}_{2-x}(\text{Sr,Ba})_x\text{CuO}_4$



Coldea *et al.*,
PRL (2001)

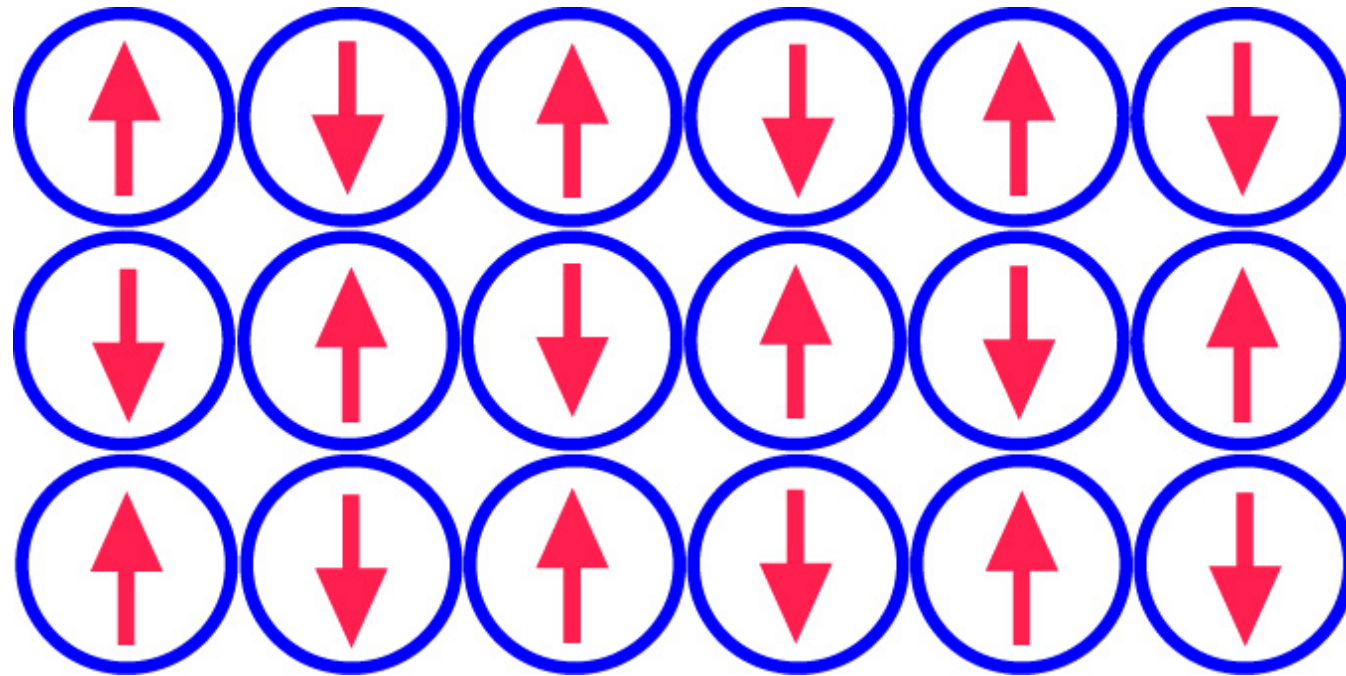


Goka *et al.*,
Physica C (2003)

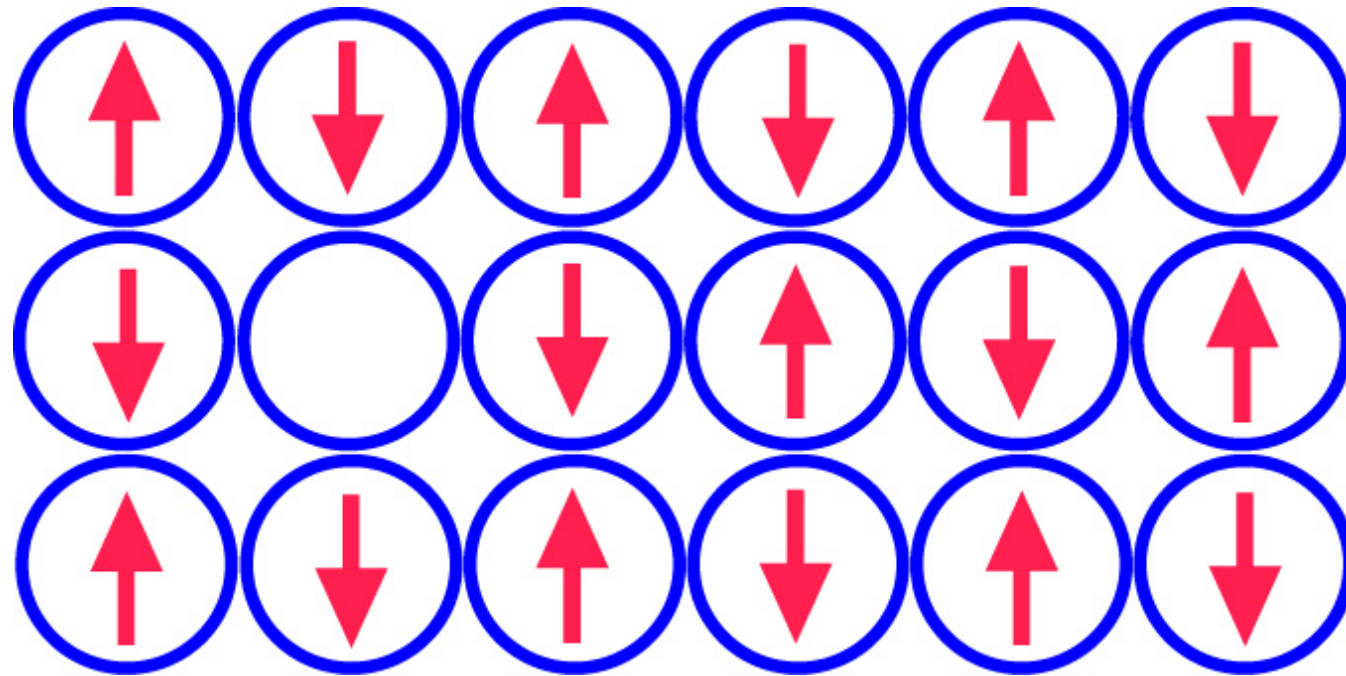


JMT *et al.*,
Nature (2004)

