Interplay between SDW and PDW orders in the cuprates

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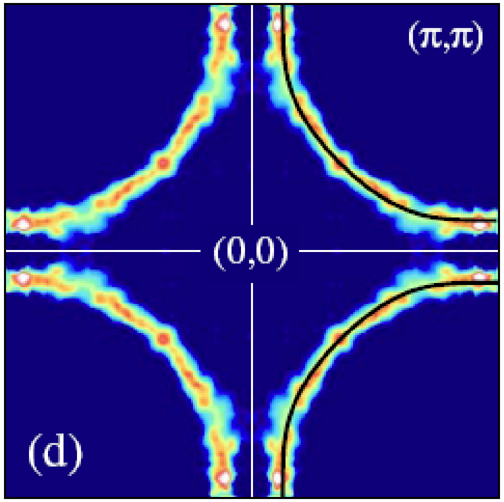
Original motivation: to verify whether both superconductivity and charge order in underdoped, yet still metallic cuprates, come from the same spin-fluctuation exchange

It ended up with: a generic analysis of charge orders in systems with cuprate Fermi surface

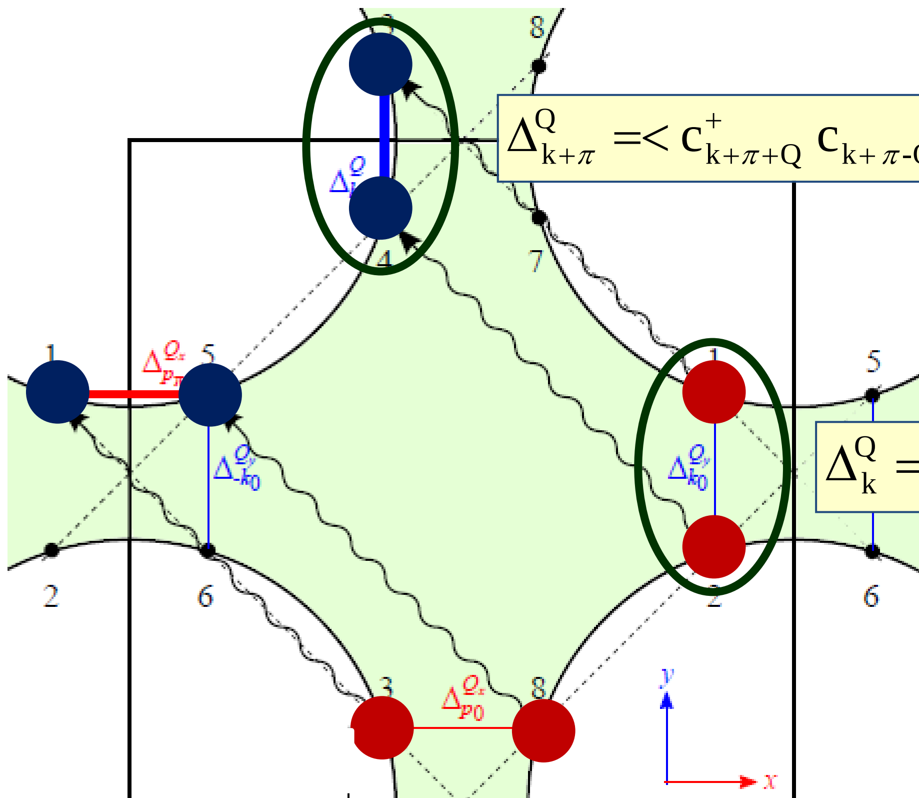


Our first interest was to analyze CDW order with (Q,0)/(0,Q)

following Metlitski and Sachdev
Efetov, Pepin and Meier on (Q,Q) order
La Placa and Sachdev on a generic CDW

- This order does develop, despite anti-nesting of fermions in blue region
- Δ_k changes sign between red and blue regions, but magnitudes are not equal.

$$\mathrm{sign}\,(\Delta^Q_{k+\pi}) = -\mathrm{sign}\,(\Delta^Q_k)$$
$$|\Delta^Q_{k+\pi}| \neq |\Delta^Q_k|$$



$$\Delta^Q_{k+\pi} = \langle c^+_{k+\pi+Q}\, c_{k+\pi-Q} \rangle$$

$$\Delta^Q_k = \langle c^+_{k+Q}\, c_{k-Q} \rangle$$

The outcome:

$$\Delta^Q_k = A + \overline{A}\,(\cos k_x + \cos k_y) + B\,(\cos k_x - \cos k_y) + \ldots$$

d-wave component is larger because interaction is repulsive and is peaked at large momentum transfer ((π,π) in our case)

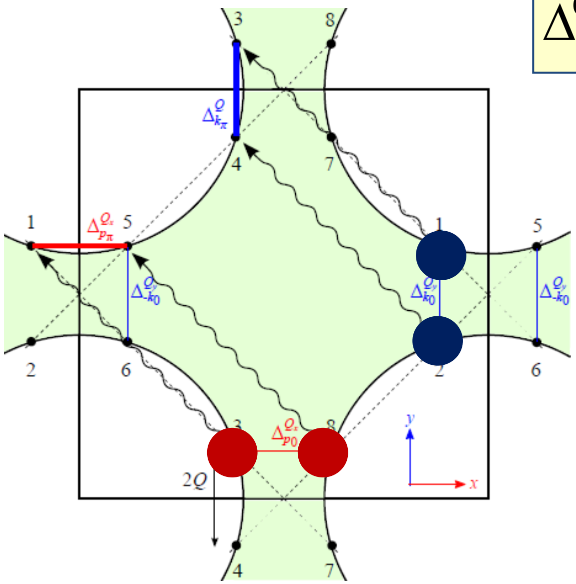
d-wave (bond order) and s-wave (CDW) are both present, d-wave is larger

