How spin, charge and superconducting orders intertwine in the cuprates

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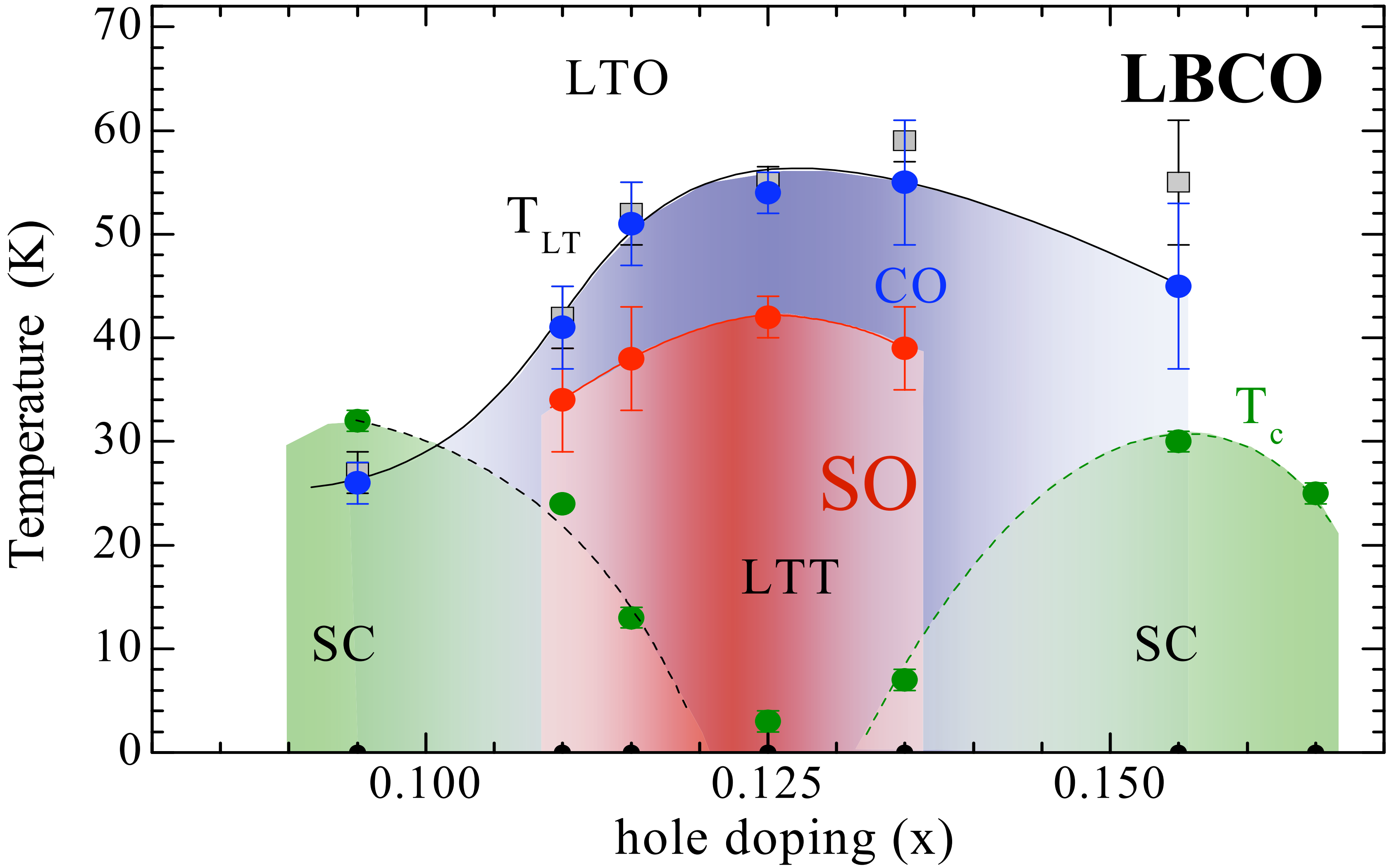
E. Berg, E. Fradkin, E.-A. Kim, S. Kivelson, V. Oganesyan, J. M. Tranquada, and S. -C. Zhang, Phys. Rev. Lett. **99**, 127003 (2007).
E. Berg, E. Fradkin and S. Kivelson, *The striped superconductor,* Phys. Rev. B **79**, 064515 (2009); arXiv:0810.1564.
E. Berg, E. Fradkin, S. Kivelson, and J. Tranquada, *Striped Superconductors: How the cuprates intertwine spin, charge, and superconducting orders,* to appear in New. J. Phys, arXiv:0901.4826 (2009).
E. Berg, E. Fradkin, and S. Kivelson, *Charge 4e superconductivity from pair density wave order in certain high temperature superconductors*, to appear in Nature Physics; arXiv:0904.1230 (2009).

Outlook

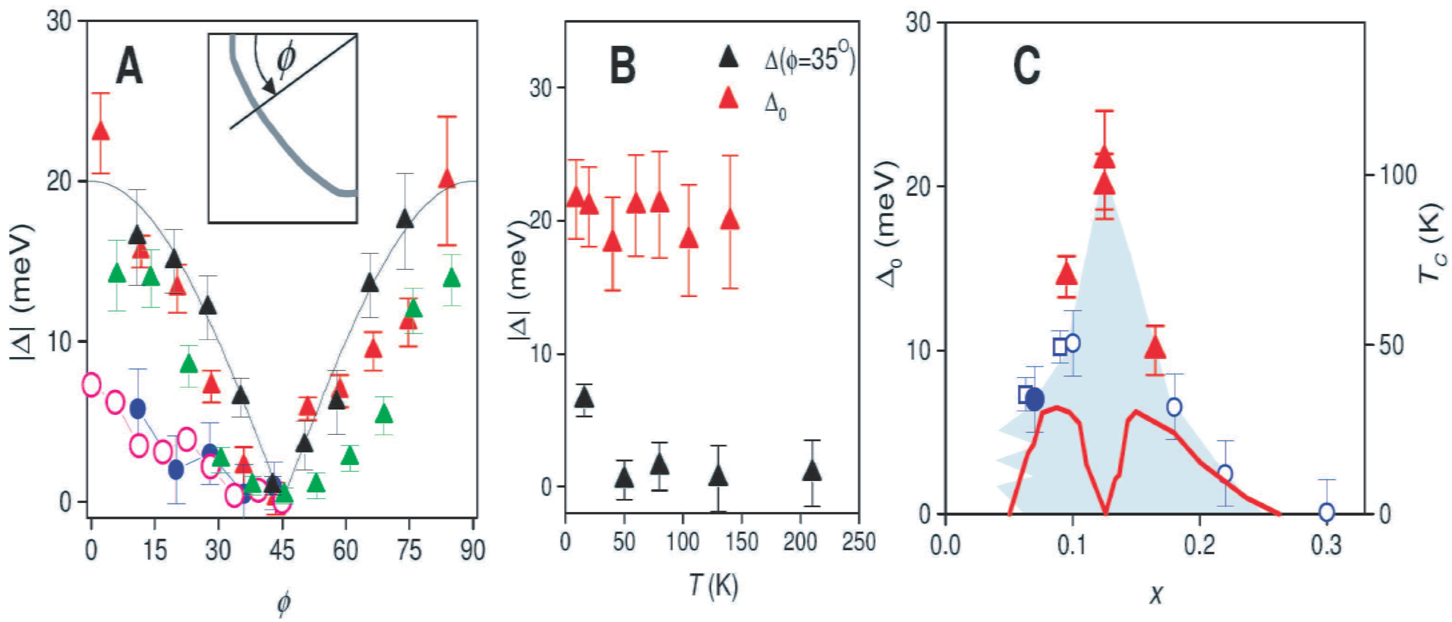
- LBCO is known to exhibit low energy stripe fluctuations in its superconducting state
- It has a very low T_c near x=1/8 where it shows static stripe order in the LTT crystal structure
- Experimental evidence for superconducting layer decoupling in LBCO at x=1/8
- Layer decoupling, long range charge and spin stripe order and superconductivity: a novel striped superconducting state, a Pair Density Wave, in which charge, spin, and superconducting orders are intertwined!

