Quantum antiferromagnetism and the high temperature superconductors

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Transparencies on-line at
http://pantheon.yale.edu/~subir

Science **286**, 2479 (1999).

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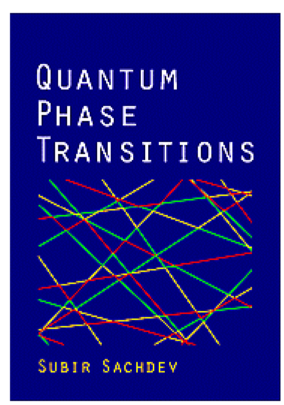
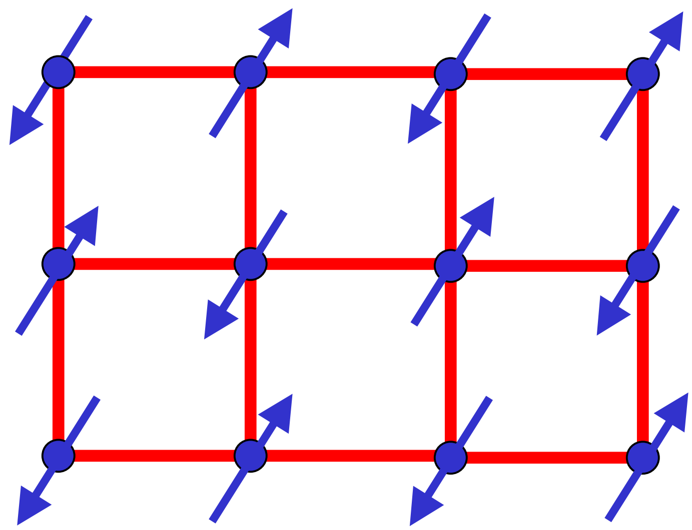


Quantum Phase Transitions
Cambridge University Press

Parent compound of the high temperature superconductors: La_2CuO_4

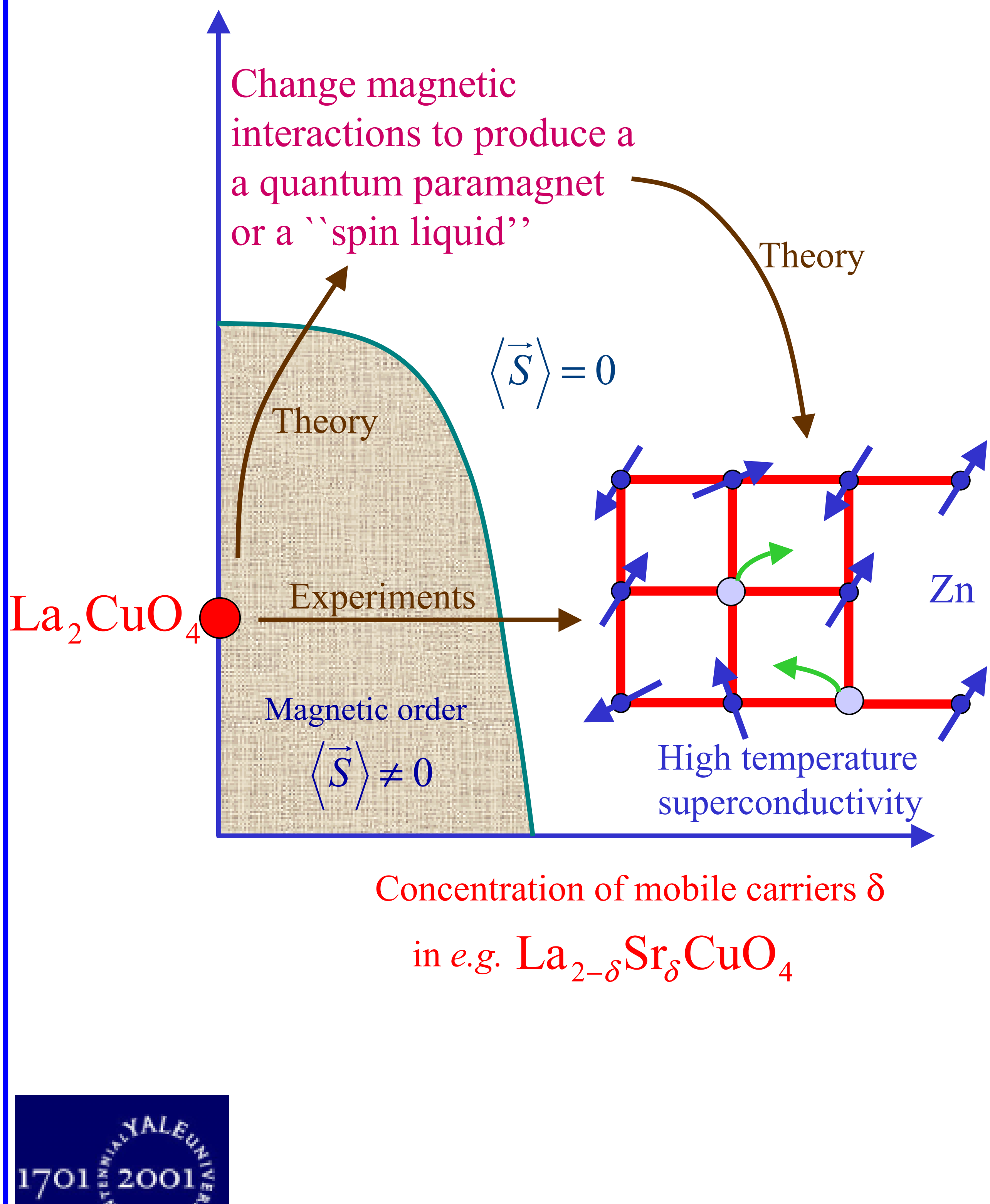
Square lattice antiferromagnet



$$H = J_1 \sum_{<ij>} \vec{S}_i . \vec{S}_j$$

Ground state has long-range magnetic (Neel) order

$$\left\langle \vec{S}_i \right\rangle = \left(-1\right)^{i_x + i_y} N_0 \neq 0$$


Change magnetic
interactions to produce a
a quantum paramagnet
or a ``spin liquid''
Theory
Theory
$\langle \vec{S} \rangle = 0$
La_2CuO_4
Experiments
Zn
Magnetic order
$\langle \vec{S} \rangle \neq 0$
High temperature
superconductivity
Concentration of mobile carriers δ
in *e.g.* $La_{2-\delta}Sr_{\delta}CuO_4$
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Outline

1. Paramagnetic ground states of two-dimensional antiferromagnets and their response to static non-magnetic impurities.

   A. Spinon confinement

   vs.

