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I am a quantum condensed matter theorist focusing primarily on characterising phases of strongly correlated **quantum matter**. These are novel states that appear at zero temperature and display emergent exotic properties, often driven by strong interactions between the constituent particles. Such phases are interesting because they cannot be described within the paradigm of spontaneous symmetry breaking and local order parameters. Instead, phase transitions involving such phases often involve changes in **topology**.

My work presently focuses on understanding various features of repulsion-driven Mott metal-insulator transitions from the perspective of **Kondo breakdown**. Impurity models (models with a correlated electronic orbital hybridising with a "sea" of non-interacting electrons) involving destruction of magnetic screening often displays quantum criticality, non-Fermi liquid physics and pseudogapped phases. This has allowed us to propose simple impurity models that are able to capture and understand crucial features of Mott transitions, lending valuable insights into this complicated problem.

One of the important diagnostics of Kondo breakdown that we have identified is the **thermalisation** of the correlated impurity orbital with the non-interacting sea. In ongoing work, we are exploring how the rate of impurity dynamics thermalisation (or its breakdown) can serve as a probe of quantum criticality. This resonates well with the work of **Prof. Olexei I. Motrunich** at the Walter Burke Institute for Theoretical Physics, Caltech, who investigates the absence of thermalisation in isolated finite-energy states (many-body scars) in interacting systems. I believe this conceptual overlap opens exciting opportunities for fresh collaborative research in the field of eigenstate thermalisation, in the context of quantum impurity models.

Kondo breakdown as route to understanding Mott transitions [1, 2]

Mott transition on Bethe lattice: $d = \infty$

The rich physics of metal–insulator transitions (MITs) in strongly correlated systems has been an active subject of study for quite some time. While DMFT obtains a self-consistent solution of the **Mott MIT** for the $1/2$ –filled Hubbard model in infinite dimensions, important questions such as the precise nature of the impurity model and the nature of quantum critical metal at the transition remain controversial.

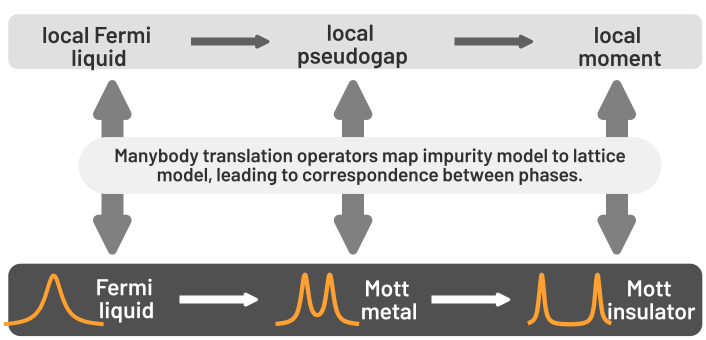

FIG 1: In [2], we define a lattice-embedded impurity model (guided by phenomenology) and obtain its low-energy phases (top row) using an impurity solver. Using manybody translation operators and Bloch's theorem, we map the phases of the impurity model to those of a lattice model (bottom row).

In order to address this, we proposed [1] an **extended Anderson impurity model** that captures the infinite dimensional Mott transition in remarkable detail, in the form of a **localisation-delocalisation transition** of the impurity electron. Using this model, we demonstrated the presence of **charge fluctuations** proximate to the impurity site in the conduction bath as the driver of the transition, and the emergence of quantum critical **non-Fermi liquid** excitations at the transition.

Mott transition in 2D

We then applied our approach to the case of two dimensions, in order to address some of the open questions pertaining to the mysterious pseudogap and non-Fermi liquid phases that arise in the **copper-oxide and heavy-fermion materials**. In [2], we updated the extended Anderson impurity model by **embedding the impurity site** within a 2D square lattice and "periodised" our impurity model using manybody translation operators to make contact with an **extended Hubbard model** (see FIG 1). We showed that the transition from a Fermi liquid to a symmetry-preserved Mott insulator goes through a quantum critical **Mott metal** characterised by non-Fermi liquid excitations with anomalous self-energy behaviour and long-range spin correlations and entanglement (see FIG 1).

