Continuous quantum Mott and related transitions

T. Senthil (MIT)

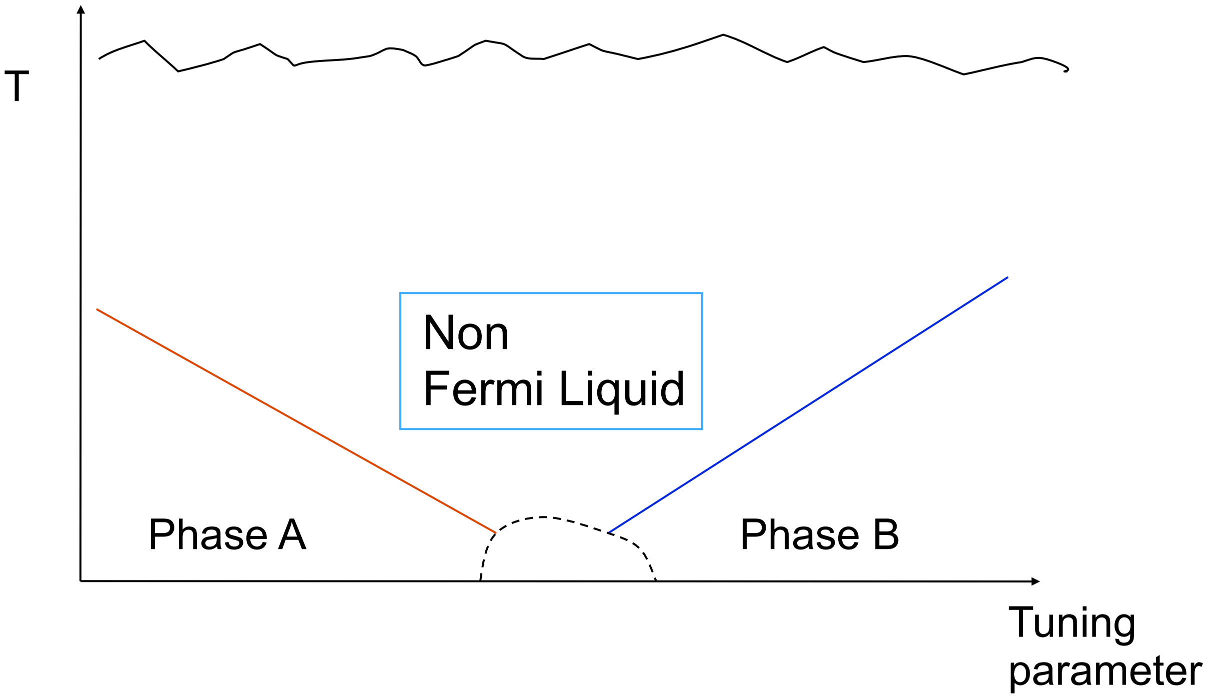
TS, PR B 78, 045109 (2008)
TS, PR B 78, 035103 (2008)

W. Witczak-Krempa, P. Ghaemi, Y.B. Kim, TS, PR B 2012

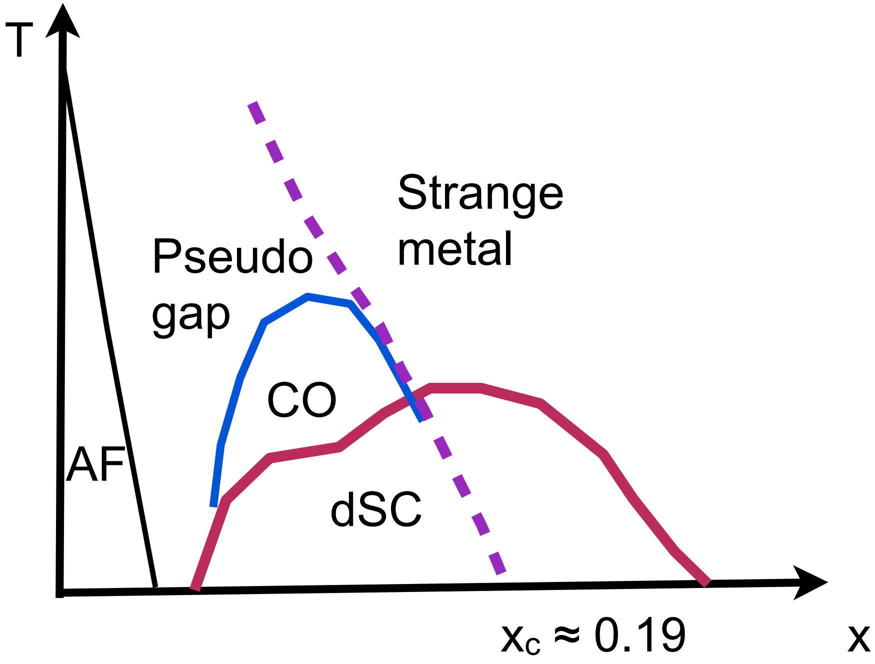
TS, arxiv, 2014

TS, unpublished

A common phase diagram



Cuprate phase diagram



CO: charge order

Most mysterious:
strange metal
regime

Ideas on strange metal

Strange metal plausibly linked to quantum criticality

Increasing evidence for a quantum critical point around $x_c \approx 0.19$ in ``normal” state:

1. Termination of pseudogap crossover at T = 0 (Tallon, Loram 2000)

2. Onset of charge order at T = 0 (Keimer et al, 14).

Quasiparticle mass enhancement approaching optimal doping in a high-T_c superconductor

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In the quest for superconductors with higher transition temperatures (T_c), one emerging motif is that electronic interactions favorable for superconductivity can be enhanced by fluctuations of a broken-symmetry phase. Recent experiments have suggested the existence of the requisite broken-symmetry phase in the high-T_c cuprates, but the impact of such a phase on the ground-state electronic interactions has remained unclear. We used magnetic fields exceeding 90 tesla to access the underlying metallic state of the cuprate $YBa_2Cu_3O_{6+d}$ over a wide range of doping, and observed magnetic quantum oscillations that reveal a strong enhancement of the quasiparticle effective mass toward optimal doping. This mass enhancement results from increasing electronic interactions approaching optimal doping, and suggests a quantum critical point at a hole doping of $p_{crit} \approx 0.18$.

Science, 2015.

How do pseudogap and charge order onset as doping is decreased?

