Title: TBADeconfined metallic quantum criticality: a U(2) gauge theoretic approach

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Series: Condensed Matter

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Abstract: We discuss a new class of quantum phase transitions --- Deconfined Mott Transition (DMT) --- that describe a continuous transition between a Fermi liquid metal with a generic electronic Fermi surface and an insulator without emergent neutral Fermi surface. We construct a unified U(2) gauge theory to describe a variety of metallic and insulating phases, which include Fermi liquids, fractionalized Fermi liquids (FL*), conventional insulators and quantum spin liquids, as well as the quantum phase transitions between them. Using the DMT as a basic building block, we propose a distinct quantum phase transition --- Deconfined Metal-Metal Transition (DM2T) --- that describes a continuous transition between two metallic phases, accompanied by a jump in the size of their Fermi surfaces (also dubbed a 'Fermi transition'). We study these new classes of deconfined metallic quantum critical points using a renormalization group framework at the leading nontrivial order in a controlled double-expansion and comment on the various interesting scenarios that can emerge going beyond this leading order calculation.

Deconfined Metallic Quantum Criticality: A U(2) gauge theoretic approach

Liujun Zou

Debanjan Chowdhury

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

CONDENSED MATTER

I am complex but don't let that scare you off. Sometimes that means I'm scattered, but under great pressure, I can do amazing things. Exotic and unusual I'm looking for someone who can help harness my untapped potential

Hobbies: Packing lots of stuff into teeny, tiny spaces just to see what happens.

Likes: Liquids right now, but it's just a phase.

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“More is Richer”

(by William Blake)

To see a world in a grain of sand,

And a heaven in a wild flower,

Hold infinity in the palm of your hand,

And eternity in an hour.

Bottom line: Every quantum matter is an own universe.

Quantum phases of matter (as of 2020-02-18)

- Gapped
  - Short-range entangled (SRE)
    - trivial trivial (EX: product state)
    - symmetry-protected trivial (SPT) (EX: Haldane chain, bosonic integer QH)
  - Long-range entangled (LRE)
    - topological order (TO) (EX: Z_2 TO, chiral spin liquid)
    - fracton-like
- Gapless
  - Protected by spontaneously broken continuous symmetry (EX: crystals, Neel state)
  - Protected by symmetries (EX: Fermi liquid)
  - Protected by entanglement pattern (EX: 3D U(1) quantum spin liquid)

Quantum phase transitions: manifesto

- Universality class
- Intricate interplay among all moving parts
- Unified understanding of the phases and crossover

