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, arxiv, 1206.3309

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).

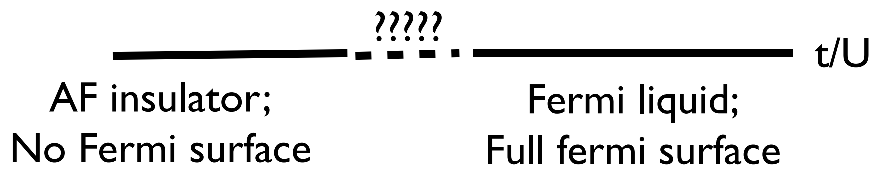
New questions/insights inspired by quantum spin liquid theory/experiments.

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

$ZnCu_3(OH)_6Cl_2$

Volborthtite, ...

2d Kagome lattice (`strong' Mott insulator)

Some phenomena in experiments

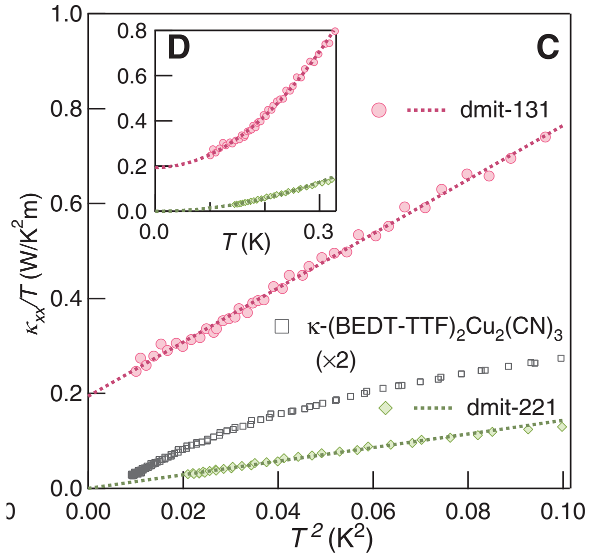
ALL candidate quantum spin liquid materials:

<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.

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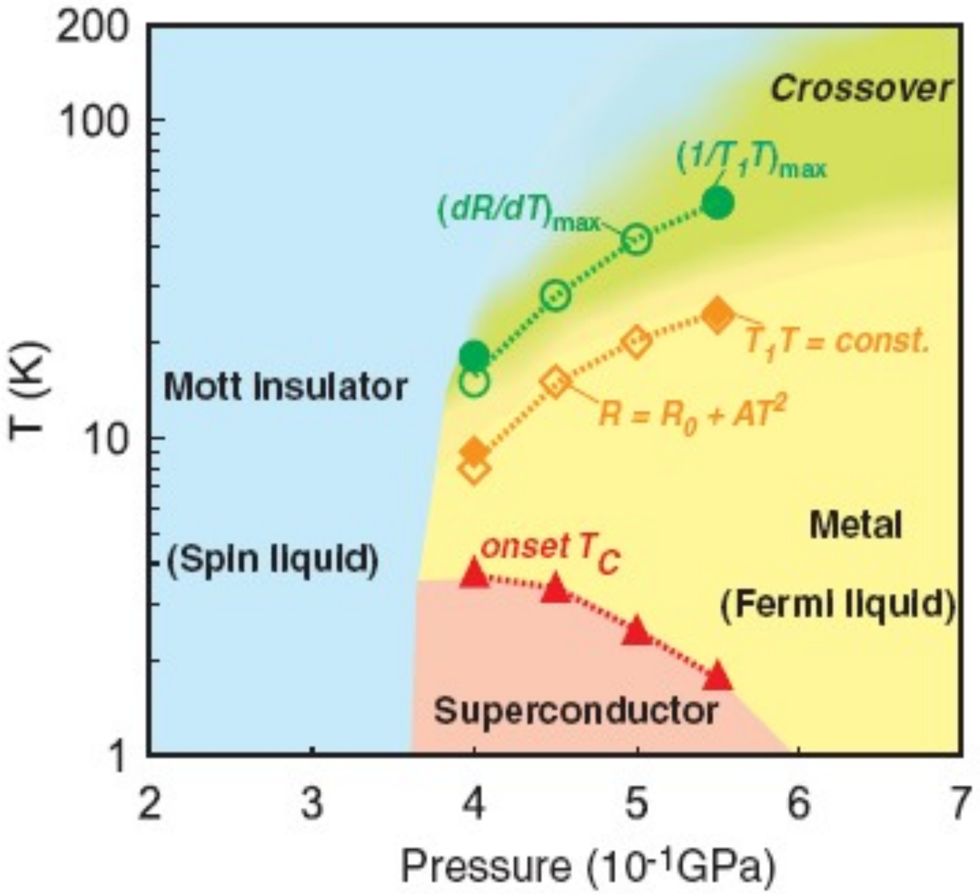
Possible experimental realization of a second order(?) Mott transition