   B. spinon deconfinement (spin-charge separation)

2. Connection to d-wave superconductors

3. Recent experiments on non-magnetic impurities

   a. NMR

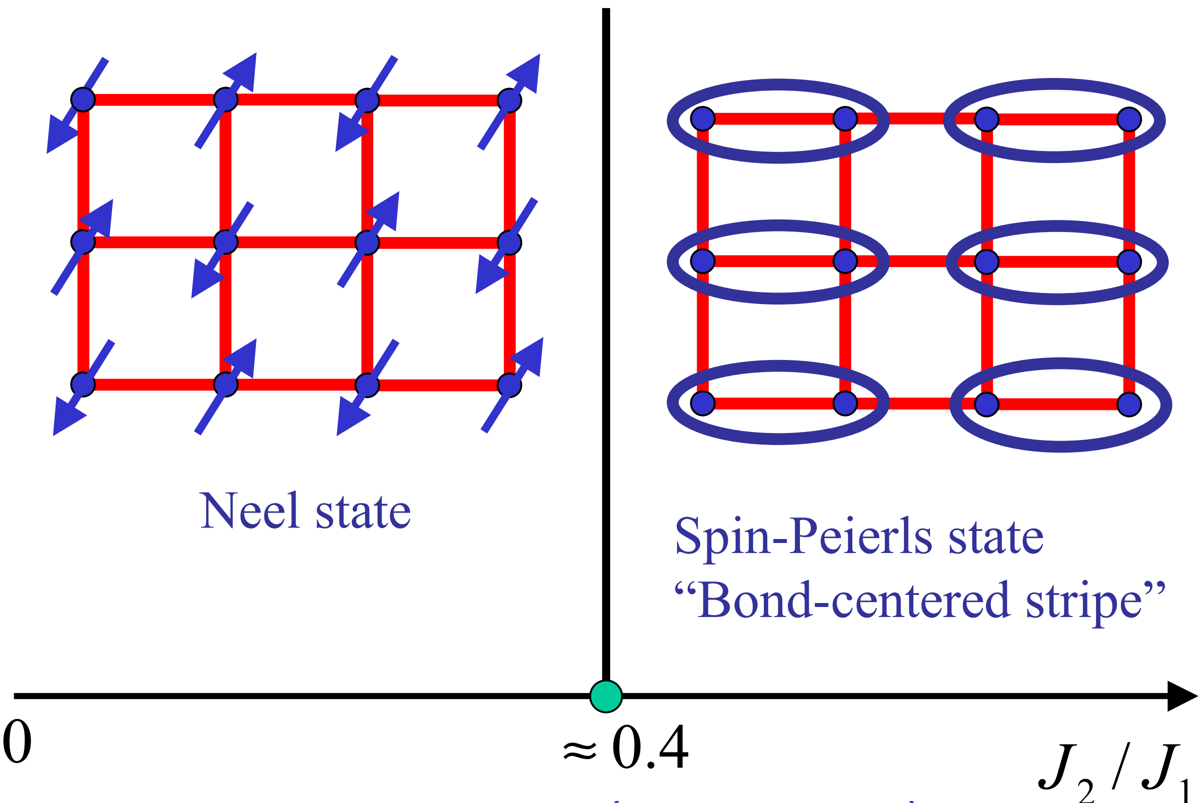
   b. Neutron scattering

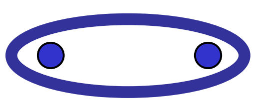
   c. Tunneling

4. Conclusions

1. Quantum paramagnets in two dimensional antiferromagnets

Square lattice with first (J_1) and second (J_2) neighbor exchange interactions

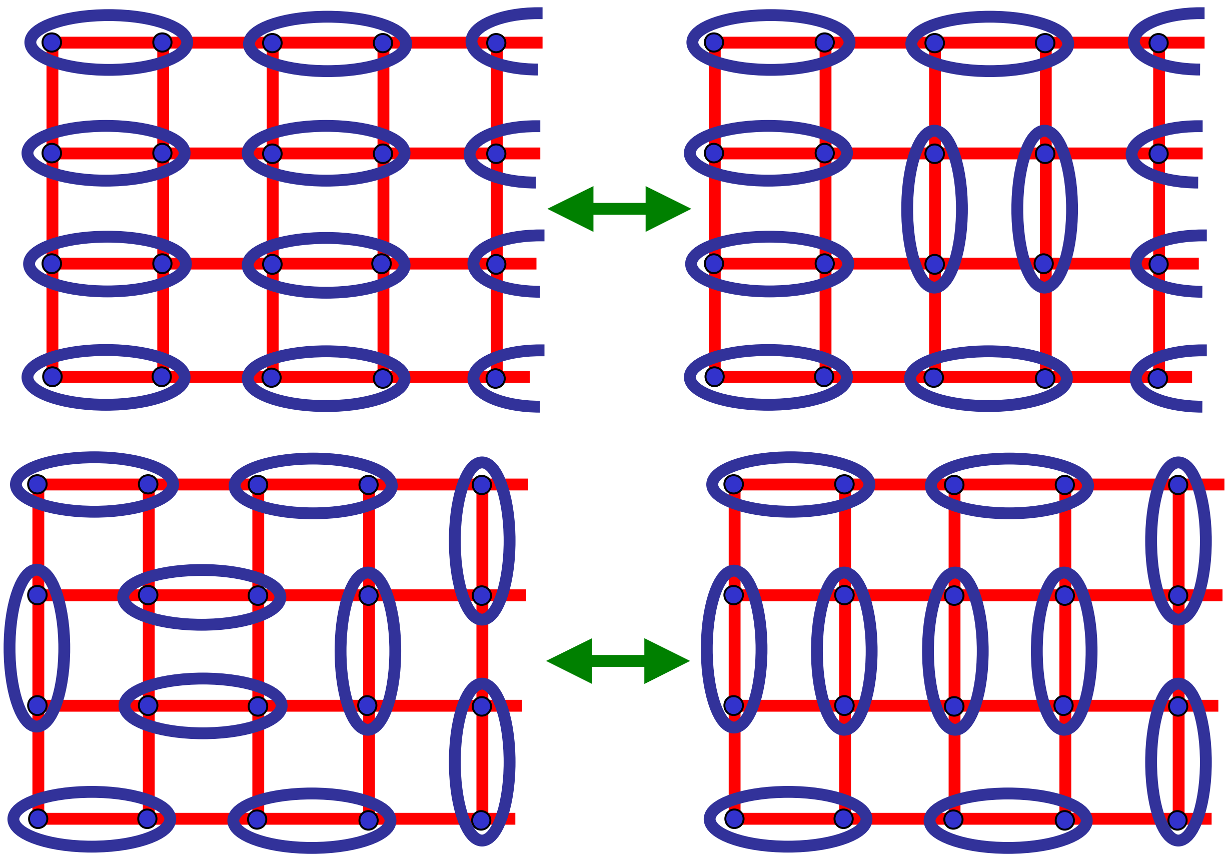


 $= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle \right)$

N. Read and S. Sachdev, Phys. Rev. Lett. **62**, 1694 (1989)
O. P. Sushkov, J. Oitmaa, and Z. Weihong, condmat/0007329.
M.S.L. du Croo de Jongh, J.M.J. van Leeuwen, W. van Saarloos, cond-mat/0002116.

Quantum dimer model –

D. Rokhsar and S. Kivelson Phys. Rev. Lett. **61**, 2376 (1988)



Quantum "entropic" effects prefer one-dimensional striped structures in which the largest number of singlet pairs can resonate. The state on the upper left has more flippable pairs of singlets than the one on the lower left. These effects always lead to a broken square lattice symmetry near the transition to the Neel state.

N. Read and S. Sachdev Phys. Rev. B **42**, 4568 (1990).

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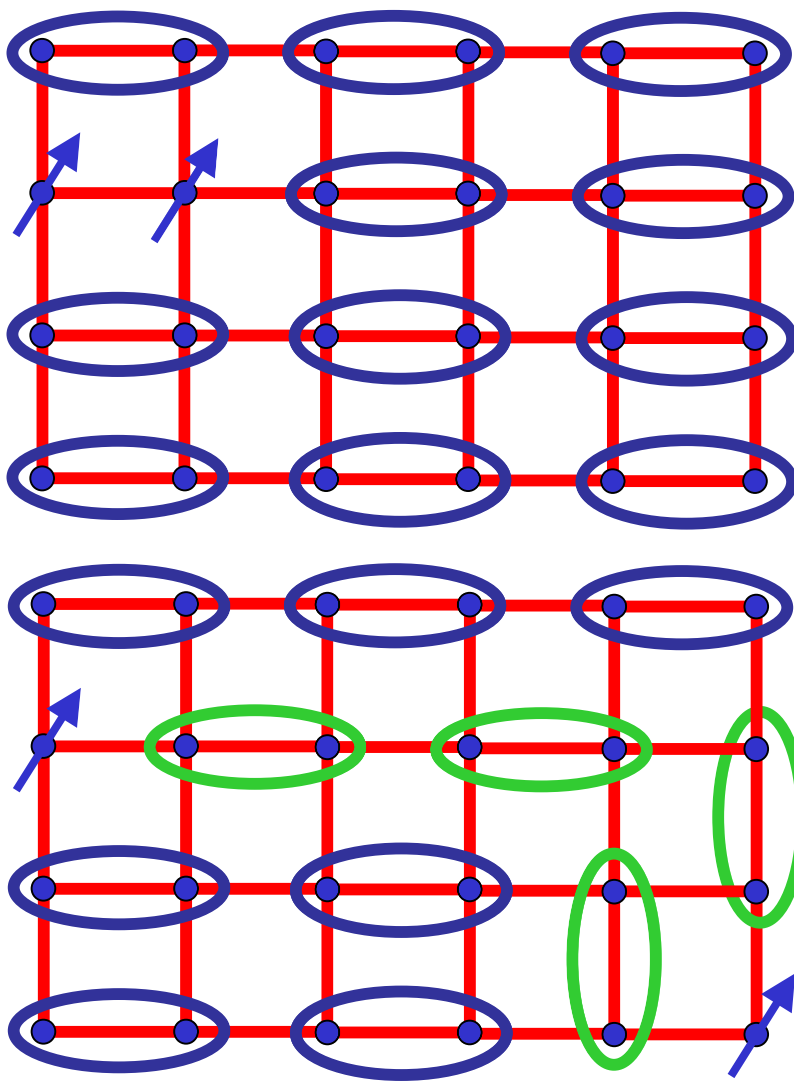
Excitations

Stable S=1 particle

Energy dispersion $$\varepsilon_k = \Delta + \frac{c_x^2 k_x^2 + c_y^2 k_y^2}{2\Delta}$$

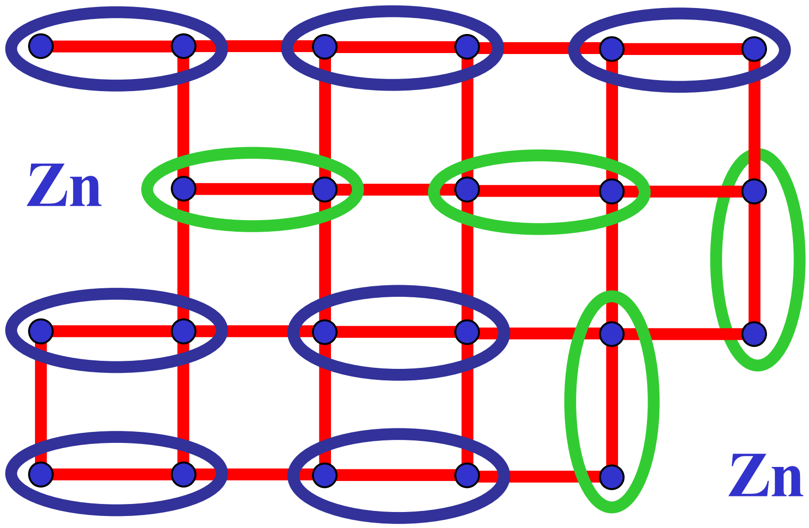
$\Delta \rightarrow$ Spin gap

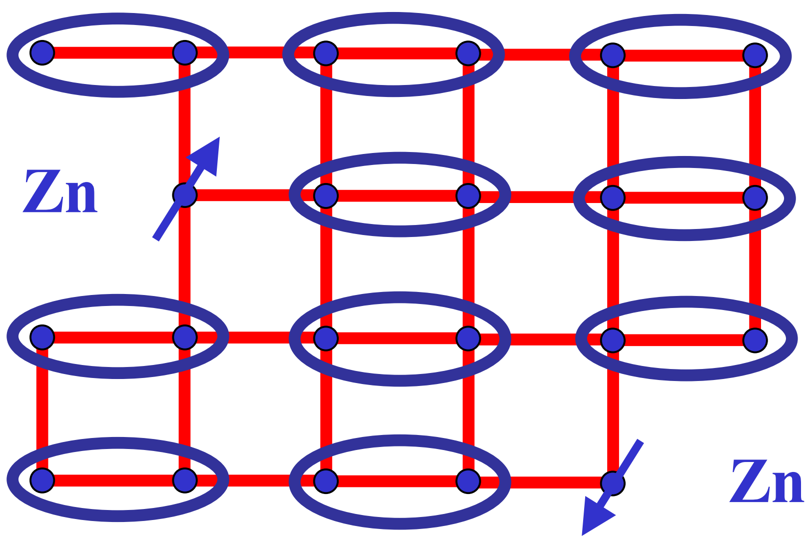


S=1/2 spinons are linearly confined by the line of "defect" singlet pairs between them

Effect of static non-magnetic impurities (Zn or Li)

