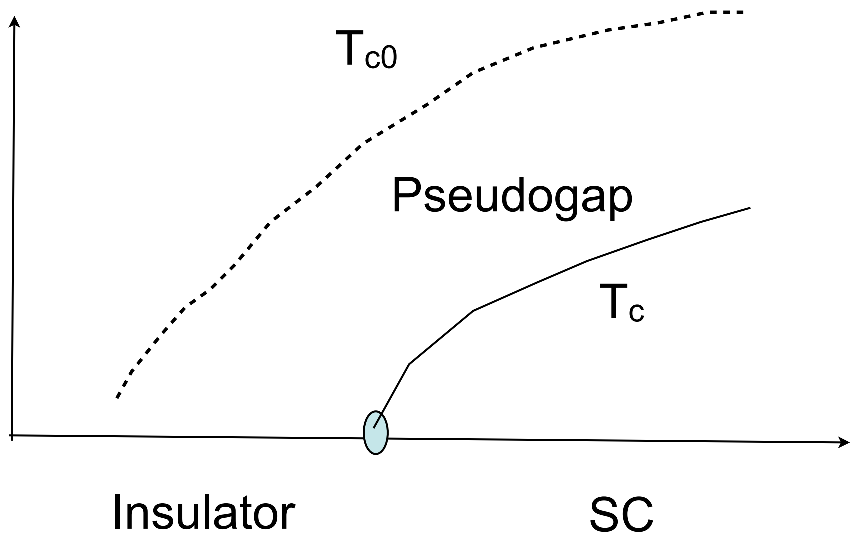
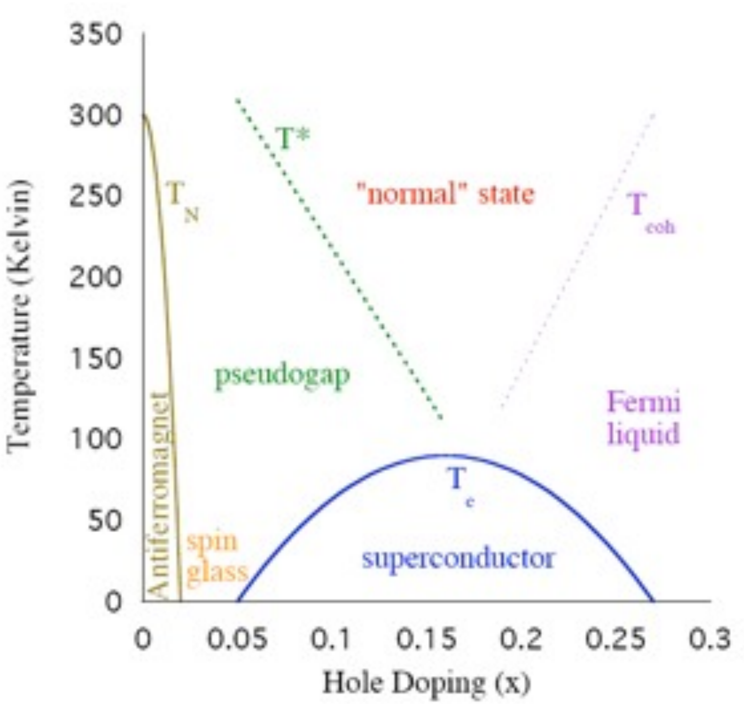
Superconductor-Mott insulator transitions

T. Senthil (MIT)

A pseudogap in density of states is a generic feature of phase fluctuation driven superconductor-insulator transitions.



Pseudogap versus PSEUDOGAP



Most famous pseudogap:
Underdoped cuprates above Tc.

?? Is this just the same phenomenon as at familiar superconductor-insulator transitions??

Some differences

Two striking differences:

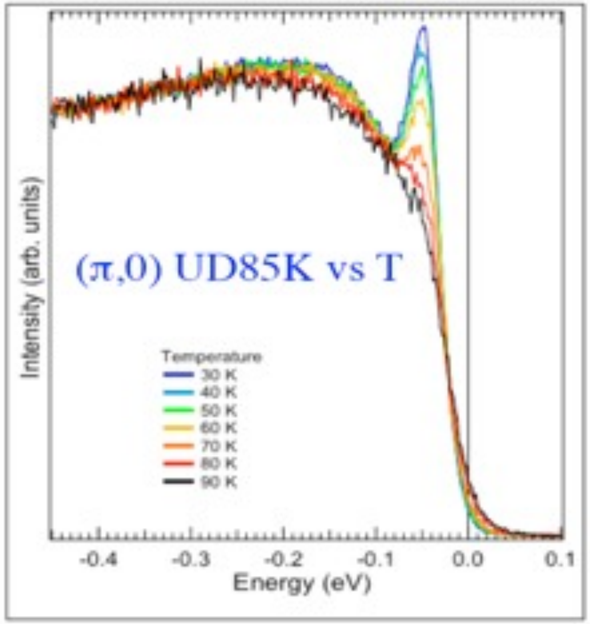
1. Tc in underdoped cuprates is not just a phase disordering transition of Cooper pairs.

Also lose single particle coherence.

2. Local fluctuating orders other than superconductivity rear their head.

Example: Short range antiferromagnetism, ...

(Sound bite: ``Competing order")



Campuzano et al, Shen et al, 1990s

Some differences

Often ignored but clearly very important!

