Tuning spin and charge order in the cuprate superconductors

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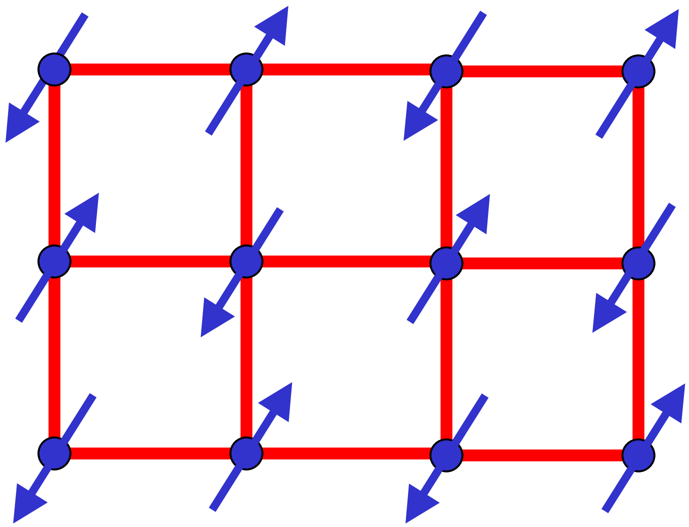
Ying Zhang

Talk online at
http://pantheon.yale.edu/~subir

Parent compound of the high temperature superconductors: La_2CuO_4

Mott insulator: square lattice antiferromagnet



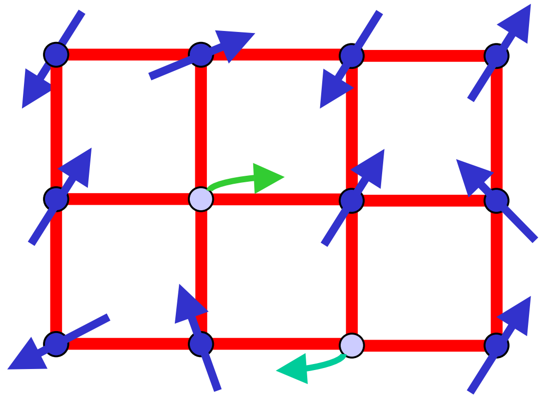
$$H = \sum_{<ij>} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

Ground state has long-range magnetic Néel order, or a "spin density wave (SDW)"

Néel order parameter: $\boldsymbol{n}_i \sim \eta_i \vec{S}_i$ with $\eta_i = (-1)^{i_x + i_y}$

$$\langle \boldsymbol{n} \rangle \neq 0 \quad ; \quad \langle \vec{S}_i \rangle \neq 0$$

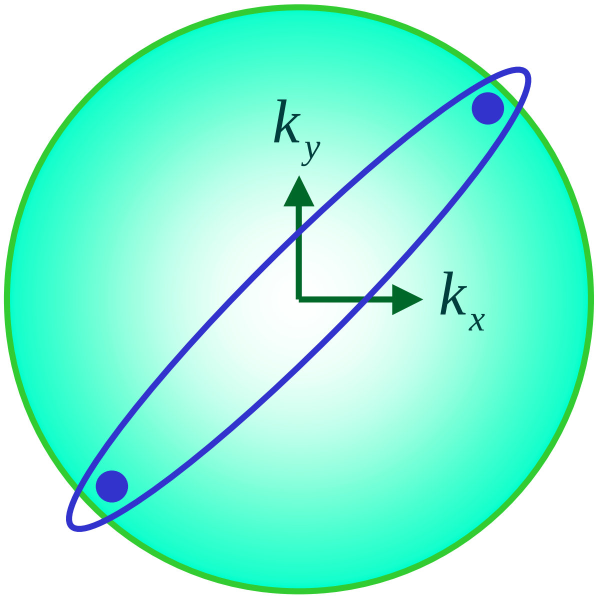
Introduce mobile carriers of density δ by substitutional doping of out-of-plane ions *e.g.* $La_{2-\delta}Sr_{\delta}CuO_4$



Exhibits superconductivity below a high critical temperature T_c

Superconductivity in a doped Mott insulator

BCS superconductor obtained by the Cooper instability of a metallic Fermi liquid



Pair wavefunction

$$\Psi = \left(k_x^2 - k_y^2\right)\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

$$\left\langle \vec{S} \right\rangle = 0$$

Some ***low*** temperature properties of the cuprate superconductors appear to be qualitatively similar to those predicted by BCS theory.

Many experiments above T_c are not described quantitatively by BCS theory: this is probably due to strong-coupling "crossover" effects, and I will not discuss this issue further.

Superconductivity in a doped Mott insulator

When superconductivity is disrupted at low temperatures, BCS theory predicts that the Fermi surface will reappear.

Instead, we obtain states characterized by competing order parameters.

Theory and experiments indicate that the most likely competing orders are spin and "charge" density waves.

Superconductivity can be suppressed globally by a strong magnetic field or large current flow.

Competing orders are also revealed when superconductivity is suppressed locally, near impurities or around vortices.

S. Sachdev, *Phys. Rev*. B **45**, 389 (1992); N. Nagaosa and P.A. Lee, *Phys. Rev*. B **45**, 966 (1992);
D.P. Arovas, A. J. Berlinsky, C. Kallin, and S.-C. Zhang *Phys. Rev. Lett.* **79**, 2871 (1997);
K. Park and S. Sachdev *Phys. Rev*. B **64**, 184510 (2001).

Outline

I. Phenomenological theory of competing order parameters: phase diagram in a magnetic field.

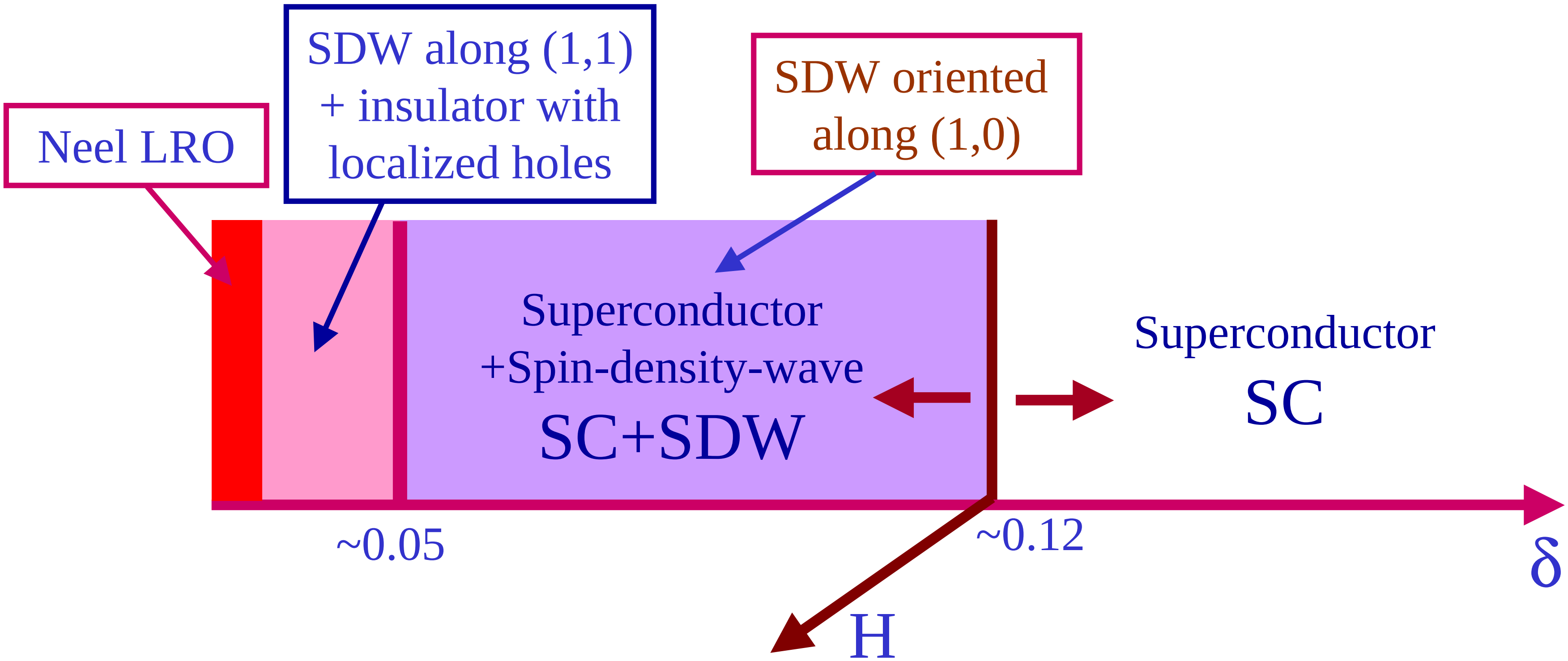
II. Neutron scattering and STM observations.

III. Magnetic quantum phase transitions in the Mott insulator: microstructure of charge order in the Mott insulator and the superconductor.

IV. Neutron scattering and STM observations

V. Conclusions

Phase diagram of LSCO at zero temperature measured by neutron scattering



Theory for a system with strong interactions: describe SC and SC+SDW phases by expanding in the deviation from the quantum critical point between them.

B. Keimer *et al*. Phys. Rev. B **46**, 14034 (1992).
S. Wakimoto, G. Shirane *et al*., Phys. Rev. B **60**, R769 (1999).
G. Aeppli, T.E. Mason, S.M. Hayden, H.A. Mook, J. Kulda, Science **278**, 1432 (1997).
Y. S. Lee, R. J. Birgeneau, M. A. Kastner *et al*., Phys. Rev. B **60**, 3643 (1999).
J. E. Sonier *et al*., cond-mat/0108479.
C. Panagopoulos, B. D. Rainford, J. L. Tallon, T. Xiang, J. R. Cooper, and C. A. Scott, preprint.

I. Phenomenological theory of SDW order

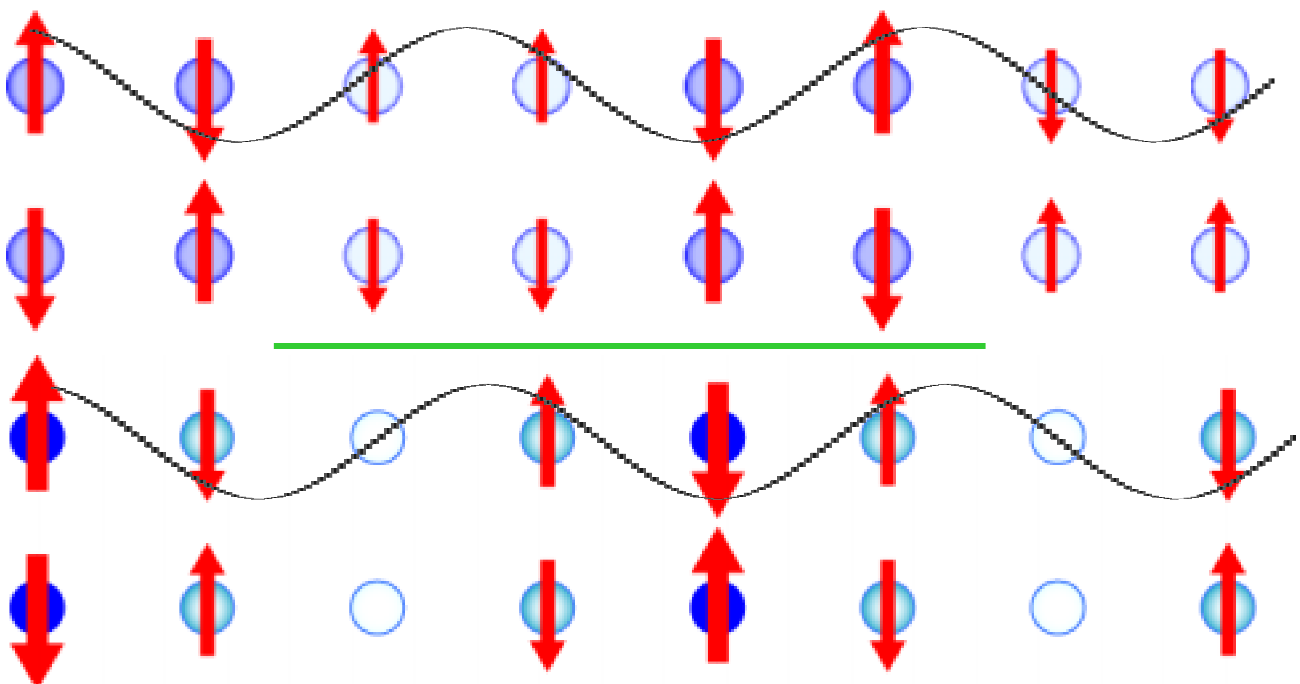
Spin density wave order parameter for general ordering wavevector

$$S_\alpha(\boldsymbol{r}) = \Phi_\alpha(\boldsymbol{r}) e^{i\boldsymbol{K}\cdot\boldsymbol{r}} + \text{c.c.}$$

$\Phi_\alpha(\boldsymbol{r})$ is a ***complex*** field $\left(\text{except for } \boldsymbol{K}=(\pi,\pi) \text{ when } e^{i\boldsymbol{K}\cdot\boldsymbol{r}} = (-1)^{r_x+r_y}\right)$

Symmetry implies a co-existing "CDW" $\delta\rho(\boldsymbol{r}) \propto S_\alpha^2(\boldsymbol{r}) = \sum_\alpha \Phi_\alpha^2(\boldsymbol{r}) e^{i2\boldsymbol{K}\cdot\boldsymbol{r}} + \text{c.c.}$

(modulation in spin-singlet, time-reversal invariant observables, such as the exchange and pairing energy per link, while that in the site charge density may be unobservably small.)



