High-T_c Superconductivity: Known Knowns and Unknowns

Brad Marston
Brown University

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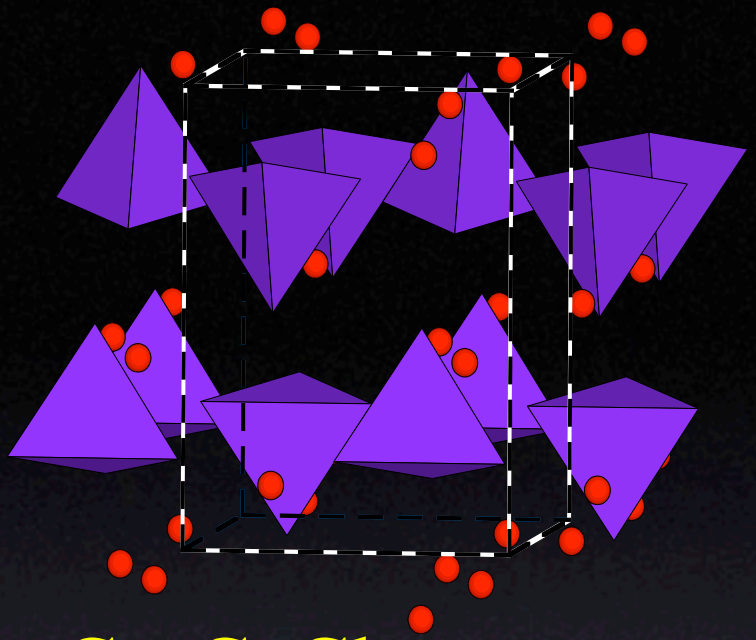
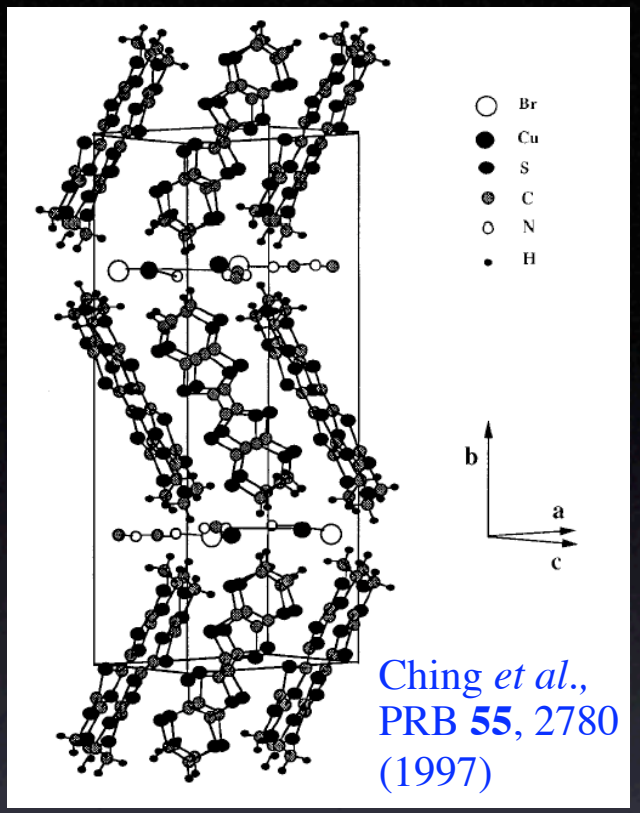
"As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know."

-- Donald Rumsfeld, Secretary of Defense
February 12, 2002 Department of Defense briefing

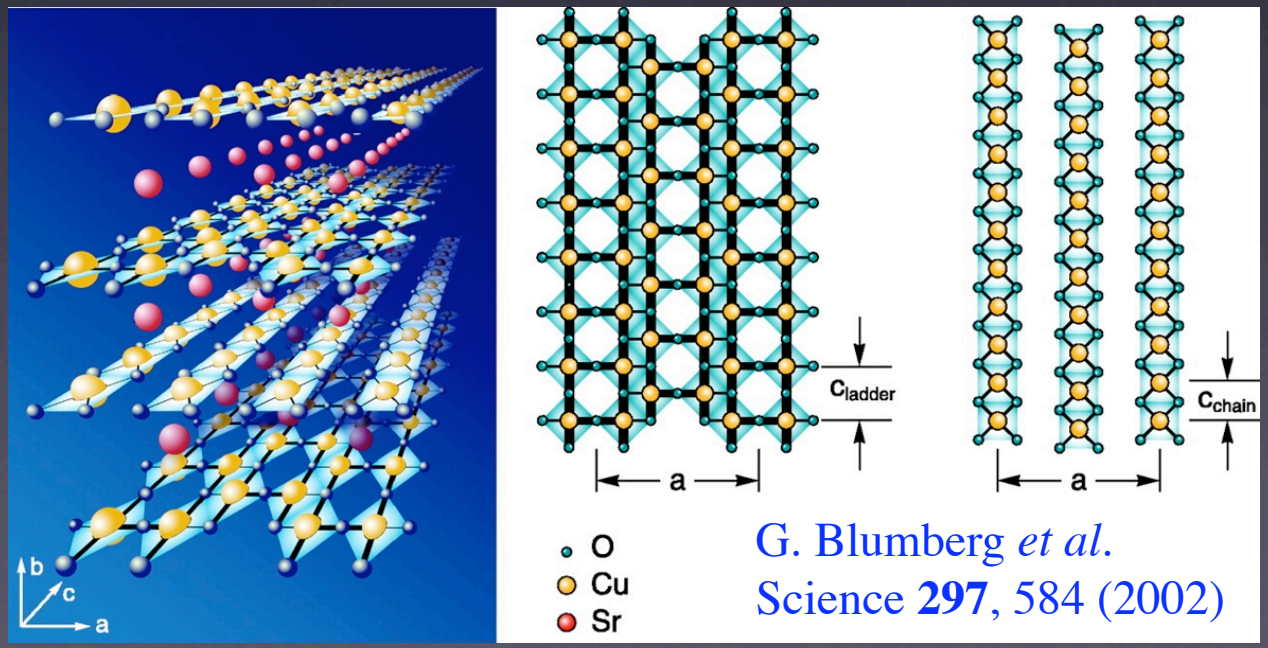


Cs_2CuCl_4 (R. Coldea)



Ching *et al.*, PRB **55**, 2780 (1997)

$Sr_{14}Cu_{24}O_{41}$



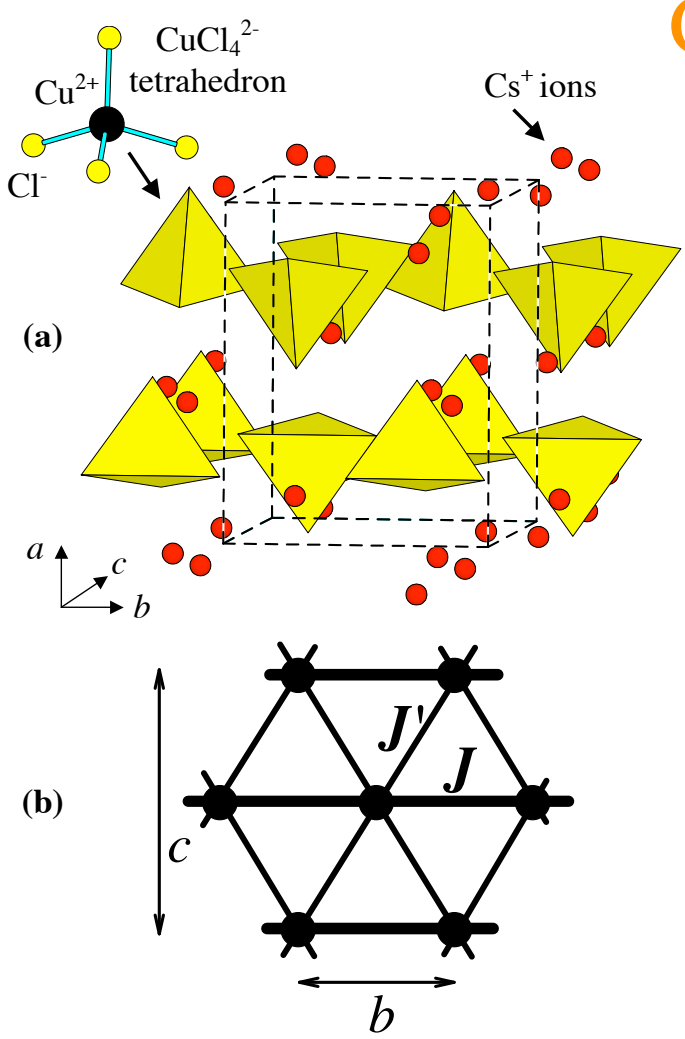
G. Blumberg *et al.* Science **297**, 584 (2002)