Phase Diagram of LBCO



M. Hücker et al (2009)

ARPES and the 1/8 anomaly: Optimal Inhomogeneity in LBCO

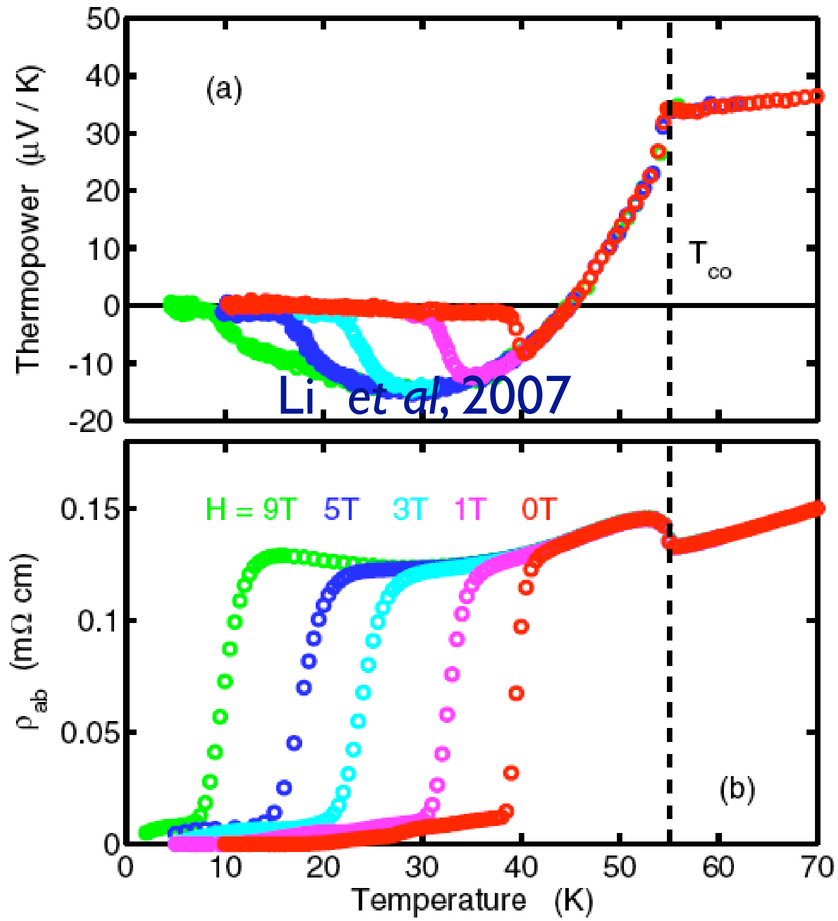


T.Valla *et al* (BNL) (2005), He *et al* (Stanford)(2008)

Li *et al* (2007): Dynamical Layer Decoupling in LBCO

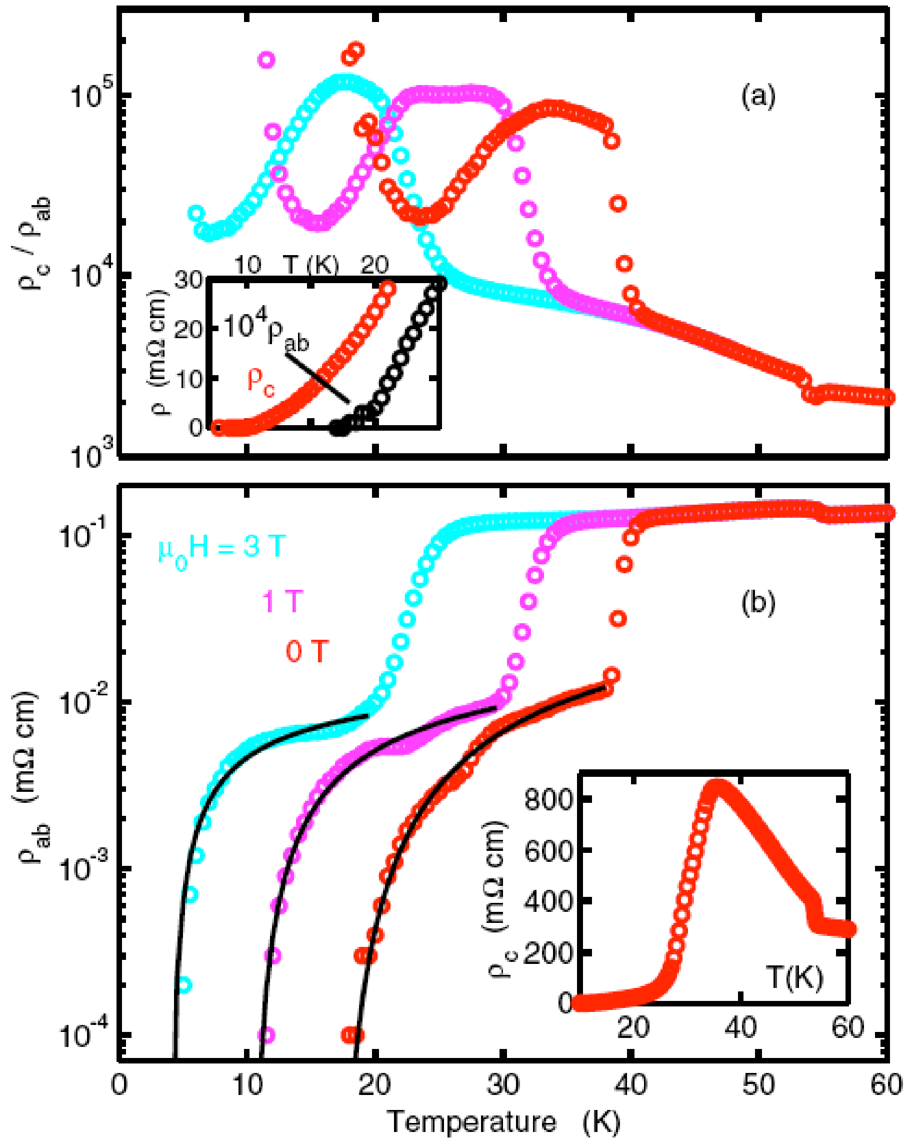
- ARPES: anti-nodal d-wave SC gap is large and unsuppressed at 1/8
- Static charge stripe order for $T < T_{charge} = 54$ K
- Static Stripe Spin order $T < T_{spin} = 42$K
- ρ_{ab} drops rapidly to zero from T_{spin} to T_{KT}
- ρ_{ab} shows KT behavior for $T_{spin} > T > T_{KT}$
- $\rho_c \uparrow$ as $T \downarrow$ for $T > T^{**} \approx 35$K
- $\rho_c \rightarrow 0$ as $T \rightarrow T_{3D} = 10$K
- $\rho_c / \rho_{ab} \rightarrow \infty$ for $T_{KT} > T > T_{3D}$
- Meissner state only below $T_c = 4$K