Bond-centered

$$\Phi_\alpha = e^{i\theta} n_\alpha$$

Site-centered

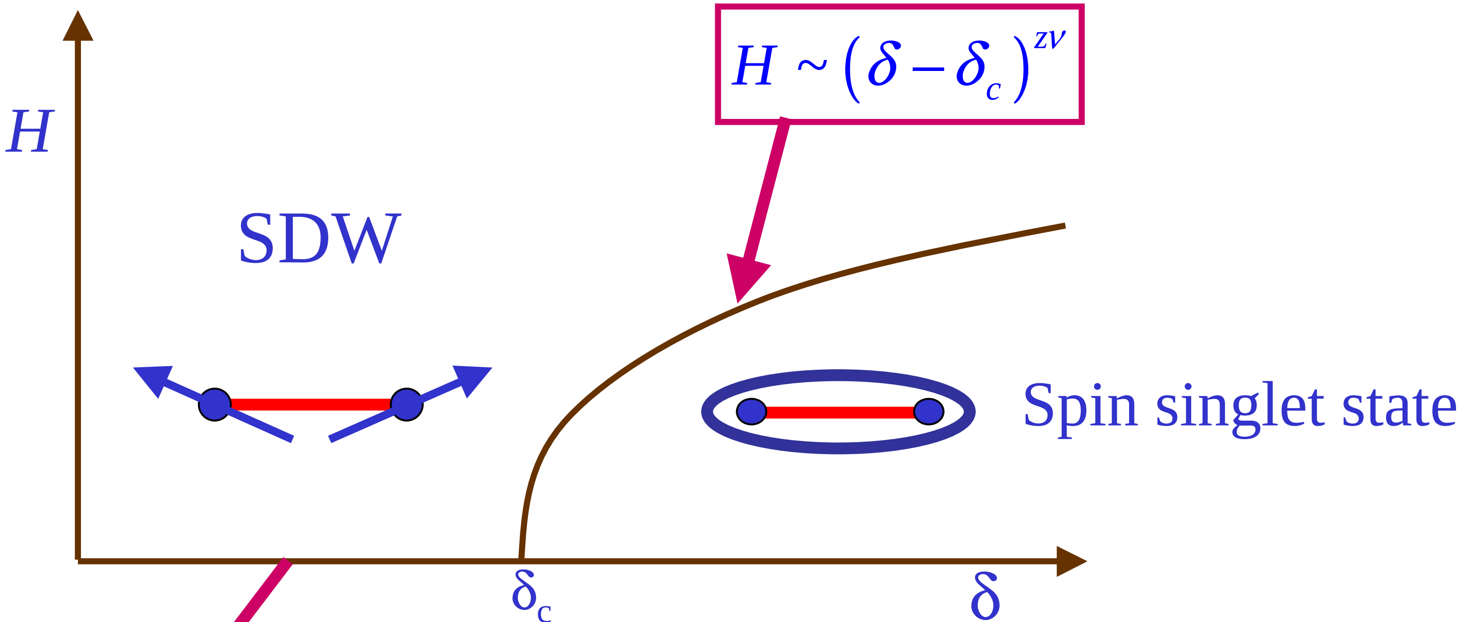
Wavevector $\boldsymbol{K}=(3\pi/4,\pi)$

J. Zaanen and O. Gunnarsson, *Phys. Rev.* B **40**, 7391 (1989).
H. Schulz, *J. de Physique* **50**, 2833 (1989).
O. Zachar, S. A. Kivelson, and V. J. Emery, *Phys. Rev.* B **57**, 1422 (1998).

I. Phenomenological theory of SDW order

Effect of the Zeeman term

$$\left|\partial_\tau \Phi_\alpha\right|^2 \Rightarrow \left(\partial_\tau \Phi^*_\alpha - i\varepsilon_{\alpha\sigma\rho} H_\sigma \Phi_\rho\right)\left(\partial_\tau \Phi_\alpha - i\varepsilon_{\alpha\beta\gamma} H_\beta \Phi_\gamma\right)$$



Elastic scattering intensity

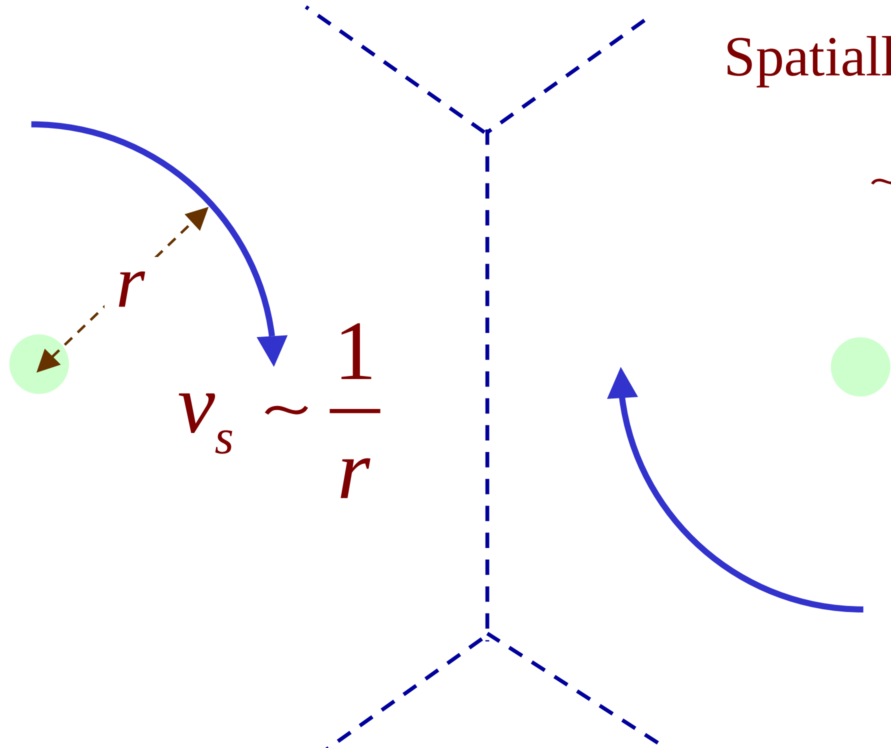
$$I(H) = I(0) + a\left(\frac{H}{J}\right)^2$$

Characteristic field $g\mu_B H = \Delta$, the spin gap

1 Tesla = 0.116 meV

Effect is negligible over experimental field scales

Dominant effect: **uniform** softening of spin excitations by superflow kinetic energy



$$v_s \sim \frac{1}{r}$$

Spatially averaged superflow kinetic energy

$$\sim \left\langle v_s^2 \right\rangle \sim \frac{H}{H_{c2}} \ln \frac{3H_{c2}}{H}$$

Competing order is enhanced in a "halo" around each vortex

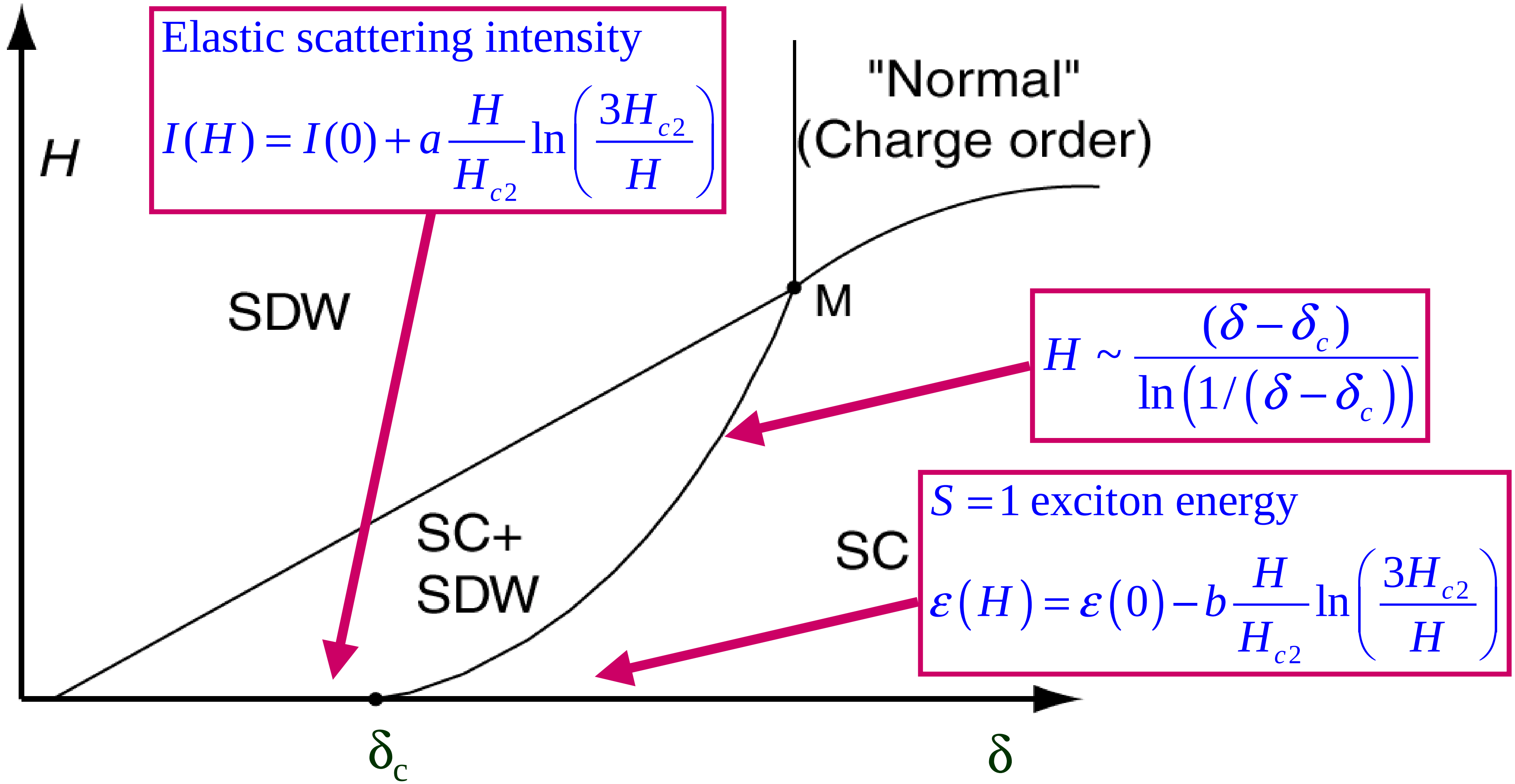
The presence of the field replaces δ by

$$\delta_{eff}\left(H\right) = \delta - C\frac{H}{H_{c2}} \ln\left(\frac{3H_{c2}}{H}\right)$$

E. Demler, S. Sachdev, and Y. Zhang, *Phys. Rev. Lett.* **87**, 067202 (2001).

Main results

$T=0$



Elastic scattering intensity

$$I(H) = I(0) + a\frac{H}{H_{c2}}\ln\left(\frac{3H_{c2}}{H}\right)$$

$$H \sim \frac{(\delta - \delta_c)}{\ln\left(1/\left(\delta-\delta_c\right)\right)}$$