Kanoda et al '03 - '08



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

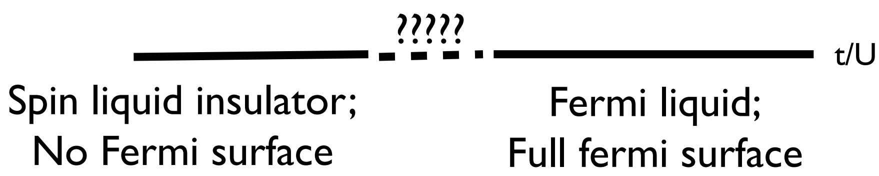
under pressure

Quantum spin liquids and the Mott transition

Some questions:

1. Can the Mott transition be continuous?

2. Fate of the electronic Fermi surface?



Slave particle framework

Split electron operator

$$c^\dagger_{r\sigma} = b^\dagger_r f_{r\alpha}$$

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

Mott insulator: b_r gapped

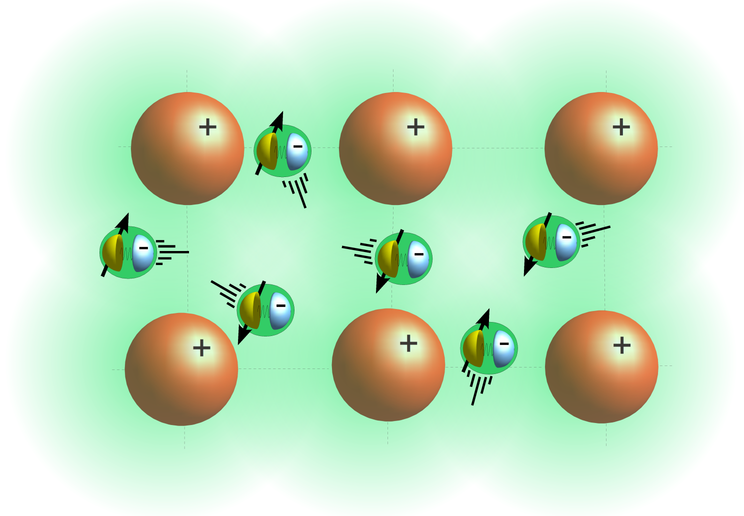
Mott transition: b_r critical

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

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

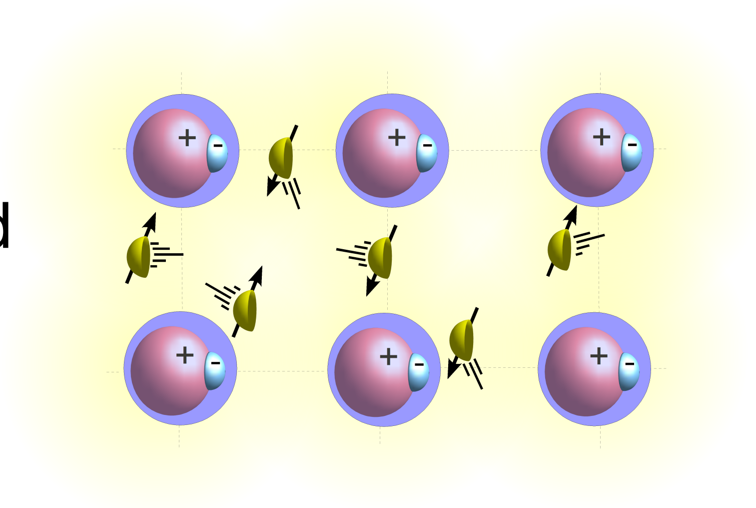
Picture of Mott transition

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.

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Quantum spin liquids and the Mott transition

1. Can the Mott transition be continuous?

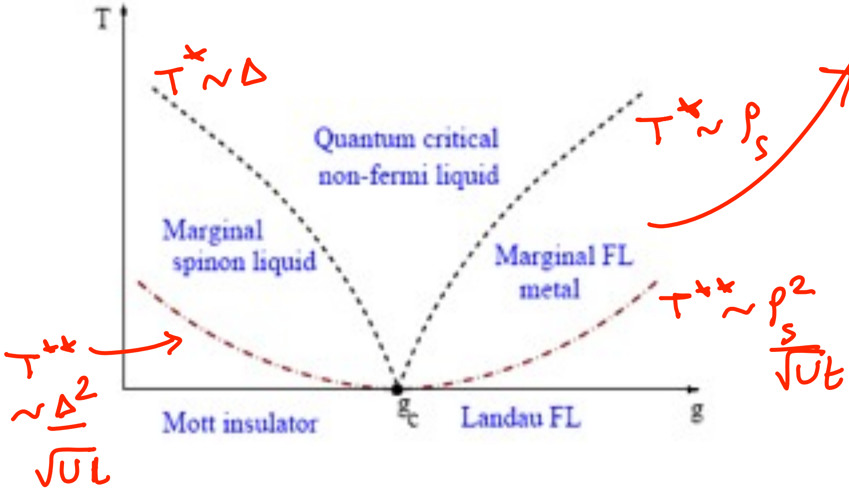
2. Fate of the electronic Fermi surface?

