Local metal-insulator transition in an extended Anderson impurity model

JRF-to-SRF Upgradation Presentation

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Summary of Work

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Completed Projects

✓ Unveiling the Kondo cloud: Unitary renormalization-group study of the Kondo model

Phys. Rev. B 105, 085119, arXiv:2111.10580v3

A. Mukherjee, *Abhirup Mukherjee*, N. S. Vidhyadhiraja, A. Taraphder, and S. Lal

✓ Frustration shapes multi-channel Kondo physics: A star graph perspective

under review at PRB, arXiv:2205.00790

S. Patra, *Abhirup Mukherjee*, A. Mukherjee, N. S. Vidhyadhiraja, A. Taraphder, S. Lal

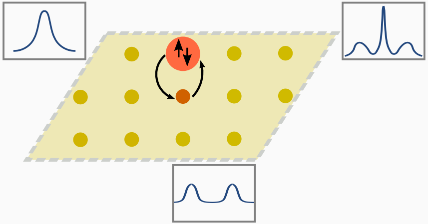
Ongoing Projects

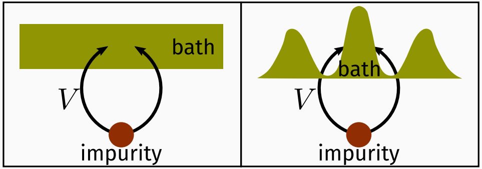
✓ Metal-insulator transition in an extended Anderson impurity model (*manuscript in preparation*)

✓ Holography and topology of entanglement scaling in free fermions (*manuscript in preparation*)

✓ URG-based auxiliary model approach to correlated systems (*ongoing*)

Local MIT in an extended Anderson impurity model

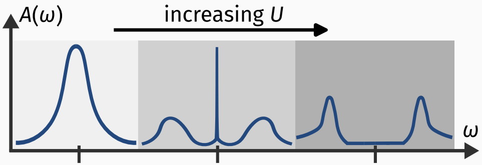




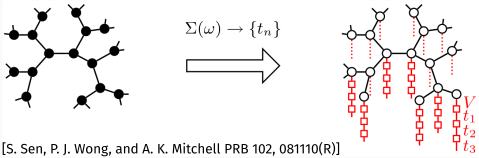
Introducing the extended Anderson impurity model

DMFT on the Bethe lattice: Exact in $d = \infty$

✓ shows **metal-insulator transition** on the Bethe lattice with ∞ coordination number

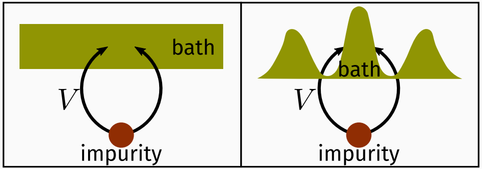


✓ Conduction bath obtained by imposing self-consistency shows **non-trivial correlations**



[S. Sen, P. J. Wong, and A. K. Mitchell PRB 102, 081110(R)]

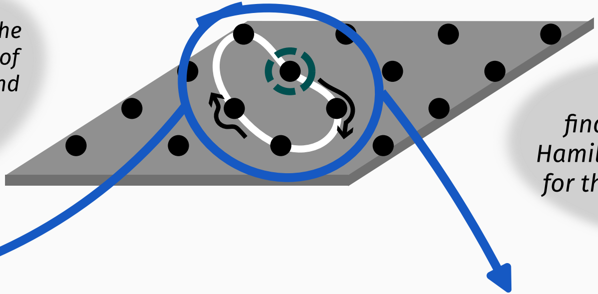
✓ Spectral function develops three peaks and then **gaps out**



Metzner et al. 1989; Georges et al. 1992; Parcollet et al. 2004; Maier et al. 2005; Kotliar et al. 2006; Ohashi et al. 2008; Held et al. 2013; Sen et al. 2020.

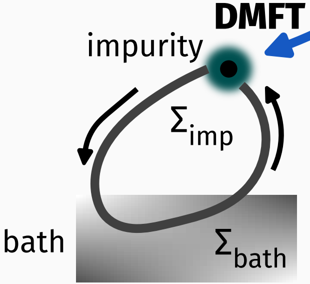
DMFT on the Bethe lattice: Exact in $d = \infty$

DMFT *represents excursions from a site into the correlated bath in the form of self-energies for the bath and the impurity. This results in a three-peak DOS of the bath.*

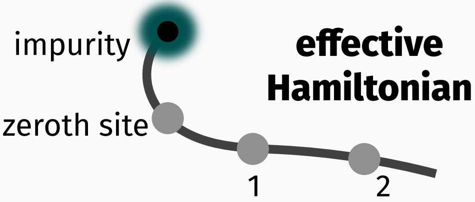


Our Goal:

finding an effective Hamiltonian description for the Σ that gives rise to the MIT.



Similar approach adopted by Si & Kotliar for extended Hubbard model

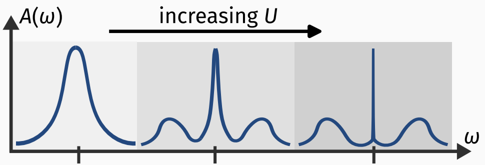


Si et al. 1993; Kotliar et al. 1993.

Introducing the extended Anderson impurity model

Standard Anderson impurity model

- ✓ no local-moment phase, $A(\omega)$ gapless
- ✓ cannot explain insulating phase of DMFT



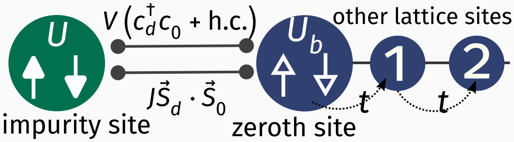
Gap in spectral function requires additional physics!

Anderson 1961; Anderson 1978; Wilson et al. 1974; Nozieres 1974; Krishna-murthy et al. 1980; Andrei 1980; Tsvelick et al. 1983; Hewson 1993; Costi et al. 1990; Costi 2000; Kuramoto et al. 1987; Cox et al. 1988.

Introducing the extended Anderson impurity model

Extended **Anderson impurity model**

- ✓ impurity-bath spin correlation: J
- ✓ bath zeroth site local correlation: U_b



$$H = H_{\text{KE}} + V\sum_\sigma \left(c_{d\sigma}^\dagger c_{0\sigma} + \text{h.c.}\right) + \frac{U}{2}\left(\hat{n}_{d\uparrow} - \hat{n}_{d\downarrow}\right)^2 + J\vec{S}_d \cdot \vec{S}_0 + U_b\left(\hat{n}_{0\uparrow} - \hat{n}_{0\downarrow}\right)^2$$

Anderson 1961; Anderson 1978; Wilson et al. 1974; Nozieres 1974; Krishna-murthy et al. 1980; Andrei 1980; Tsvelick et al. 1983; Hewson 1993; Costi et al. 1990; Costi 2000; Kuramoto et al. 1987; Cox et al. 1988.