Transport Below The Charge Order Transition



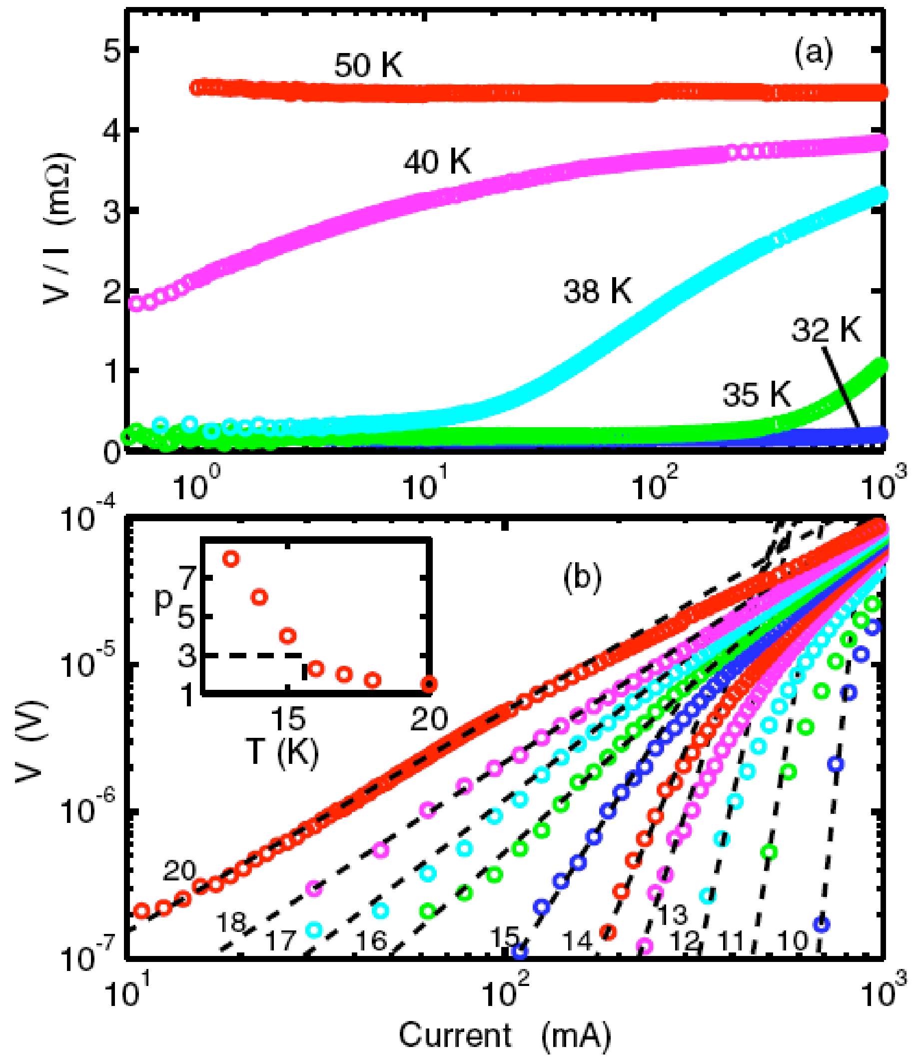
Li *et al*, 2007

Anisotropic Transport



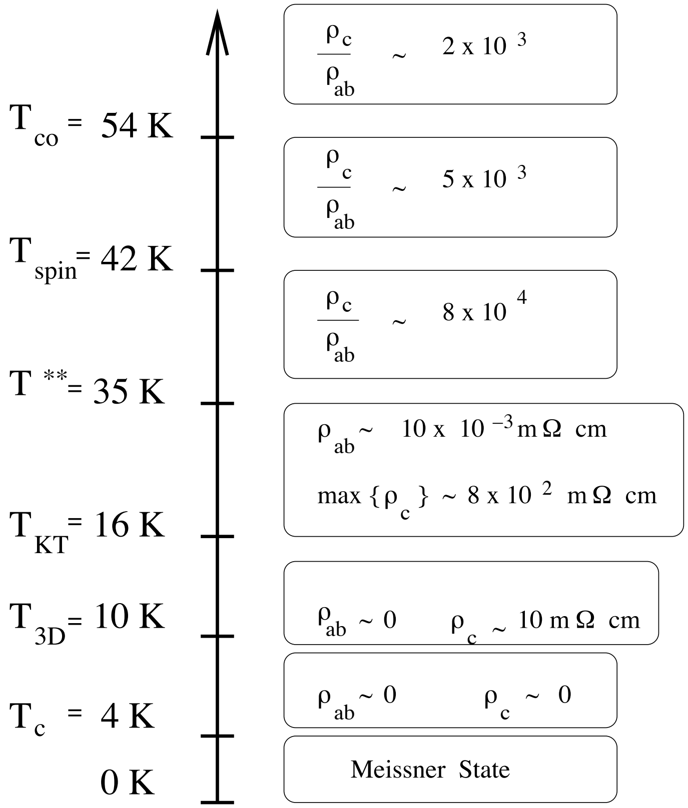
Li *et al*, 2007

The 2D Resistive State and 2D Superconductivity



Li *et al*, 2007

A hierarchy of ordering scales in $La_{2-x}Ba_xCuO_4$ at x=1/8



Static Charge Stripe Order

Long Range Stripe Spin Order

2D Superconducting Fluctuations

2D Superconducting Order

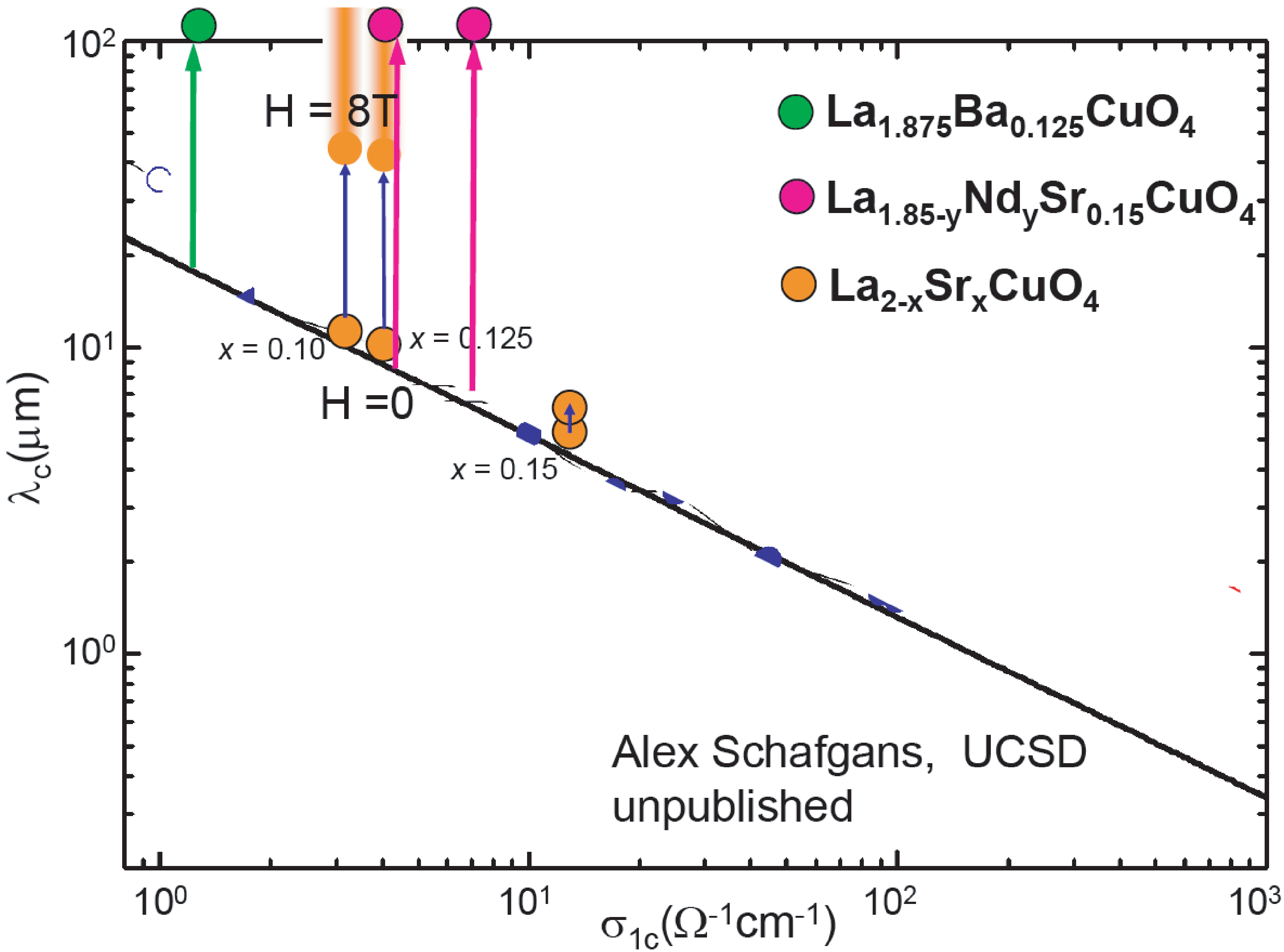
3D Superconducting Order

Li, Hücker, Gu, Tsvelik and Tranquada, PRL 99, 067001 (2007)

Connection with "Fluctuating" Stripe Phases in LSCO

- SC phase of LSCO has "fluctuating" stripes: inelastic neutron scattering detects low energy incommensurate spin fluctuations (Tranquada and coworkers, 1998)
- Upon doping with low amounts of Zn (< 1 %) the stripe state becomes static and sharp