$S=1$ exciton energy

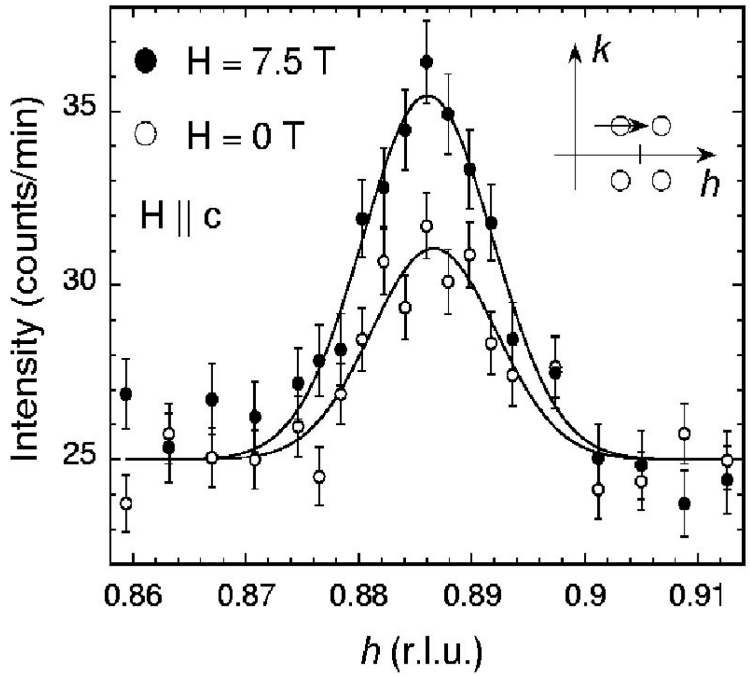
$$\varepsilon(H) = \varepsilon(0) - b\frac{H}{H_{c2}}\ln\left(\frac{3H_{c2}}{H}\right)$$

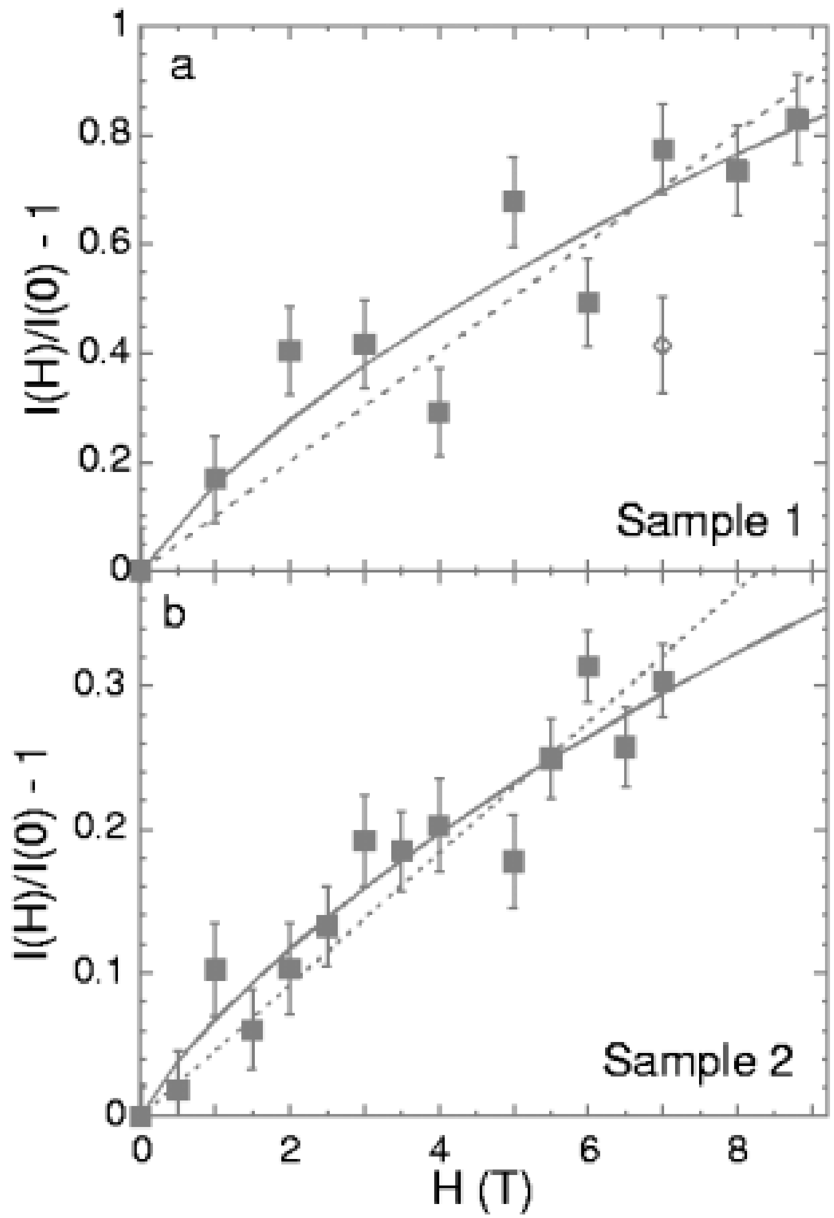
E. Demler, S. Sachdev, and Y. Zhang, *Phys. Rev. Lett.* **87**, 067202 (2001).

II. Neutron scattering measurements of static spin correlations of the superconductor+spin-density-wave (SC+SDW) in a magnetic field

Elastic neutron scattering off La_2CuO_{4+y}

B. Khaykovich, Y. S. Lee, S. Wakimoto,
K. J. Thomas, M. A. Kastner,
and R.J. Birgeneau, cond-mat/0112505.



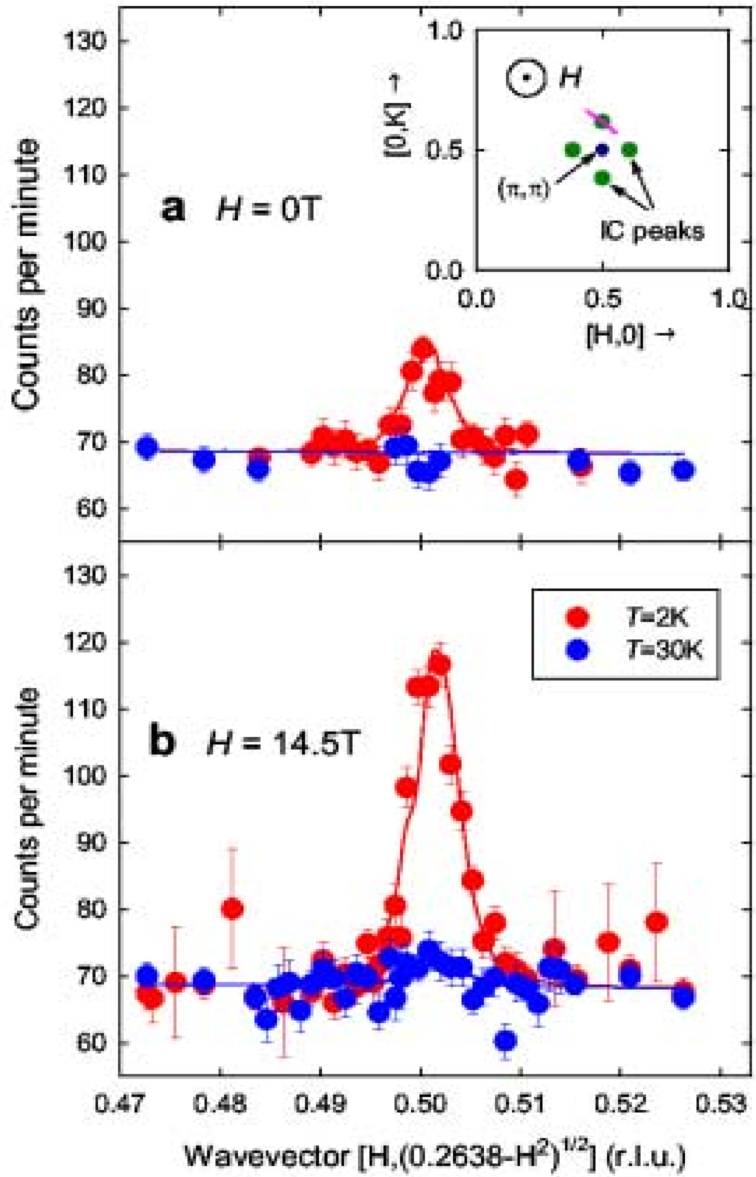


Solid line --- fit to : $\frac{I(H)}{I(0)} = 1 + a\frac{H}{H_{c2}}\ln\left(\frac{3.0H_{c2}}{H}\right)$

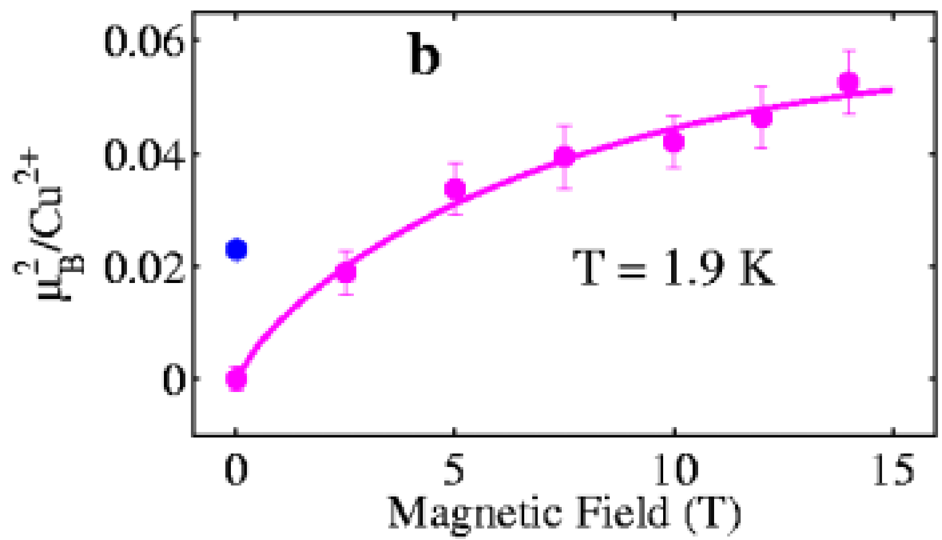
a is the only fitting parameter

Best fit value - a = 2.4 with H_{c2} = 60 T

Neutron scattering of $La_{2-x}Sr_xCuO_4$ at x=0.1



B. Lake, H. M. Rønnow, N. B. Christensen, G. Aeppli, K. Lefmann, D. F. McMorrow, P. Vorderwisch, P. Smeibidl, N. Mangkorntong, T. Sasagawa, M. Nohara, H. Takagi, T. E. Mason, *Nature*, **415**, 299 (2002).

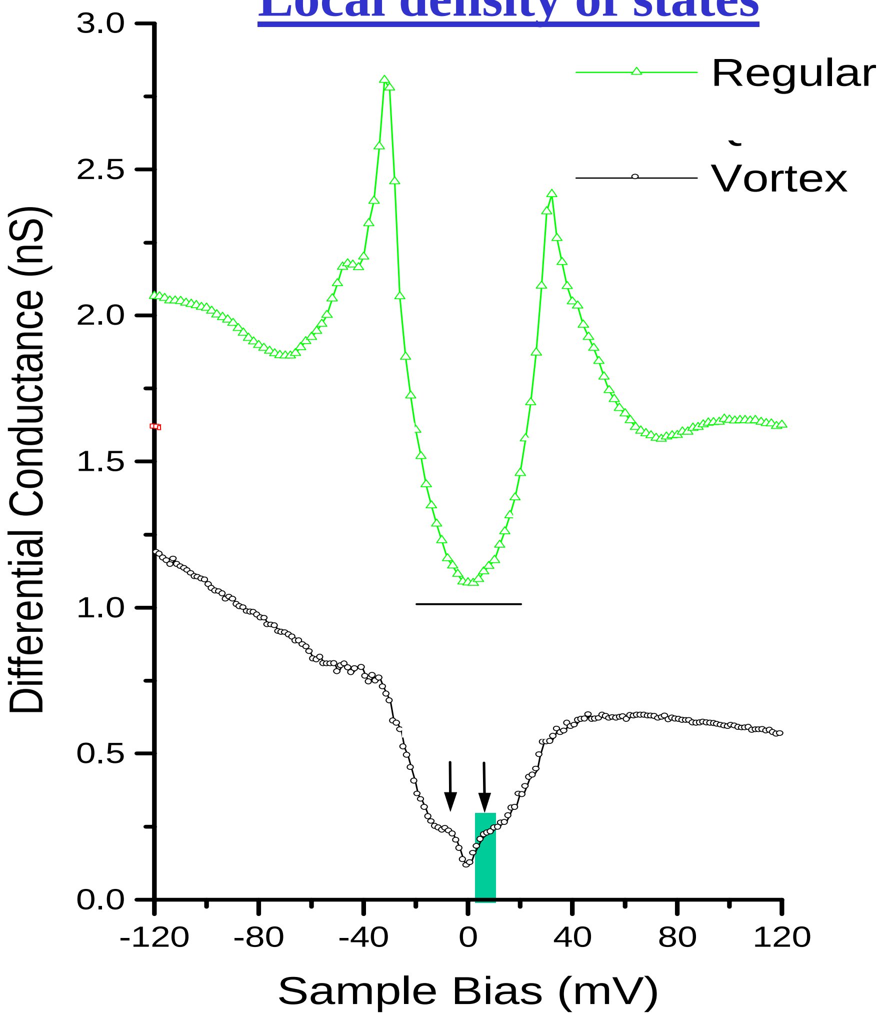


Solid line - fit to : $I(H) = a\frac{H}{H_{c2}}\ln\left(\frac{H_{c2}}{H}\right)$

II. STM around vortices induced by a magnetic field in the superconducting state

J. E. Hoffman, E. W. Hudson, K. M. Lang, V. Madhavan, S. H. Pan, H. Eisaki, S. Uchida, and J. C. Davis, *Science* **295**, 466 (2002).