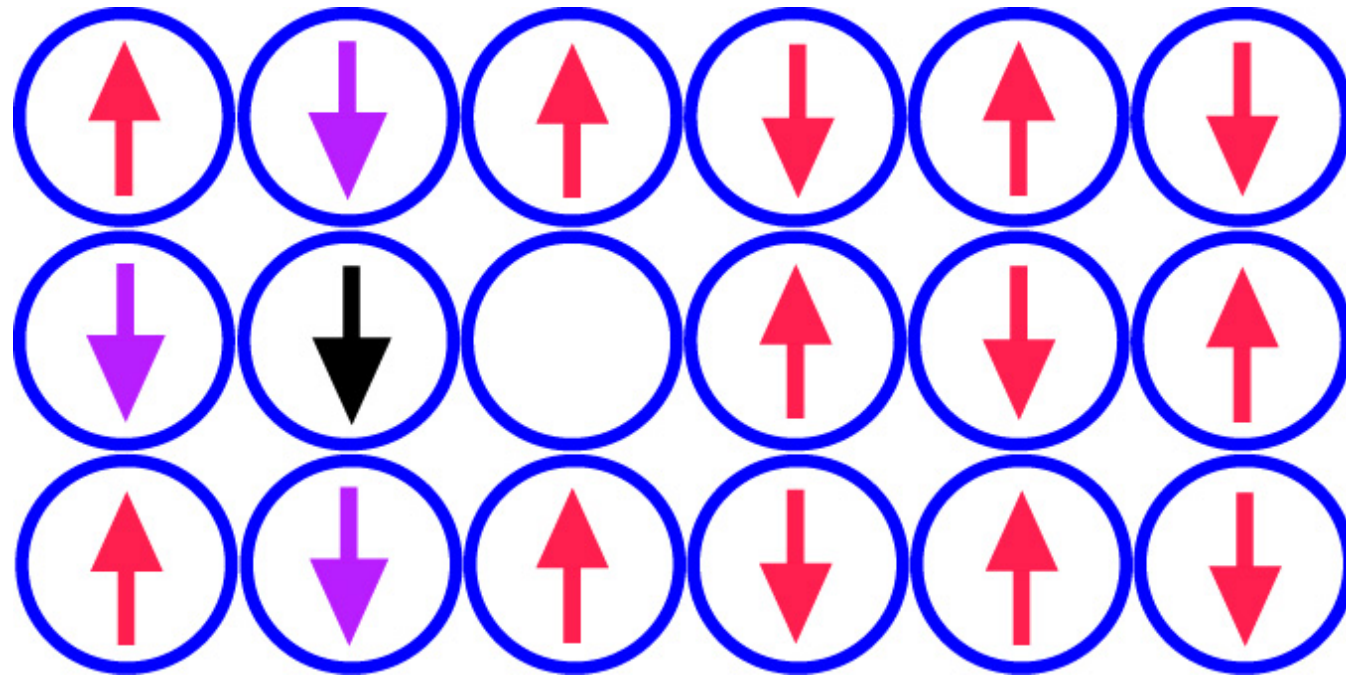
Competition between t and J



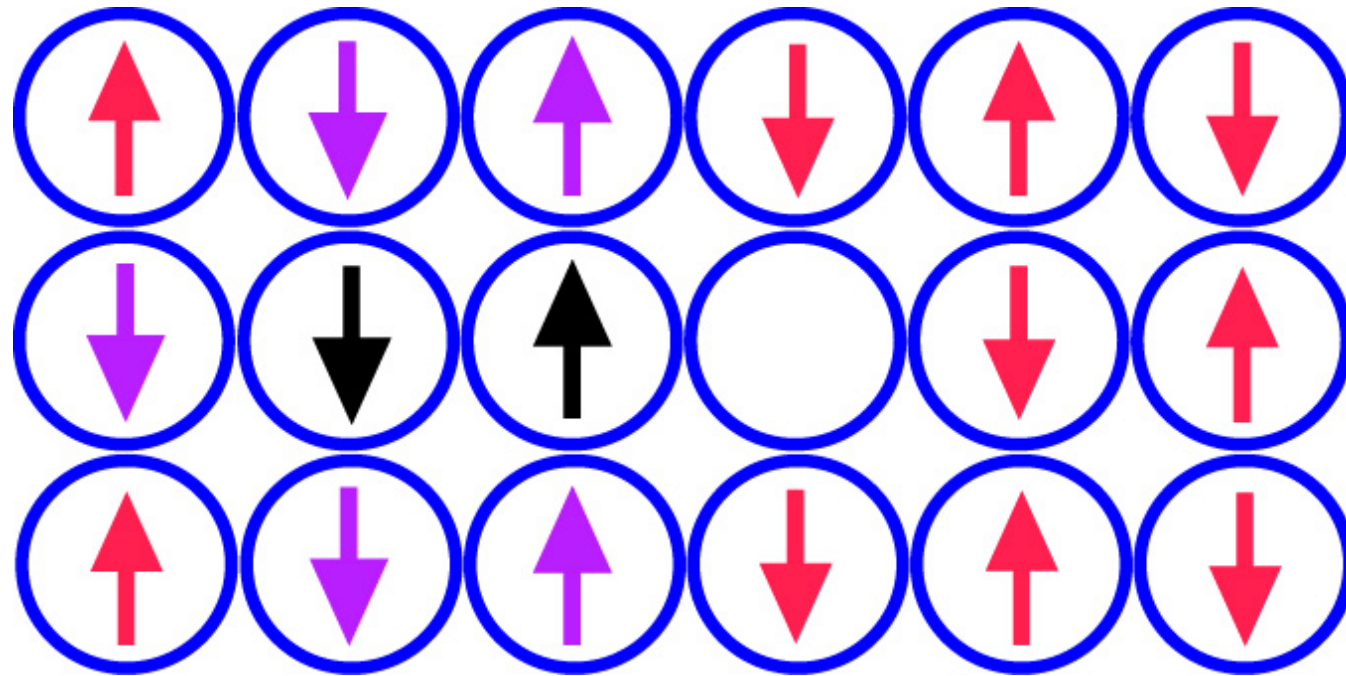
Competition between t and J



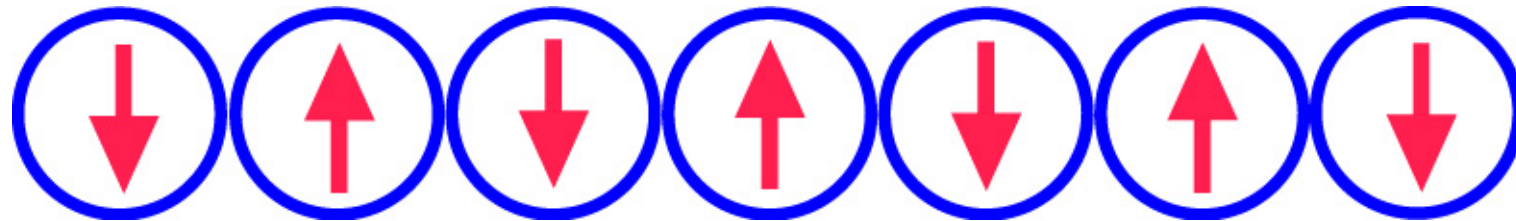
Competition between t and J



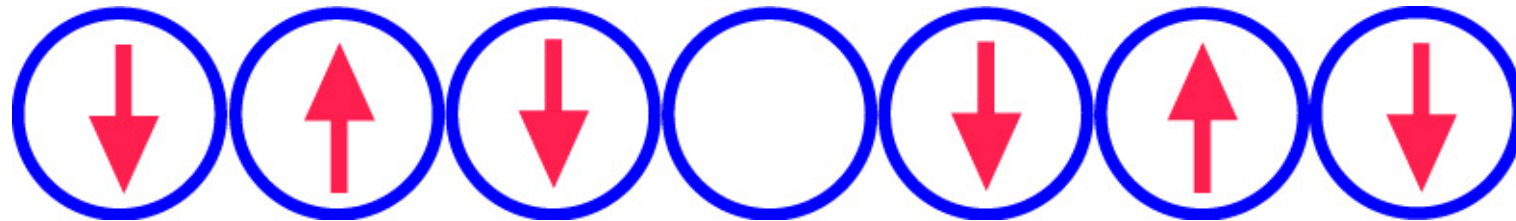
Competition between t and J



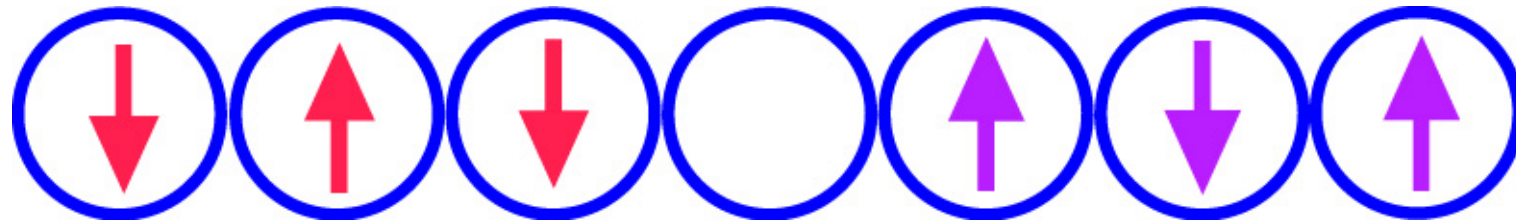
Cooperative hole and spin correlations



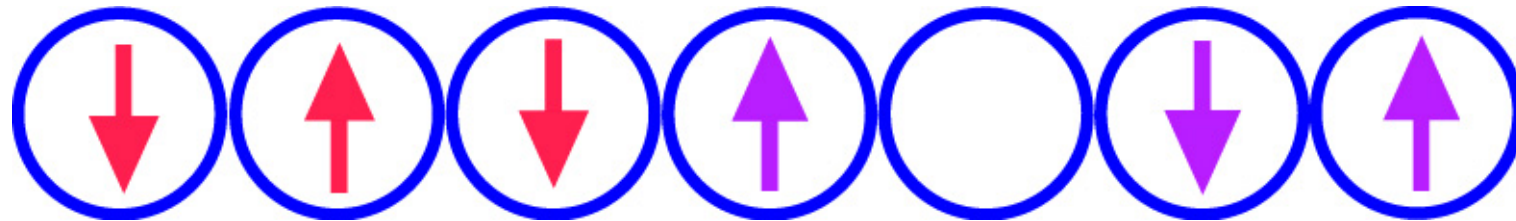
Cooperative hole and spin correlations



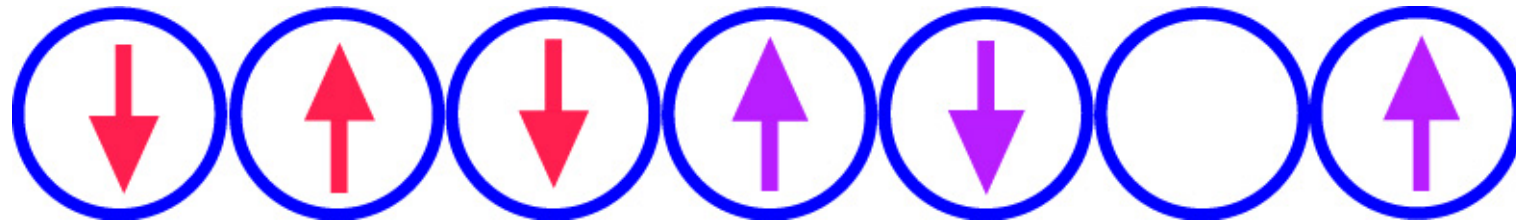
Cooperative hole and spin correlations



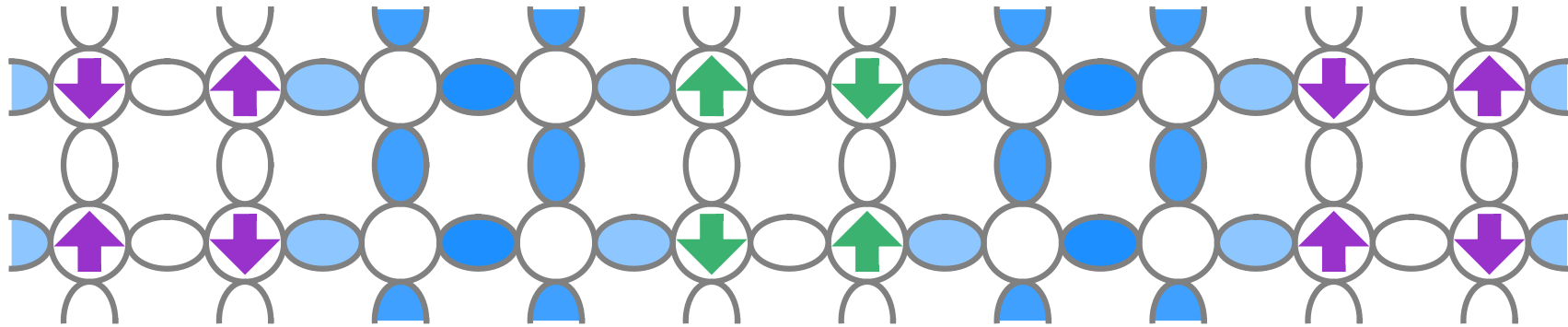
Cooperative hole and spin correlations



Cooperative hole and spin correlations

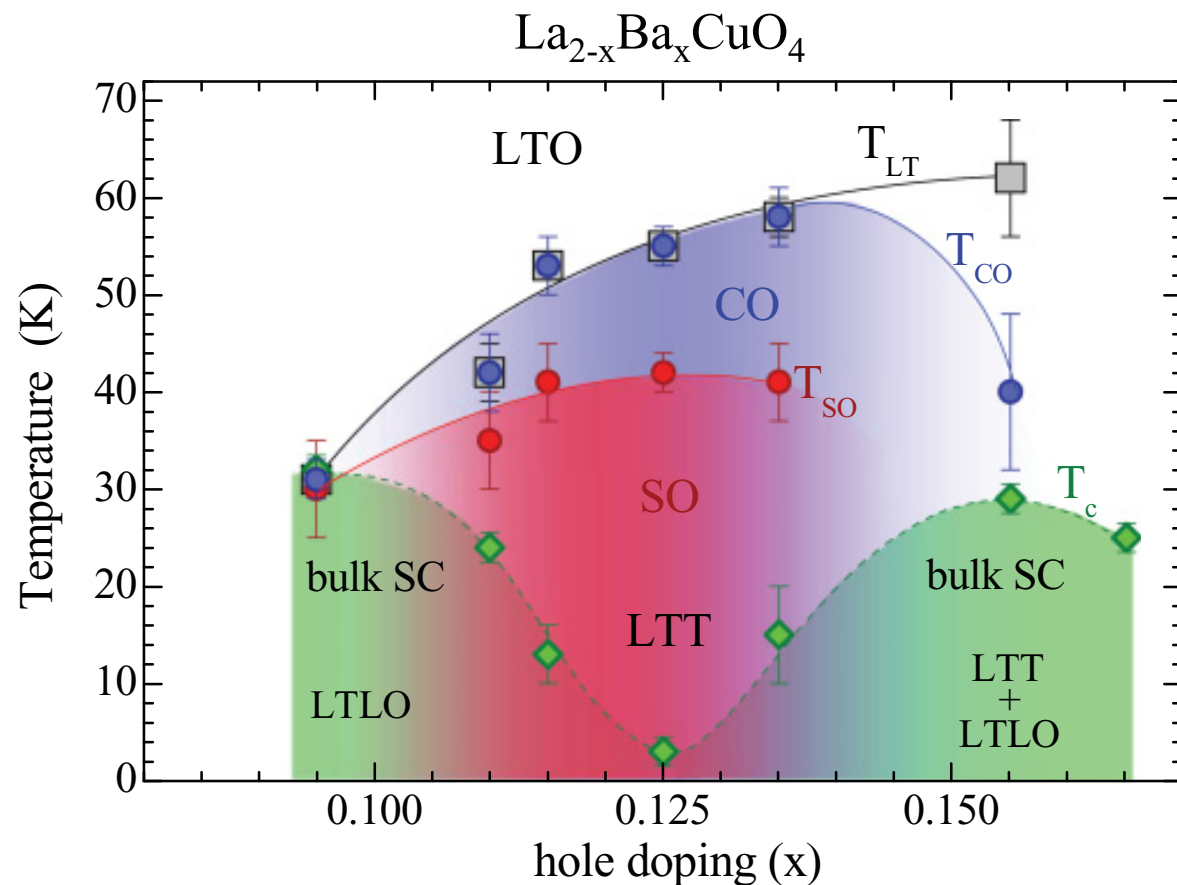


Spin and charge stripe order

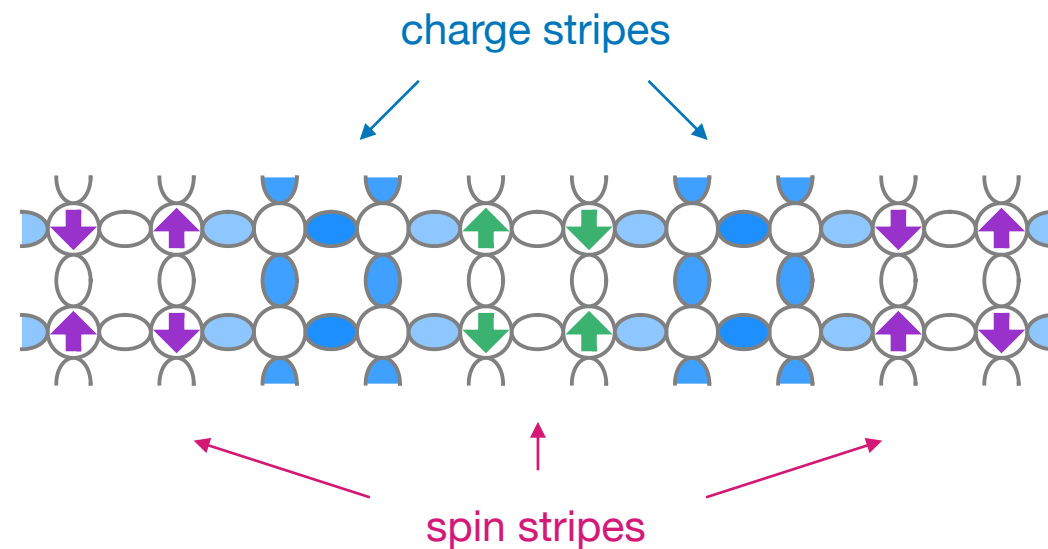


1 hole / 4 Cu sites

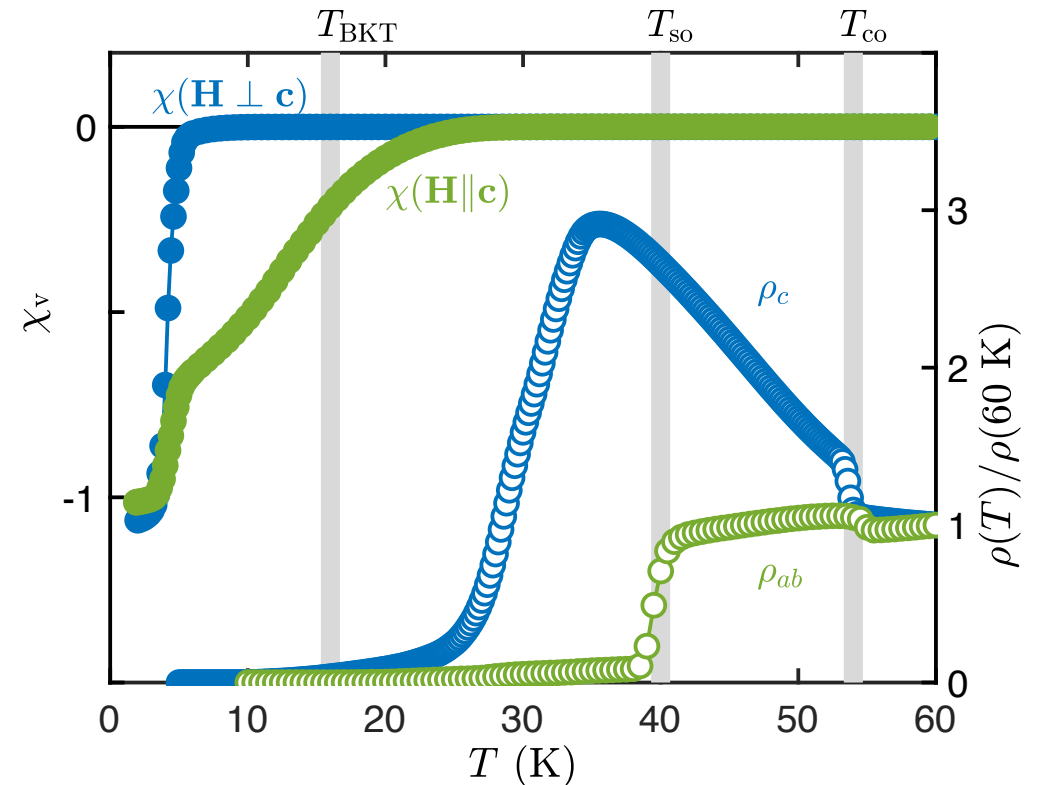
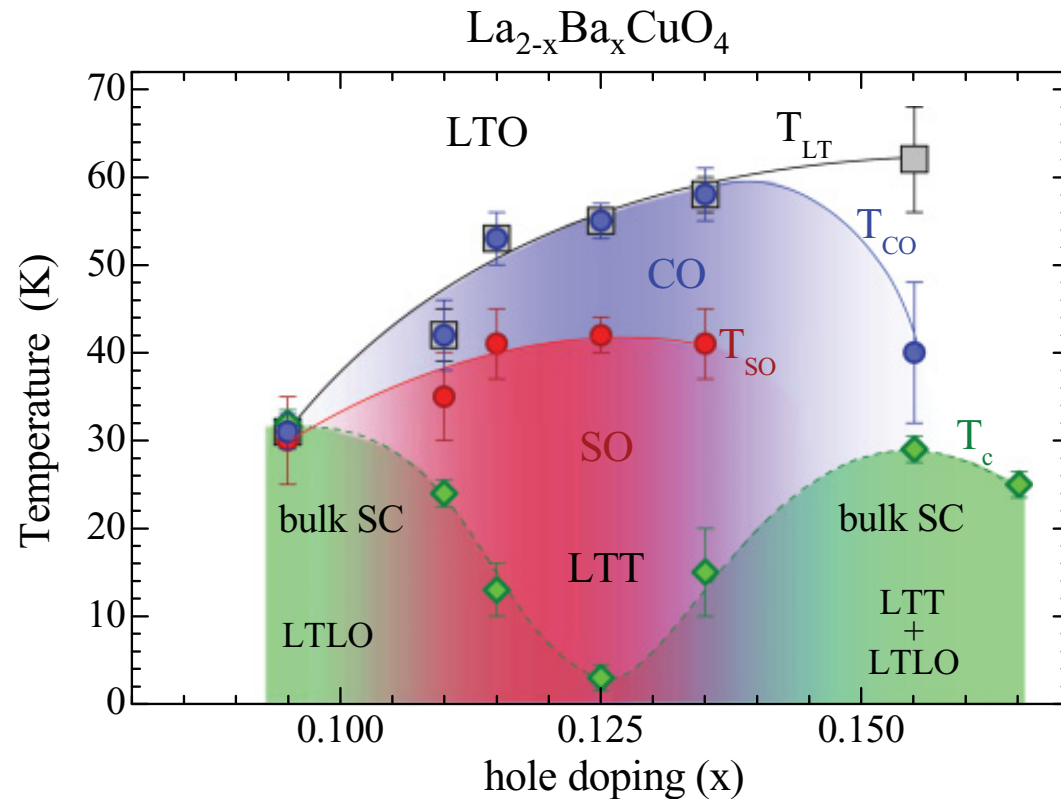
Charge stripe order competes with 3D SC order



Hücker *et al.*, PRB **83**, 104506 (2011)



But charge stripes coexist with 2D superconductivity



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

Holes remain paired in high field

LBCO $x = 1/8$ in a c -axis magnetic field

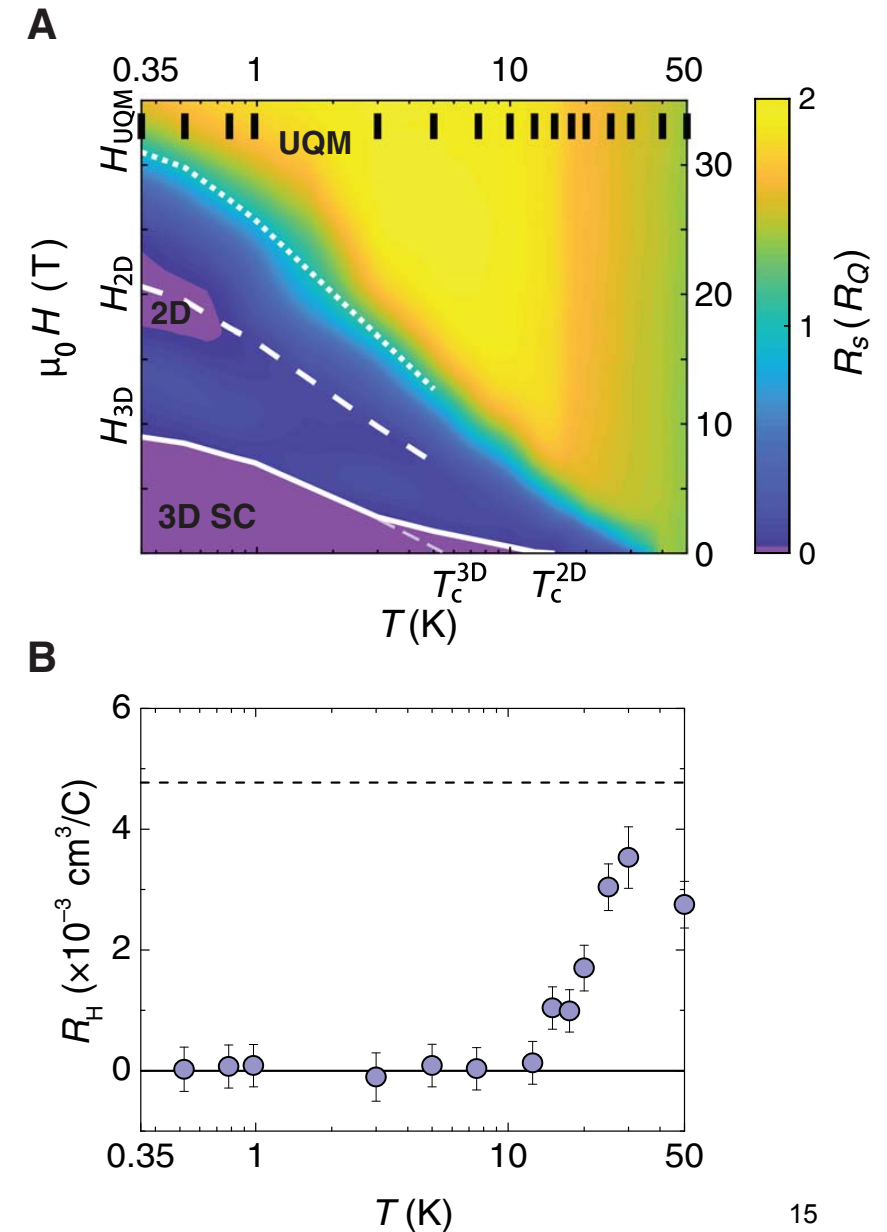
● Sheet resistance saturates at high field

* Ultra-Quantum Metal phase

● Hall constant remains negligible at high field

* Particle-hole symmetry in UQM phase

Y. Li *et al.*, *Sci. Adv.* **5**, eaav7686 (2019)



Charge stripes and superconductivity

C. Castellani, C. Di Castro, and M. Grilli, Z. Phys. B **103**, 137 (1997).

“Non-Fermi-liquid behavior and *d*-wave superconductivity near the CDW QCP”

S. Caprara, C. Di Castro, G. Seibold, and M. Grilli, Phys. Rev. B **95**, 224511 (2017).

“Dynamical CDWs rule the phase diagram of cuprates”

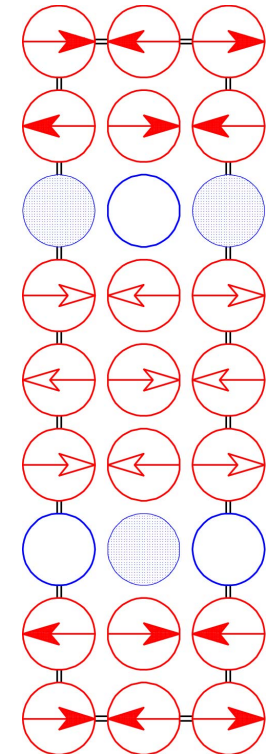
V.J. Emery, S.A. Kivelson, and O. Zachar, Phys. Rev. B **56**, 6120 (1997).

