Pseudogapped non-Fermi liquid phase arising from Kondo breakdown at the Mott transition

What lies between a Fermi liquid and a Mott insulator in 2D?

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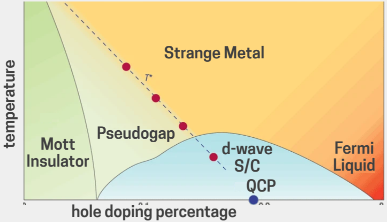
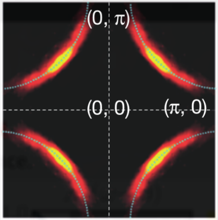
Some Questions

The anomalous **pseudogap** (PG) phase exhibits nodal-antinodal dichotomy.

No general consensus yet regarding

- its **relation** to the Mott insulating and superconducting phases proximate to it
- how it **evolves** from weak-coupling to strong-coupling
- whether the **nodal-antinodal dichotomy** is intrinsic to the model





Keimer et al. 2015; Proust and Taillefer 2019; Loeser et al. 1996; Norman et al. 1998; Hashimoto et al. 2014; Kyung et al. 2006; Macridin et al. 2006; Wu et al. 2018; Mukherjee and Lal 2020; Hille et al. 2020.

A New Auxiliary Model Approach Towards Interacting Models

1. Solve an appropriate impurity model, H_{imp}
   - Lattice symmetry
   - Impurity phase transition

2. Explicitly construct lattice model by applying manybody translation operators:

$$H_{\text{latt}} = \sum_{\mathbf{r}} T^{\dagger}(\mathbf{r}) H_{\text{imp}}(\mathbf{r_0}) T(\mathbf{r})$$

3. Relate computables across the models, using manybody Bloch's theorem

Greens functions: $\tilde{G}(\mathbf{K}\sigma; \omega) = G^{>}(T^{\dagger}_{\mathbf{K}\sigma}, \omega - \varepsilon_{\mathbf{K}}) + G^{<}(T^{\dagger}_{\mathbf{K}\sigma}, \omega + \varepsilon_{\mathbf{K}})$

Equal-time correlation functions:
$C_O(\mathbf{k}_1, \mathbf{k}_2) = \sum_{\Delta} \langle \mathbf{r}_c + \Delta | \tilde{O}(\mathbf{k}_2) | \mathbf{r}_c \rangle \langle \mathbf{r}_c | \tilde{O}^{\dagger}(\mathbf{k}_1) | \mathbf{r}_c \rangle$

where

$$G^{>}(O^{\dagger}, t) = -i \langle O(t) O^{\dagger} \rangle$$

$$T_{\mathbf{K}\sigma} = c_{\mathbf{K}\sigma} \left(\sum_{\sigma'} c^{\dagger}_{d\sigma} + \text{h.c.} \right) + c_{\mathbf{K}\sigma} \left(S^{+}_{d} + \text{h.c.} \right)$$

$$\tilde{O}(\mathbf{r}) = O(\mathbf{r}) O^{\dagger}(d)$$

The Core Ingredient: A Lattice-Embedded Impurity Model

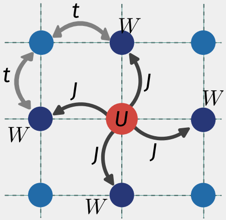
$$H = H_{\text{cbath}} + H_{\text{imp-cbath}} + H_{\text{cbath-int}} ,$$

$$H_{\text{cbath}} = -2t \sum_{\mathbf{k}} \left[\cos(ak_x) + \cos(ak_y)\right] c^\dagger_{\mathbf{k},\sigma} c_{\mathbf{k},\sigma} .$$

$$H_{\text{imp-cbath}} = \frac{1}{2} J \sum_{\sigma_1,\sigma_2} \sum_{Z} \mathbf{S}_d \cdot c^\dagger_{Z\sigma_1} \tau_{\sigma_1,\sigma_2} c_{Z\sigma_2} ,$$

$$H_{\text{cbath-int}} = -\frac{W}{2} \sum_{Z} \left(n_{Z\uparrow} - n_{Z\downarrow}\right)^2 ,$$

(1)



$$J_{\mathbf{k},\mathbf{k}'} = \frac{J}{2} \left[\cos\left(\mathbf{k}_x - \mathbf{k}'_x\right) + \cos\left(\mathbf{k}_y - \mathbf{k}'_y\right)\right] ,$$