Engineering non-Fermi liquids from critical impurity models [3 - 5]

Another aspect of my work that is closely allied with the previous theme is the study of non-Fermi liquid phases emerging from quantum impurity models. This is relevant because non-Fermi liquids often arise in correlated materials, particularly in the proximity of quantum phase transitions. This makes characterisation of such non-Fermi liquids crucial.

Emergence of non-Fermi liquids

In [3], we investigated the **single-channel Kondo model** and demonstrated the presence of **two-particle correlations** and entanglement within the Kondo cloud in the form of an effective Hamiltonian; we also calculated how they evolved during the high to low-temperature crossover. This work set the stage for exploring breakdown of such strong-coupling behaviour in other models.

We next turned our focus to the **multichannel Kondo problem** that displays breakdown of Kondo screening, and shed light on the role played by the **ground state degeneracy** in the non-Fermi liquid physics - how it leads to an orthogonality catastrophe in the low-energy excitations and how it modified the various correlations into anomalous forms [4]. This work also emphasized the importance of using **simpler models** (the star graph in this case) to capture the essential physics.

Quantum critical lattice models

We next wanted to use our approach to study the **exotic critical point** demonstrated in some recent works (Phys. Rev. B 93 155136 (2016), Phys. Rev. B 107 205104 (2023)) within a three-orbital lattice model. We have showed ([5]) that a single f −impurity hybridising with two independent conduction baths leads (FIG 2) to similar quantum critical phases with non-Fermi liquid excitations and pseudogapped spectral functions. This is in contrast to the isolated critical points that appear in other impurity models and that require fine-tuning of parameters.

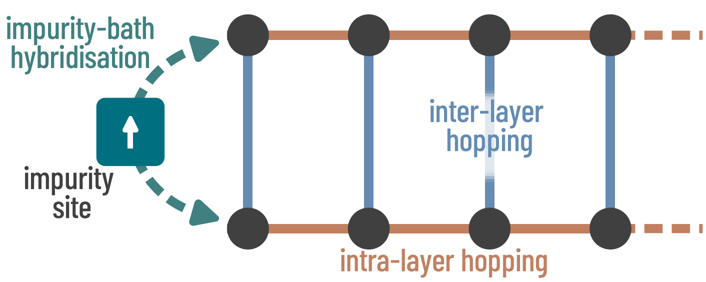

FIG 2: In [5], we have studied an impurity model analogue of a three-layer periodic Anderson model, where the impurity site represents the f −layer hybridising with the two conduction bath layers. We find signatures of a quantum critical phase displaying non-Fermi liquid excitations and long-range entanglement. This gives insight into the continuous transition obtained in the full three-layer model.

Bulk-boundary correspondence & entanglement renormalisation [6]

The work in [6] differs somewhat from the others because it involves non-interacting electrons, but it speaks to the broader theme of emergence and **topological transitions** in fermionic systems. Specifically, this work involves a demonstration of the holographic principle by constructing the emergent dimension from the quantum field theory, which is typically more difficult than the top-down approach of studying strongly-coupled quantum theories by mapping them to their semiclassical gravity duals.

In [6], we provide such a construction by showing how the **entanglement renormalisation** in a free fermion system (with and without a mass gap) leads to the emergence of a holographic dimension. Tuning the system from a gapless phase into a gap leads to a change in curvature of the emergent space; we argue that this topological transition (and the underlying critical Fermi surface at this transition) coincides with the formation of a **quantum wormhole geometry** that connects the UV and the IR of the emergent dimension (FIG 3).