- In a magnetic field ~ 8T LSCO has static spin stripe order (B. Lake and coworkers, 2002)
- In the same range of magnetic fields, Josephson resonance experiments (Basov *et al*, 2008) also detect dynamical layer decoupling in LSCO
- LNSCO also displays similar temperature-dependent anisotropic transport (Ding *et al*, 2008)

• Dynamical Layer Decoupling in the Cuprates



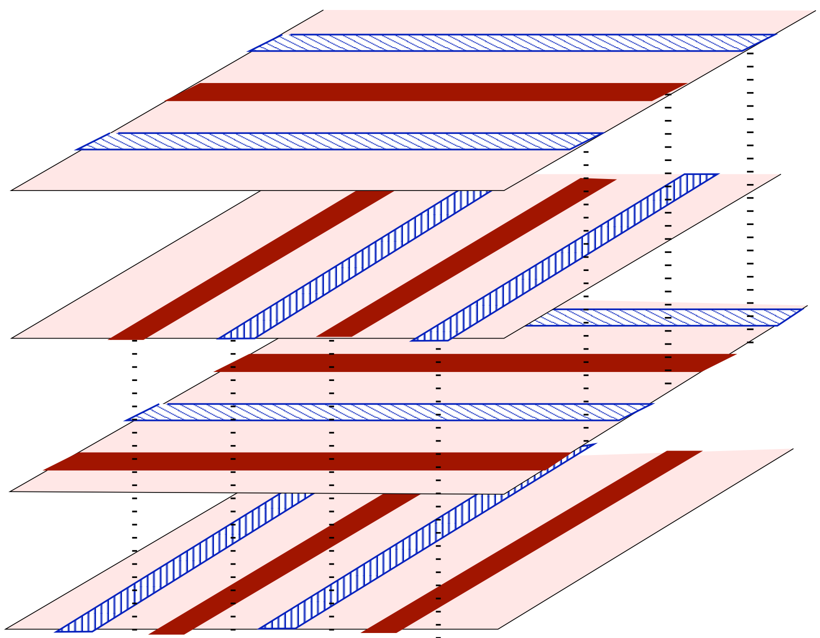
How Do We Understand This Remarkable Effects?

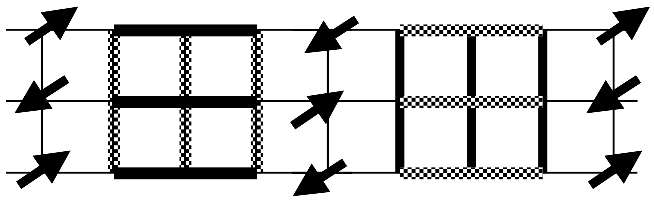
- Broad temperature range, $T_{3D} < T < T_{2D}$ with 2D superconductivity but not in 3D, as if there is not interlayer Josephson coupling
- In this regime there is both striped charge and spin order
- This can only happen if there is a special symmetry of the superconductor in the striped state that leads to an almost complete cancellation of the c-axis Josephson coupling.