Davis, Sachdev

There is more: (Q,0)/(0,Q) order can break several symmetries

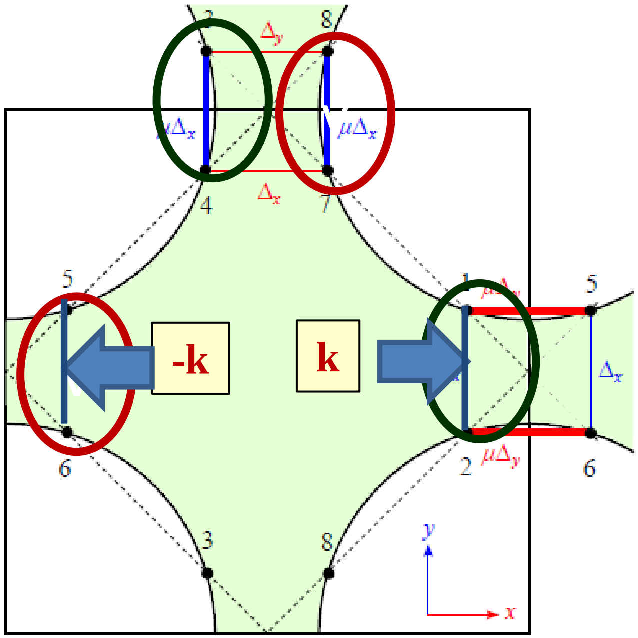
Expected: incommensurate CDW breaks translational U(1):

$$\Delta_k^Q = < c^+_{k+Q}\, c_{k-Q} > = (\Delta_k^Q)^* = |\Delta_k^Q|\, e^{i\varphi}$$



It may also break C_4 lattice rotational symmetry by choosing (Q,0) or (0,Q)

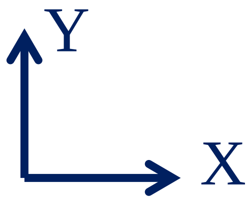
Less expected: CDW can also break time-reversal symmetry



If the phases of $\boxed{\Delta_k^Q}$ and $\boxed{\Delta_{-k}^Q}$ differ by +- $\pi/2$, T symmetry is broken and the order has incommensurate density modulation and incommensurate current

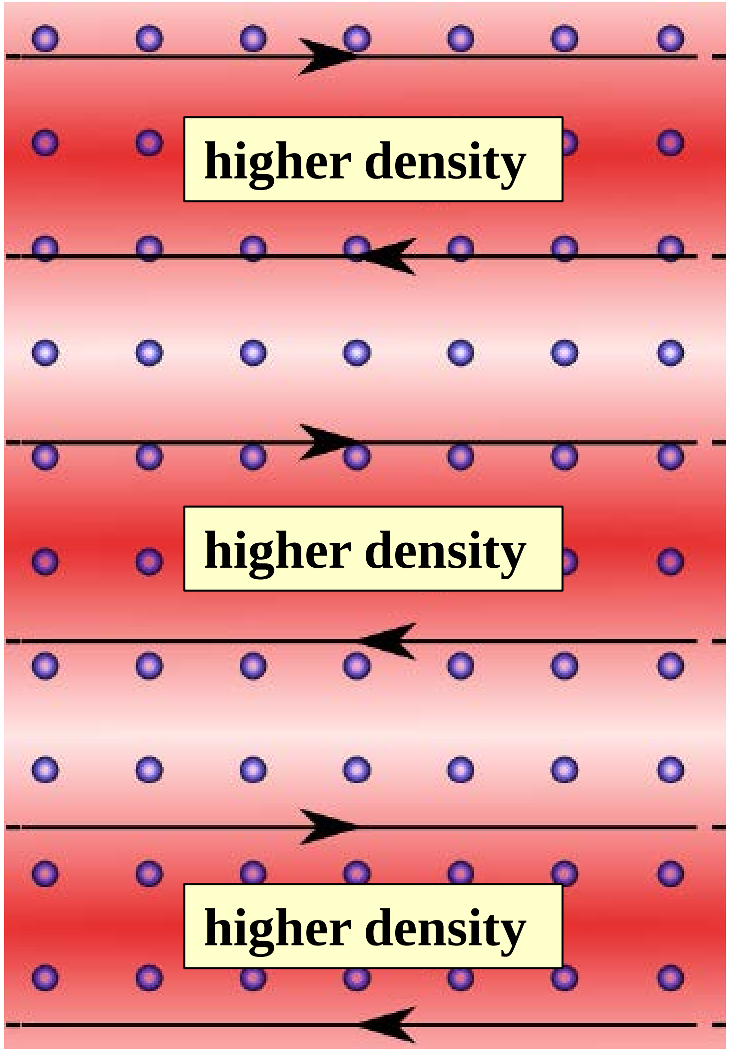
$$\hat{T}\, \Delta_k^Q = c^+_{-k+Q}\, c_{-k-Q} = \Delta_{-k}^Q$$