“Spin-gap proximity effect mechanism of high-temperature superconductivity”

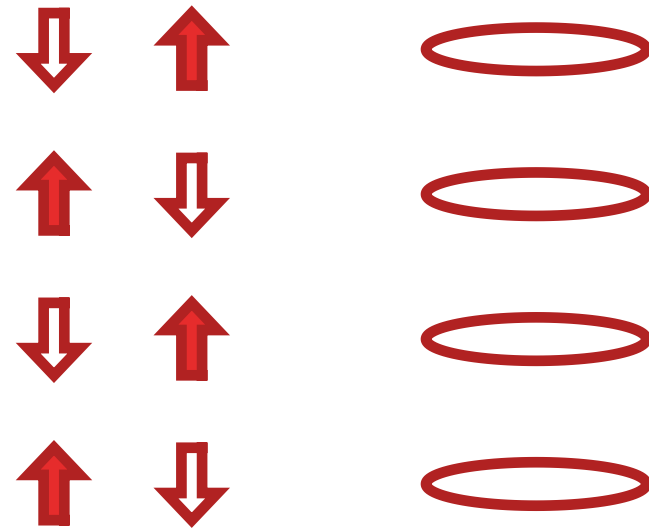
Charge stripe = 1D electron gas

Spin gap from environment induces pairing correlations

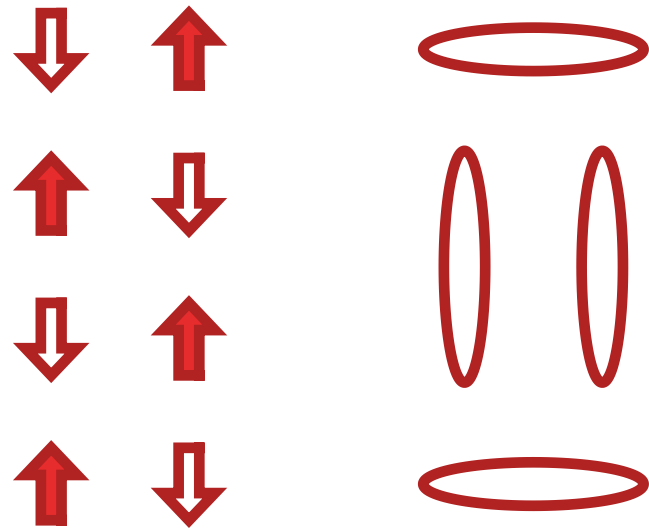
Problem: cannot explain SC in LBCO at $x=1/8$
Spin-stripe order so no spin gap



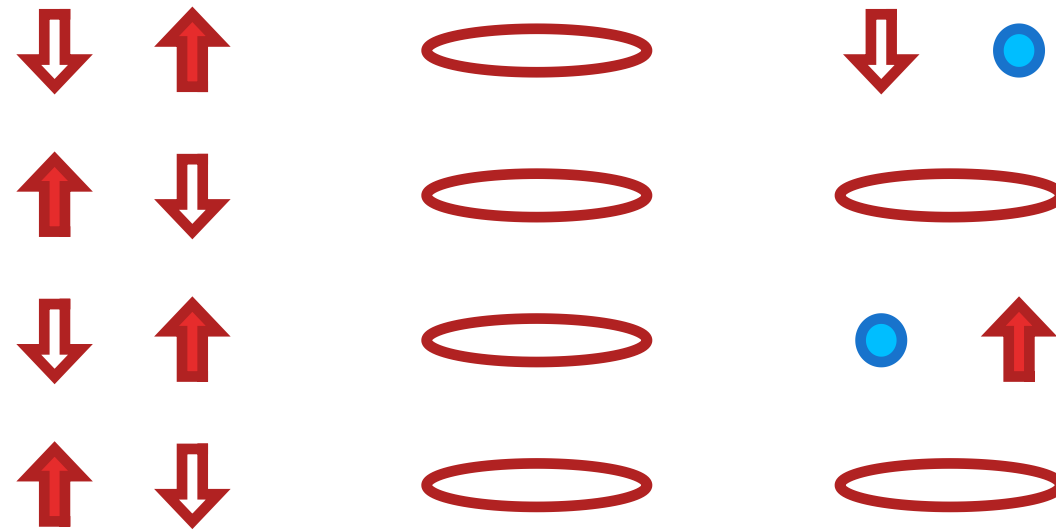
Solution: Charge stripes as doped 2-leg spin ladders



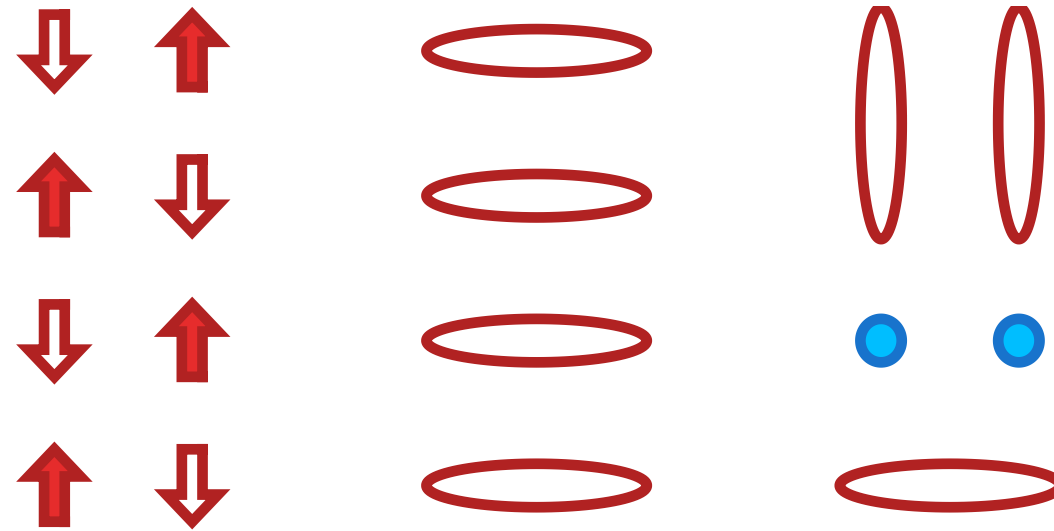
Solution: Charge stripes as doped 2-leg spin ladders



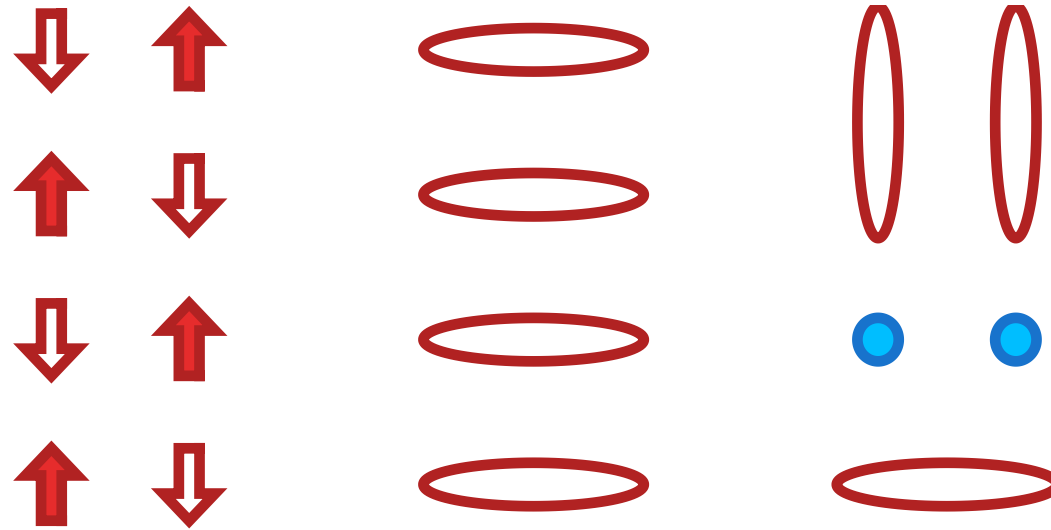
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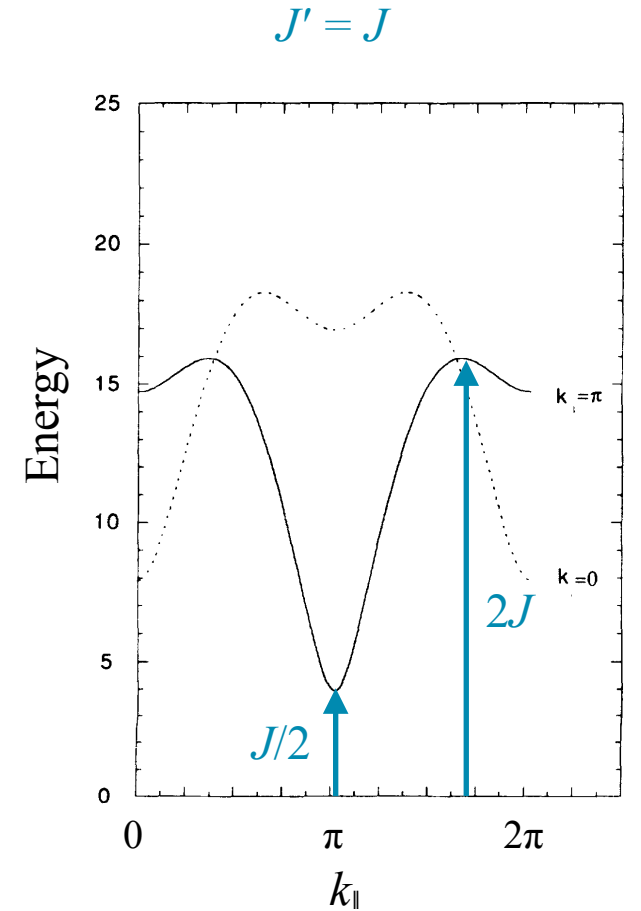


Solution: Charge stripes as doped 2-leg spin ladders



E. Dagotto, J. Riera, D. Scalapino, PRB **45**, 5744 (1992).
 “Superconductivity in ladders and coupled planes”

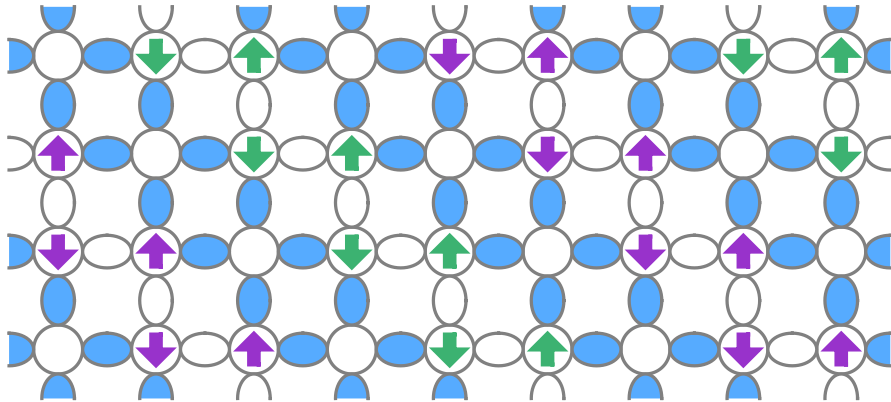
E. Dagotto and T.M. Rice, Science **271**, 618 (1996).
 “Surprises on the Way from 1D to 2D Quantum Magnets”



Barnes+Riera, PRB **50**, 6817 (1994)

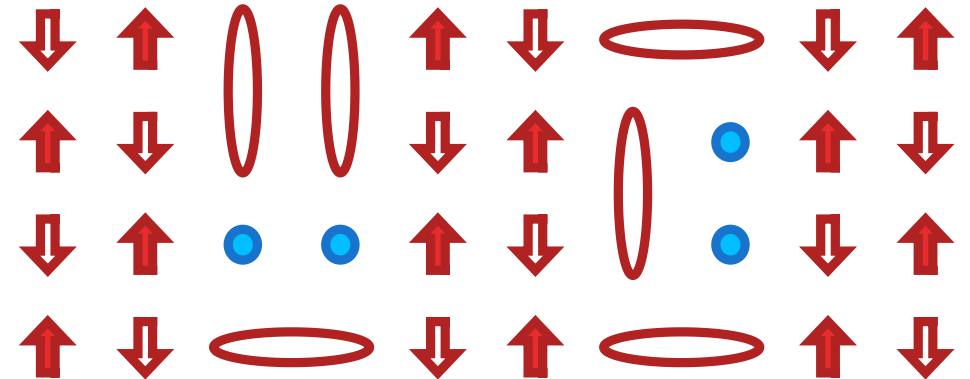
Charge stripes have spin excitations

$\text{La}_{2-x}\text{Sr}_x\text{NiO}_4$ with $x = 1/3$



Gapless 1D spin excitations

$\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$ with $x = 1/8$



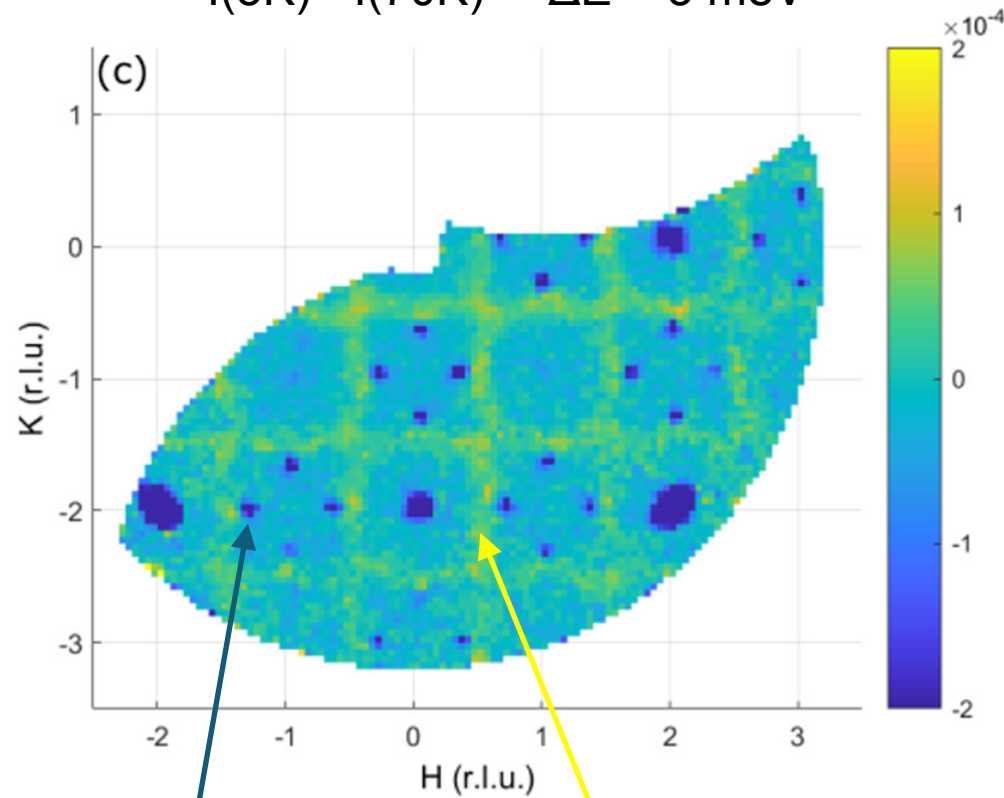
Large spin gap on charge stripes

1D spin excitations on charge stripes

First detected by:
A.T. Boothroyd *et al.*,
PRL **91**, 257201 (2003)



$I(5\text{K}) - I(70\text{K})$ $\Delta E = 3 \text{ meV}$

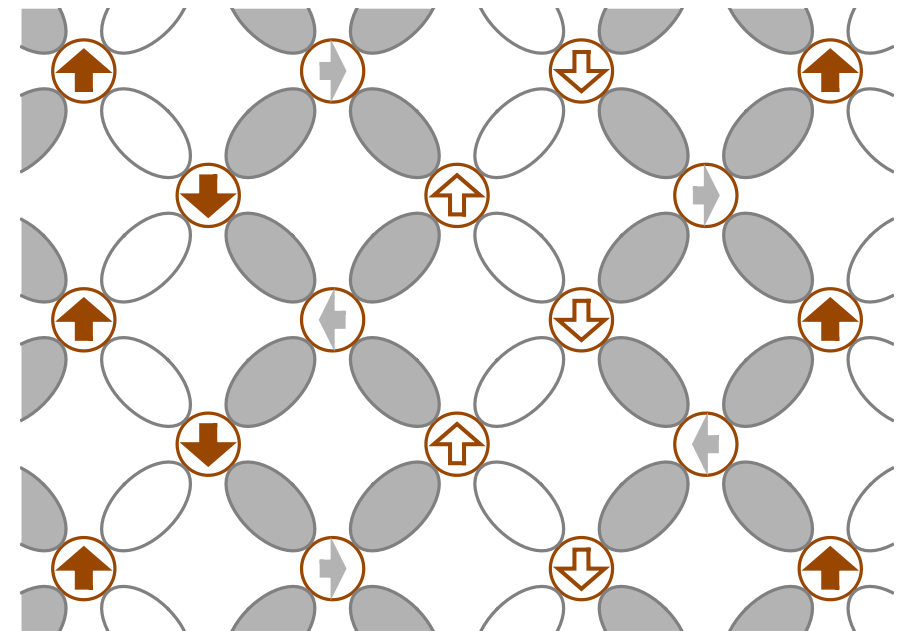


Data from
HYSPEC

3D spin-stripe
excitations

1D excitations
on charge stripes

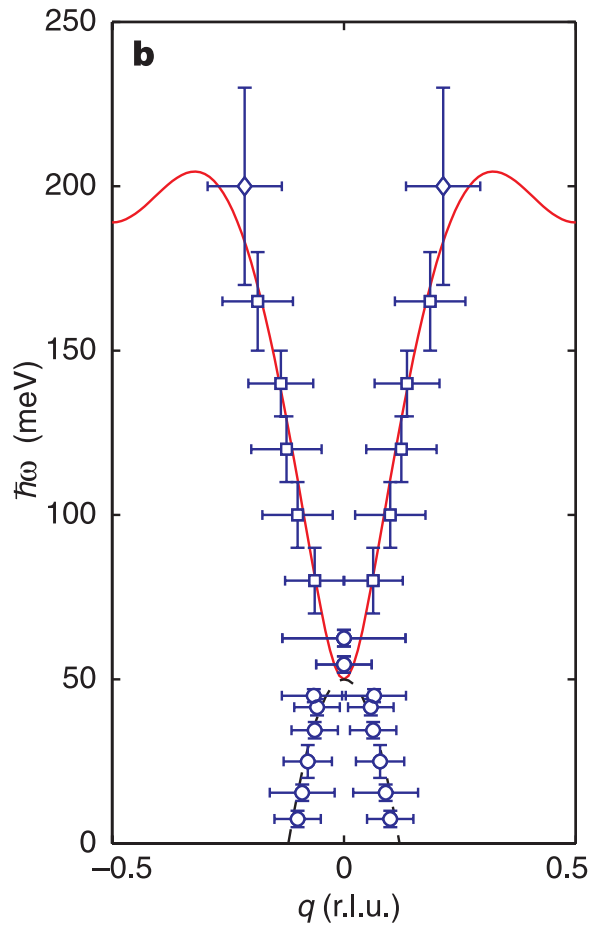
Ni^{2+} $\text{Ni}^{2++\text{hole}}$
 $S = 1$ $S = 1/2$



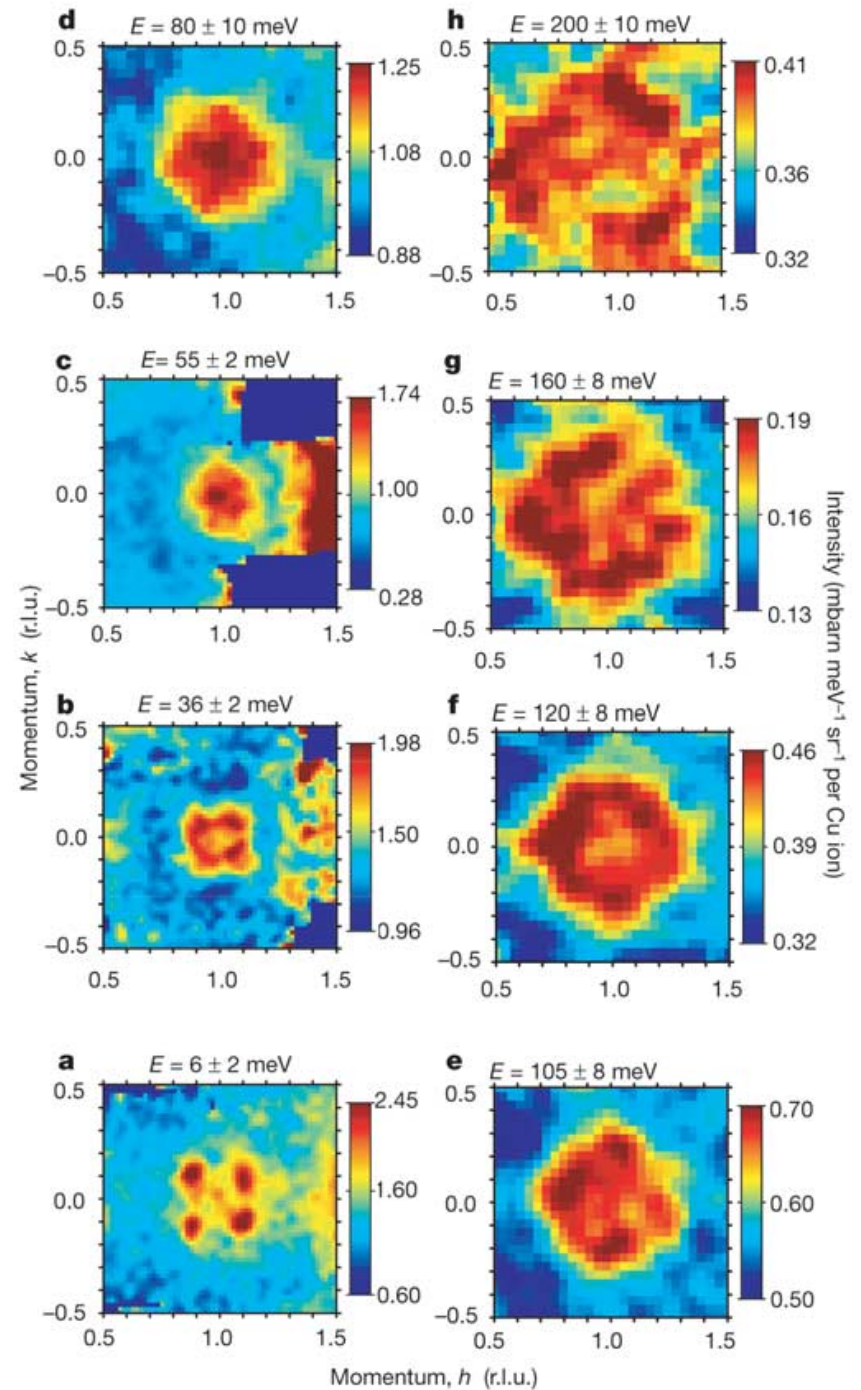
Geometric frustration decouples
spin excitations on charge stripes

