Quantum spin liquids and continuous metal-insulator transitions

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TS, PR B 08.

D. Podolsky, A. Paramekanti, Y.B. Kim, TS, PRL 09.

D. Mross and TS, PRB 11.

A. Potter, M. Barkeshli, J. McGreevy, TS, PRL 2012 .

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

Plan of talk

Part 1. Theory of a continuous Mott metal-insulator transition in d = 2.

Evolution from Fermi liquid to quantum spin liquid insulator:
Predictions for transport experiments

Part 2. Metal-insulator transitions in doped semiconductors (Si:P, Si:B).

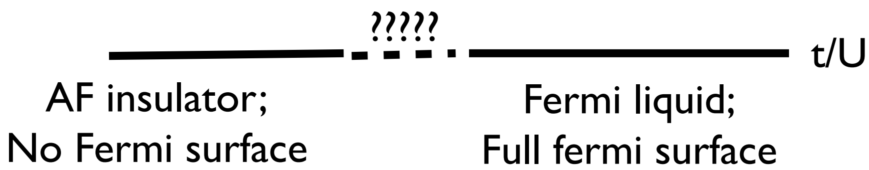
New questions/insights inspired by quantum spin liquid theory/experiments.

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



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

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Volborthtite, ...

2d Kagome lattice (`strong' Mott insulator)

Some phenomena in experiments

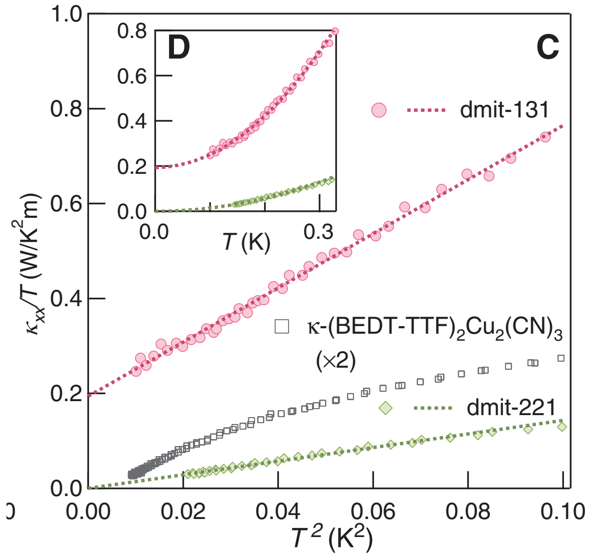
ALL candidate quantum spin liquid materials:

<u>Gapless</u> 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!