Local density of states

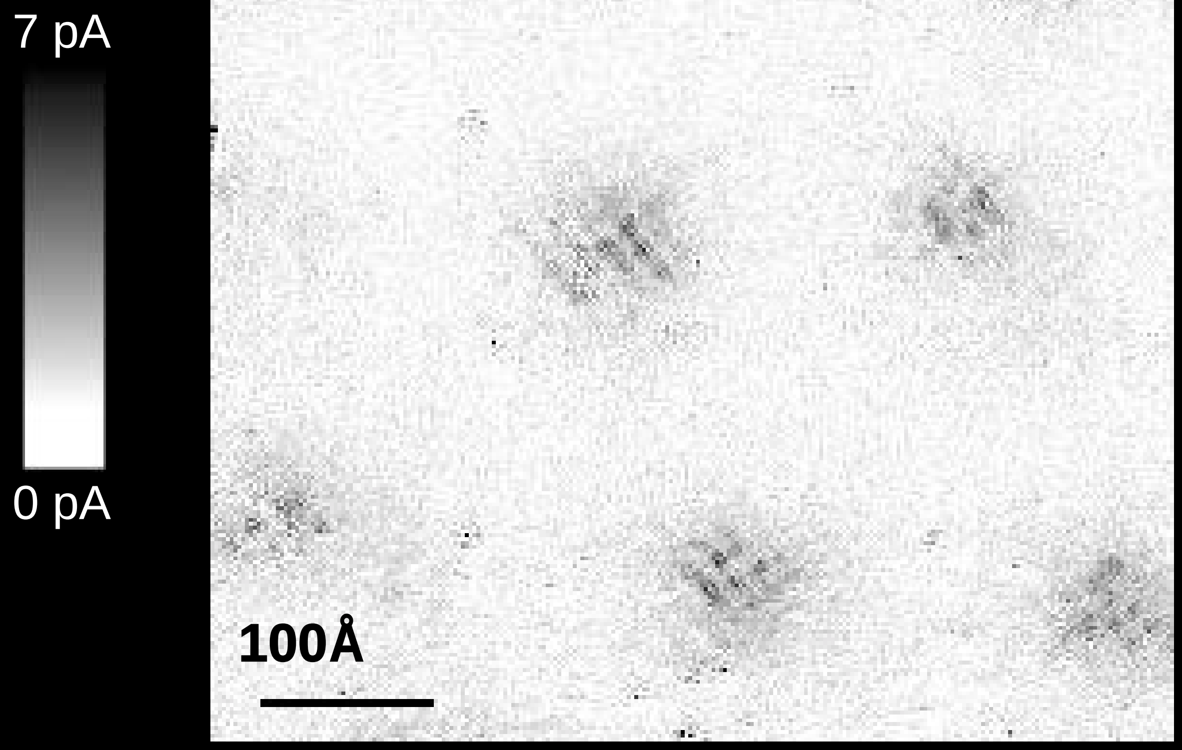


S.H. Pan *et al*. *Phys. Rev. Lett*. **85**, 1536 (2000).

1Å spatial resolution image of integrated LDOS of $Bi_2Sr_2CaCu_2O_{8+\delta}$

(1meV to 12 meV) at B=5 Tesla.

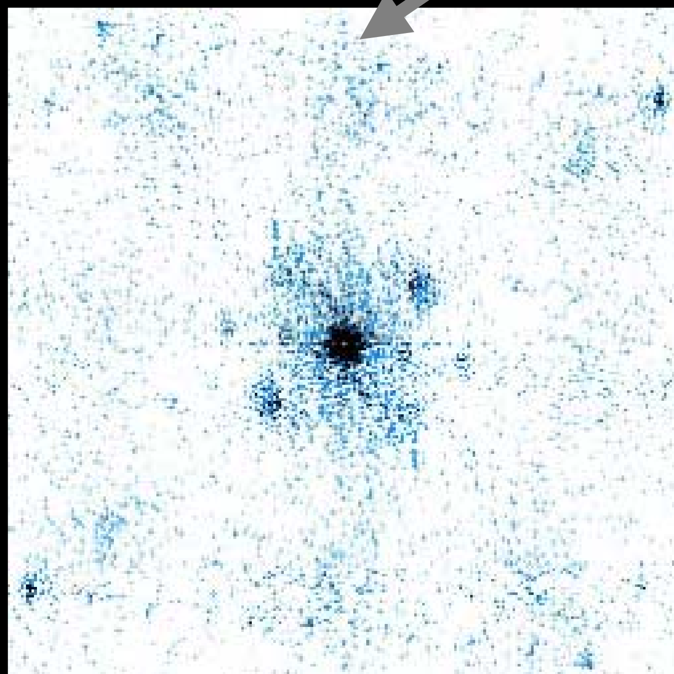
Vortex-induced LDOS of $Bi_2Sr_2CaCu_2O_{8+\delta}$ integrated from 1meV to 12meV

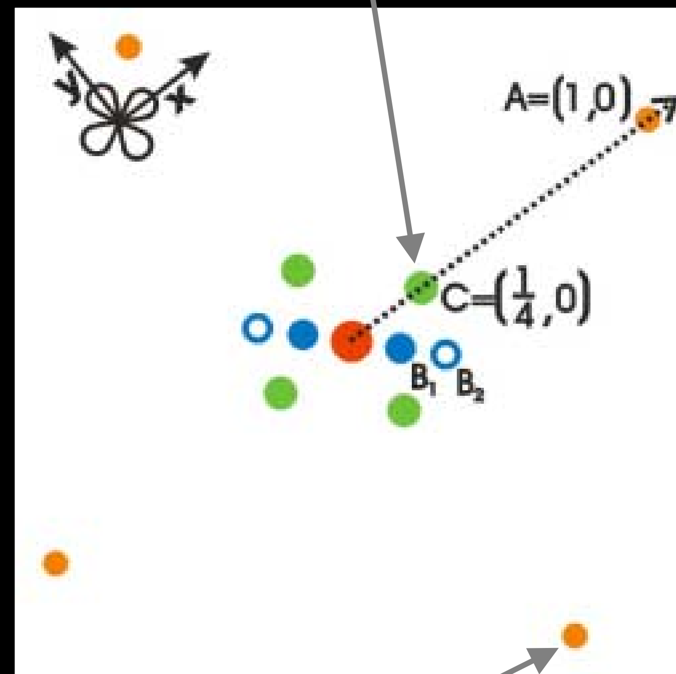


J. Hoffman E. W. Hudson, K. M. Lang, V. Madhavan, S. H. Pan, H. Eisaki, S. Uchida, and J. C. Davis, *Science* 295, 466 (2002).

Fourier Transform of Vortex-Induced LDOS map

K-space locations of vortex induced LDOS





K-space locations of Bi and Cu atoms

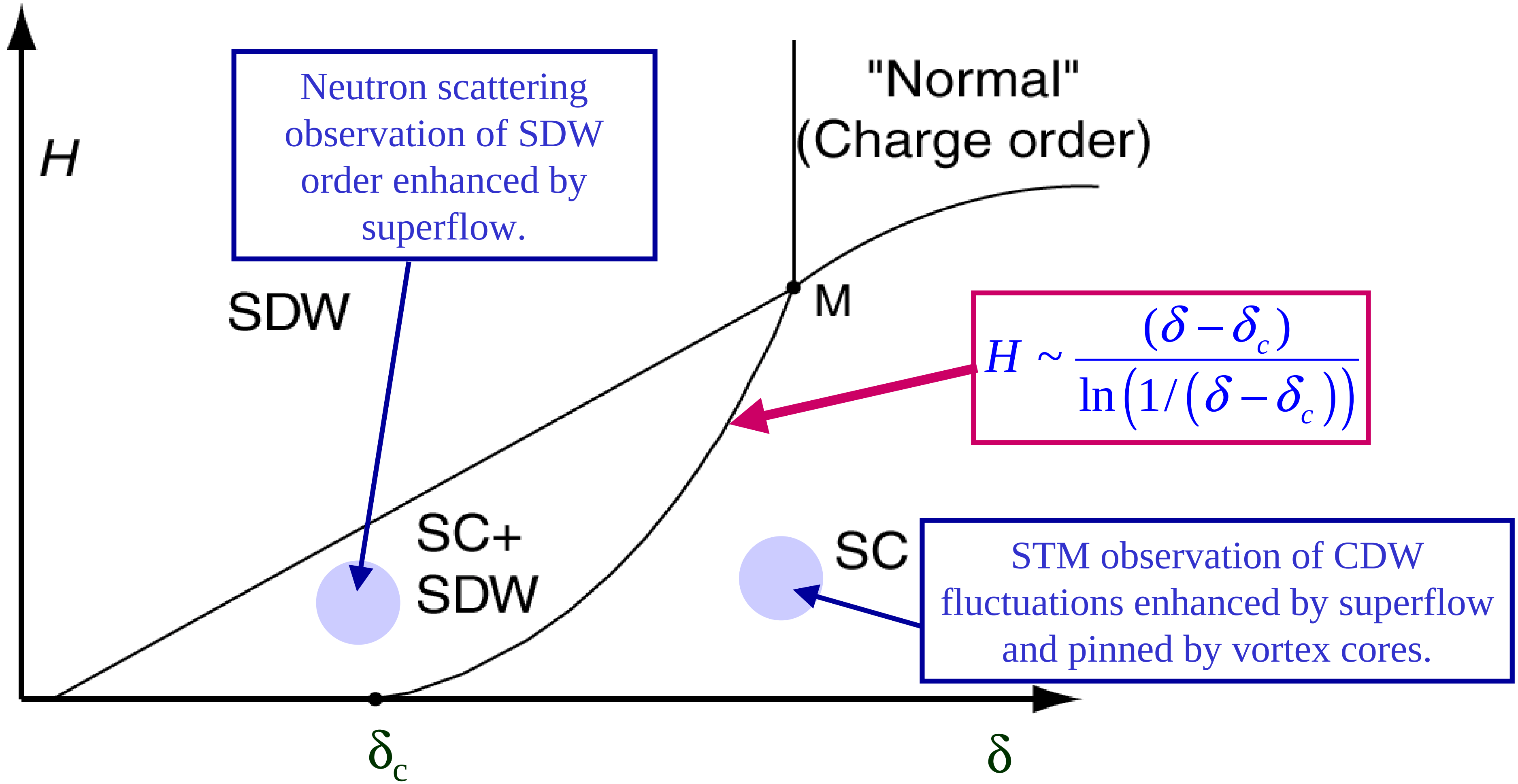
Distances in k –space have units of $2\pi/a_0$
a_0=3.83 Å is Cu-Cu distance

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

Summary of theory and experiments

(extreme Type II superconductivity)