A.M. Merritt *et al.*, Phys. Rev. B **100**, 195122 (2019)

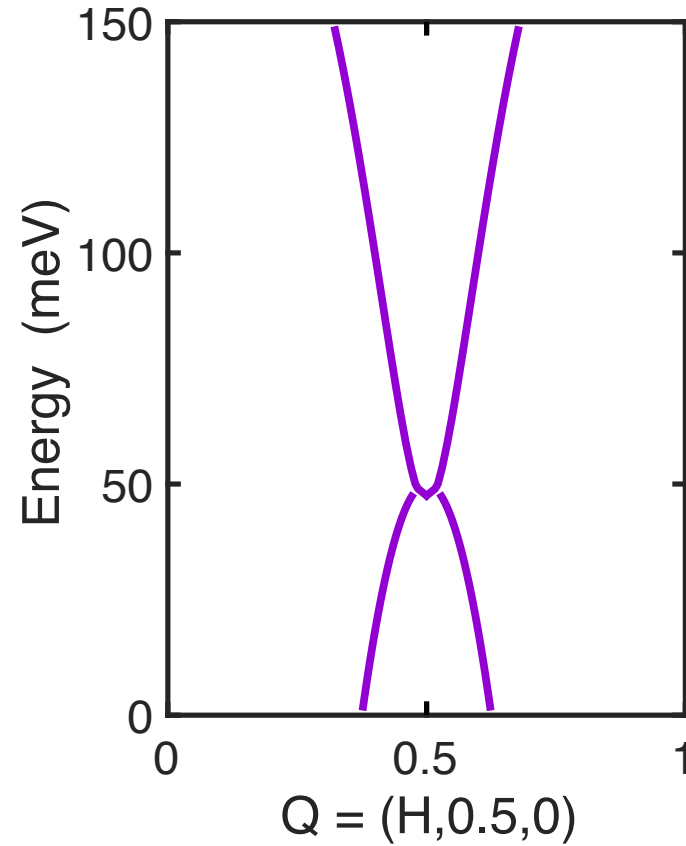
LBCO $x = 1/8$



Nature **429**, 534 (2004)



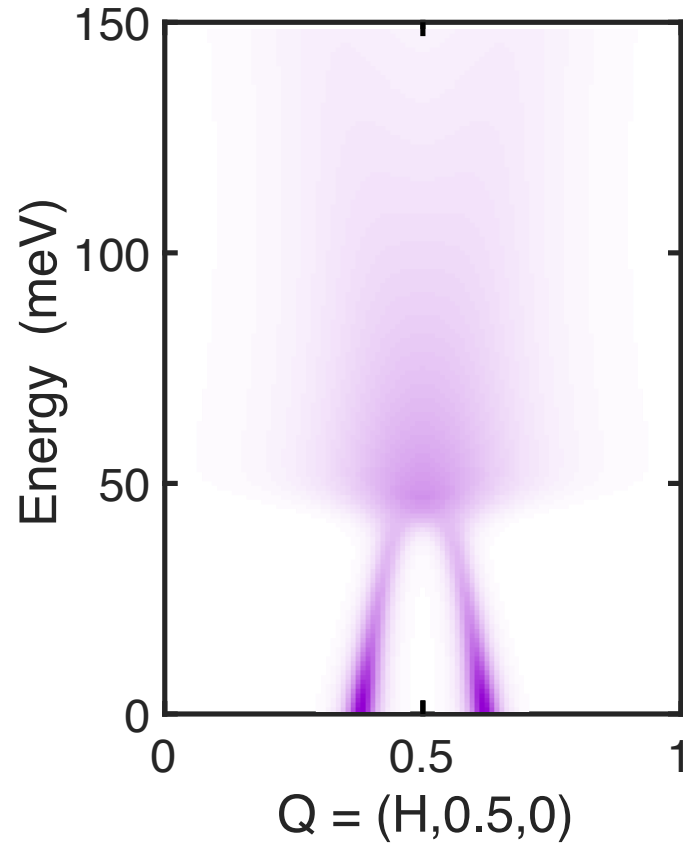
LBCO $x=1/8$: New analysis of spin excitations



LBCO: JMT *et al.*, Nature **429**, 163 (2004)
LSCO: Vignolle *et al.*, Nat. Phys. **3**, 163 (2007)

JMT, Adv. Phys. **69**, 437 (2020)