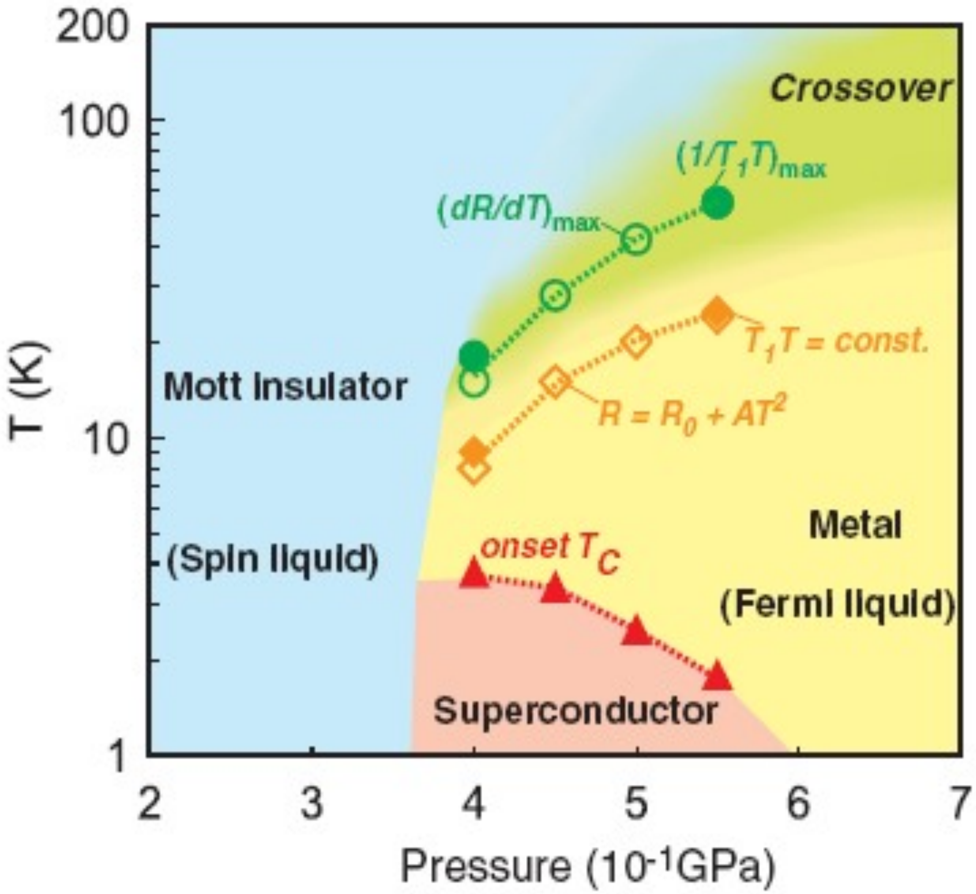


M. Yamashita et al, Science 2010.

Friday, June 6, 14

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

Kanoda et al '03 - '08



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

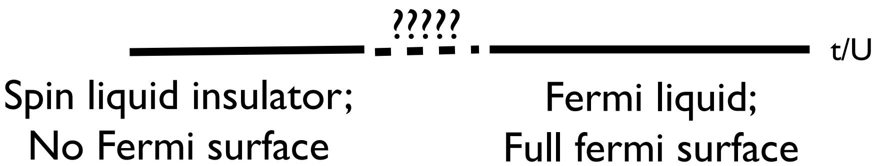
under pressure

Quantum spin liquids and the Mott transition

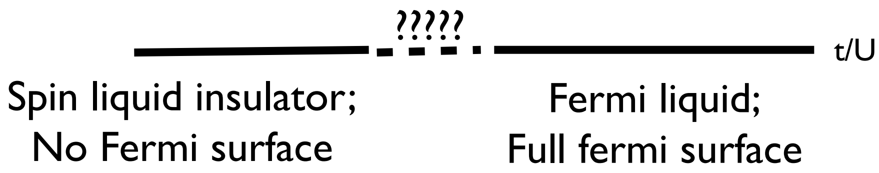
Some questions:

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

2. Fate of the electronic Fermi surface?



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.

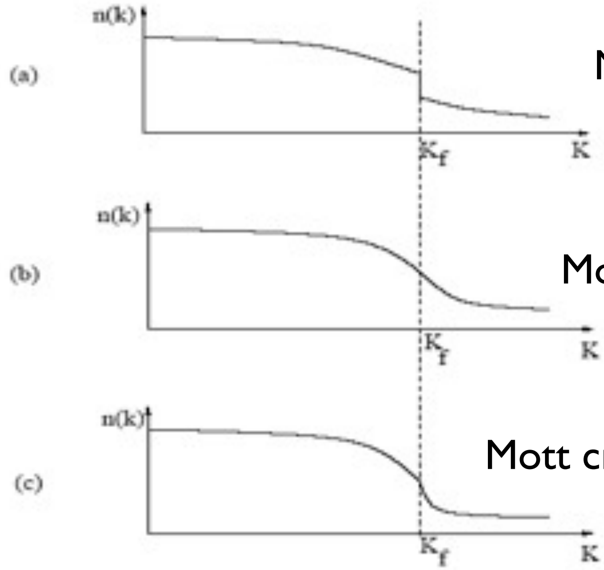
``Fermi surface on brink of disappearing" - expect non-Fermi liquid physics.

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?

1. Quasiparticle weight Z vanishes continuously everywhere on the Fermi surface (Brinkman, Rice, 1970)*

2. Fermi surface remains sharp at critical point: ``Critical Fermi surface'' (TS, 2008)



*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)

Quantum spin liquids and the Mott transition

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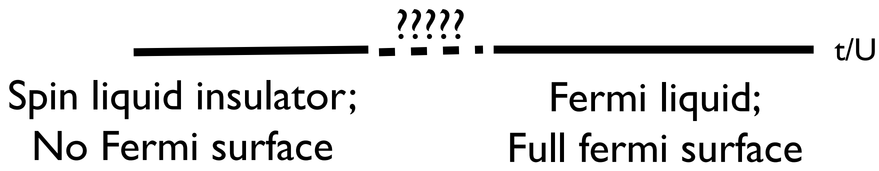


Only currently available theoretical framework to answer these questions is slave particle gauge theory.

(Mean field: Florens, Georges 2005;
Spin liquid phase: Motrunich, 07, S.S. Lee, P.A. Lee, 07)