Quantum phase transitions: examples

- Spontaneous symmetry breaking in insulators

1. Landau-Ginzburg paradigm
2. Deconfined quantum criticality

- Metal-insulator transitions

1. Lifshitz transition: shrinking the FS
2. Senthil transition: turning an electronic FS into a neutral FS

Senthil's metal-insulator transition

$c_{1,2}$: spinful electron

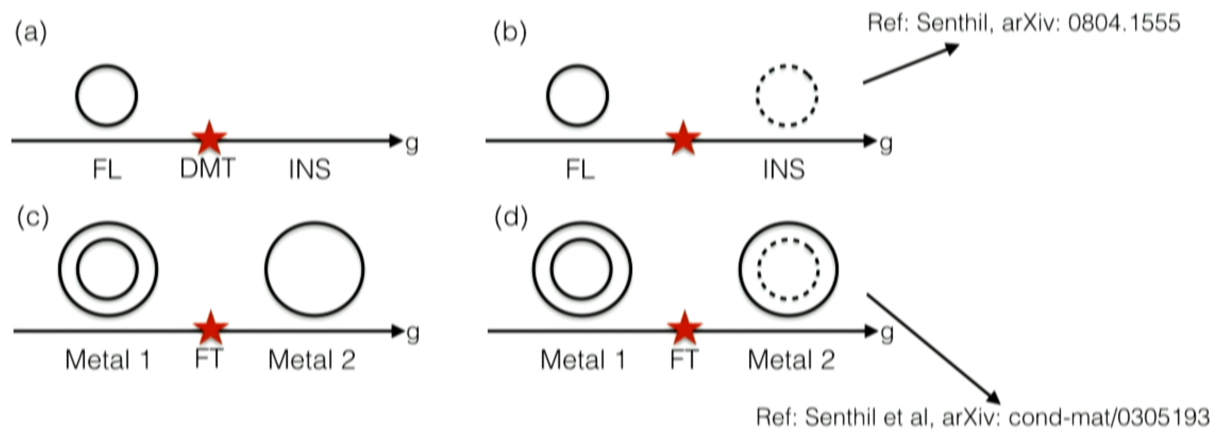
b : charged boson

$f_{1,2}$: spinful fermion

- Parton construction: $c_{1,2} = b \cdot f_{1,2}$
- U(1) gauge redundancy: $\begin{pmatrix} b \\ f \end{pmatrix} \to \begin{pmatrix} e^{-i\theta} \cdot b \\ e^{i\theta} \cdot f \end{pmatrix}$ ➡ emergent U(1) gauge field a
- Fermionic parton f: generic FS
- Bosonic parton b
  - condensed ➡ Higgs a ➡ FL
  - gapped ➡ FS coupled to a ➡ insulator with neutral ghost FS
- Transition: condensation transition of b

Ref: Senthil, arXiv: 0804.1555

Deconfined Metallic Quantum Criticality

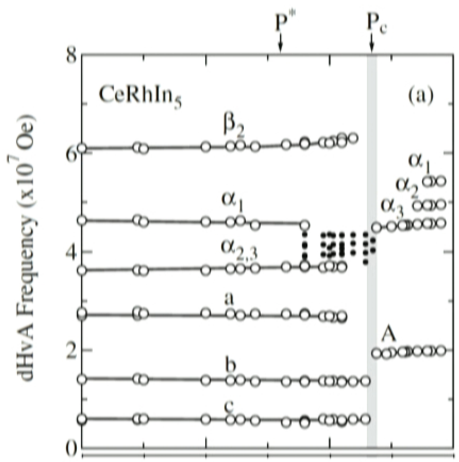


Deconfined Mott Transition (**DMT**): transition between a FL and an INS without NFS

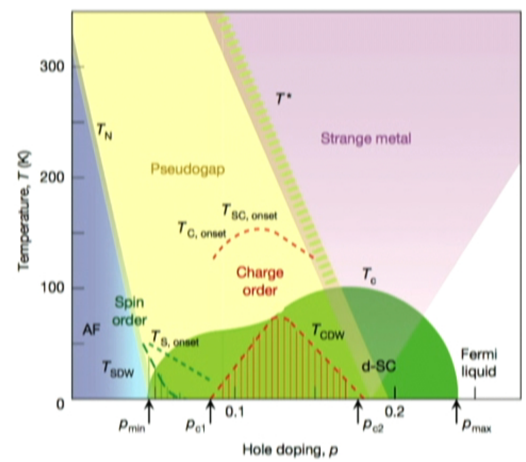
Fermi Transition (**FT**): transition between 2 metals with different sizes of FS
(aka **Deconfined Metal-Metal Transition**, **DM²T**)

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

Experimental motivations



CeRhIn5



Ref: Shishido et al, J. Phys. Soc. Jpn, **74**, 1103 (2005)
Keimer et al, arXiv: 1409.4673


WANTED!
Critical theories for
DMT & FT

Outline

- Introduction
- U(2) gauge theory
- Deconfined Mott transitions and Fermi transitions
- Renormalization group analysis
- Discussion

U(2) gauge theory: parton construction

$c_{1,2}$: Spinful electrons
B : Bosonic
f : Fermionic

- Parton construction $\begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix} \cdot \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}$
- U(2) gauge redundancy: $B \to BU^\dagger, \ f \to Uf$ ➡ emergent U(2) gauge field
- Symmetry assignment: $U(1) : B \to e^{i\theta} B, \quad f \to f$

$SU(2) : B \to VB, \quad f \to f$

$\mathcal{T} : B \to \epsilon B, \quad f \to f$

$\text{lattice} : B(\vec{r}) \to B(\vec{r}'), \quad f(\vec{r}) \to f(\vec{r}')$

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

U(2) gauge theory: metallic phases

- Fermionic parton f : generic Fermi surface
- Bosonic parton B: condense → Higgs U(2) gauge field → FL
- EX 1: $\langle B_{11}\rangle = \langle B_{12}\rangle = \langle B_{21}\rangle = -\langle B_{22}\rangle \neq 0$ → symmetric FL
- EX 2: $\langle B_{11}\rangle = 2\langle B_{22}\rangle \neq 0, \langle B_{12}\rangle = \langle B_{21}\rangle = 0$ → ferromagnetic FL