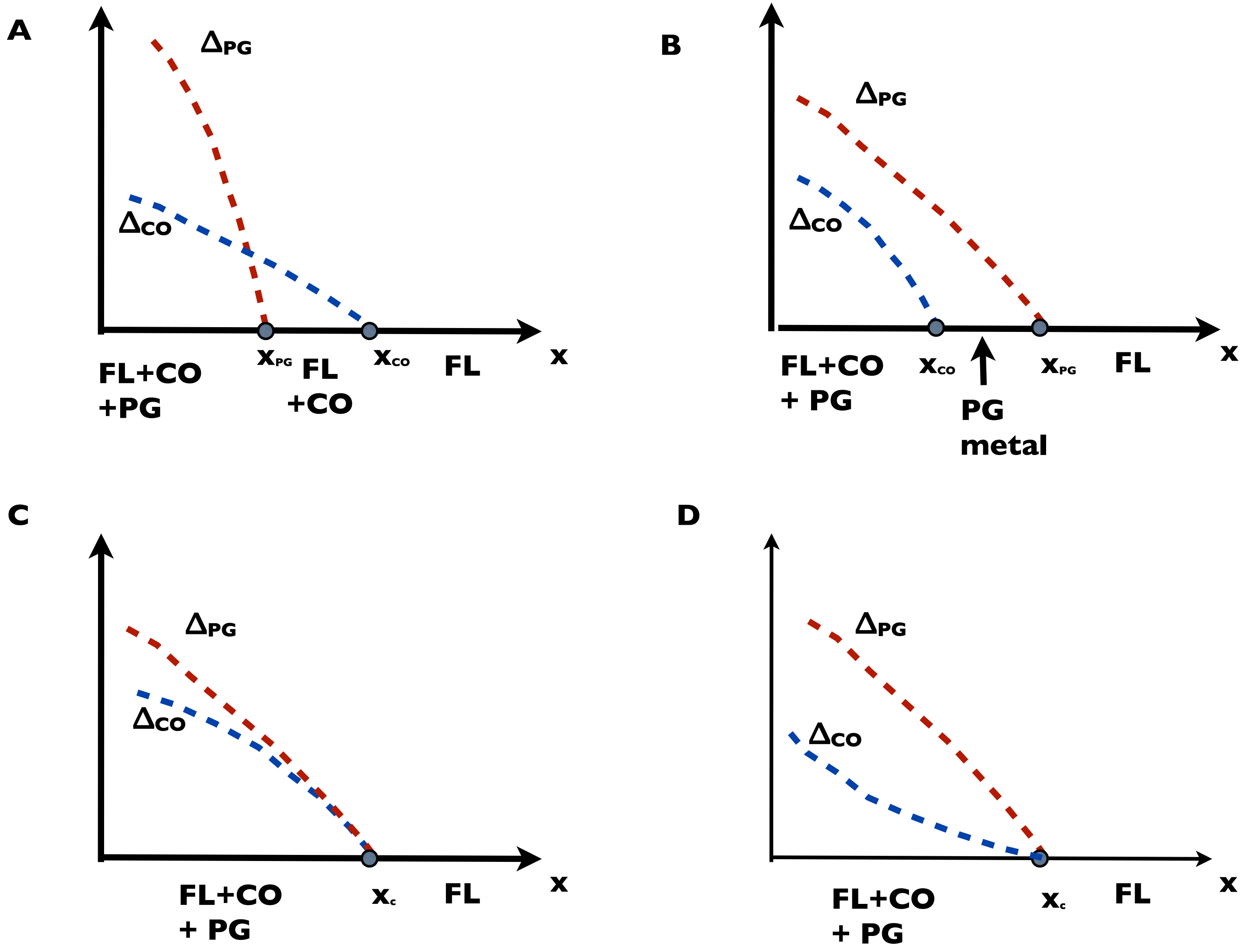
Some comments:

1. Onset of pseudogap at T = 0 involves a sharp change of electronic structure => a bonafide quantum phase transition.

2. At T = 0, a pseudogap state without broken translation symmetry is necessarily an exotic non-fermi liquid ground state

Onset of pseudogap and charge order at T = 0: four general possibilities.

TS, 2014.



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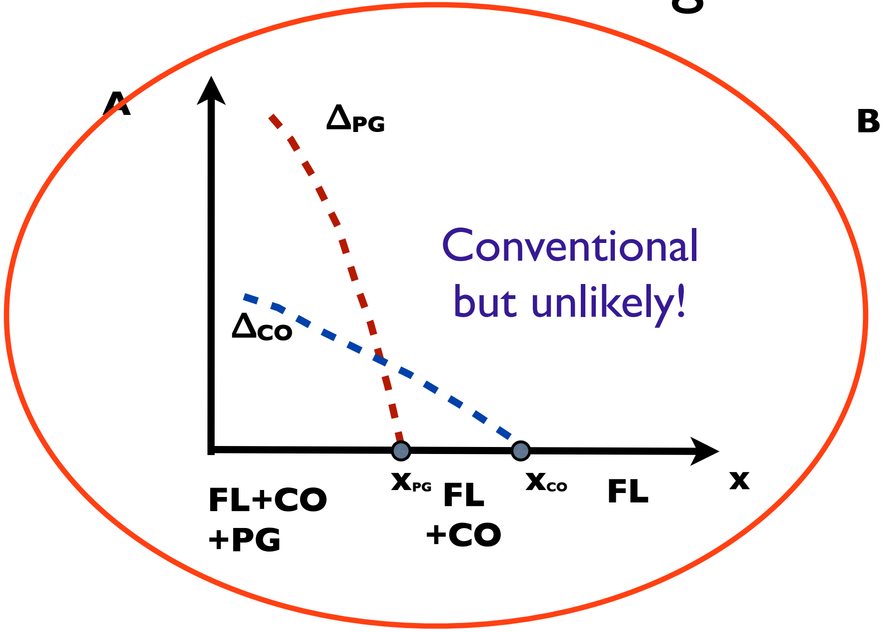
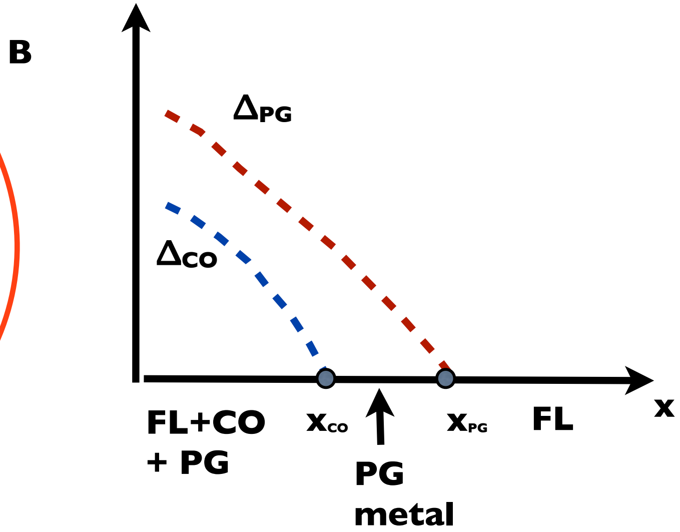
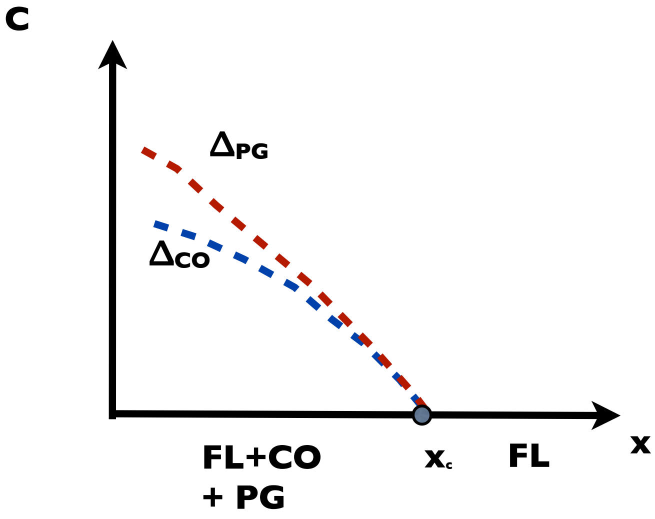
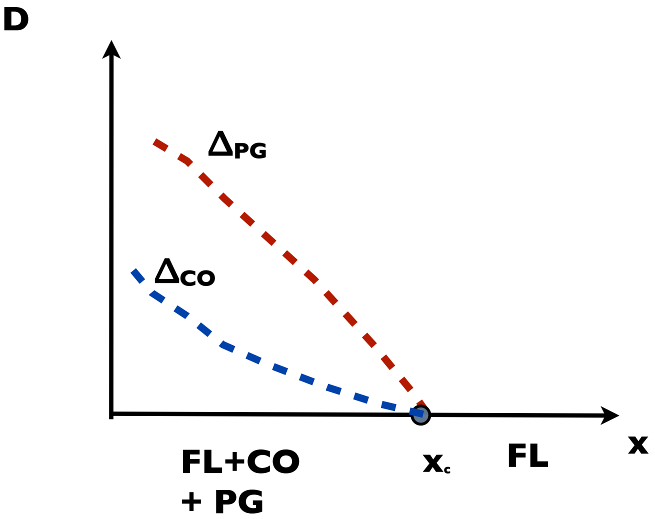


