Kondo Breakdown and a possible connection with Strange and Bad metals.

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FIG. 1. (a) The uniform frequency domain is

(B) shows the local

characteristic fluctuation temperature

the transport decay rate at

the increase in

the properties of other materials and theories of

It is instructive to compare our findings with

This gives us an important clue as to how magnetic field

First, an AF instability is present in all three

and thus the WF law to prevail, as found here for

Second, CeCoIn

3

is a candidate for the anisotropic quantum criticality

The characteristic spin fluctuation temperature

The holon modes have an emergent coupling to the elec-

trons and

To obtain a rough estimate of this quantity, we can replace

Approaching the

Near the pressure-tuned QCP where its AF

The peak position is unchanged (unlike the 1D FM case

we discuss in the following.

The results of a single-iteration of these equations.

although we have numerically obtained the solution to

$\mu/T \propto \log\left[\cos 2\pi T/T_c\right]$ at each site of the chain, in which the electrons and

Z

N

cte

$c$

$B$

$G$

$q$

$K$

$T/T_c$}
• Heavy Fermions: tunable strange metals
• Schwinger Bosons and the Kondo Lattice
• Quantum Criticality in a simple KL
• Possible link with Strange Metals

Yashar Komijani & PC PRL 122, 217001 (2019)
spin susceptibility but the uniform susceptibility is only sup-gap size, bringing the gap edge close to the chemical potential shifts to positive frequencies and, maintaining overall a phase shift which each sublattice is in the symmetric spin-QCP implies a zero-point entropy due to entropy balance. Again, this momentum sum can be done analytically to obtain $K_T = J/z! J/dS/dT$ at the QCP. The Fermi liquid (blue) exhibits $T/T_J = J^2_{\phi}(\nu)$ from a decrease of the energy scale $J^2_{\phi}(\nu)$ as $\nu$. As $\nu$, the collapse of the energy scale, consistent with a zero-point collapse to a single curve that is well described by a scaling analysis $[5, 15-17]$. For $T/T_J = J^2_{\phi}(\nu)$, this quantity perfectly can-
Heavy Fermions: Tunable Strange Metals
Strange Metals: Electrons at the Brink of Localization

- Mystery of Linear resistivity in strange metals

![Graph showing linear resistivity vs. temperature for different materials](image)

- **Cuprates**: $T_c = 11 - 92$ K

![Diagram showing periodic table and magnetic moments](image)

- Increasing localization
- Magnetic moments
- Superconductivity
Strange Metals: Electrons at the Brink of Localization

- Mystery of Linear resistivity in strange metals

**Graphical Content:***

- **Graph of $\rho_{ab}$ vs. $T$** (Takagi et al, PRL '92)
- **Diagram of magnetic moments** showing superconductivity
- **Cuprates** $T_c = 11-92$K
- **Iron-based SC** $T_c = 5-65$K $\text{BaFe}_2\text{As}_{2-x}\text{P}_x$ ($x=0.31$)

**Equation 1:**

\[
\rho(T) = \rho(0) + \frac{\alpha}{T}
\]

**Note:**

Although we cannot account for this in our ansatz, we observe that for any combination of field and temperature each influence the scattering, it is possible to relate the scattering rate directly to the temperature dependence of the optical conductivity in URu$_2$Si$_2$. This suggests a revision of the functional form of the resistivity, which appears as sub-linear behavior in magnetic field, choosing the lowest temperature curve so that magnetic field is certain to be a cross over from unconventional Fermi liquids [4]. This is indeed observed, as can be seen by comparing the data to collapse to a single curve that is well described by a hyperbolic function of $B/T$. Note that we remove the residual resistivity $\rho(0)$ and other unconventional superconductors [19, 27, 28].

**Fig. 1.**

(A) $\rho(T)$ for a fixed magnetic field.

(B) $\rho(T)$ for fixed magnetic field.