T=0



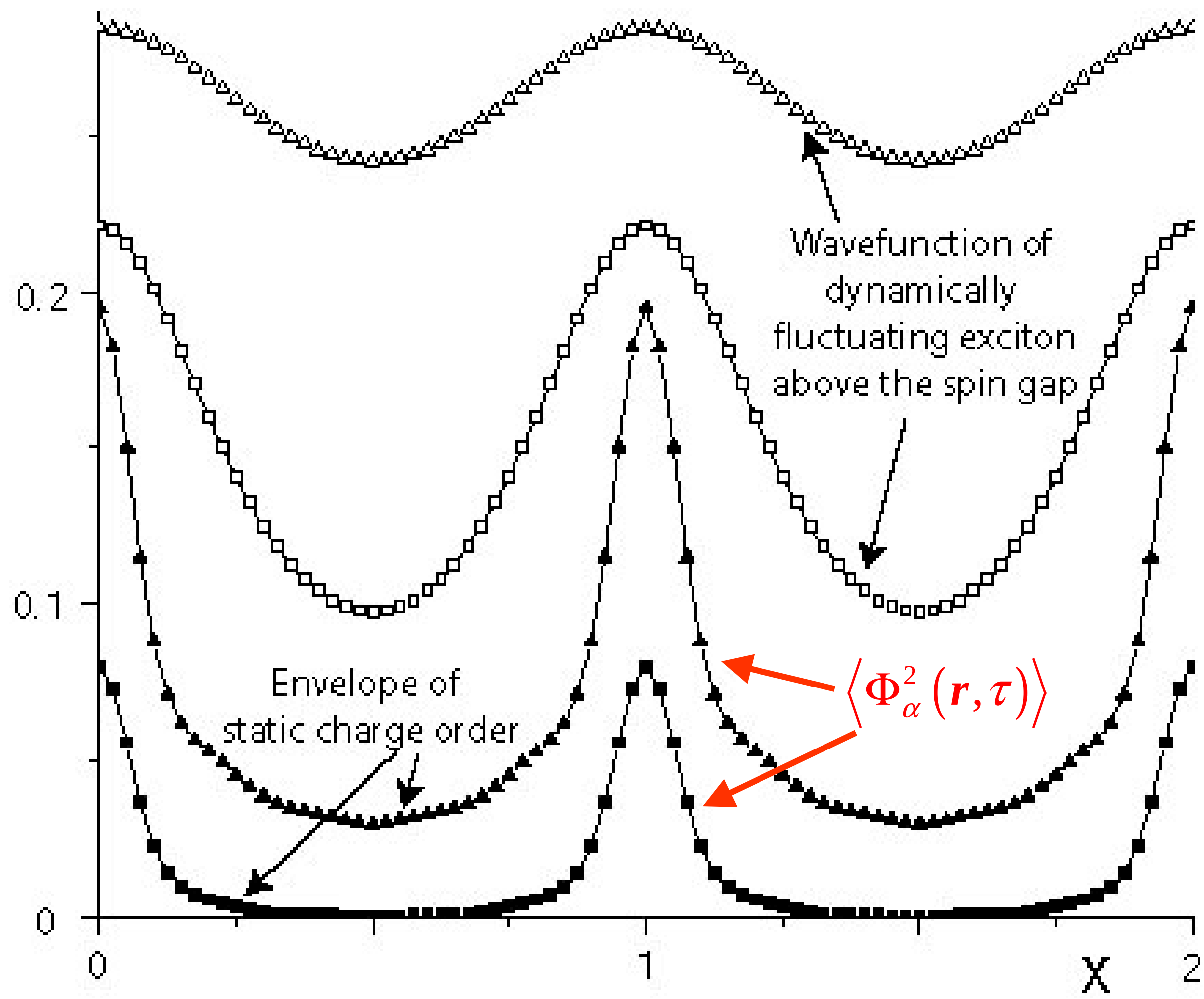
E. Demler, S. Sachdev, and Y. Zhang, *Phys. Rev. Lett.* **87**, 067202 (2001).

Quantitative connection between the two experiments ?

Pinning of CDW order by vortex cores in SC phase

Y. Zhang, E. Demler, and S. Sachdev, cond-mat/0112343.

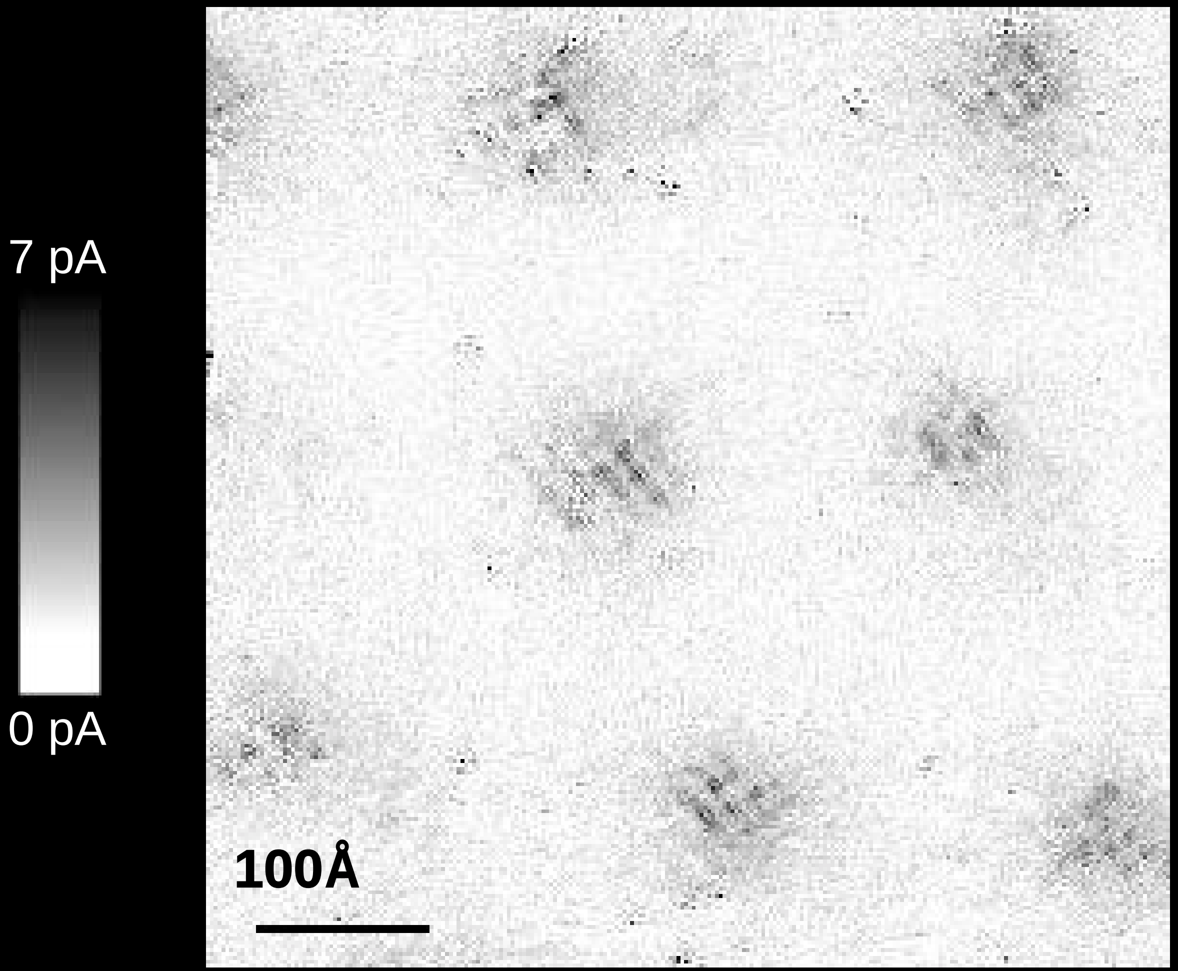
$$\left\langle \Phi_\alpha^2(\boldsymbol{r},\tau)\right\rangle \propto \zeta \int d\tau_1 \left\langle \Phi_\alpha(\boldsymbol{r},\tau)\Phi_\alpha^*(\boldsymbol{r}_v,\tau_1)\right\rangle^2$$



□ → low magnetic field

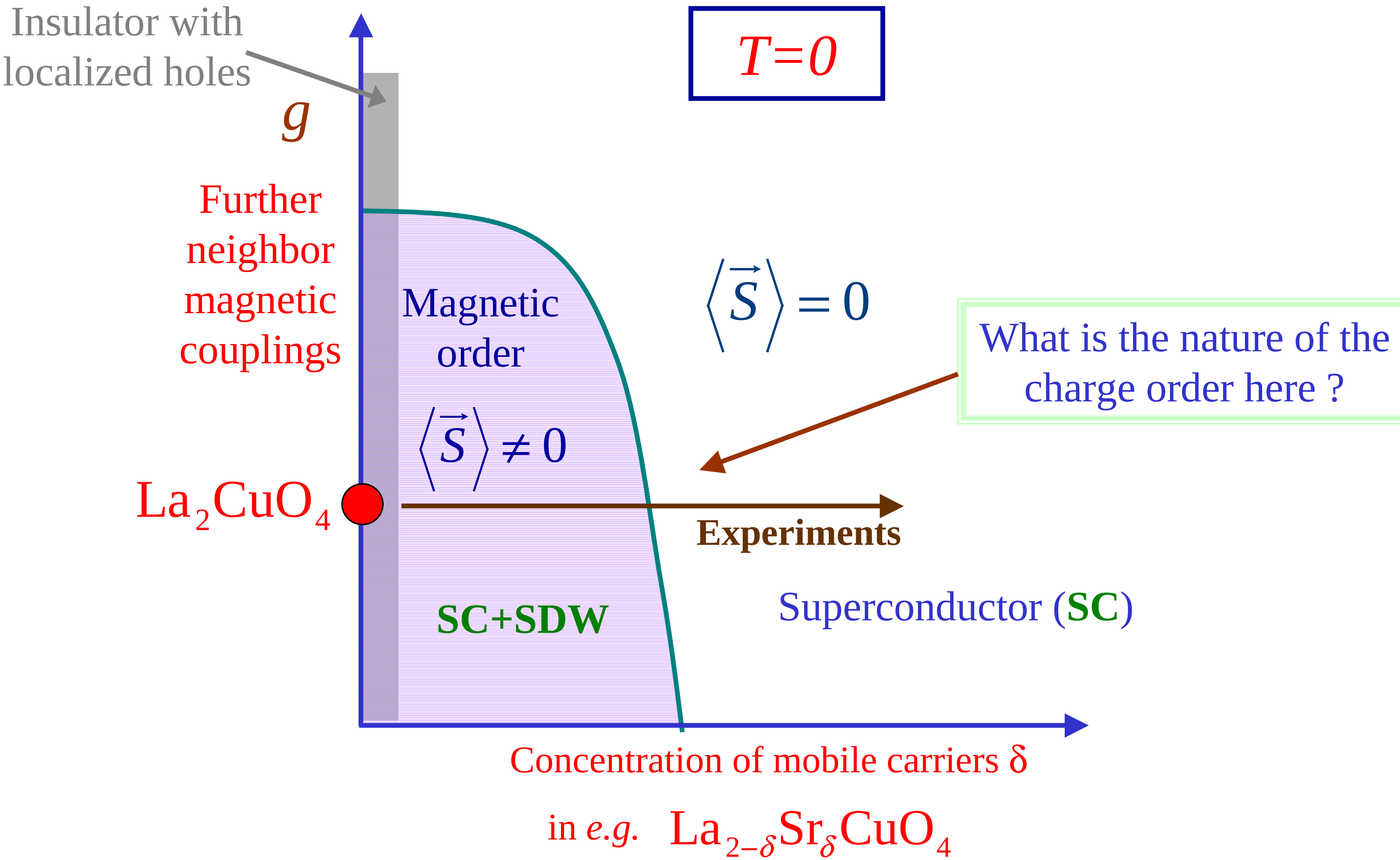
△ → high magnetic field near the boundary to the SC+SDW phase

Vortex-induced LDOS of $Bi_2Sr_2CaCu_2O_{8+\delta}$ integrated from 1meV to 12meV



J. Hoffman E. W. Hudson, K. M. Lang, V. Madhavan, S. H. Pan, H. Eisaki, S. Uchida, and J. C. Davis, *Science* 295, 466 (2002).

