Research Progress Report: 2024 - 2025

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July 23, 2025

Acknowledgements

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Funding agencies : IISER Kolkata, SERB

Publications and Ongoing Projects

Published

- 2023 New J. Phys. 25 113011
- 2024 J. Phys. A: Math. Theor. 57 275401
- 2022 Phys. Rev. B 105, 085119
- 2023 J. Phys.: Condens. Matter 35 315601

Currently in Progress

- Development of auxiliary model-based method for interacting electrons [**arXiv**:2507.xxxxx].
- Studies of plateau-to-plateau transition in integer quantum hall systems.

Ongoing Collaborations

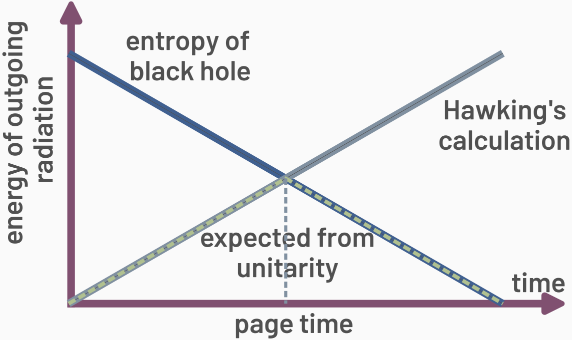
- Breakdown of Kondo screening in presence of magnetic field [DD, **AM**, SL]
- Quantum critical Mott MIT in 3-orbital impurity model [AK, DD, **AM**, NSV, SL]
- Universal features of Kondo breakdown in impurity models [DD, **AM**, SL]
- Search for non-Fermi liquid physics in mixed-valence eSIAM [AS, **AM**, SL]
- Spin-liquid and non-Fermi liquid phases in frustrated systems [SD, **AM**, SL]
- Hawking-Page entanglement transition in a Kondo system [DD, **AM**, SL]

Ongoing Collaborations

Hawking-Page Entanglement Transition in a Kondo System

Hawking radiation + black hole evaporation appears to **violate unitarity**

- Initially system is in **pure state** .
- Hawking's calculation: increasing entanglement between radiation and interior
- This leads to **mixed state** at $t = \infty$, but mixedness cannot change under **unitary evolution** .

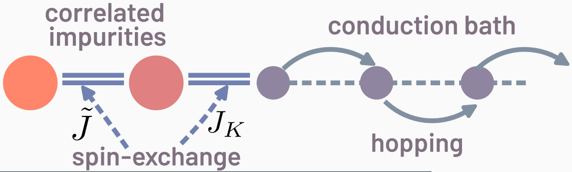


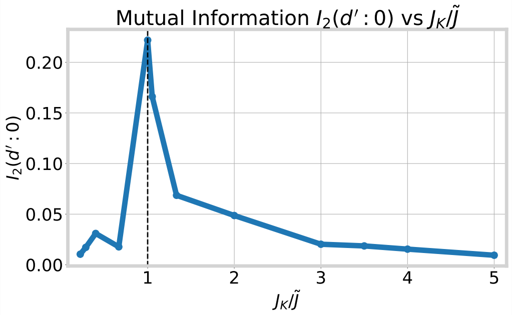
- Unitarity means entanglement of radiation **must decrease** after page time.
- Can we replicate this behaviour in a **quantum system** ?

Hawking-Page Entanglement Transition in a Kondo System

A unified framework for Kondo breakdown, in terms of entanglement measures
(D Debata, A Mukherjee, S Lal) [*in preparation*]

- Universal signatures of Kondo breakdown include **partial magnetisation** and phase shift.
- Entanglement within the **Kondo cloud** also suffers at Kondo breakdown.





Mukherjee et al. 2023; Patra et al. 2023.

Universal Features of Kondo Breakdown in Impurity Models

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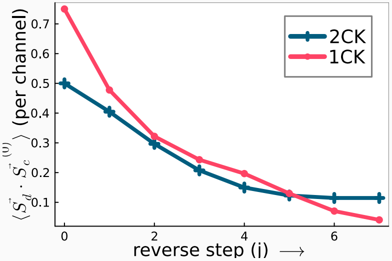
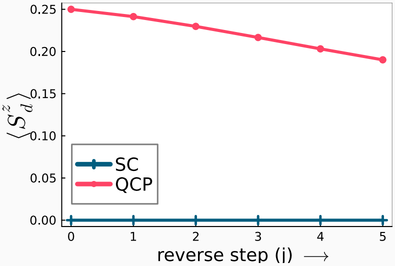


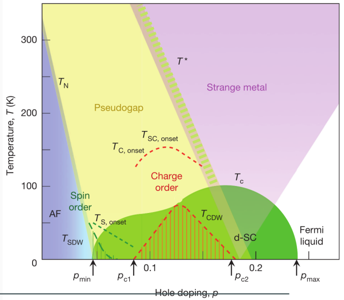


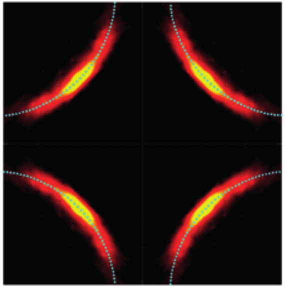
Mukherjee et al. 2023; Patra et al. 2023.