**Table:***


**Increased Localization vs. Magnetic Moments**

**Increasing Localization vs. Magnetic Moments**
Strange Metals: Electrons at the Brink of Localization

- Mystery of Linear resistivity in strange metals

Cuprates $T_c=11-92K$
Heavy Fermions: Tunable Strange Metals

- Mystery of Linear resistivity in strange metals
- Heavy Fermions: highly tunable.

Cuprates Tc=11-92K

CeCoIn$_5$

![Diagram showing the resistivity of CeCoIn$_5$ as a function of temperature and magnetic field. The graph shows a clear linear relationship between resistivity and temperature at various magnetic fields, with a sharp transition at 5.3 T.]
• Mystery of Linear resistivity in strange metals
• Heavy Fermions: highly tunable.
• Link with Quantum Criticality
Extrapolating the isothermal crossover to lower temperatures provides evidence that the quasiparticle residues vanish at the QCP, for inter-plane transport. However, the magnetic moments of the antiferromagnetic fluctuations that are characterized by a power law at high symmetries and field-tuned QCP of YbRh$_2$Si$_2$ can be viewed as the result of AF fluctuations in 3D prompted the proposal of a 2D quantum phase diagram, strong anisotropy, multiple energetics and incommensurate along the c-axis but not in the plane. As a result, the break-down of the Fermi surface can also cause an instability of the Fermi surface can also cause mass divergences at QCP, for inter-plane transport. Recent calculations have shown that the WF law is violated near the pressure-tuned QCP where its AF order vanishes ($T_c = 5.3$). Indeed, as temperature is lowered, the full width at half maximum resistivity is observed in CeRhIn$_5$. In this scenario, critical fluctuations in the resistivity are expected to be described by a $T^2$ dependence, and incommensurate along the c-axis but not in the plane. As a result, the breakdown of the Fermi surface can also cause mass divergences at QCP, for inter-plane transport. This is consistent with the helical ordering of CeRhIn$_5$, which is characterized by a $T^2$ dependence.

The full width at half maximum resistivity is observed in CeRhIn$_5$. In this scenario, critical fluctuations in the resistivity are expected to be described by a $T^2$ dependence, and incommensurate along the c-axis but not in the plane. As a result, the breakdown of the Fermi surface can also cause mass divergences at QCP, for inter-plane transport. This is consistent with the helical ordering of CeRhIn$_5$, which is characterized by a $T^2$ dependence.
Figure 2: Jump of Fermi surface across the critical pressure in CeRhIn$_5$, observed by dHvA measurements (adapted from [11]).

Upper critical field for superconductivity. Quantum oscillations have been observed by de Haas–van Alphen (dHvA) measurements at various pressures at magnetic fields between 10 T and 17 T [11]. A jump of the Fermi surface has been evidenced by the observation that the dHvA frequencies undergo a jump at the critical pressure $p_c$. The dHvA frequencies are compatible with a small Fermi surface in the antiferromagnetically ordered state at $p < p_c$, and with a large Fermi surface in the paramagnetic state at $p > p_c$. The dHvA measurements also indicate that the cyclotron mass diverges at $p_c$, providing evidence that the quasiparticle residues $z_L$ and $z_S$ indeed vanish at the QCP, see Fig. 1, bottom.

4. Extrapolating the isothermal crossover to lower temperatures

For YbRh$_2$Si$_2$, the isothermal crossovers as a function of magnetic field $B$ have been studied between 0.02 K and 1 K. The pertinent measurements include magnetotransport, Hall effect and magnetoresistance, as well as thermodynamic properties, including magnetization and magnetostriction. To draw conclusions about the nature of the QCP, the efforts have been directed towards the evolution of the isothermal crossover behavior as temperature is lowered. The lowest temperature of the studies is about 20 mK [15]. Importantly, as temperature is lowered, the full width at half maximum

$C/T \sim S_0/T^* \ln(T^*/T)$

$S_0 \sim (0.1-0.3) \ R \ln 2$

Mass diverges at QCP
What happens to the charge fluctuations at a small-large FS transition?
YbRh$_2$Si$_2$

CeCoIn$_5$

“Kondo Breakdown”
“Partial Mott Localization”