III. Microstructure of the charge order: magnetic transitions in Mott insulators and superconductors



S. Sachdev and J. Ye, *Phys. Rev. Lett.* **69**, 2411 (1992).
A.V. Chubukov, S. Sachdev, and J. Ye, *Phys. Rev.* B **49**, 11919 (1994)

III. Magnetic ordering transitions in the insulator

$$H = \sum_{i<j} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

Action for quantum spin fluctuations in spacetime

Discretize spacetime into a cubic lattice with Néel order orientation $\mathbf{n}_a$

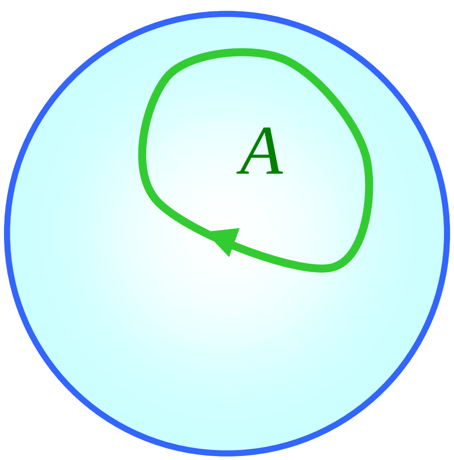
$$Z = \prod_a \int d\mathbf{n}_a \delta\left(\mathbf{n}_a^2 - 1\right) \exp\left(\frac{1}{g} \sum_{a,\mu} \mathbf{n}_a \cdot \mathbf{n}_{a+\mu} \right)$$

$a \rightarrow$ cubic lattice sites; $\mu \rightarrow x, y, \tau$;

S. Chakravarty, B.I. Halperin, and D.R. Nelson, *Phys. Rev.* B **39**, 2344 (1989).

Quantum path integral for two-dimensional quantum antiferromagnet
$\Leftrightarrow$ Partition function of a classical three-dimensional ferromagnet at a "temperature" g

Missing: Spin Berry Phases



$$e^{iSA}$$

Berry phases profoundly modify paramagnetic states with $\langle \mathbf{n}_a \rangle = \langle \vec{S} \rangle = 0$

Computations with Berry phases fully reproduce known states in one dimension: Bethe and Majumdar-Ghosh states for S=1/2, and Haldane states for S=1

K. Park and S. Sachdev, cond-mat/0108214

Field theory of paramagnetic ("quantum disordered") phase

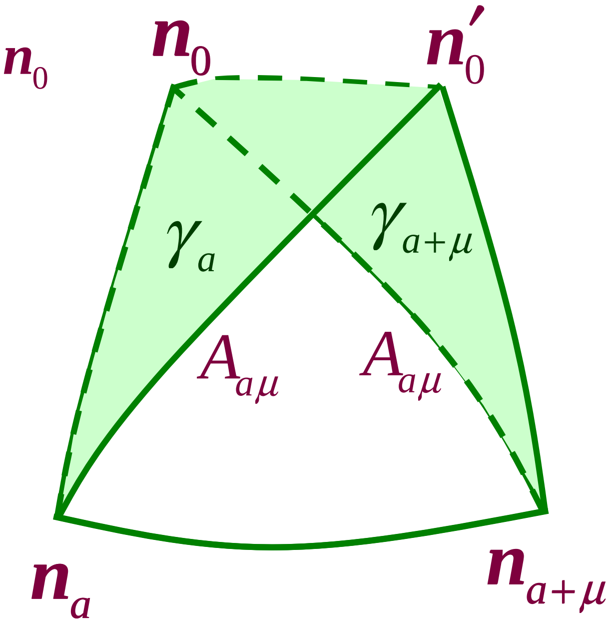
Discretize spacetime into a cubic lattice:

$$Z = \prod_a \int d\boldsymbol{n}_a \delta\left(\boldsymbol{n}_a^2 - 1\right) \exp\left(\frac{1}{g} \sum_{a,\mu} \boldsymbol{n}_a \cdot \boldsymbol{n}_{a+\mu} - \frac{i}{2} \sum_a \eta_a A_{a\tau} \right)$$

$\eta_a \rightarrow \pm 1$ on two square sublattices ; $\boldsymbol{n}_a \sim \eta_a \vec{S}_a \rightarrow$ Neel order parameter;

$A_{a\mu} \rightarrow$ oriented area of spherical triangle

formed by $\boldsymbol{n}_a$, $\boldsymbol{n}_{a+\mu}$, and an arbitrary reference point $\boldsymbol{n}_0$



Change in choice of $\boldsymbol{n}_0$ is like a "gauge transformation"

$$A_{a\mu} \rightarrow A_{a\mu} - \gamma_{a+\mu} + \gamma_a$$

(γ_a is the oriented area of the spherical triangle formed by $\boldsymbol{n}_a$ and the two choices for $\boldsymbol{n}_0$).

The area of the triangle is uncertain modulo 4π, and the action is invariant under

$$A_{a\mu} \rightarrow A_{a\mu} + 4\pi$$

These principles strongly constrain the effective action for $A_{a\mu}$

Simplest large g effective action for the $A_{a\mu}$

$$Z = \prod_{a,\mu} \int dA_{a\mu} \exp\left(-\frac{1}{2e^2} \sum_{\square} \cos\left(\frac{1}{2} \varepsilon_{\mu\nu\lambda} \Delta_\nu A_{a\lambda} \right) - \frac{i}{2} \sum_a \eta_a A_{a\tau} \right)$$

with $e^2 \sim g^2$

This is compact QED in 2+1 dimensions with Berry phases.

This theory can be reliably analyzed by a duality mapping.

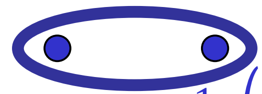
The gauge theory is *always* in a *confining* phase:

There is an energy gap and the ground state has **spontaneous bond order**.

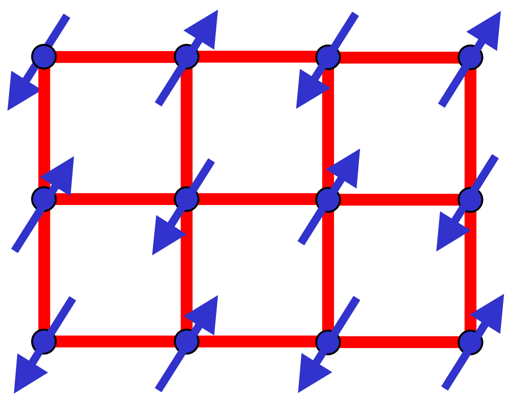
N. Read and S. Sachdev, *Phys. Rev. Lett.* **62**, 1694 (1989).
S. Sachdev and R. Jalabert, *Mod. Phys. Lett.* B **4**, 1043 (1990).
K. Park and S. Sachdev, cond-mat/0108214

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

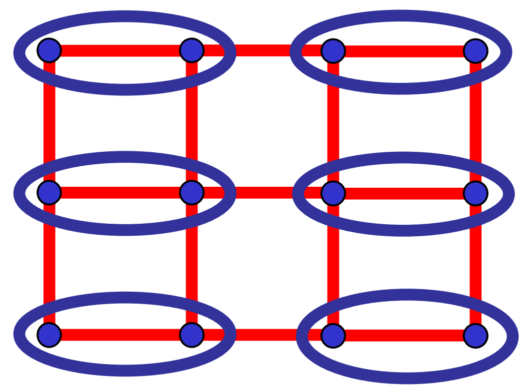
$$H = \sum_{i<j} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



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



Neel state



Spin-Peierls (or plaquette) state
"Bond-centered charge stripe order"

$g = J_2 / J_1$

N. Read and S. Sachdev, *Phys. Rev. Lett*. **62**, 1694 (1989).

O. P. Sushkov, J. Oitmaa, and Z. Weihong, *Phys. Rev*. B **63**, 104420 (2001).

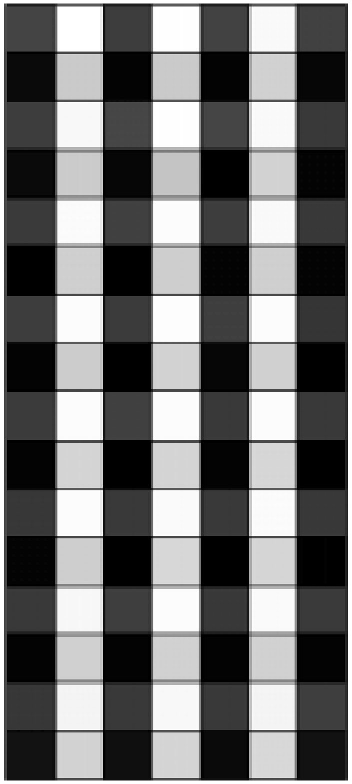
M.S.L. du Croo de Jongh, J.M.J. van Leeuwen, W. van Saarloos, *Phys. Rev*. B **62**, 14844 (2000).

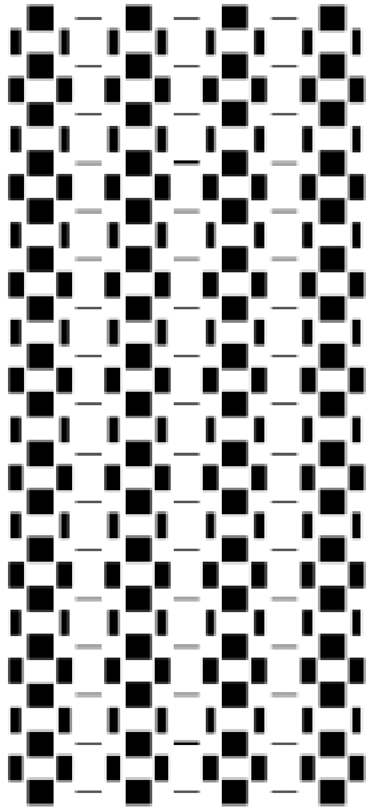
See however L. Capriotti, F. Becca, A. Parola, S. Sorella, cond-mat/0107204 .

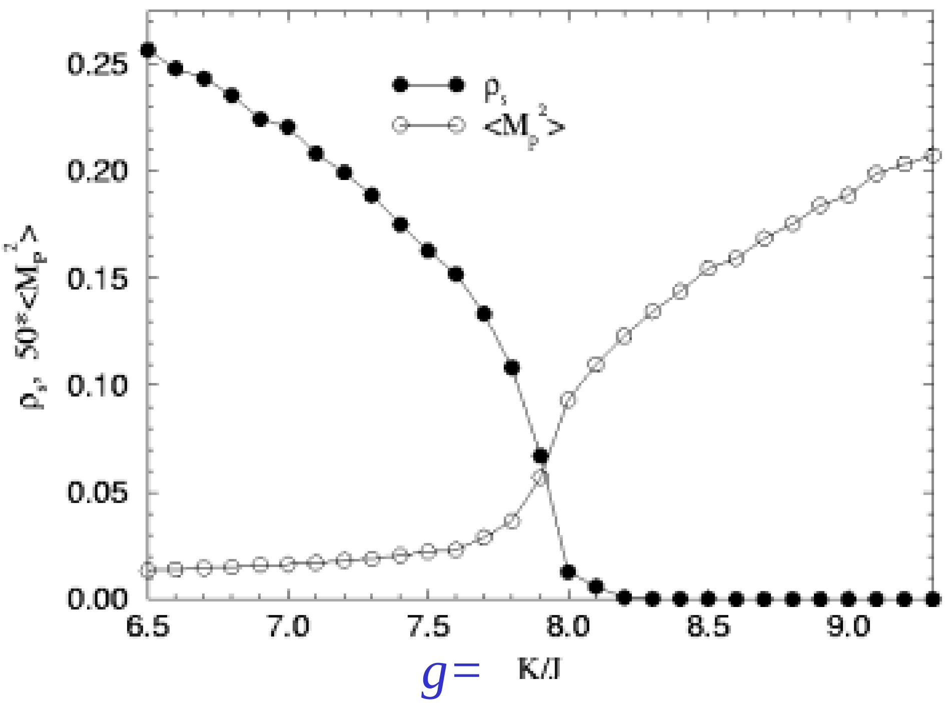
Studies on the 2D pyrochlore lattice agree with related predictions of theory:

J.-B. Fouet, M. Mambrini, P. Sindzingre, C. Lhuillier, cond-mat/0108070.
R. Moessner, Oleg Tchernyshyov, S.L. Sondhi, cond-mat/0106286.