Conventional but unlikely!







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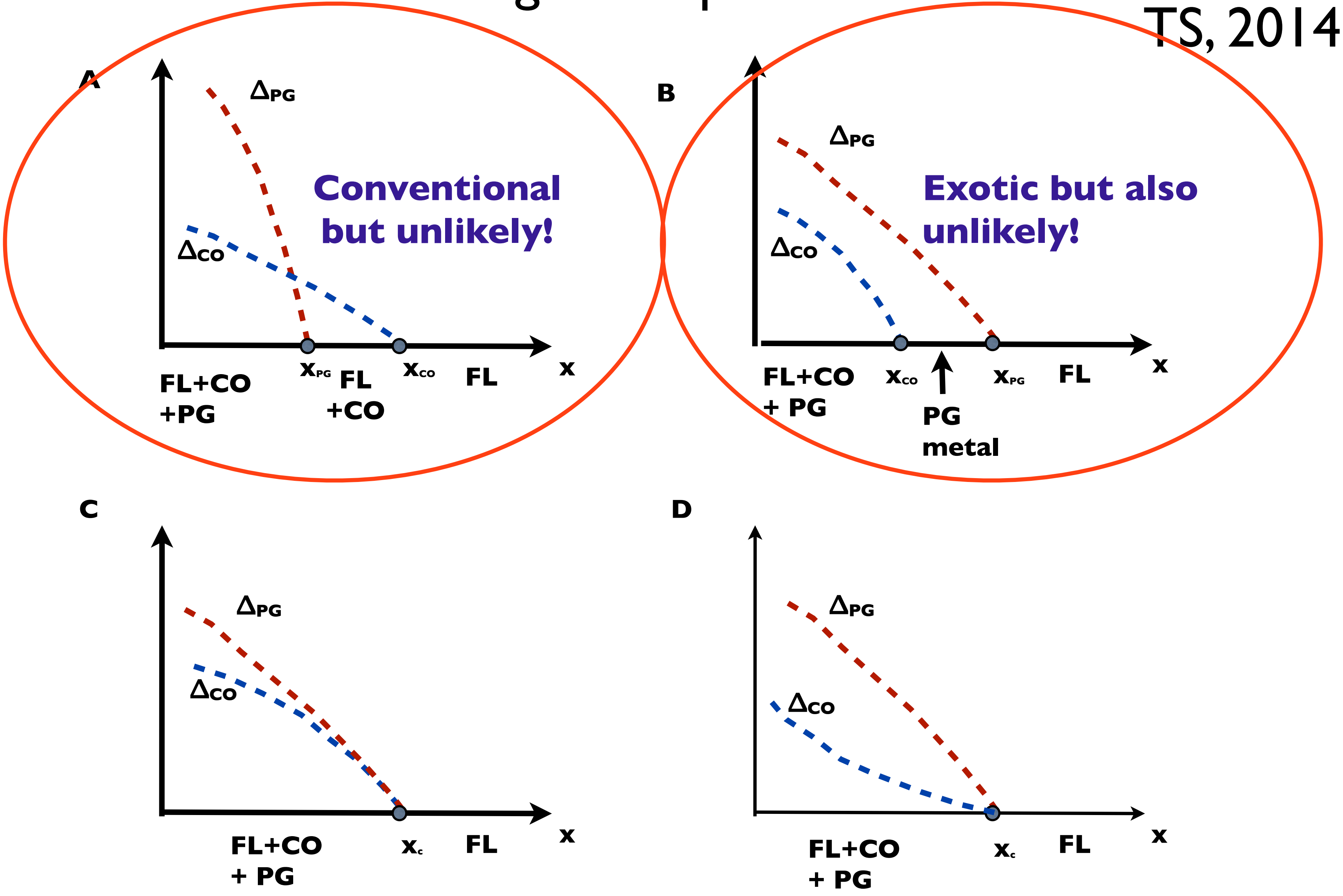