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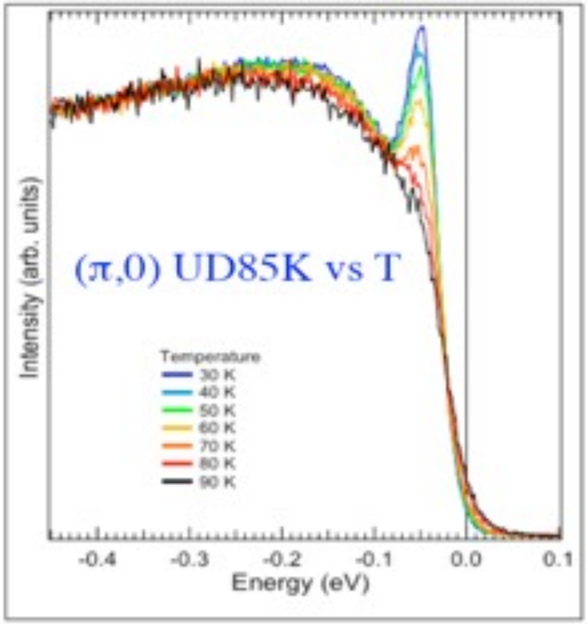


Campuzano et al, Shen et al, 1990s

Most fundamental difference

Suppression of phase stiffness due to proximity to Mott insulator.

Familiar theory of superconductor- insulator transitions:
Insulator is band/disordered insulator.

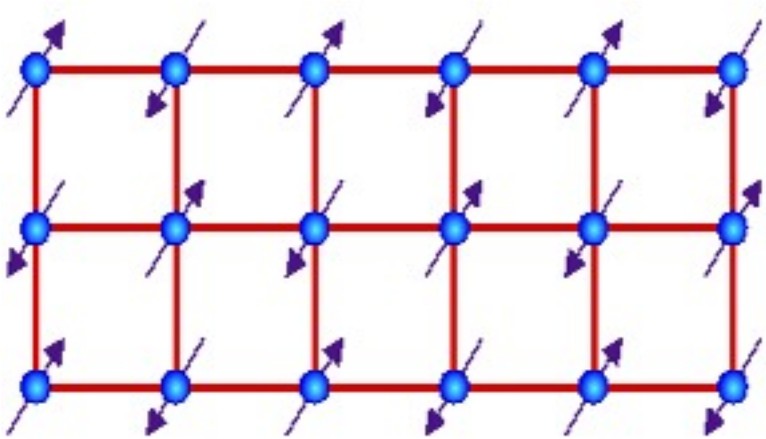
To confront cuprates, must study SC- Mott insulator transitions.

Other examples: Organic superconductors

Pressure-tuned superconductor-Mott insulator transitions at fixed filling (of one electron/site).

First complication: magnetism

In the cuprates and many organics, Mott insulator has AF long range order.



Must understand interplay of superconductivity with Mott localization and the resulting antiferromagnetism.

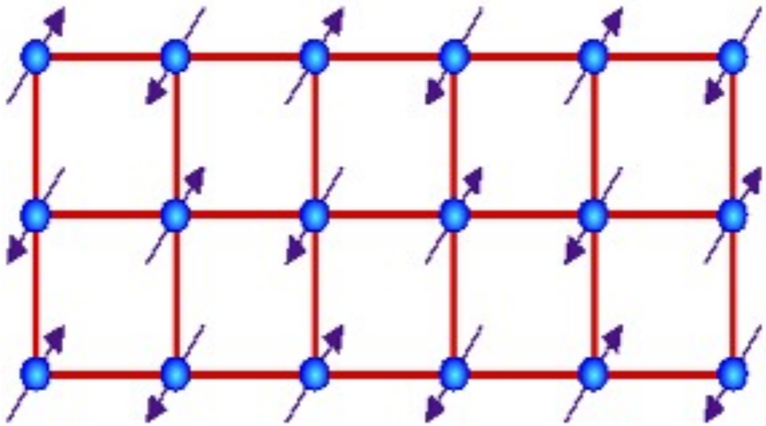
Hard problem: to get some intuition broaden to study various kinds of Mott insulators, not necessarily only antiferromagnets

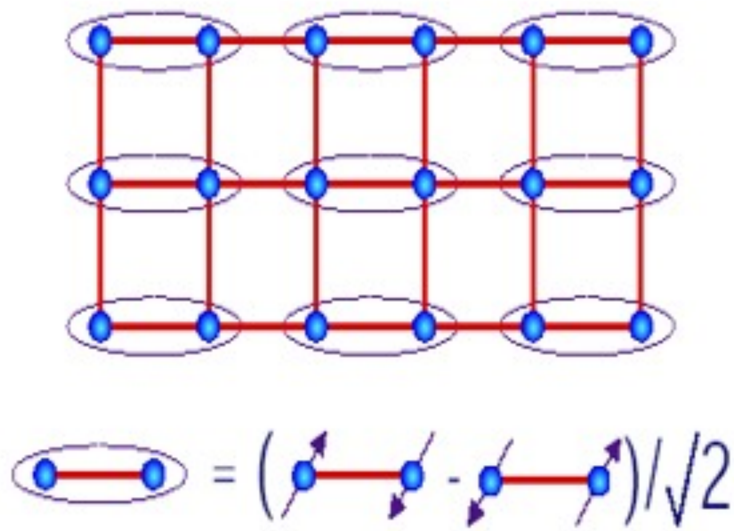
Varieties of Mott insulators

Mott insulators typically break symmetry at low-T.