What happens to the charge fluctuations at a small-large FS transition?
What are the requirements for strange metal behavior?
β-YbAlB₄: Effect of Pressure

T. Tomita, K. Kuga, et al.

Science 349, 506 (2015)

Resistivity under pressure (piston/cubic anvil)

\[ \Delta \rho \sim T^\alpha \]

![Graph showing resistivity vs. temperature under pressure](image)
CeRh$_6$Ge$_4$: Strange metal at a FM QCP


**A**

Strange metal behavior at a FM QCP

(Strong xy anisotropy: spin entanglement)
Strange Metals: Summary

- Ubiquity of strange metal behavior, in transition metal and rare-earth materials.
- Linear Resistivity can’t be explained by spin fluctuations
- Logarithmic C/T~ \( S_0/T^* \log_e(T^*/T) \).
- AFM QCP not necessary: Kondo breakdown in FM in CeRh\(_6\)Ge\(_4\) and away from QCP in YbAlB\(_4\)
- Common feature: partial Mott localization/Kondo Breakdown
Schwinger Bosons and the Kondo Lattice
Kondo Lattice: introduction

\[ H = J_H \sum_{(i,j)} \vec{S}_i \cdot \vec{S}_j \]

QCP:
Transformation in pattern of entanglement

Doniach, 1976
AFM/Spin Liquid

\[ T_K \sim D \exp \left[ -\frac{1}{J_H} \right] \]

Kondo Singlet
Simplified Kondo Lattice

\[ H = J_H \sum_{(i,j)} \vec{S}_i \cdot \vec{S}_j + \sum_j H_c(j) + J_K \sum_j \vec{\sigma}_j \cdot \vec{S}_j \]

Each magnetic site has its own conduction screening bath. The model captures the essential competition between magnetic and Kondo entanglement.

Doniach, 1976

AFM/Spin Liquid

Fermi Liquid

QCP
Schwinger Bosons and the Kondo Lattice

\[
\hat{S}_j = b_j^\dagger \left( \frac{\sigma}{2} \right) b_j
\]
Schwinger Bosons and the Kondo Lattice

**Parcollet-Georges Approach**

**Arovas Auerbach Approach (Large N)**
D. P. Arovas and A. Auerbach, PRB 38, 316 (1988).

\[ J_H \mathbf{\hat{S}}_i \cdot \mathbf{\hat{S}}_j \longrightarrow \left[ \tilde{\Delta}_{ij}(\tilde{\sigma}\bar{b}_j\bar{\sigma}_i b_{i\sigma}) + H.c \right] + \frac{N|\Delta_{ij}|^2}{J_H} \]

Captures the physics of fluctuating magnetism in one and two dimensions as a bosonic RVB.

\[ \mathbf{S}_j = b_j \left( \frac{\hbar^2}{2} \right) b_j \]
Schwinger Bosons and the Kondo Lattice

Parcollet-Georges Approach

\[ J_H \vec{S}_i \cdot \vec{S}_j \rightarrow \left[ \bar{\Delta}_{ij} (\vec{\sigma} b_j \bar{\sigma} b_i \sigma) + \text{H.c} \right] + \frac{N|\Delta_{ij}|^2}{J_H} \]

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Arovas Auerbach Approach (Large N)
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\[ \vec{S}_j = b_j^\dagger (\frac{\vec{\sigma}}{2}) b_j \]
Schwinger Bosons and the Kondo Lattice

\[ \hat{S}_j = b_j^\dagger \left( \frac{\hat{\sigma}}{2} \right) b_j \]

**Parcollet-Georges Approach**


\[ H_K(j) \rightarrow [(b_{j\alpha}^\dagger \psi_{j\alpha}) \chi_{ja} + \text{h.c}] + \frac{N \bar{\chi}_{ja} \chi_{ja}}{J_K} \]

Treats the Kondo effect as an fractionalization of spins into heavy electrons and Kondo singlets

**Arovas Auerbach Approach (Large N)**

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\[ J_H \hat{S}_i \cdot \hat{S}_j \rightarrow \left[ \bar{\Delta}_{ij} (\bar{\sigma} b_{j\bar{\sigma}} b_{i\sigma}) + \text{H.c} \right] + \frac{N|\Delta_{ij}|^2}{J_H} \]