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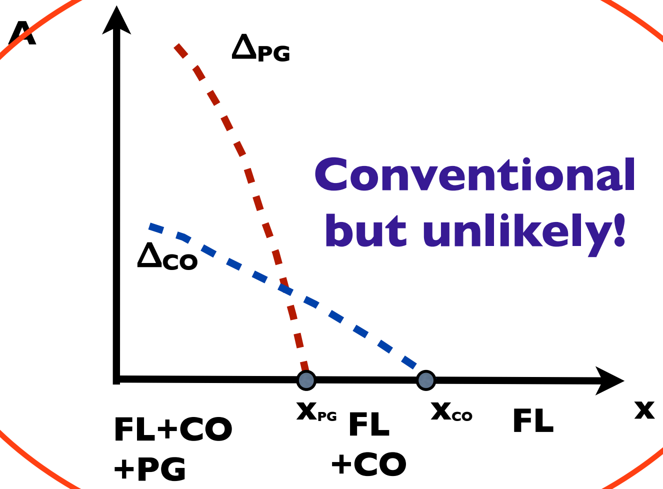
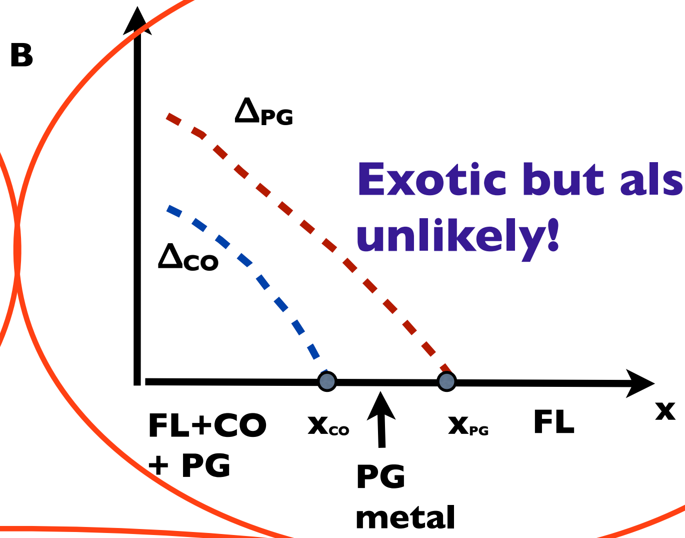
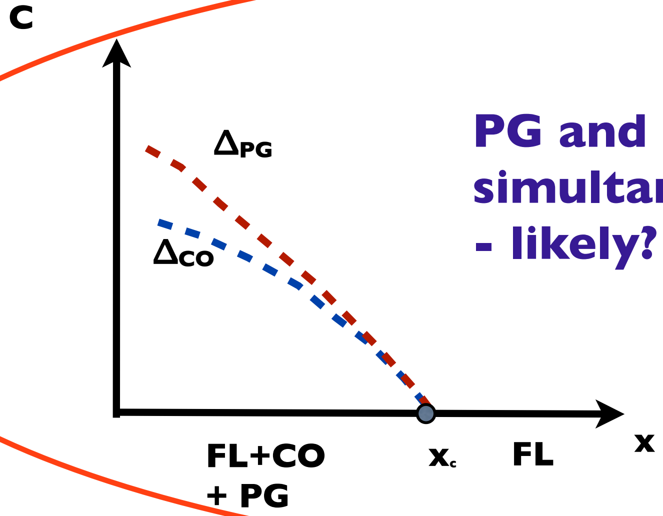


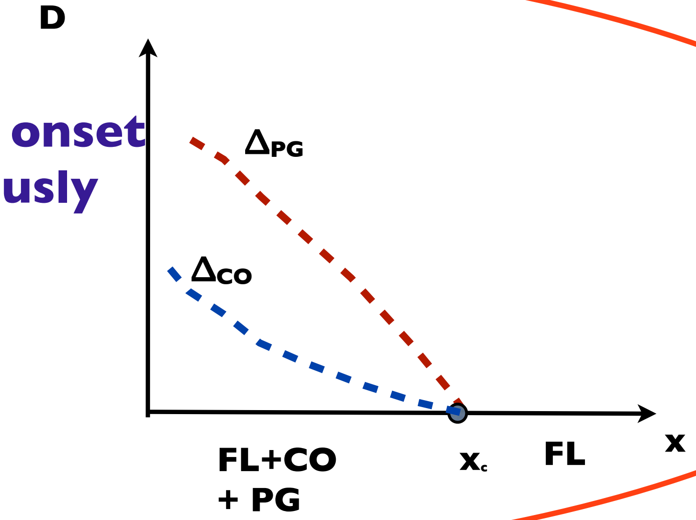
Conventional but unlikely!



Exotic but also unlikely!



PG and CO onset simultaneously - likely?



Simultaneous onset of PG and CO: some support from experiments.

Requires a ``jump” of Fermi surface from overdoped to underdoped through a continuous quantum phase transition.

Similar phenomena suspected in heavy electron quantum critical metals for many years.

Very little theoretical understanding.

Comments

Possibly a harder version of a hard classic problem: the electronic Mott transition.

Across a Mott transition, the Fermi surface jumps discontinuously.

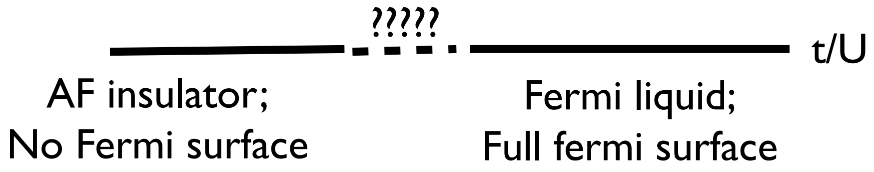
Can the transition still be continuous?

The electronic Mott transition

Difficult old problem in quantum many body physics

How does a metal evolve into a Mott insulator?

Prototype: One band Hubbard model at half-filling on non-bipartite lattice



AF insulator;
No Fermi surface

Fermi liquid;
Full fermi surface

Why hard?

1. No order parameter for the metal-insulator transition

2. Need to deal with gapless Fermi surface on metallic side

3. Complicated interplay between metal-insulator transition and magnetic phase transition

Typically in most materials the Mott transition is first order.

But (at least on frustrated lattices) transition is sometimes only weakly first order - fluctuation effects visible in approach to Mott insulator from metal.

Quantum spin liquid Mott insulators:

Opportunity for progress on the Mott transition -
study metal-insulator transition without complications of magnetism.

Some candidate spin liquid materials

$\kappa - (ET)_2Cu_2(CN)_3$

$EtMe_3Sb[Pd(dmit)_2]_2$

Quasi-2d, approximately isotropic triangular lattice; best studied candidate spin liquids

$Na_4Ir_3O_8$

Three dimensional `hyperkagome' lattice

$ZnCu_3(OH)_6Cl_2$

Volborthtite, ...

2d Kagome lattice (`strong' Mott insulator)

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Three dimensional `hyperkagome' lattice

Close to pressure driven Mott transition: `weak' Mott insulators

$ZnCu_3(OH)_6Cl_2$

Volborthtite, ...