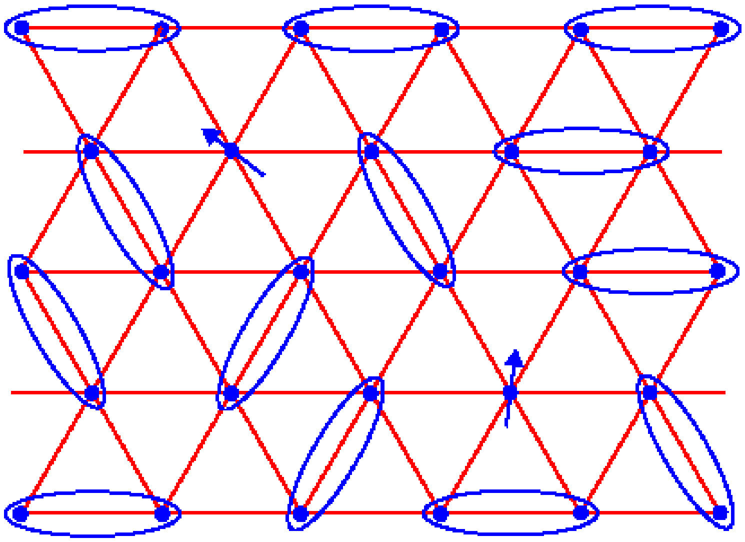
Impurities substitute for Cu ions





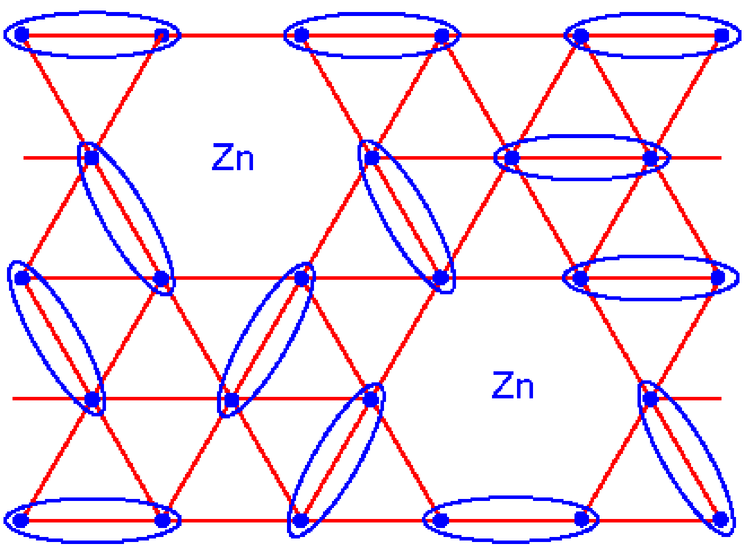
Spinon confinement implies that free S=1/2 moments **must** form near each impurity

B. Paramagnetic ground state with spinon deconfinement



Spinons are deconfined

"Spin Liquid"



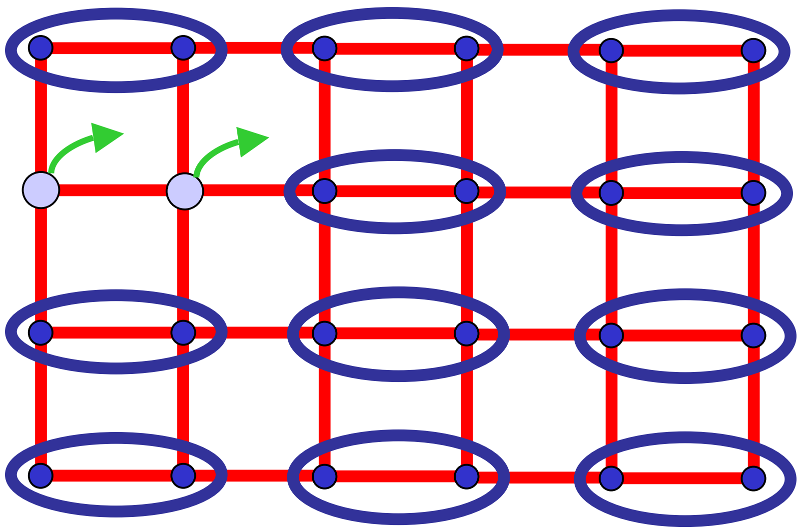
Free S=1/2 moments need not be present near the impurities

P. Fazekas and P.W. Anderson, Phil Mag **30**, 23 (1974).
S. Sachdev, Phys. Rev. B **45**, 12377 (1992).
G. Misguich and C. Lhuillier, cond-mat/0002170.
R. Moessner and S.L. Sondhi, cond-mat/0007378.

2. Evolution with density of mobile carriers of density δ

δ is controlled by changing concentration of dopant ions outside the planes containing the Cu spins

A. Doping a paramagnet with confinement



Condensate of hole pairs

E. Fradkin and S. Kivelson, Mod. Phys. Lett B **4**, 225 (1990).
S. Sachdev and N. Read, Int. J. Mod. Phys. B **5**, 219 (1991).

B. Doping a deconfined paramagnet

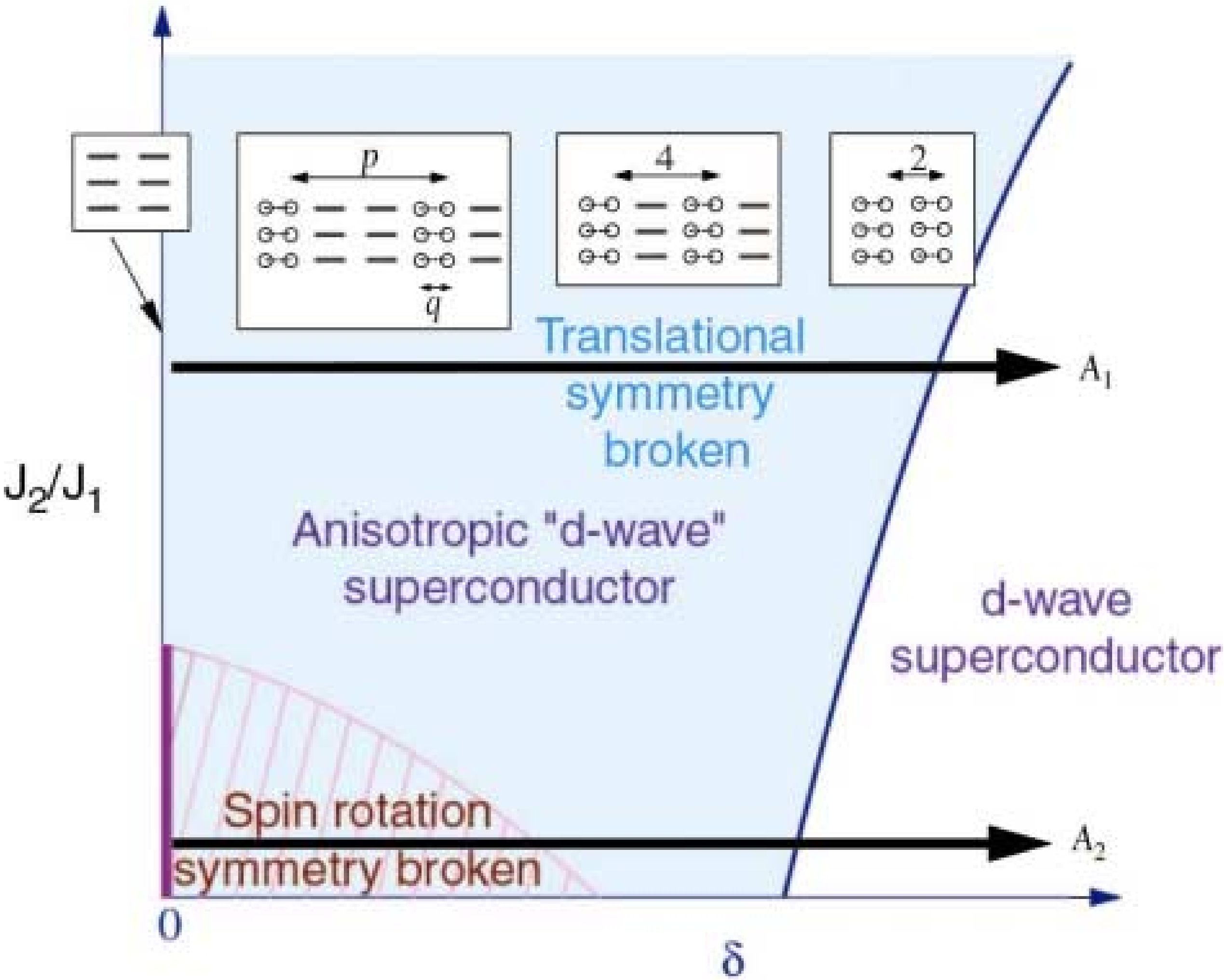
Single hole condensate

hc/(2e) flux quantum (S. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. 6, 353 (1988))

Stable hc/e vortices (S. Sachdev, Phys. Rev. B 45, 389 (1992))

\+ other exotica (T. Senthil and M.P.A. Fisher, cond-mat/0006481)

