FROM NODAL LIQUID TO NODAL INSULATOR

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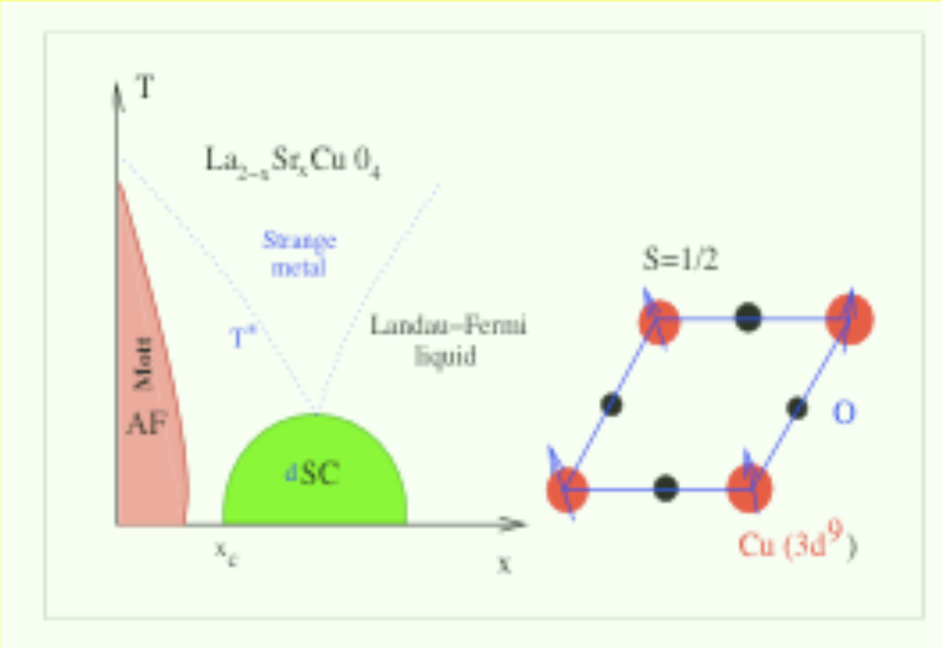
Fonds de recherche sur la nature et les technologies Québec

GORDON, 2004, Oxford

NSERC CRSNG

CIAR The Canadian Institute for Advanced Research

Doped Mott insulator?



Mott physics: U

Antiferro fluctuations: J

SC fluctuations above Tc

Nernst effet?

Strange metal at optimal doping: $\rho(T) \sim T$

Pseudo-gap phase $T \leq T^*$: **reduct^o of e^-, spin excitat^o...**;

possibly, an RVB spin liquid **"Small Fermi surface"**
recent cond-mat of Anderson, Lee, Rice, Zhang, Randeria et Trivedi

RVB <> BCS nicely connected

$| \Psi\rangle = \exp(iS)\, P_G\, |BCS\rangle$

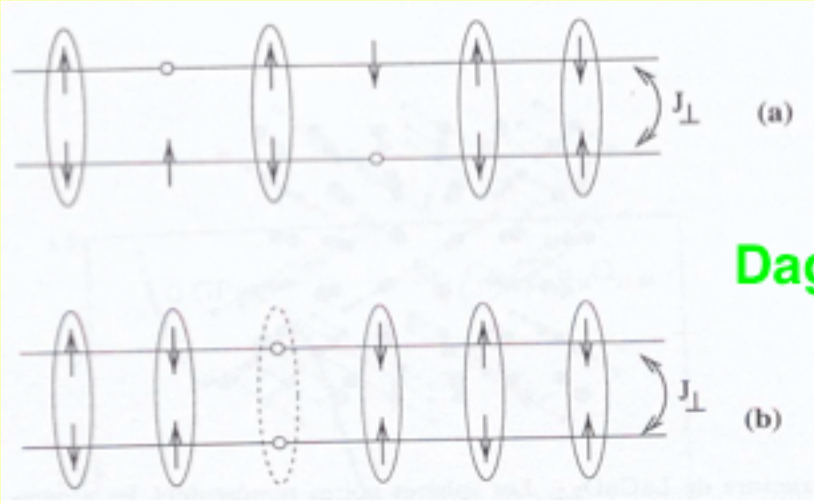
P_G **Gutzwiller projector**

BUT $\langle\psi|O|\psi\rangle$ difficult to compute…

EXCITATIONS?

-Gutzwiller approximations: F.C. Zhang, Anderson
-Variational Quantum Monte Carlo: M. Randeria
-two-patch model in 2D: RG+exact diagonalization (A. Laeuchli, K. Honerkamp, and M. Rice)
-quasi-1D or ladder-type approaches: my talk…

Two-leg ladder superconductor



Shelton and Tsvelik, 1996

Dagotto & Rice, Science 271, 618 (1996)