Most common: Antiferromagnetism

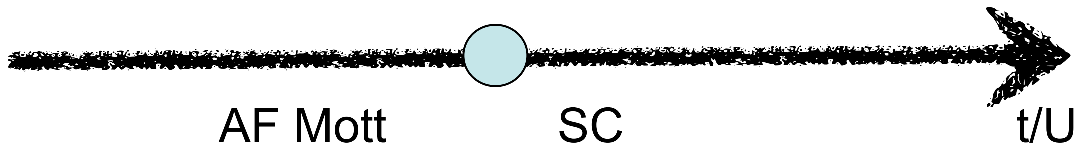
Other broken symmetry states: Spin-Peierls/valence bond solid.





Symmetry-preserving Mott insulators: Quantum spin liquids (resonating liquid of valence bonds).

Landau theory and the SC-Mott transition



Neel order breaks
spin rotation symmetry

SC order breaks charge U(1)
symmetry

Landau theory: Two unrelated order parameters;
No direct second order transition.

Transition either first order, or goes through intermediate phase.

Consequences of a first order transition

First order => phase separation, possibly frustrated by Coulomb repulsion.

``Messy” phenomena: Sensitivity to disorder, stripe and other inhomogeneities.

Strong first order - no precursor fluctuations associated with transition in either phase.

However ....

Simplicity at intermediate scales

Intermediate scale physics in SC (not asymptopia) knows about impending Mott transition => not too strongly first order.

Cuprates: Homogenous stoichiometric underdoped cuprates exist (eg $YBa_2Cu_4O_8$) that show a pseudogap and other properties that are affected by interplay between Mott physics and superconductivity.

Organics: Suppression of superconductivity, pseudogap seen near the Mott transition

=> precursor effects of the Mott transition; not so strong first order transition.

Focus on intermediate scale physics

Questions

1. Should we even trust Landau theory?

Are superconductor-AF/spin Peierls Mott insulator transitions allowed to be second order theoretically?

2. What if the Mott insulator is a quantum spin liquid?

Can we study the superconductor-Mott transition without complications of additional broken symmetries in the insulator?

3. Lessons for pseudogap physics in cuprates?

Questions

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Landau-forbidden quantum criticality

Senthil et al, Science 2004; PR B 2004

Many examples of quantum phase transitions where the Landau-Ginzburg-Wilson paradigm fails.

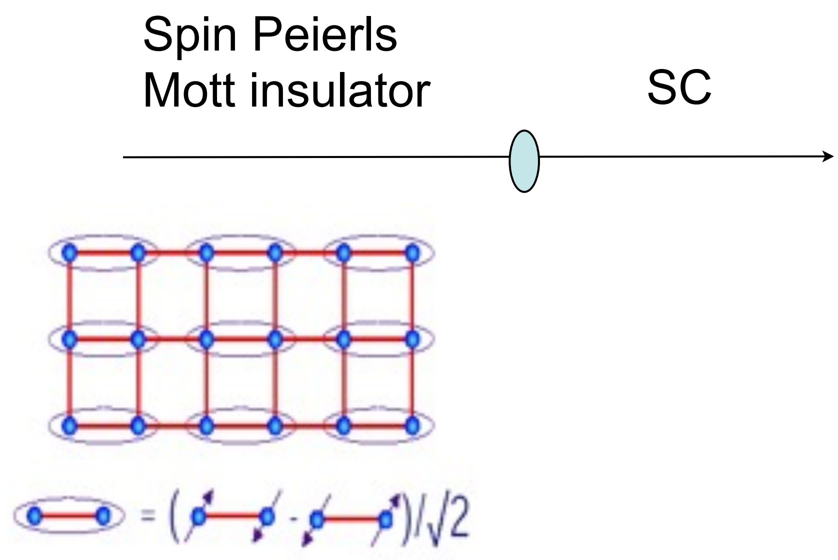
Landau-forbidden second order quantum phase transitions between unrelated order parameters possible in several cases.

Concrete example:

Gapped SC - spin-Peierls Mott insulator at half-filling on square lattice.

Critical theory - NOT in terms of order parameter fluctuations but in terms of exotic degrees of freedom with fractional charge (and associated gauge fields).

``Deconfined quantum criticality"



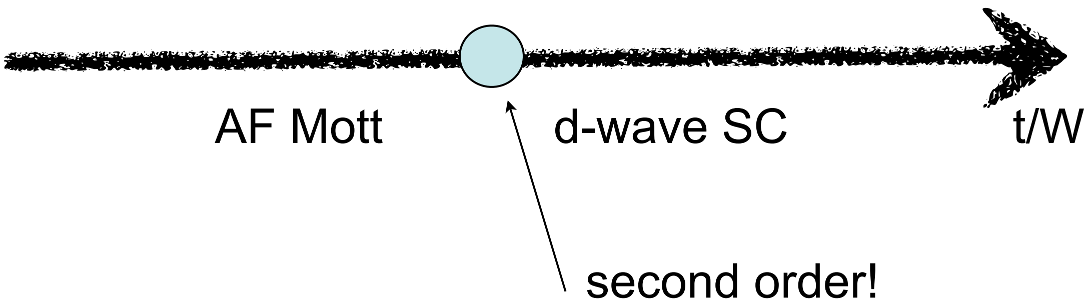
Second order SC - AF Mott transition?