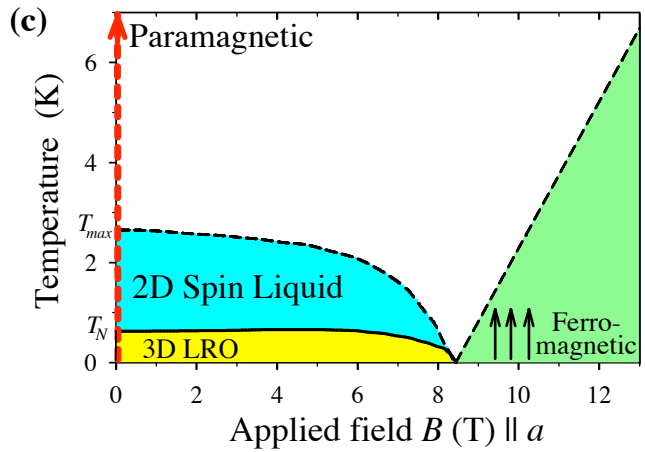
κ-$(BEDT\text{-}TTF)_2X$

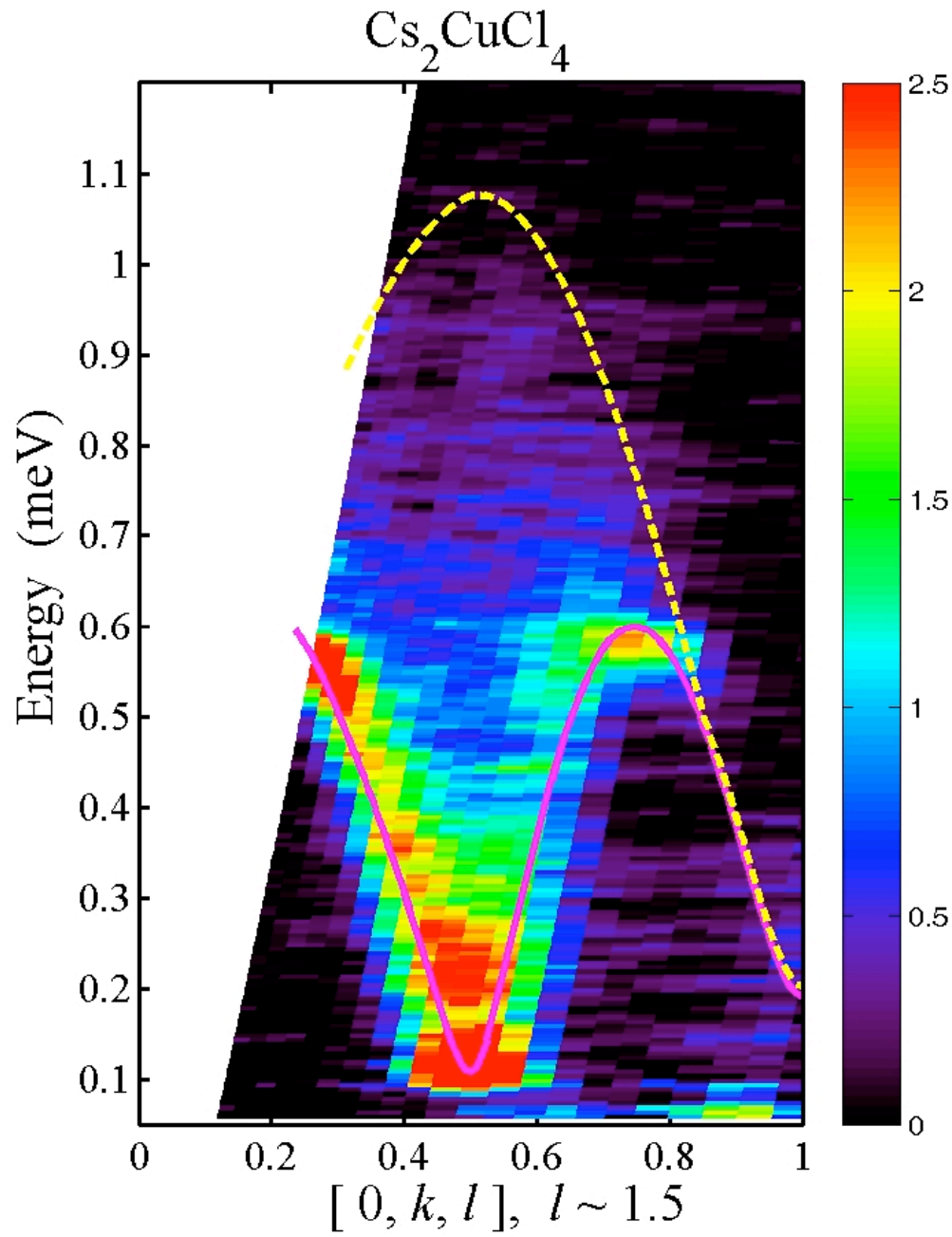
High-T_c

If T_c were not high, would the layered cuprate superconductors still stand out among all the other interesting layered strongly correlated materials?

Cs_2CuCl_4







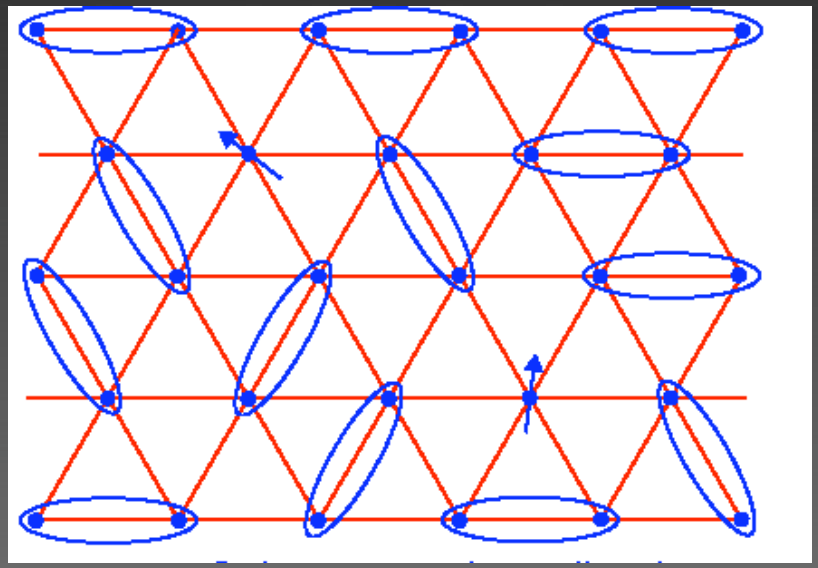
Coldea, Tennant, Tylczynski, PRB**68**, 134424 (2003)

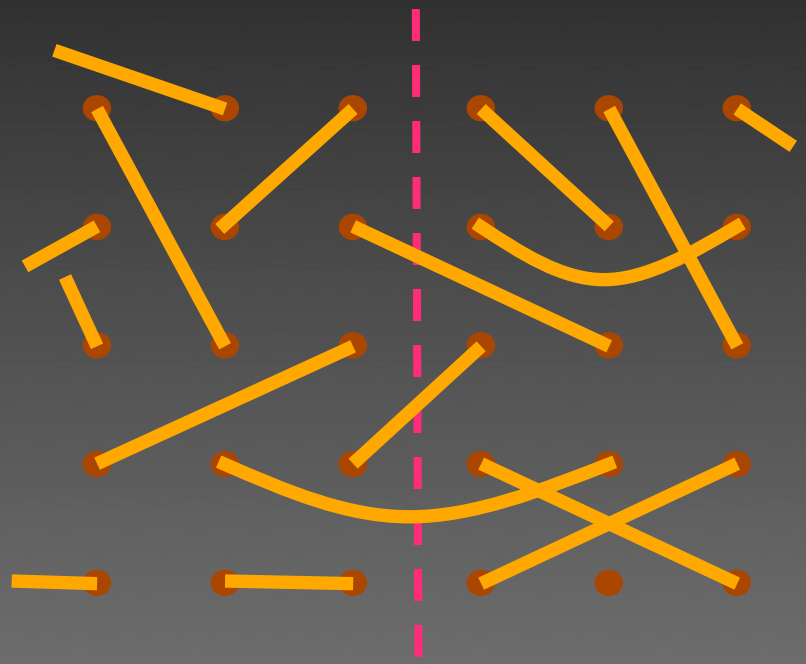
Known Unknowns

- Do spin liquids exist in D > 1?
- If so, can topological order be detected?
- Are gapless spinons possible in D > 1?
- Can fermionic and bosonic spinons be distinguished?