1D system: no long-range order - Bethe, before the 2nd war

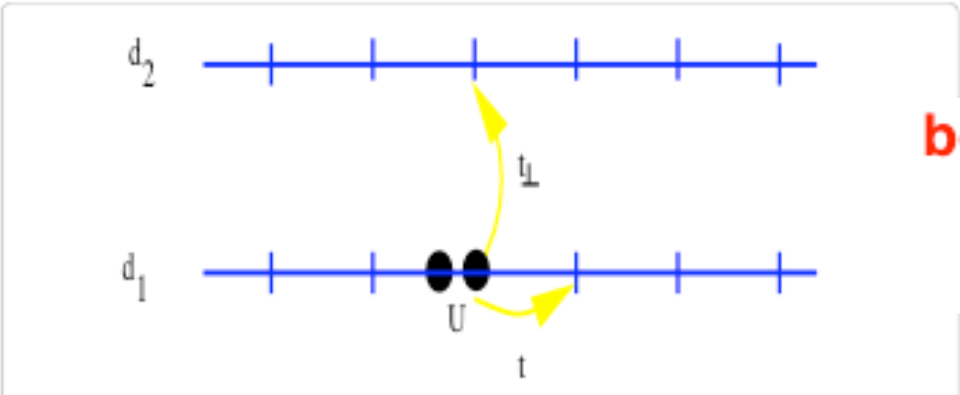
Undoped case: RVB system with Spin Gap

P.W. Anderson, Science **235**, *1196 (1987)*

Doping: d-wave like superconductivity

$$< \Delta^\dagger(x)\Delta(0) > \propto x^{-1/2}$$

weak-coupling approach for RVB

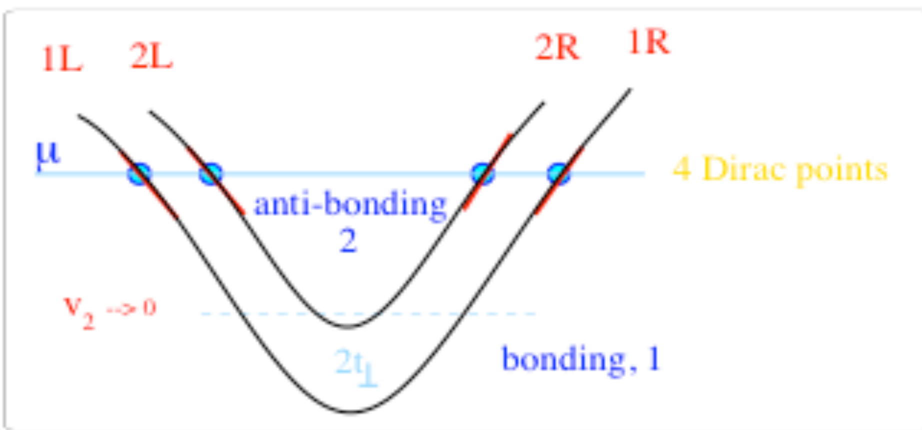


bonding-antibonding bands $\Psi_{1,2}$

$$\Psi_{1,2} = \frac{1}{\sqrt{2}}\{d_1 \pm d_2\}$$

Limit of large $t_\perp \gg U$

Band structure:



$$\epsilon_j(k) = \mp t_\perp - 2t\cos(k)$$

Half-filling: $\mathbf{v_1 = v_2}$
and $k_{F1} + k_{F2} = \pi$

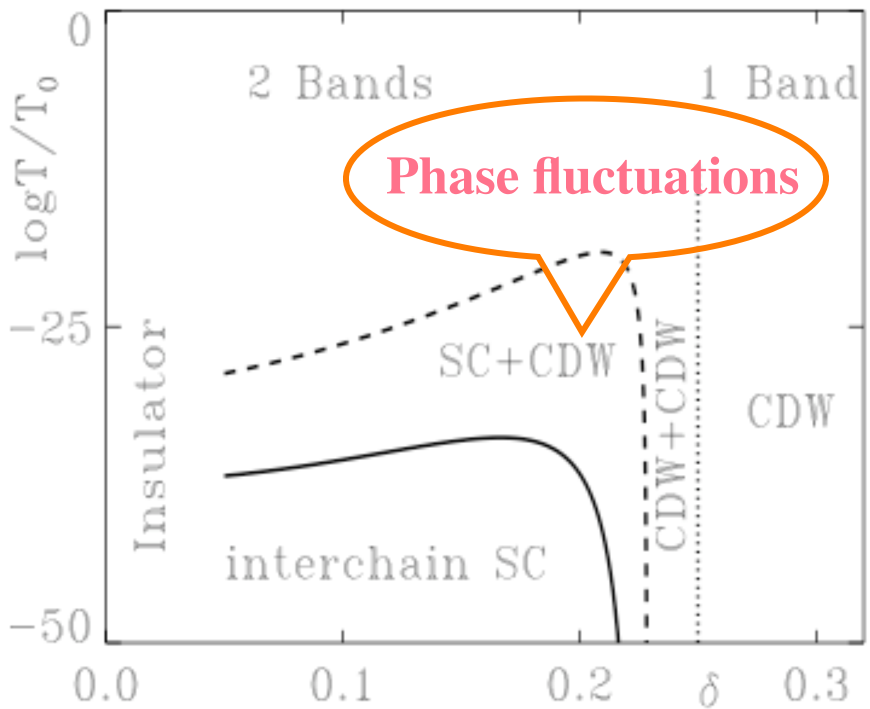
Large Doping: $\mathbf{v_2 \ll v_1}$

Half-filling: 7 Couplings diverge with a fixed ratio

"SO(8) Gross-Neveu Model"

Spin- & Charge Gaps $\propto \exp -\pi v_1/U$

Short-Range RVB insulating system with preformed Cooper pairs



U. Ledermann and K. Le Hur, PRB 61, 2497 (2000)

Doping:

Cooper pairs liberated

Symmetry S0(6)