Concrete tractable theory of a continuous Mott transition;
demonstrate critical Fermi surface at Mott transition;
definite predictions for many quantities (TS, 2008).

Example: universal jump of residual resistivity on approaching from metal,
weak divergent effective mass,......

Finite-T crossovers: emergence of a Marginal Fermi Liquid

TS, 2008



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.

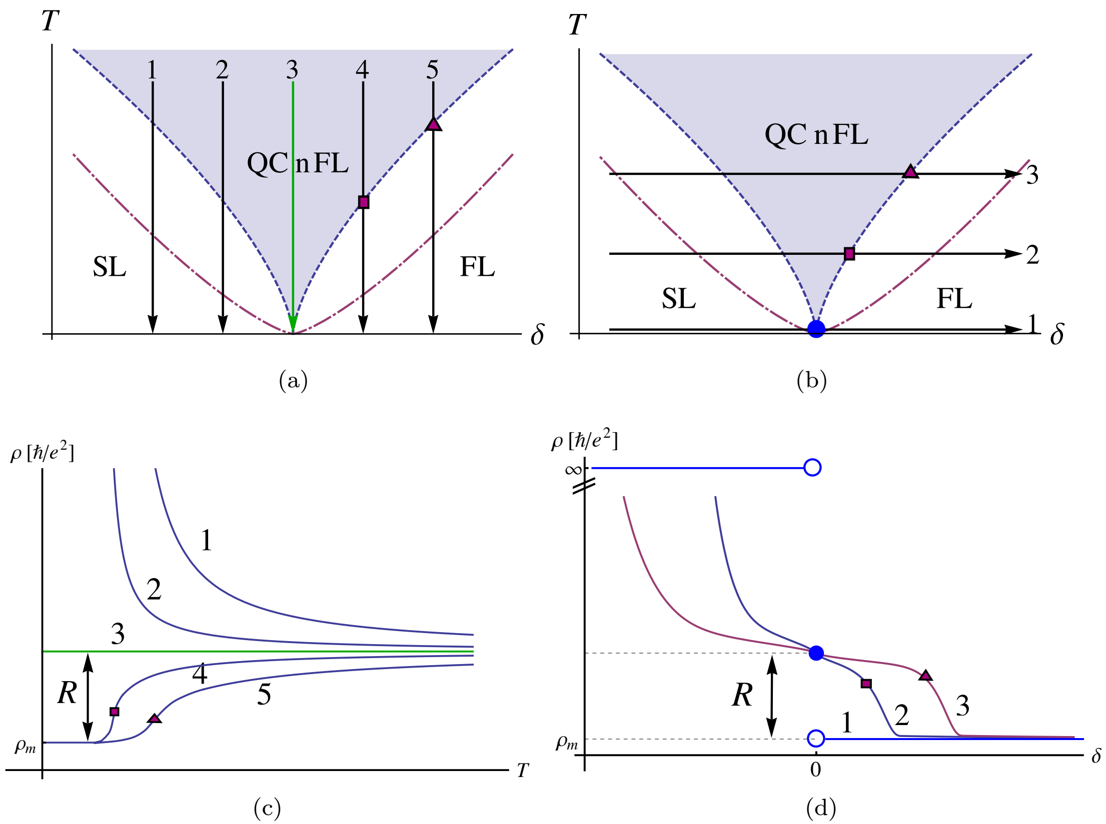
Universal transport in a large-N approximation (Witzcak-Krempa, Ghaemi, TS, Y.B. Kim, 2012):

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



$$\rho - \rho_m = \frac{\hbar}{e^2} G\left(\frac{\delta^{z\nu}}{T}\right) \qquad z = 1,\ \nu \approx 0.672$$