Bond-centered stripe order in a frustrated S=1/2 XY magnet



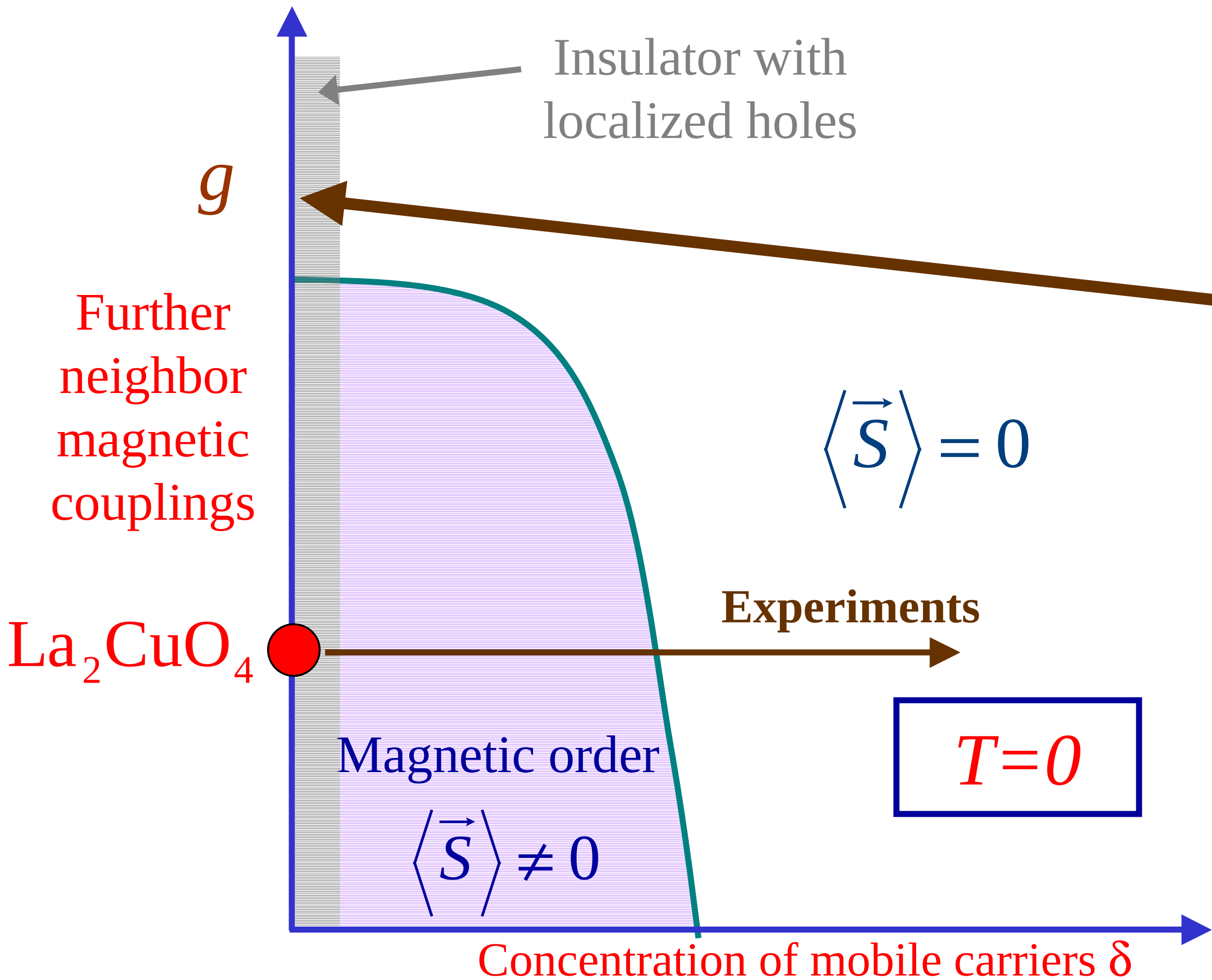




$$H = -2J \sum_{\langle ij \rangle} \left(S_i^x S_j^x + S_i^y S_j^y \right) - K \sum_{\langle ijkl \rangle \subset \square} \left(S_i^+ S_j^- S_k^+ S_l^- + S_i^- S_j^+ S_k^- S_l^+ \right)$$

A. W. Sandvik, S. Daul, R. R. P. Singh, and D. J. Scalapino, cond-mat/0205270

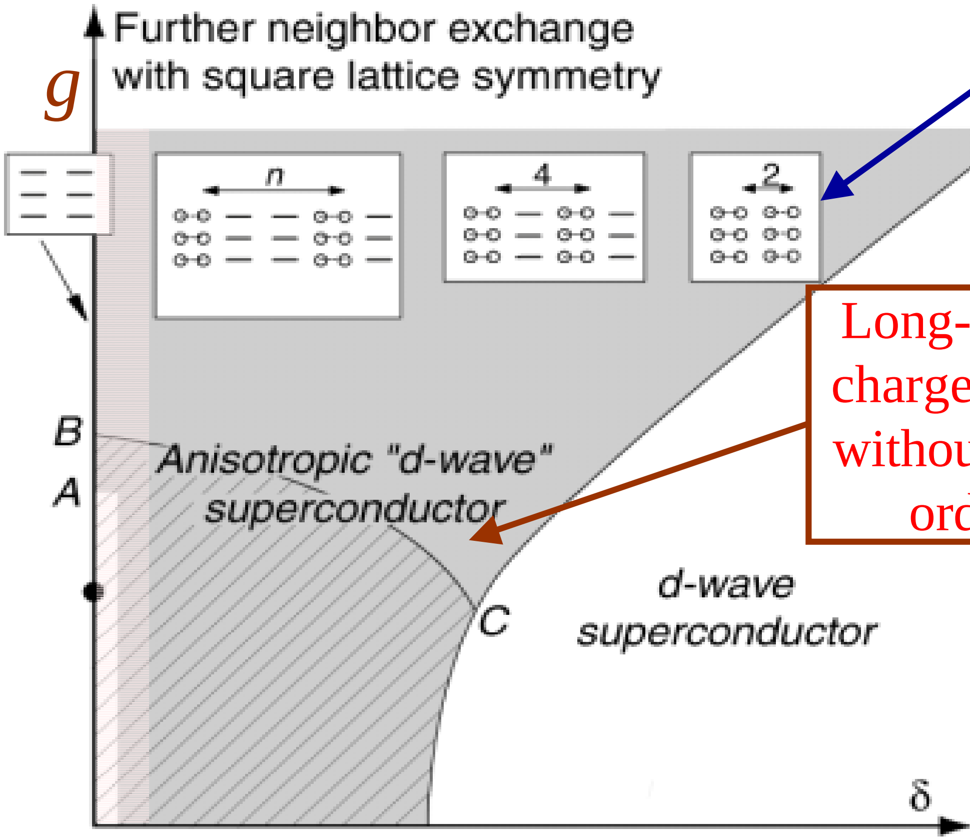
Framework for spin/charge order in cuprate superconductors



Confined, paramagnetic Mott insulator has

1. Stable S=1 spin exciton.
2. Broken translational symmetry:- bond-centered charge order.
3. S=1/2 moments near non-magnetic impurities

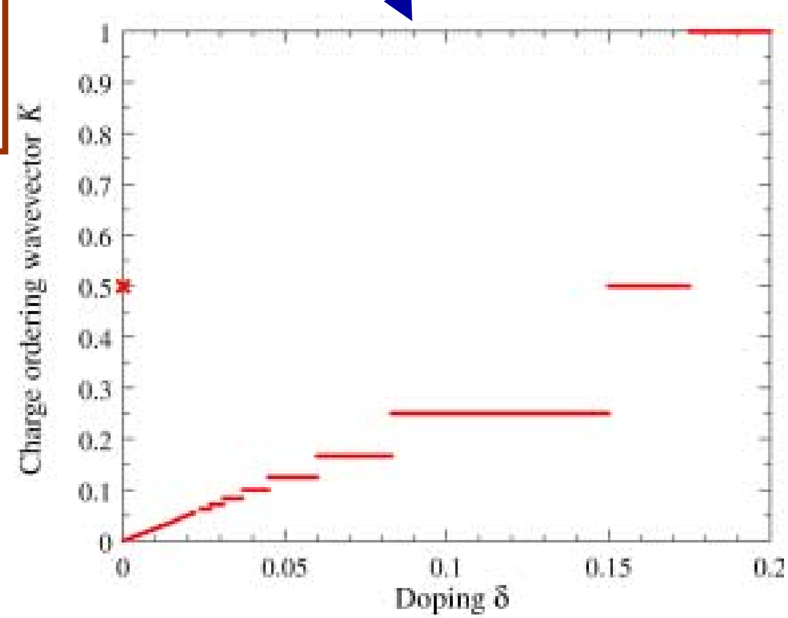
III. Charge order in the superconductor.



"Large *N*" theory in region with preserved spin rotation symmetry

S. Sachdev and N. Read, *Int. J. Mod. Phys*. B **5**, 219 (1991).
M. Vojta and S. Sachdev, *Phys. Rev. Lett*. **83**, 3916 (1999).
M. Vojta, Y. Zhang, and S. Sachdev, *Phys. Rev*. B **62**, 6721 (2000).

Long-range charge order without spin order

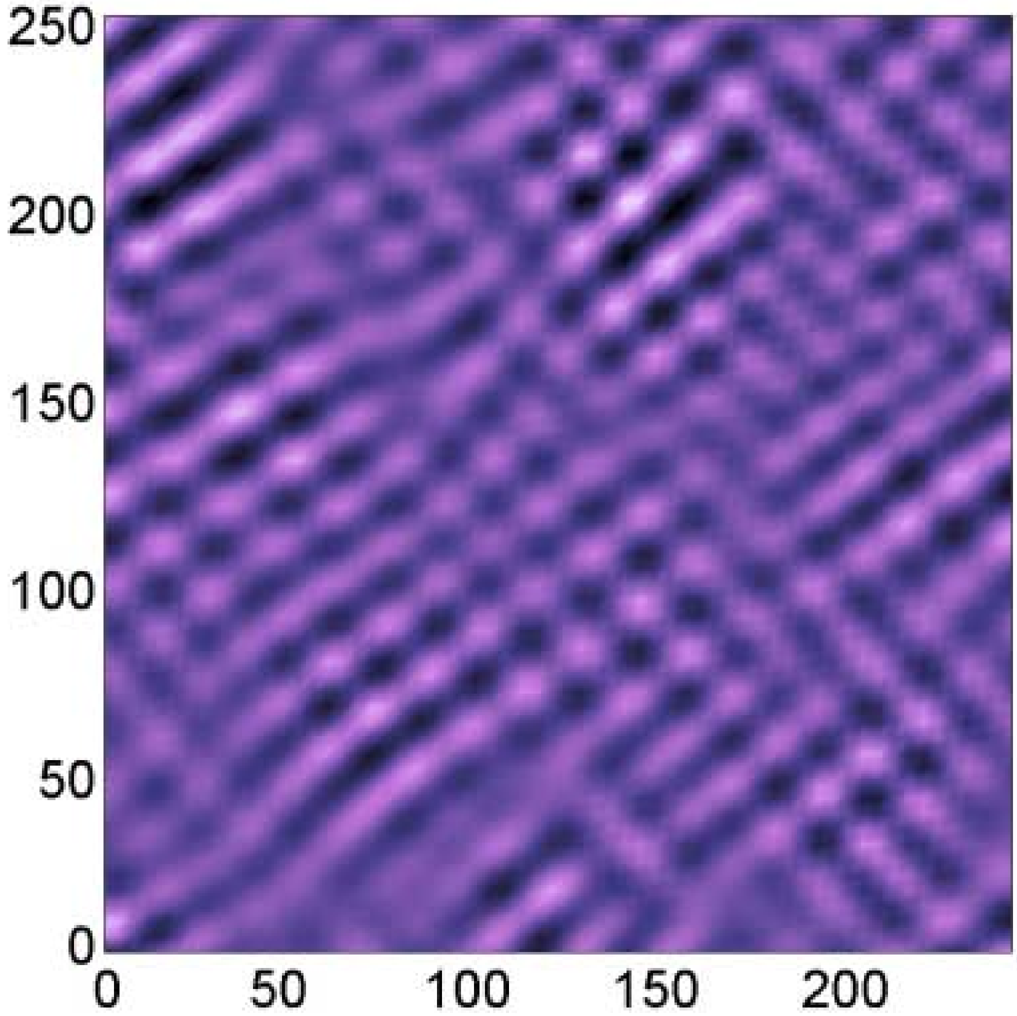


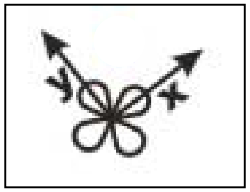
Hatched region --- spin order
Shaded region ---- charge order

Charge order is bond-centered and has an even period.

See also J. Zaanen, *Physica* C **217**, 317 (1999),
S. Kivelson, E. Fradkin and V. Emery, *Nature* **393**, 550 (1998),
S. White and D. Scalapino, *Phys. Rev. Lett*. **80**, 1272 (1998).
C. Castellani, C. Di Castro, and M. Grilli, *Phys.Rev. Lett*. **75**, 4650 (1995).