Deconfined spinons and topological order

RVB state with free spinons



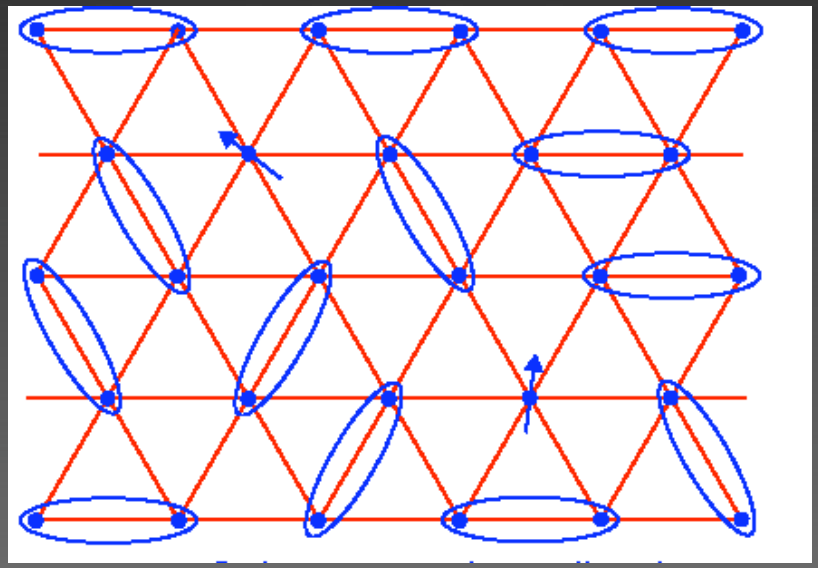


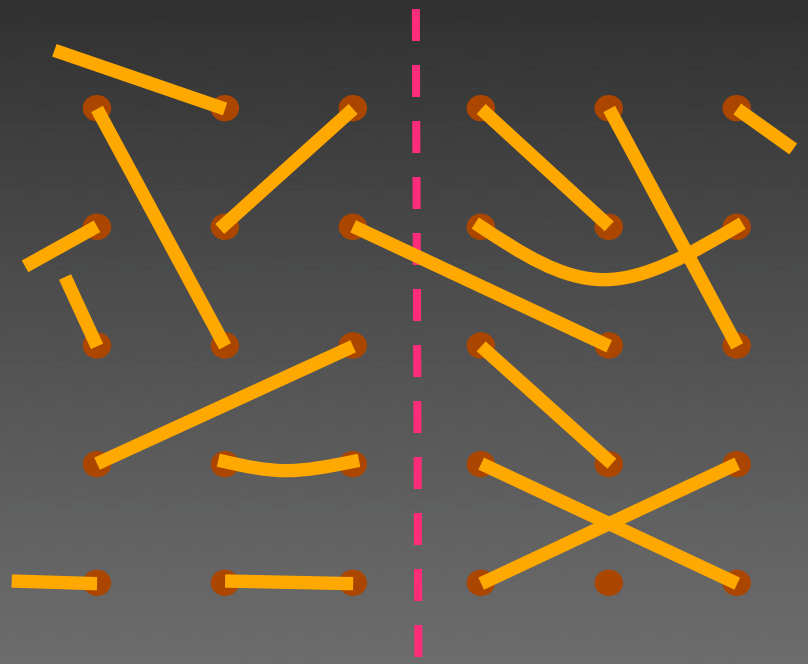
P. Fazekas and P.W. Anderson,
Phil Mag **30**, 23 (1974).

www.nordita.dk/~sylju/Nordic/meeting2/**sachdev**.ppt

Deconfined spinons and topological order

RVB state with free spinons

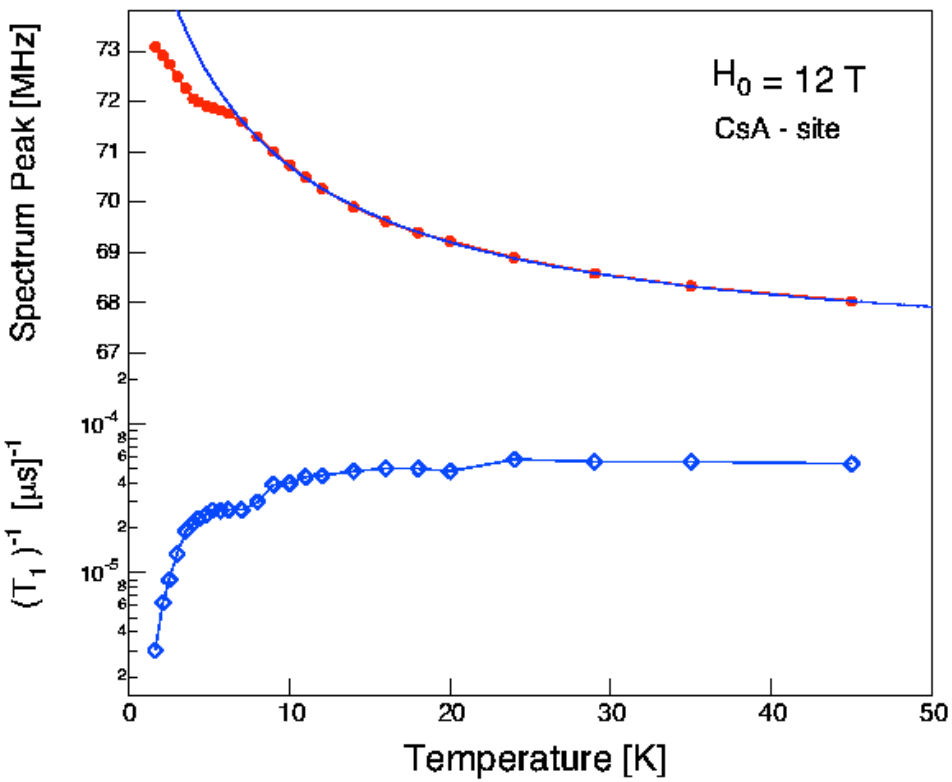


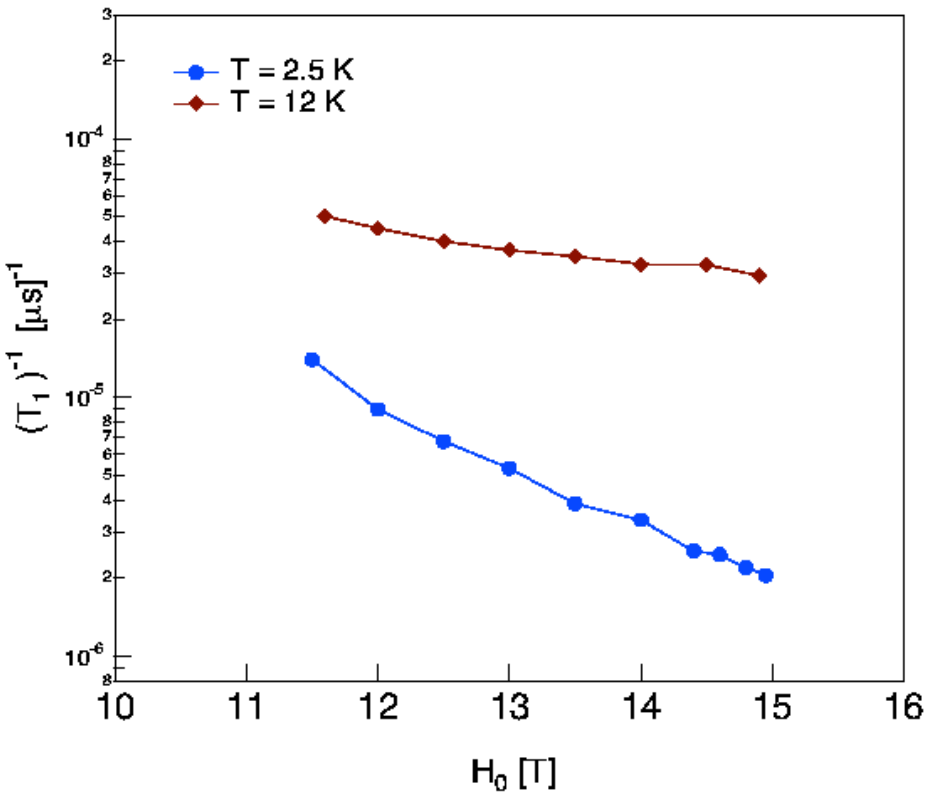


P. Fazekas and P.W. Anderson,
Phil Mag **30**, 23 (1974).

www.nordita.dk/~sylju/Nordic/meeting2/**sachdev**.ppt

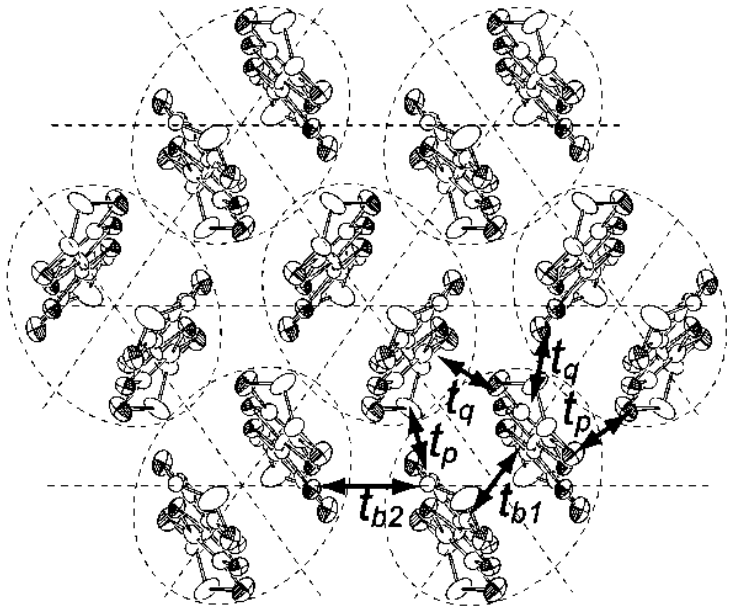
NMR Investigation of Low Energy Behavior