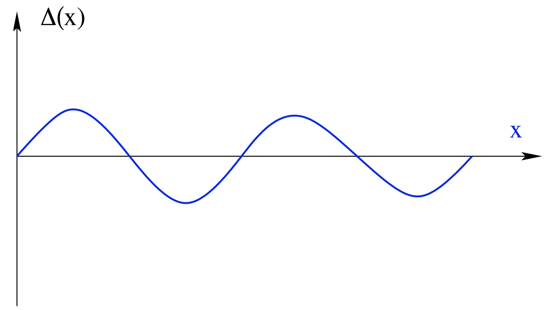
A Striped Textured Superconducting Phase

- The stripe state in the LTT crystal structure has two planes in the unit cell.
- Stripes in the 2nd neighbor planes are shifted by half a period to minimize the Coulomb interaction: 4 planes per unit cell
- The AFM spin order suffers a π phase shift accross the charge stripe which has period 4
- We propose that the superconducting order is also striped and also suffers a π phase shift.
- The superconductivity resides in the spin gap regions and there is a π phase shift in the SC order across the AFM regions

Period 4 Striped Superconducting State







- This state has intertwined striped charge, spin and superconducting orders.
- A state of this type was found in variational Monte Carlo (Ogata *et al* 2004) and MFT (Poilblanc *et al* 2007)

How does this state solve the puzzle?

- If this order is perfect, the Josephson coupling between neighboring planes cancels exactly due to the symmetry of the periodic array of π textures
- The Josephson couplings J_1 and J_2 between planes two and three layers apart also cancel by symmetry.
- The first non-vanishing coupling J_3 occurs at four spacings. It is quite small and it is responsible for the non-zero but very low T_c
- Defects and/or discommensurations gives rise to small Josephson coupling J_0 neighboring planes

Are there other interactions?

- It is possible to have an inter-plane biquadratic coupling involving the product SC of the order parameters between neighboring planes $\Delta_1 \Delta_2$ and the product of spin stripe order parameters also on neighboring planes $\mathbf{M_1} . \mathbf{M_2}$
- However in the LTT structure $\mathbf{M_1} . \mathbf{M_2}$=0 and there is no such coupling
- In a large enough perpendicular magnetic field it is possible (spin flop transition) to induce such a term and hence an effective Josephson coupling.
- Thus in this state there should be a strong suppression of the 3D SC T_c but not of the 2D SC T_c

Away from x=1/8

- Away from x=1/8 there is no perfect commensuration
- Discommensurations are defects that induce a finite Josephson coupling between neighboring planes $J_1 \sim |x-1/8|^2$, leading to an increase of the 3D SC T_c away from 1/8
- Similar effects arise from disorder which also lead to a rise in the 3D SC T_c

Landau-Ginzburg Theory of the striped SC: Order Parameters

- Striped SC: $\Delta(\mathbf{r})=\Delta_{\mathbf{Q}}(\mathbf{r})\, e^{i\,\mathbf{Q}\cdot\mathbf{r}}+\Delta_{-\mathbf{Q}}(\mathbf{r})\, e^{-i\mathbf{Q}\cdot\mathbf{r}}$, complex charge 2e singlet pair condensate with wave vector, (*i.e.* an FFLO type state at zero magnetic field)
- Nematic: detects breaking of rotational symmetry: N, a real neutral pseudo-scalar order parameter
- Charge stripe: $\rho_{\mathbf{K}}$, unidirectional charge stripe with wave vector $\mathbf{K}$
- Spin stripe order parameter: $\mathbf{S}_{\mathbf{Q}}$, a neutral complex spin vector order parameter, $\mathbf{K}=2\mathbf{Q}$

Rotations by $\pi/2$

- The nematic order parameter changes sign: $N \to -N$
- The CDW ordering wave vector rotates: $\rho_{\mathbf{K}} \to \rho_{\mathbf{K'}}$
- The SDW ordering wave vector rotates: $\mathbf{S}_{\mathbf{Q}} \to \mathbf{S}_{\mathbf{Q'}}$
- The striped SC (s or d wave): $\Delta_{\pm\mathbf{Q}} \to \pm\, \Delta_{\pm\mathbf{Q}}$

Translations

- Under a translation by **r**
  - $N \to N$, $\rho_{\mathbf{K}} \to e^{i\mathbf{K}.\mathbf{r}} \rho_{\mathbf{K}}$, $\mathbf{S}_{\mathbf{Q}} \to e^{i\mathbf{Q}.\mathbf{r}} \mathbf{S}_{\mathbf{Q}}$

Ginzburg-Landau Free Energy Functional

- $F = F_2 + F_3 + F_4 + \ldots$
- The quadratic and quartic terms are standard
- $F_3 = \gamma_s\, \rho_{\mathbf{K}}^{*}\, \mathbf{S}_{\mathbf{Q}} \,.\, \mathbf{S}_{\mathbf{Q}}$ + π/2 rotation + c.c.
  $+\gamma_{\Delta}\, \rho_{\mathbf{K}}^{*}\, \Delta_{-\mathbf{Q}}^{*}\, \Delta_{\mathbf{Q}}$ + π/2 rotation + c.c.
  $+g_{\Delta}\, N\, (\Delta_{\mathbf{Q}}^{*}\, \Delta_{\mathbf{Q}} + \Delta_{-\mathbf{Q}}^{*}\, \Delta_{-\mathbf{Q}}$ -π/2 rotation) + c.c.
  $+g_s\, N\, (\mathbf{S}_{\mathbf{Q}}^{*} \,.\, \mathbf{S}_{\mathbf{Q}}$ -π/2 rotation)
  $+g_c\, N\, (\rho_{\mathbf{K}}^{*}\, \rho_{\mathbf{K}}$ -π/2 rotation)

Some Consequences of the GL theory

- The symmetry of the term coupling charge and spin order parameters requires the condition $\mathbf{K} = 2\mathbf{Q}$
- Striped SC order implies charge stripe order with 1/2 the period, and of nematic order
- Charge stripe order with wave vector $2\mathbf{Q}$ and/or nematic order favors stripe superconducting order which may or may not occur depending on the coefficients in the quadratic part

Charge 4e SC order

- Coupling to a charge 4e SC order parameter Δ_4
- $F'_3 = g_4 \, [\Delta_4^* \, (\Delta_{\mathbf{Q}} \, \Delta_{-\mathbf{Q}} + \text{rotation}) + \text{c.c.}]$
- Striped SC order (PDW) ⇒ uniform charge 4e SC order!
- Since the coupling is independent of θ_-, the charge 4e SC order is unaffected by the Bragg glass of the pinned CDW
- The half vortices of θ_+ are the fundamental hc/4e vortices of the charge 4e SC.