A New Auxiliary Model Approach to Systems of Interacting Electrons

Broad Objectives

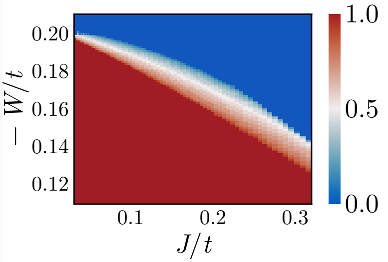
- ✓ Designing a **new method** by which to leverage quantum impurity models towards understanding phase transitions in correlated electrons in low dimensions
- ✓ Study the highly non-trivial Mott MIT through the **pseudogap** in the context of the cuprates
- ✓ Characterise the **parent metal** that gives way to an interacting Mott insulator.





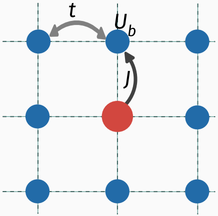
Keimer et al. 2015; Sebastian et al. 2014; Norman et al. 1998.

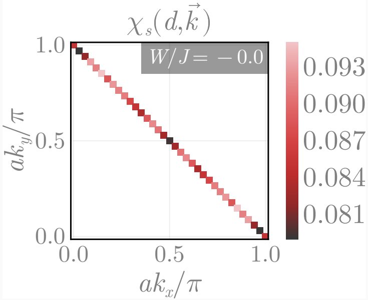
Momentum-Resolved Renormalisation Group Flows

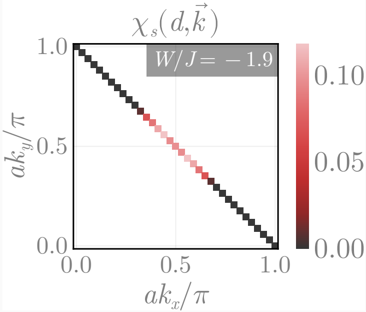


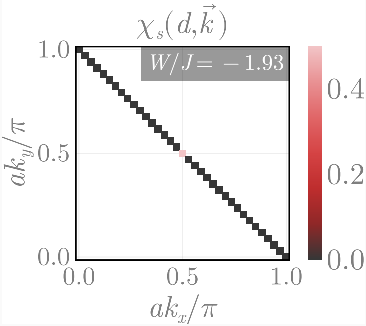
Hamiltonian RG equations of
embedded e-SIAM

$$\Delta J^{(j)}_{k_1,k_2} = -\sum_{q\in \mathrm{PS}} \frac{J^{(j)}_{k_2,q}J^{(j)}_{q,k_1} + 4J^{(j)}_{q,\bar{q}}W_{\bar{q},k_2,k_1,q}}{\omega - \frac{1}{2}|\varepsilon_j| + J^{(j)}_q/4 + W_q/2}$$









‘Periodising’ the Hamiltonian and Eigenstates

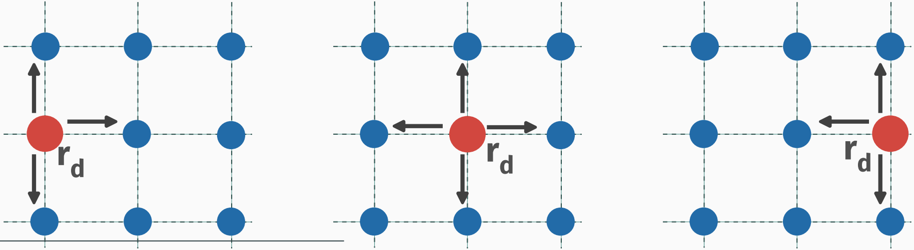
Periodising the Hamiltonian creates a **Hubbard-Heisenberg** model:

Wavefunctions can be related using a many-body **Bloch’s theorem** :

$$H_{\text{tiled}} = \sum_{\mathbf{r}} T^{\dagger}(\mathbf{r}-\mathbf{r}_d) H_{\text{aux}}(\mathbf{r}_d) T(\mathbf{r}-\mathbf{r}_d)$$

$$|\Psi_{\text{gs}}\rangle = \frac{1}{\sqrt{N}} \sum_{\mathbf{r}_d} e^{i\mathbf{k}\cdot\mathbf{r}_d} |\psi_{\text{gs}}(\mathbf{r}_d)\rangle$$

$$H_{\text{tiled}} = -\frac{\tilde{t}}{\sqrt{Z}} \sum_{\langle \mathbf{r}_i,\mathbf{r}_j\rangle;\sigma} \left(c^{\dagger}_{\mathbf{r}_i,\sigma} c_{\mathbf{r}_j,\sigma} + \text{h.c.}\right) + \frac{\tilde{J}}{Z} \sum_{\langle \mathbf{r}_i,\mathbf{r}_j\rangle} \mathbf{S}_{\mathbf{r}_i} \cdot \mathbf{S}_{\mathbf{r}_j} - \frac{\tilde{U}}{2} \sum_{\mathbf{r}} \left(\hat{n}_{\mathbf{r},\uparrow} - \hat{n}_{\mathbf{r},\downarrow}\right)^2$$