Captures the physics of fluctuating magnetism in one and two dimensions as a bosonic RVB.
Schwinger Bosons and the Kondo Lattice

**Parcollet-Georges Approach**

\[
\hat{S}_j = b^\dagger_j \left( \frac{\hat{\sigma}_j}{2} \right) b_j
\]

\[
\Sigma_b(\omega) = \chi
\]

spinon self-energy

\[
\Sigma_\chi(\omega) = \chi
\]

holon self-energy

**Diagram:**
- Large, heavy FS
- \(-(Q + n_c) e\)
- Kondo singlets: \(+Qe\)
- Faithfully captures
- Fully screened FL

\(\chi(T)\)

\(\frac{C_v}{T}\)

**Figures:**
1. Spinon self-energy
2. Holon self-energy
3. Large, heavy Fermi surface
4. Kondo singlets

\(k=0.7\)
\(k=0.5\)
\(k=0.3\)

\(T/T_K\)

\(W^2\)
Schwinger Bosons and the Kondo Lattice

Parcollet-Georges Approach

\[ H_K(j) \rightarrow [(b_{j\alpha}^{\dagger} \psi_{ja\alpha}) \chi_{ja} + \text{h.c}] + \frac{N\bar{\chi}_{ja} \chi_{ja}}{J_K} \]

Kondo effect as an fractionalization of spins into heavy electrons and Kondo singlets (holons)

\[ \Sigma_b(\omega) = \]

spinon self-energy

\[ \Sigma_\chi(\omega) = \]
holon self-energy

(a)

small, light FS

-\( n_c e \)

(b)

large, heavy FS

-(\( Q + n_c \)) e

Kondo singlets: +\( Qe \)
Schwinger Bosons and the Kondo Lattice

Parcollet-Georges Approach

\[ \tilde{S}_j = b_j^\dagger \left( \frac{\sigma^z}{2} \right) b_j \]

\[ \Sigma_b(\omega) = b \text{ spinon self-energy} \]

\[ G(q, \omega) = \left[ (\omega \tau_3 - \lambda - i\Delta_q \tau_2) - \Sigma_b(\omega) \right]^{-1} \]

Arovas Auerbach Approach (Large N)
D. P. Arovas and A. Auerbach, PRB 38, 316 (1988).

Unified approach

Captures the physics of fluctuating magnetism in one and two dimensions as a bosonic RVB.
Application to 1D Kondo Lattices
**Schwinger Boson approach to the KL**

\[ H = \sum_j \left[ H_C(j) + J_K \vec{S}_j \cdot \vec{\sigma}_j + J_H \vec{S}_j \cdot \vec{S}_{j+1} \right]. \]

**Yashar Komijani & PC PRL 122, 217001 (2019)**

[Diagram of 1D Kondo lattice]

**Simplified 1D Kondo Lattice**

**Doniach, 1976**

AFM/Spin Liquid

QCP

Fermi Liquid

**FIG. 1.** (color online) (a) Model 1D Kondo lattice, with local moment. (b) The conduction electron phase shift cuts showing the accumulation of entropy at the QCP.

**FIG. 2.** (color online) (a) Calculated spectral function of spinons from SL (in green) and FL (in red). The conduction electron phase shift cuts showing the collapse of energy scales at the QCP. Watanabe and Miyake have argued that the deconfined spinons are protected by an emergent charge mode, directly associated with the break-up of Kondo singlets.

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**Emergent critical charge fluctuations at the Kondo breakdown of Heavy Fermions**

The Kondo effect has long fascinated the physics community. In the eighties, Anderson introduced the concept of a ferromagnetic (AFM) quantum critical point (QCP), a phase transition that accompanies heavy fermion criticality and leads to critical charge fluctuations.

In this perspective, a shift in nominal valence is associated with a change in the Kondo screening conditions. From the core-level valence, inferred from spectroscopy, the Kondo lattice in which each moment is connected to a separate conduction bath, we show a Kondo breakdown that arises from the localization of the virtual valence fluctuations.