Slave particle framework

Split electron operator

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

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

Mott insulator: b_r gapped

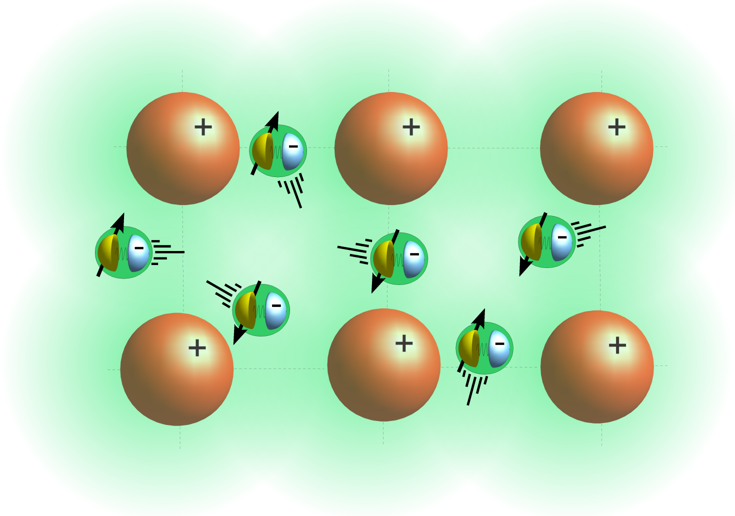
Mott transition: b_r critical

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

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

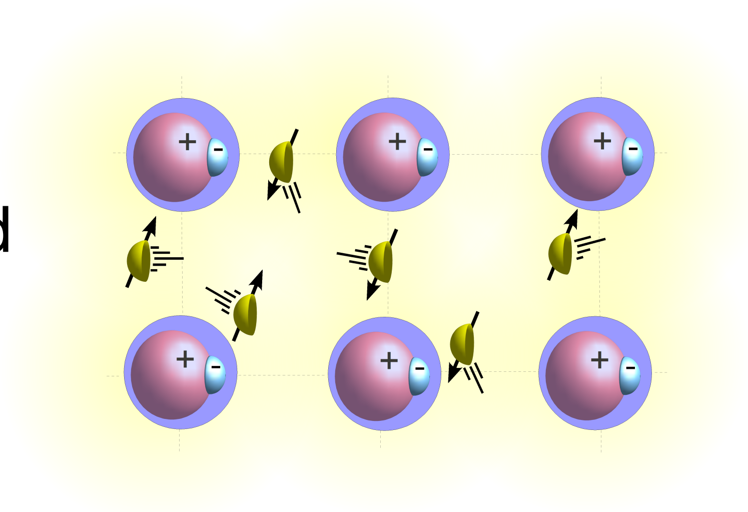
Picture of Mott transition

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?

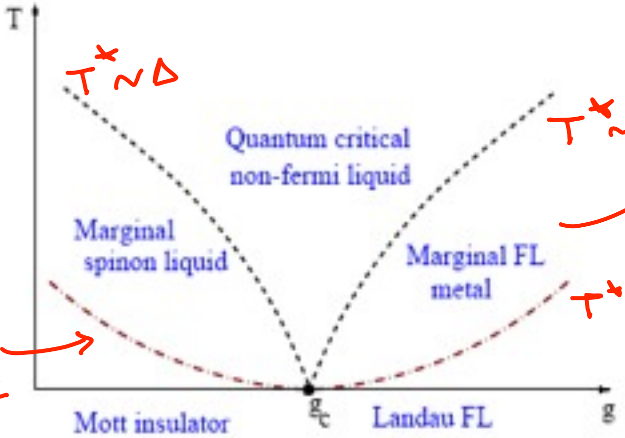
Concrete tractable theory of a continuous Mott transition;
demonstrate critical Fermi surface at Mott transition;

Definite predictions for many quantities (TS, 2008).

- 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



$T^* \sim \Delta$

$T^* \sim \rho_s$

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

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

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.
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):

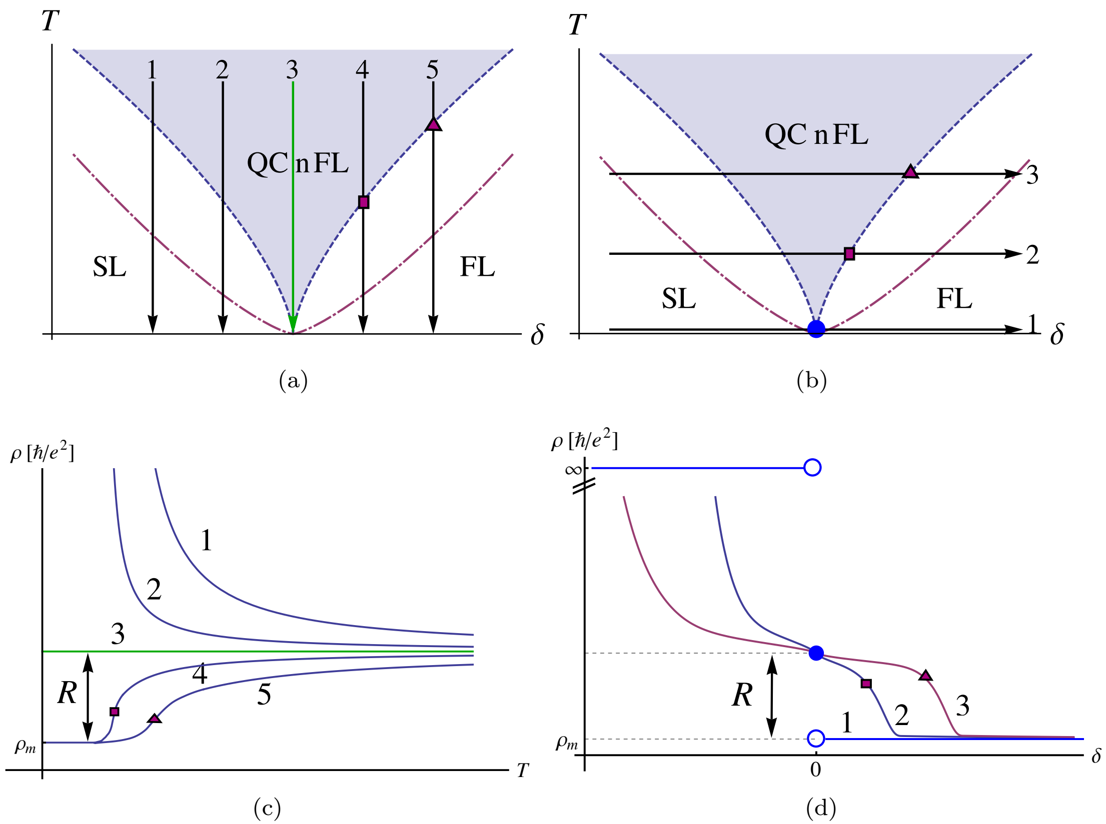
Gauge scattering reduces universal conductivity by factor of ≈ 8 from $3D$ XY result (Damle, Sachdev '97).