IV. STM image of pinned charge order in $Bi_2Sr_2CaCu_2O_{8+\delta}$ in zero magnetic field

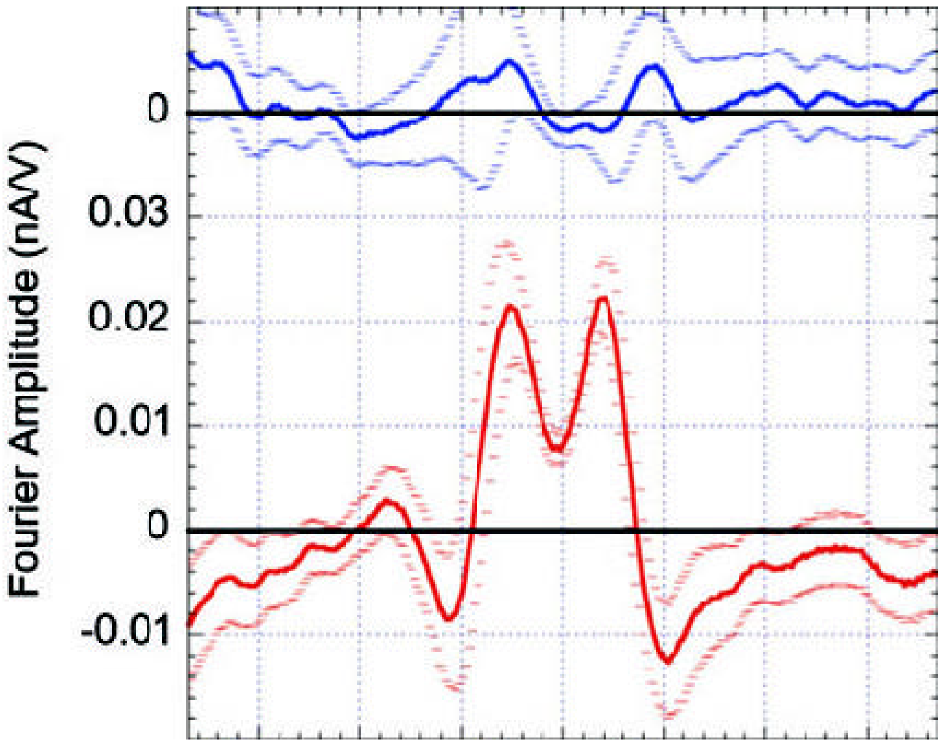




Charge order period = 4 lattice spacings

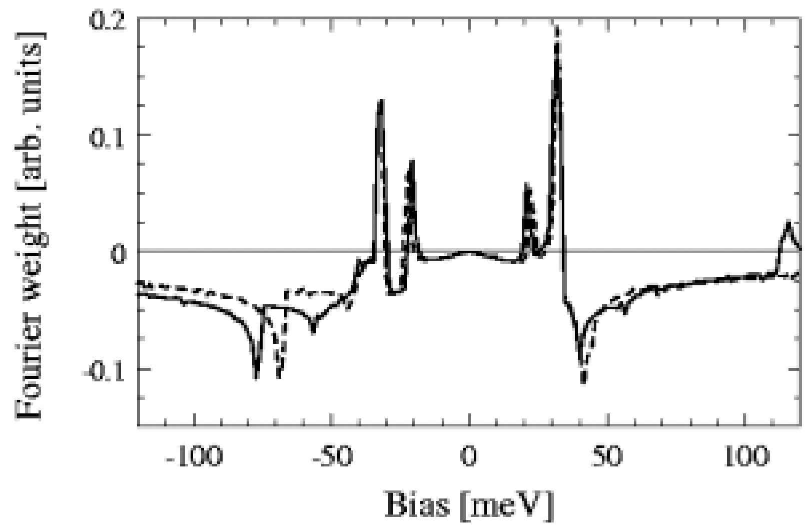
C. Howald, H. Eisaki, N. Kaneko, and A. Kapitulnik, cond-mat/0201546

Spectral properties of the STM signal are sensitive to the microstructure of the charge order



Measured energy dependence of the Fourier component of the density of states which modulates with a period of 4 lattice spacings

C. Howald, H. Eisaki, N. Kaneko, and A. Kapitulnik, cond-mat/0201546



Theoretical modeling shows that this spectrum is best obtained by a modulation of bond variables, such as the exchange, kinetic or pairing energies.

M. Vojta, cond-mat/0204284.
D. Podolsky, E. Demler, K. Damle, and B.I. Halperin, cond-mat/0204011

IV. Neutron scattering observation of static charge order in $YBa_2Cu_3O_{6.35}$

(spin correlations are dynamic)

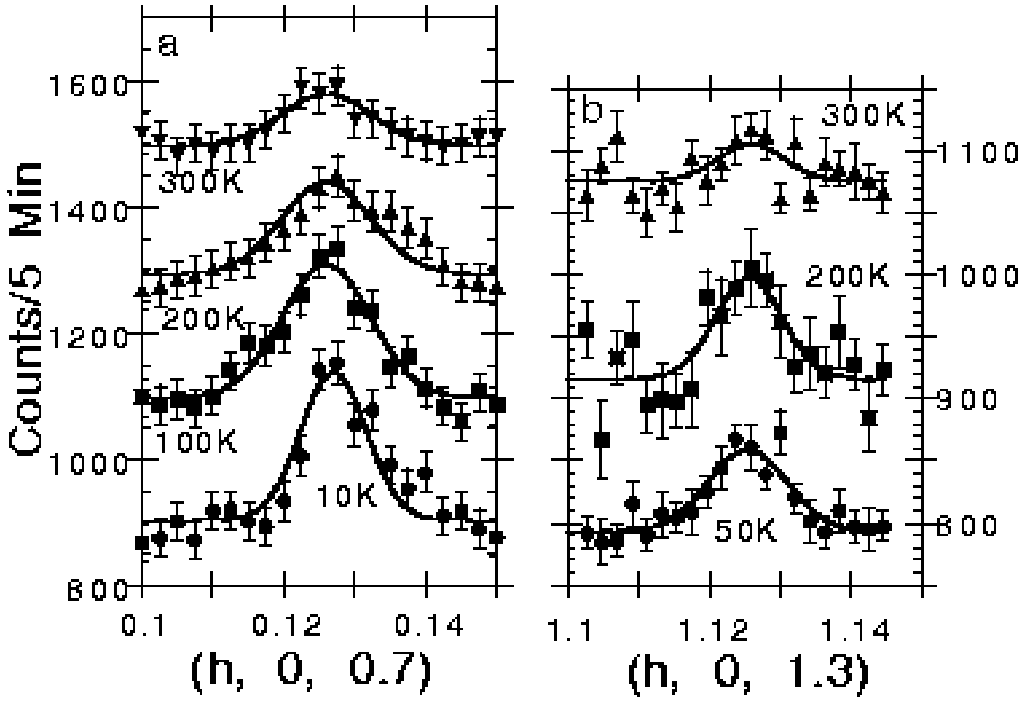
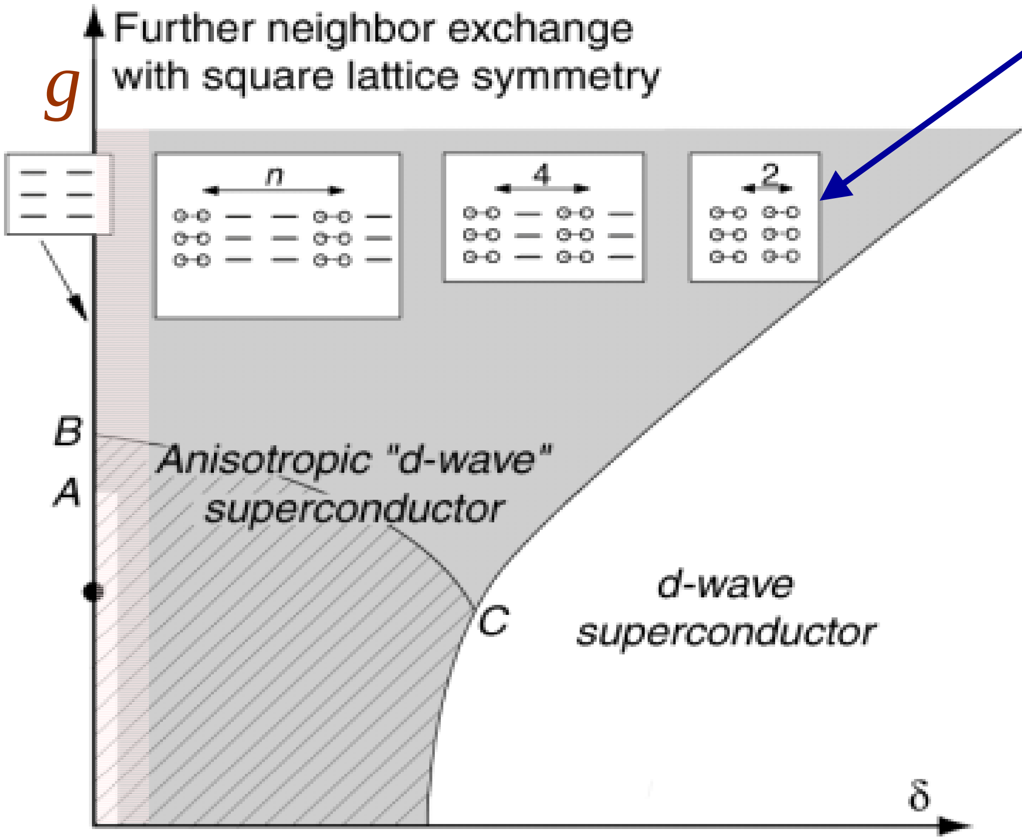


FIG. 1. Measurements of the charge order for YBCO6.35. (a) Measurements obtained at a small momentum transfer so the results are not affected by impurity powder lines. Powder lines were also avoided around the (1.125, 0, 1.3) r.l.u. position shown in (b). The lines are Gaussian fits to the data. In (a) 200 and (b) 100 additional counts were added onto successive scans so the data could be presented on the same plot. The scattering broadens at higher temperatures.

Charge order period
= 8 lattice spacings

H. A. Mook, Pengcheng Dai, and F. Dogan
Phys. Rev. Lett. **88**, 097004 (2002).

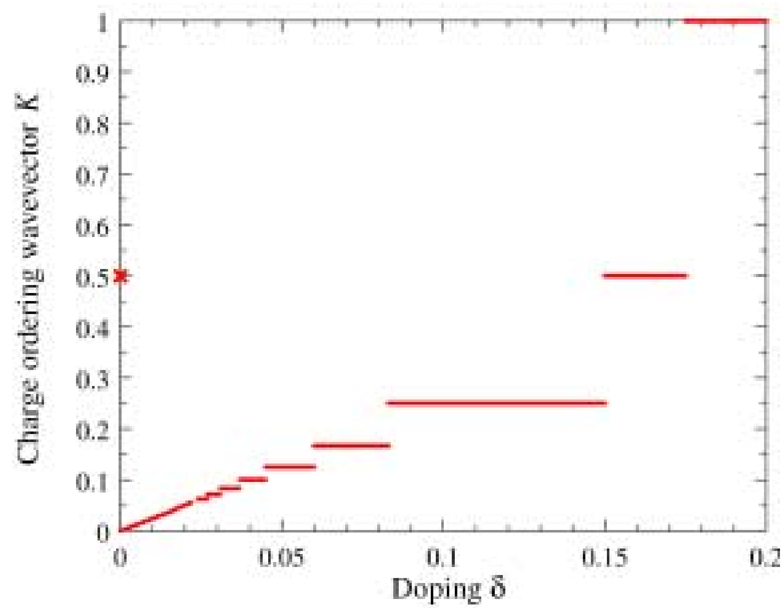
Charge order in the superconductor



Hatched region --- spin order
Shaded region ---- charge order

"Large *N*" theory in region with preserved spin rotation symmetry

S. Sachdev and N. Read, *Int. J. Mod. Phys*. B **5**, 219 (1991).
M. Vojta and S. Sachdev, *Phys. Rev. Lett*. **83**, 3916 (1999).
M. Vojta, Y. Zhang, and S. Sachdev, *Phys. Rev*. B **62**, 6721 (2000).



See also J. Zaanen, *Physica* C **217**, 317 (1999),
S. Kivelson, E. Fradkin and V. Emery, *Nature* **393**, 550 (1998),
S. White and D. Scalapino, *Phys. Rev. Lett*. **80**, 1272 (1998).
C. Castellani, C. Di Castro, and M. Grilli, *Phys.Rev. Lett*. **75**, 4650 (1995).

Conclusions

I. Cuprate superconductivity is associated with doping Mott insulators with charge carriers

II. The correct paramagnetic Mott insulator has charge-order and confinement of spinons

III. Mott insulator reveals itself vortices and near impurities. Predicted effects seen recently in STM and NMR experiments.

IV. Semi-quantitative predictions for neutron scattering measurements of spin-density-wave order in superconductors; theory also establishes connection to STM experiments.

V. Future experiments should search for SC+SDW to SC quantum transition driven by a magnetic field.

VI. Major open question: how does understanding of low temperature order parameters help explain anomalous behavior at high temperatures ?