Symmetry S0(5) with Coulomb term

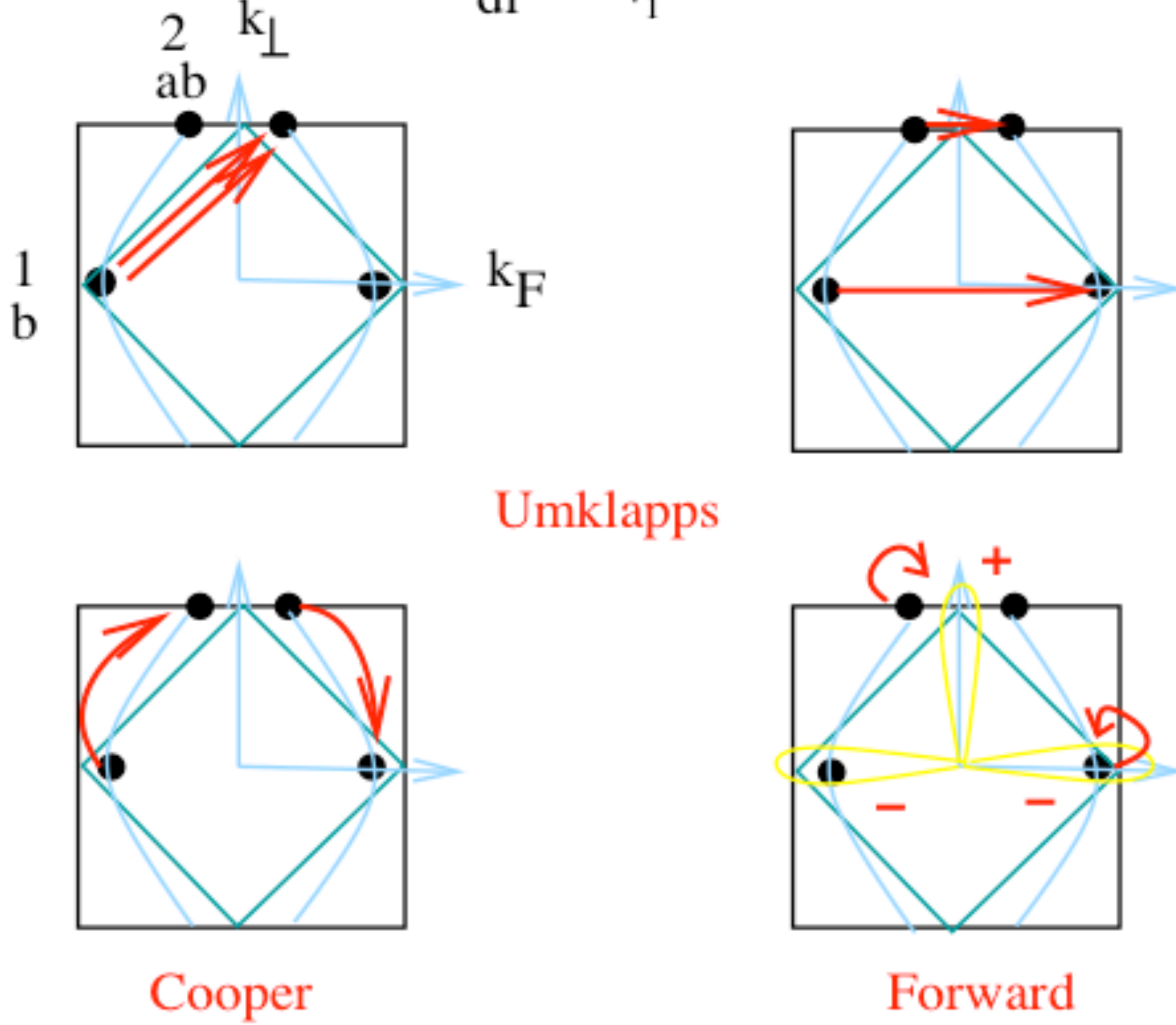
Lin-Balents-Fisher

Schulz

2D: Demler-Zhang

Some deep connection with the antinodal physics in 2D

$$\frac{dg_i}{dl} = \frac{1}{v_l}(\ldots)\, g_j g_k; \quad l = -\ln(T;\omega)$$



How to include the nodal direction?

Ladders: Route to High-Tc materials

2-leg ladder, Nice prototype system:

"doping RVB material, d-wave superconductivity"

(Rice *et al.* - Schulz - Balents and MPA Fisher - Emery-Kivelson...)

3-leg ladder, still better:

Focus both at nodal and antinodal points

Possibility of truncation of FS and significance in real space (holes in a d-RVB state)

U. Ledermann, K. Le Hur and T.M. Rice, PRB 62, 16383 2000

J. Hopkinson and K. Le Hur, PRB 69, 245105 2004

Truncation of the Fermi surface

$$\epsilon_j(k) = -2t\cos(k) - 2t_\perp \cos(k^y_{Fj})$$

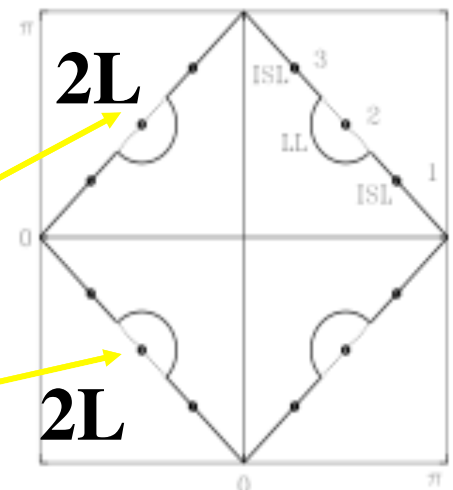
2D Mapping

Longitudinal Fermi momentum of the band j:

$$\mathbf{k}_{Fj} = \pi - \arccos\left[\frac{t_\perp}{t}\cos\left(\frac{\pi j}{N+1}\right)\right]$$

Corresponding transverse Fermi momentum:

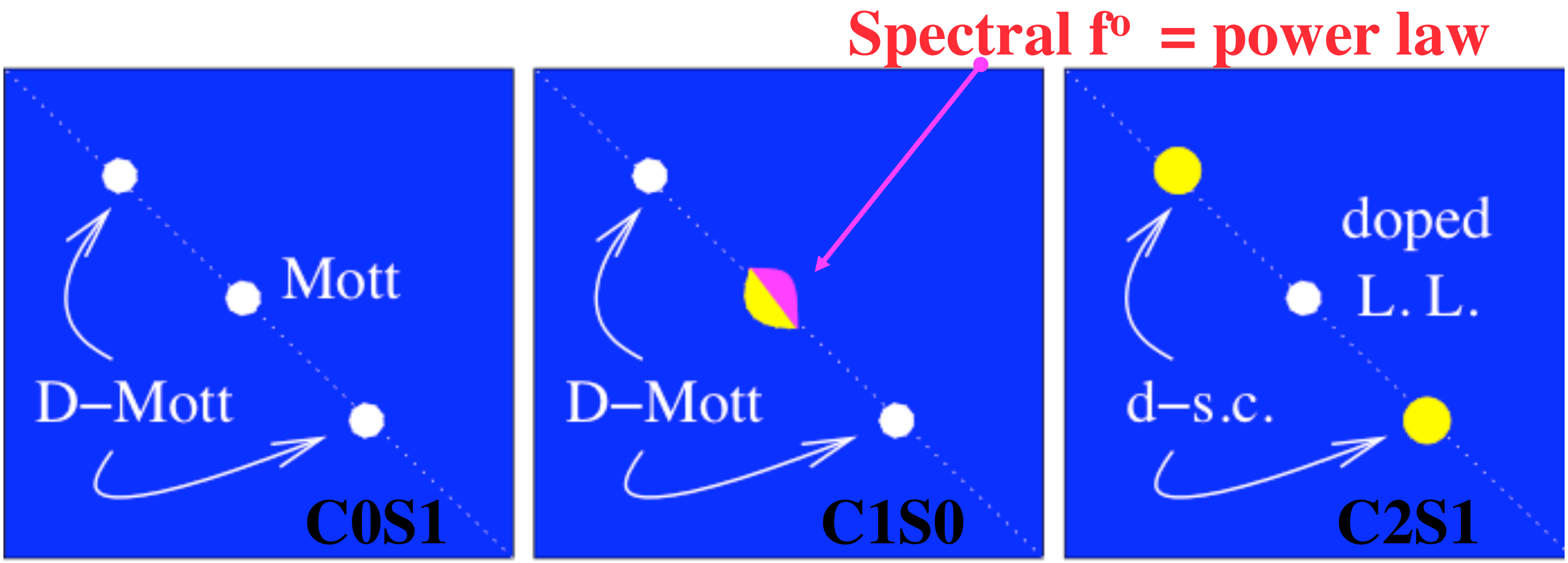
$$\mathbf{k}^y_{Fj} = \pm\frac{\pi j}{N+1}$$