Electronic Mott transition: Net resistivity $\rho = \rho_b + \rho_f$

Universal resistivity jump $= \rho_b$ enhanced by factor of ≈ 8.

Non-zero temperature transport

Witczak-Krempa, Ghaemi, TS, Kim, 2012



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

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

Part 2: Metal-insulator transitions in doped semiconductors

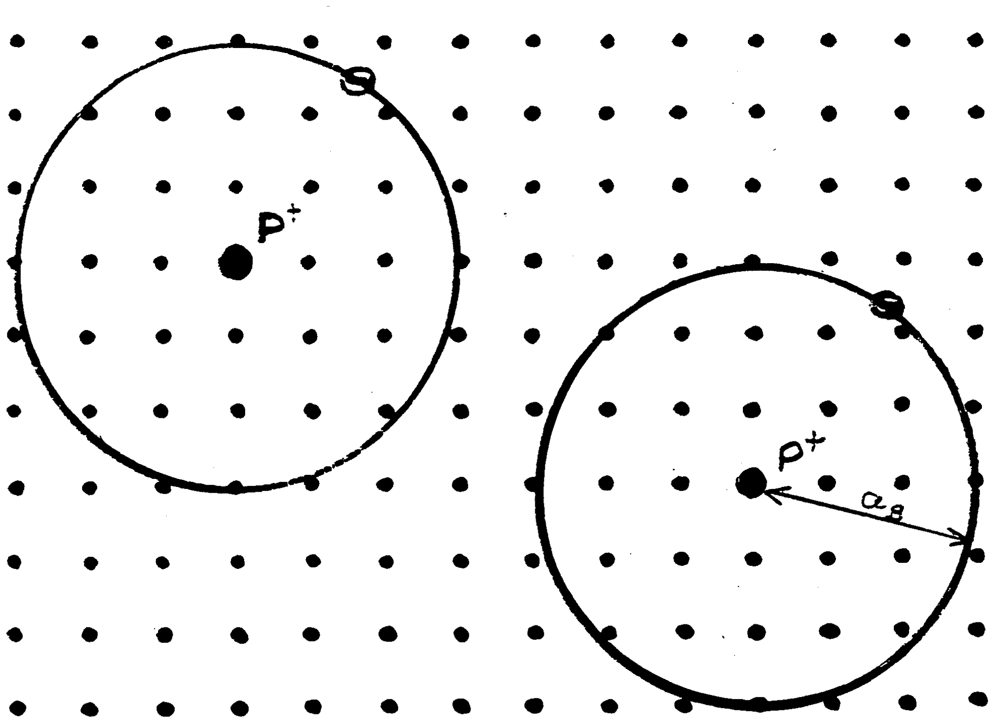
Eg: Si:P, Si:B

Subject of many studies over last 3 decades.

``Anderson-Mott" transition

Is there a quantum spin liquid?
(Potter, Barkeshli, McGreevy, TS, PRL 2012)

Basic picture for Si:P (Si:B, etc)