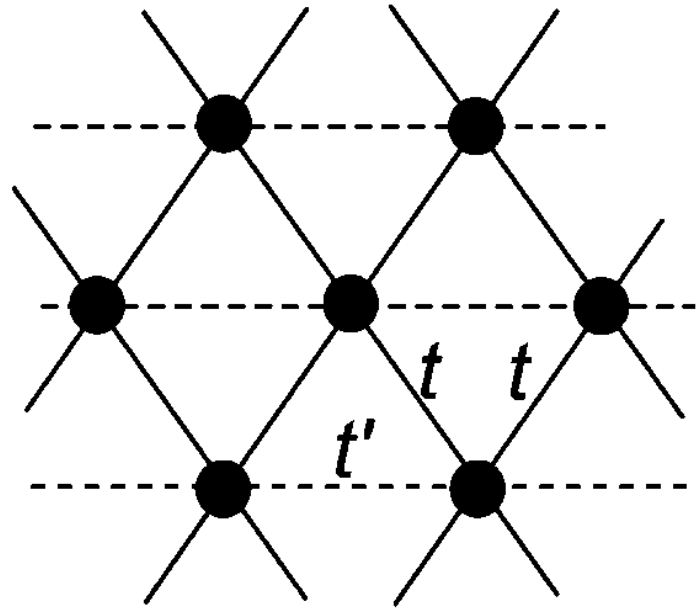


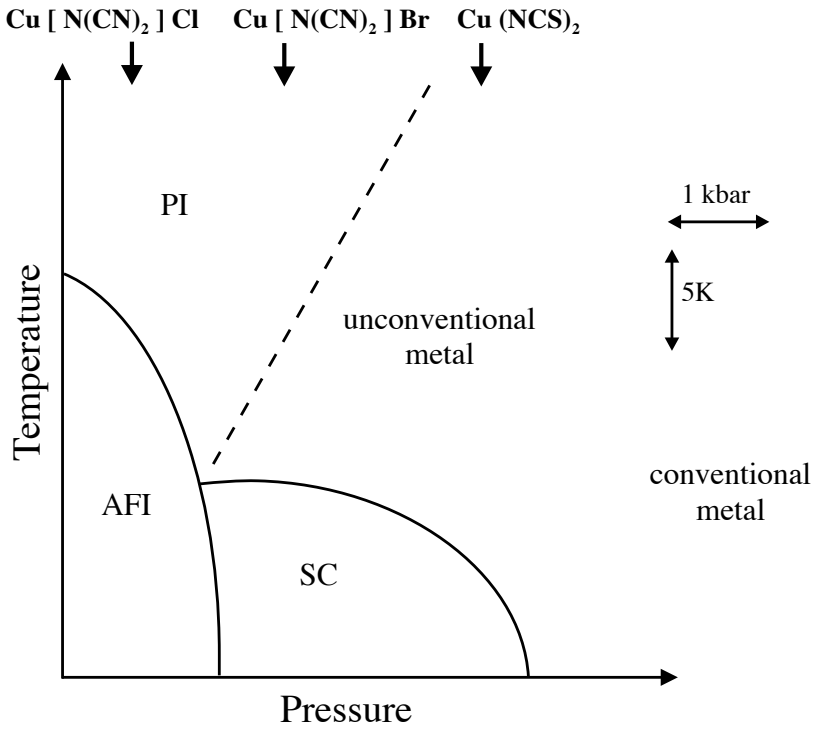


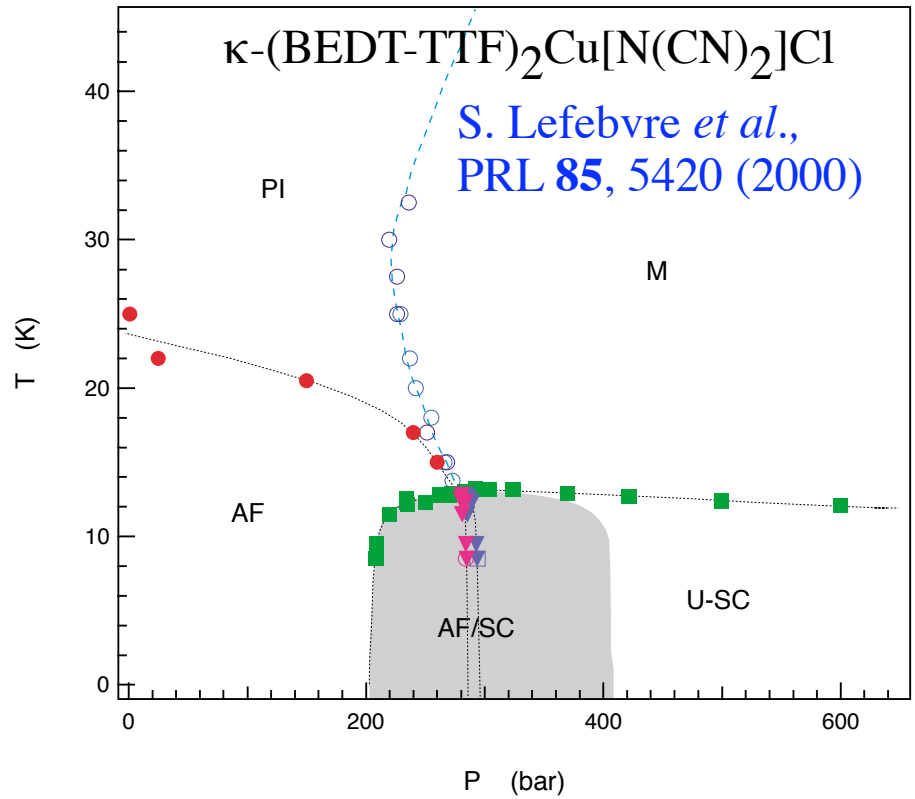
Vesna Mitrovic *et al.* NHMFL report (2004)

κ-(BEDT-TTF)$_2$X









Ross McKenzie, *Science* **278**, 820 (1997)

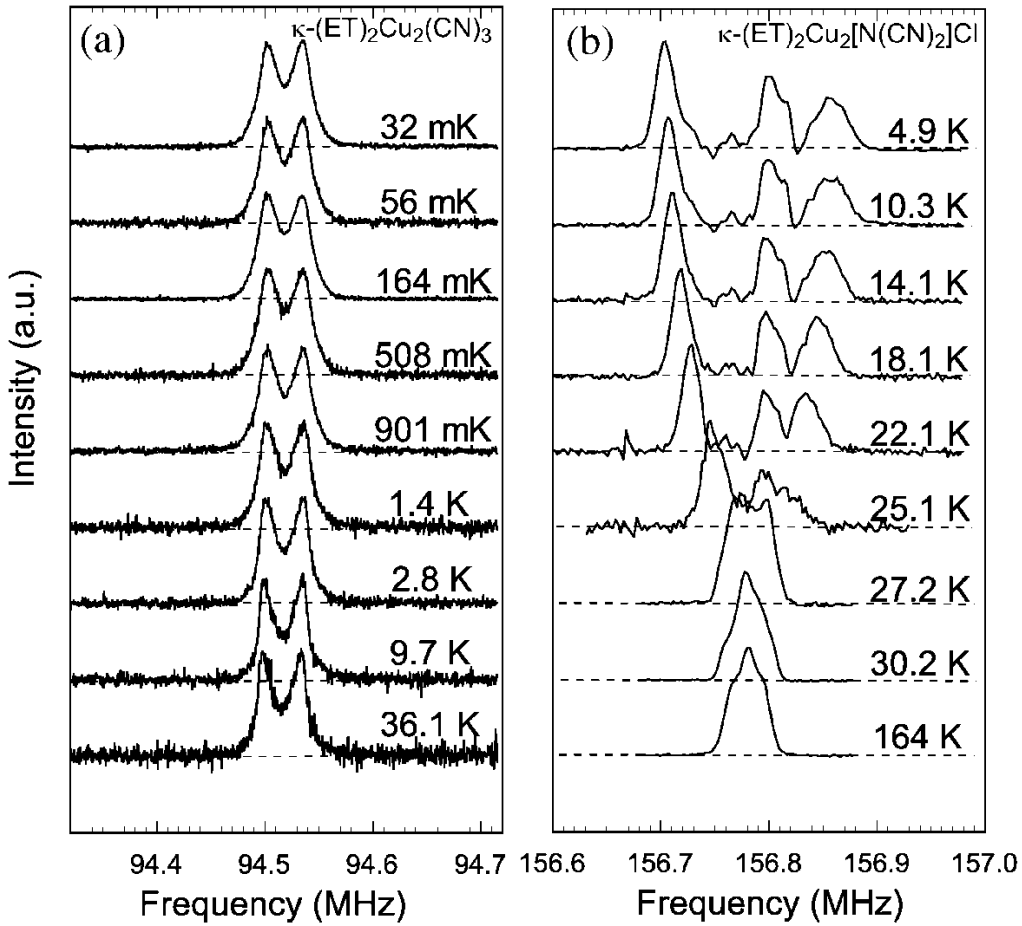


FIG. 3. (a) ^{1}H NMR absorption spectra for single crystals of κ-$(ET)_2Cu_2(CN)_3$ and κ-$(ET)_2Cu[N(CN)_2]Cl$ [9] under the magnetic field perpendicular to the conducting planes.