for open boundaries in y direction

HOT spots and COLD spots

Gapful points and gapless points



Nodal liquid **D-wave SC**

& preformed pairs

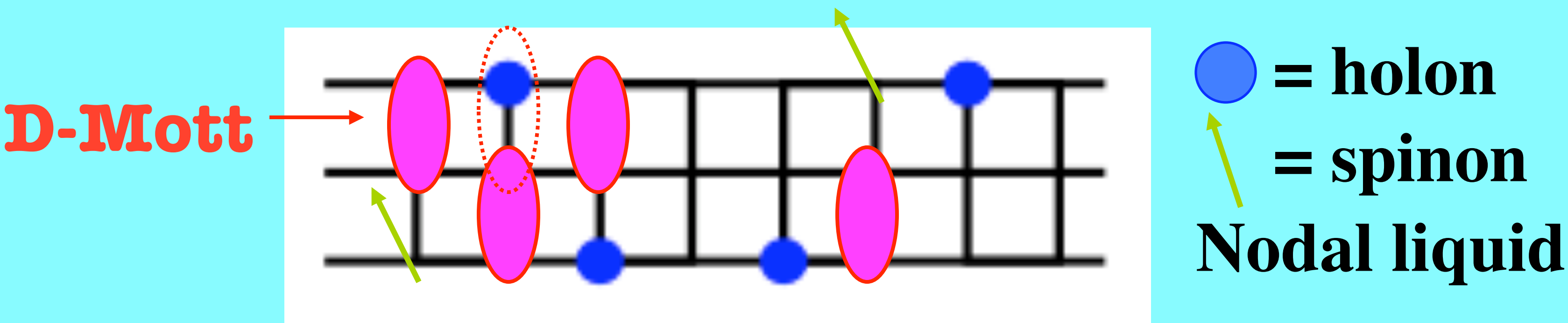
insulating *(2D, Balents et al.)*

U. Ledermann, K. Le Hur and T.M. Rice, PRB 62, 16383 2000

Strong U: T.M. Rice, S. Haas, M. Sigrist and F.C. Zhang, PRB 97

DMRG: White & Scalapino

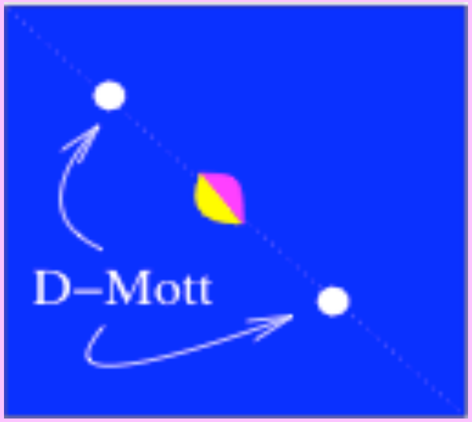
Picture in real space



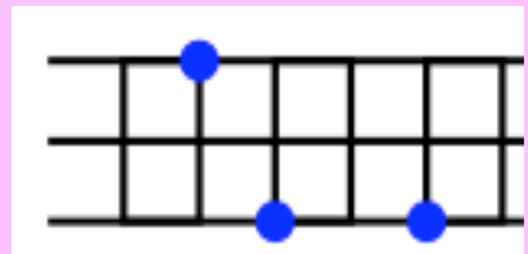
Conductº by holons at the edges: Cooper pairs frozen but resonating

Nodal liquid fragile against disorder
Karyn Le Hur, unpublished
following Giamarchi & Schulz

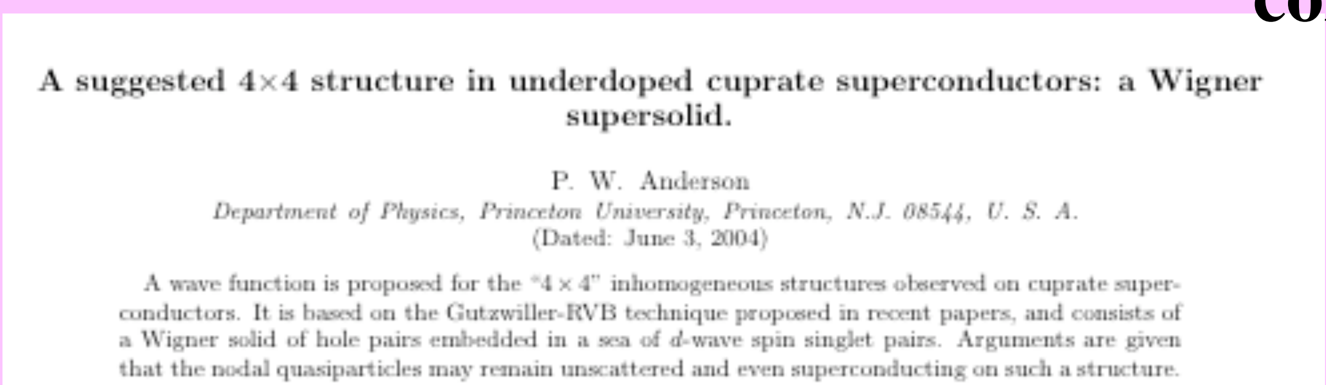
Effect of long-range repulsion?



Wigner crystal of holes?



cond-mat/0406038



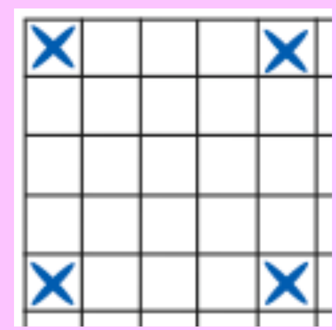
A suggested 4×4 structure in underdoped cuprate superconductors: a Wigner supersolid.