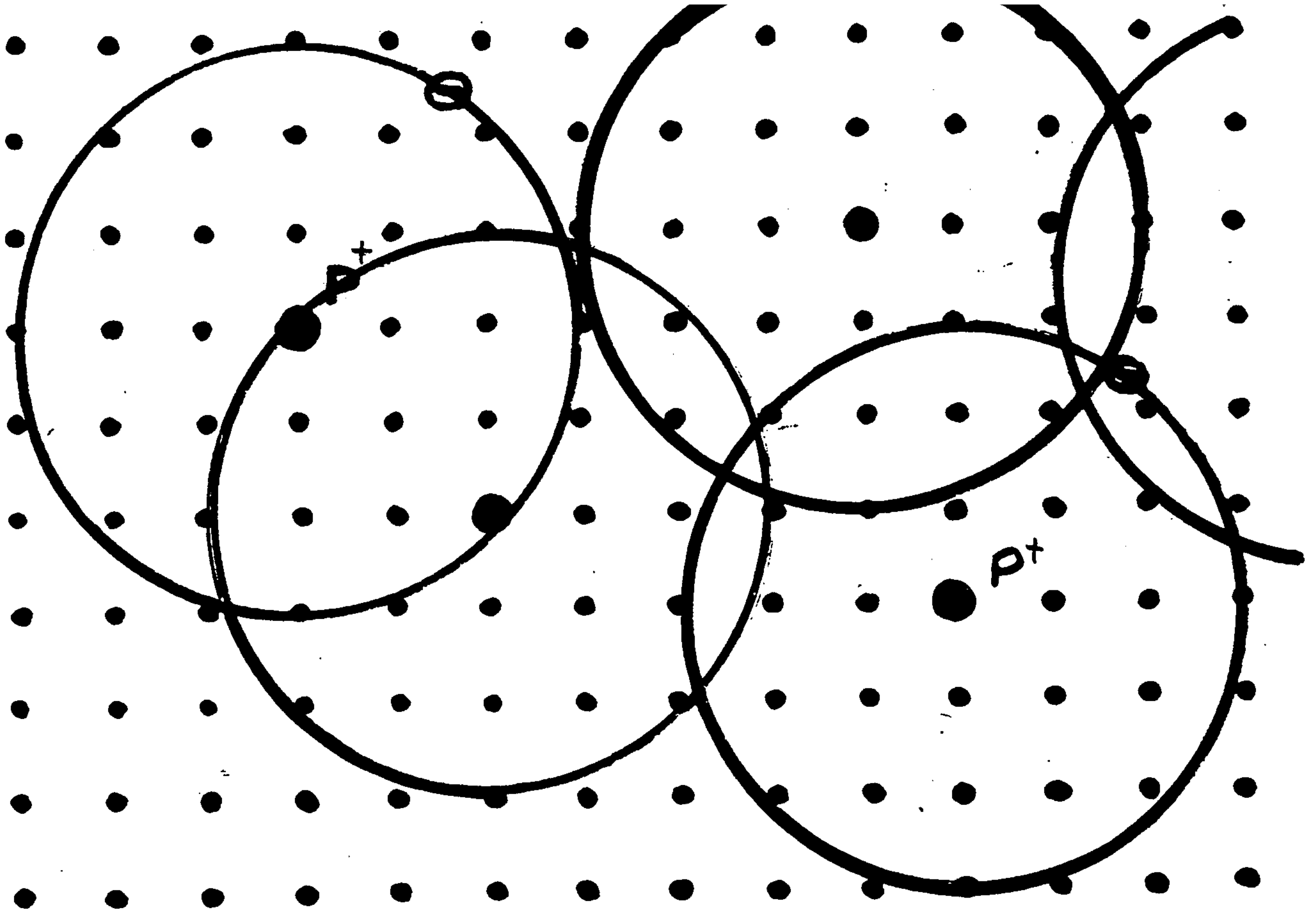


Extra electron of P forms a hydrogen-like state.

$$a_B \approx 20A$$

Simple model: Randomly placed ``Hydrogen atoms''.
Half-filled Hubbard model on random lattice.

Increase P concentration to get metal



Local moments in insulator: Random singlets

Bhatt, Lee, 1982

Each local moment forms a singlet bond with a fixed partner.

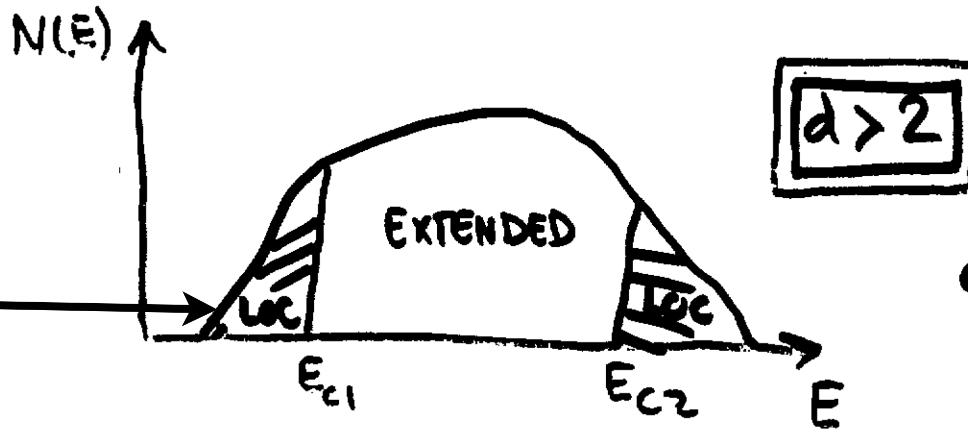
Broad distribution of singlet bond energies.

Anomalous low-T thermodynamics: diverging spin susceptibility, C/T (dominated by rare weakly coupled spin pairs).

Metallic phase: persistence of some local moments

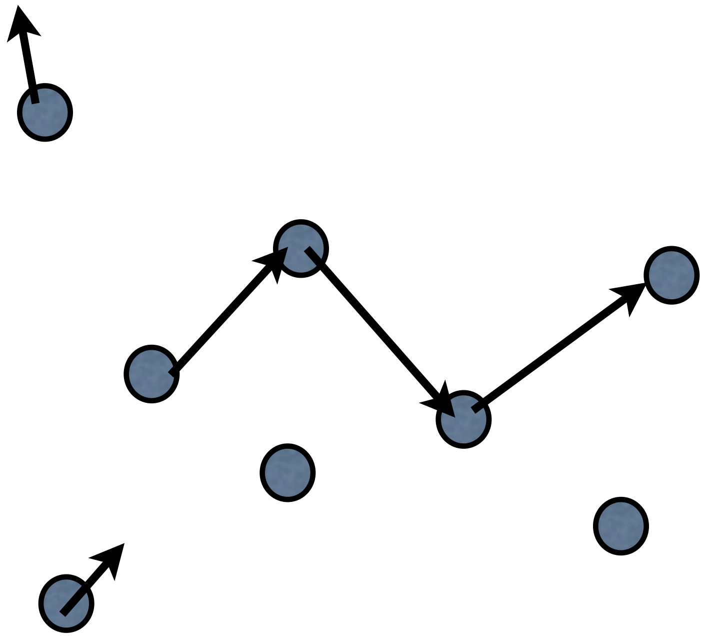
Near transition, some rare fraction of sites retain local moments which then dominate low-T thermodynamics.