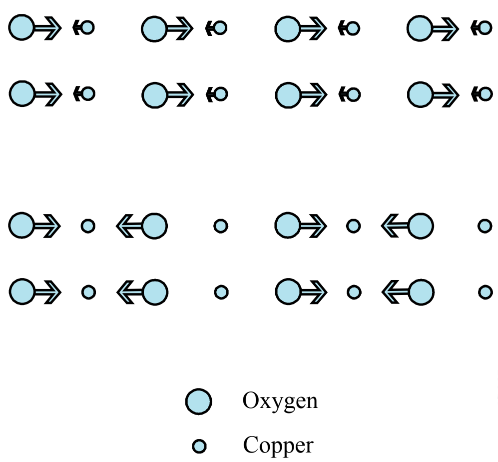
Phase diagram for case A

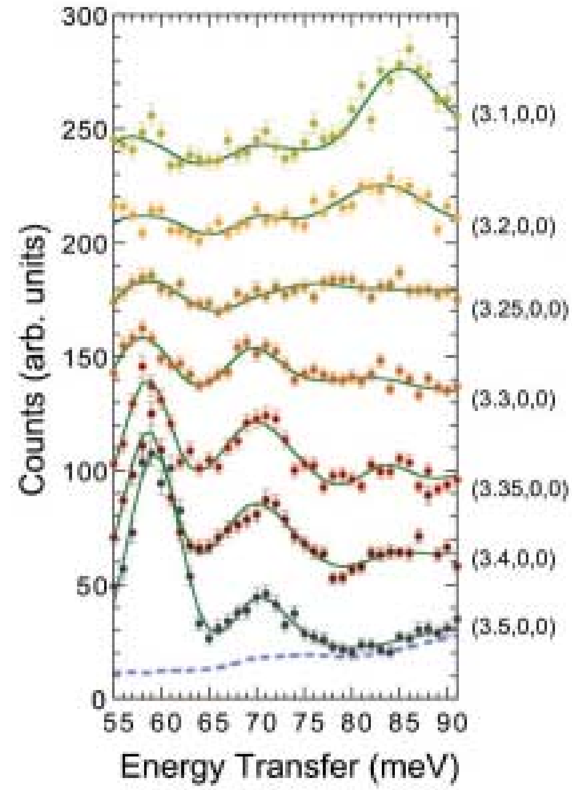


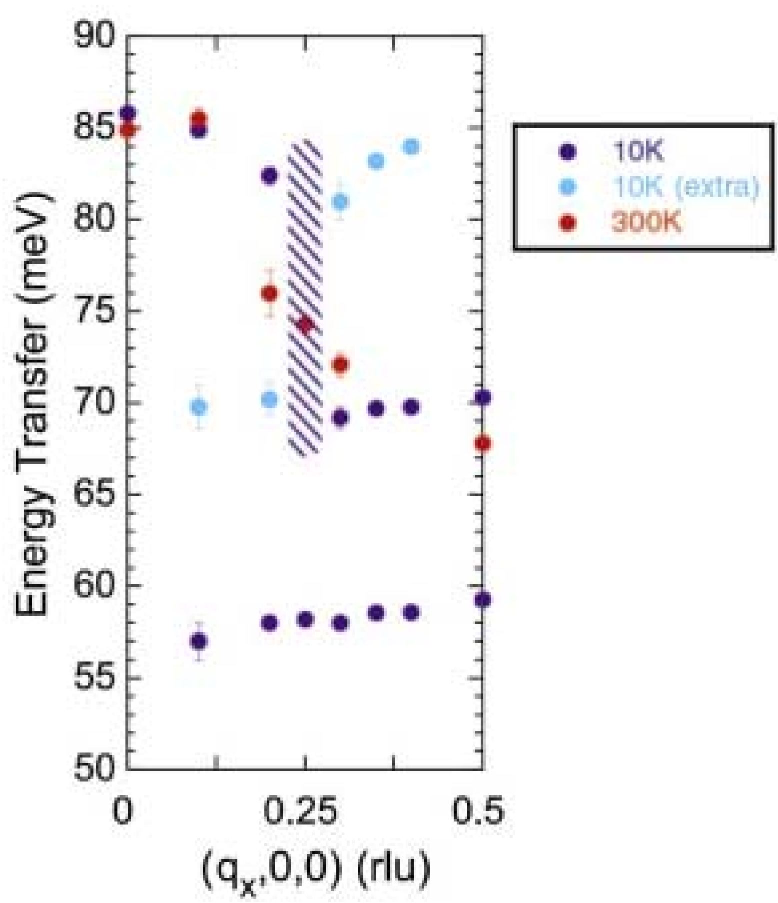
Superconductivity coexists with stripe order

S. Sachdev and N. Read, Int. J. Mod. Phys. B **5**, 219 (1991).
M. Vojta and S. Sachdev, Phys. Rev. Lett. **83**, 3916 (1999).
See also J. Zaanen, Physica C **217**, 317 (1999) and
S. Kivelson, E. Fradkin and V. Emery, Nature **393**, 550 (1998)

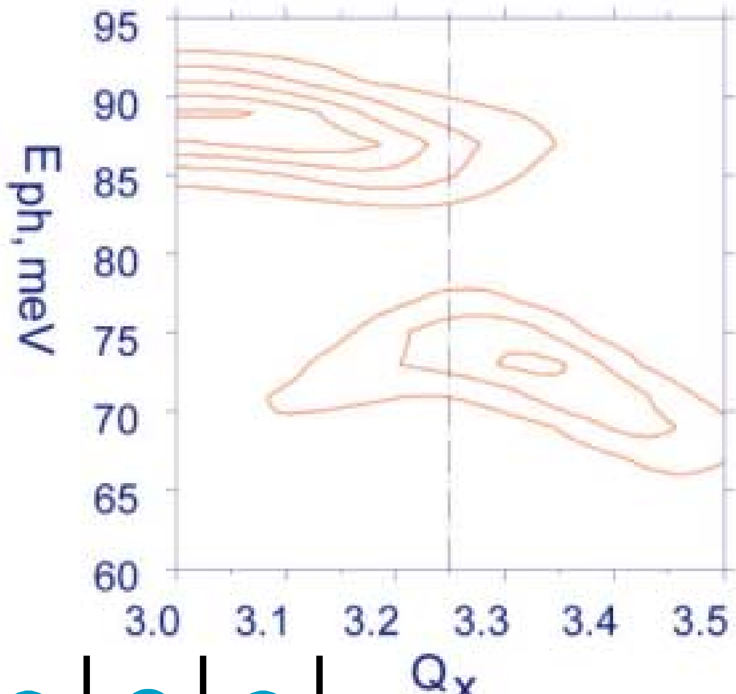
Neutron scattering measurements of phonon spectrum of superconducting $La_{1.85}Sr_{0.15}CuO_4$ by R. J. McQueeney, Y. Petrov, T. Egami, M. Yethiraj, G. Shirane, and Y. Endoh, Phys. Rev. Lett. **82**, 628 (1999)

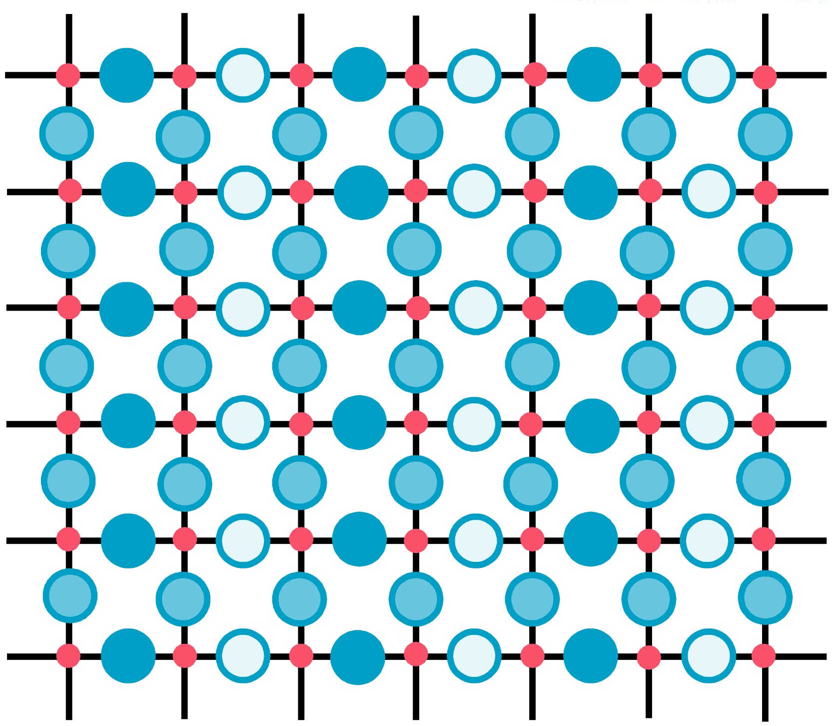






Computation of phonon spectrum by McQueeney *et al* using a simple model based on lattice modulation below





Evidence for predicted coexistence of spin-Peierls order and "d-wave" superconductivity.

S. Sachdev & N. Read, Int. J. Mod. Phys. B **5**, 219 (1991).

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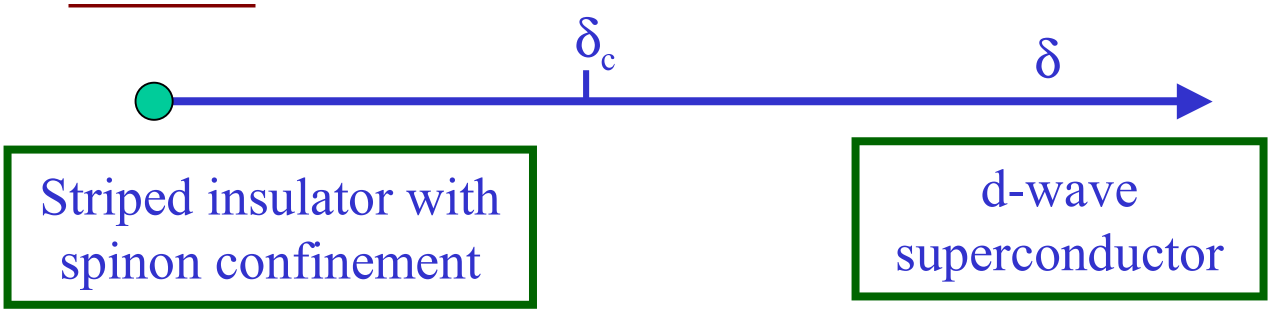
Zn or Li impurities in doped Mott insulators

Case A

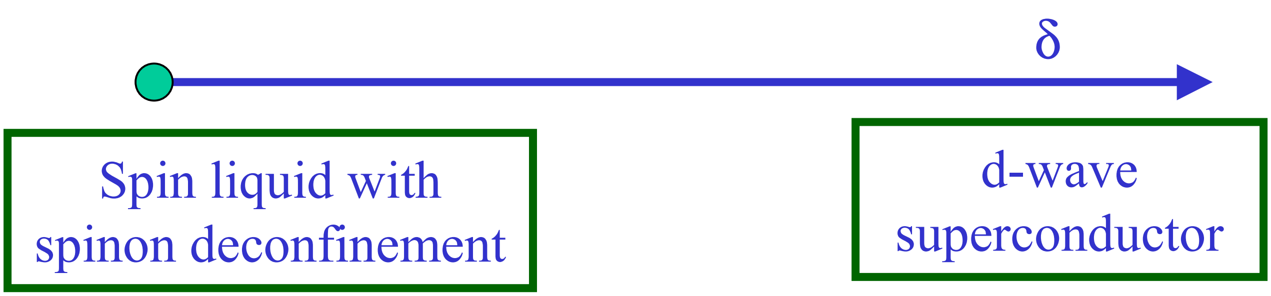


Moments form near each Zn or Li.