Part 2: Metal-insulator transitions in doped semiconductors

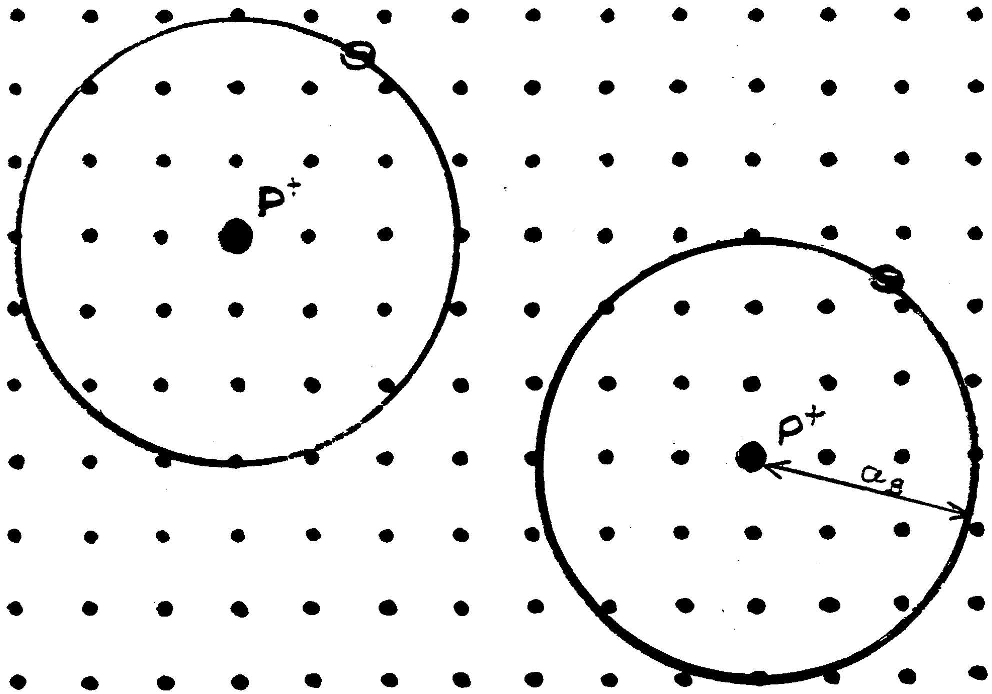
Eg: Si:P, Si:B

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)