Real space picture for stripe CDW with $\boxed{\Delta^{Q}_{-k} = i\ \Delta^{Q}_{k}}$



$$\boxed{\begin{aligned} \delta\rho &= \Delta^{Q}_{k} + \Delta^{Q}_{-k} \propto \cos Qy, \\ j_x &= \Delta^{Q}_{k} - \Delta^{Q}_{-k} \propto \sin Qy \end{aligned}}$$

$Q = (0,Q)$



Such an order also breaks
X and Y mirror symmetries
and give rise to Kerr effect

It generates incommensurate
magnetic field but no bulk
homogeneous magnetic field

A possibility that CDW order breaks additional discrete symmetries is quite encouraging as there is exp evidence for discrete symmetry breaking near the onset of CDW

- NMR, structural, X-ray, STM, ARPES measurements – incommensurate static charge order U(1)

Julien, Proust, Le Tacon, Chang, Davis, Damascelli

- resistivity anisotropy measurements – lattice rotational C_4 symmetry is broken down to C_2 Z_2

Taillefer, Kivelson, Tremblay

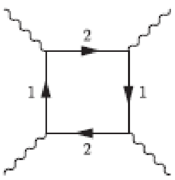
- Kerr effect and neutron scattering measurements time-reversal symmetry is broken Z_2

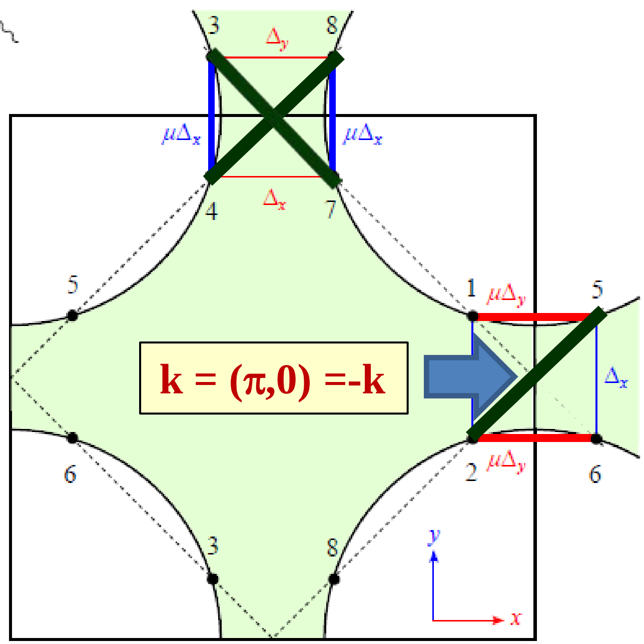
Kapitulnik, Bourges

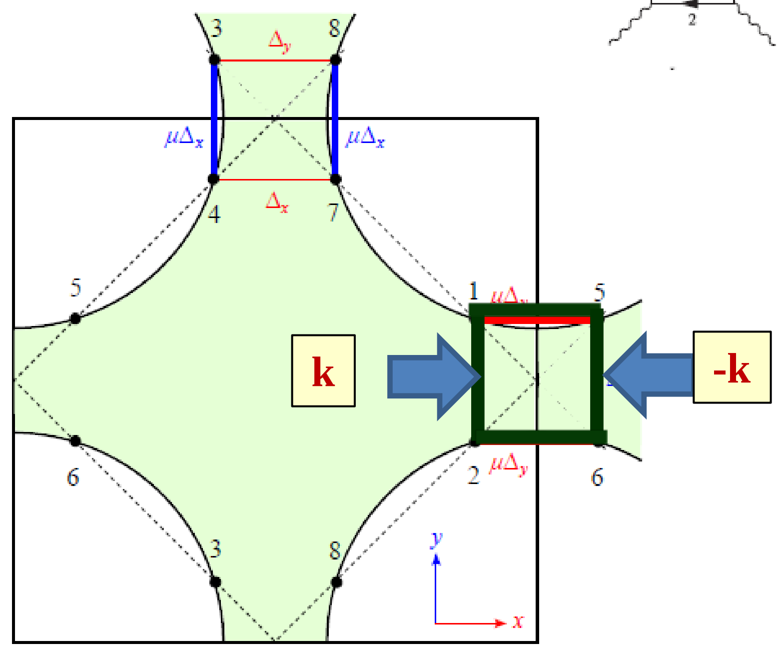
No discrete symmetry breaking for bond order with (Q,Q)

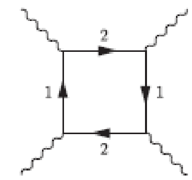
Orders with (Q,Q) and (-Q,Q)
do not couple to each other, hence
no C_4 symmetry breaking between the two

(Q,Q) and (0,Q) orders do
couple to each other, and the
coupling, if strong enough,
leads to C4 breaking (stripes)