P. W. Anderson

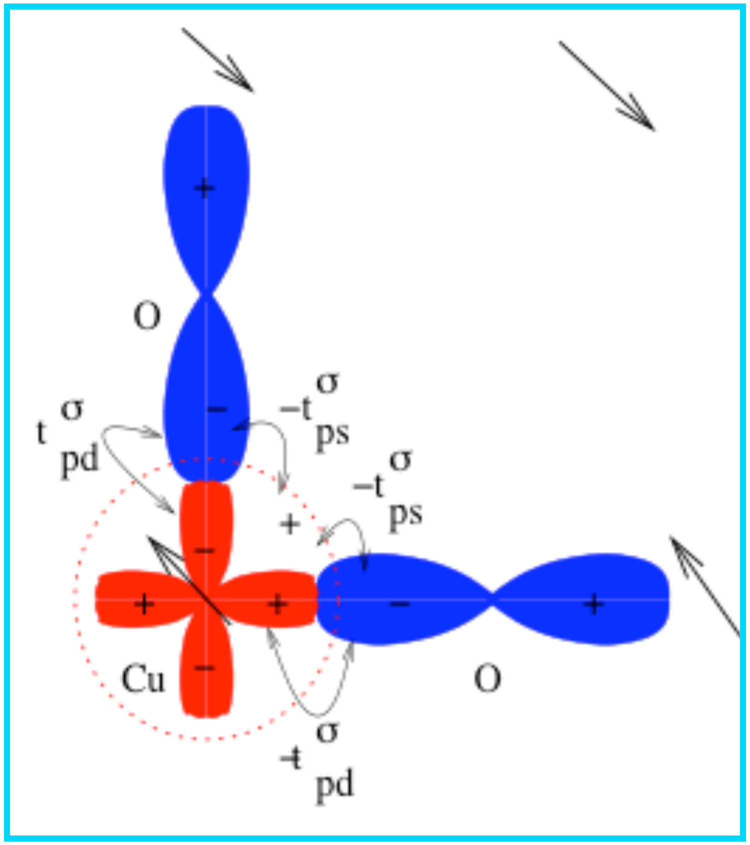
Department of Physics, Princeton University, Princeton, N.J. 08544, U. S. A.

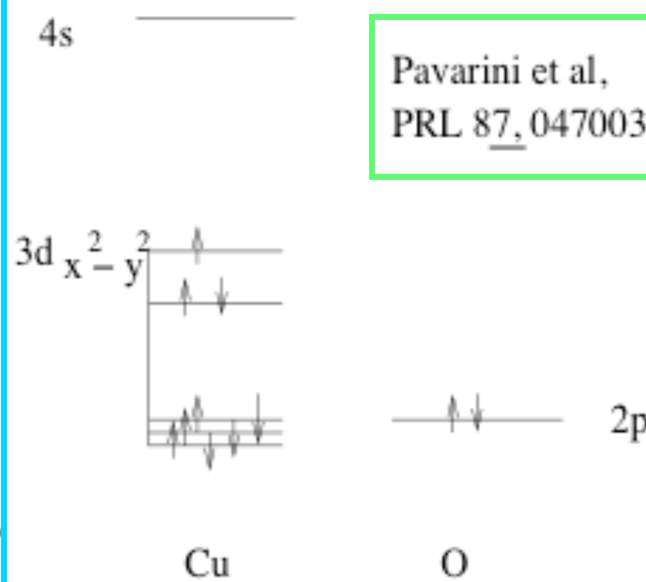
(Dated: June 3, 2004)

A wave function is proposed for the "4 × 4" inhomogeneous structures observed on cuprate superconductors. It is based on the Gutzwiller-RVB technique proposed in recent papers, and consists of a Wigner solid of hole pairs embedded in a sea of *d*-wave spin singlet pairs. Arguments are given that the nodal quasiparticles may remain unscattered and even superconducting on such a structure.



The need for ***frustrated*** hopping: Chemistry





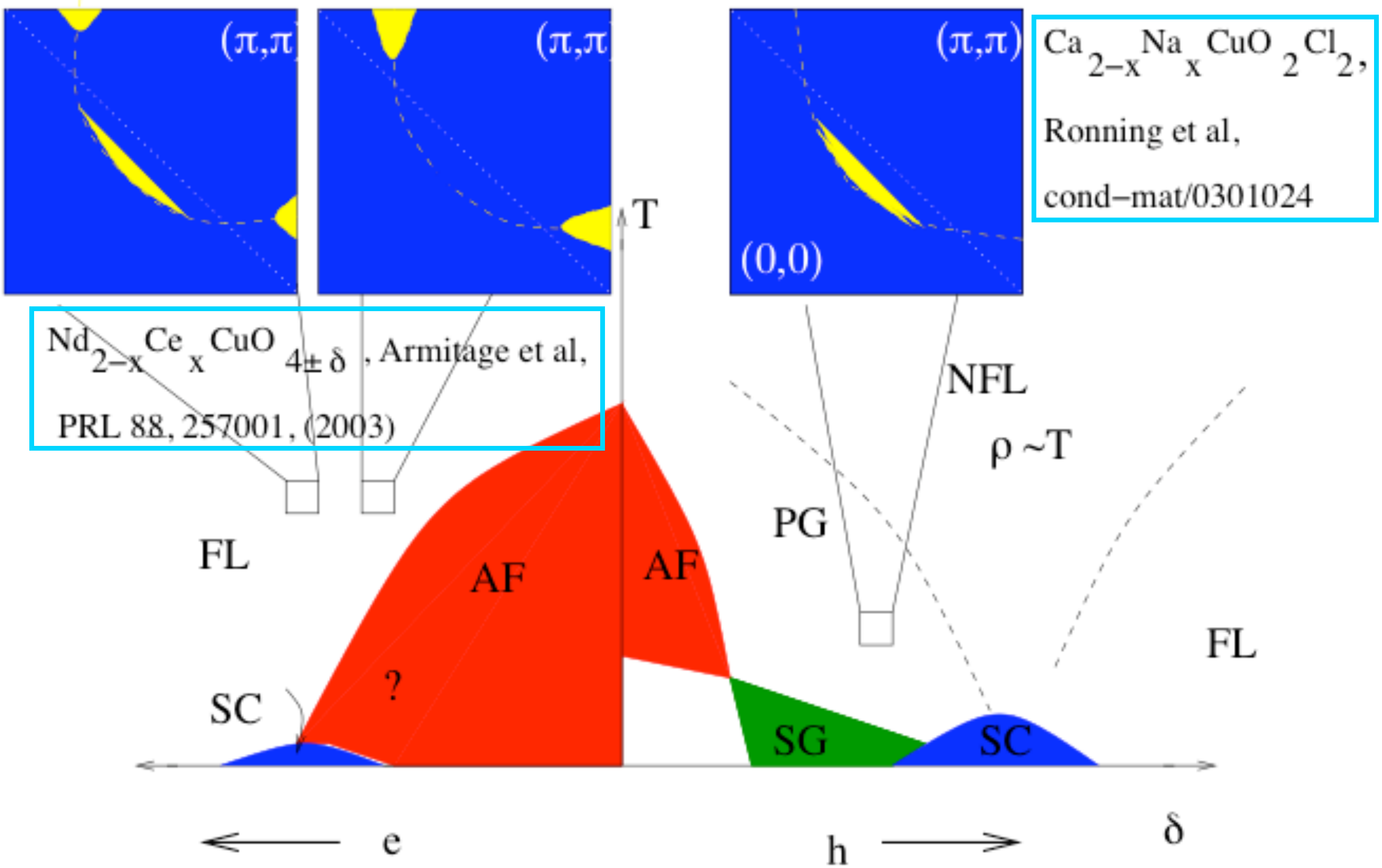
Pavarini et al,
PRL 87, 047003,(2001)