Phase Diagram & Ground-States

Nature of RG flows

✓ URG Equations reveal **critical** point at $r = -U_b/J = 1/4$

✓ RG equation for most dominant coupling J:

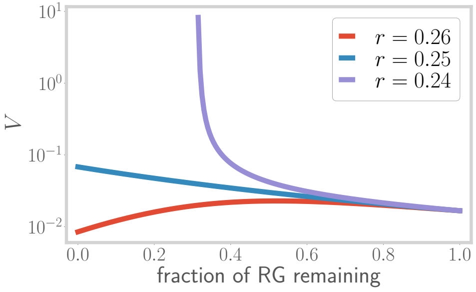
$$\Delta J = \frac{-J(J + 4U_b)n(D)}{\omega - D/2 + U_b/2 + J/4}$$

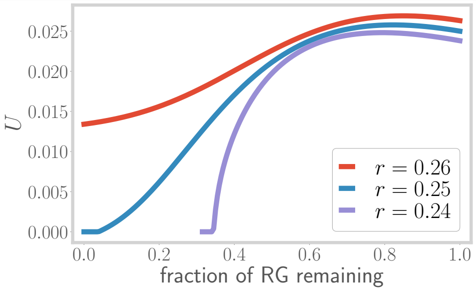
✓ Numerator structure allows **averting** strong-coupling behaviour

Nature of RG flows

✓ J, V, U reverse their behaviour across the critical point; leads to **phase transition**

✓ Bath correlation U_b is always **marginal**

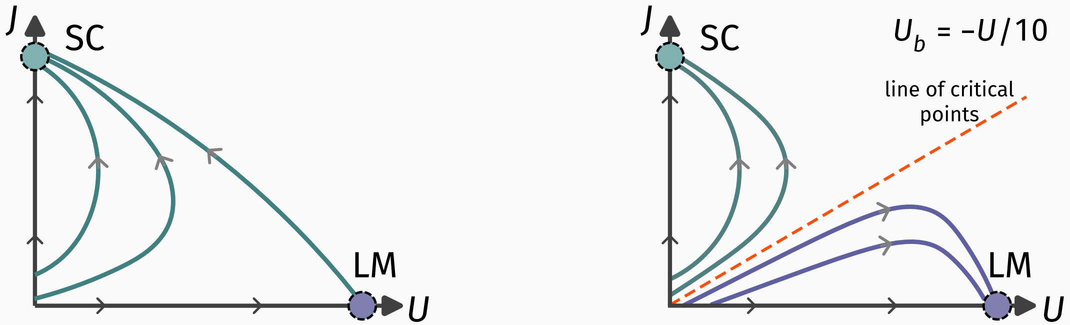




Nature of RG flows

✓ RG equation reveals competition between Kondo flow and pairing physics

$$\Delta J = \underbrace{-\frac{(J + 2U_b)^2 n(D)}{\omega - D/2 + U_b/2 + J/4}}_{\text{usual Kondo physics}} + \underbrace{\frac{(2U_b)^2 n(D)}{\omega - D/2 + U_b/2 + J/4}}_{\text{competing pairing physics}}$$

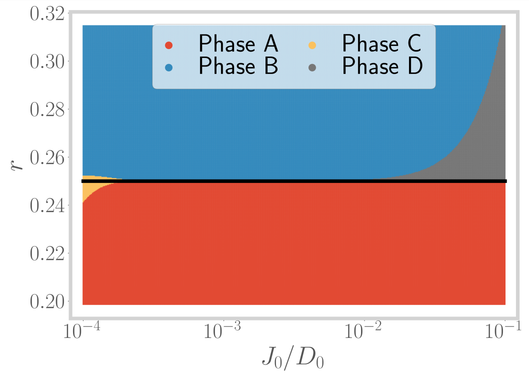


RG Phase Diagram

✓ blue phase $\longrightarrow$ $U_b < -J/4$: V, J are **irrelevant** $\longrightarrow$ local moment flows

✓ yellow phase: $J \ll D_0$: involves V, U, U_b

vanishes for large systems



✓ gray phase: $J \sim D_0$: **all** couplings irrelevant

vanishes for large systems

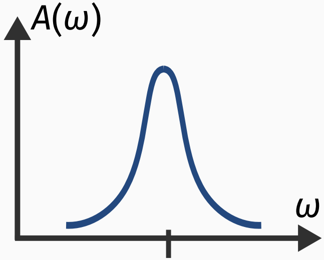
✓ red phase $\longrightarrow$ $U_b > -J/4$: V, J are **relevant** $\longrightarrow$ strong-coupling flows

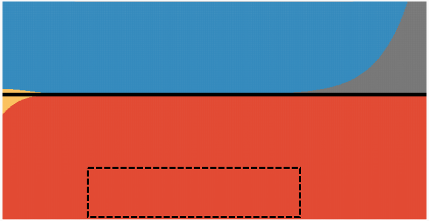
Low-energy effective Hamiltonians and ground-states

Regime 1: $|U_b| < J/4$

- ✓ J relevant,
- ✓ V subdominant,
- ✓ U irrelevant

$$H = J\vec{S}_d \cdot \vec{S}_0 - U_b \left(\hat{n}_{0\uparrow} - \hat{n}_{0\downarrow}\right)^2 + \sum_{k<\Lambda^*} \epsilon_k \hat{n}_{k\sigma}$$

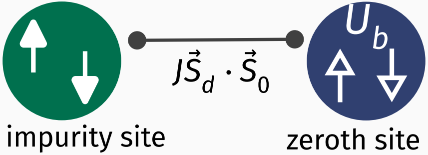




Low-energy effective Hamiltonians and ground-states

Regime 1: $|U_b| < J/4$

Zero-bandwidth limit

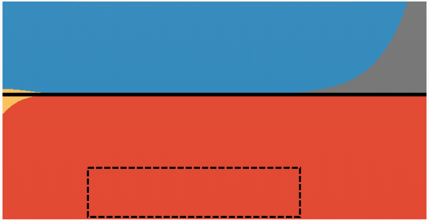


$$H = J\vec{S}_d \cdot \vec{S}_0 - U_b\left(\hat{n}_{0\uparrow} - \hat{n}_{0\downarrow}\right)^2$$

✓ two-spin Heisenberg, attractive zeroth site

✓ **singlet** ground state

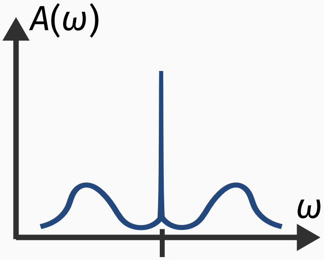
$$|\Psi\rangle_{GS} = \frac{1}{\sqrt{2}}\left[|\uparrow_d \downarrow_0\rangle - |\downarrow_d \uparrow_0\rangle\right]$$



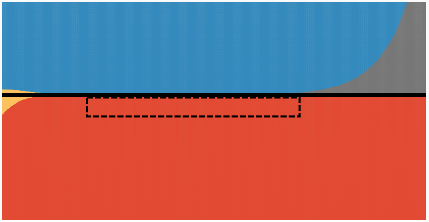
Low-energy effective Hamiltonians and ground-states

Regime 2: $|U_b| \sim J/4$

- ✓ J relevant,
- ✓ V relevant,
- ✓ U irrelevant



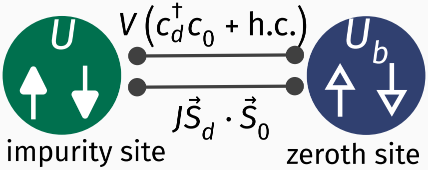
$$H = J\vec{S}_d\cdot\vec{S}_0 + V\sum_\sigma\left(c^\dagger_{d\sigma}c_{0\sigma} + \text{h.c.}\right) - U_b\left(\hat{n}_{0\uparrow} - \hat{n}_{0\downarrow}\right)^2 + \sum_{k<\Lambda^*}\epsilon_k\hat{n}_{k\sigma}$$