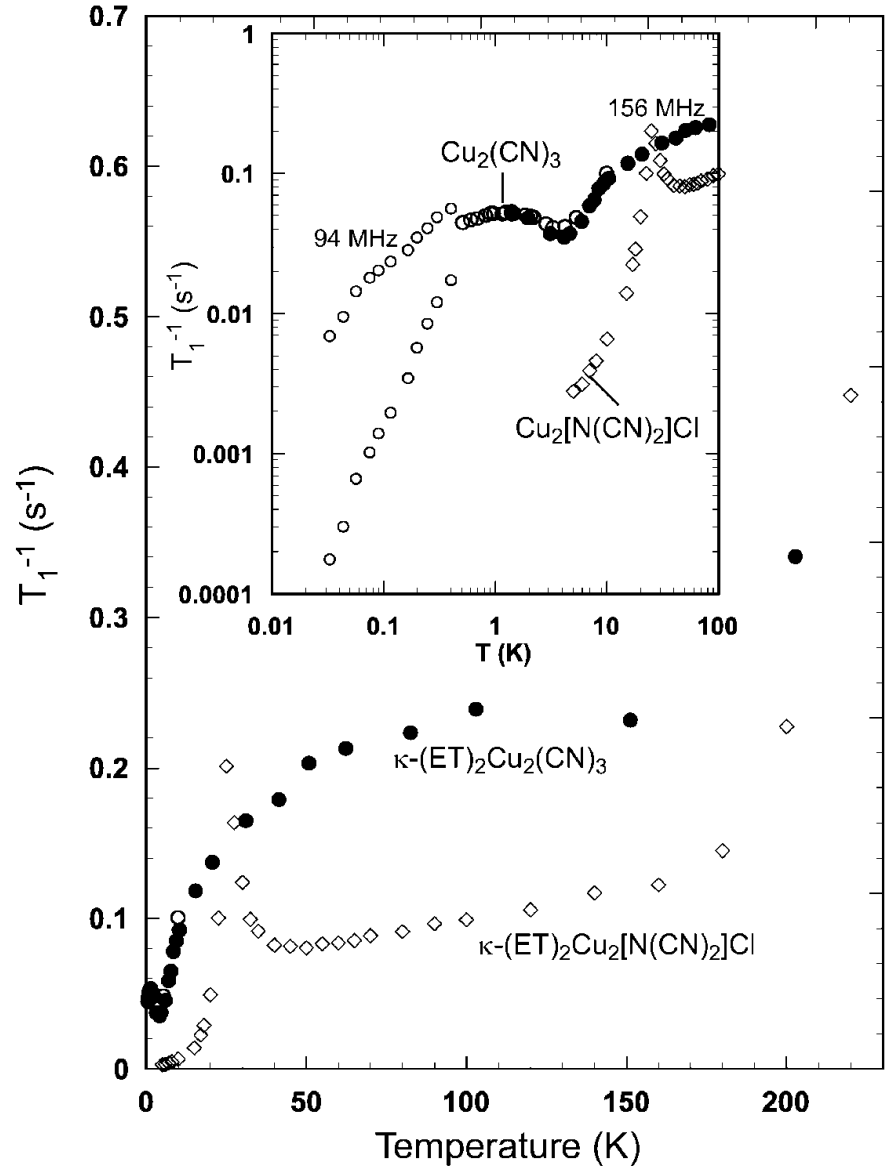


FIG. 4. ^{1}H nuclear spin-lattice relaxation rate T_1^{-1} above 1 K for a single crystal (open circles) and a polycrystalline sample (closed circles) of κ-$(ET)_2Cu_2(CN)_3$ and a single crystal of κ-$(ET)_2Cu[N(CN)_2]Cl$ (open diamonds) [9]. The inset shows the data down to 32 mK in logarithm scales.

Known Unknowns

- What causes the pseudogap in the layered organic materials?
- Do gapless spinon excitations exist?
- Do these materials furnish an example of unconventional superconductivity with no lurking charge modulations?

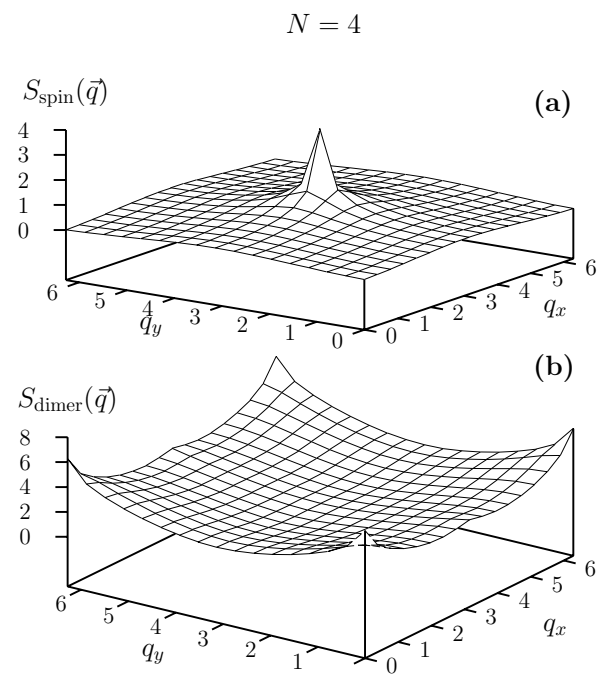
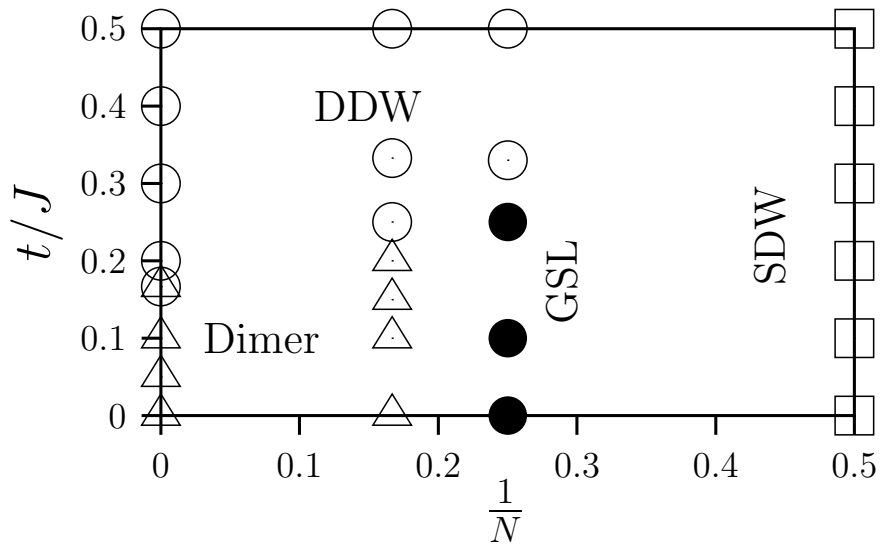
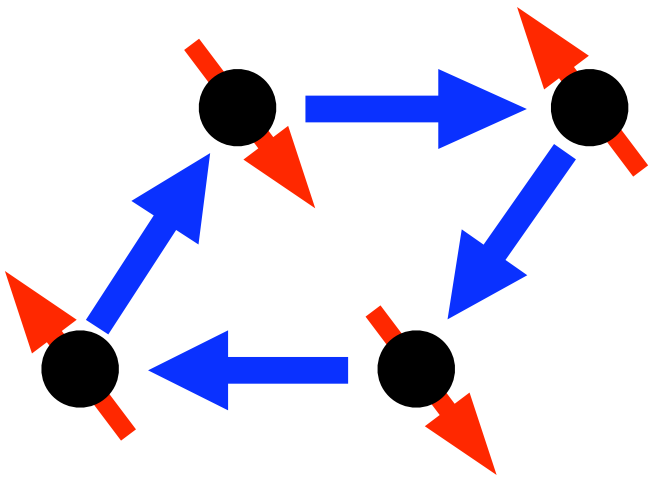


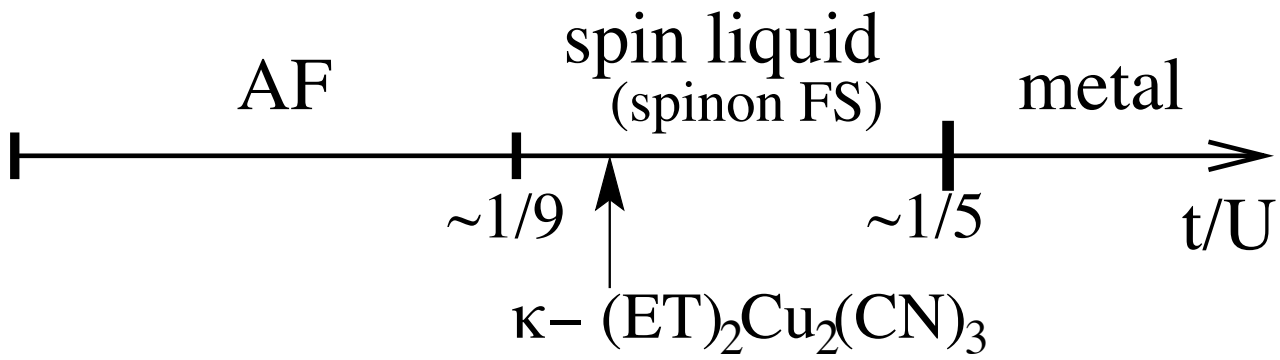
FIG. 10: Equal time dimer and spin correlation functions for the $SU(4)$ Heisenberg model.