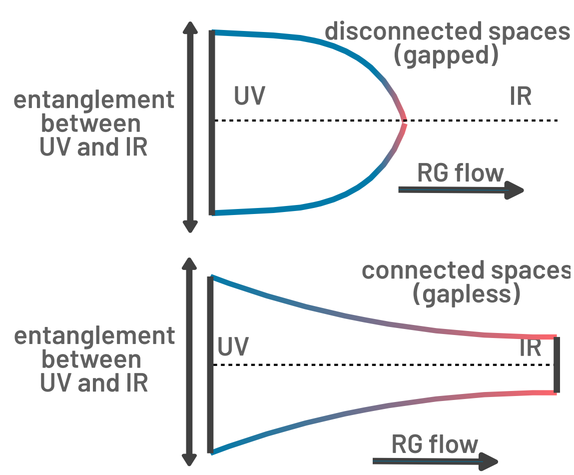

FIG 3: In [6], we show that entanglement renormalisation in a 2D system of free electrons leads to the emergence of a holographic dimension. While the gapless RG flow involves a growth in the entanglement between the UV and IR spaces, the latter leads to the vanishing of UV-IR entanglement. This results in the emergence of connected (left) and disconnected (right) geometries, respectively.

Magnetic dimensional crossover in $CrSiTe_3$ [7]

A recurring theme in my work has been to use simple theoretical models to interpret emergent experimental signatures of correlated matter. In this spirit, I recently collaborated [7] with Prof. N Kamaraju's experimental group on a project investigating the two-step **magnetic dimensional crossover** (paramagnet -> long-range fluctuations -> 3D ferromagnet) in the van der Waals ferromagnet CrSiTe $_3$. The experimental involves mapping out the two-stpe crossover by studying a bulk sample of $CrSiTe_3$ with ultrafast pulses using **pump-probe spectroscopy** and tracking the acoustic strain pulse generated during relaxation of the carriers.

The shape of the acoustic pulses tracks the various steps of the magnetic crossover through several signatures, such as a phase reversal of the strain pulse in the ferromagnetic phase, a red-shift (softening) of the high-frequency phonons and a gapping out of the low-frequency phonon modes within the strain pulse. In order to explain these signatures, I (along with Prof. S Lal) came up with a simple model of **phonons interacting with the lattice spin fluctuations**. By treating the spin interactions using mean-field theory, we showed that the interacting model can be understood as a theory of new phonon fields with a modified dispersion. More specifically, we showed that the renormalisation of the phonon characteristics due to its interaction with the spin-fluctuations explains the various features mentioned above.

Future Research Directions

In addition to extending my current work on Mott physics and Kondo breakdown, I envision several near-term projects that overlap with ongoing research at Caltech, particularly with the work of **Prof. Olexei I. Motrunich**.

Investigating many-body scars in Hatsugai-Kohmoto model. The Hatsugai-Kohmoto model H_{KM} is an exactly solvable, integrable model of correlated electrons, displaying non-Fermi liquid excitations. Following **PRL 134 050403**, it is worth investigating whether a perturbatively non-integrable model (such as $H = H_{\text{KM}} + P_v H_{\text{Hub}} P_v$, where H_{Hub} is the Hubbard model and P_v projects onto some symmetry sectors) can host many-body scars (through approximate symmetries remnant from H_{KM}). The entanglement structure of the states in such a model should also be interesting to explore.

Effect of correlated impurities on dynamics of integrable systems. Taking arXiv:2503.14608 forward, one can study the effect of correlated impurities on the revival of ergodicity in integrable models, in the form of quantum impurity models. More specifically, one can consider various geometries of impurities which are known to host non-Fermi liquid excitations, and study the dependence of thermalisation on the nature of excitations.

Long-term Research Goals

Developing a unifying framework for fermionic criticality. Developing an overaching theory of interacting electrons in that explains the mechanism of phase transitions in many of these systems (such as cuprates, heavy fermion materials, iron-based superconductors, etc), and also accounting for the exotic parent phases which turn critical during such transitions. Our work on the Mott metal ([2]) is a step in this direction.

Topology and entanglement as probes for transitions in strongly correlated electrons, instead of local order parameters. It would be interesting to make these ideas more precise and identify concrete topological order parameters for the phase transitions and characterise phases of quantum matter using patterns of entanglement. There are already hints of this in the literature (**New J. Phys. 22 063011 (2020)**, **arXiv:2506.04342 (2025)**, [2]).

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