This moment is quenched at a quantum phase transition at $\delta=\delta_c$.

D. Withoff and E. Fradkin, Phys. Rev. Lett. **64**, 1835 (1990).
C. Gonzalez-Buxton and K. Ingersent, Phys. Rev. B **57**, 14254 (1998).

Case B



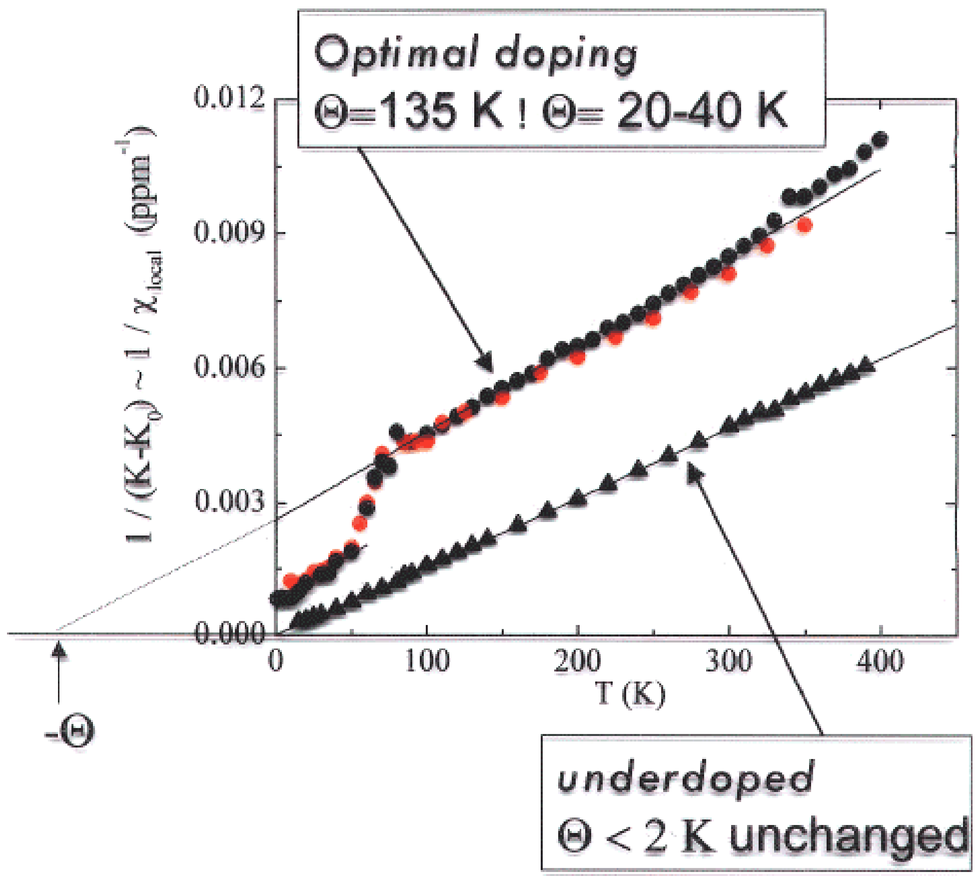
No moments form near Zn or Li ions substituted for Cu and impurity response evolves smoothly

3. Recent experiments

a. NMR

J. Bobroff, H. Alloul, W.A. MacFarlane, P. Mendels, N. Blanchard, G. Collin, and J.-F. Marucco, cond-mat/0010234.

^{7}Li NMR below T_c



Inverse local susceptibility of isolated Li impurities in YBCO

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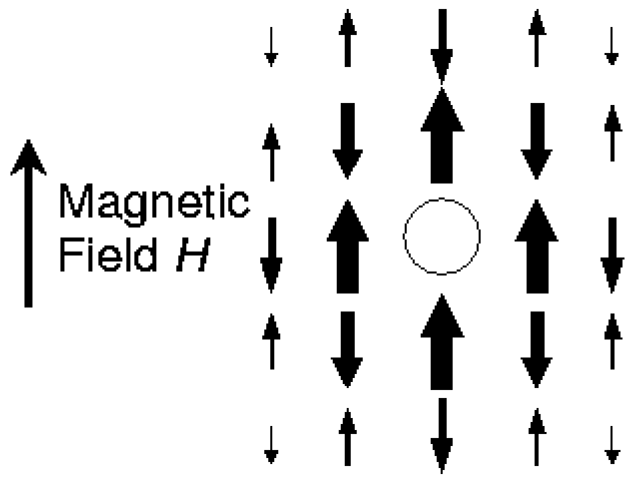
a. NMR

Zn impurity in $YBa_2Cu_3O_{6.7}$

Moments measured by analysis of Knight shifts

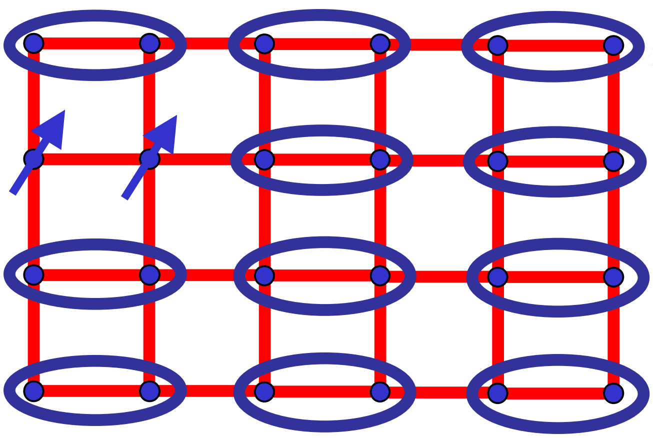
M.-H. Julien, T. Feher, M. Horvatic, C. Berthier, O. N. Bakharev, P. Segransan, G. Collin, and J.-F. Marucco, Phys. Rev. Lett. **84**, 3422 (2000); also earlier work of the group of H. Alloul and the original experiment of A.M Finkelstein, V.E. Kataev, E.F. Kukovitskii, and G.B. Teitel'baum, Physica C **168**, 370 (1990).

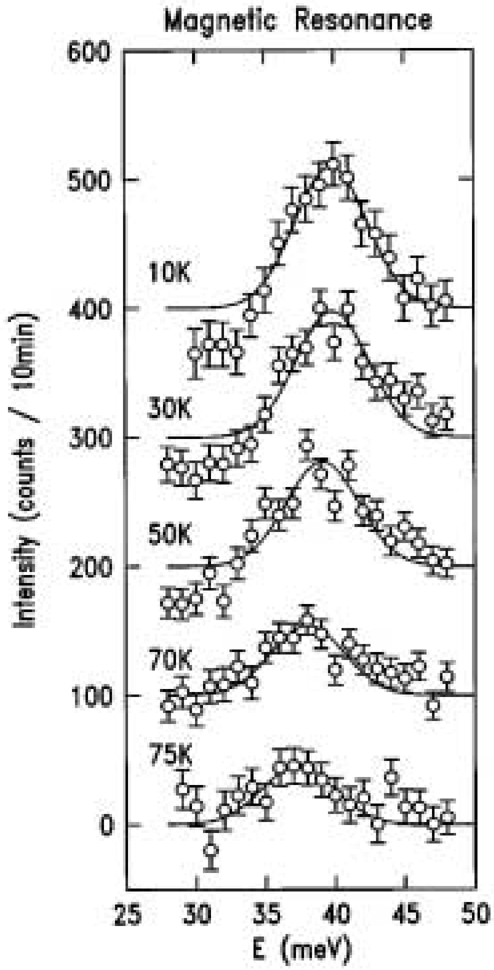


Berry phases of precessing spins do not cancel between the sublattices in the vicinity of the impurity: net uncancelled phase of S=1/2

b. Neutron scattering

S=1 resonance mode in YBCO





H.F. Fong, B. Keimer, D. Reznik, D.L. Milius, and I.A. Aksay, Phys. Rev. B **54**, 6708 (1996)

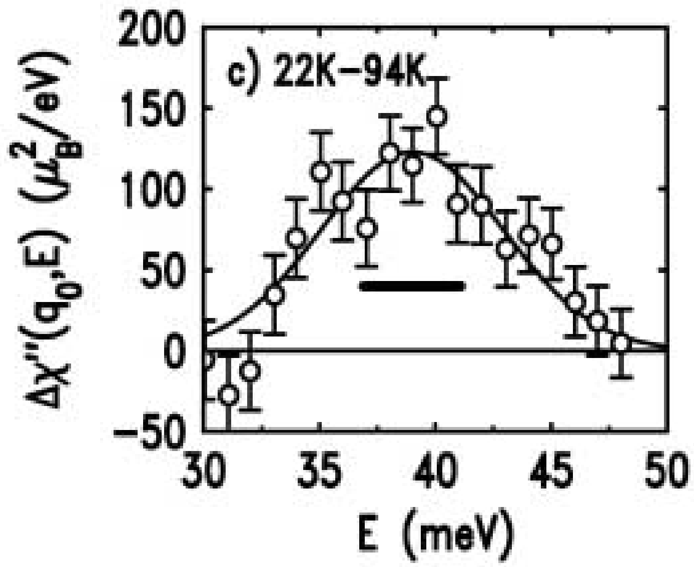
FIG. 8. Unpolarized beam, constant-**Q** data [**Q**=(3/2,1/2,−1.7)] of the 40 meV magnetic resonance obtained by subtracting the signal below T_c from the T=100 K background. The lines are fits to Gaussians, as described in the text. For clarity successive scans are offset by 100.