4 band $\Rightarrow$ 1 band + 4t'cos(k_x)cos(k_y) +..$\Rightarrow$curved F.S.

e↔h symmetry broken

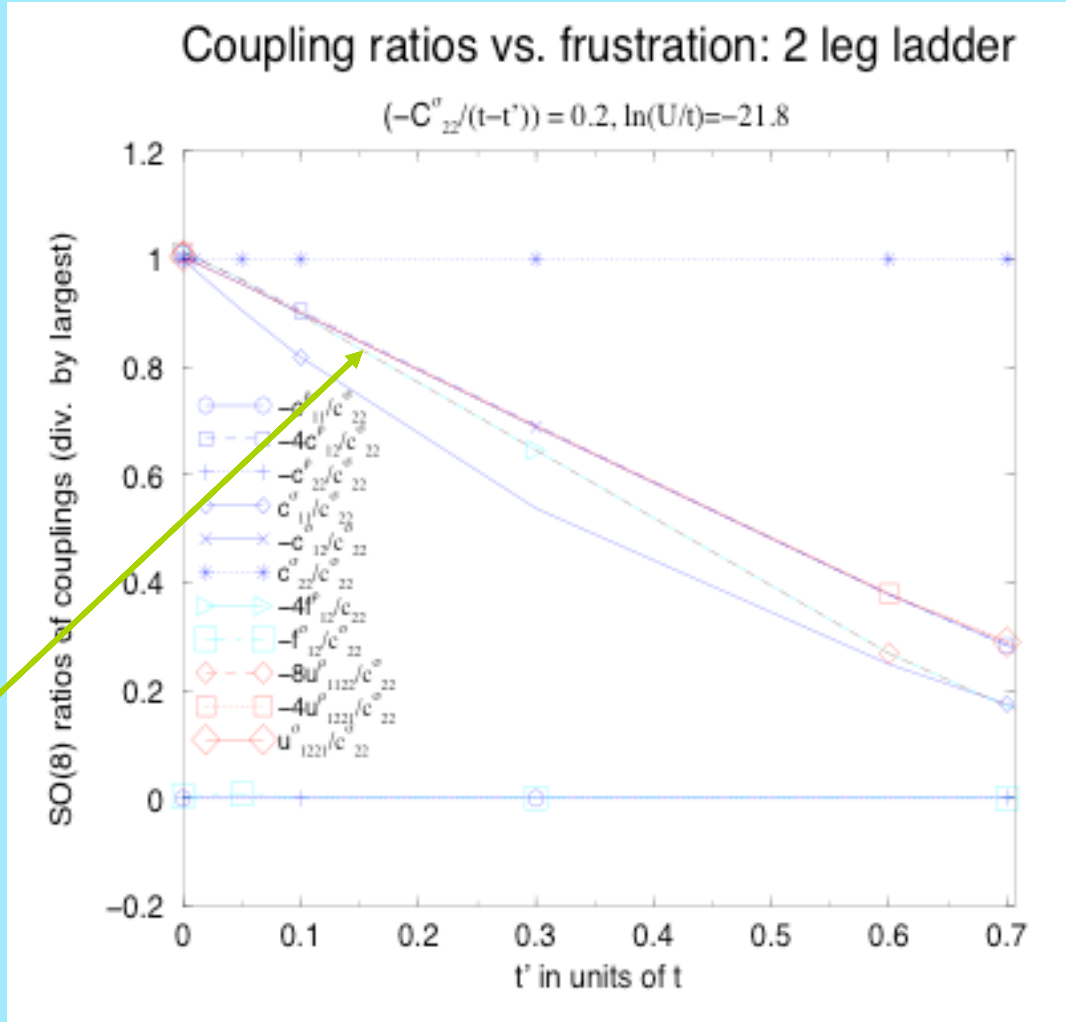
Opposite sign!

High-Tc: doped Mott insulators



Effect of t’ on the 2-leg ladder physics

John Hopkinson& K. Le Hur, PRB 69, 245105 2004

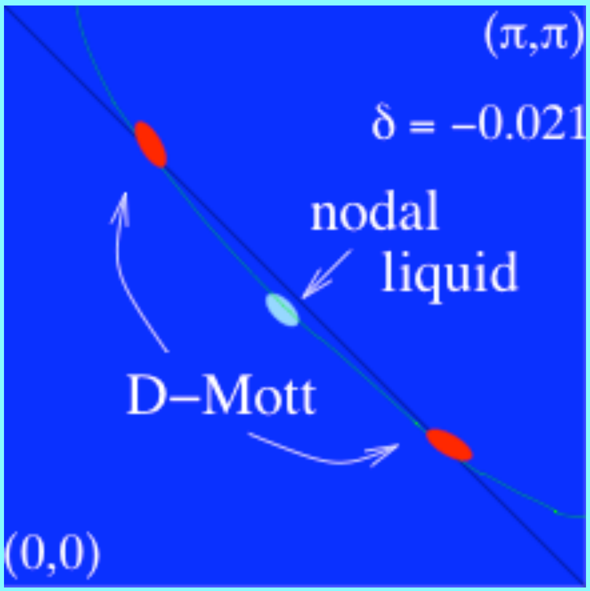


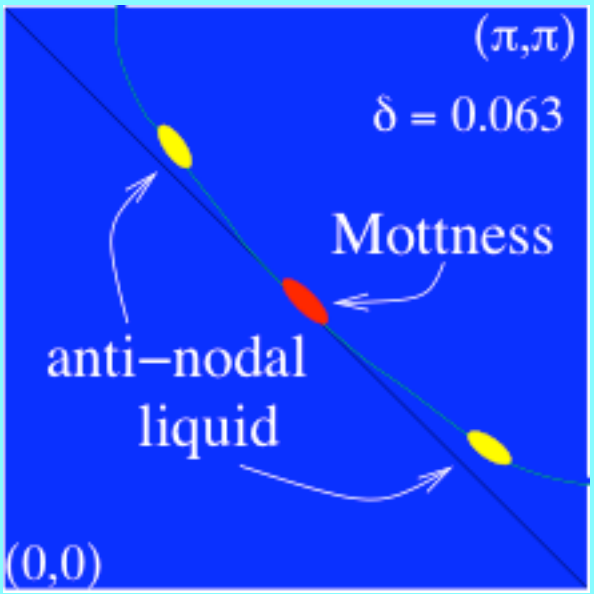
Link with 2D-patch Model…

Breaking S0(8) symmetry but still <u>charge and spin gaps</u>

Revisiting the 3-leg Hubbard ladder with t'

Possibility to separate umklapp processes!