No T-breaking

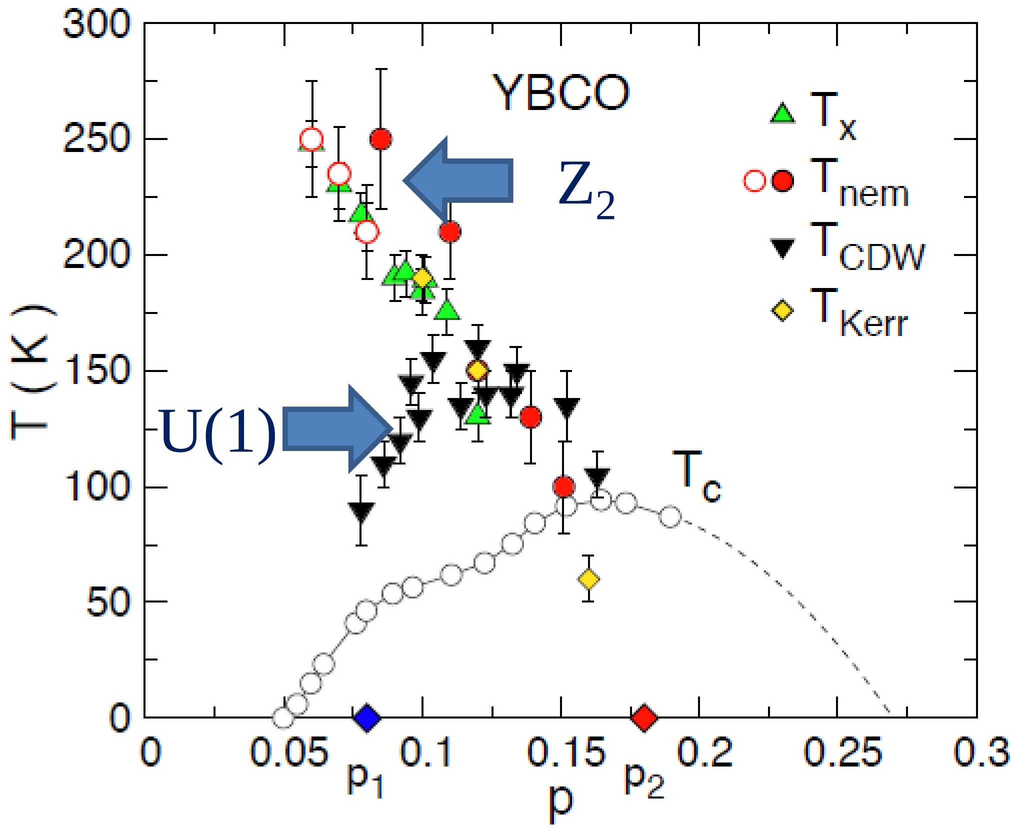
Allows for T-breaking

A generic reasoning: if the ordered state breaks both continuous and discrete symmetries (U(1) and $Z_2 * Z_2$ for CDW), discrete symmetries generally get broken at higher T and at intermediate T the system has a "nematic" order

Kivelson

At least at some dopings discrete symmetry breaking has been observed at higher temperatures than static CDW

Taillefer

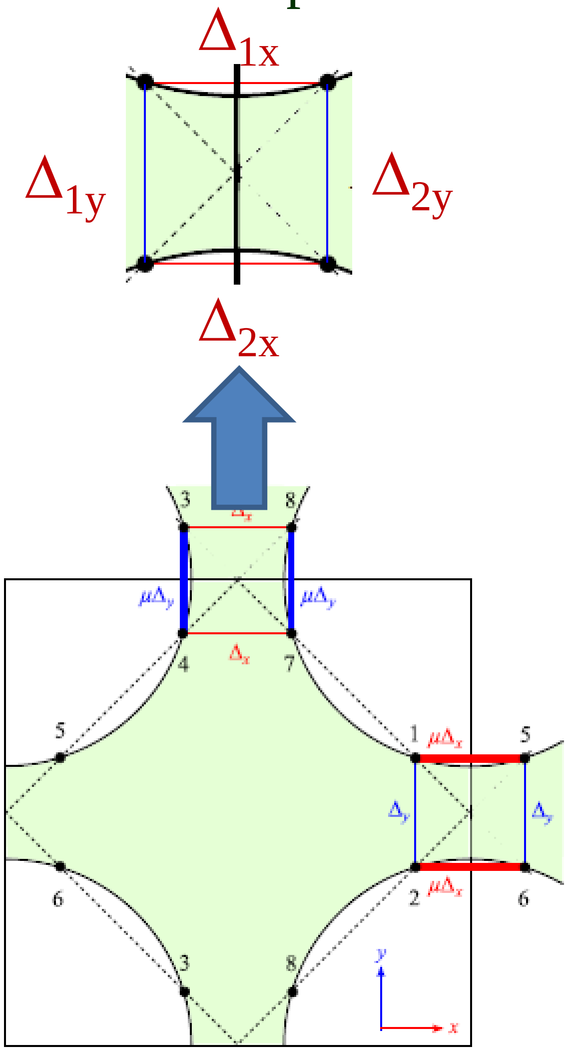


Let's see what theory says about discrete symmetry breakings

- Ginzburg-Landau analysis for 4-component order parameter

$\Delta_{1x}, \Delta_{2x}, \Delta_{1y}, \Delta_{2y}.$

"Hot spot" CDW model
(low-energy fermions separated by Q)



Parameters: coupling g and energy cutoff Λ,
theory is under control when $g < \Lambda$

The results of the GL analysis

- We did obtain stripe phase, with $\Delta_{1x} = \pm\, \mathbf{i}\, \Delta_{2x}$ but ONLY when $g \sim \Lambda$