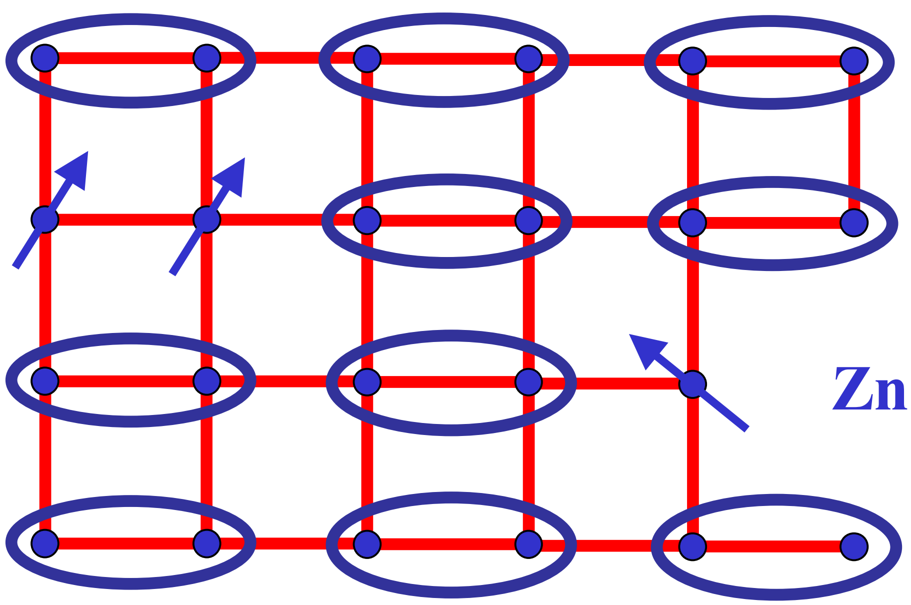
Spin-1 collective mode in $YBa_2Cu_3O_7$- little observable damping at low T.

Coupling to superconducting quasiparticles unimportant

$YBa_2Cu_3O_7 + 0.5\%\ Zn$

H. F. Fong, P. Bourges, Y. Sidis, L. P. Regnault, J. Bossy, A. Ivanov, D.L. Milius, I. A. Aksay, and B. Keimer, Phys. Rev. Lett. **82**, 1939 (1999)





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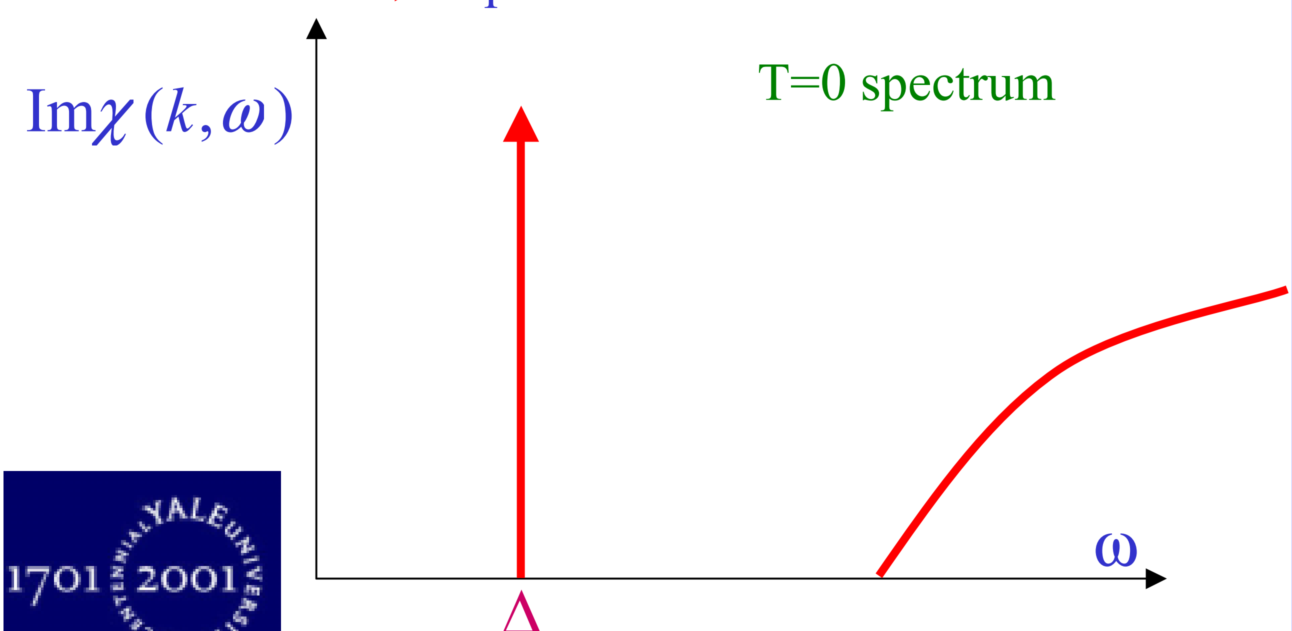
Quantum field theory for S=1 particle near magnetic ordering transition

$$\mathcal{S}_b = \int d^2x\, d\tau \left[\frac{1}{2}\left(\left(\nabla_x \phi_\alpha\right)^2 + c^2 \left(\partial_\tau \phi_\alpha\right)^2 + r\phi_\alpha^2 \right) + \frac{g}{4!}\left(\phi_\alpha^2\right)^2 \right]$$

ϕ_α → 3-component antiferromagnetic order parameter

Oscillations of ϕ_α about zero (for $\boldsymbol{r} > 0$)
→ spin-1 collective mode



Quantum field theory for S=1 resonance in the presence of a non-magnetic impurity

Orientation of "impurity" spin -- $n_\alpha(\tau)$ (unit vector)

Action of "impurity" spin

$$\mathcal{S}_{\text{imp}} = \int d\tau \left[iSA_\alpha(n)\frac{dn_\alpha}{d\tau} - \gamma S n_\alpha(\tau)\phi_\alpha(x=0,\tau) \right]$$

$A_\alpha(n)$ → Dirac monopole function

Boundary quantum field theory: $\mathcal{S}_b + \mathcal{S}_{\text{imp}}$

Recall -

$$\mathcal{S}_b = \int d^2x d\tau \left[\frac{1}{2}\left((\nabla_x \phi_\alpha)^2 + c^2 (\partial_\tau \phi_\alpha)^2 + r\phi_\alpha^2 \right) + \frac{g}{4!}\left(\phi_\alpha^2\right)^2 \right]$$

Renormalization group analysis: g and γ reach non-zero fixed point values

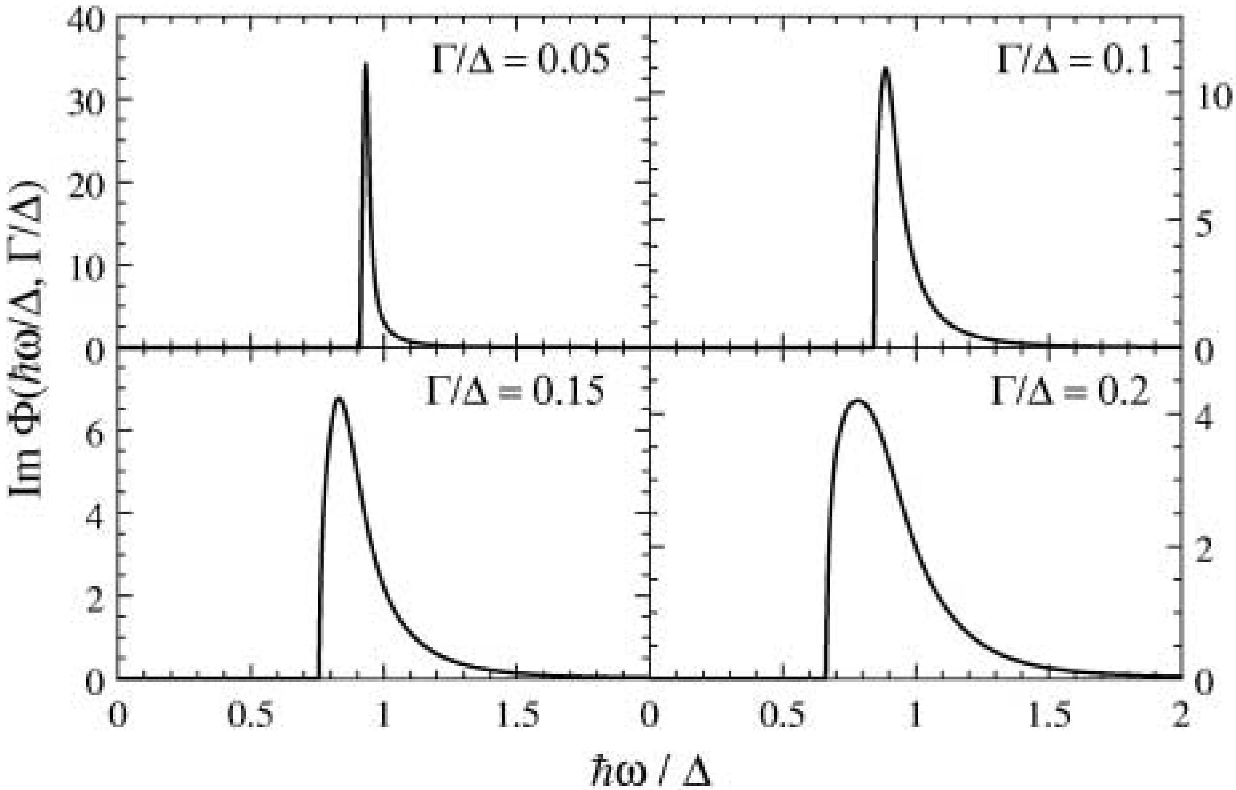
Predictions of quantum field theory

Without impurities $$\chi(G,\omega) = \frac{A}{\Delta^2 - \omega^2}$$

With impurities $$\chi(G,\omega) = \frac{A}{\Delta^2}\Phi\left(\frac{\hbar\omega}{\Delta}, \frac{\Gamma}{\Delta}\right)$$

$$\Gamma \equiv \frac{n_{\text{imp}}(\hbar c)^2}{\Delta}$$

Φ → *Universal* scaling function. We computed it in a "self-consistent, non-crossing" approximation



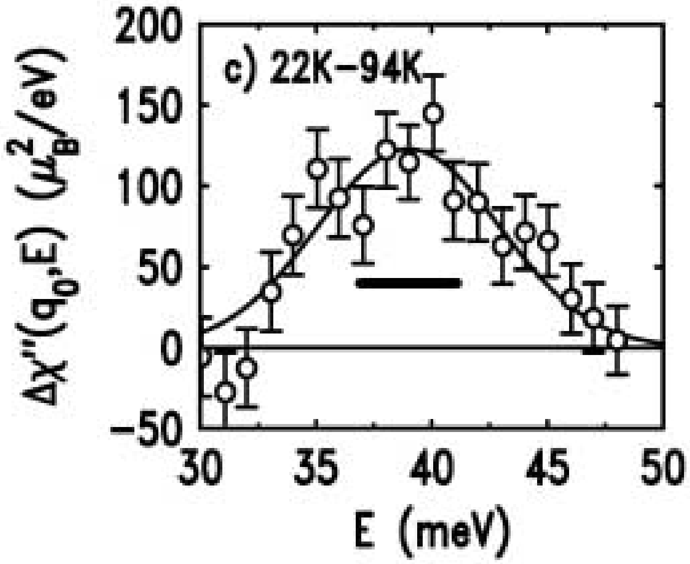
Predictions: Half-width of line $\approx \Gamma$

Universal asymmetric lineshape

S. Sachdev, C. Buragohain, M. Vojta, Science **286**, 2479 (1999)
M. Vojta, C. Buragohain, and S. Sachdev,
Phys. Rev. B **61**, 15152 (2000).