Coexisting uniform and striped SC order

- PDW order Δ_Q and uniform SC order Δ_0
- $F_{3,u}=\gamma_\Delta \Delta_0^* \rho_{\mathbf{Q}} \Delta_{-\mathbf{Q}}+\rho_{-\mathbf{Q}} \Delta_{\mathbf{Q}}+g_\rho \rho_{-2\mathbf{Q}} \rho_{\mathbf{Q}}^2$ +rotation +c.c.
- If $\Delta_0 \neq 0$ and $\Delta_{\mathbf{Q}} \neq 0 \Rightarrow$ there is a $\rho_{\mathbf{Q}}$ component of the charge order!
- The small uniform component Δ_0 removes the sensitivity to quenched disorder of the PDW state

Topological Excitations of the Striped SC

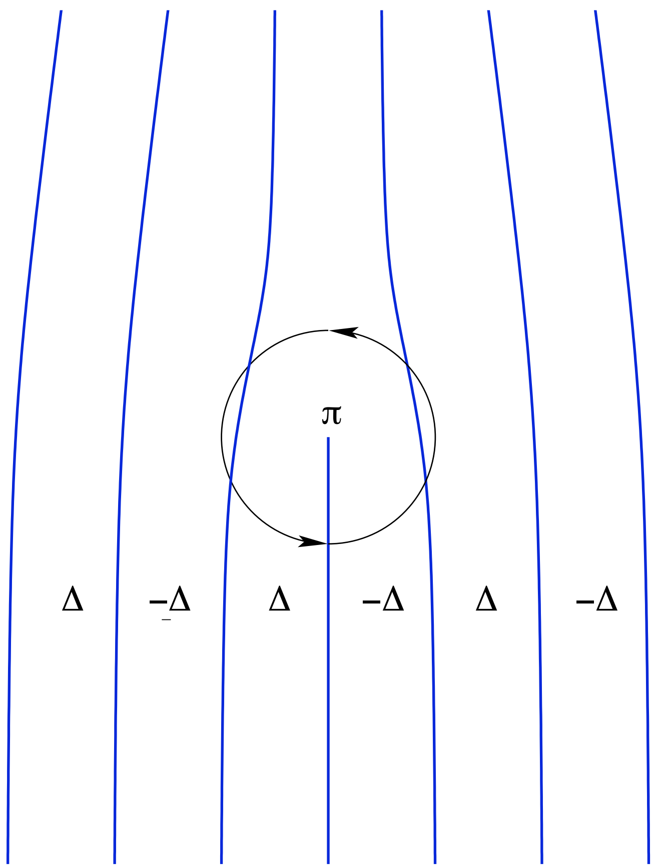
- $\rho(r)=|\rho_{\mathbf{K}}| \cos[K\, r+ \Phi(r)]$
- $\Delta(r)=|\Delta_{\mathbf{Q}}| \exp[i\, \mathbf{Q}\, \mathbf{r} + i\, \theta_{\mathbf{Q}}(r)]+|\Delta_{-\mathbf{Q}}| \exp[-i\, \mathbf{Q}\, \mathbf{r} + i\, \theta_{-\mathbf{Q}}(r)]$
- $F_{3,\Upsilon}=2\Upsilon_{\Delta}\, |\rho_{\mathbf{K}}\, \Delta_{\mathbf{Q}}\, \Delta_{-\mathbf{Q}}| \cos[2\, \theta_{-}(r)-\Phi(r)]$
- $\theta_{\pm Q}(r)=[\theta_{+}(r) \pm \theta_{-}(r)]/2$
- $\theta_{\pm Q}$ single valued mod $2\pi \Rightarrow \theta_{\pm}$ defined mod π
- ϕ and θ_{-} are locked $\Rightarrow$ topological defects of ϕ and θ_{+}

Topological Excitations of the Striped SC

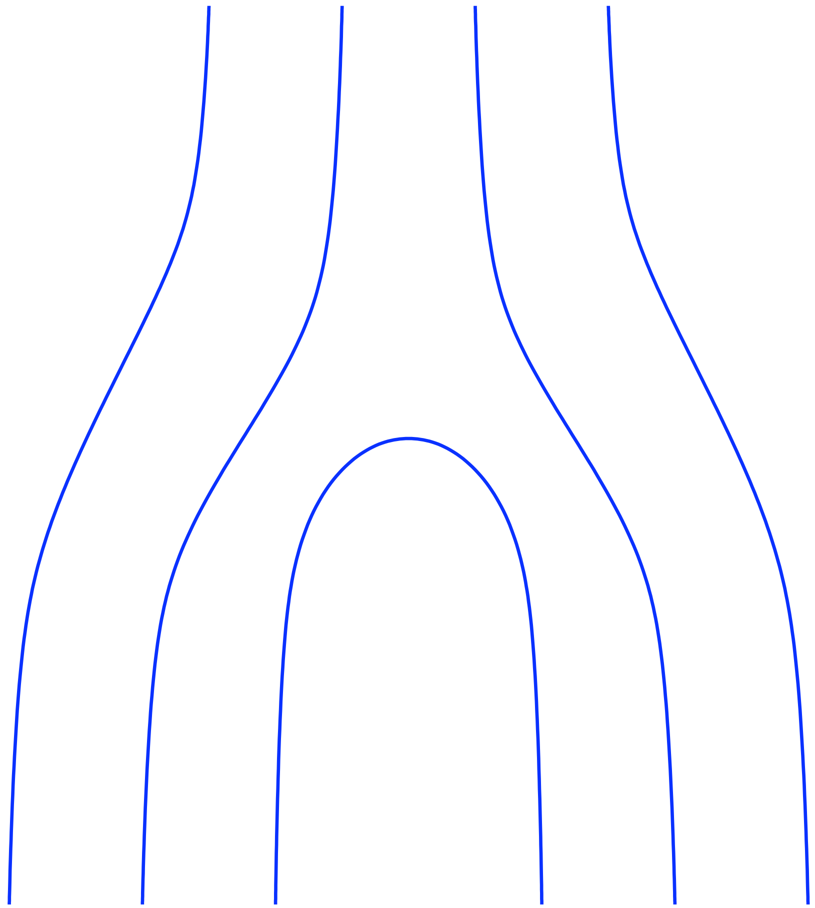
- SC vortex with $\Delta\theta_+ = 2\pi$ and $\Delta\phi=0$
- Bound state of a 1/2 vortex and a dislocation

  $\Delta\theta_+ = \pi, \Delta\phi= 2\pi$
- Double dislocation, $\Delta\theta_+ = 0, \Delta\phi= 4\pi$
- All three topological defects have logarithmic interactions