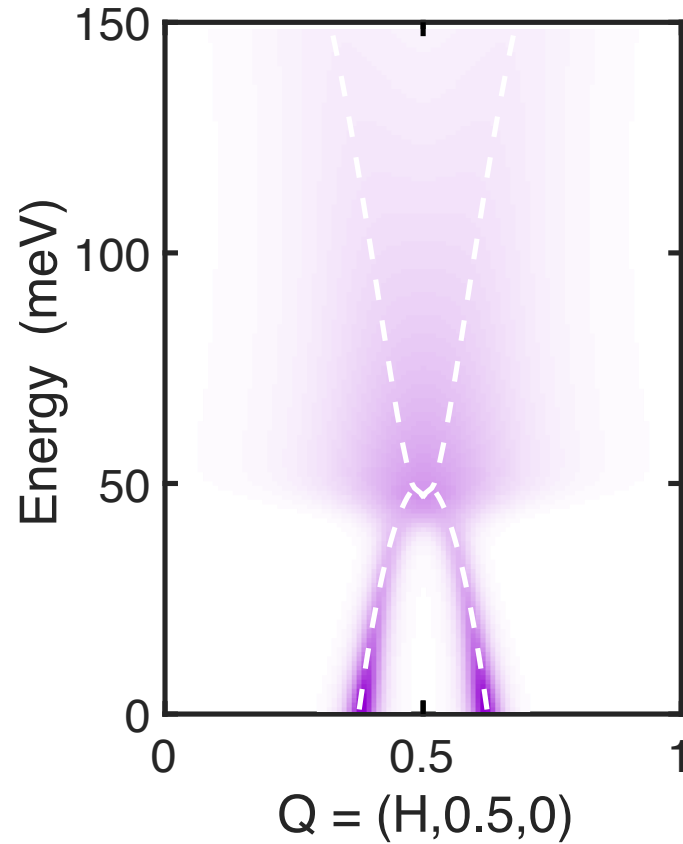
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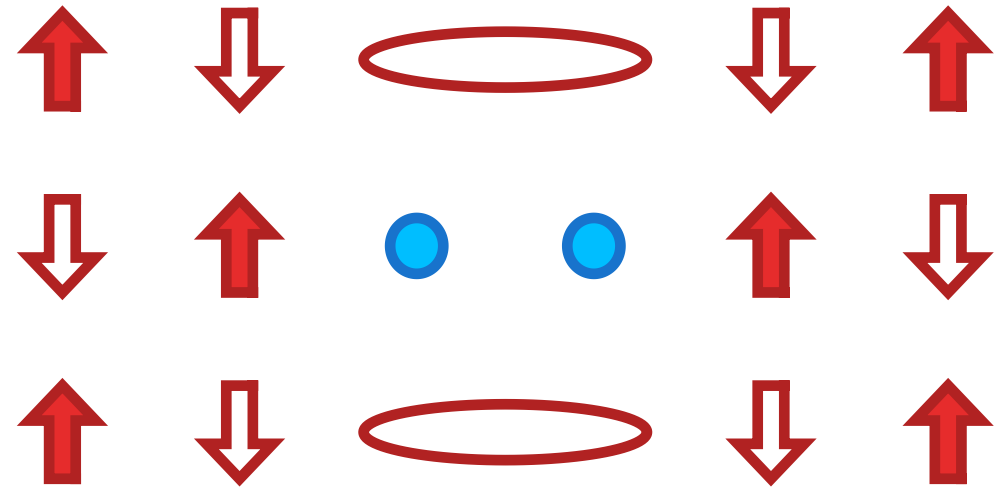
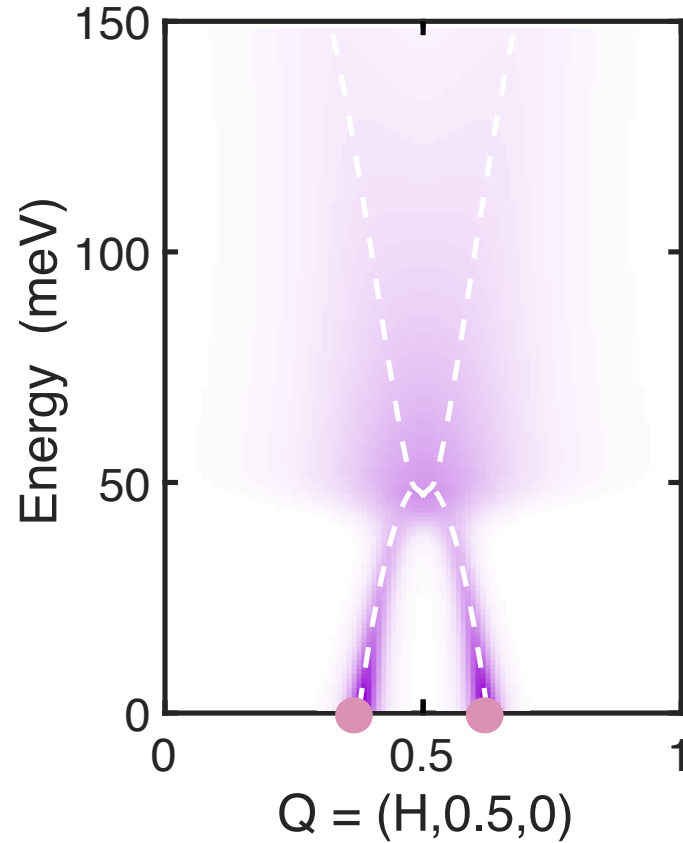
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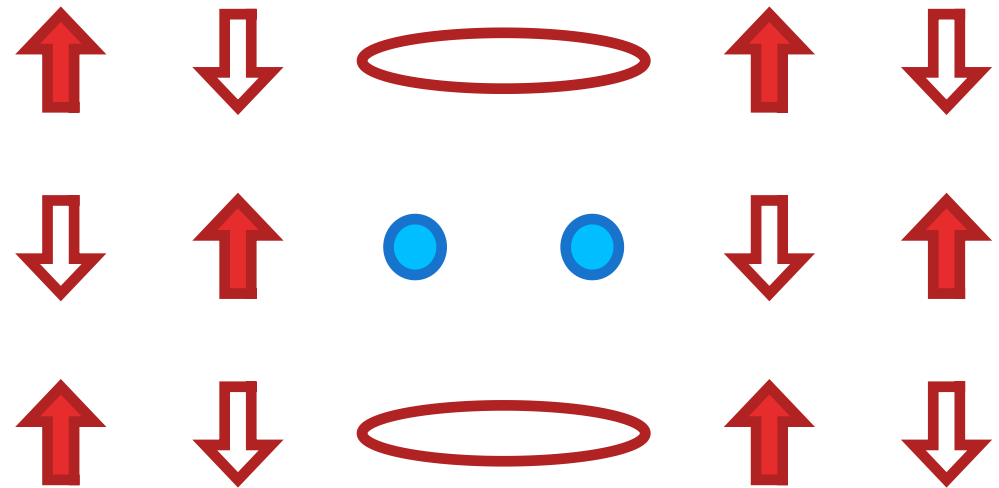
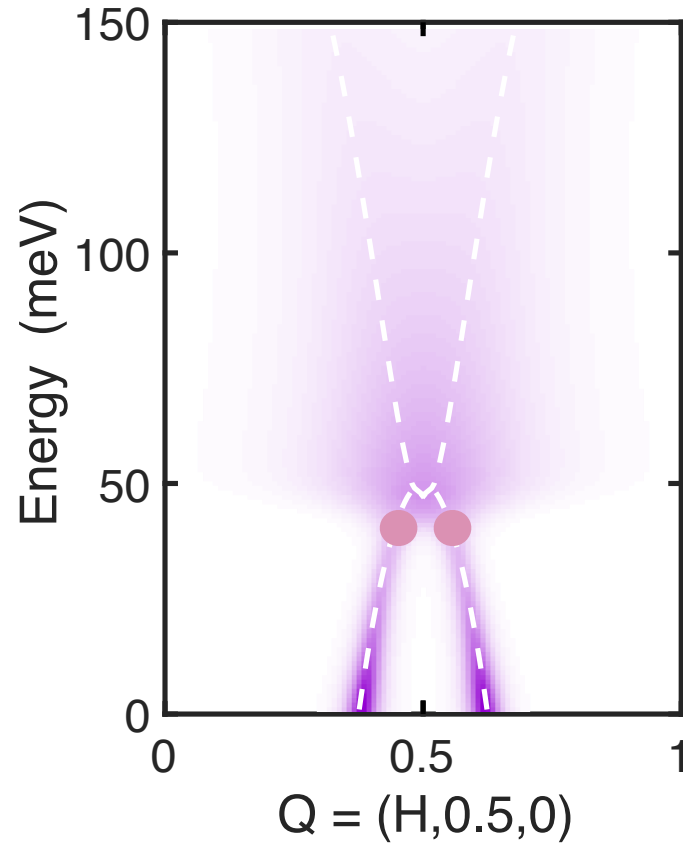
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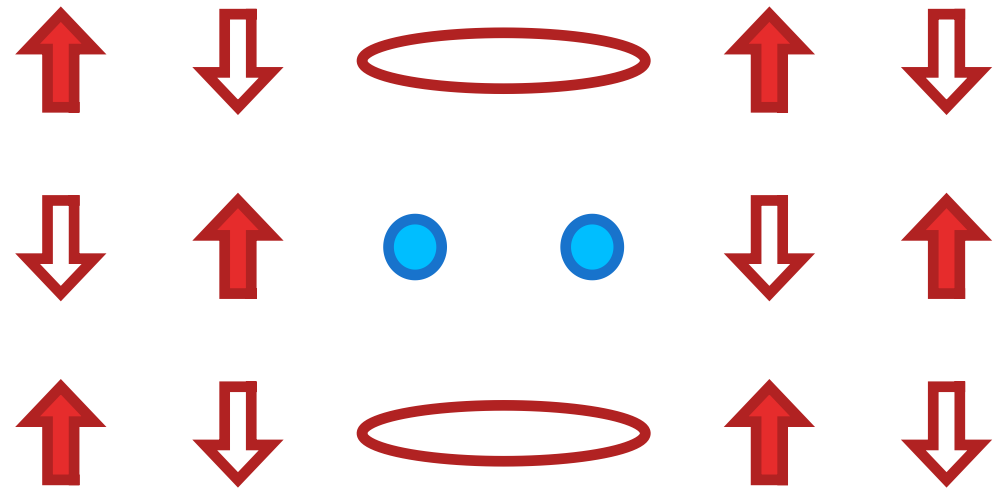
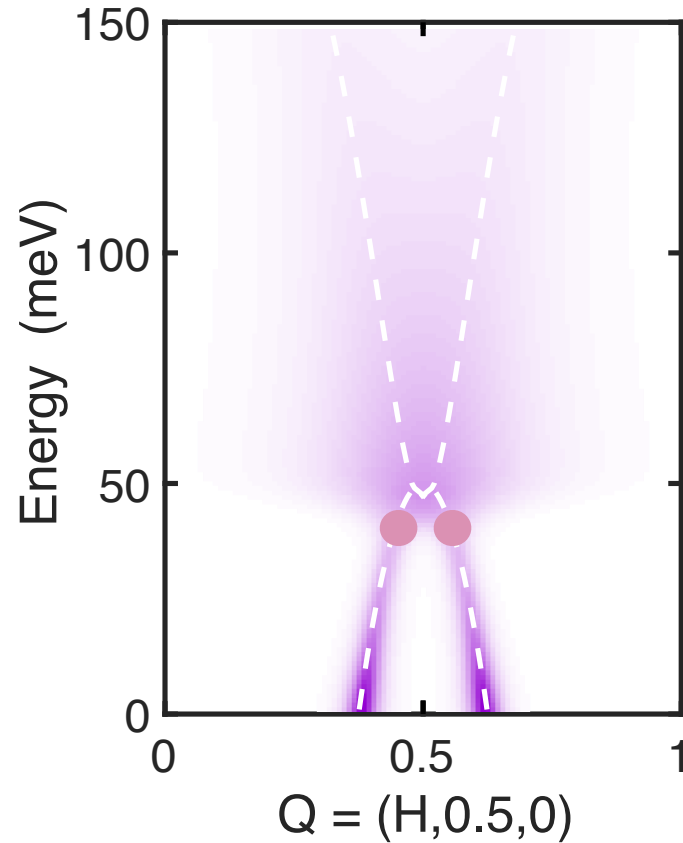
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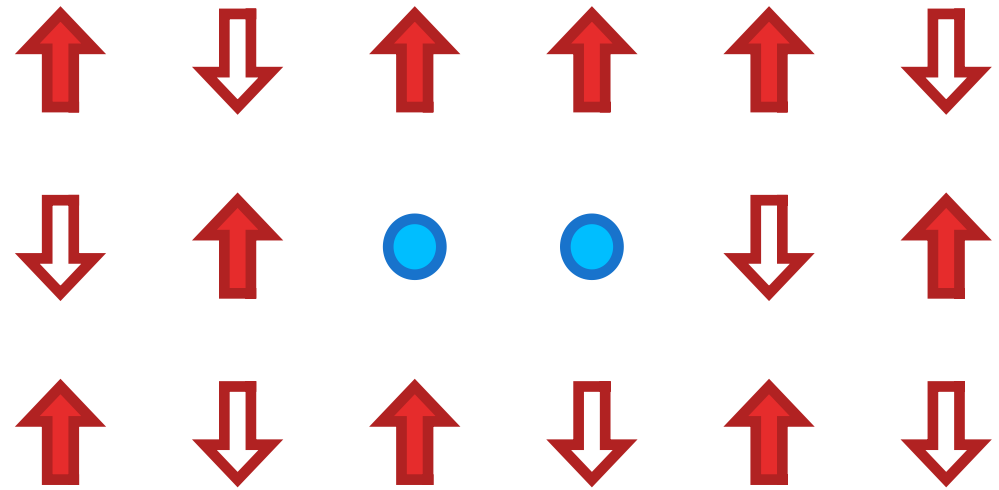
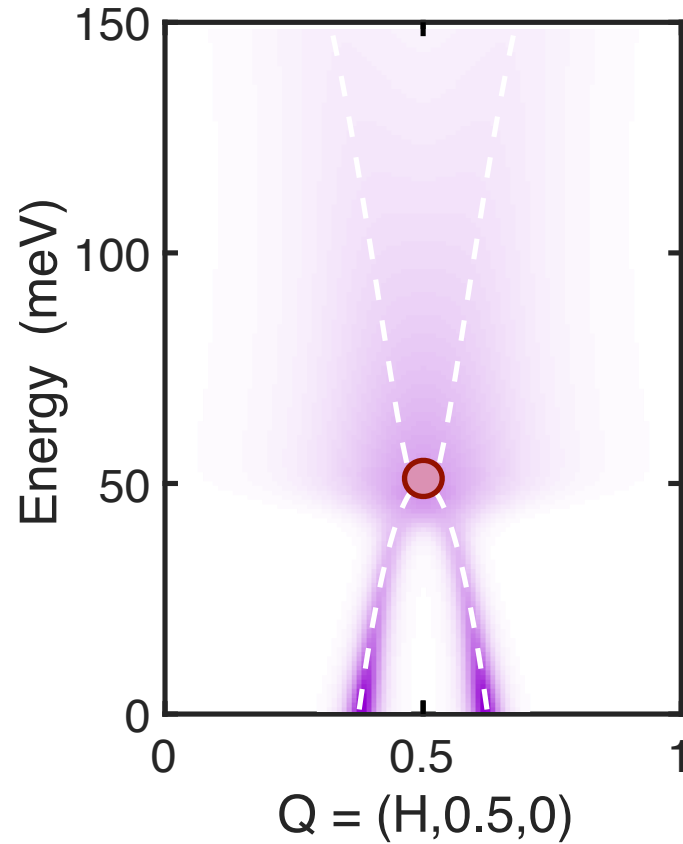
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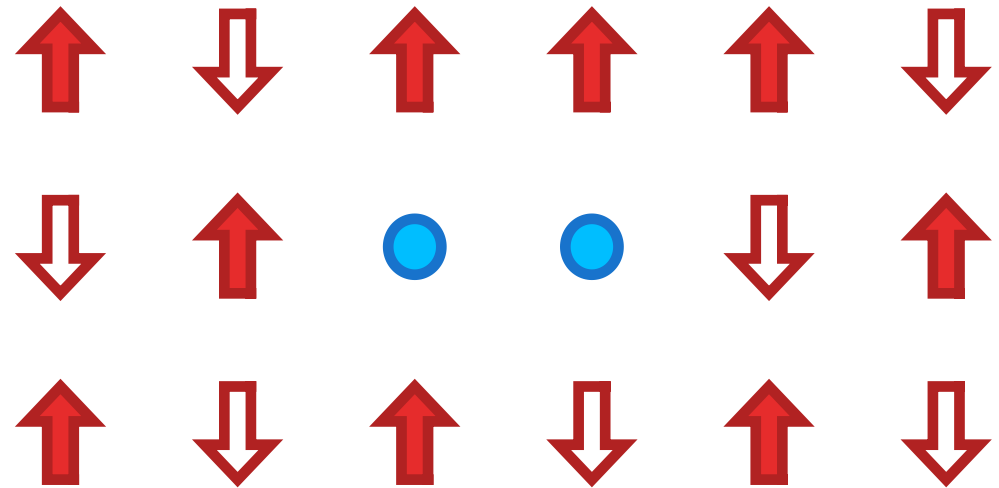
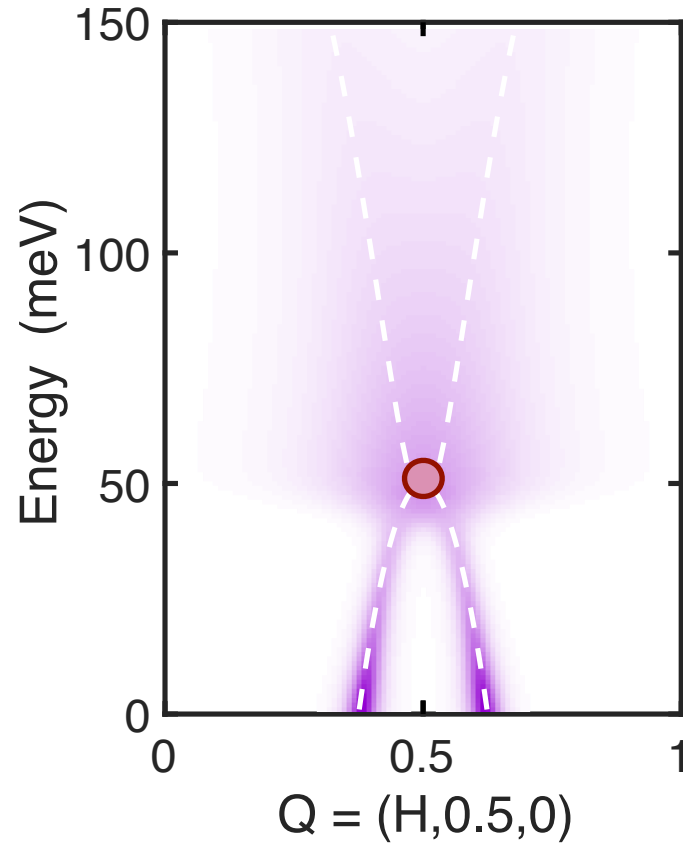
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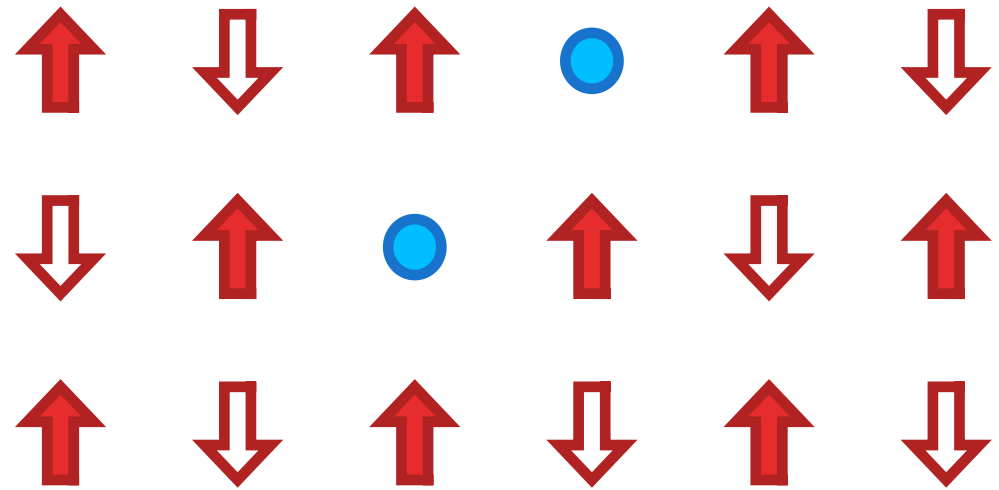
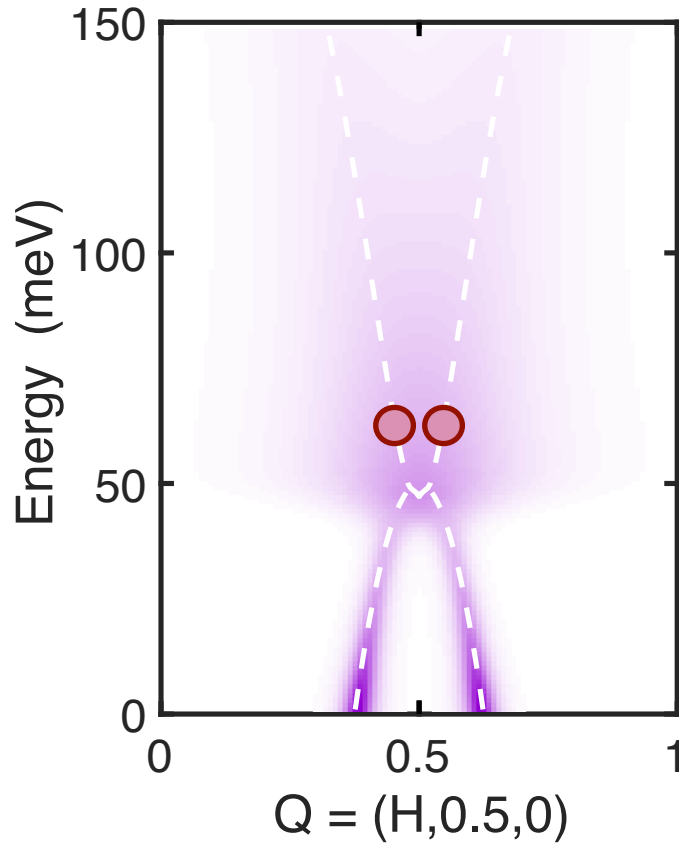
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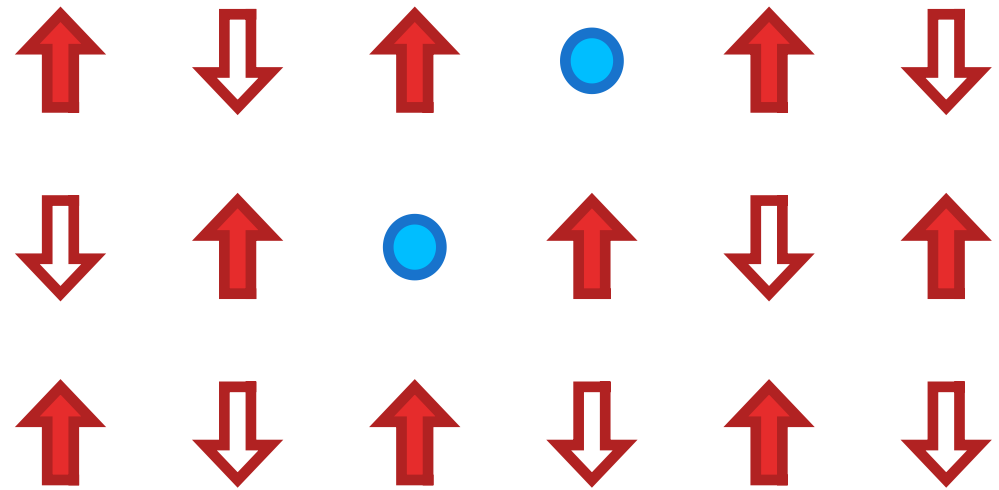
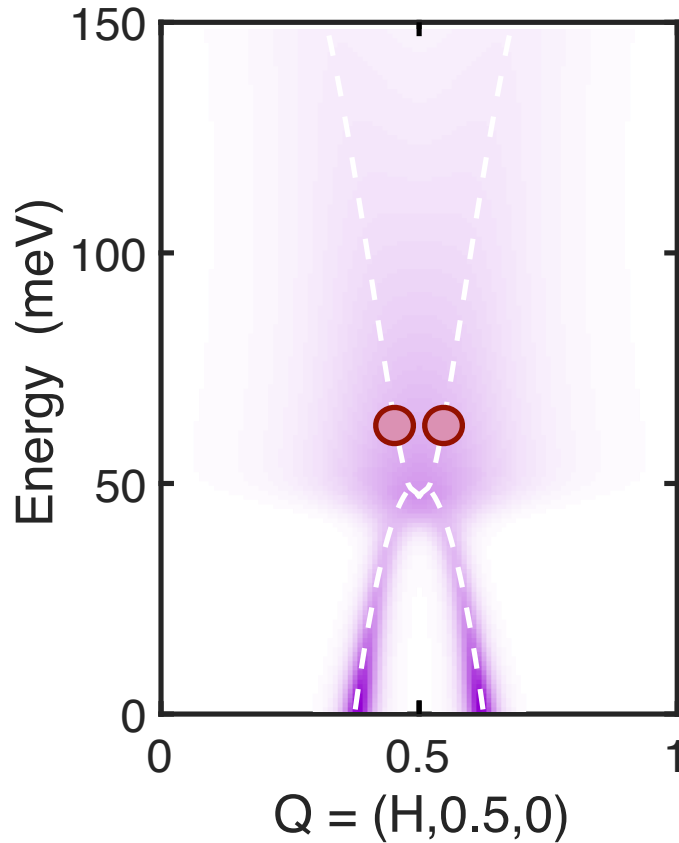
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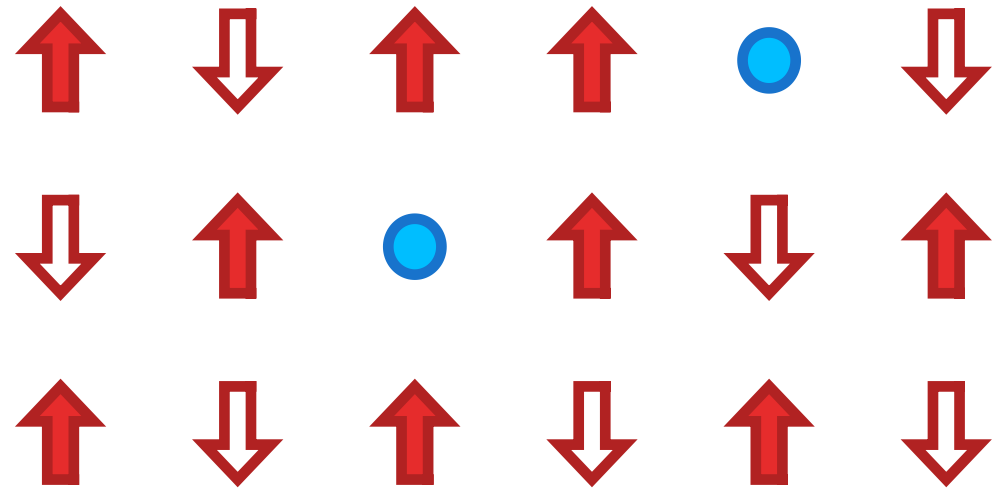
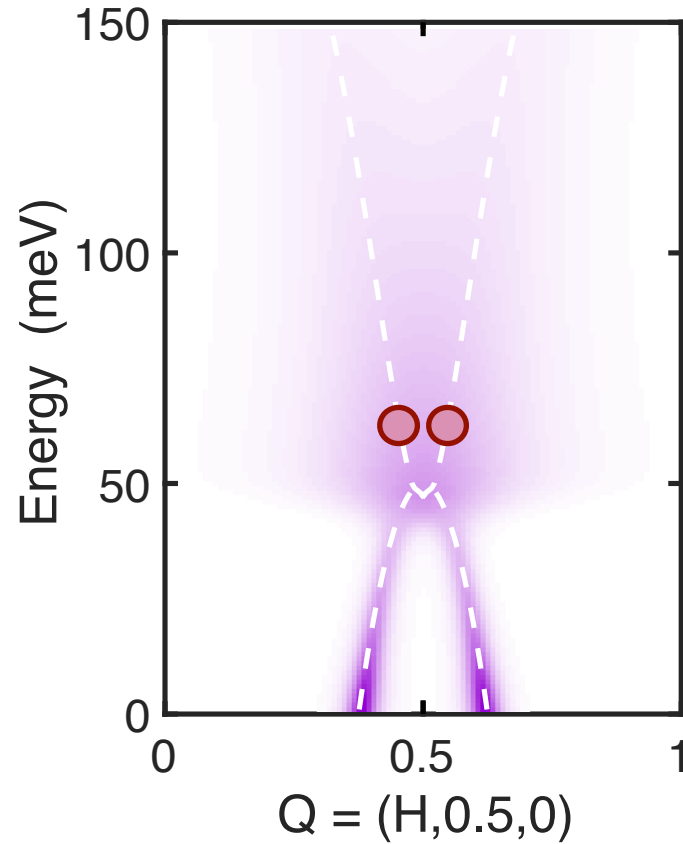
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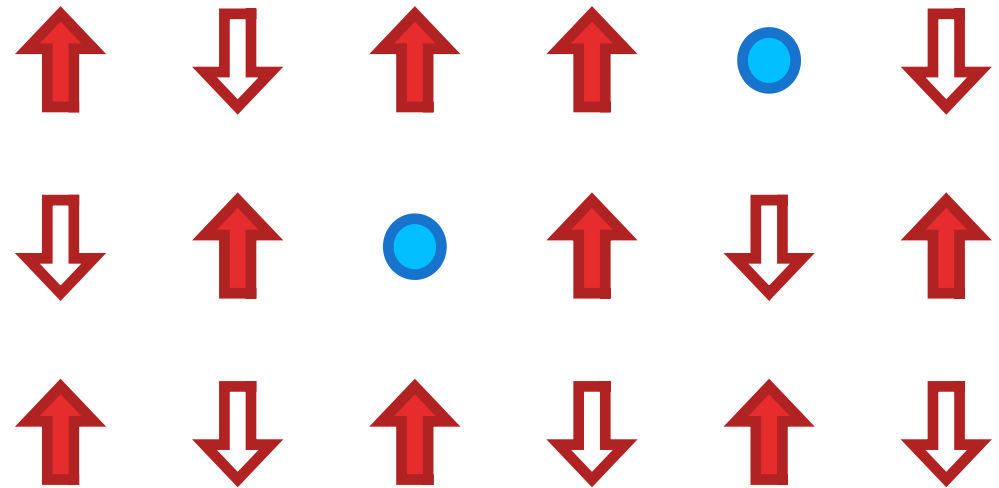
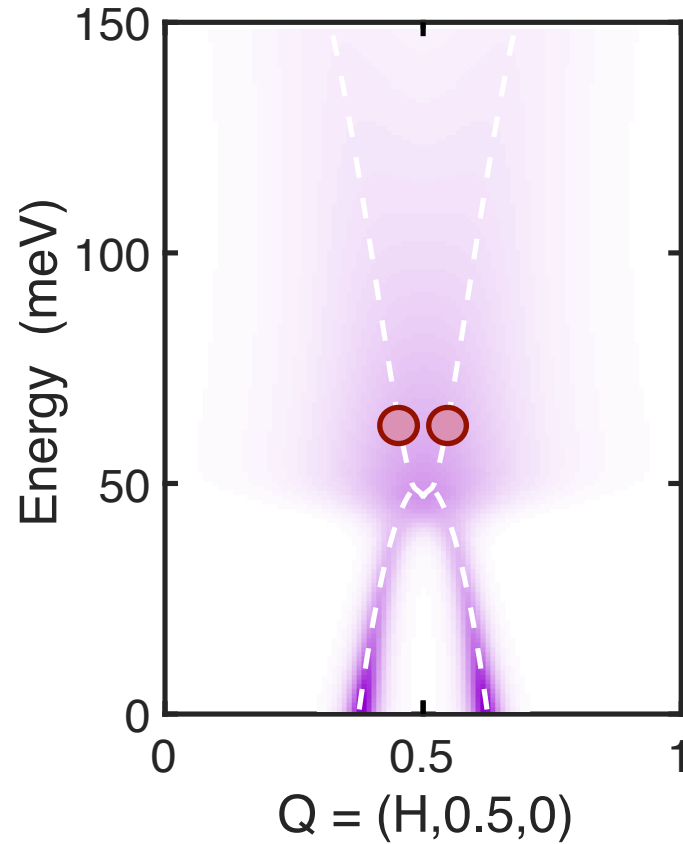
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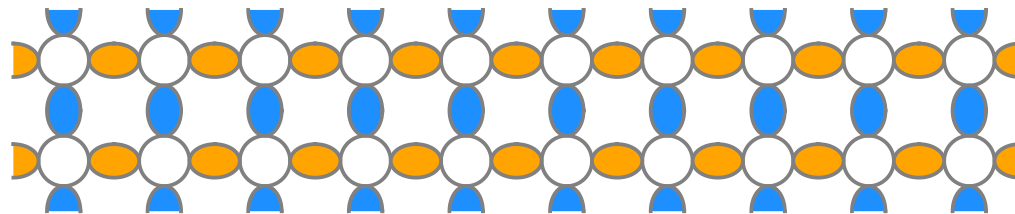
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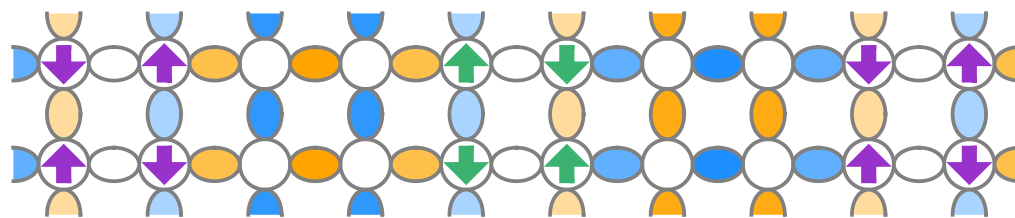
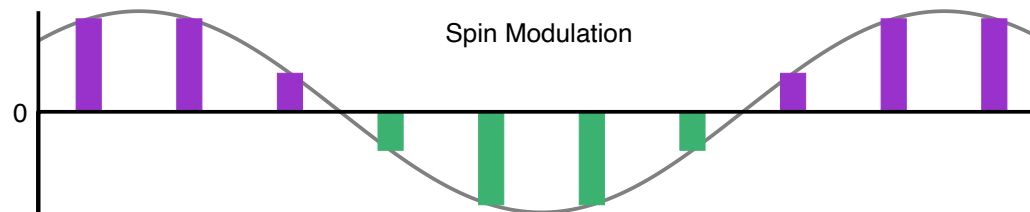
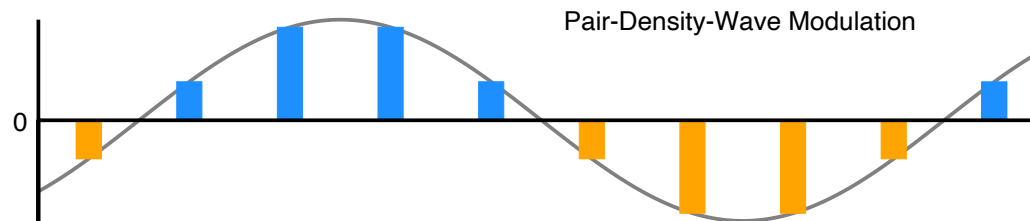
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Spin stripe order competes with uniform SC