VOLUME 77, NUMBER 22 PHYSICAL REVIEW LETTERS 25 NOVEMBER 1996

Quantum Transition between an Antiferromagnetic Mott Insulator and $d_{x^2-y^2}$ Superconductor in Two Dimensions

F. F. Assaad,[1] M. Imada,[2] and D. J. Scalapino[1]
[1]*Department of Physics, University of California, Santa Barbara, California 93106-9530*
[2]*Institute for Solid State Physics, University of Tokyo, 7-22-1 Roppongi, Minato-ku, Tokyo 106, Japan*
(Received 4 September 1996)

Numerical study of a specific extended Hubbard model on square lattice at half-filling

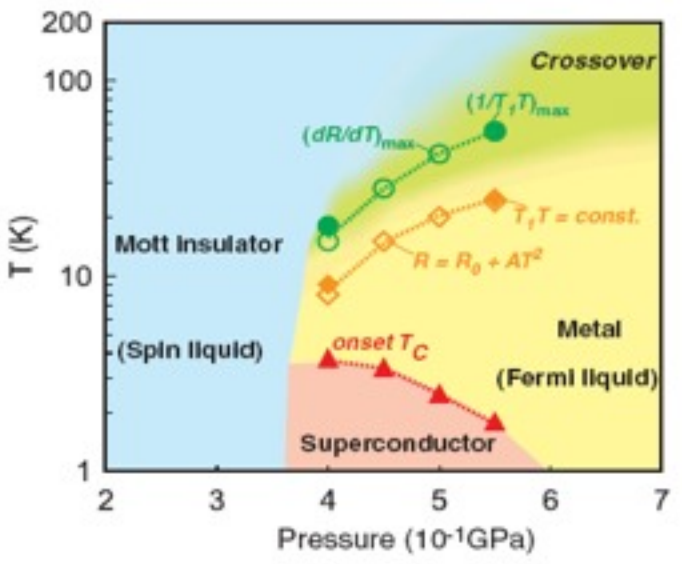


No clarification so far!

``Matter of principle" question of whether SC-AF Mott transition can be generically second order remains open!

SC- spin liquid Mott insulator transitions

Substantial theoretical progress possible if Mott insulator is a certain type of quantum spin liquid.



Kanoda group, 2003-present

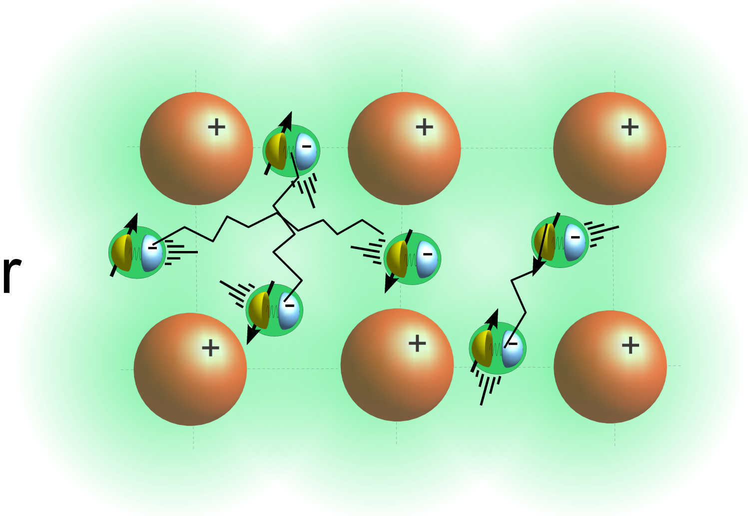
To obtain a quantum spin liquid from a SC, freeze out charge motion but retain spin correlations of SC.

Describe insulator as Gutzwiller projected SC.

SC-such spin liquid transitions can be second order; properties well understood.
(TS, Fisher, 1999; Paramekanti, Zhao, 2007).