Picture: Hubbard-U on localized states produces local moments.



Two fluid phenomenology of metal

Paalanen et al, 1988; Gan, Lee, 86;
Milovanovic, Sachdev, Bhatt, 1989;
Bhatt, Fisher, 1992



Itinerant electron fluid coexisting with small fraction of local moments.

Near transition, fraction of local moment sites about 15%.

Thermodynamics: independent contribution from both fluids.

Evolution across Metal-Insulator Transition (MIT)

What is fate of conducting fluid?

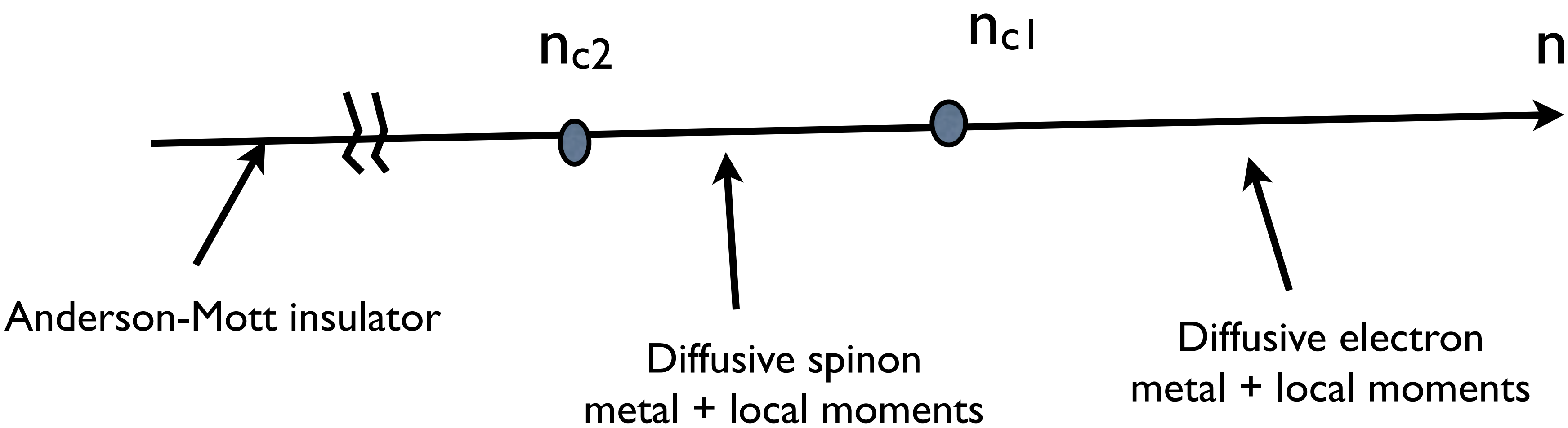
Three possibilities:

1. ``Conventional wisdom''
Itinerant electrons -------> Anderson insulator

2. Fraction of sites with local moments increases to approach 1 at MIT (generically unlikely).

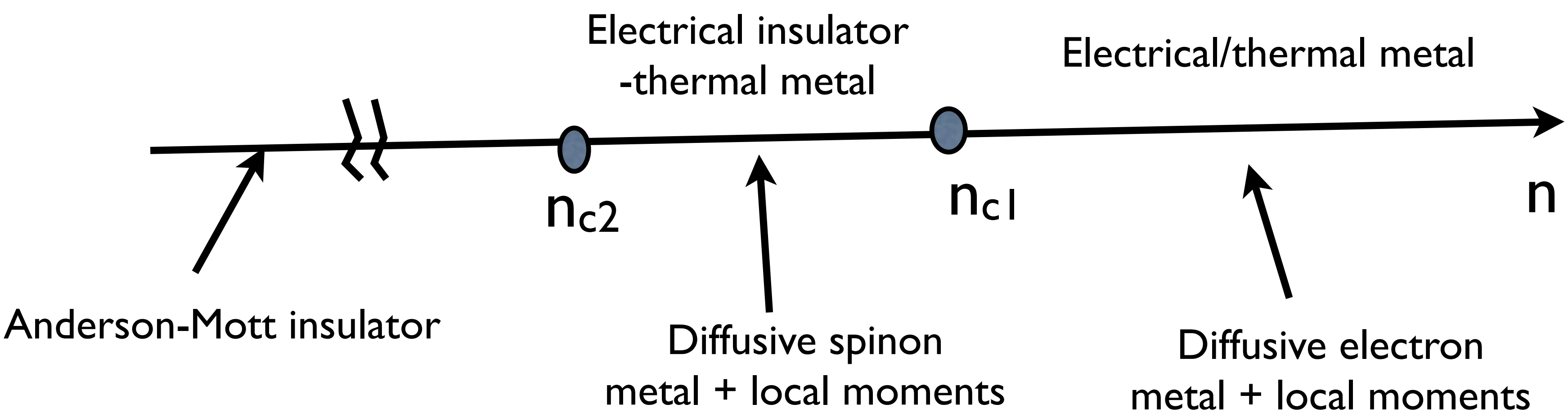
3. New possibility: Conducting fluid Mott localizes into a quantum spin liquid with diffusive spinons (Potter, Barkeshli, McGreevy, TS, 2012)