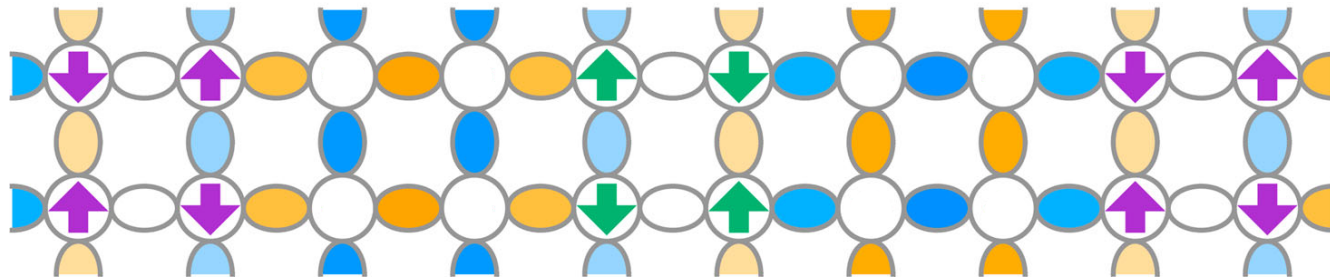


uniform d -wave SC order

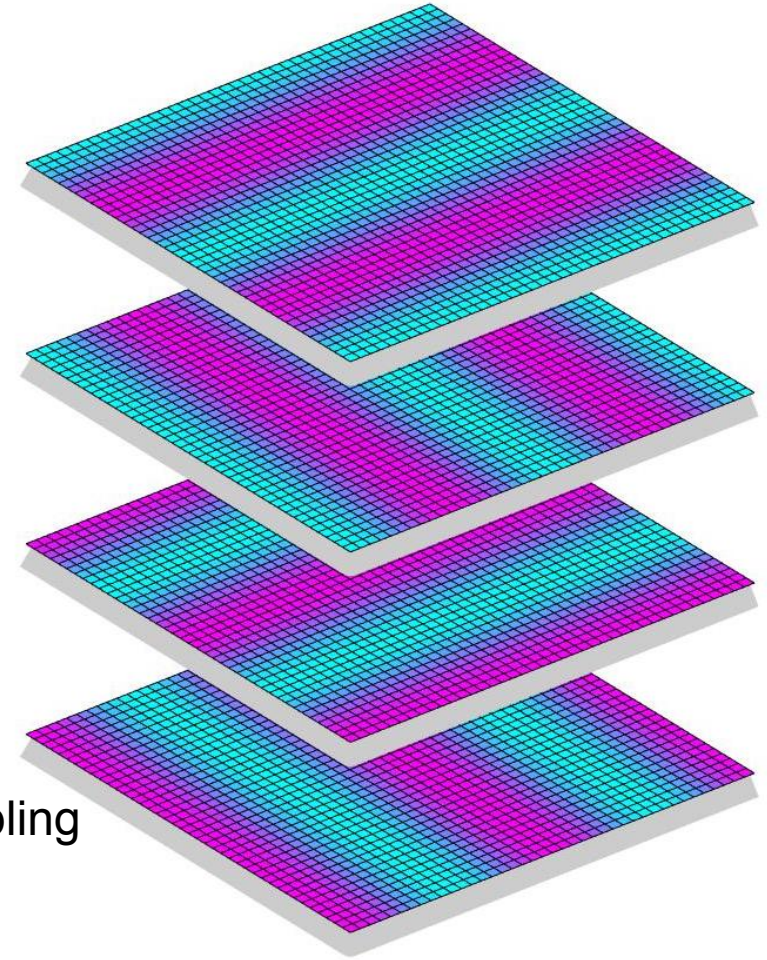


pair-density-wave order

PDW order explains 2D SC in LBCO $x = 1/8$

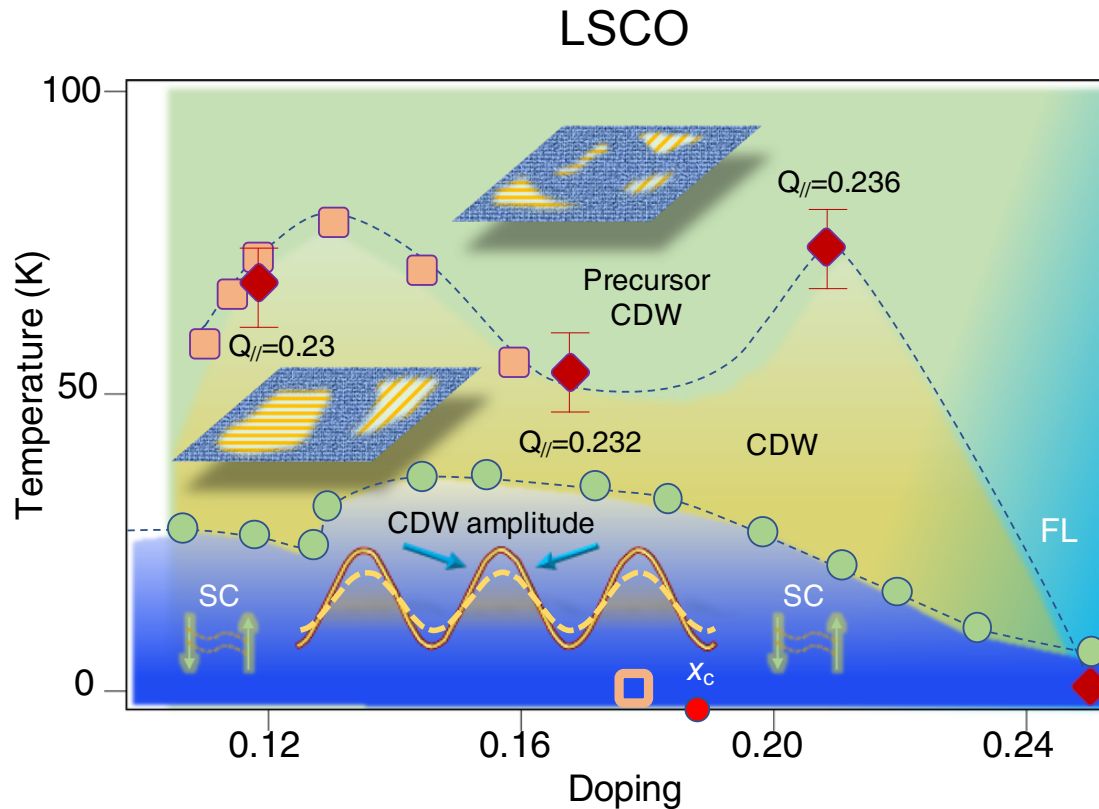


Interlayer Josephson coupling
is frustrated.



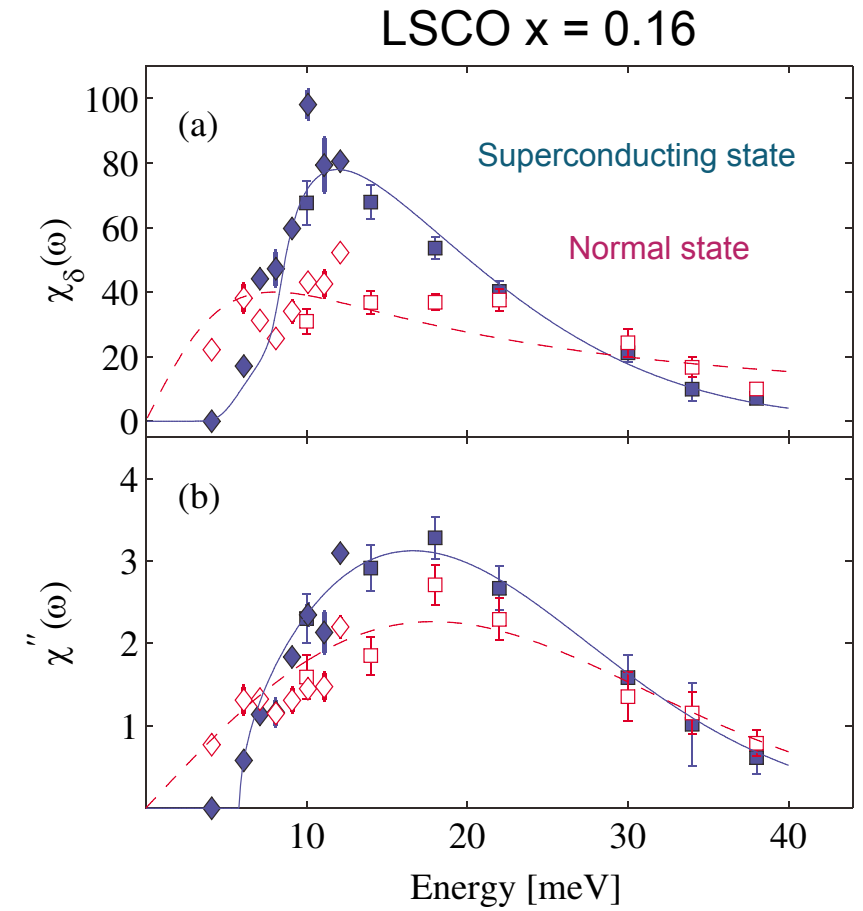
Need a spin gap to get uniform SC order

Hard x-ray scattering shows charge stripe correlations over substantial doping range



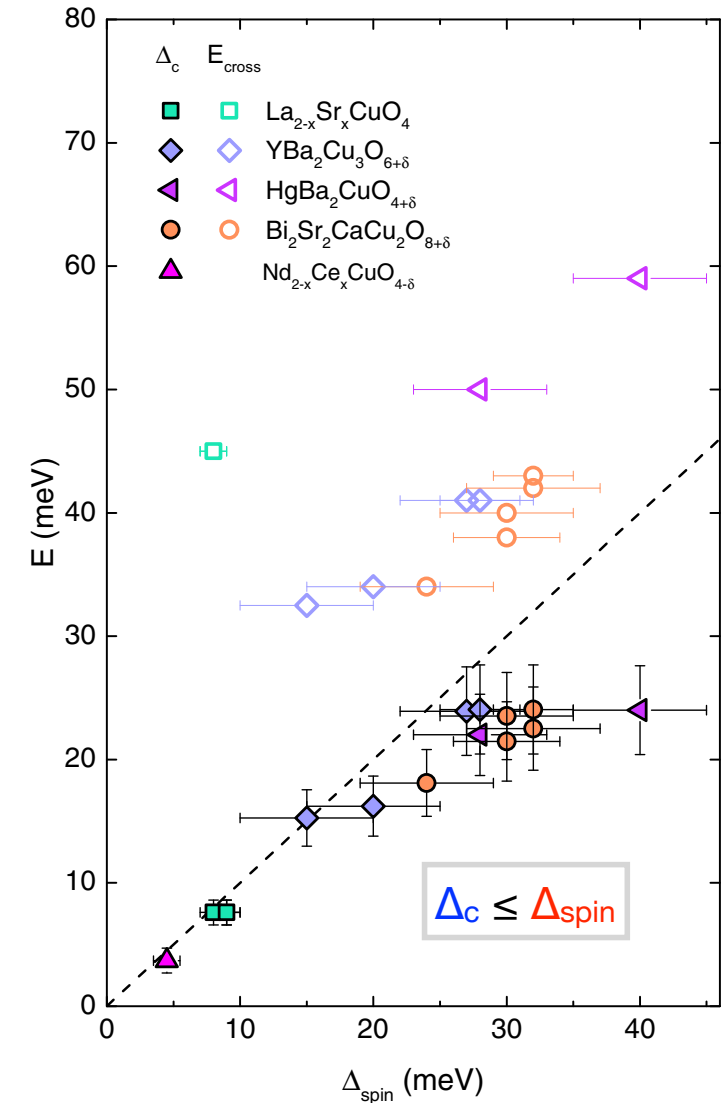
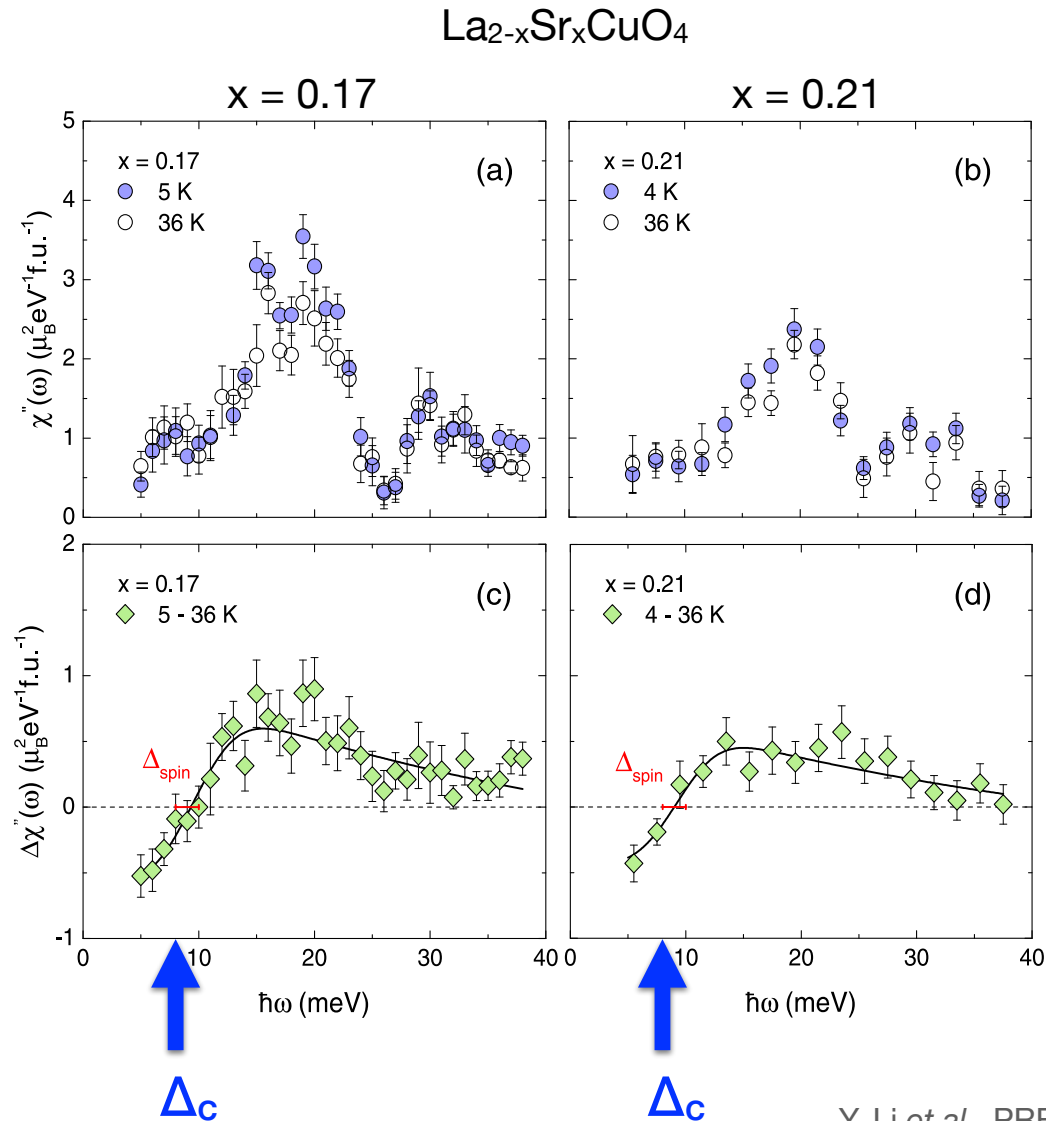
H. Miao *et al.*, npj Quantum Mater. **6**, 31 (2021)