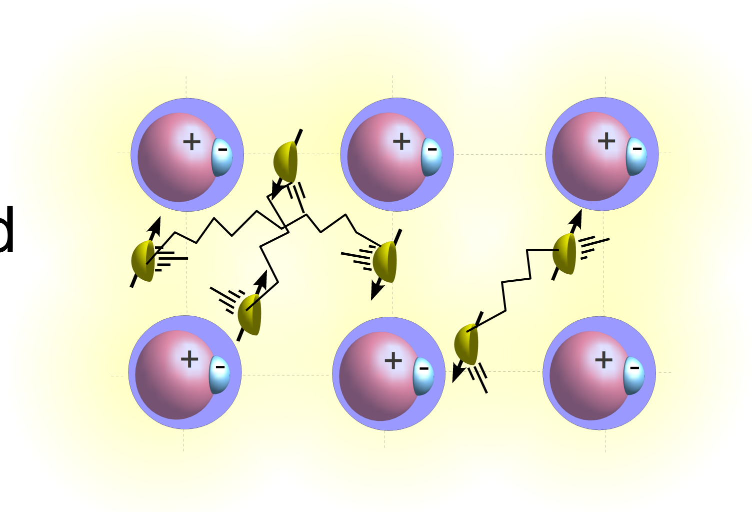
Picture of Mott transition

Superconductor



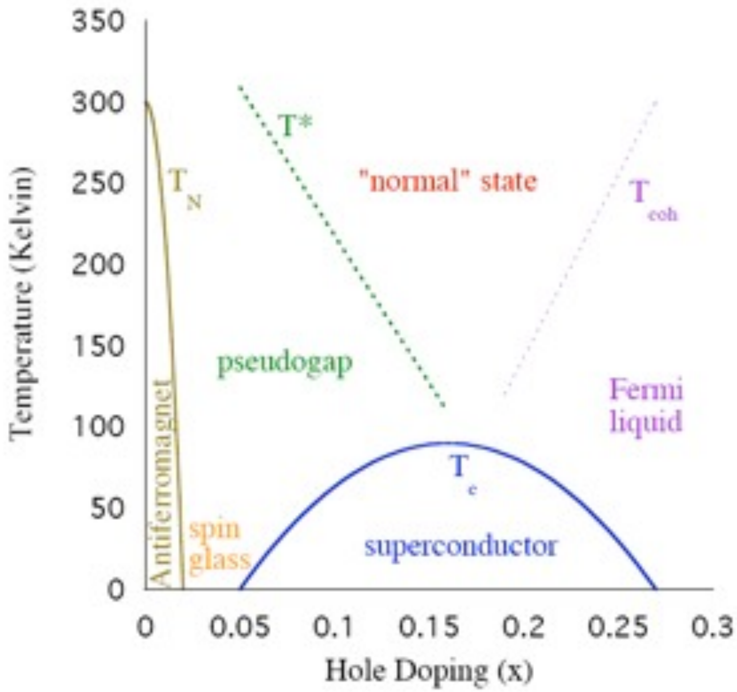
Paired electrons swimming in sea of +vely charged ions

Mott spin liquid near SC



Electron charge gets pinned to ionic lattice while paired spins continue to swim freely.

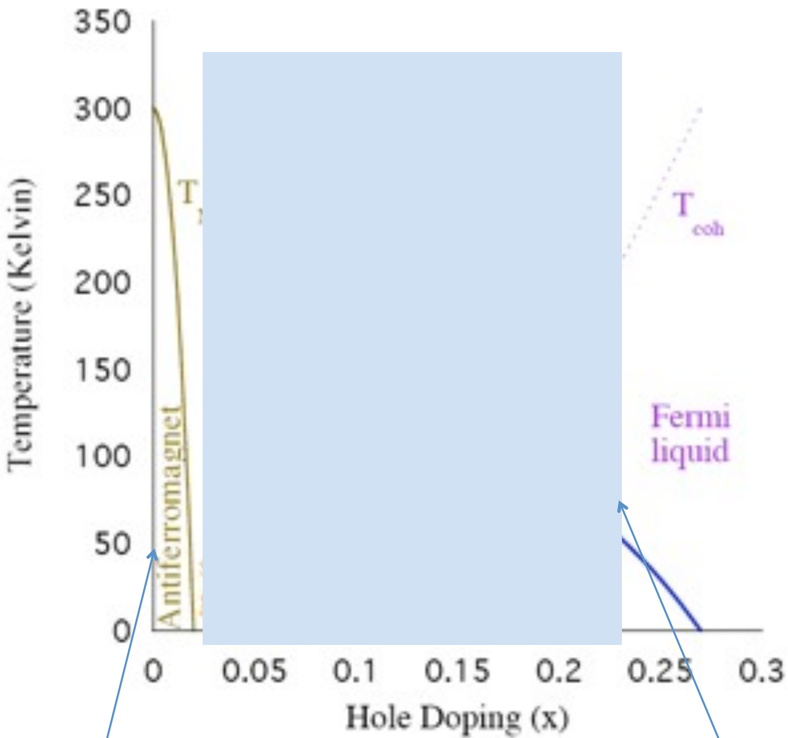
Back to cuprates



Description of pseudogap necessarily entangled with bigger fundamental issue of Mott metal-insulator transition.

SC- AF Mott transition is a low energy consequence of a Fermi liquid - Mott insulator transition.

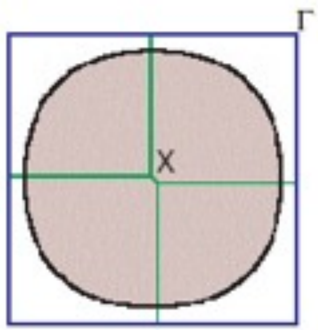
High Tc cuprates: how does a Fermi surface emerge from a doped Mott insulator?



Evolution from Mott insulator to overdoped metal : emergence of large Fermi surface with area set by usual Luttinger count.

Mott insulator:
No Fermi surface

Overdoped metal:
Large Fermi surface



ADMR, quantum oscillations (Hussey), ARPES (Damascelli,....)

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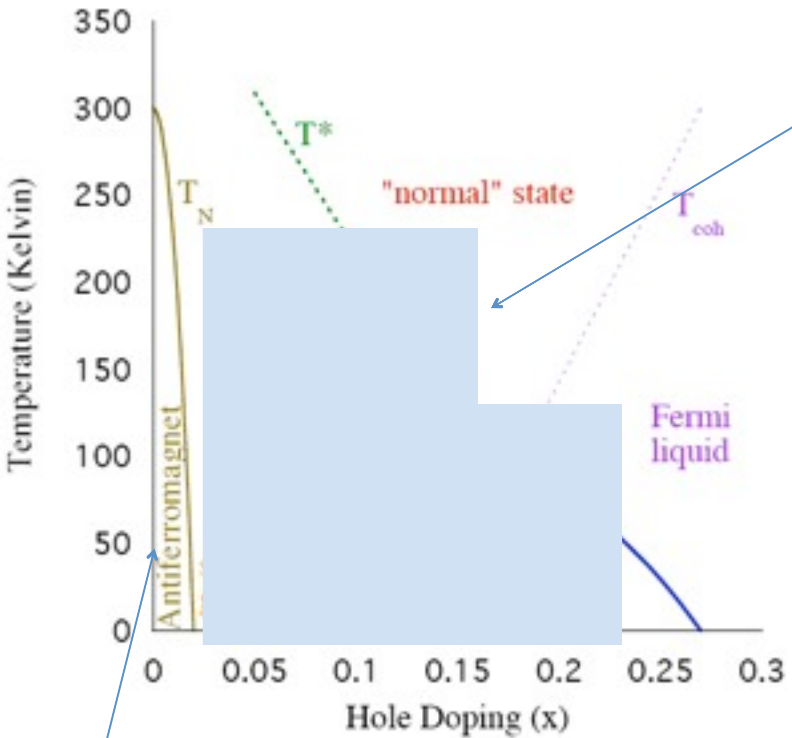

Large gapless Fermi surface present even in
optimal doped strange metal albeit without
Landau quasiparticles .