2d Kagome lattice (`strong' Mott insulator)

Some phenomena in experiments

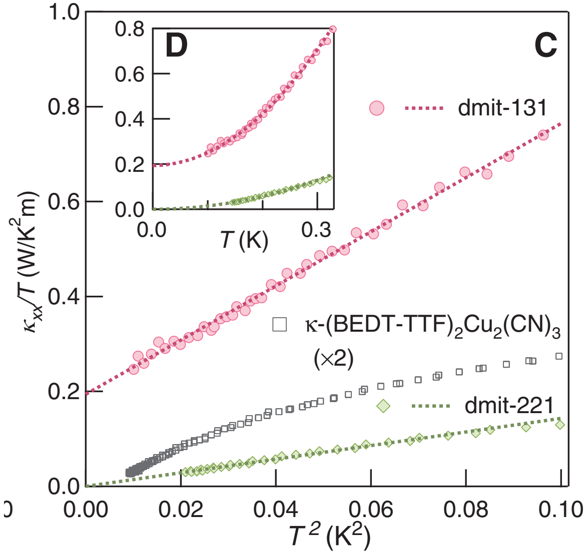
ALL candidate quantum spin liquid materials:

Gapless excitations down to T << J.

Most extensively studied in organic spin liquids with J ≈ 250 K.

Example: Thermal transport in dmit SL.

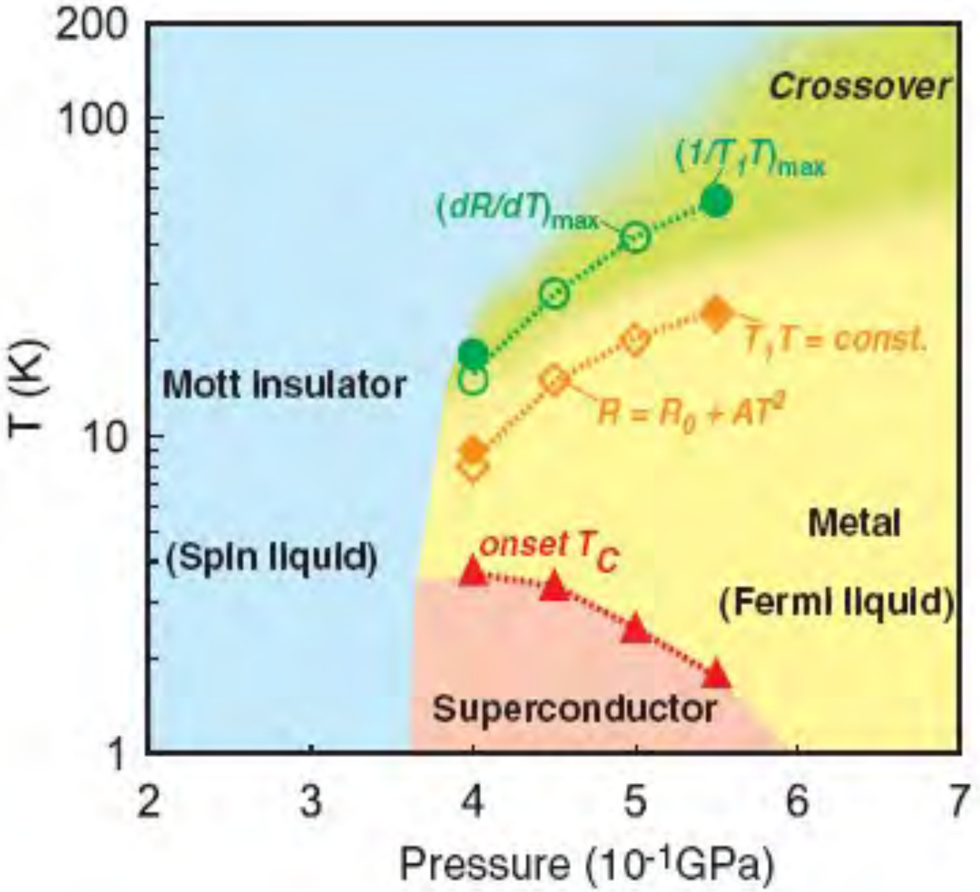
Electrical Mott insulator but thermal metal!



M. Yamashita et al, Science 2010.

Possible experimental realization of a second order(?) Mott transition

Kanoda et al
'03 - '08



κ-$(ET)_2Cu_2(CN)_3$

under pressure

Quantum spin liquids and the Mott transition

Some questions:

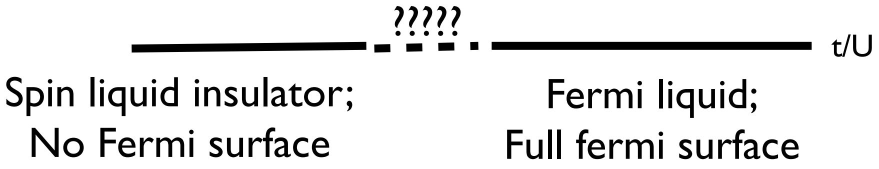
1. Can the Mott transition be continuous?

2. Fate of the electronic Fermi surface?

Spin liquid insulator;
No Fermi surface

Fermi liquid;
Full fermi surface

Killing the Fermi surface



At half-filling, through out metallic phase,
Luttinger theorem => size of Fermi surface is fixed.

Approach to Mott insulator: entire Fermi surface must
die while maintaining size (cannot shrink to zero).

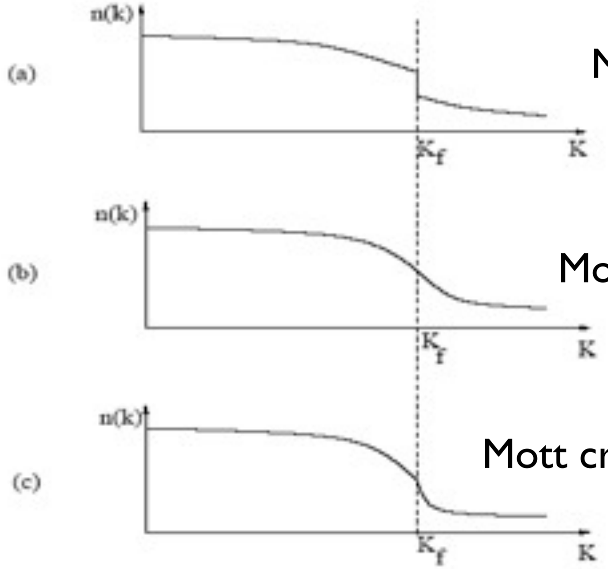
If Mott transition is second order, critical point necessarily very unusual.

``Fermi surface on brink of disappearing” - expect non-Fermi liquid physics.

Similar ``killing of Fermi surface” also at Kondo breakdown transition
in heavy fermion metals, and may be also around optimal doping in cuprates.

How can a Fermi surface die continuously?