Low-energy effective Hamiltonians and ground-states

Regime 2: $|U_b| \sim J/4$

Zero-bandwidth limit

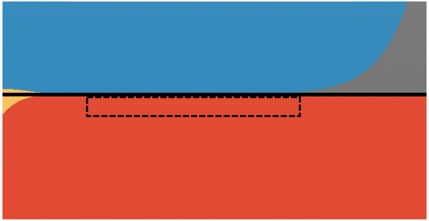


$$H = J\vec{S}_d \cdot \vec{S}_0 + V \sum_\sigma \left(c_{d\sigma}^\dagger c_{0\sigma} + \text{h.c.}\right) - U_b \left(\hat{n}_{0\uparrow} - \hat{n}_{0\downarrow}\right)^2$$

✓ **spin+charge** dimer with attractive 0^{th} site

✓ spin-singlet + charge-triplet-zero in gr-state

$$|\Psi\rangle_{GS} = \frac{1}{2\sqrt{2}}\left[|\uparrow_d \downarrow_0\rangle - |\downarrow_d \uparrow_0\rangle\right] + \frac{1}{2\sqrt{2}}\left[|2_d, 0_0\rangle + |0_d, 2_0\rangle\right] \tag{1}$$



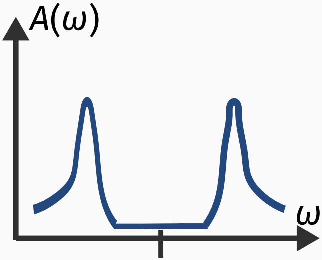
Low-energy effective Hamiltonians and ground-states

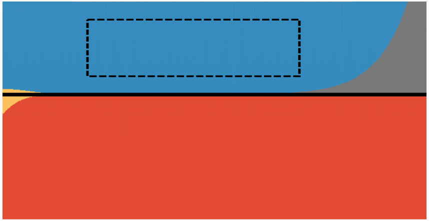
Regime 3: $|U_b| > J/4$

✓ J, V irrelevant,

✓ U relevant,

$$H = -U/2\left(\hat{n}_{d\uparrow} - \hat{n}_{d\downarrow}\right)^2 - U_b\left(\hat{n}_{0\uparrow} - \hat{n}_{0\downarrow}\right)^2 + \sum_{k<\Lambda^*} \epsilon_k \hat{n}_{k\sigma}$$

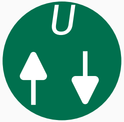




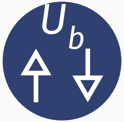
Low-energy effective Hamiltonians and ground-states

Regime 3: $|U_b| > J/4$

Zero-bandwidth limit



impurity site



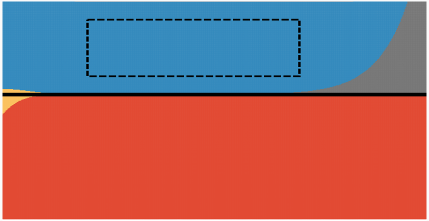
zeroth site

$$H = -U/2\left(\hat{n}_{d\uparrow} - \hat{n}_{d\downarrow}\right)^2 - U_b\left(\hat{n}_{0\uparrow} - \hat{n}_{0\downarrow}\right)^2$$

✓ impurity site detaches from bath

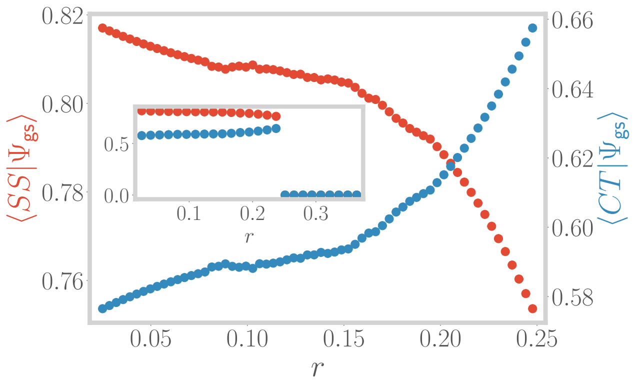
✓ **local moment** ground-state

$$|\Psi\rangle_{GS} = |\uparrow,\downarrow\rangle_d \otimes |0,2\rangle_0$$



Low-energy effective Hamiltonians and ground-states

Ground-state overlaps with spin singlet and charge triplet zero

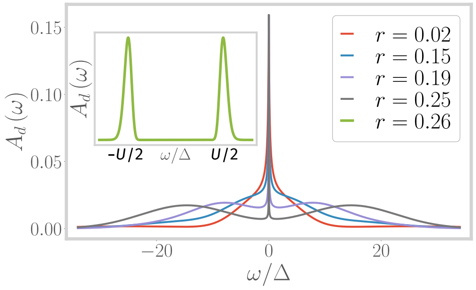


Nature of the Transition

Gapping of the impurity spectral function

✓ Correlated **three peak** structure at $|U_b| \lesssim J/4$

✓ Broad central peak at $|U_b| \ll J/4$

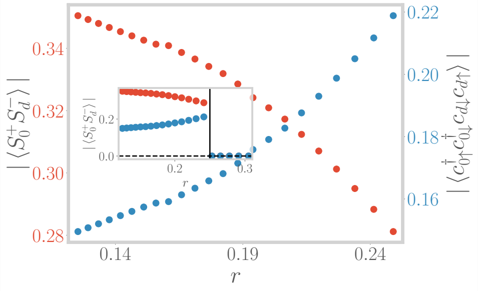


✓ hard central **gap** for $|U_b| > J/4$

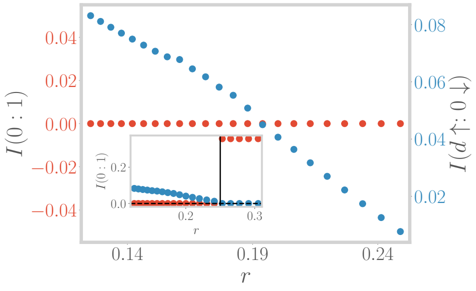
Destruction of the Kondo cloud

The Kondo cloud weakens, and is destroyed at the transition.

✓ vanishing of impurity-bath correlations



✓ transfer of entanglement into the bath

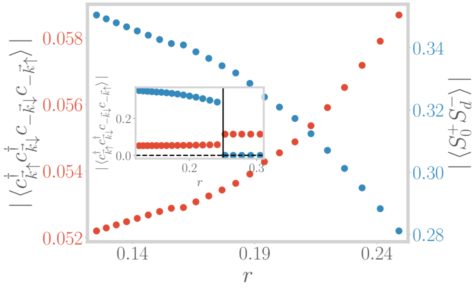


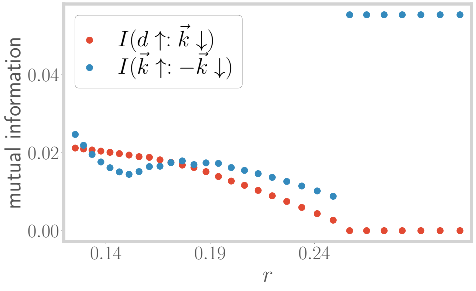
Growth of pairing fluctuations in the bath

Subdominant pairing fluctuations, near the transition...