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

U(2) gauge theory: insulating phases

- f: pair up in the SU(2) singlet channel ➡ Higgs U(2) to SU(2)
- B: give it a gap ➡ gap of c ➡ insulator

1. Type-I: trivial trivial state of B ➡ confinement ➡ conventional INS
2. Type-II: SPT of B ➡ CS for SU(2) ➡ TO
3. Type-III: TO of B ➡ confinement ➡ TO
4. Type-IV: TO + SPT of B ➡ TO

- EX: bosonic integer QH of B ➡ chiral spin liquid

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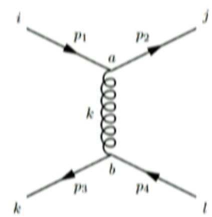
Deconfined Mott transition

- FL = condensed B + FS of f
- INS = gapped B + paired f
- DMT = gap out B + pair up f
- Can we do two things at a time?

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

Color superconductivity



SU(2) gauge field mediates attraction in the singlet channel

Simplified picture: $a = a^{\alpha} T^{\alpha} \rightarrow a^3 T^3$

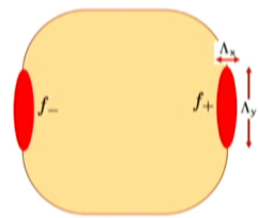
$T^3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ → $f_{1,2}$ carry opposite charges under a^3 → attraction

↓

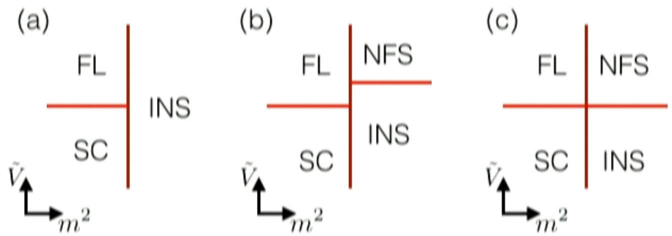
fermions will automatically pair up due to the SU(2)

Ref: Shovkovy, arXiv: nucl-th/0410091
Alford et al, arXiv: 0709.4635

What about U(2)?



- U(1): suppress pairing due to Amperean interaction
- Stable against pairing? ← Competition between U(1) and SU(2)



Assume SU(2) wins
(examine later)

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

Critical theory for DMT

assuming the insulator of B is type-I, and other types are analogous

$$S_{\mathrm{DMT}} = S_{[B,\mathbf{a}]} + S_{[B,f]} + S_{[f,\mathbf{a}]} + S_{[\mathbf{a}]}$$

$$\mathcal{L}_{[B,\mathbf{a}]} = \mathrm{Tr}\left(D^{\mu}_{\mathbf{a}} B^{\dagger} D^{\mu}_{\mathbf{a}} B\right) + m^2 \mathrm{Tr}\left(B^{\dagger} B\right) + \cdots$$

$$\mathcal{L}_{[B,f]} = \lambda_1 f^{\dagger} B^{\dagger} B f + \lambda_2 f^{\dagger} f \cdot \mathrm{Tr}\left(B^{\dagger} B\right) + \cdots$$

$$\mathcal{L}_{[f,\mathbf{a}]} = f^{\dagger}\left(-i\omega - \mu_f + i\mathbf{a}_0 + \epsilon^{f}_{\vec{k}+\vec{\mathbf{a}}}\right) f + V \cdot f^{\dagger} f f^{\dagger} f$$

$$\mathcal{L}_{[\mathbf{a}]} = \frac{1}{2e^2} \tilde{f}_{\mu\nu} \tilde{f}_{\mu\nu} + \frac{1}{2g^2} \mathrm{Tr}\left(f_{\mu\nu} f_{\mu\nu}\right)$$

Key: pairing of fermions is dangerously irrelevant at the criticality

(the U(1) gauge field is to make this possible)

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

A possible mechanism for FT

- Introducing cold electrons: d
- Combined system: $S_{\mathrm{FT}} = S_{\mathrm{DMT}} + S_{[d]} + S_{[c,d]}$