Mott insulator:
No Fermi surface

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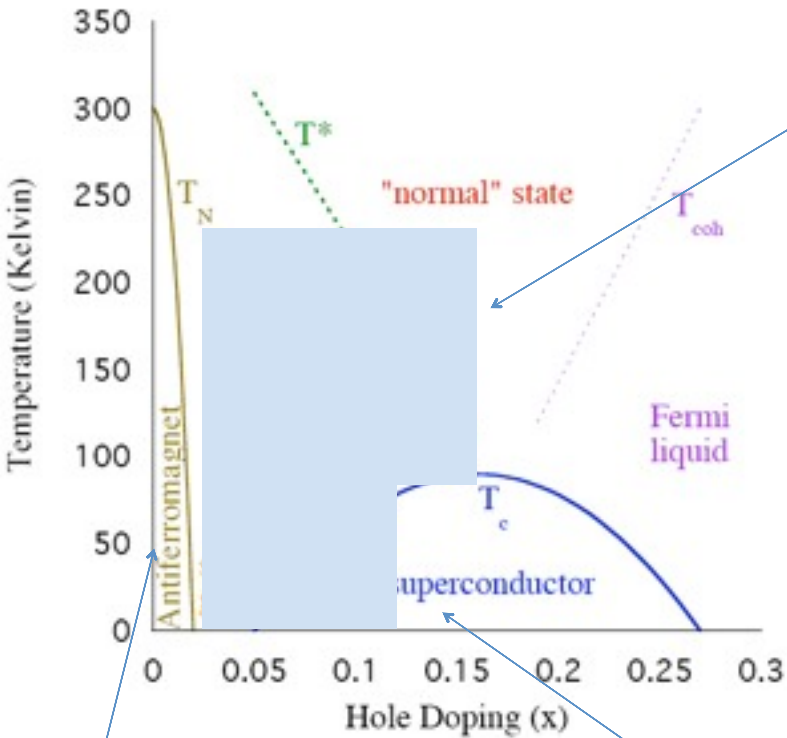

Large gapless Fermi surface present also in
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Mott insulator:
No Fermi surface

In SC state, the d-wave gap is centered on the large Fermi surface down to low doping.

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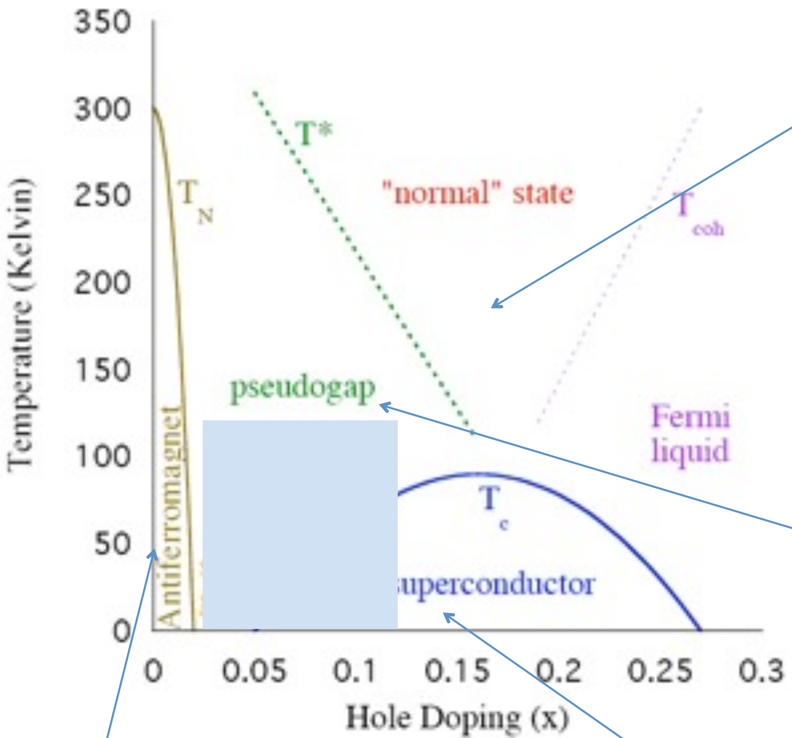


Large gapless Fermi surface present also in
optimal doped strange metal albeit without
Landau quasiparticles .

Even in the pseudogap regime the minimum gap features (nodal Fermi arcs, antinodal gaps) in ARPES are located at large Fermi surface!