✓ growth of fluctuations in Cooper channel, at the cost of spin-flip fluctuations

✓ mutual information within the bath maximised after transition





Universal Theory near the Transition

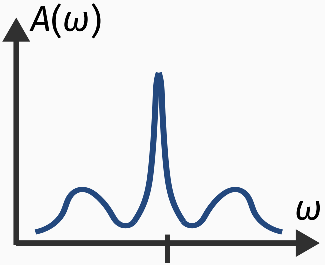
Minimal effective model for the transition

✓ For $|U_b| \lesssim J/4$, central peak and side peaks are **well-separated**

✓ **Integrate out** charge fluctuations through Schrieffer-Wolff transformation

$$H_{\text{eff}} = \tilde{J}\vec{S}_d \cdot \vec{S}_0 - \tilde{U}_b\left(\hat{n}_{0\uparrow} - \hat{n}_{0\downarrow}\right)^2 + H_{\text{K.E.}}$$

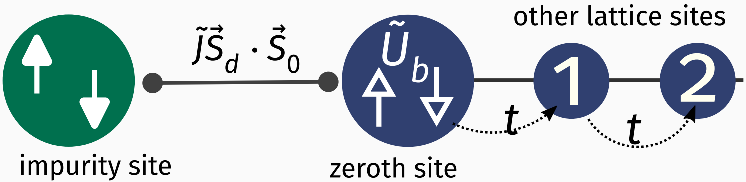
RG equation for $\tilde{J}$: $\Delta\tilde{J} \sim \tilde{J}\left(\tilde{J} + 4\tilde{U}_b\right)$



Moeller et al. 1995; Held et al. 2013.

Minimal effective model for the transition

✓ **captures the criticality**, and the strong-coupling and local moment phases

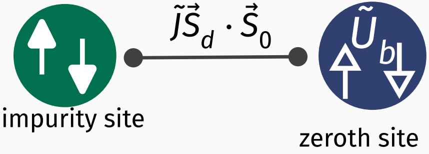


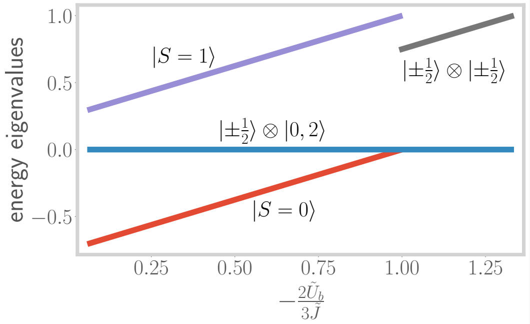
Suggests that J and U_b are the minimal & universal ingredients for transition!

Capturing the level crossing at the transition from a two-site model

✓ Obtain two-site model by taking **zero bandwidth** limit

✓ spectrum shows **level crossing** between singlet and local moment states

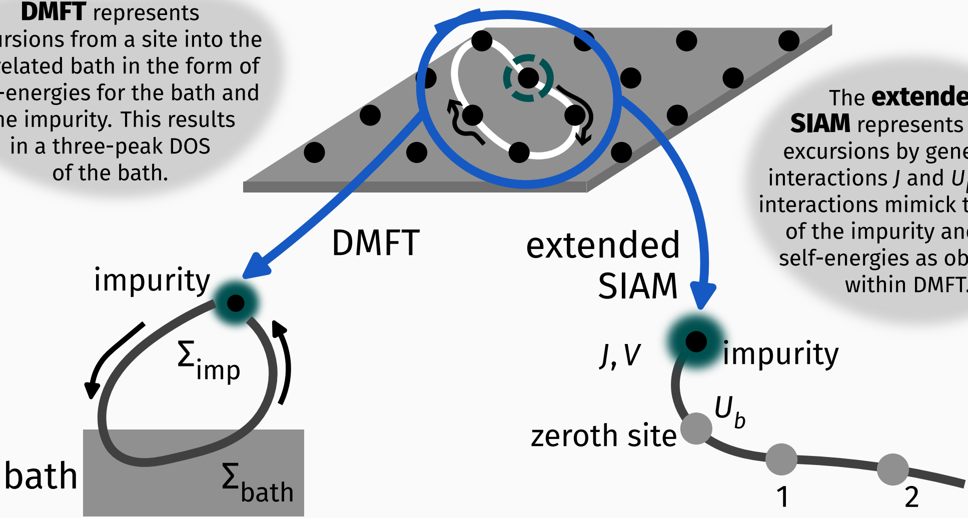




Insights into DMFT

Extended SIAM in the context of DMFT

DMFT represents excursions from a site into the correlated bath in the form of self-energies for the bath and the impurity. This results in a three-peak DOS of the bath.

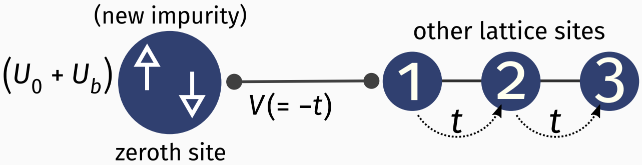


The **extended SIAM** represents these excursions by generating interactions J and U_b. These interactions mimick the effect of the impurity and bath self-energies as observed within DMFT.

Equivalence of the impurity site and the bath zeroth site

✓ **Integrate out impurity site** from fixed point Hamiltonian via a single URG transformation

✓ Generates additional correlation U_0 on zeroth site



✓ J is relevant and the largest scale $\longrightarrow$ **repulsive correlation**:

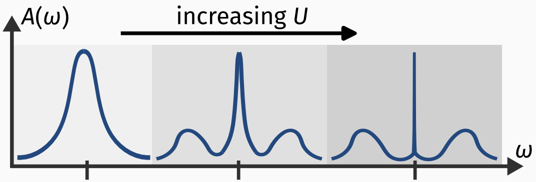
$$U_0 + U_b \simeq J > 0$$

Moeller et al. 1995.

Equivalence of the impurity site and the bath zeroth site

✓ J acts a **symmetrisation mechanism** between impurity and zeroth sites

✓ **Coherent** spin-flip scatterings ensure similarity of spectral functions

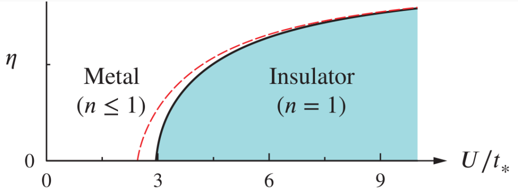


Essence of self-consistency: Equivalence of impurity and zeroth sites!

Moeller et al. 1995.

Observation of a coexistence region

- ✓ DMFT observes a **coexistence region** near the critical point, for $U_{c1} < U < U_{c2}$
- ✓ Insulating when coming in from the insulator, metallic when coming in from the metal



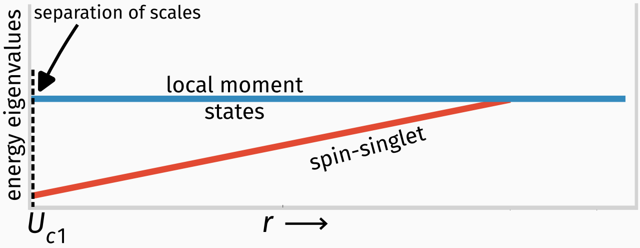
(D.E. Logan and M.R Galpin 2016 JPCM 28 025601)

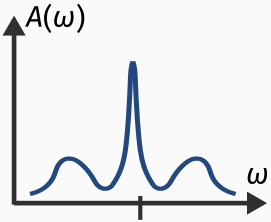
- ✓ Mott gap appears **discontinuously** after the transition, through a **continuous** sharpening of the central peak.
- ✓ **True** transition believed to occur at U_{c2}.