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Numerical and experimental studies testify to the role of valence fluctuations in the emergence of this Kondo breakdown.

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- The relation between valence fluctuations and Kondo breakdown is a natural consequence theoretically.

In the eighties, Anderson introduced the concept of a ferromagnetic (AFM) quantum critical point (QCP), a phase transition that accompanies heavy fermion criticality and leads to critical charge fluctuations. Using a model one dimensional, we discuss the possible implications of this emergent charge mode for experiment.

Numerical and experimental studies testify to the role of valence fluctuations in the emergence of this Kondo breakdown.
Schwinger Boson approach to the KL

Yashar Komijani & PC PRL 122, 217001 (2019)

\[ H = \sum_j \left[ H_C(j) + J_K \vec{S}_j \cdot \vec{\sigma}_j + J_H \vec{S}_j \cdot \vec{S}_{j+1} \right]. \]

“Jump in the Fermi Surface”
Schwinger Boson approach to the KL

Yashar Komijani & PC PRL 122, 217001 (2019)

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“Jump in the Fermi Surface”

Doniach, 1976

AFM/Spin Liquid

QCP

Fermi Liquid

Doniach, 1976

FIG. 1. (color online) (a) Model 1D Kondo lattice, with local moments using Schwinger bosons (“spinons”), \( \mathcal{a} \), examining the quantum phase transition transition

\[ \Delta > 0 \]

\[ \Delta = 0 \]

\[ C / T \]

\[ T / T_K \]

\[ T_K / J_H \]

\[ N_{\delta / \pi} \]

\[ T / T_K = 0.1 \]

\[ 0.05 \]

\[ 0.01 \]

\[ T_K / J_H \]

\[ \text{Hot} \]

\[ \text{Cold} \]
Schwinger Boson approach to the KL

\[ H = \sum_j \left[ H_C(j) + J_K \vec{S}_j \cdot \vec{\sigma}_j + J_H \vec{S}_j \cdot \vec{S}_{j+1} \right]. \]

Yashar Komijani & PC PRL 122, 217001 (2019)

“Jump in the Fermi Surface”

Doniach, 1976

AFM/Spin Liquid

Fermi Liquid

QCP

Global phase diagram showing the transition between heavy-electron phases at a QCP. (c) Conduction electron phase shift and has no quantum fluctuations, corresponding to a crossover from Curie law magnetization of a 1D FM system. (d) Shows the colormap of the entropy. Here we present an explanation of the Kondo screened one-dimensional (1D) AFM mean-field theory and simulated using dynamical dissipative transverse-field Ising model. Corresponding to scaling of the holon Green’s function.

A mean-field RVB description of the 1D magnetism is obtained, which can be done analytically. The holon Green’s function shows that the constraint is satisfied with a gap in the FL and SL, and deconfined with a soft excitation.

Global phase diagram (c) and (d) shows the colormap of the entropy. Here we present an explanation of the Kondo screened one-dimensional (1D) AFM mean-field theory and simulated using dynamical dissipative transverse-field Ising model. Corresponding to scaling of the holon Green’s function.
Yashar Komijani & PC PRL 122, 217001 (2019)

\[ \frac{N_\delta}{\pi} = \begin{cases} 0.1 & T/T_K = 0.1 \\ 0.05 & T/T_K = 0.05 \\ 0.01 & T/T_K = 0.01 \end{cases} \]

\[ T_K/J_H = 0.8, 1.2, 1.6, 2, 2.4 \]

\[ \text{Hot} \quad \text{Cold} \]

\[ \omega/T_K = \begin{cases} -2 & \omega/T_K = -2 \\ 0 & \omega/T_K = 0 \end{cases} \]

\[ T_K/J_H = 1, 2, 3 \]

\[ G''_x \]

\[ \text{gap} \]

holons crossing chemical potential

“Jump in the Fermi Surface”
“Jump in the Fermi Surface”
valence will give rise to an observable soft charge mode.