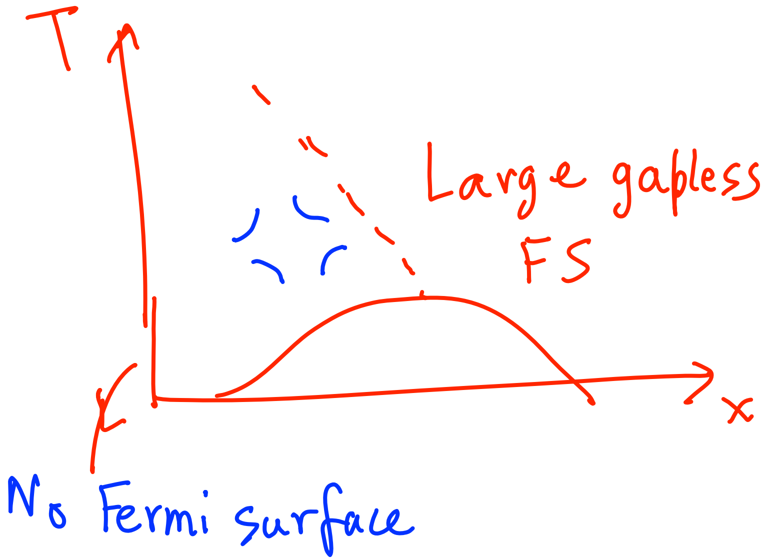
Mott insulator:
No Fermi surface

In SC state, the d-wave gap is centered on the large Fermi surface down to low doping.

A basic question

Quite generally, large Fermi surface visible (at least at short time scales) already in underdoped.

How should we understand the emergence of the large Fermi surface in a doped Mott insulator?



Theory: How does the Fermi surface die?

Recent progress in spin liquid based theories of the cuprates

TS, Lee, 2009

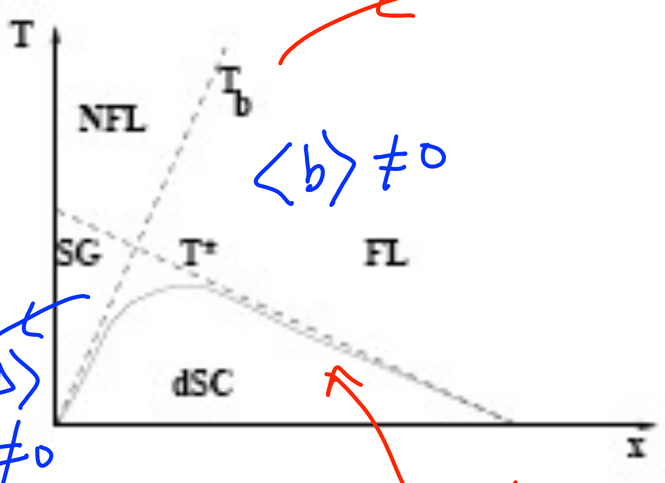
Old idea: deal with doped cuprate as a doped spin liquid – worry about magnetism later.

RVB ``slave boson" theory: represent electron operator as

$$c_{i\alpha} = \underbrace{b_i^\dagger}_{\text{holon}} \underbrace{f_{i\alpha}}_{\text{spinon}}$$

``Standard” slave boson RVB theory of doped Mott insulator

coherence scale $T_{coh} \approx$ "Higgs" condensation of b



(a)

$\langle b \rangle \neq 0$

$\langle \Delta \rangle \neq 0$

$\langle b \rangle \neq 0, \ \langle \Delta \rangle \neq 0$

Old problem: T_{coh}, T_c far too high.

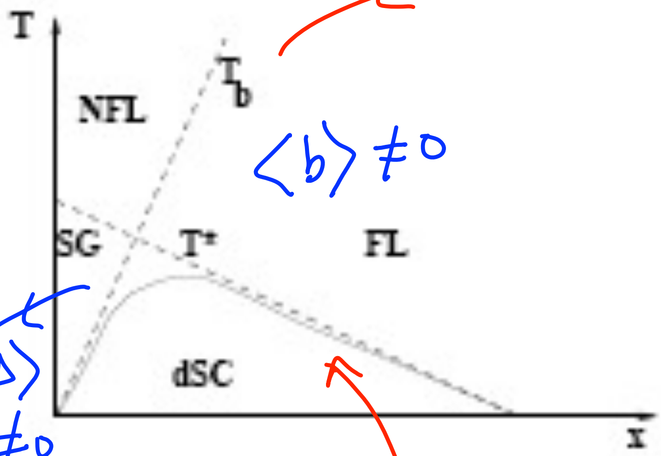
Fluctuations gauge theory;

$\Delta \sim f^\dagger f^\dagger$

Describe as doping a spin liquid Mott insulator

``Standard" slave boson RVB theory of doped Mott insulator

coherence scale $T_{coh} \simeq$ "Higgs" condensation of b



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$\Delta \sim f^\dagger f^\dagger$

Old problem: T_{coh}, T_c far too high.

Fluctuations: Gauge theory;

Landau-damped dynamics for transverse gauge field

$$S_{eff}[a] = \int d^2q \, d\omega \left(\frac{|\omega|}{q} + q^2 \right) |a(q\omega)|^2 \quad (\text{at high-}T)$$

True coherence scale: Anderson is different

(TS '08)

"Naive" coherence scale: Higgs condensation of b

For $T \ll T_b$, $S_{eff}[a] \simeq \int_{q,\omega} \left(\frac{|\omega|}{q} + q^2 + \rho_{bs} \right) |a(q,\omega)|^2$

phase stiffness of b $\sim O(T_b)$

Landau-damped dynamics

$\Rightarrow$ Anderson "plasmonization" scale $\approx \rho_{bs}^{3/2} \ll T_b$

$\Rightarrow$ Anderson differs from Higgs parametrically !