Observation of a coexistence region

Can be explained heuristically using the two site spectrum

✓ Initial point is when the side peaks get separated (near-zeroes in the spectral function)

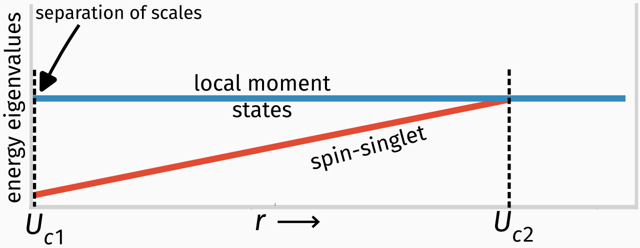


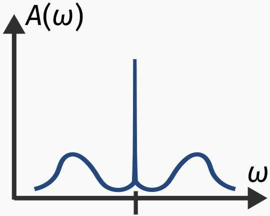


Observation of a coexistence region

Can be explained heuristically using the two site spectrum

✓ U_{c2} is the point where the levels cross

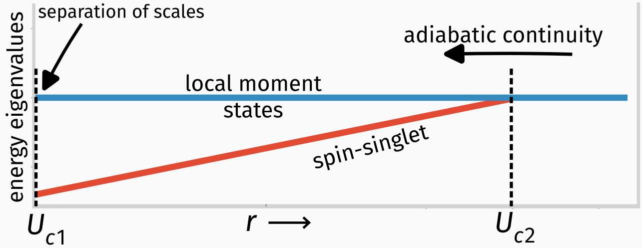


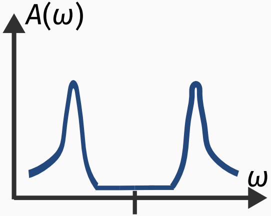


Observation of a coexistence region

Can be explained heuristically using the two site spectrum

✓ Coming from $U > U_{c2}$, **adiabatic continuity** allows DMFT to stay on the local moment state...

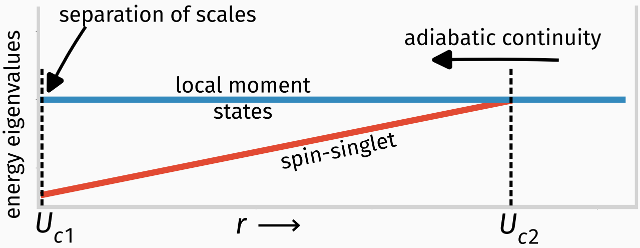


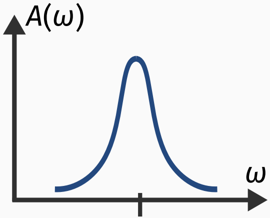


Observation of a coexistence region

Can be explained heuristically using the two site spectrum

✓ For $U < U_{c1}$, local moment state is too unstable, **relaxes** to the true ground state.

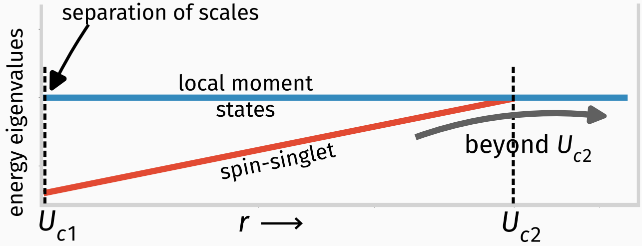


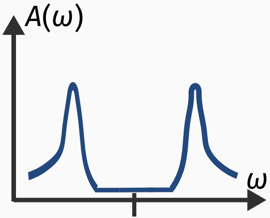


Observation of a coexistence region

Can be explained heuristically using the two site spectrum

✓ For $U > U_{c1}$, charge sector separated by large U, leads to the **discontinuous** appearance of finite gap





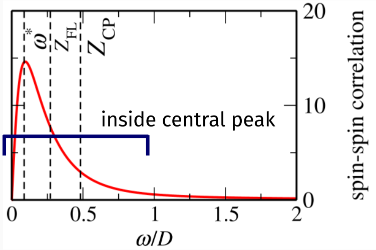
Comparison against NRG-DMFT correlation functions

Poor Man's scaling of the effective Kondo model
[K. Held, R. Peters, and A. Toschi. PRL 2013]

✓ shows **quantitative** agreement with NRG-DMFT (crossover scale and kinks in self-energy)

✓ Suggests that the minimal model can capture **spin susceptibility**

[K. Held, R. Peters, and A. Toschi. PRL 110, 246402 (2013)]



✓ Our $J - U_b$ model **goes further** by capturing physics beyond the transition

Comparison against NRG-DMFT correlation functions

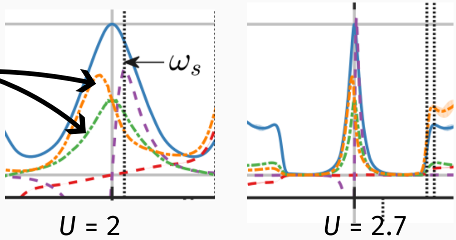
Doublon-holon correlators of the Hubbard model

[S. B. Lee, J. v Delft, and A. Weichselbaum. PRL 2017]

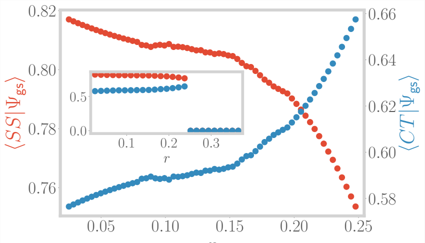
Lee et. al show **peaks** in doublon-holon correlators near zero energy within the central Kondo peak.

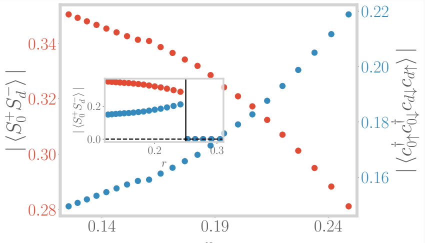
doublon-holon correlators

[S. B. Lee, J. v Delft, and A. Weichselbaum. PRL 2017]



We find support for this in the form of **increasing ground-state charge correlations and overlap**.



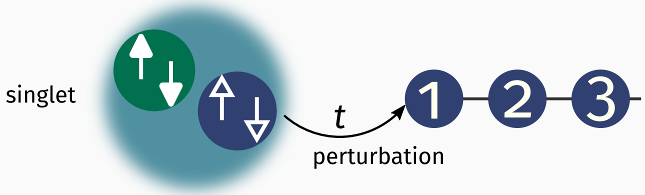


Low-energy excitations of the bath

Effect on the local Fermi liquid

What about the low-energy excitations of the bath, that lie above the singlet ground state?