Hole doping

Nodal liquid+D-Mott

Electron doping

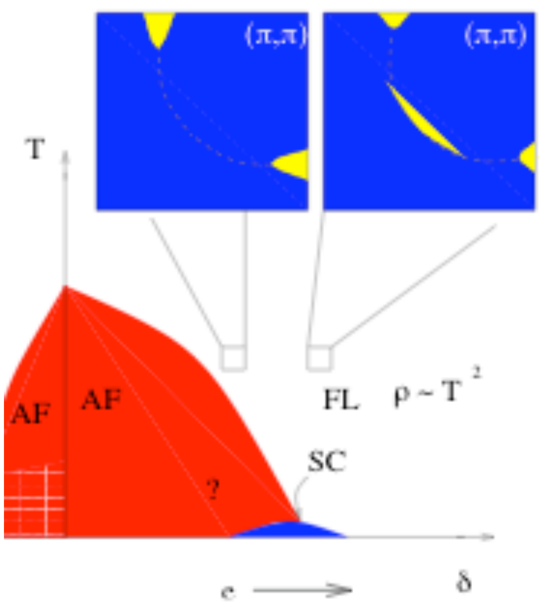
Nodal insulator+ d-wave pairing

Interpretation in real space?

Main message

Hole doped: pseudogap = d-RVB state from corners
short-range magnetism

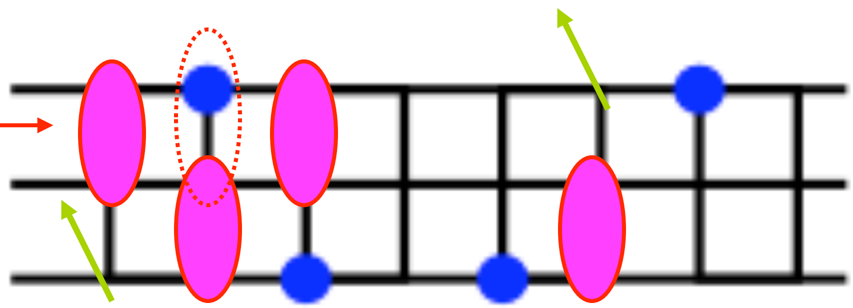
Electron doped: pseudogap = Mottness at the nodes
dominant SDW