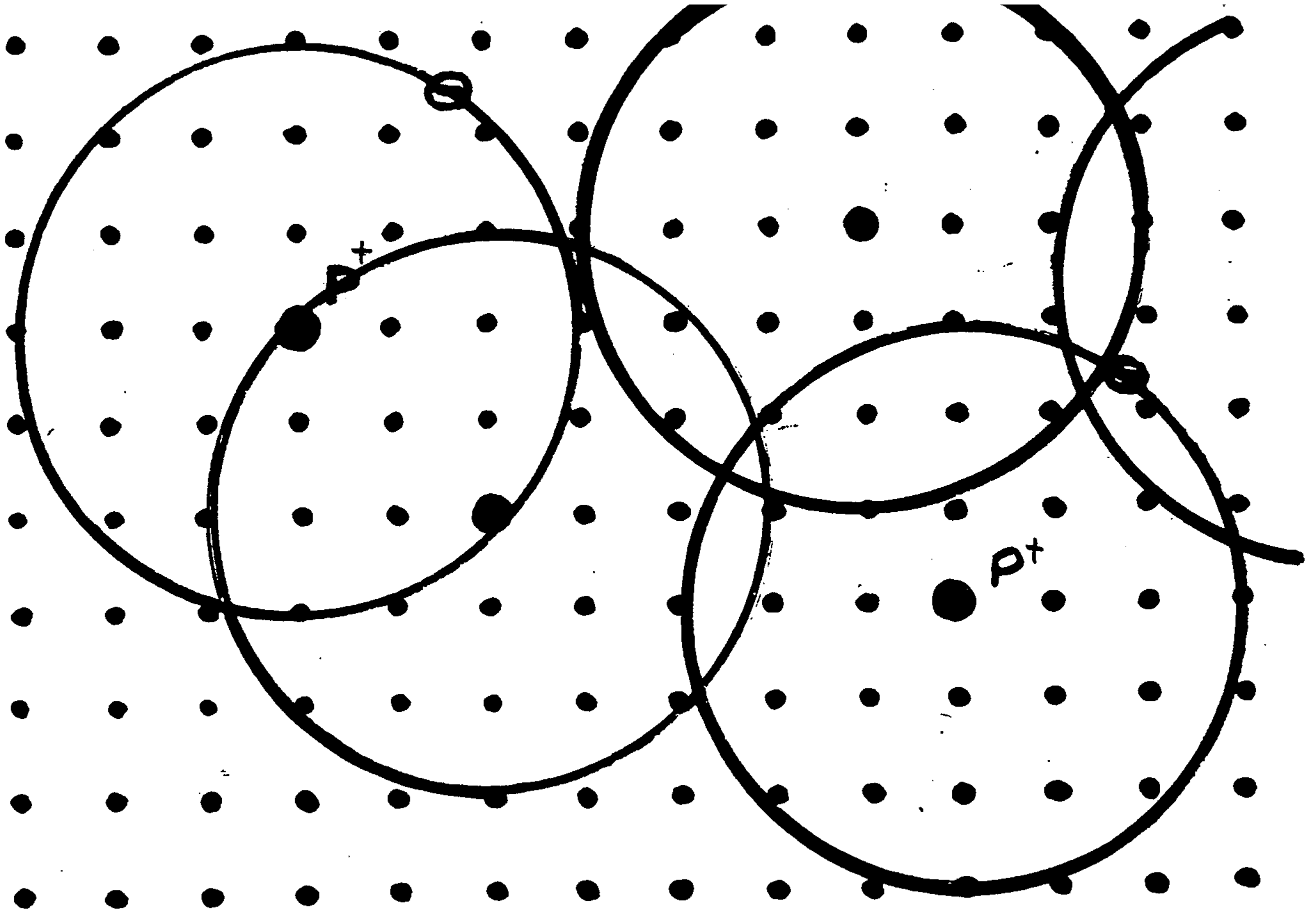


Extra electron of P forms a hydrogen-like state.

$$a_B \approx 20A$$

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.

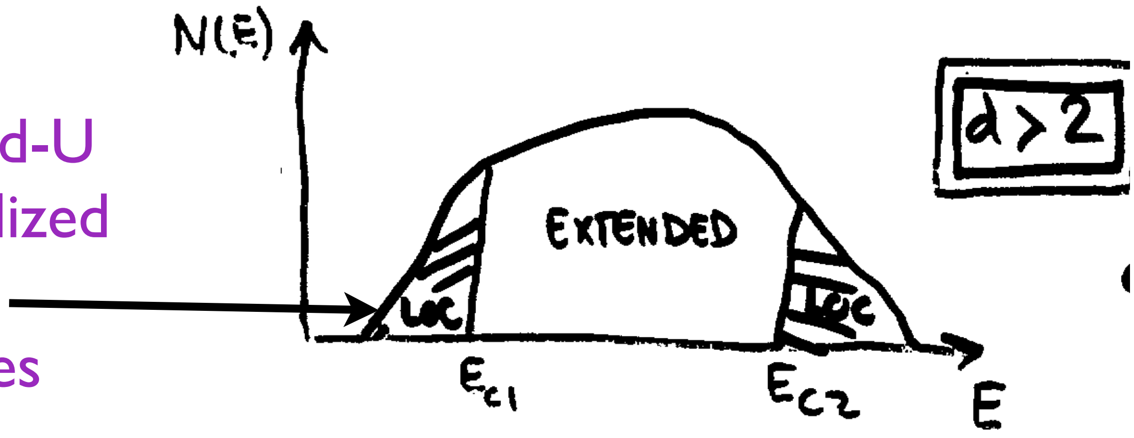
Broad distribution of singlet bond energies.

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

Metallic phase: persistence of some local moments

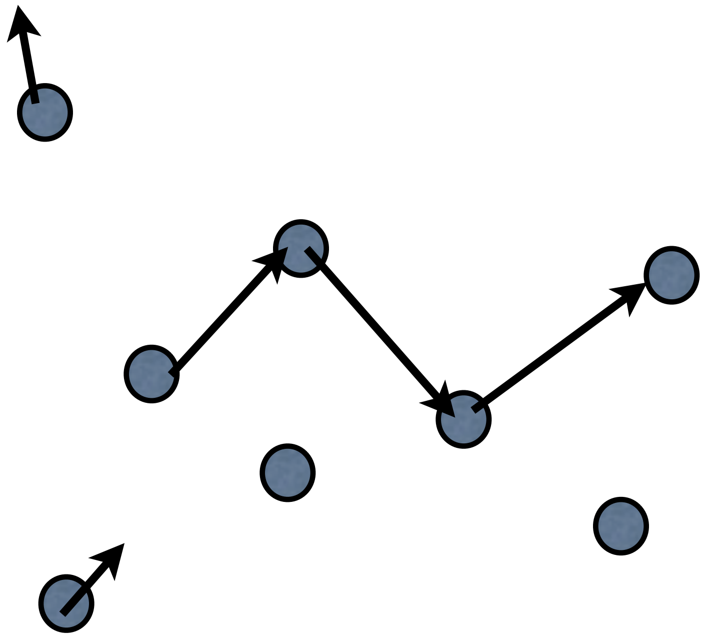
Near transition, some rare fraction of sites retain local moments which then dominate low-T thermodynamics.