✓ treat hopping between singlet and bath as perturbation



✓ Up to fourth order, charge sector becomes repulsive...

$$H_{\text{eff}} = \frac{2t^4}{\tilde{J}\left(3\tilde{J}/4 + \tilde{U}_b\right)^2}\left[\hat{n}_{1\uparrow}\hat{n}_{1\downarrow} + \left(1 - \hat{n}_{1\uparrow}\right)\left(1 - \hat{n}_{1\downarrow}\right)\right] + H_{\text{K.E.}}$$

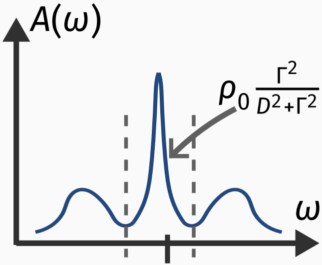
✓ FL term blows up towards transition, signaling **breakdown** of Fermi liquid theory and loss of adiabaticity.

Effect on the local Fermi liquid

Vanishing of the Kondo scale T_K towards the transition

✓ Consider the $J - U_b$ model, but with a **Lorentzian DOS** in the bath:

$$\rho = \rho_0 \frac{\Gamma^2}{D^2 + \Gamma^2}$$



✓ Near the transition $r = -U_b/J_0 \to \frac{1}{4}$ and $\Gamma \to 0$, the **IR energy scale** D^* can be approximated as

$$D^* = D_0 \exp\left[\frac{\left(2\omega + U_b + J_0/2\right)^2}{8|U_b|\rho_0\Gamma^2} \ln|1 - 4r|\right], \quad D_0 = \text{UV cutoff} .$$

Held et al. 2013.

Effect on the local Fermi liquid

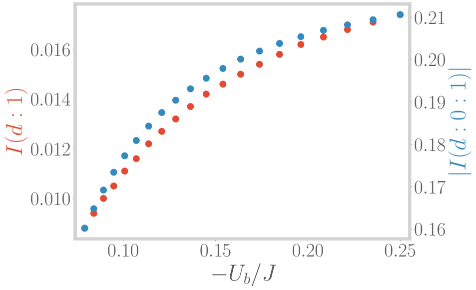
Vanishing of the Kondo scale T_K towards the transition

✓ **Kondo temperature** can be defined as $T_K = D^* / k_B$:

$$T_K = \frac{D_0}{k_B} \exp\left[\frac{\left(2\omega + U_b + J_0/2\right)^2}{8|U_b|\rho_0\Gamma^2} \ln|1 - 4r| \right]$$

✓ Kondo temperature vanishes as $r \to 1/4$:

$$T_K \sim (1 - 4r)^\alpha \to 0$$



Held et al. 2013.

Effect on the local Fermi liquid

How do the imaginary part of self-energy and the qp residue behave near the transition?

✓ Following the renormalised perturbation theory approach of Hewson, $\mathrm{Im}\left[\Sigma(\omega)\right]$ is

$$\mathrm{Im}\left[\Sigma(\omega)\right] \sim u^2\omega^2, \quad u = \frac{2t^4}{\tilde{J}\left(3\tilde{J}/4 + \tilde{U}_b\right)^2}$$

✓ As $r \to 1/4$, $u \to \infty$, signalling a vanishing lifetime of the quasiparticles

✓ Quasiparticle residue Z for 1-particle excitations is proportional to T_K:

$$Z \sim T_K$$

$$Z \to 0 \text{ as } r \to 1/4$$

Hewson 1993; Coleman 2015.

Effective Hamiltonian at the critical point

What is the nature of the low-energy excitations exactly at the critical point?

✓ Singlets become **degenerate** with local moment states at the critical point:

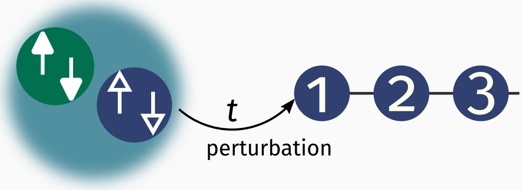
$$\frac{1}{\sqrt{2}}\left(|\uparrow,\downarrow\rangle - |\downarrow,\uparrow\rangle\right), \quad |\sigma\rangle\,|0\rangle, \quad |\sigma\rangle\,|2\rangle$$

✓ **Non-zero degeneracy** exists even in presence of hopping perturbation:

$$|N_{\text{tot}} = 2,\ S^z_{\text{tot}} = 0\rangle, \quad |N_{\text{tot}} = 3,\ S^z_{\text{tot}} = \pm 1/2\rangle\,,$$

$$|N_{\text{tot}} = 4,\ S^z_{\text{tot}} = 0\rangle$$

$$N_{\text{tot}} = \hat{n}_d + \hat{n}_0 + \hat{n}_1, \quad S^z_{\text{tot}} = S^z_d + S^z_0 + S^z_1$$



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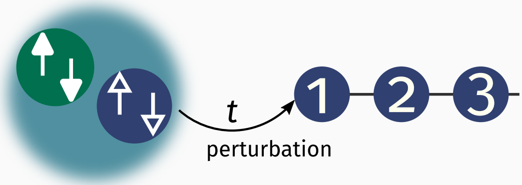


✓ Presence of magnetic states with $S^z_{tot} \neq 0$ indicates **breakdown of screening**

✓ Non-vanishing degeneracy will lead to critical correlations and **non-Fermi** liquid physics

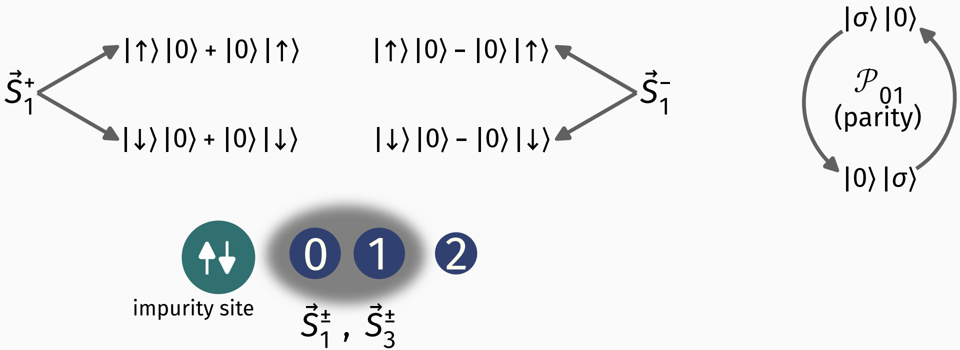
Varma et al. 2002.

Effective Hamiltonian at the critical point

What is the nature of the low-energy excitations exactly at the critical point?

✓ $S^z_{\text{tot}} = 0$ first order effective Hamiltonian acquires quasi non-local terms:

$$H_{\text{eff}} = t\vec{S}_d \cdot \left(\vec{\mathcal{S}}^-_1 + \vec{\mathcal{S}}^-_3 - \vec{\mathcal{S}}^+_1 - \vec{\mathcal{S}}^+_3\right) + \frac{t}{4}\mathcal{P}_{01} + H_{\text{K.E.}}$$



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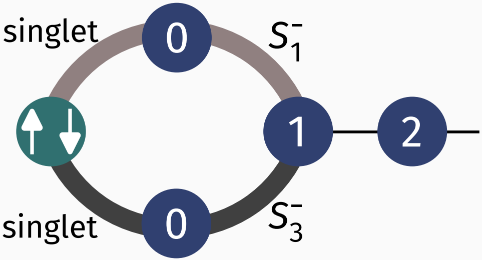
✓ Ground-state dictated by $\mathcal{S}^-_1, \mathcal{S}^-_3$: degenerate singlets

✓ Spreading of extent of bath spin indicates **stretching** of singlet in real space



Effective Hamiltonian at the critical point

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- ✓ Shows the **dispersion** of entanglement across the lattice at critical point. Precursor to decoupling of impurity spin.