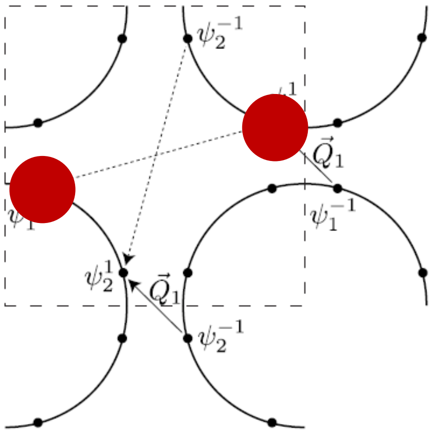
- When $g < \Lambda$, we did find a checkerboard state

And this forced us to realize that the analysis is incomplete

Back to Catherine's talk

d-wave superconductivity and
(Q,Q) charge order are degenerate "twins"

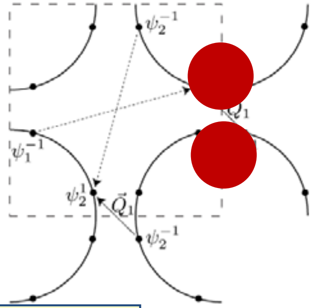
Metlitski and Sachdev
Efetov, Pepin and Meier



Does CDW has a "twin"?

Yes, its twin is superconductivity
with a finite momentum of a pair (PDW)

Kivelson and Fradkin
P.A. Lee, D. Agrerberg….



$$\Delta_k^Q = < c^+_{k+Q}\ c_{k-Q} >$$

CDW

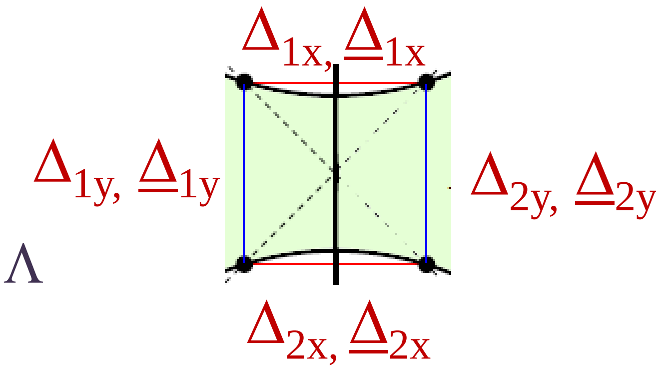
$$\overline{\Delta}_k^Q = < c^+_{k+Q}\ c^+_{k-Q} >$$

PDW

- Ginzburg-Landau analysis for 8-component order parameter

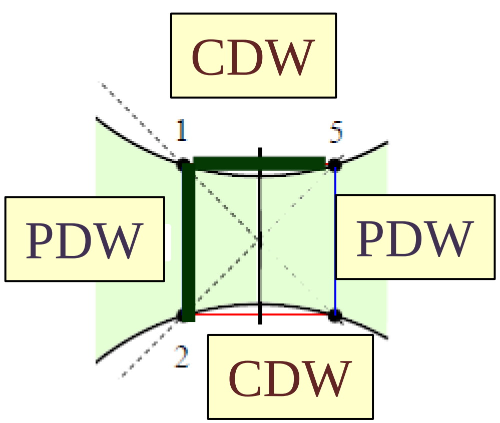
CDW: Δ_{1x}, Δ_{2x}, Δ_{1y}, Δ_{2y}, PDW: $\underline{\Delta}_{1x}$, $\underline{\Delta}_{2x}$, $\underline{\Delta}_{1y}$, $\underline{\Delta}_{2y}$

Same hot spot model
(low-energy fermions separated by Q)



Same parameters: coupling g and energy cutoff Λ
Let's set $g < \Lambda$ and play "by the rules"

We still get a checkerboard state, but a rather specific one:
CDW along one direction, PDW along the other



CDW between 1 and 5: 1= $(\pi-k,k)$, 5=$(\pi+k,k)$,
transferred momentum 1-5 = $(-2k,0)$

PDW between 1 and 2: 1= $(\pi-k,k)$, 2=$(\pi-k,-k)$,
total momentum 1+2 = $(-2k,0)$

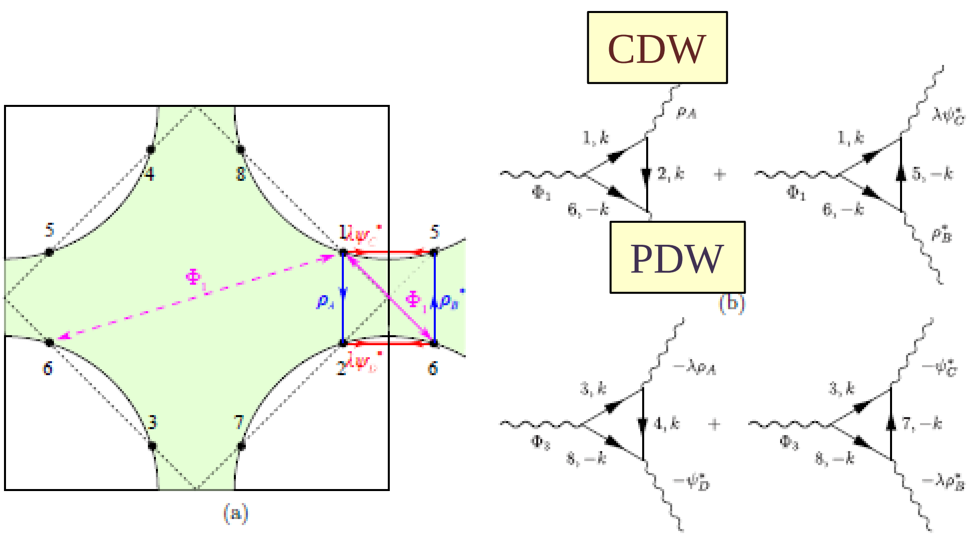
"Orthogonal" CDW and PDW orders
carry the same momentum!