Continuous disappearance of Fermi surface if quasiparticle weight Z vanishes continuously everywhere on the Fermi surface (Brinkman, Rice, 1970).



Metal

Mott insulator

Mott critical point

Concrete examples: DMFT in infinite d (Vollhardt, Metzner, Kotliar, Georges 1990s), slave particle theories in d = 2, d = 3 (TS, Vojta, Sachdev 2003, TS 2008)

Basic question for theory

Crucial question: Nature of electronic excitations right at quantum critical point when Z = 0.

Claim: At critical point, Fermi surface remains sharply defined even though there is no Landau quasiparticle.

TS, 2008

``Critical Fermi surface”.

Why a critical Fermi surface?

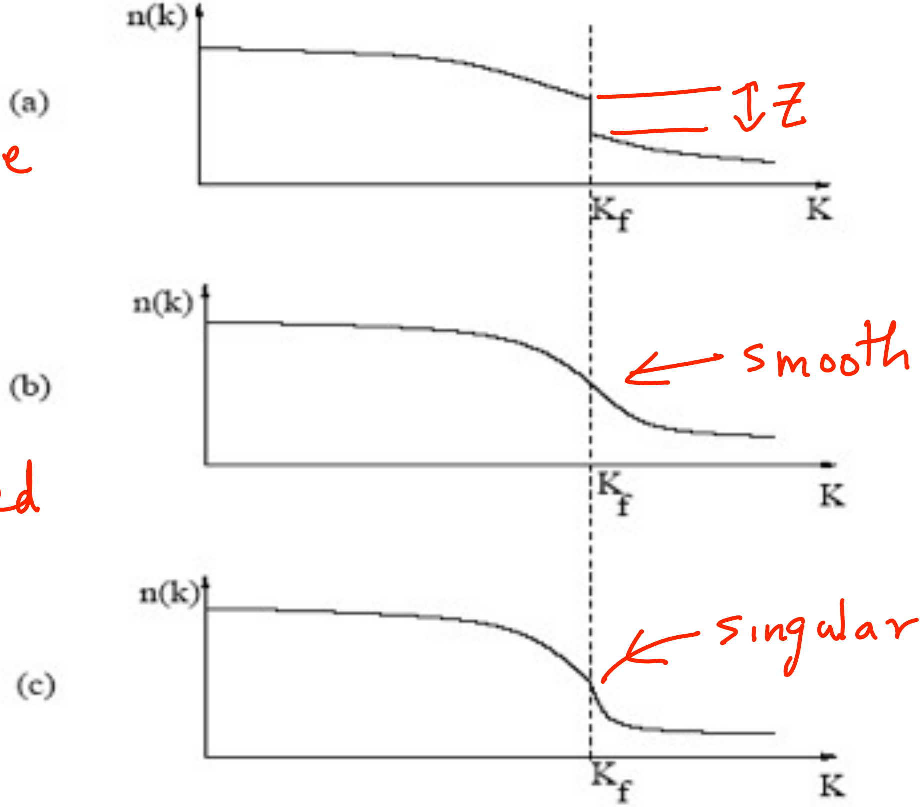
Evolution of momentum distribution

Metal with Fermi surface

Phase where Fermi surface has disappeared

Critical point

$n(K)$ continuous at K_F but is singular

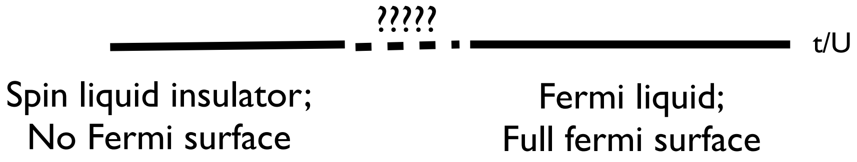


Quantum spin liquids and the Mott transition

Some questions:

1. Can the Mott transition be continuous at $T = 0$?

2. Fate of the electronic Fermi surface?



Only currently available theoretical framework to answer these questions is slave particle gauge theory.

(Mean field: Florens, Georges 2005;
Spin liquid phase: Motrunich, 05, S.S. Lee, P.A. Lee, 05)

Slave particle framework

Split electron operator

$$c_{r\sigma} = b_r f_{r\alpha}$$

Fermi liquid: $\langle b \rangle \neq 0$

Mott insulator: b_r gapped

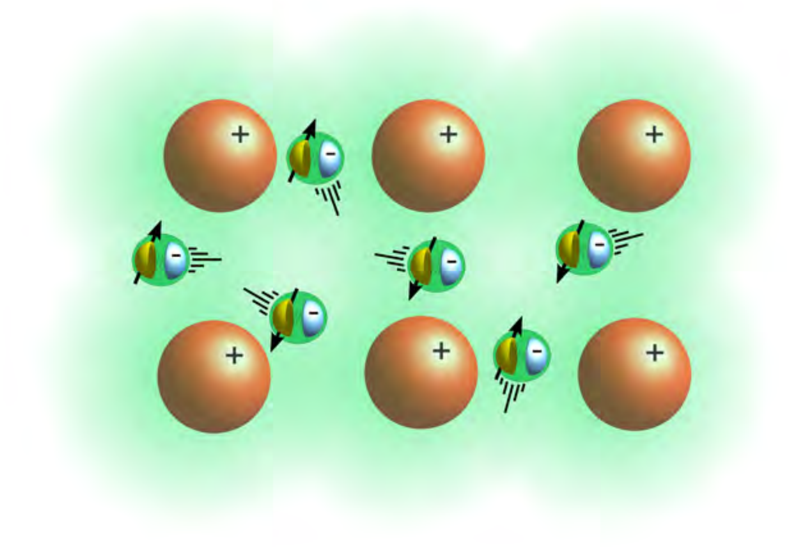
Mott transition: b_r critical

In all three cases $f_{r\alpha}$ form a Fermi surface.

Low energy effective theory: Couple b, f to fluctuating $U(1)$ gauge field.