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?

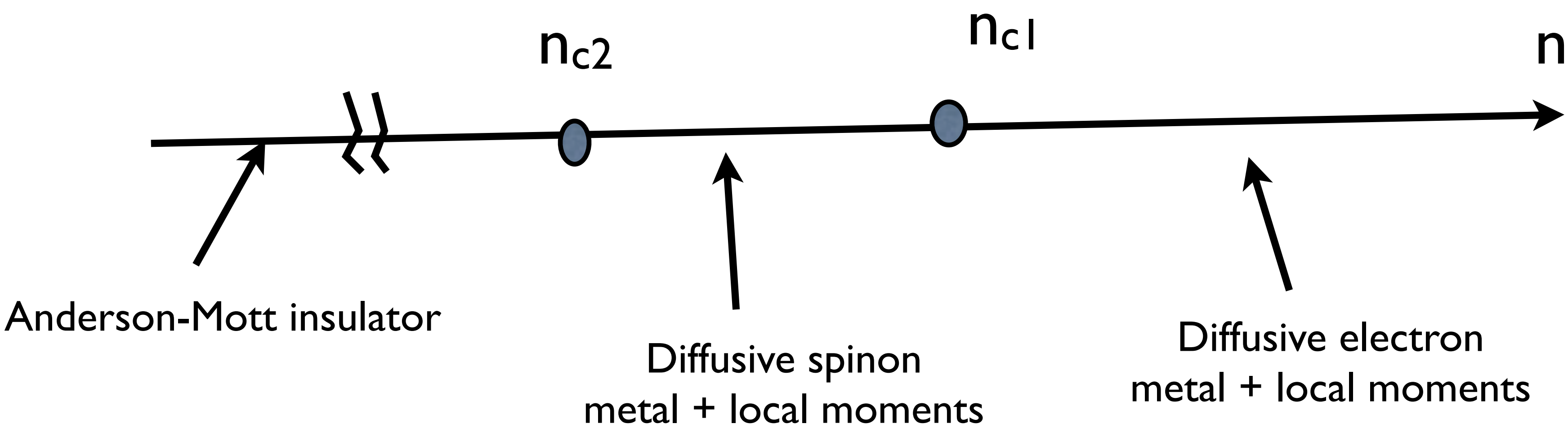
Three possibilities:

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

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

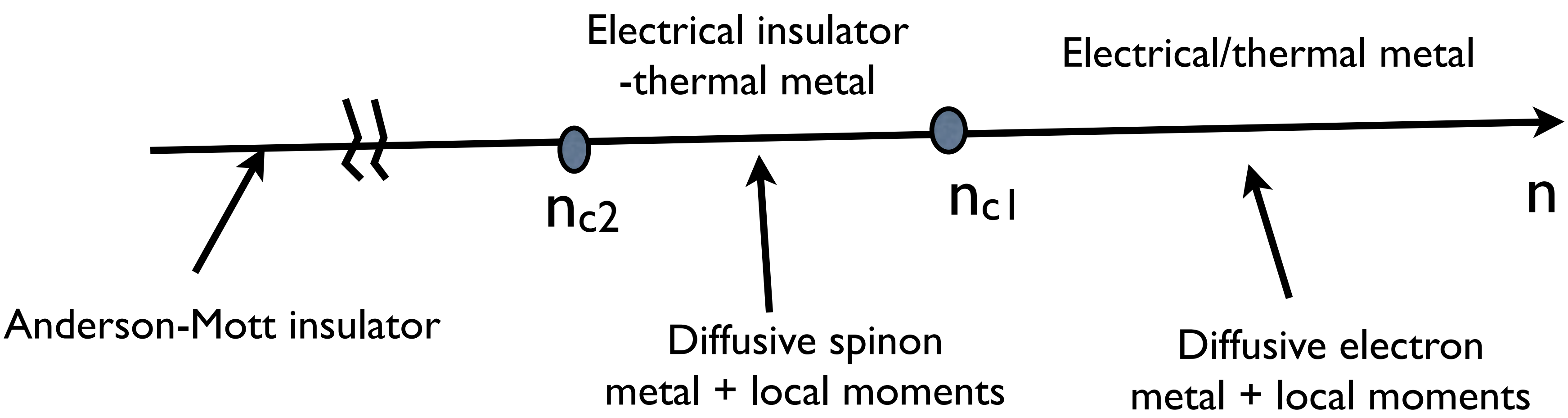
3. New possibility: Conducting fluid Mott localizes into a quantum spin liquid with diffusive spinons (Potter, Barkeshli, McGreevy, TS, 2012)