$S_{[d]}$: generic FS

$S_{[c,d]} = \int d\tau d^d x \lambda d^\dagger B f + \mathrm{h.c.}$

Key: cold electrons are spectators to the DMT of the hot electrons
($S_{[c,d]}$ is dangerously irrelevant at the DMT of the hot electrons)

Ref: **Zou**, Chowdhury, arXiv: 2002.02972


WANTED!
Justification

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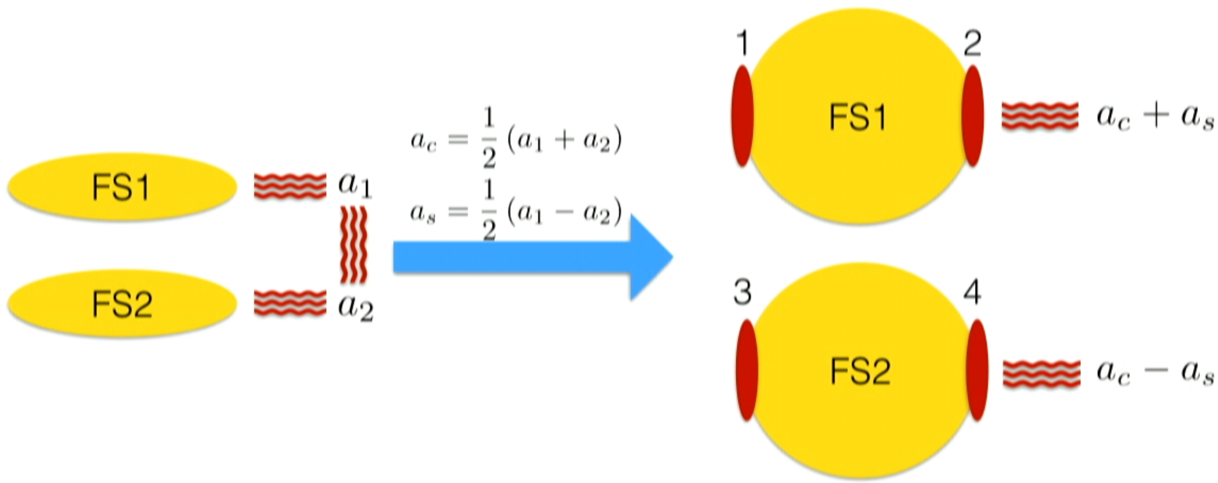
Are FS coupled to a U(2) gauge field stable against pairing?

Simplified version: U(1) x U(1) gauge theory

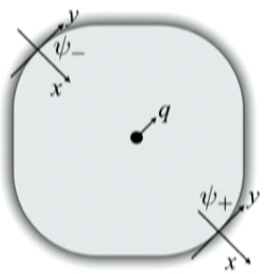


a_c generates repulsive Amperean interaction for all patches
a_s generates attractive Amperean interaction for (1, 4) and (2, 3)

a_c : suppress pairing
a_s : promote pairing
competition → stability

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

Patch formulation



focus on the coupling between antipodal patches on the FS and the transverse gauge fields

Ref: Lee, arXiv: 0905.4532
Metlitski et al, arXiv: 1001.1153
Mross et al, arXiv: 1003.0894

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_{[a_c, a_s]}$$

$$\mathcal{L}_f = \sum_{p=\pm, \alpha=1,2} \psi^\dagger_{\alpha p} \left[\eta\partial_\tau - ip\partial_x - \partial_y^2\right] \psi_{\alpha p} - \sum_{p=\pm} p \left[(a_c + a_s)\, \psi^\dagger_{1p}\psi_{1p} + (a_c - a_s)\, \psi^\dagger_{2p}\psi_{2p}\right]$$

$$\mathcal{L}_{[a_c, a_s]} = \frac{N}{2e_c^2}|k_y|^{1+\epsilon}|a_c|^2 + \frac{N}{2e_s^2}|k_y|^{1+\epsilon}|a_s|^2$$

Dimensionless gauge couplings: $\alpha_{c,s} = \dfrac{e^2_{c,s}}{4\pi^2\eta\Lambda^\epsilon}$