This charge order:

- breaks C_4 (CDW is a stripe along X or along Y)
- breaks time-reversal symmetry and generate incommensurate density fluctuations and incommensurate current

The reason it minimizes GL energy is rather subtle:

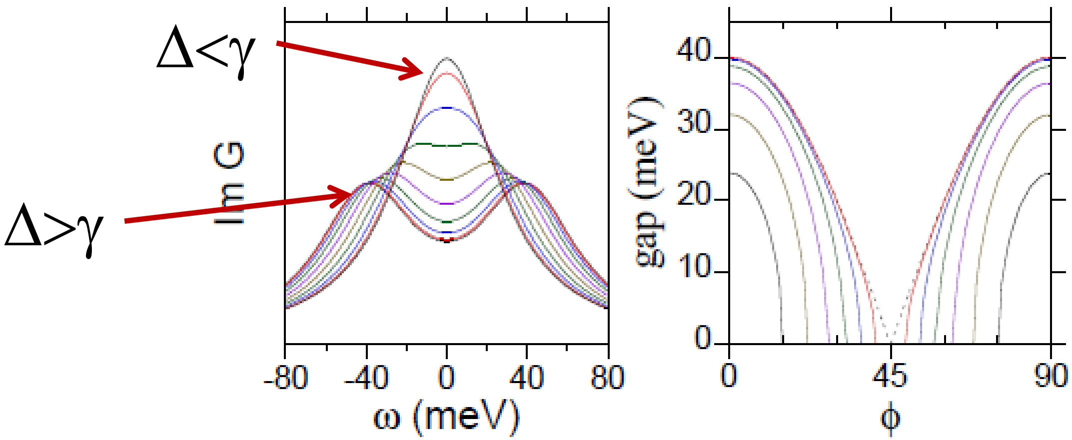
CDW and PDW, which carry the same momentum, together generate a secondary uniform s- type superconductivity



Triple coupling generates uniform SC order, and this reduces the energy of the CDW/PDW state

This leads to the specific prediction:

- In the normal state, fermionic damping is non-zero, hence a small SC gap is difficult to detect in ARPES



Abrahams, Millis, Norman, A.C

- But in a co-existence state with a true d-wave SC with a large gap and reduced fermionic damping, additional s-wave gap component can be detectable. Two states are possible: s+d and s + $e^{i\phi}$ d. In both cases, the gap along the nodal direction is non-zero

Search for s-wave component of SC gap in the co-existence state

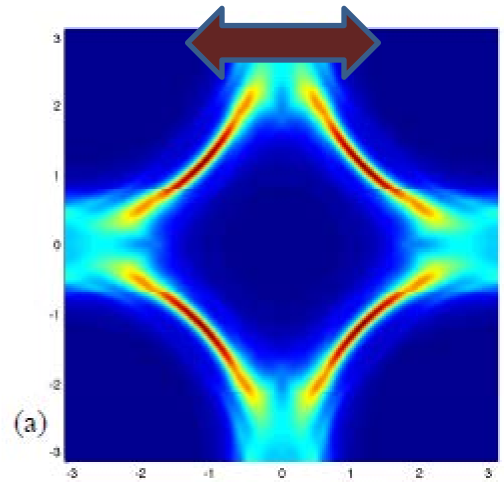
The presence of PDW also helps explain ARPES data, which without PDW component would be inconsistent with the theory

P.A. Lee

Comparison with ARPES

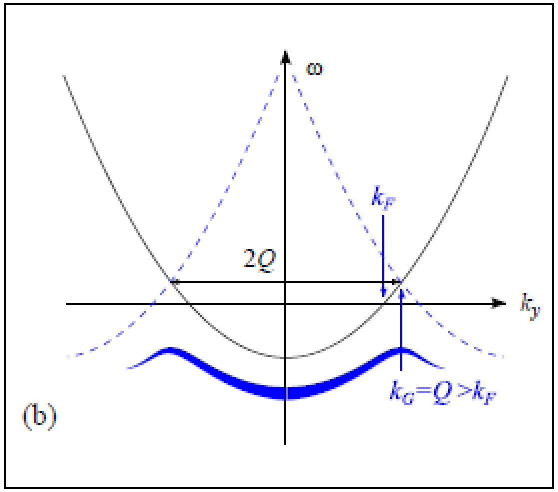
Pure CDW state

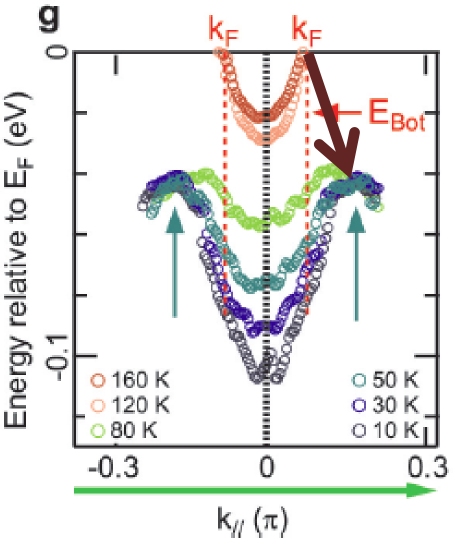
1. Fermi arc



Model: domains of CDW (0,Q) and (Q,0), plus a finite damping to model a disordered CDW between T* and T_{CDW}