Half-vortex and a Dislocation



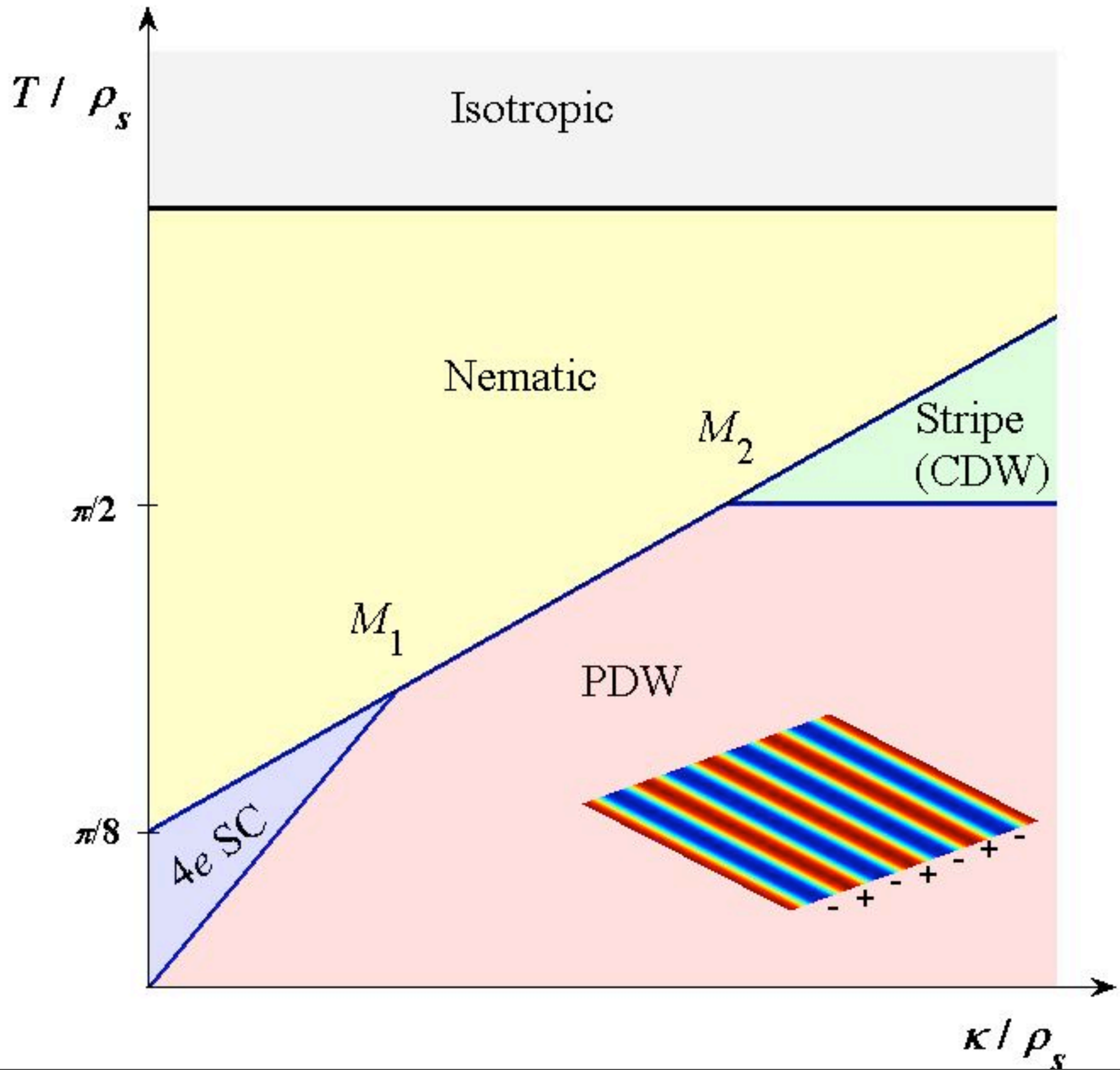
Double Dislocation



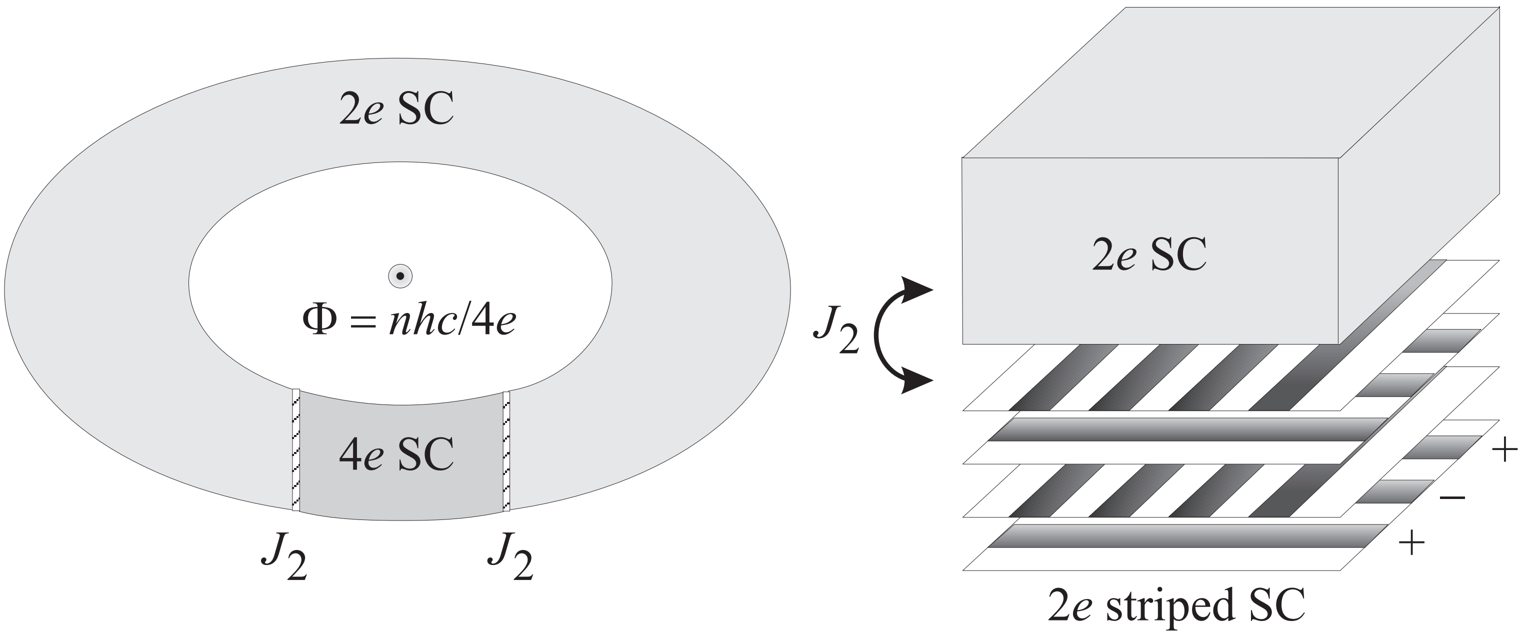
Thermal melting of the PDW state

- Three paths for thermal melting of the PDW state
- Three types of topological excitations: (1,0) (SC vortex), (0,1) (double dislocation), (±1/2, ±1/2) (1/2 vortex, single dislocation bound pair)
- Scaling dimensions: $\Delta_{p,q}=\pi(\rho_{sc}\, p^2+\kappa_{cdw}\, q^2)/T=2$ (for marginality)
- Phases: PDW, Charge 4e SC, CDW, and normal (Ising nematic)