(2)

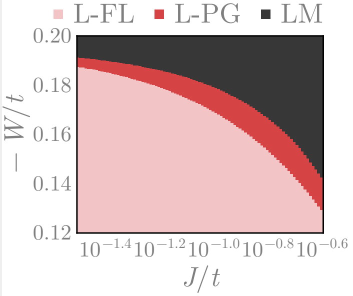
$$W_{\mathbf{k},\mathbf{k}',\mathbf{q},\mathbf{q}'} = W \left[\cos\left(\mathbf{k}_x - \mathbf{k}'_x + \mathbf{q}_x - \mathbf{q}'_x\right) + \cos\left(\mathbf{k}_y - \mathbf{k}'_y + \mathbf{q}_y - \mathbf{q}'_y\right)\right] .$$

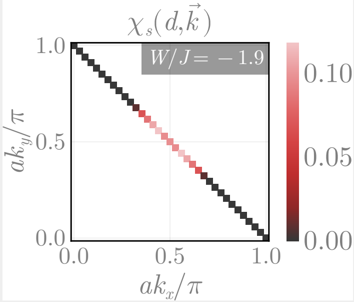
Pseudogapping Transition from Kondo Breakdown

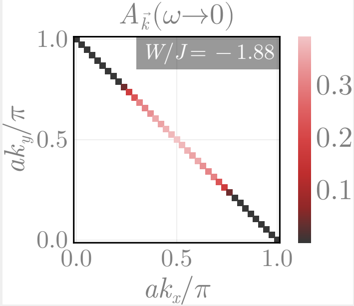
Unitary RG analysis - integrate out high-energy states in the conduction bath:

$$\Delta J^{(j)}_{\mathbf{k}_1,\mathbf{k}_2} = - \sum_{\mathbf{q}\in \mathrm{PS}} \frac{J^{(j)}_{\mathbf{k}_2,\mathbf{q}} J^{(j)}_{\mathbf{q},\mathbf{k}_1} + 4 J^{(j)}_{\mathbf{q},\bar{\mathbf{q}}} W_{\bar{\mathbf{q}},\mathbf{k}_2,\mathbf{k}_1,\mathbf{q}}}{\omega - \frac{1}{2}|\varepsilon_j| + J^{(j)}_{\mathbf{q}}/4 + W_{\mathbf{q}}/2}$$

- Impurity model shows momentum-anistropic screened phase between SC and LM phases.
- Impurity-bath spin correlations show anisotropy
- Lattice model DOS shows pseudogap







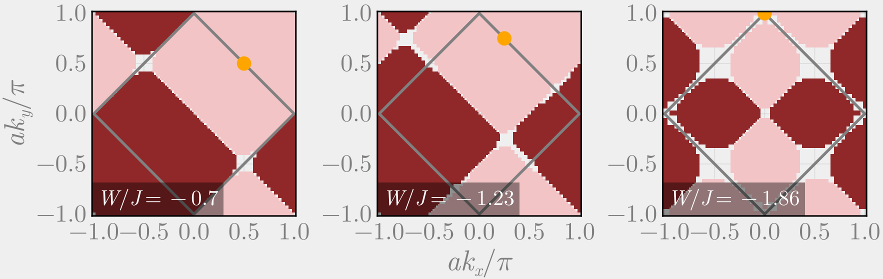
Unraveling of Kondo screening

The k–space anisotropic nature of the Kondo breakdown process can be visualised in terms of zeros of $J_{\mathbf{k}_N,\mathbf{k}}$.

- $J_{\mathbf{k}_N,\mathbf{k}}$ for $\mathbf{k}$ close to the adjacent nodes turn RG irrelevant first, and a patch of zeros subsequently appears in $J_{\mathbf{k}_N,\mathbf{k}}$ around this point.
- Tuning W/J further extends the patch of zeros in $J_{\mathbf{k}_1,\mathbf{k}_2}$ for all $\mathbf{k}_1$ lying between a given node and the nearest antinodes.
- At $W/J = (W/J)_{\mathrm{PG}}$, the antinode joins this connected region of zeros in $J_{\mathbf{k}_1,\mathbf{k}_2}$, marking the onset of the PG.