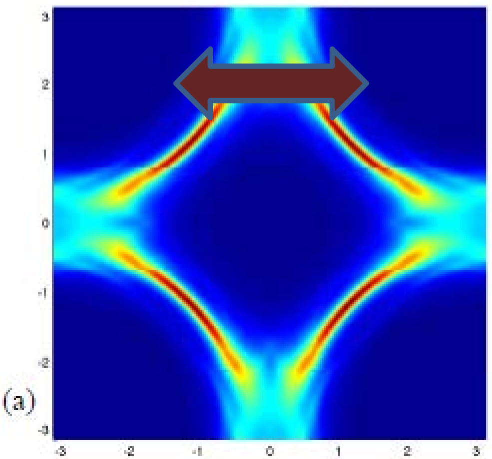
2. Shift of the position of the minimum to a larger value

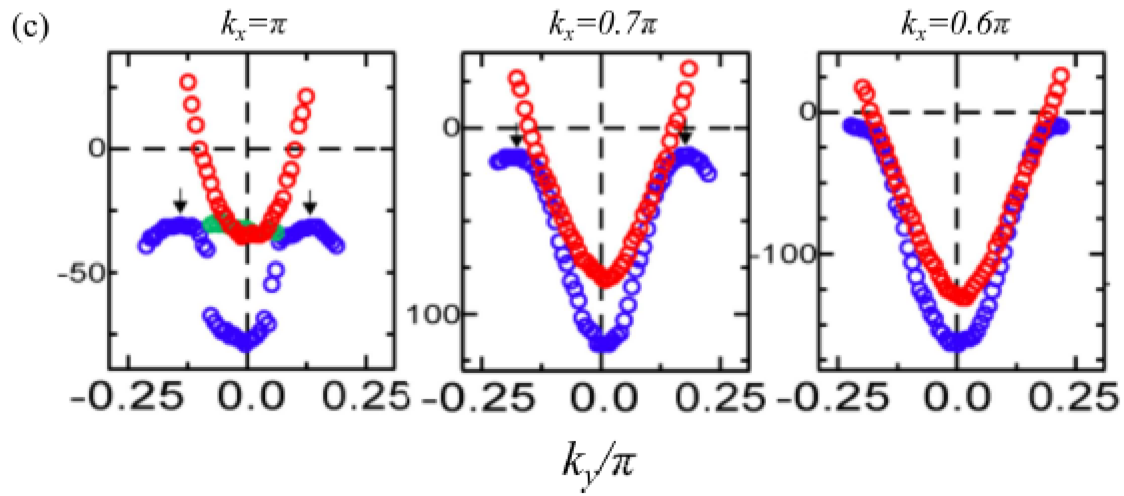




I. Vishik et al,
Rui-Hua He et al

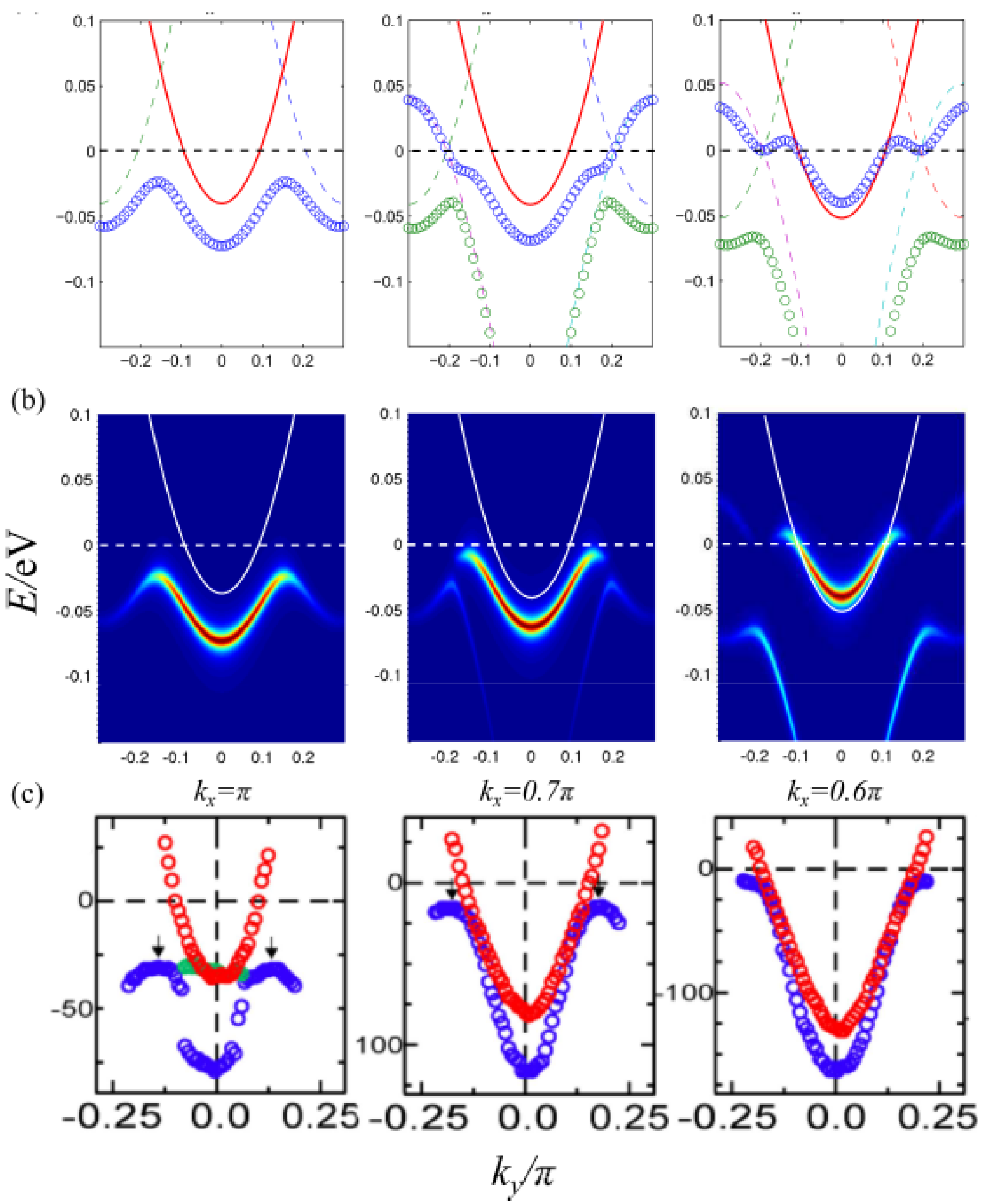
However, pure CDW cannot explain
the behavior closer to zone diagonals