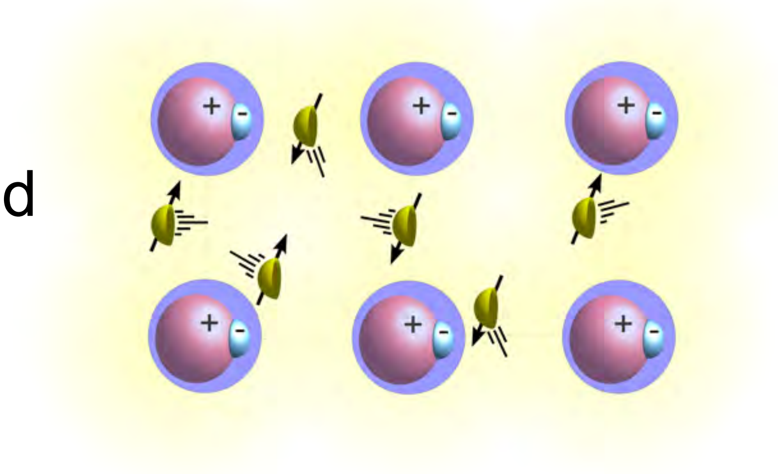
Picture of Mott transition

Metal



Electrons swimming in sea of +vely charged ions

Mott spin liquid near metal



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

Quantum spin liquids and the Mott transition

1. Can the Mott transition be continuous?

2. Fate of the electronic Fermi surface?

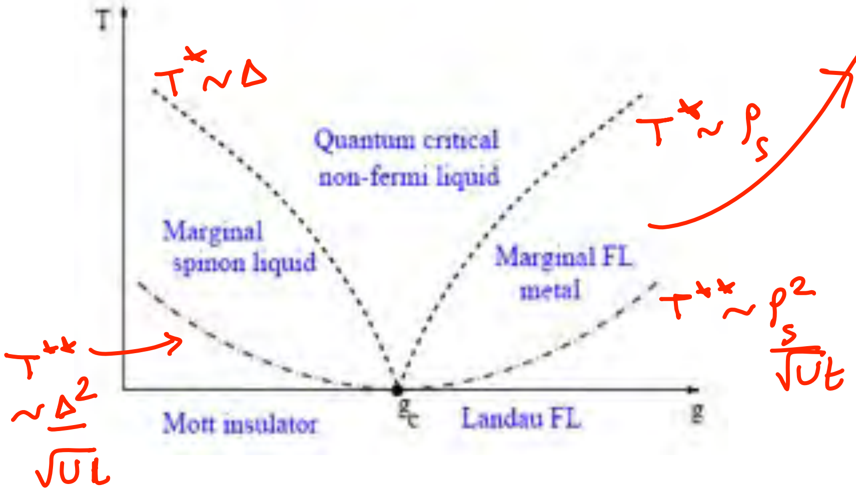
Analyse fluctuations: Concrete tractable theory of a continuous Mott transition (TS 2008); demonstrate critical Fermi surface at Mott transition;

Definite predictions for many quantities (TS, 2008, Witczak-Krempa, Ghaemi, Kim, TS, 2012).

- Universal jump of residual resistivity on approaching from metal
- Log divergent effective mass
- Two diverging time/length scales near transition
- Emergence of marginal fermi liquids

Finite-T crossovers: emergence of a Marginal Fermi Liquid

TS, 2008



$T^* \sim \Delta$

$T^{**} \sim \frac{\Delta^2}{\sqrt{Ut}}$

$T^* \sim \rho_s$

$T^{**} \sim \frac{\rho_s^2}{\sqrt{Ut}}$

In this regime electron Greens function

$$G(\vec{k}, i\omega) \sim \frac{|\langle b\rangle|^2}{i\omega\left(1+a\ln\frac{1}{|\omega|}\right) - \epsilon_k}$$

= Marginal FL form

proposed for hiTc by Varma et al '89

Structure of critical theory

Field theory for critical point

$$S = S[b, a] + S[f_\alpha, a]$$

Gauge fluctuations are Landau damped by spinon Fermi surface:

$$S_{eff}[a] = \int_{\mathbf{q},\omega} \left(K_F \frac{|\omega|}{|\mathbf{q}|} + .. \right) |\mathbf{a}(\mathbf{q}, \omega)|^2$$

=> at low energies gauge field decouples from critical b fluctuations.
Charge sector is described by $S[b]$ = critical D = 2+1 XY model

Structure of critical theory (cont'd)

Though boson criticality is not affected by the gauge fields, the gauge fields are affected by the bosonic criticality.

Effective gauge dynamics

$$S_{eff}[a] = \int_{q,\omega} \left(K_F \frac{|\omega|}{|\mathbf{q}|} + \sigma_0 \sqrt{\omega^2 + q^2} \right) |\mathbf{a}(\mathbf{q}, \omega)|^2$$

Second term: response of critical boson to the gauge field.

Anticipate that for fermions $|\omega| \ll |\mathbf{q}|$, replace by

$$S_{eff}[a] = \int_{q,\omega} \left(K_F \frac{|\omega|}{|\mathbf{q}|} + \sigma_0 |\mathbf{q}| \right) |\mathbf{a}(\mathbf{q}, \omega)|^2$$

Spinon Fermi surface coupled to Landau damped gauge field with $z_b = 2$ (a well understood theory).

Critical theory

Effective critical action

$$S_{eff} = S[b] + S[f, a]$$

$S[b]$: critical D = 2+1 XY model
$S[f]$: spinon Fermi surface + Landau damped gauge field with $z_b = 2$
Both individually understood.

Non-zero temperature transport/dynamics

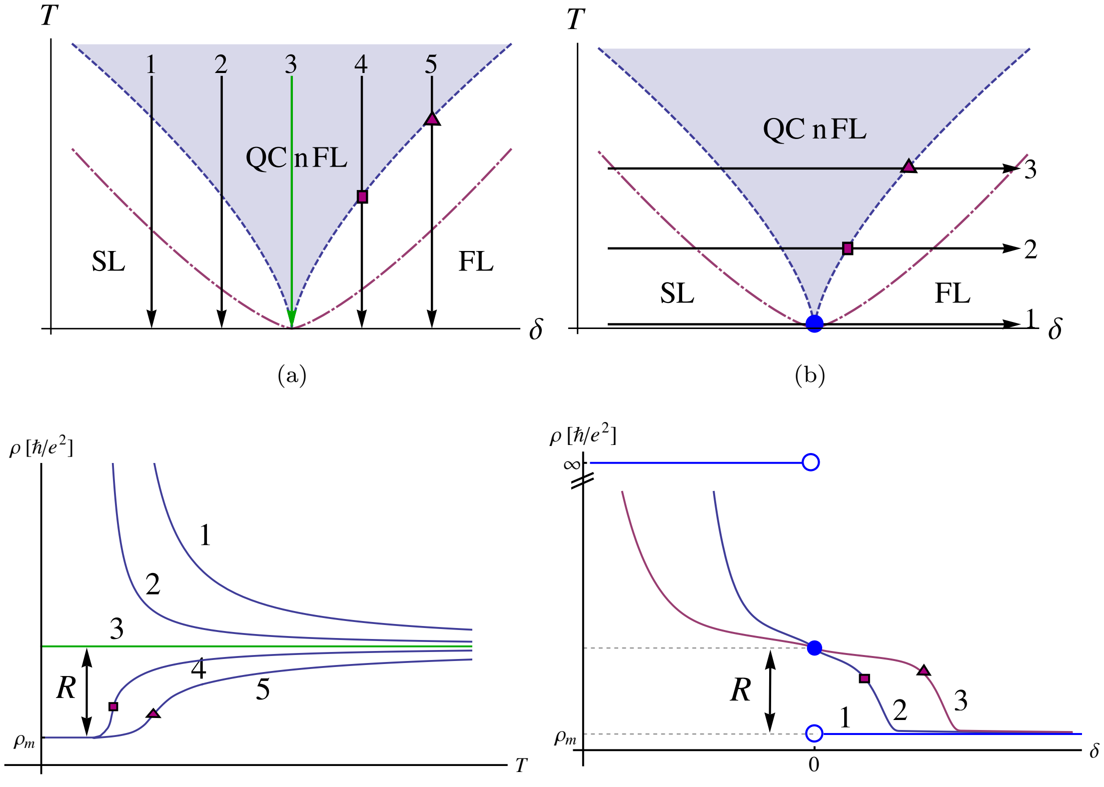
$$S_{eff}[a] = \int_{\mathbf{q}} \frac{1}{\beta} \sum_{\omega_n} \left(K_F \frac{|\omega_n|}{|\mathbf{q}|} + .. \right) |\mathbf{a}(\mathbf{q}, \omega_n)|^2$$