True coherence scale: Anderson is different

(TS '08)

Intermediate energies – holons "condensed" but a_μ "gapless"

$\Rightarrow$ Electrons strongly scattered by a_μ fluctuations

True coherence scale = Anderson scale

$$T_{coh} \sim T_b^{3/2} \ll T_b \quad (= \text{"Higgs" scale})$$

"INCOHERENT FERMI LIQUID" (IFL)

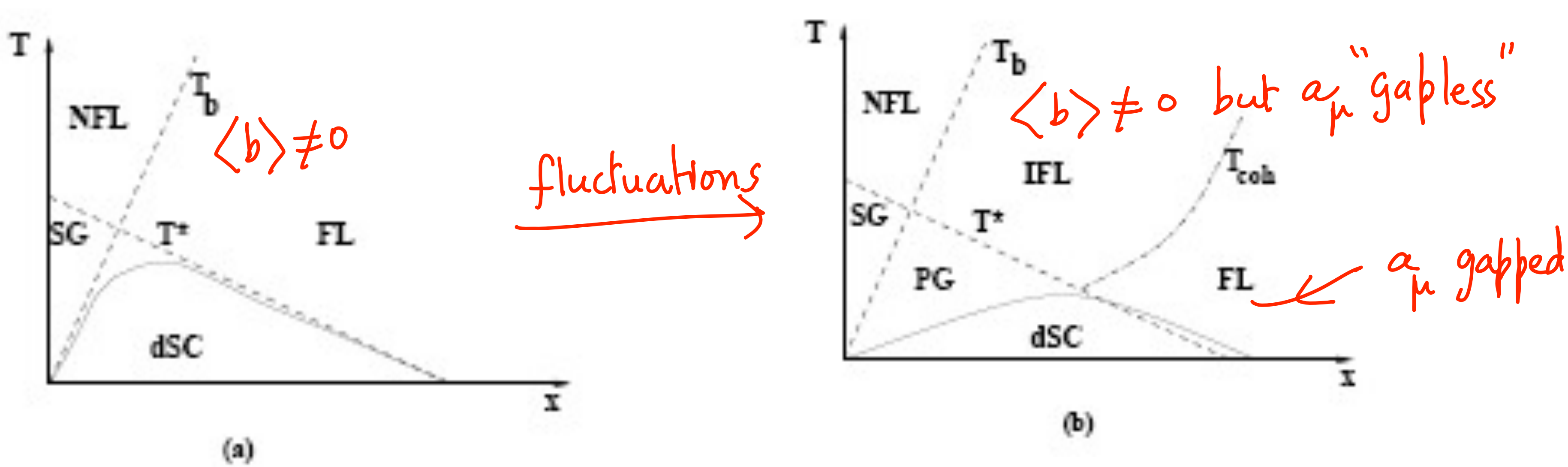
for $T_{coh} \ll T \ll T_b$ as a description of "strange optimal doped metal"

Modified slave boson gauge theory

(TS, Lee '09)

IFL regime: linear-T single particle scattering rate

+ other non-fermi liquid properties



Underdoped: IFL → pseudogap (PG) state

Underdoped: theory of a pseudogap state

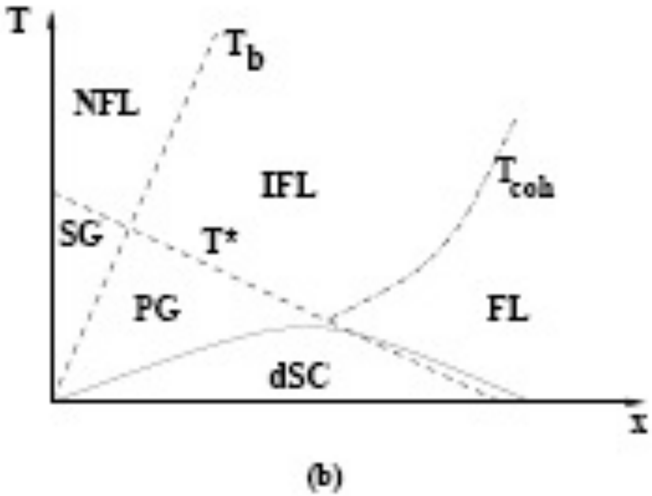
$$S = S_{IFL} + \int_{x\tau} \Delta^*(x\tau)\left(q_\uparrow q_\downarrow\right) + h.c$$

fluctuating d-wave pair field

Pair amplitude gaps out antinode of IFL
($\Rightarrow$ pseudogap)

but nodal Fermi arc and linear-T scattering rate
survive down to $T \approx T_c$
($\Rightarrow$ in underdoped $T_{coh} \approx T_c$, and not supressed by H-field)

Summary -I



New non-fermi liquid regimes overlooked in standard slave boson gauge theory: updated phase diagram

Interesting description of a candidate strange metal and a descendant pseudogap state with gapless Fermi arcs.

Some difficulties with experiments persist.

Summary – II

To confront pseudogap phenomena in cuprates must study SC - Mott insulator transitions.

SC - Mott transitions may be second order if insulator is a quantum spin liquid or a spin Peierls state.

? Possibility of second order SC - AF Mott insulator?

In cuprates, SC-Mott transition closely related to old and fundamental problem of the Mott metal-insulator transition.

Key questions: 1. How does the Fermi surface die?

2. Are competing orders a consequence of vortex fluctuations near SC - Mott transition?