Possible route to metal-insulator transition



Some consequences-I

Diffusive spinon metal is electrical insulator but a thermal conductor.
=> **electrical metal-insulator transition separated from thermal metal-insulator transition.**



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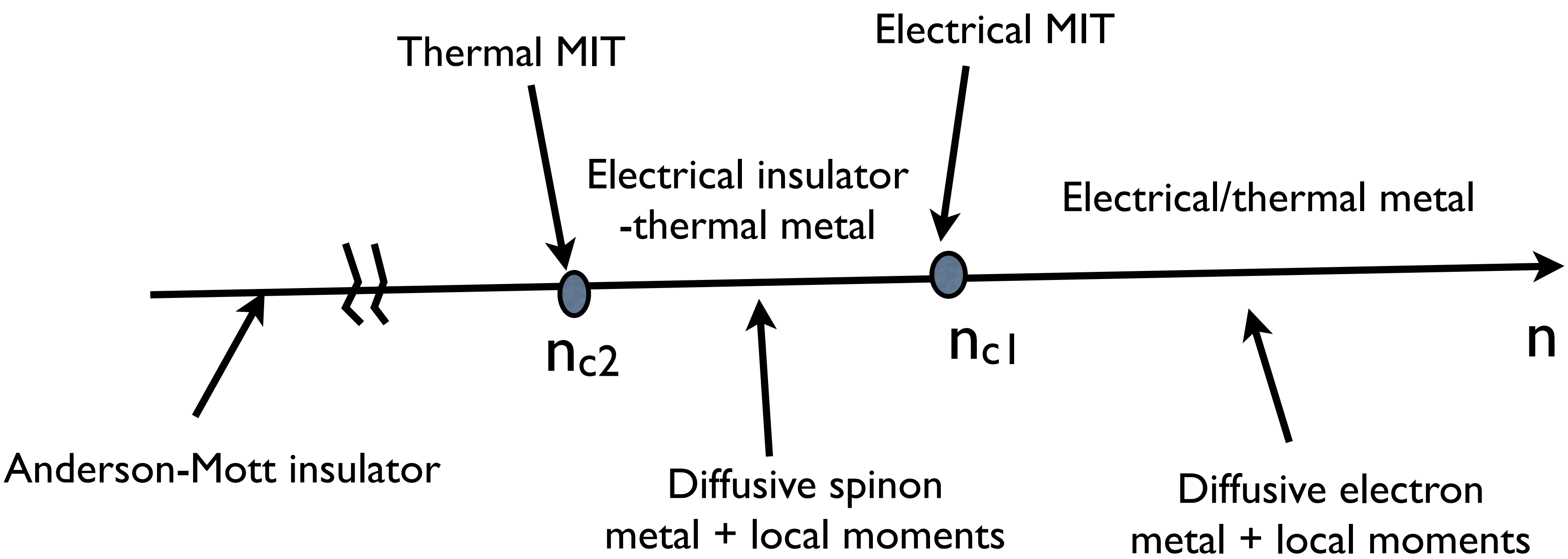
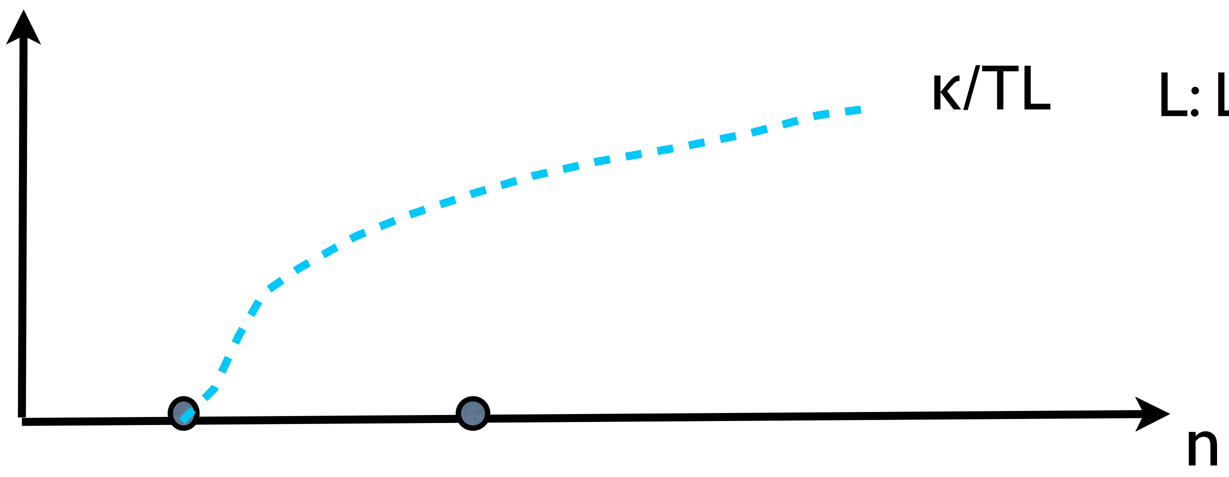


Crucial test: measure thermal transport in insulator.