F. Assaad, cond-mat/0406074



M. Hermele *et al.* "On the stability of U(1) spin liquids in two dimensions," PRB**70**, 214437 (2004)





Motrunich, cond-mat/0412556

$Sr_{14}Cu_{24}O_{41}$

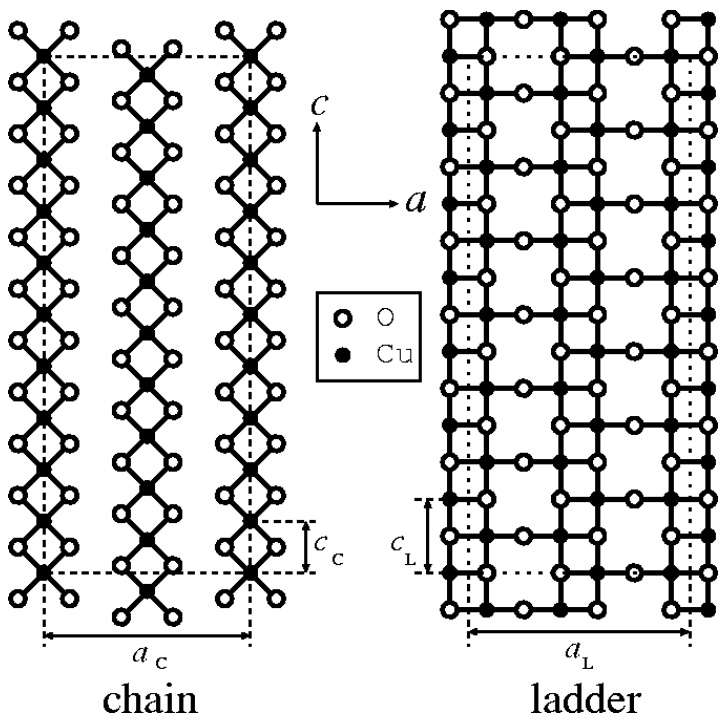
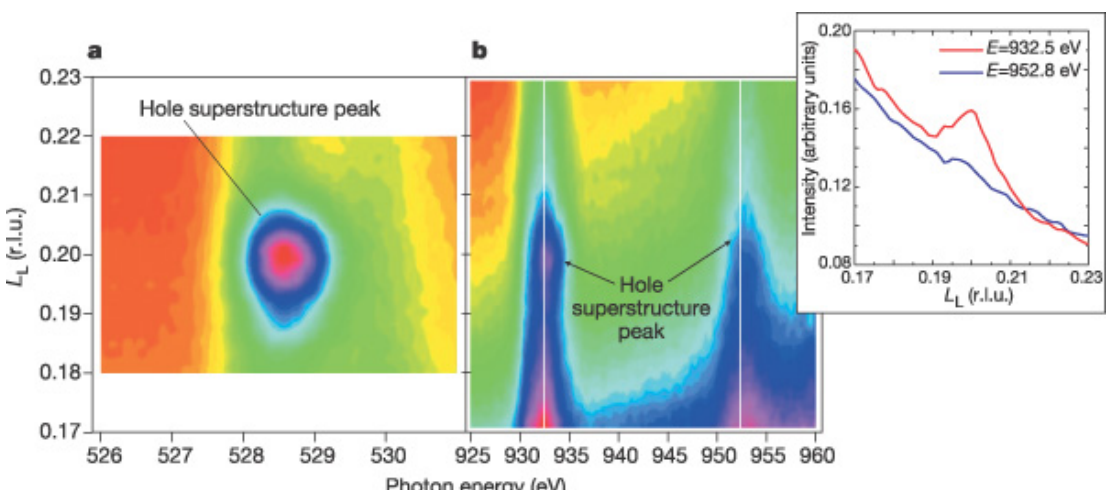
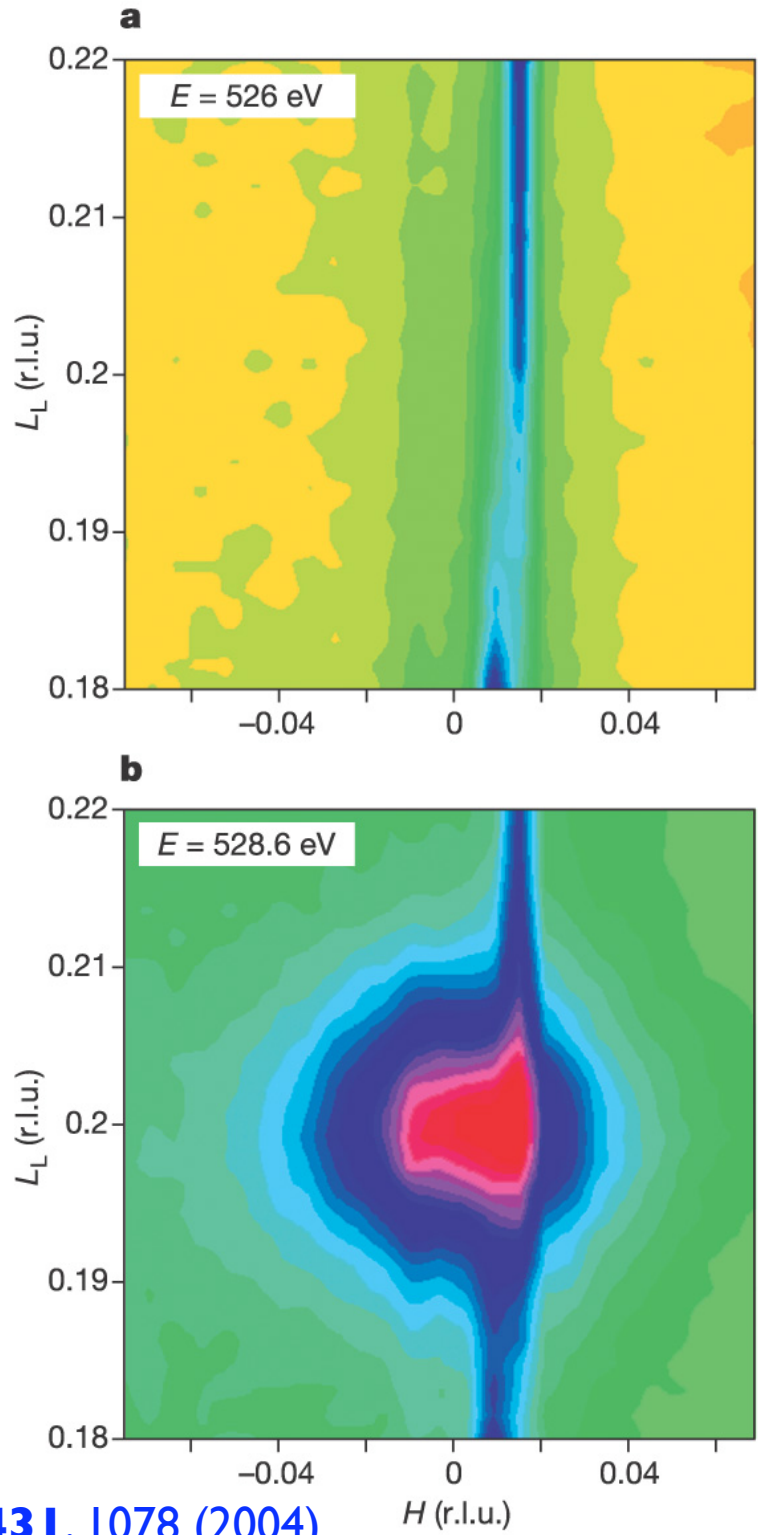
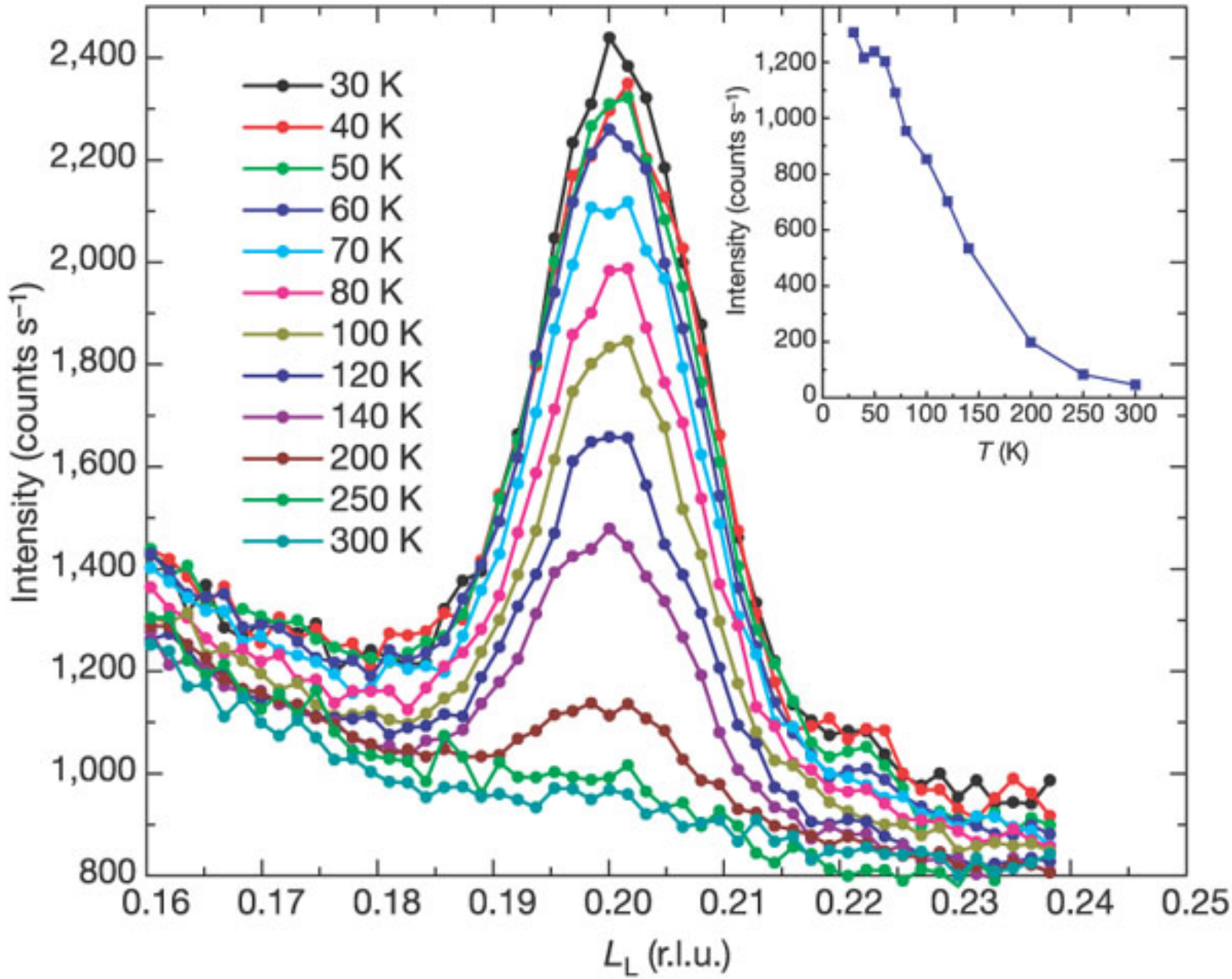