Static gauge fluctuations ($\omega_n = 0$) escape Landau damping, and do not decouple from critical bosons.

Universal transport in a large-N approximation (Witzcak-Krempa, Ghaemi, TS, Y.B. Kim, 2012):
Gauge scattering reduces universal conductivity by factor of ≈ 8 from $3D$ XY result (Damle, Sachdev '97).

Electronic Mott transition: Net resistivity $\rho = \rho_b + \rho_f$
Universal resistivity jump $= \rho_b$ enhanced by factor of ≈ 8.

Non-zero temperature transport



(a) (b)

(c) (d)

$$\rho - \rho_m = \frac{\hbar}{e^2} G\left(\frac{\delta^{z\nu}}{T}\right)$$

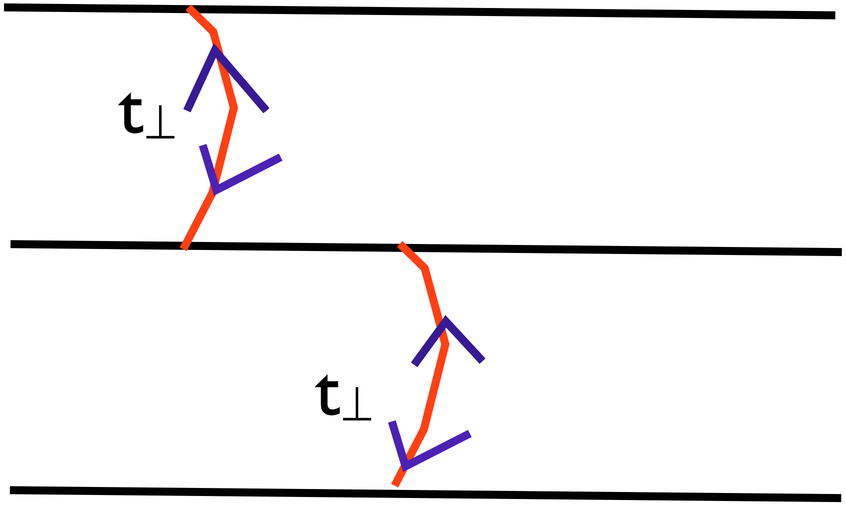
$$z = 1,\ \nu \approx 0.672$$

Some new results: The continuous Mott transition in a layered system

Real materials: Layered 3d with weak interlayer tunneling of electrons.

Fermi liquid regime: Interlayer tunneling coherent => 3d metal.

Spin liquid Mott insulator: Spinons cannot tunnel coherently => different layers dynamically decouple (in-plane spinon metal but interlayer spinon insulator).



TS, unpublished

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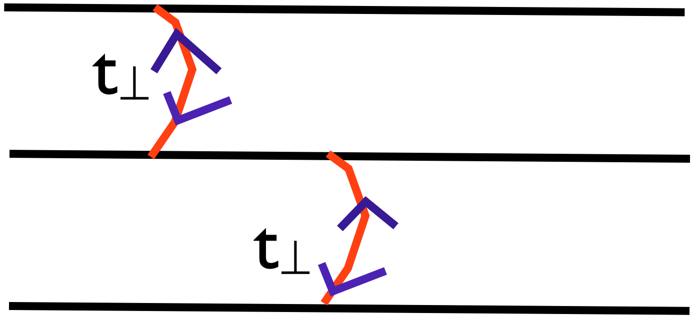
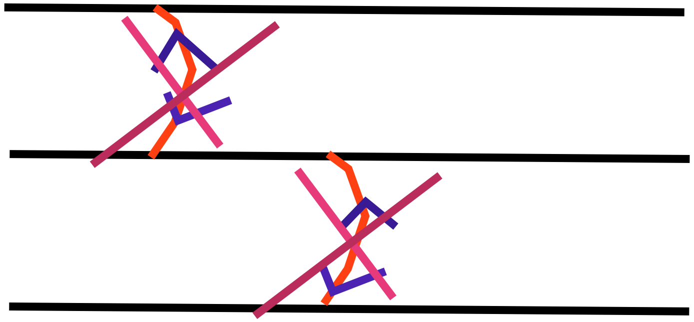
Interlayer coherence: Metal vs spin liquid Mott insulator





Metal: coherent 3d metal at T = 0.

Spin liquid: interlayer hopping of spinons is blocked; interlayer thermal insulator at T = 0 (but in-plane thermal conductor).

What happens to Mott quantum crtical point?

Interlayer coupling at Mott critical point

TS, unpublished

In layered system, Fermi liquid- spin liquid Mott transition is a dimensionality changing transition.

Interlayer transport occurs thru tunneling of electrons
=> determined by electron spectral function.

$$\sigma_\perp \sim (t_\perp)^2 \int d\omega \, d^2K \, (- df/d\omega) \, (A(K, \omega))^2$$

Use known form of spectral function:

$$\sigma_\perp \sim T^{(1 + 2\eta)} \sim T$$

At criticality: interlayer electrical insulator but in-plane electrical conductor!

Summary

Quantum spin liquids provide an opportunity for progress on classic old problems:
Mott and other metal-insulator transitions.

Half-filling (organics):
Continuous Mott transition possible; several predictions for experiment (eg: universal resistivity jump in $d = 2$ plus incoherent interlayer insulator)

Other (not discussed in this talk):
(i) 3d (hyperkagome iridates): resistivity peak neat continuous Mott transition.
(ii) Disordered limit (doped semiconductors Si:P, Si:B).
Do electrical and thermal metal-insulator transitions occur simultaneously?

Lessons for cuprates, heavy fermions????