$YBa_2Cu_3O_7 + 0.5\%$ Zn

H. F. Fong, P. Bourges, Y. Sidis, L. P. Regnault, J. Bossy, A. Ivanov, D.L. Milius, I. A. Aksay, and B. Keimer, Phys. Rev. Lett. **82**, 1939 (1999)



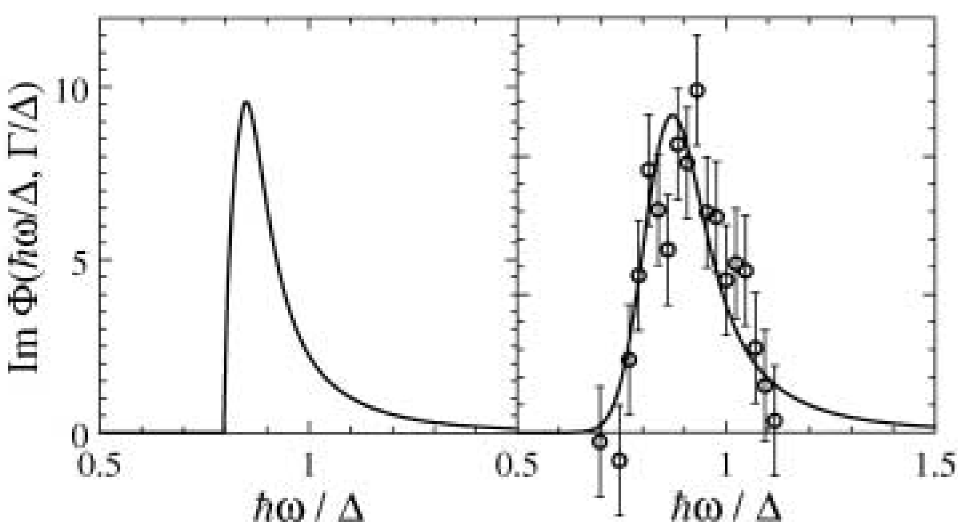
$$n_{imp} = 0.005$$

$$\Delta = 40 \text{ meV}$$

$$\hbar c = 0.2 \text{ eV}$$

$$\Rightarrow \quad \Gamma = 5 \text{ meV}, \ \Gamma/\Delta = 0.125$$

Quoted half-width = 4.25 meV



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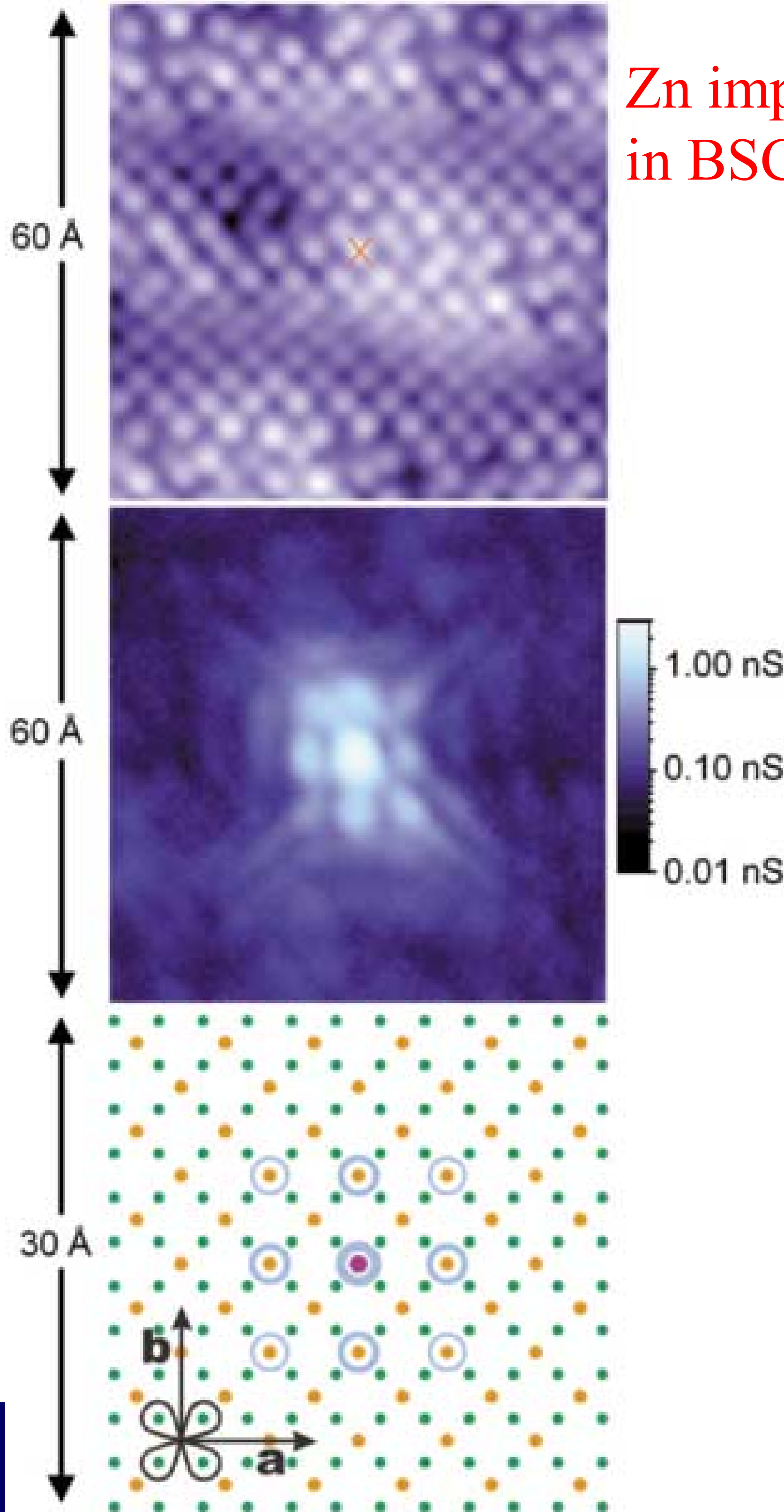
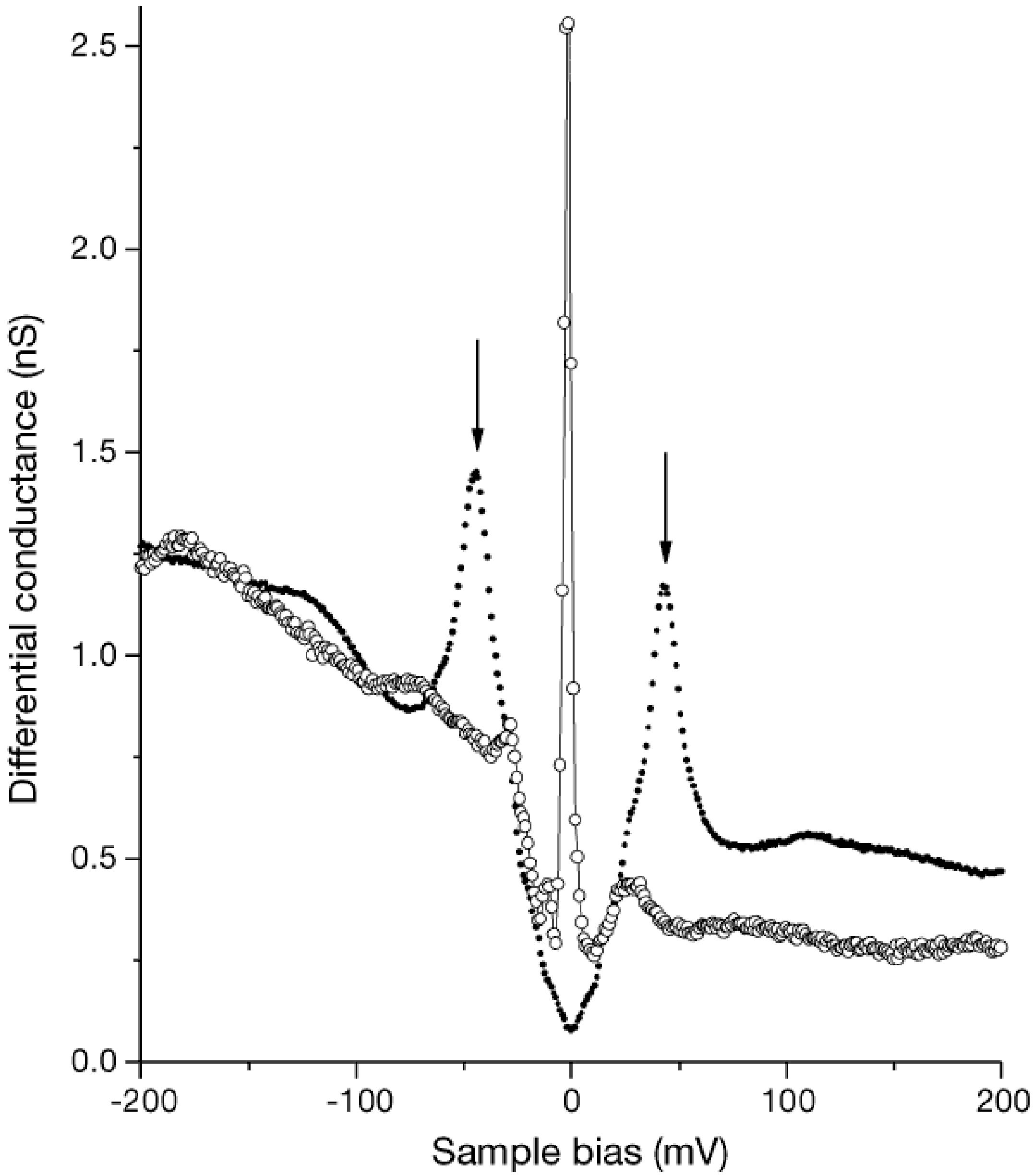
c. Tunneling