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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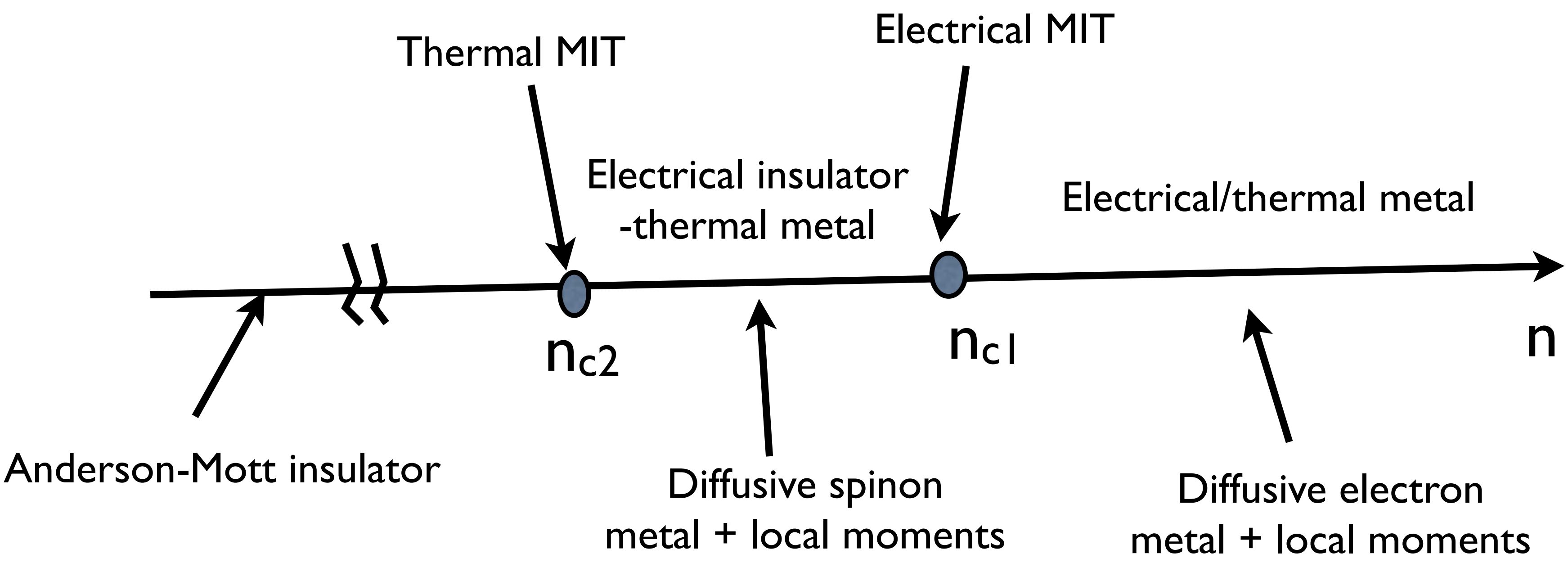
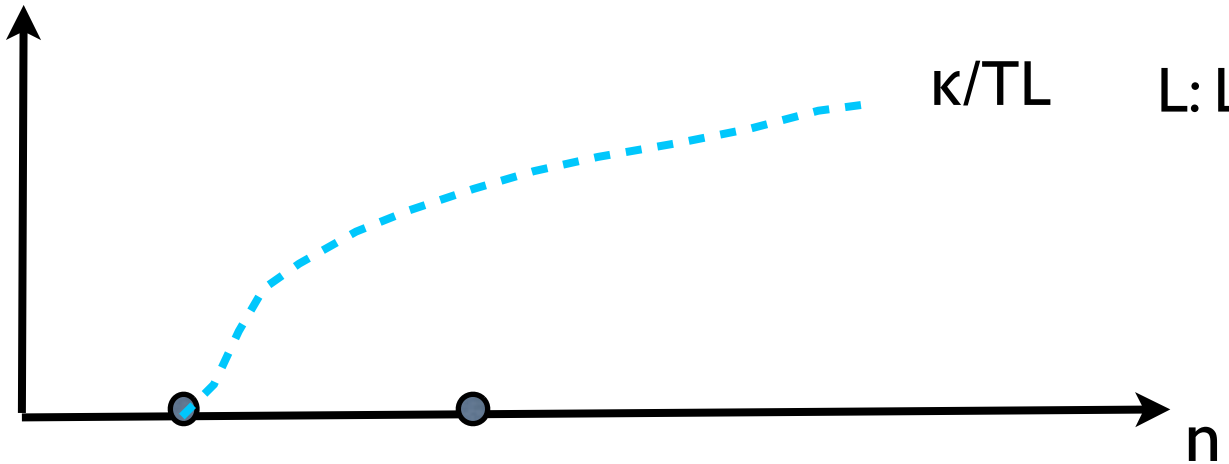


Crucial test: measure thermal transport in insulator.