FIG. 1. Structure of CuO_2 chains (left) and Cu_2O_3 ladders (right) in $Sr_{14}Cu_{24}O_{41}$. Fukuda *et al.* PRB**66**, 12104 (2002)





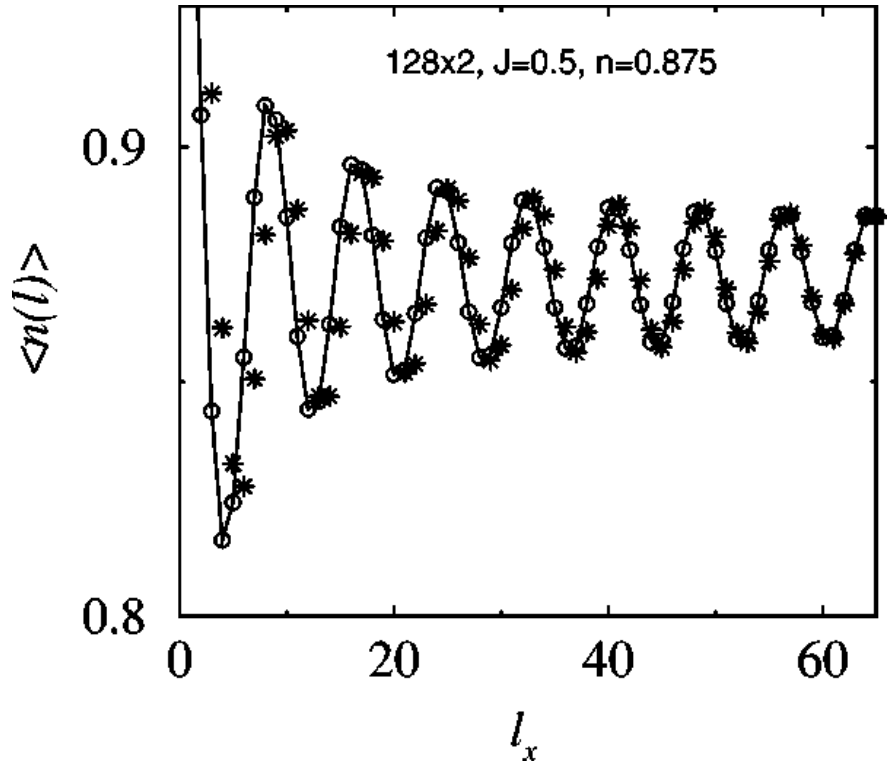
P.Abbamonte *et al.* Nature **431**, 1078 (2004)



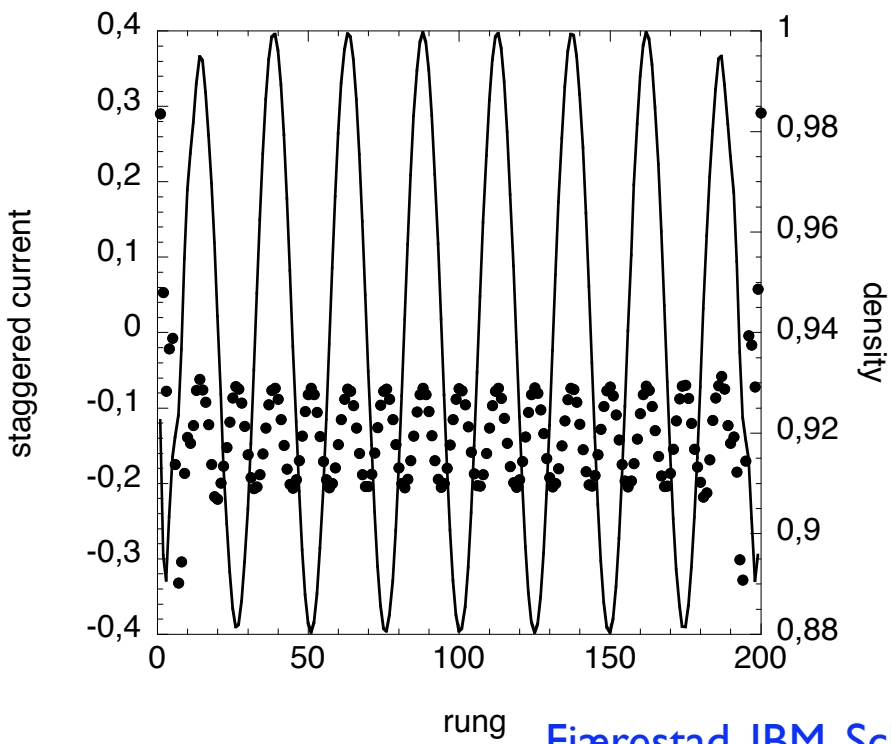
P. Abbamonte *et al.* Nature **431**, 1078 (2004)

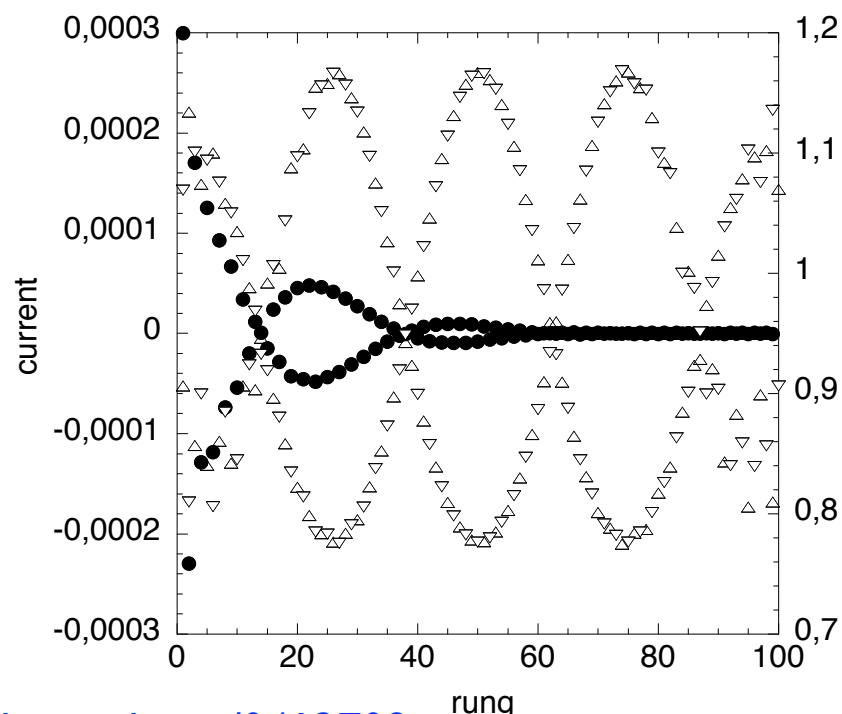
Known Unknowns

- Is the CDW intrinsic or just due to defects and impurities? True LRO?
- If so, how to understand the discrepancy with the accepted value of the doping?
- What relation, if any, is there between the CDW and the superconductivity?