Quantum critical point, degenerate fluctuations in the nominal char-
tice where the core-level valence is fixed. Interpreted liter-

valence fluctuations and Kondo breakdown is a natural consequence

QCP is likely a result of a quantum-critical end-point, in

YbAlB

tiferromagnetic (AFM) quantum critical point (QCP), a phe-
collapse when Kondo screening is disrupted |

On the other hand, in heavy fermion systems, the Kondo-

spin-fluctuations, while leaving its charge essentially frozen.

and the Kondo effect has long fascinated the physics com-

spin susceptibility but the uniform susceptibility is only sup-
a characteristic peak at

a crossover from Curie law

temperature dependence of the staggered spin susceptibil-

S

cates a second order phase transition for the internal variable

trons) and the Fermi-liquid. From the perspective of conduc-

electron phase shift

formula for the entropy |

electron and holon phase shifts

body equations can be derived from a Luttinger Ward func-

gap of the size

emergent critical charge fluctuations at the Kondo break-down of Heavy Fermions

that accompanies heavy fermion criticality leads to critical charge fluctuations. Using a model one dimensional

vertex correction that couples to the electric potential as

potential as

representa-

at each site of the chain, in which the electrons and

lim, with

conduction electrons (d) and through Hall coefficient |

is varied between the above two limits, which

pressure protects topological phase |

U(1) gapped spin liquid |

Recently, a number of experiments have observed a coin-

Introduction

Magnetic excitations

S

=0

π

Nδc/π

Nδc/π

Tc/π

0

0.2

0.4

0.6

0.8

1

1.2

1.6

2

2.4

0

0.05

0.1

0.01

Hot

Cold

10K

8K

6K

4K

2K

0

holons crossing

chemical potential

gap

t

χa

δμ

cαα

bα

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Holons Develop a Physical Charge

\[ \chi_c \sim \frac{n_h e^2}{k_B T} \]

\( \frac{T}{T_K} = 0.0075 \ldots 0.05 \)

\( \omega/T \) scaling at the QCP.
A possible link between Kondo Breakdown and Strange Metals
New Rule: Strange Metals are Bad Metals

Ubiquitous linear resistivity of strange metals is often regarded as a result of a marginal Fermi liquid with a Planckian relaxation time.

\[ \tau = \frac{\hbar}{k_B T} \]


But the linear resistivity continues unabated from the strange metal regime to the bad metal regime.
New Rule: Strange Metals are Bad Metals

Measurement of conductivity in optical trap Hubbard model using Einstein-Nernst equation.

$$\sigma = D\chi_c$$
New Rule: Strange Metals are Bad Metals

Measurement of conductivity in optical trap Hubbard model using Einstein-Nernst equation.

\[ \sigma = D \chi_c \]

At high temperatures the incoherent transport is classical, with

\[ D = \frac{l^2}{\tau} = \frac{\hbar}{m} \quad \chi_c = \frac{ne^2}{k_B T} \]

\[ \Rightarrow \sigma = \left( \frac{ne^2}{m} \right) \frac{\hbar}{k_B T} \]
New Rule: Strange Metals are Bad Metals

Remarkably, even though $\chi$ departs from its high temperature Curie law, and $D$ becomes temperature dependent, the resistivity remains linear to low temperatures.

Does the linear resistance derive from an underlying classical gas of gapless holons formed at the QCP?

Resistors in Series

$R = R_h + R_e \sim AT + C$?

cf Ioffe Larkin

$\Rightarrow \sigma = \left( \frac{ne^2}{m} \right) \frac{\hbar}{k_B T}$
Kondo Breakdown and a possible connection with Strange and Bad metals: **Conclusions**

- Ubiquity of strange metal behavior, in transition metal and rare-earth materials.

- Common feature appears to be the partial Mott localization. AFM not necessary.

- Schwinger Boson Scheme allows unification of magnetic and Kondo entanglement physics

- Emergent charge fluctuations associated with small to large FS transition (Kondo breakdown/Mott) may have a link with the linear resistivity of Strange Metals.
Thank you!