Neutron scattering reveals a spin gap

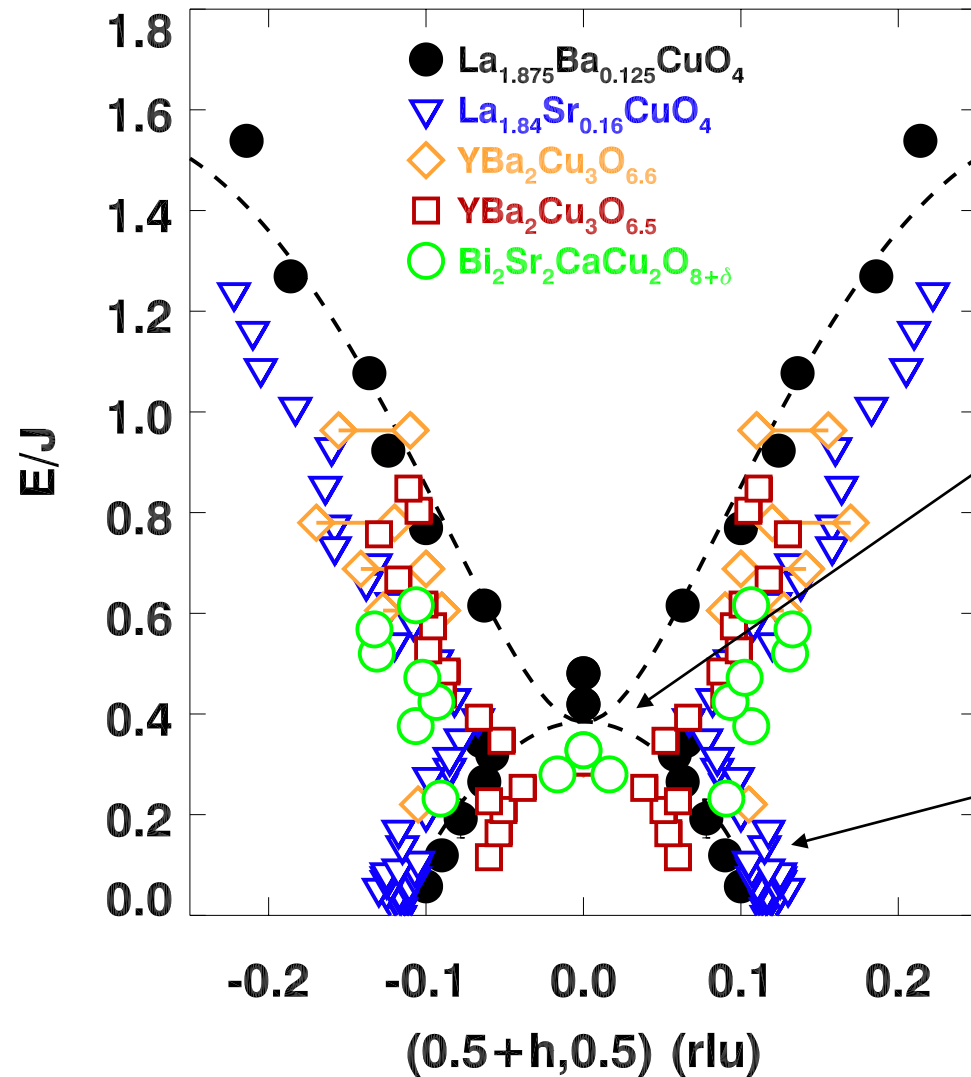


N.B. Christensen *et al.*, PRL **93**, 147002 (2004)

Spin gap limits coherent superconducting gap



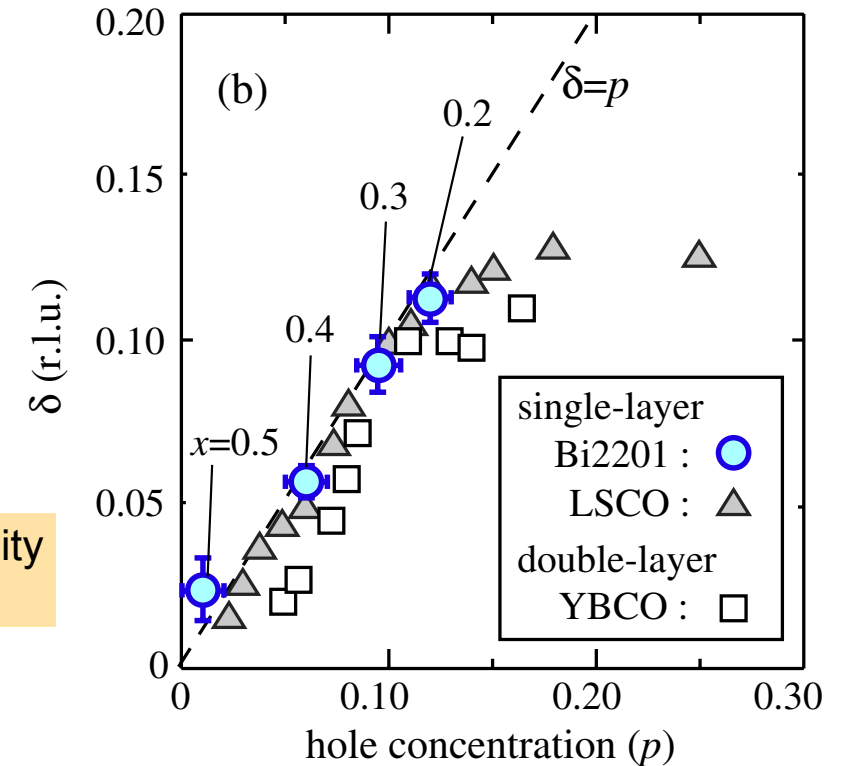
Universal magnetic spectrum



JMT *et al.*, Nature (2004)
 Vignolle *et al.*, Nat. Phys. (2007)
 Hayden *et al.*, Nature (2004)
 Stock *et al.*, Phys. Rev. B (2005), (2010)
 Xu *et al.*, Nat. Phys. (2009)

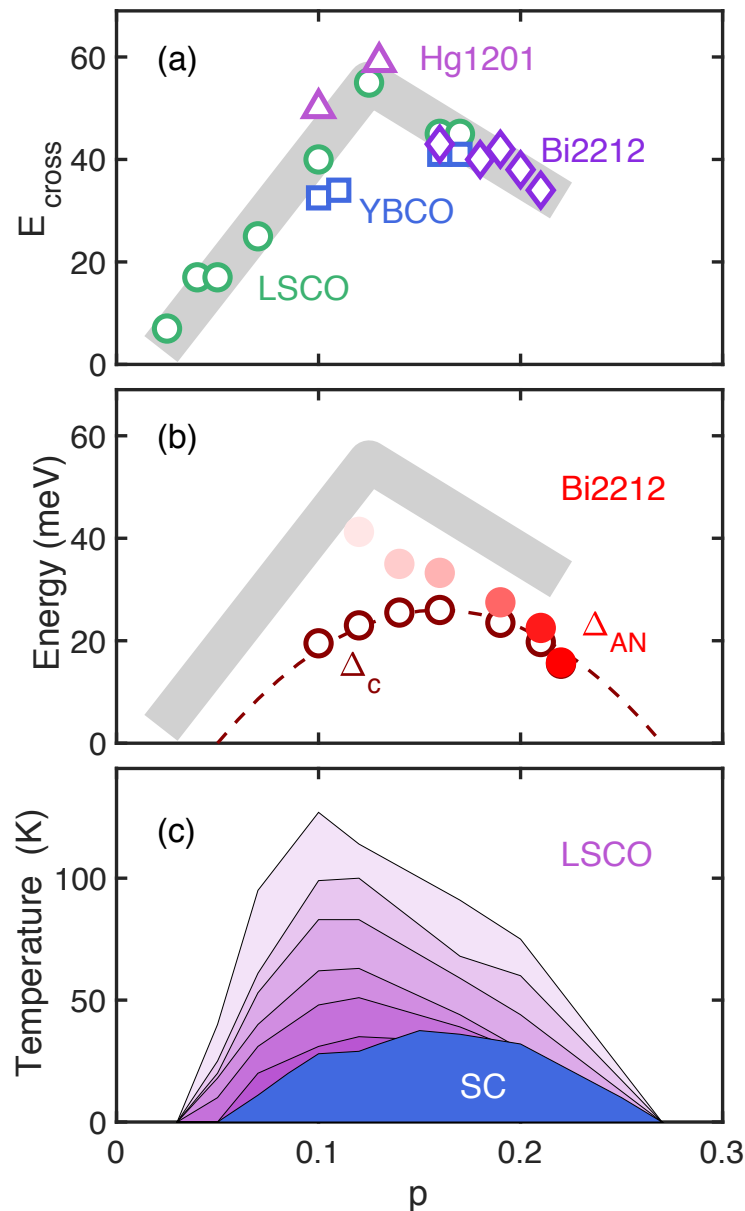
$E_{\text{cross}} \sim 0.4J$
 upper limit for pairing

Spin incommensurability
 grows with doping



Doping dependence of pairing scale

JMT, Adv. Phys. **69**, 437 (2020)

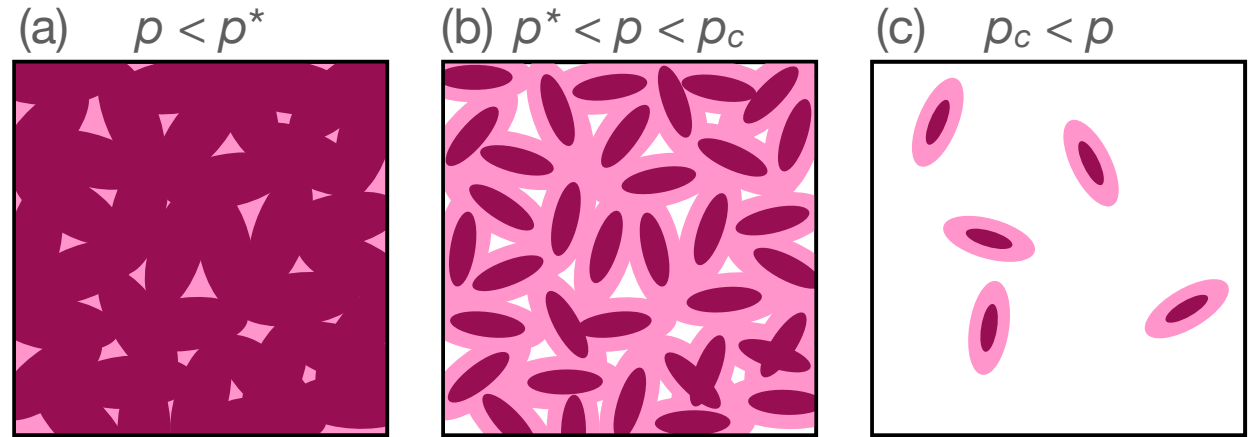
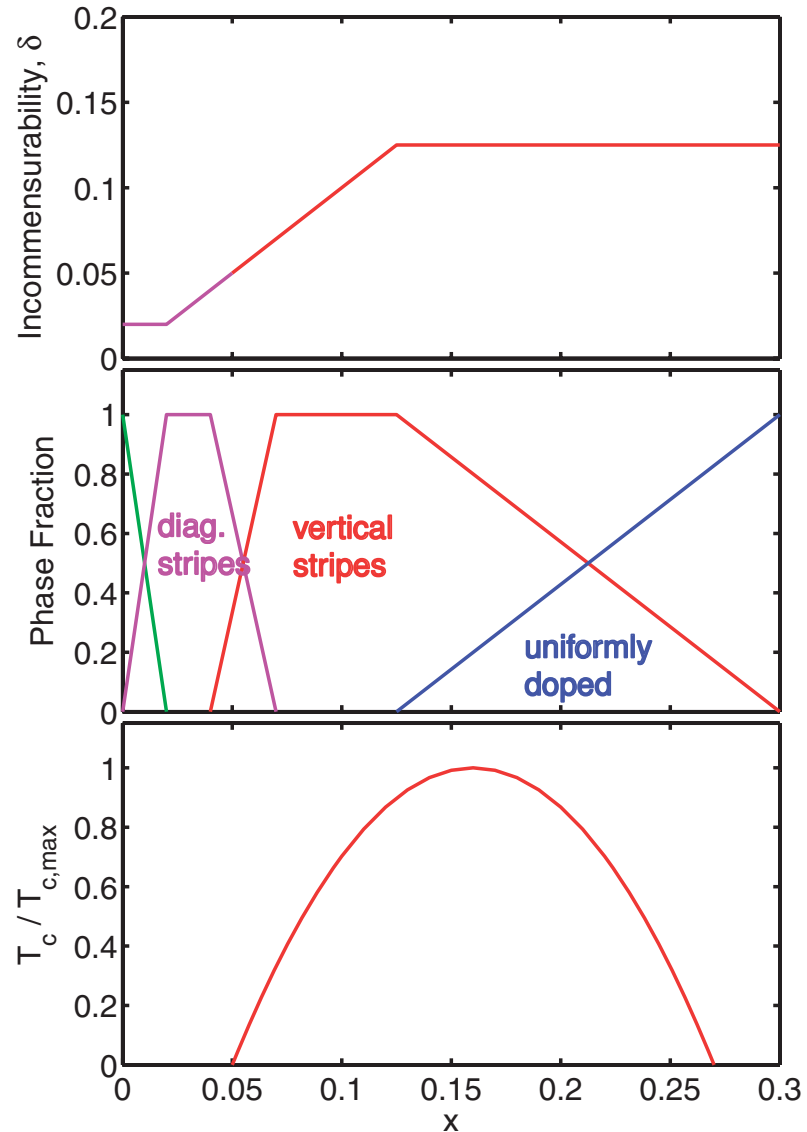


Upper limit on pairing scale is similar for all cuprates

E_{cross} provides envelope for superconducting pseudogap, Δ_{AN} , as well as coherent gap, Δ_{c}

SC fluctuations in LSCO peak near $p \sim 0.1$ and extend far above T_{c}

Loss of superconductivity with overdoping



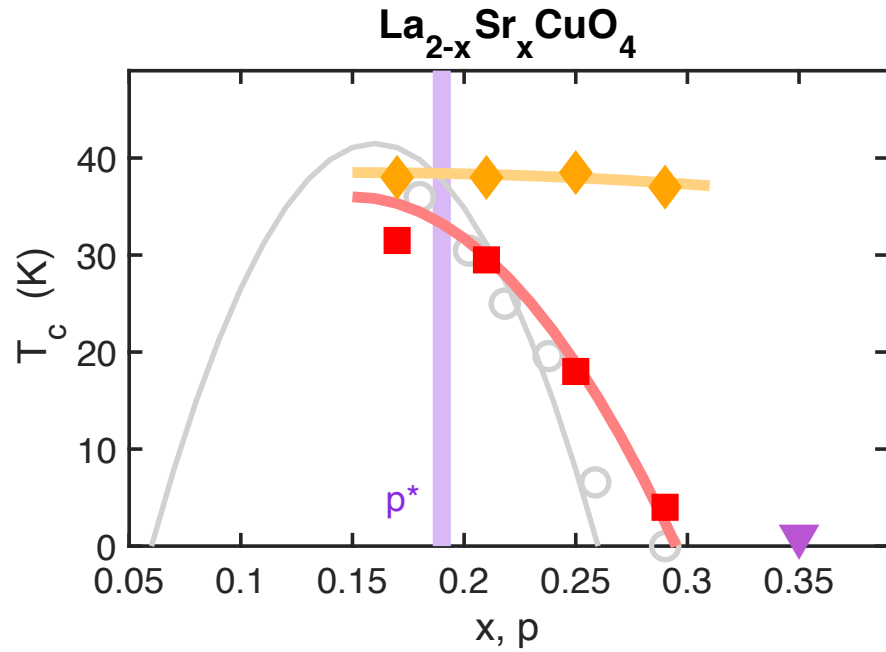
Y. Li *et al.*, arXiv:2205.01702

Self-organized granular superconductivity
near the superconductor-to-metal transition

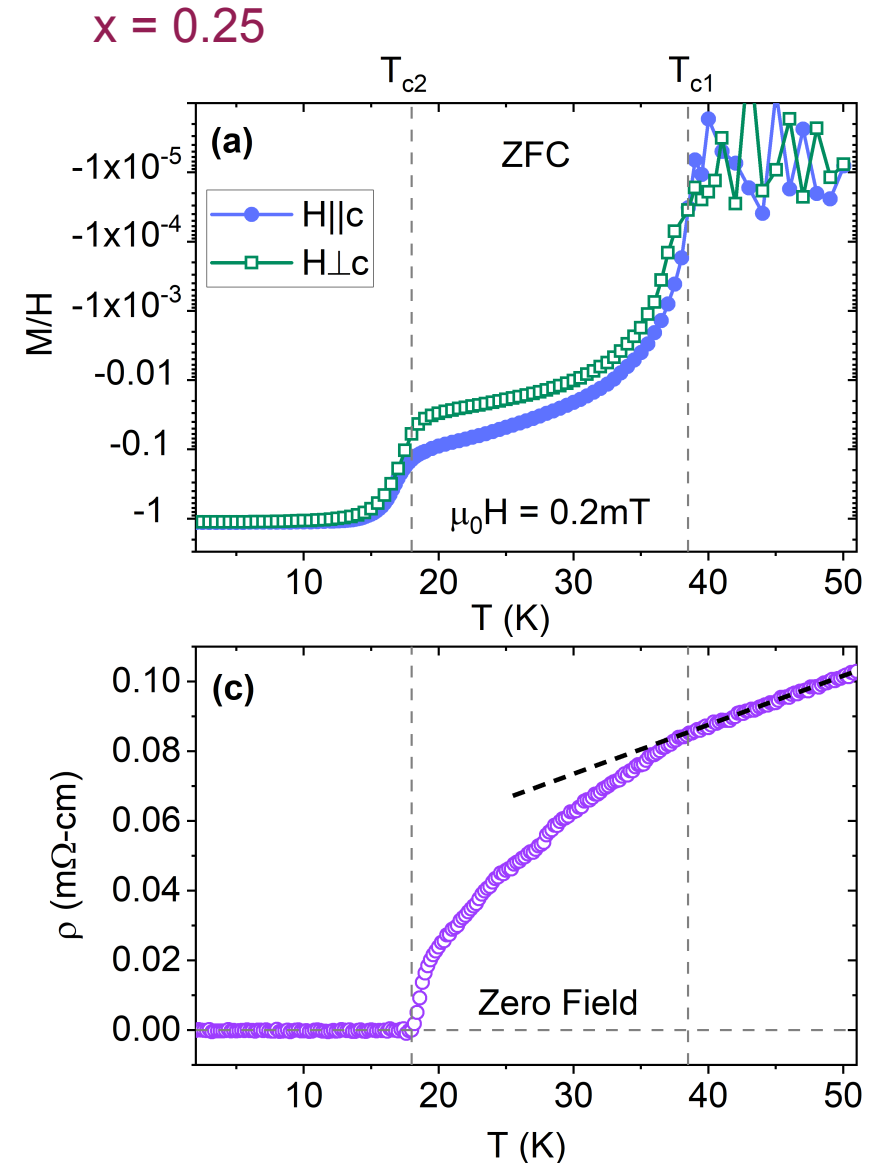
Spivak, Oreto, Kivelson, PRB **77**, 214523 (2008).
ZX Li, Kivelson, DH Lee, npj QM **6**, 36 (2021).