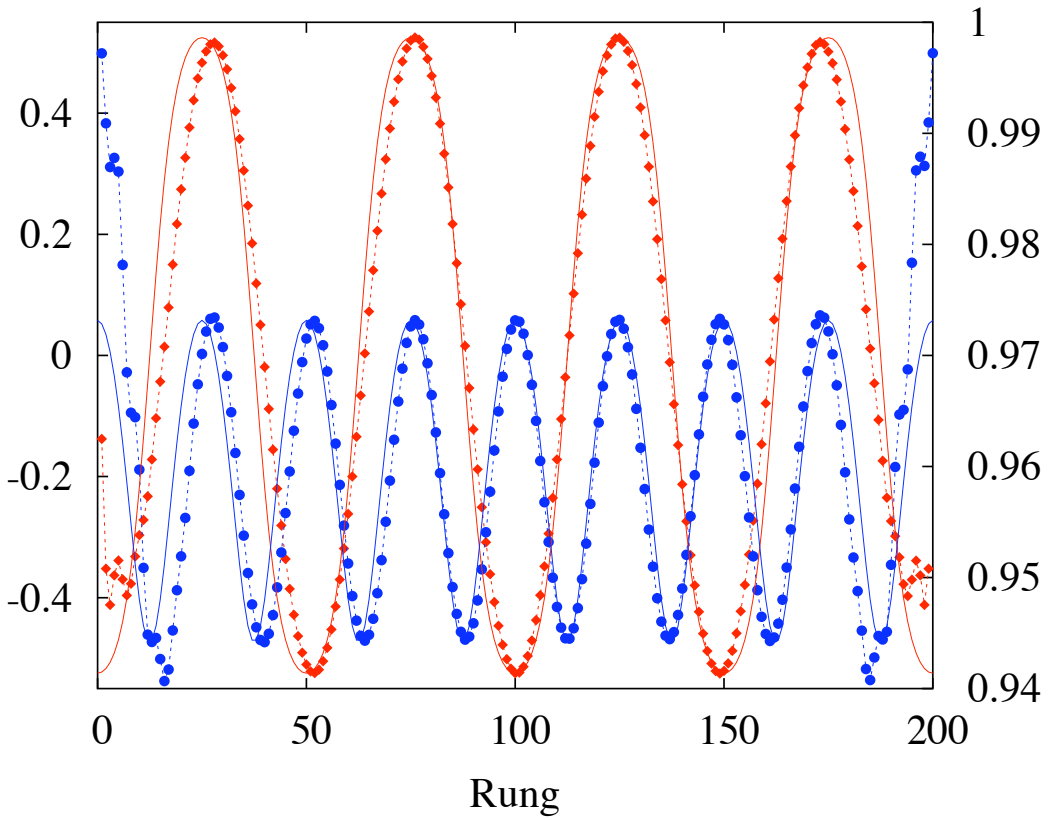


White, Affleck, Scalapino
PRB**65**, 165122 (2002)





Fjærestad, JBM, Schollwöck, cond-mat/0412709



$$\phi_{+\rho}(x) = \mathrm{am}(-x/\sqrt{a} \mid -2b)$$

Jacobian amplitude function

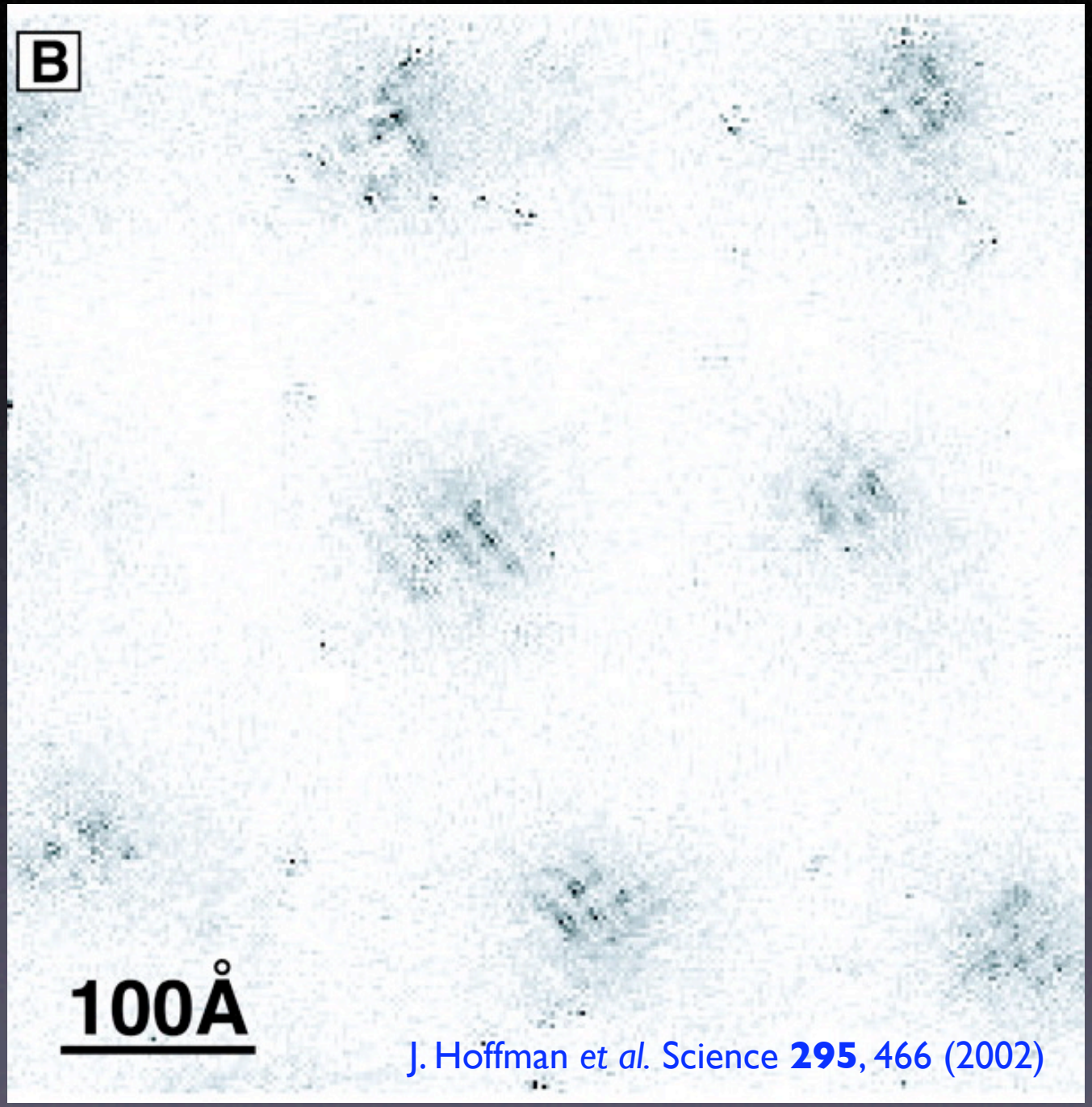
Fjærestad, JBM, Schollwöck, cond-mat/0412709

$$\frac{du}{d\ell} = \epsilon u - u^2 - u^3(1 - \ln w)$$

$$\frac{dw}{d\ell} = -2w + uw + u^2(1 - \ln w)w$$

Belitz, Kirkpatrick, and Rollbühler, PRL**93**, 155701 (2004)

Vortex induced LDOS of $Bi_2Sr_2CaCu_2O_{8+\delta}$



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

Known Unknowns

- Are charge modulations important or a red herring?
- Is there hidden and/or topological order?
- Do ladders "explain" high-T_c superconductivity?
- Is the QPT paradigm misleading?

A Known Known

"As you know, you have to work with the materials you have, not the materials you want."