Some consequences -II

Existence of diffusive spinon metal will impact critical behavior of electrical conductivity near electrical MIT.

Jump of residual conductivity at MIT; non-monotonic T-dependence.



L: Lorentz number

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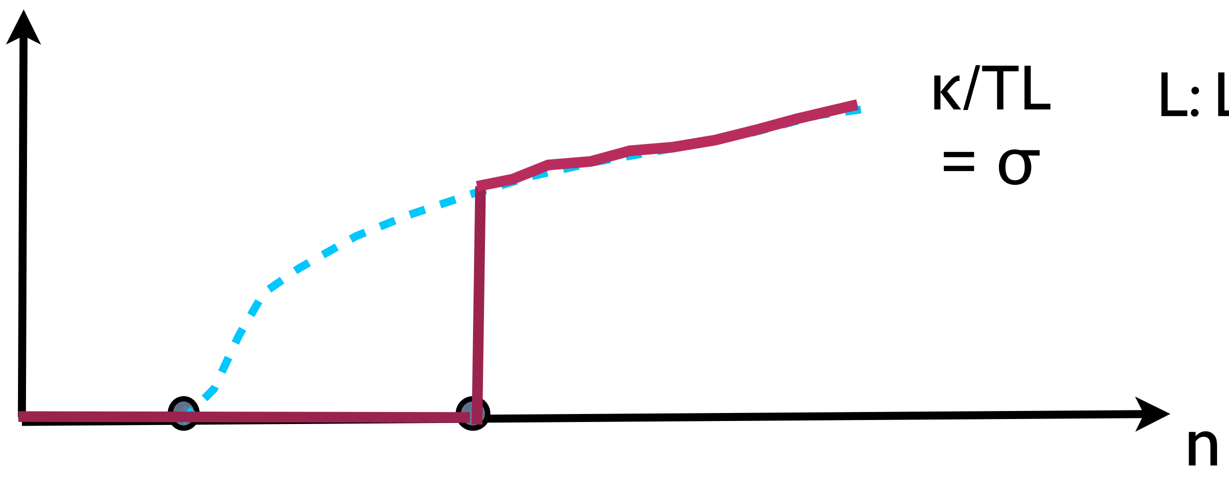

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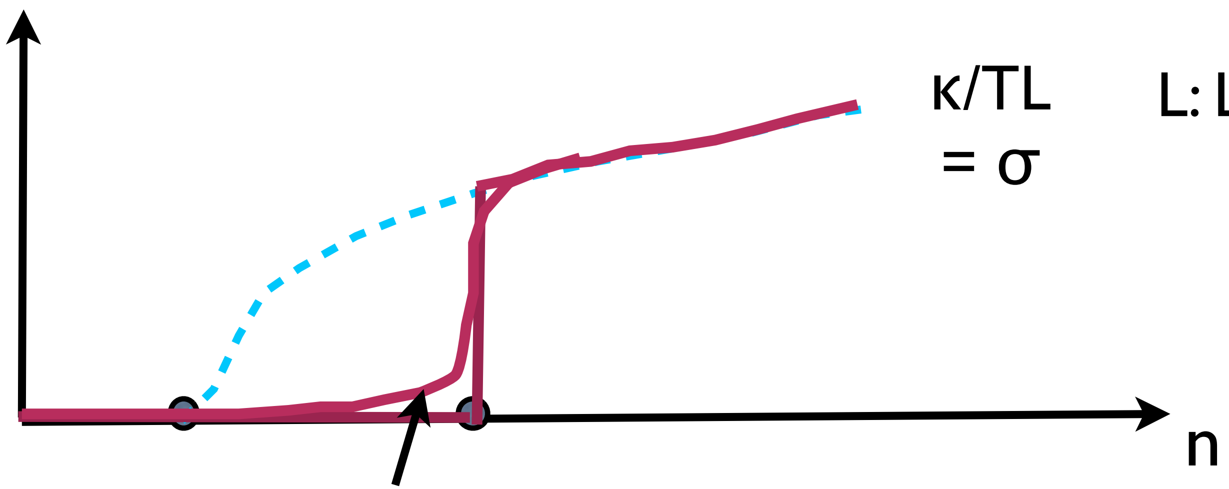

L: Lorentz number

Thermal rounding of jump; complicates extrapolation to T=0 conductivity.

Summary

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

Clean limit (organics, hyperkagome iridate):
Continuous Mott transition possible; several predictions for experiment (eg: universal resistivity jump in $d = 2$, resistivity peak in $d = 3$)

Disordered limit (doped semiconductors Si:P, Si:B):
Do electrical and thermal metal-insulator transitions occur simultaneously?