Schematic Phase Diagram



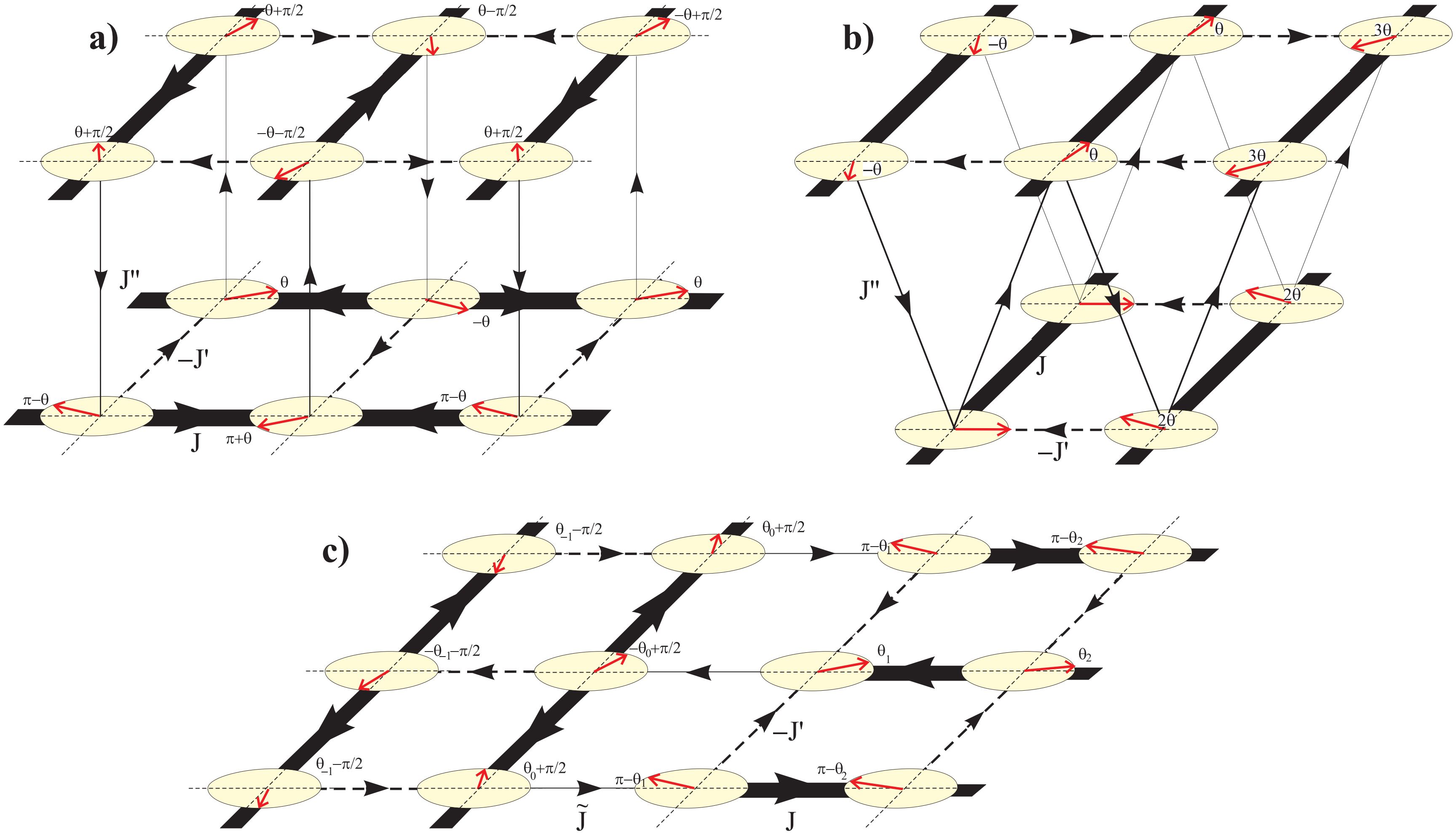
Phase Sensitive Experiments



$I = J_2 \sin(2\Delta\theta)$

Non-collinear Order and Time Reversal Symmetry Breaking

- PDW order in the planes leads to frustration of the inter-plane Josephson coupling
- We will regard the SC phase as an XY "pseudo-spin" and we get non-collinear order
- Non-collinear order ⇔ circulating currents ⇒ Time Reversal symmetry breaking effects
- The resulting non-collinear order depends on the lattice, and it is different for the LTT structure of LBCO than for the orthorhombic (chain) structure of YBCO
- Twin boundaries (domain walls) and edges also lead to non-collinear order
- The period of the Josephson coupling between a uniform and a striped SC is π



Non-collinear order and circulating currents for (a) the LTT structure (LBCO), (b) the orthorhombic (chain) structure of YBCO, and (c) an in-plane domain wall (“twin boundary”).

Effects of Disorder

- The striped SC order is very sensitive to disorder: disorder $\Rightarrow$ pinned charge density wave $\Rightarrow$ coupling to the phase of the striped SC $\Rightarrow$ SC "gauge" glass with zero resistance but no Meissner effect in 3D
- Disorder induces dislocation defects in the stripe order
- Due to the coupling between stripe order and SC, $\pm\pi$ flux vortices are induced at the dislocation core.
- Strict layer decoupling only allows for a magnetic coupling between randomly distributed $\pm\pi$ flux vortices
- Novel glassy physics and "fractional" flux

Conclusions

- LBCO at x=1/8 is a 2D HTSC with striped PDW d-wave superconductivity and very low 3D critical temperature
- It has a high pairing scale and an optimal degree of inhomogeneity
- Charge order is part of the SC order and both orders are *intertwined* rather than competing
- We introduced a striped SC, a Pair Density Wave, whose symmetries can explain the experiments
- Natural charge 4e SC order and hc/4e flux quantization

Conclusions, cont'd

- If the striped SC competes with the uniform d-wave SC in general both orders are present
- This leads to a uniform nodal d-wave SC at low energies and a striped SC at high energies, "two gaps"?
- An external magnetic field suppresses the uniform d-wave SC and can allow a striped SC to develop
- How pervasive is PDW order in the cuprates?