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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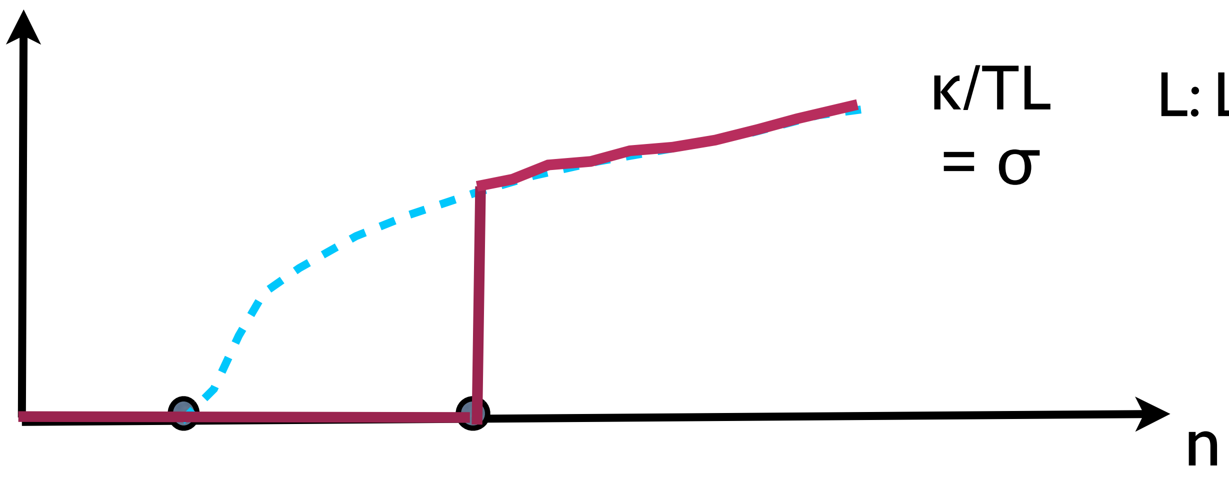

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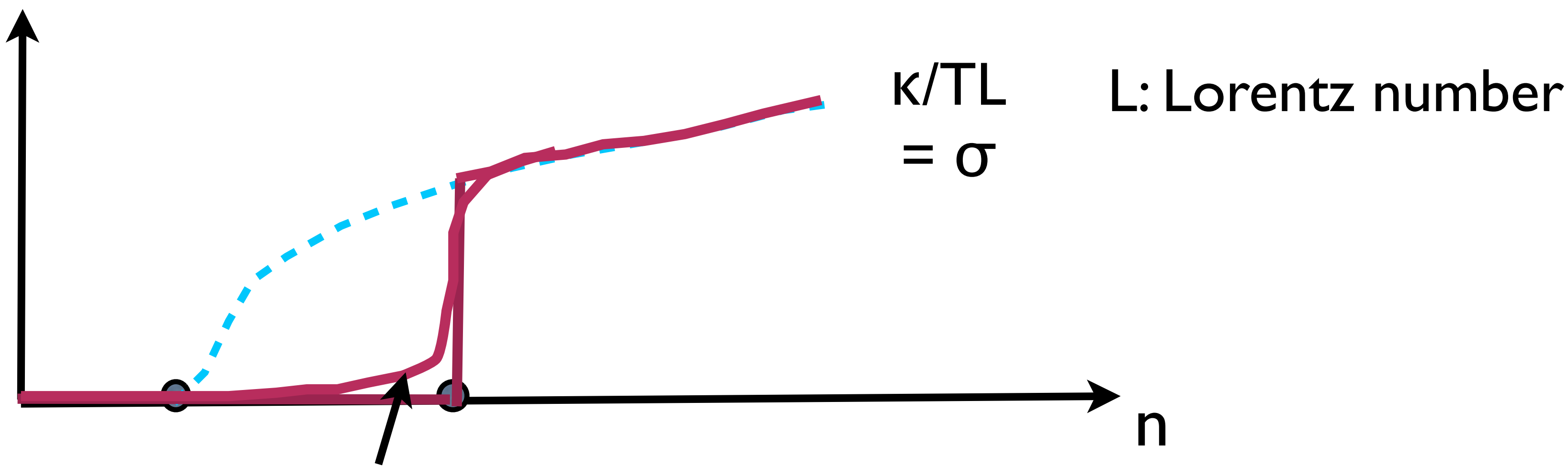

Thermal rounding of jump; complicates extrapolation to T=0 conductivity.

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?