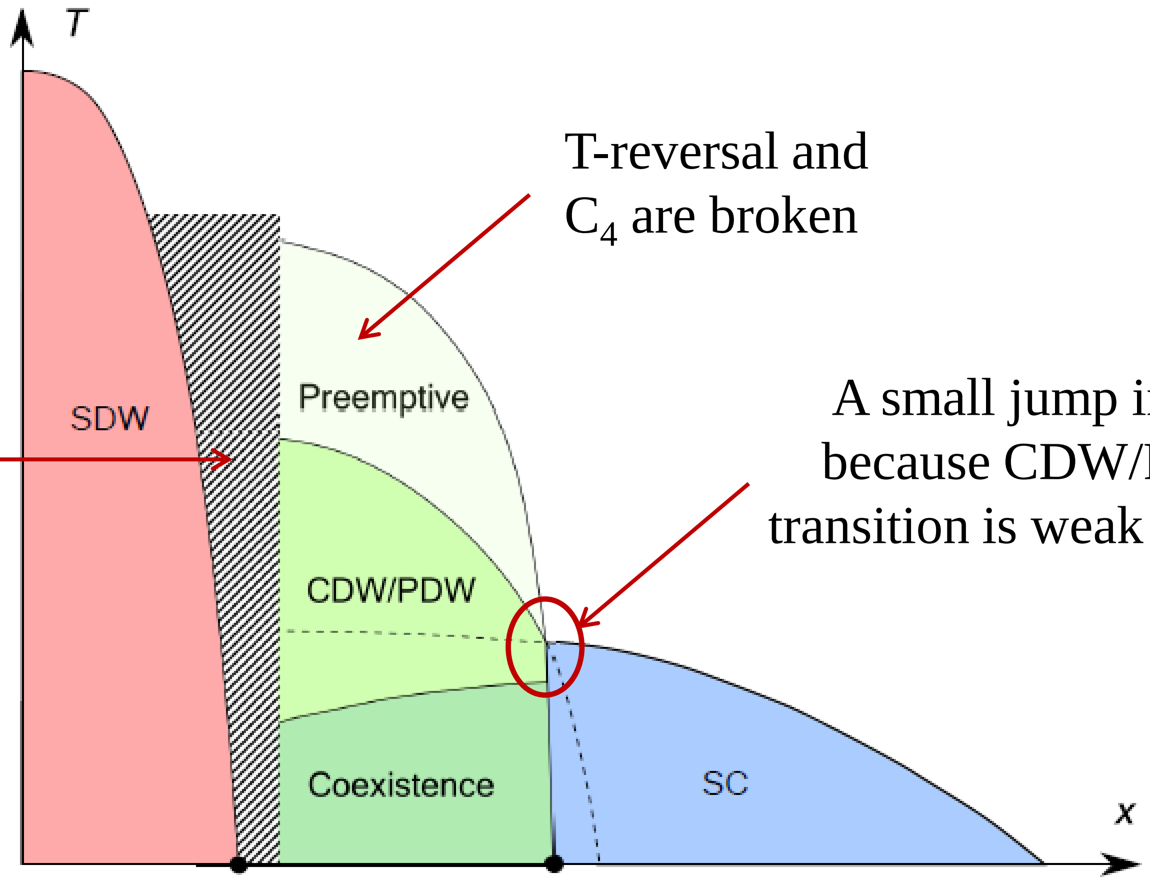
Experimental dispersion approaches Fermi level from below.
In pure CDW description, the lower branch just keeps moving down in energy, and the upper branch lowers and hits the Fermi surface

CDW + PDW



Phase diagram

Mott physics



T-reversal and C_4 are broken

A small jump in Tc because CDW/PDW transition is weak 1^{st} order

THANK YOU