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

Results at the leading nontrivial order

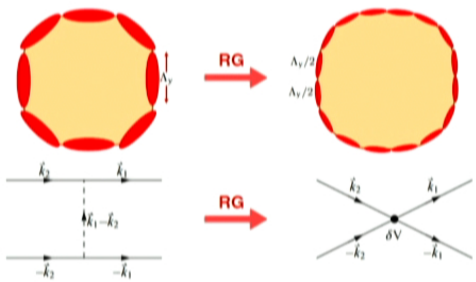
$$\beta(\alpha_c) = \left(\frac{\epsilon}{2} - \frac{\alpha_c + \alpha_s}{N}\right) \cdot \alpha_c$$
$$\beta(\alpha_s) = \left(\frac{\epsilon}{2} - \frac{\alpha_c + \alpha_s}{N}\right) \cdot \alpha_s$$

$\Rightarrow$ $\beta\left(\frac{\alpha_c}{\alpha_s}\right) = 0$ $\Rightarrow$

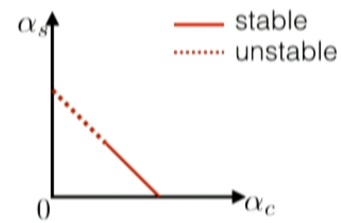
$$\alpha_{c*} = \frac{\epsilon N}{2} \cdot \frac{r}{r+1}$$
$$\alpha_{s*} = \frac{\epsilon N}{2} \cdot \frac{1}{r+1}$$

(nontrivial fixed line)

$(r = \alpha_c/\alpha_s)$



$\Rightarrow$ $$\beta(\widetilde{V}) = \frac{\alpha_c - \alpha_s}{N} - \widetilde{V}^2$$



Ref: Metlitski et al, arXiv: 1403.3694

Bottom line: stability depends on details $\begin{cases} \text{unstable, } r < 1 \\ \text{perturbatively stable, } r \geqslant 1 \end{cases}$

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

U(2) gauge theory: quasi-Abelianization

- Potential complications due to the non-Abelian nature:

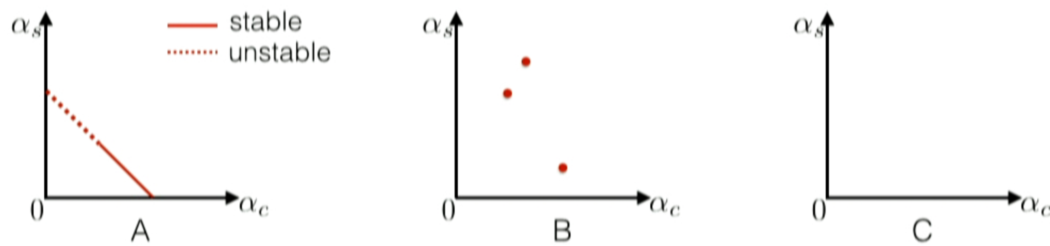
1. self-interaction among gluons
2. coupling to the Faddev-Popov ghosts

- Simplification: both are irrelevant in the patch formulation
- Results: similar to the U(1) x U(1) problem

1. in the 2-patch theory there is a nontrivial fixed line
2. stability depends on the ratio of the U(1) and SU(2) couplings

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

Discussion: what happens to the fixed line



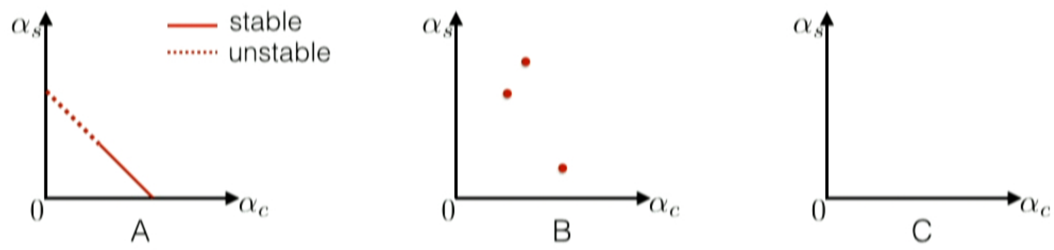
- Scenario A: robust → fascinating new quantum spin liquids
- Scenario B: collapse into some fixed points
- Scenario C: disappear altogether

Ref: **Zou**, Chowdhury, arXiv: 2002.02972

Summary

- A powerful U(2) gauge theory
- Possible mechanisms for DMT and FT
- RG analysis at the leading nontrivial order

Discussion: what happens to the fixed line



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