Birgeneau *et al.*, JPSJ **75**, 111003 (2006)

Evidence for inhomogeneous superconductivity



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



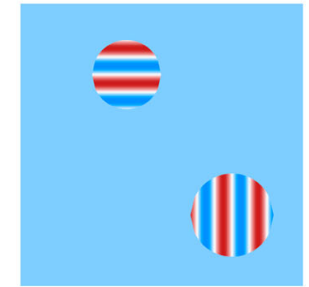
Correlations vs doping

charge, spin
distribution
in real space

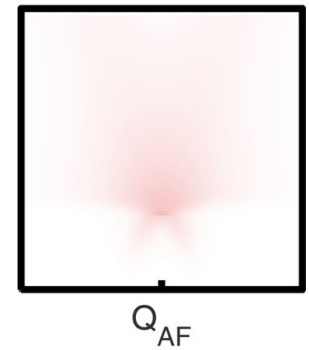
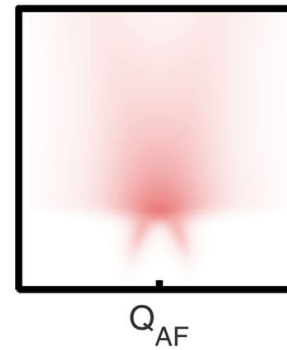
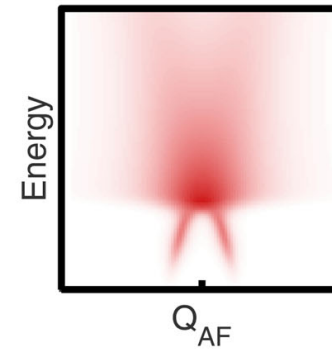
$p \sim 1/8$

$p \sim p^*$

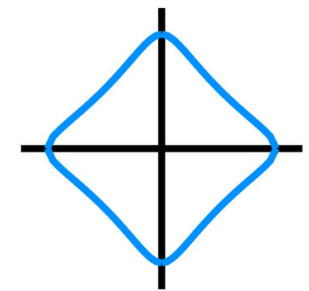
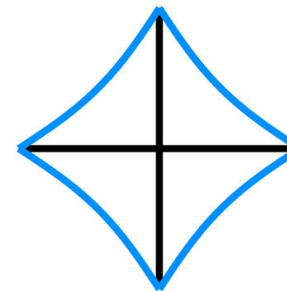
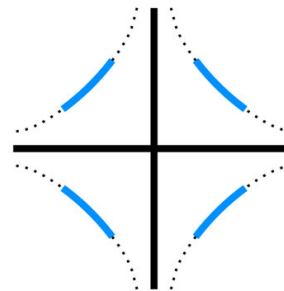
$p > p^*$



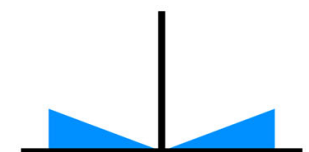
spin
response
 $\chi''(Q,E)$



Fermi
surface



coherent
SC gap

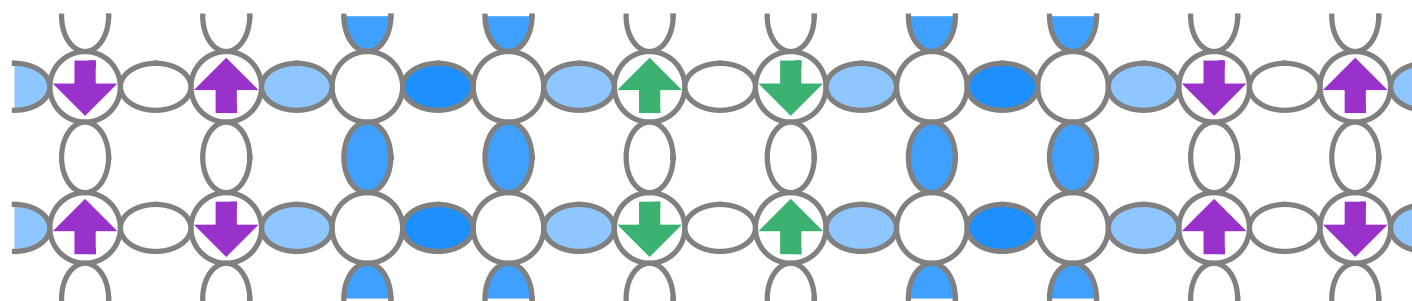


$$\cos(k_x a) - \cos(k_y a)$$

JMT, Adv. Phys. **69**, 437 (2020)

Conclusion

Snapshot of low-energy spin correlations:

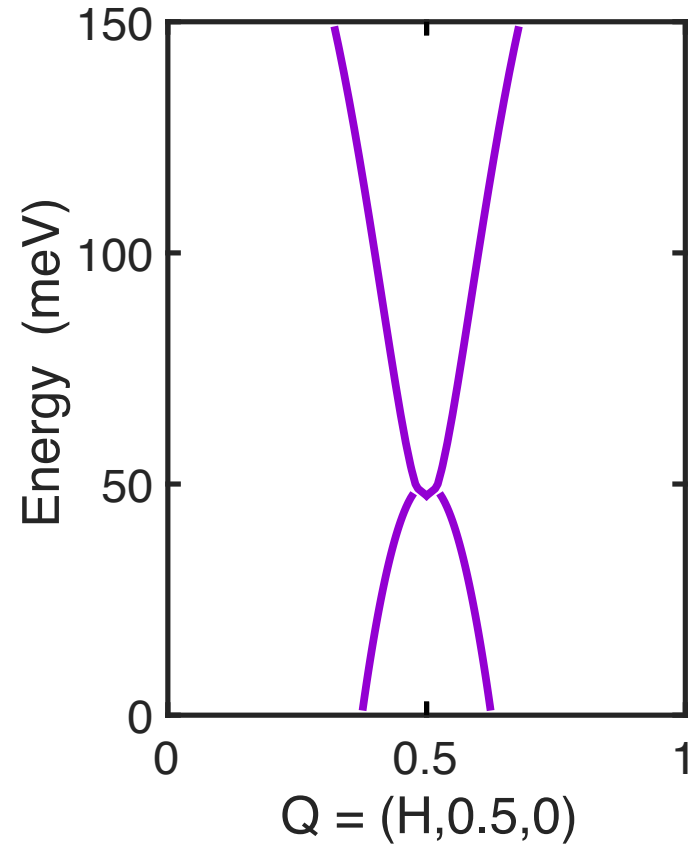


Spin gap on charge stripes
sets limit on pairing scale

Spin gap on spin stripes
limits the coherent gap scale

Cuprate superconductivity: Can't live with stripes,
Can't live without stripes.

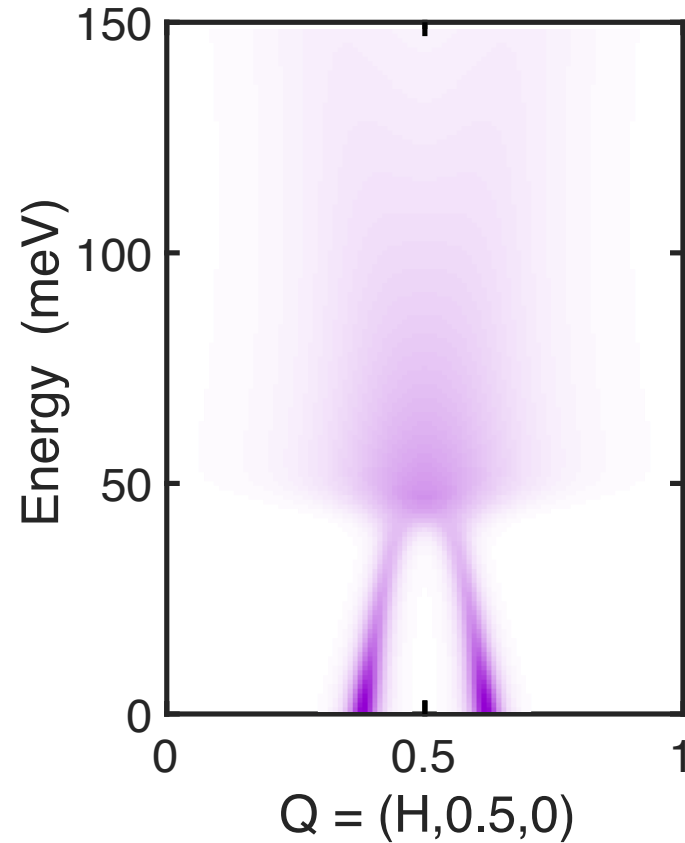
LBCO $x=1/8$: New analysis of spin excitations



LBCO: JMT *et al.*, Nature **429**, 163 (2004)
LSCO: Vignolle *et al.*, Nat. Phys. **3**, 163 (2007)

JMT, Adv. Phys. **69**, 437 (2020)

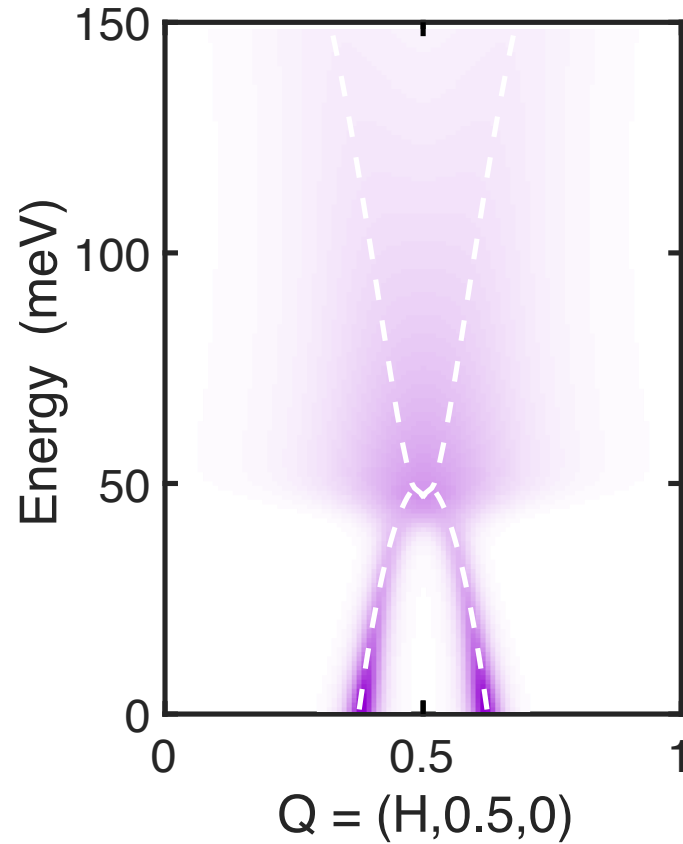
LBCO $x=1/8$: New analysis of spin excitations



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JMT, Adv. Phys. **69**, 437 (2020)

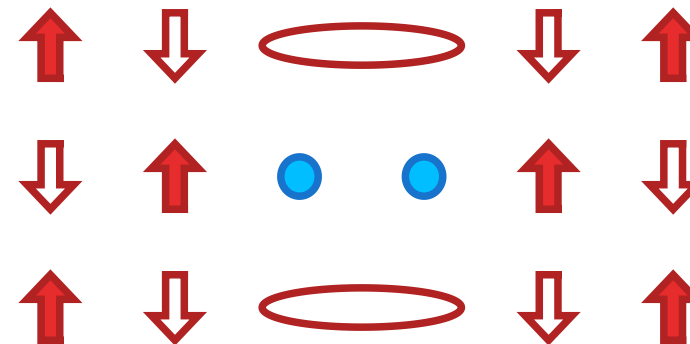
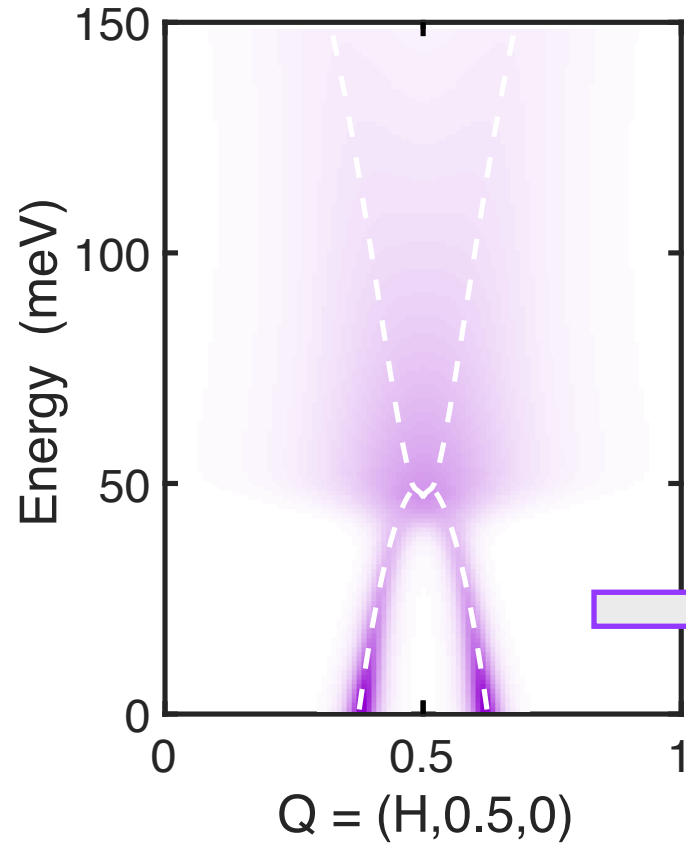
LBCO $x=1/8$: New analysis of spin excitations



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JMT, Adv. Phys. **69**, 437 (2020)

LBCO $x=1/8$: New analysis of spin excitations

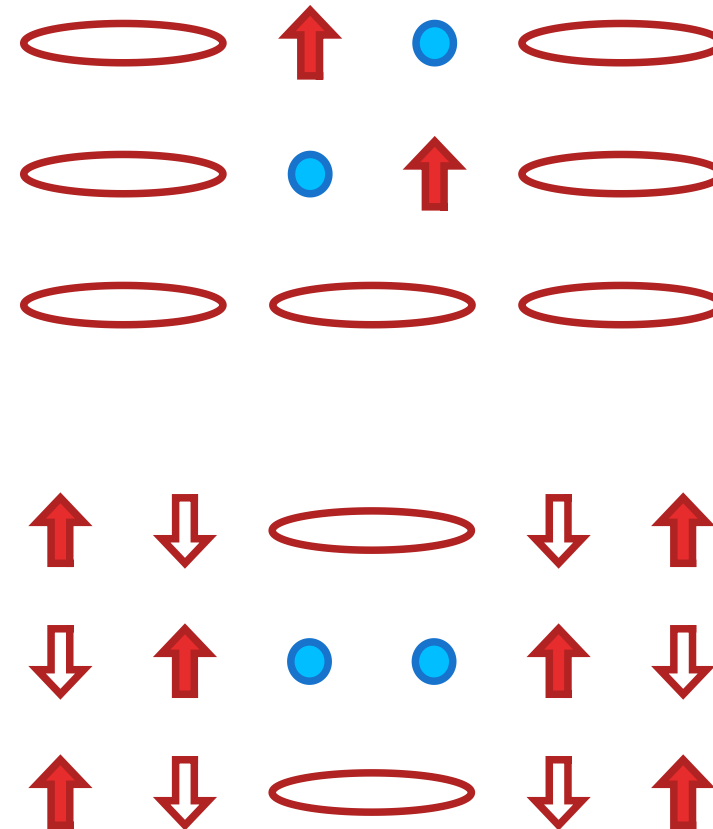
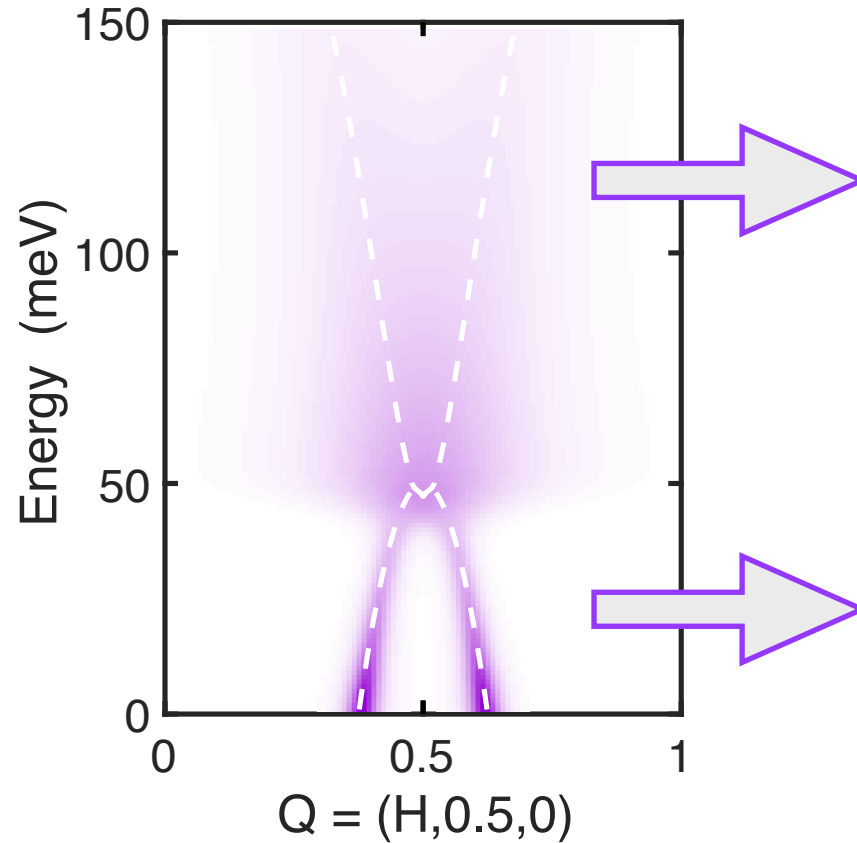


Holes
confined
in pairs

LBCO: JMT *et al.*, Nature **429**, 163 (2004)
LSCO: Vignolle *et al.*, Nat. Phys. **3**, 163 (2007)

JMT, Adv. Phys. **69**, 437 (2020)

LBCO $x=1/8$: New analysis of spin excitations



Holes
deconfined

Holes
confined
in pairs

LBCO: JMT *et al.*, Nature **429**, 163 (2004)
LSCO: Vignolle *et al.*, Nat. Phys. **3**, 163 (2007)

JMT, Adv. Phys. **69**, 437 (2020)