- ✓ Degenerate singlets connected by hopping; reminiscent of **multichannel** Kondo physics and source of non-Fermi liquid physics

Broad conclusions

- ✓ The extended SIAM appears to capture the phenomenology of the DMFT transition and **self-consistency**.
- ✓ The key ingredient is a **competition** between Kondo screening physics and a local attractive correlation in the bath.
- ✓ Crucial feature of the journey is the enhancement of **pairing fluctuations** in the bath: leads to destruction of Kondo cloud.

Broad conclusions

- ✓ An **emergent self-consistency** is achieved through the qualitative similarity of the spectral functions of the impurity and zeroth sites.

- ✓ Approach towards criticality is marked by **vanishing** metallic energy scale and quasiparticle residue.

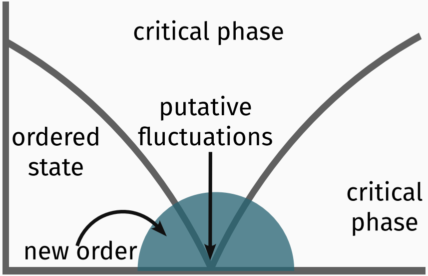
- ✓ **Non-Fermi liquid** physics arises at critical point, through the expansion of the singlet into the next lattice site.

Future Prospects

Future Prospects

✓ The extended SIAM can be improved by considering **multiple impurities** and general impurity **filling**.

✓ We are developing a new **tiling-based auxiliary model method** can used for studying other models of strong-correlations as well as topologically active or flat band systems.



✓ The URG can be applied to **heavy-fermion materials** towards a study of phase diagram and unconventional superconductivity, as well as Kondo insulators.

✓ Interacting systems in a magnetic field is also a potential area of study, specifically **fractional Chern insulators** (e.g. the fractional quantum hall effects).

Acknowledgements

Gracious thanks to

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- ✓ **Prof. H. Casini, Prof. N. Banerjee** and **Shibendu G. Chowdhury** for very fruitful discussions, and
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More insight into self-consistency

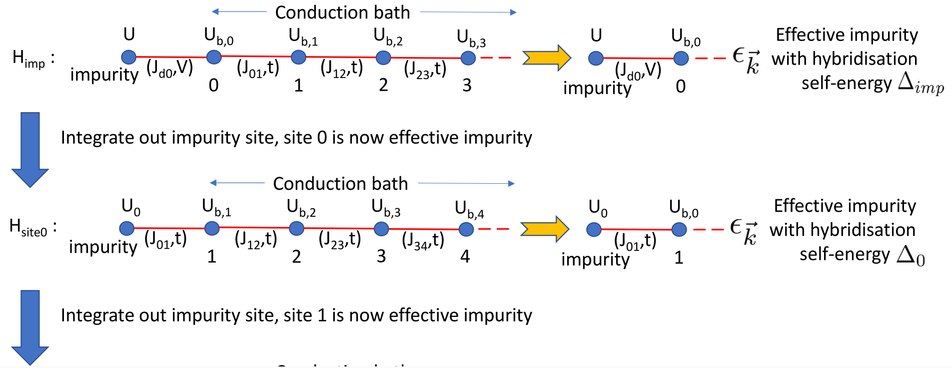
Meaning of exact self-consistency

- ✓ Minimal impurity model $\implies$ qualitative self-consistency $\implies$ impurity site = zeroth site
- ✓ Full self-consistency $\implies$ equivalence of self-energy on all sites

More insight into self-consistency

Meaning of exact self-consistency

✓ Can be achieved through an extended impurity model with U_b and J on all sites in the bath

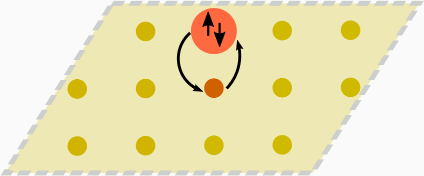


Other Projects

Theory for the single-channel Kondo cloud

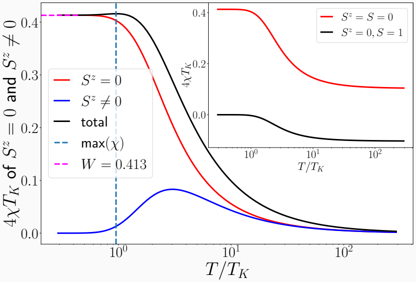
Phys. Rev. B 105, 085119

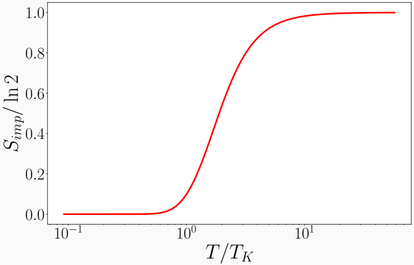
Anirban Mukherjee, **Abhirup Mukherjee**, N. S. Vidhyadhiraja,
A. Taraphder, and Siddhartha Lal



Theory for the single-channel Kondo cloud

✓ spectral function & magnetic susceptibility





✓ local Fermi liq. & orthogonality catastrophe

✓ thermal entropy

Kondo 1964; Wilson 1975; Andrei et al. 1983; Hewson 1993; Nozieres 1974; Anderson 1970; Tsvelick et al. 1983; Affleck et al. 1993; Goldhaber-Gordon et al. 1998; V. Borzenets et al. 2020; Sakai et al. 1989; Costi et al. 1990; Nozaki et al. 2012; Affleck 1995.

Role of degeneracy in the multi-channel Kondo problem

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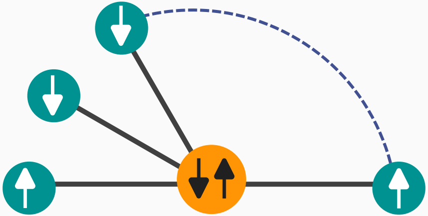
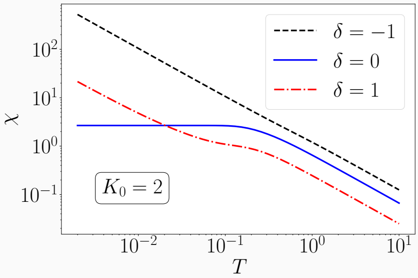
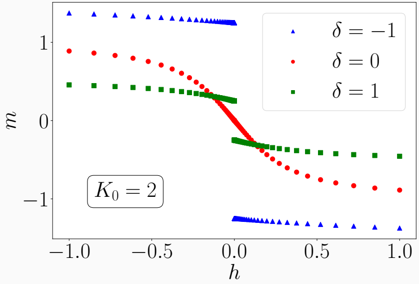


Role of degeneracy in the multi-channel Kondo problem

- ✓ Intermediate-coupling RG fixed point Hamiltonian and **degenerate** ground states
- ✓ Degree of compensation, magnetization and susceptibility show **incomplete screening**



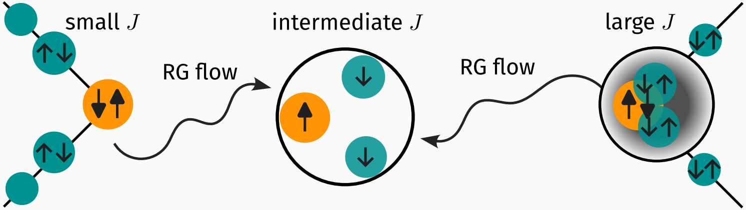


Nozières, Ph. et al. 1980; Tsvelick et al. 1985; Affleck et al. 1993; Gan 1994; Affleck et al. 1991; Emery et al. 1992; Bulla et al. 1998.