effect on low-T thermal conductivity for low doping on SC phase

Pictures in real space

D-Mott

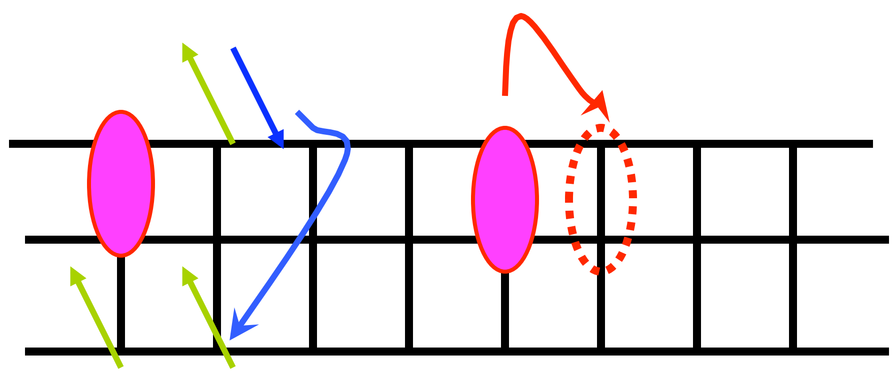


= holon

= spinon

Nodal liquid

Conductº by holons at the edges: Cooper pairs frozen but resonating



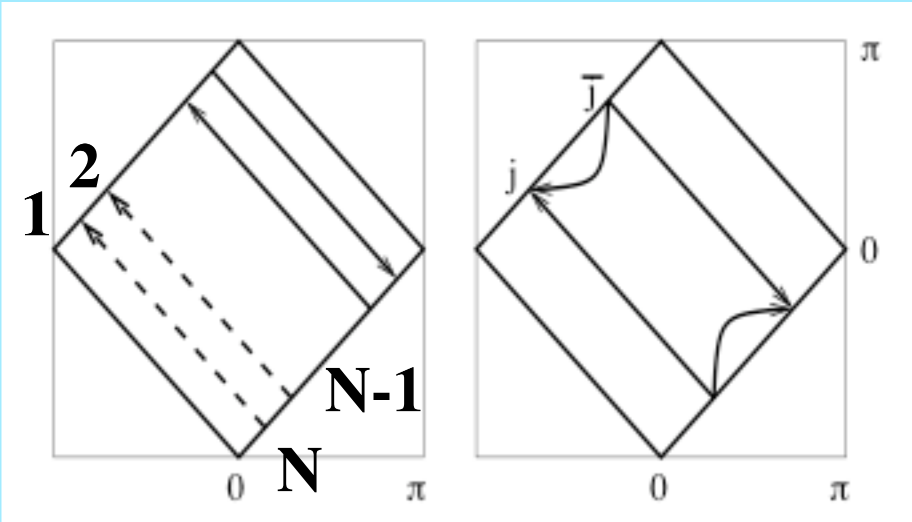
Nodal Mott gap

Electron resonating on outer chains

Electron doped case

Cooper pairs conducting

Close to half-filling: Antiferromagnetism



Urs Ledermann, PhD

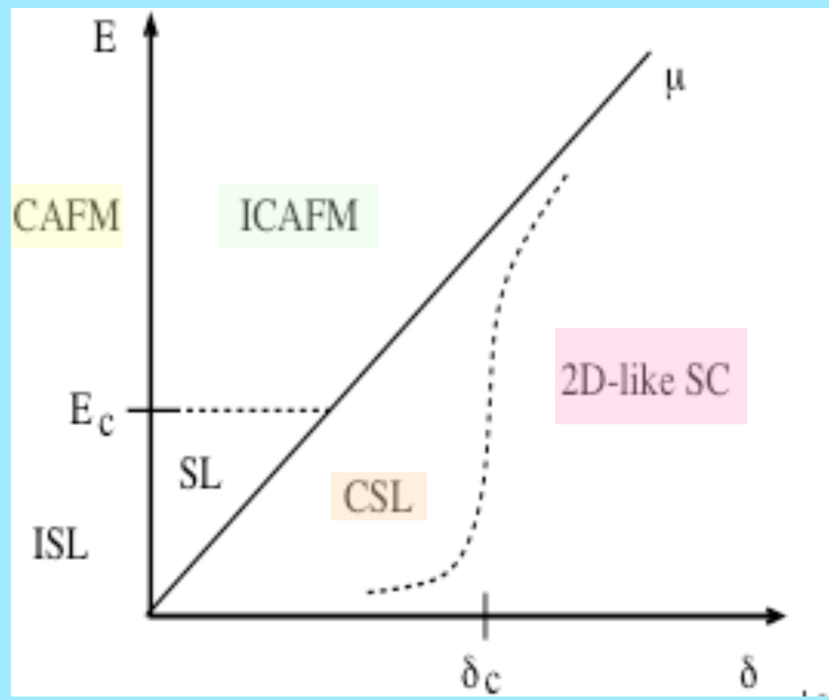
Umklapps on whole FS

Uniform Mott gap
Long-range AF at T=0

Spin gap suppression for N even

Doping = Decrease N

Expansion of phase coherence towards antinodal points



3-leg ladder: beautiful prototype system

Truncated Fermi surface: nodal- liquid or Mott gap

Breaking p-h symmetry with t' hopping term

Many open questions in 2D:

2D: nodal liquid or Fermi arcs above Tc?

Thermal conductivity: d-wave symmetry above Tc

ARPES: Fermi arcs

Recent efforts from theory to understand high-Tc

TPSC approach (Tremblay)

Cluster DMFT (Kotliar)

Variational Quantum Monte Carlo (Paramekanti, Trivedi, Randeria)

3-patch model in 2D?

N-leg ladder?

- N band model with N Fermi velocities $\mathbf{v}_j$:

At half-filling: $v_j = v_{\bar{j}} = 2\sqrt{t^2 - \{t_\perp \cos[\pi j/(N+1)]\}^2}$

$$\bar{j} = N + 1 - j$$

$v_1 = v_N < v_2 = v_{N-1} < \ldots.$

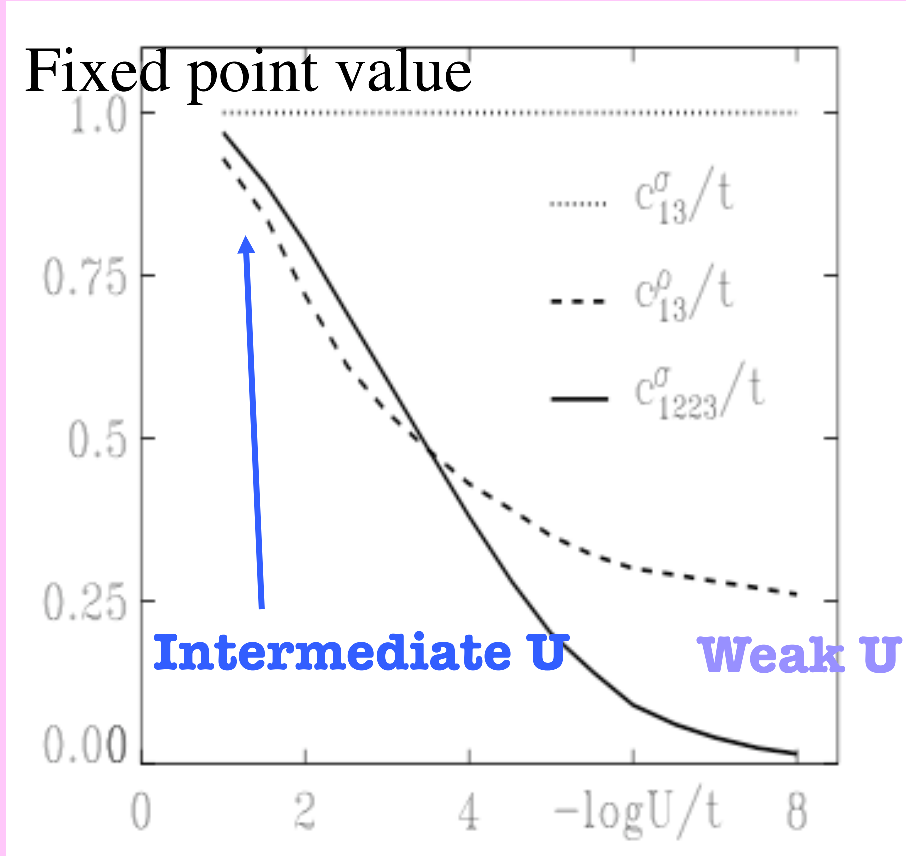
These Fermi velocities will lead to a *hierarchy* of energy scales

hierarchy of energy-scales (insulating band pairs) $\mathbf{T}_j \sim e^{-v_j/U}$

Band pairs flow towards a two-leg ladder
Rigorous decoupling at weak U

U. Ledermann, K. Le Hur, and T.M. Rice PRB 62, 16383 2000

21 coupling constants!



• **N even: Spin gap**

"disordered d-wave superconductor": 2-chain

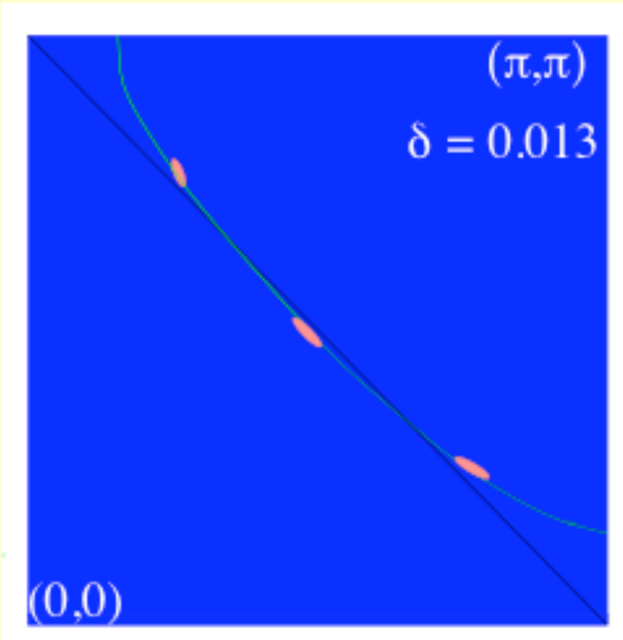
• **N odd: No spin gap**

"deconfined spinons": Insulating Single chain

Even-Odd effect like for spin ladders

$SrCu_2O_3$ Spin gap / $Sr_2Cu_3O_5$ No spin gap

Very-close to half-filling



3-band umklapp relevant: tendancy to uniform Mott gap

Difficult to tackle theoretically
Precursor of AF in 2D

Pathology of our weak-U treatment: umklapps relevant only for specific dopings
Larger U: Variational Quantum Monte Carlo, DMRG

Expectation in 2D with t'