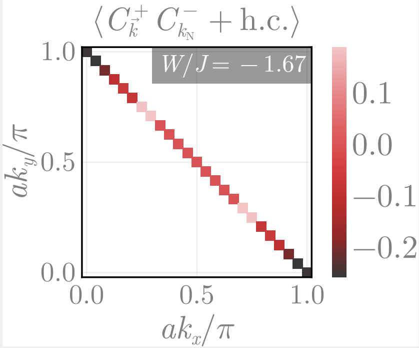
This is an interaction-driven Lifshitz transition of the Fermi surface.

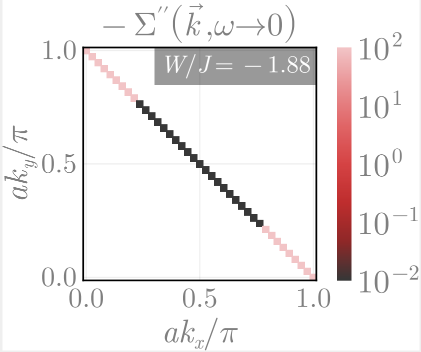
Wu et al. 2018.



Dynamical Spectral Weight Transfer

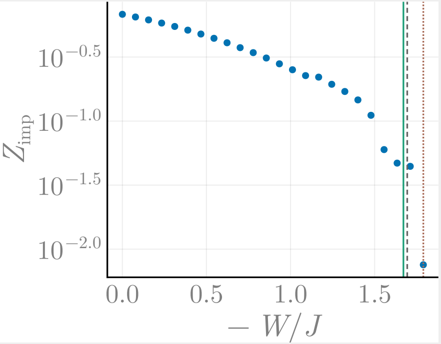
- strong fluctuations observed in **charge correlations** between the gapless nodal and gapped antinodal regions in PG regime
- PG formation results from the **transfer of spectral weight** from low to high energies
- PG coincides with the appearance of poles of the lattice model self-energy $\Sigma(\mathbf{k}, \omega = 0)$ near the antinodes

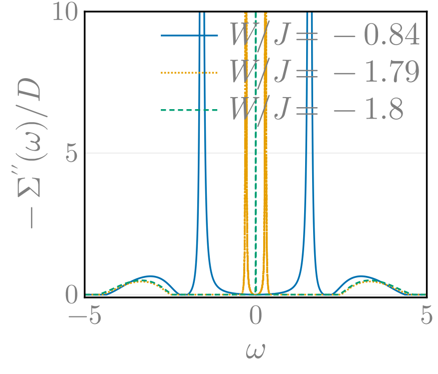




Non-Fermi liquid nature of the pseudogap

- In PG phase, Kondo processes between adjacent k–space quadrants are removed at low-energies
- Effective **two-channel Kondo** description - each pair of opposite quadrants forms a channel
- **Non-Fermi liquid** physics - vanishing quasiparticle residue, and Σ poles near $\omega = 0$

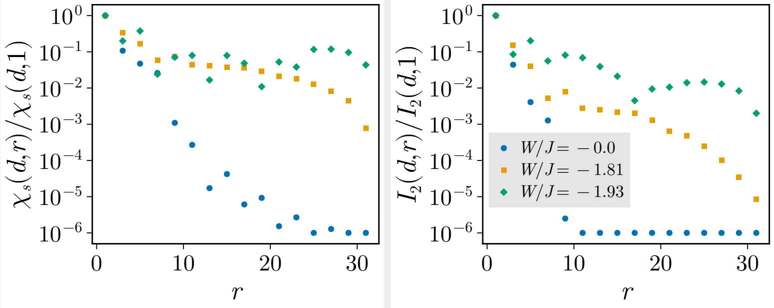




Singular Nodal Metal

Non-local nature of the pseudogap

- real-space correlations and entanglement undergo a crossover within the pseudogap from short-ranged to **long-ranged** behaviour
- This is further evidence of the **breakdown of local Kondo screening**, and resulting Landau quasiparticle excitations
- the Mott transition observed by us for the Hubbard-Heisenberg model on the square lattice lies well beyond the paradigm of **local quantum criticality**



The Final Slide

Conclusion

- we find compelling evidence that the Mott transition on the square lattice involves continuous passage through a pseudogap phase arising from the breakdown of Kondo screening
- pseudogap is comprised of gapped antinodal regions in k-space together with an increasingly non-local nodal non-Fermi liquid metal whose excitations lie proximate to a singular Fermi surface

Future Directions

- Heavy fermions?
- Doping the pseudogap phase - superconductivity?