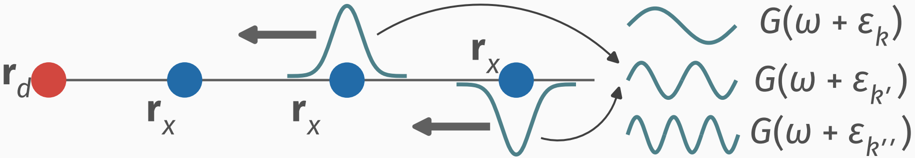


Stoyanova 2006.

Periodising the Greens Functions

Greens function = sum of 1-particle *k*-space Greens functions starting from **all sites** in impurity model.

$$\tilde{G}(\mathbf{r};\tilde{\omega}) = \frac{1}{N}\sum_{\mathbf{k},\mathbf{r}_x}\Big[e^{i(\mathbf{k}-\mathbf{k}_0)\cdot(\mathbf{r}-\mathbf{r}_x)}G_p\left(\mathbf{r}_x;\omega+\varepsilon_{\mathbf{k}}\right) + e^{-i(\mathbf{k}-\mathbf{k}_0)\cdot(\mathbf{r}-\mathbf{r}_x)}G_h\left(\mathbf{r}_x;\omega-\varepsilon_{\mathbf{k}}\right)\Big]$$



Subsequently allows periodising spectral functions and self-energies

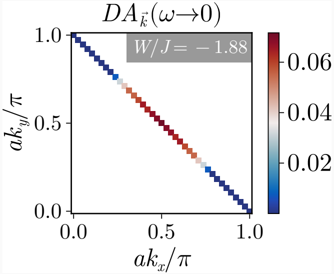
$$\tilde{A}(\mathrm{K};\omega) = -\frac{1}{\pi}\mathrm{Im}\left[\tilde{G}(\mathrm{K};\tilde{\omega})\right]$$

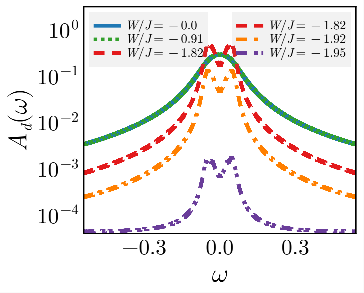
$$\tilde{\Sigma}(\mathrm{K};\omega) = \left(\tilde{G}^{(0)}(\mathrm{K};\tilde{\omega})\right)^{-1} - \left(\tilde{G}(\mathrm{K};\tilde{\omega})\right)^{-1}$$

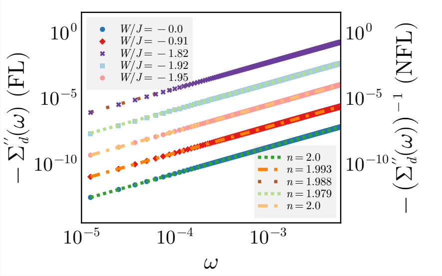
Kotliar et al. 2001; Verret et al. 2022.

Characterising Low-energy Excitations of the Pseudogap

- Impurity spectral function shows **pseudogap** (loss of central peak)
- Tiled k-space DOS shows **partial gapping** around antinodes
- Self-energy shows **anomalous exponent** throughout the phase

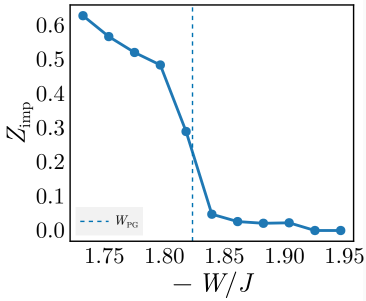


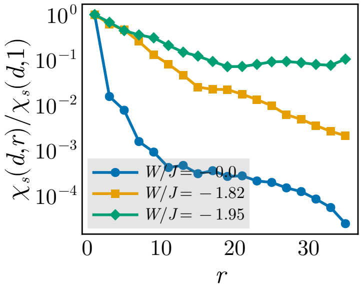


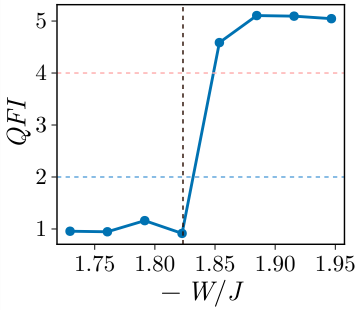


”Un-Fermi” Liquid Nature of the Pseudogap

- low-energy excitations **cannot be described** by effectively one-particle excitations (vanishing Z)
- **long-range** correlations present in the pseudogap (quantum critical matter)
- entanglement is **multipartite** (Quantum Fisher information > 4)







Future Plans

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- Study heavy-fermion physics using auxiliary model approach.
- Start consolidating results in the form of a thesis.

Thank You!