Role of degeneracy in the multi-channel Kondo problem

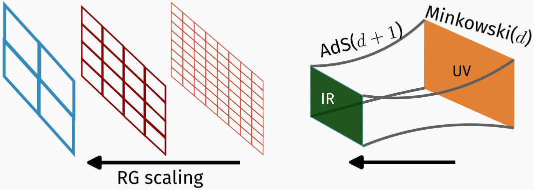
✓ Local **marginal Fermi liquid** within the low-energy excitations of the bath

✓ **Duality** relations constrain the RG flows of the MCK model



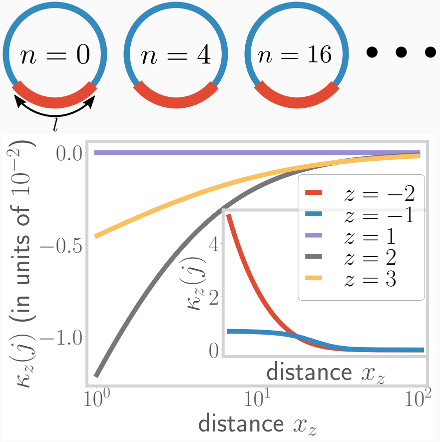
Nozières, Ph. et al. 1980; Tsvelick et al. 1985; Affleck et al. 1993; Gan 1994; Affleck et al. 1991; Emery et al. 1992; Bulla et al. 1998.

Entanglement scaling in free fermions: holography & topology



Entanglement scaling in free fermions: holography & topology - Summary

- ✓ Under coarse-graining or fine-graining in k–space, entanglement of free Dirac fermions shows hierarchical onion-like structure.
- ✓ Entanglement scaling can be used to define distances, leads to additional spatial dimension $\longrightarrow$ holography.
- ✓ Emergent distances and curvature can be related to RG beta function; the sign of the curvature is topological.
- ✓ Pole structure of the entanglement tracks the Luttinger volume - invariant under the scaling transformations.



Creating subsystems

Free Dirac fermions on torus: $k_x^n = \frac{2\pi}{L_x} n, \quad n \in \mathbb{Z}$; define **sparsity** = $\Delta n = 1$

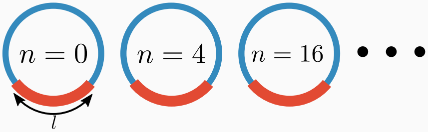
Simplest choice: the entire set

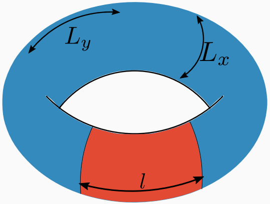
sparsity = 1 $\longrightarrow n \in \{-N, -(N-1), -(N-2), \dots, -1, 0, 1, \dots, N-2, N-1, N\}$

Coarser choices: increase sparsity

sparsity = 2 $\longrightarrow n \in \{-N, -(N-2), -(N-4), \dots, -2, 0, 2, \dots, N-4, N-2, N\}$

sparsity = 4 $\longrightarrow n \in \{-N, -(N-4), -(N-8), \dots, -4, 0, 4, \dots, N-8, N-4, N\}$





Subsystem entanglement entropy: Entanglement hierarchy

$$S_{\mathcal{A}_z(j)} = f_z(j)c\alpha L_x - c\log\left|2\sin\left(\pi f_z(j)\phi\right)\right|$$

$$i<j,\quad S_{i\cup j} = \begin{cases} S_i, & z>0 \\ S_j, & z<0 \end{cases}$$

✓ presents a **hierarchy** of entanglement $\longrightarrow$ EE distributed across RG steps
RG transformation $\longrightarrow$ reveals entanglement

✓ distribution of entanglement also present in **multipartite** entanglement

Calabrese et al. 2004; Casini et al. 2005; Arias et al. 2015; Chen et al. 2017; Murciano et al. 2020.

Mutual information = distance

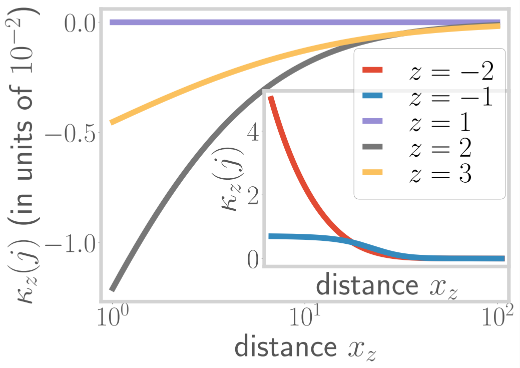
Mutual information: $I^2(A:B) \equiv S(A) + S(B) - S(A \cup B)$ (non-negative)

Define distances using mut. info.

$$x_z(j) = \log t_z(j), \quad y_z(j) = \log t_z(j \pm 1)$$

$$v_z(j) \equiv \Delta y_z(j)/\Delta x_z(j), \quad v' = \Delta v_z(j)/\Delta x_z(j)$$

Curvature as well: $\kappa_z(j) = \dfrac{v_z'(j)}{\left[1 + v_z(j)^2\right]^{\frac{3}{2}}}$



Van Raamsdonk 2010; Lee et al. 2016; Mukherjee et al. 2022; Lee 2010; Lee 2014; Qi 2013; Lee et al. 2016; Mukherjee et al. 2020a; Mukherjee et al. 2020b; Ryu et al. 2006b; Ryu et al. 2006a; Nozaki et al. 2012.

RG evolution = emergent distance

✓ Distances and curvature can be related to an RG **beta function**

✓ Amounts to an **explicit demonstration** of the holographic principle

✓ Sign of curvature is **topological**, can be written in terms of winding numbers

Maldacena 1999; Ryu et al. 2006a; Holzhey et al. 1994.

Topological nature of geometry-independent term

$$S_{\mathcal{A}_z(j)} = f_z(j) c \alpha L_x - \underbrace{c \log \left| 2 \sin \left(\pi f_z(j) \phi \right) \right|}_{=Q(\phi), \text{geometry-independent term}}$$

✓ $Q(\phi)$ is periodic in the flux ϕ, $\phi = 1$ transports a charge across Fermi surface

✓ pole structure of $\left(\sin \frac{\pi}{4} - |\sin\left(\pi f_z(j)\right) \phi| \right)^{-1}$ counts number of states $\longrightarrow$ tracks Luttinger volume

✓ Luttinger volume is topological, so is $Q(\phi)$; $Q(\phi)$ can be expressed in terms of winding numbers

Luttinger et al. 1960; Luttinger 1960; Oshikawa 2000; Seki et al. 2017; Mukherjee et al. 2020a; Heath et al. 2020.