Zn impurities in BSCCO

S. H. Pan *et al* Nature **403**, 746 (2000)

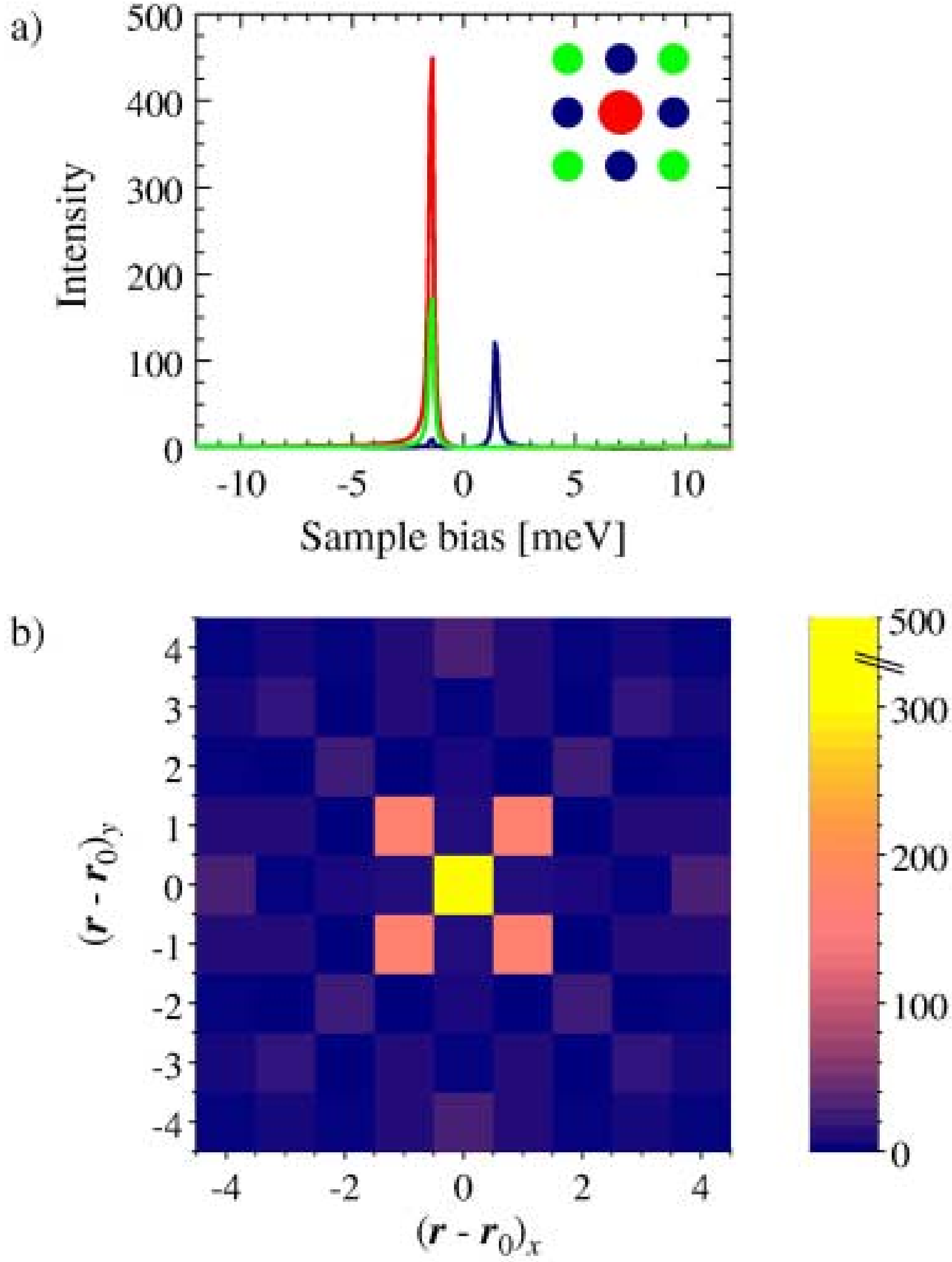
c. Tunneling



Zn impurity in BSCCO

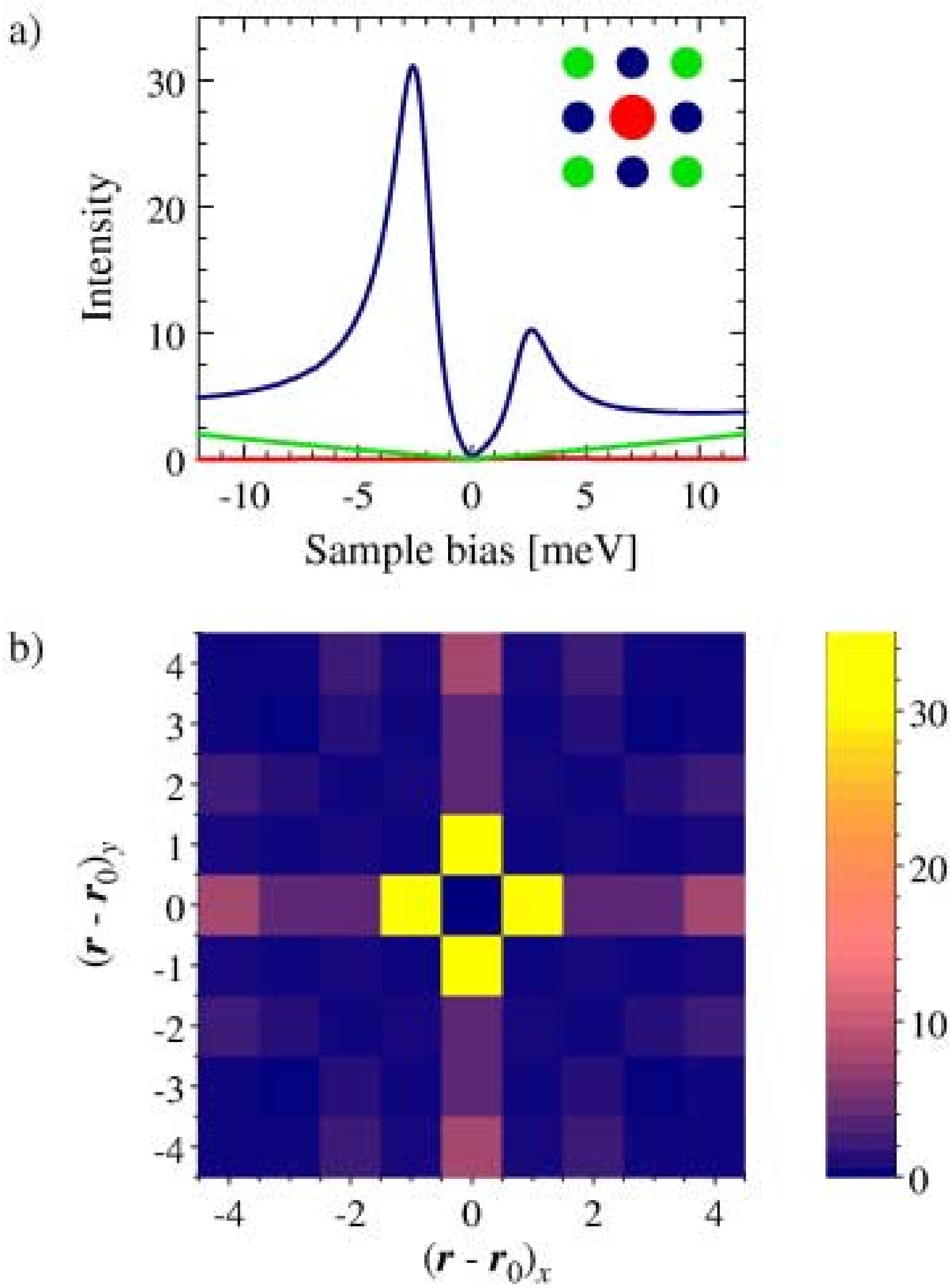
S. H. Pan *et al* Nature **403**, 746 (2000)

Theory: S=1/2 local moment coupled to Bogoluibov quasiparticles of a *d*-wave superconductor



A. Polkovnikov, S. Sachdev, and M. Vojta, cond-mat/0007431, Phys. Rev. Lett. (in press).

Theory: Impurity scattering of Bogoluibov quasiparticles



A.V. Balatsky, M. I. Salkola, and A. Rosengren, Phys. Rev. B **51**, 15547 (1995)
M. I. Salkola, A.V. Balatsky, and D. J. Scalapino, Phys. Rev. Lett.**77**,1841 (1996).
A. Polkovnikov, S. Sachdev, and M. Vojta, cond-mat/0007431 Phys. Rev. Lett. (in press)

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Conclusions

1. Strong experimental evidence for *S=1/2* moment near Zn and Li impurities in the underdoped high temperature superconductor.

2. Quantitative computations of STM tunneling and neutron scattering resonance linewidths compare well with experiments

3. Supports a reference paramagnetic Mott insulator with confinement – such a state *requires* *S=1* spin resonance, broken translational symmetry (stripe order), and moments near non-magnetic impurities.

4. Charge stripes with antiferromagnetic order are site-centered and have anti-phase domain walls.

J. Zaanen and O. Gunnarsson, Phys. Rev. B **40**, 7391 (1989)
H. Schulz, J. de Physique **50**, 2833 (1989).
K. Machida, Physica **158C**, 192 (1989).
V.J. Emery and S.A. Kivelson, Physica C **235-240**, 189 (1994).

Evidence for bond-centered stripes in paramagnetic phase with superconductivity.

N. Read & S. Sachdev, Phys. Rev. Lett. **62**, 1694 (1989)
S. Sachdev & N. Read, Int. J. Mod. Phys. B **5**, 219 (1991).