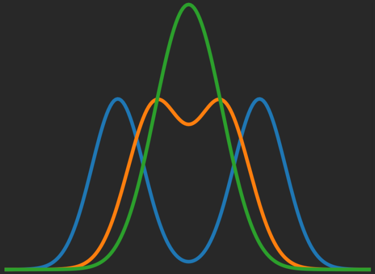
# Unveiling the Kondo cloud: unitary RG study of the Kondo model



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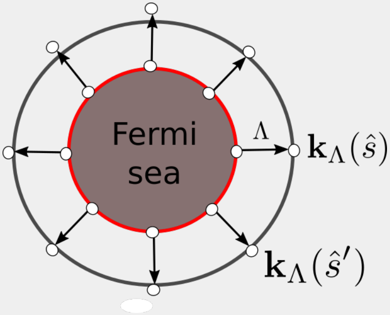
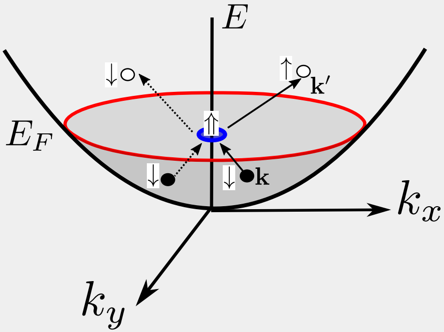
# The Model

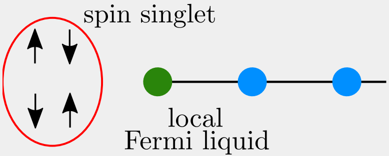
$$\mathcal{H} = \sum_{k\sigma} \epsilon_k \hat{n}_{k\sigma} + J\vec{S}_d \cdot \vec{s}, \qquad \vec{s} \equiv \sum_{kk',\alpha,\beta} \vec{\sigma}_{\alpha\beta} c^\dagger_{k\alpha} c_{k'\beta}$$



# The Model

- Kondo coupling $J$ renormalises to infinity




Anderson and Yuval 1969; Anderson 1970; Wilson 1975; Andrei, Furuya, and Lowenstein 1983a; Andrei, Furuya, and Lowenstein 1983b; Wiegmann 1981.

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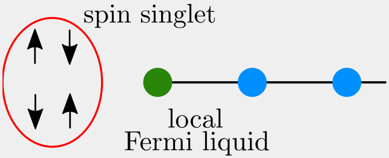


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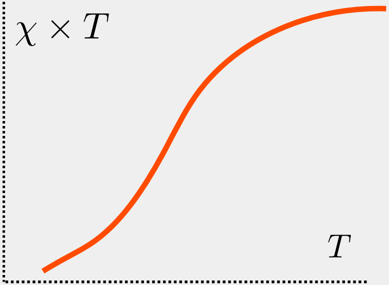


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# The Model

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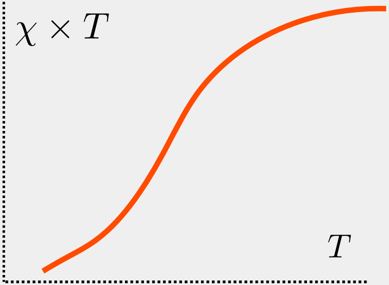
- low energy phase of metal is local Fermi liquid
- $\chi$ constant at low temperatures, $C_v$ linear
- thermal quantities functions of single scale $T/T_K$





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- Finite $J$ effective Hamiltonian at fixed point
- Effective Hamiltonian for the itinerant electrons forming the Kondo cloud
- Nature of correlations inside the Kondo cloud: Fermi liquid vs off-diagonal
- Behaviour of many-particle entanglement and many-particle correlations under RG flow

# The Unitary Renormalization Group Method

## The General Idea

- Apply unitary many-body transformations to the Hamiltonian

$$
\begin{array}{c}
H_j \\
\Big\downarrow U_j \\
H_{j-1}
\end{array}
$$

Mukherjee and Lal 2020a; Mukherjee and Lal 2020b.

## The General Idea

- Apply unitary many-body transformations to the Hamiltonian
- Successively decouple high energy states

$$H_j \xrightarrow{U_j} H_{j-1}$$

Mukherjee and Lal 2020a; Mukherjee and Lal 2020b.

# The Unitary Renormalization Group: Overview

## The General Idea

- Apply unitary many-body transformations to the Hamiltonian
- Successively decouple high energy states
- Obtain sequence of Hamiltonians and hence scaling equations

$$\begin{tikzcd} H_j \arrow[d, "U_j"] \\ H_{j-1} \end{tikzcd}$$

Mukherjee and Lal 2020a; Mukherjee and Lal 2020b.

## Step 1: Select a UV-IR Scheme

$k_N \equiv$ UV state

.

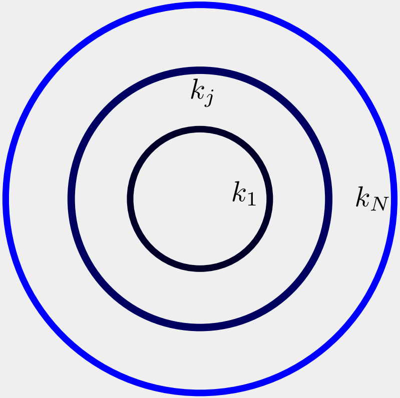
.

$k_j$

.

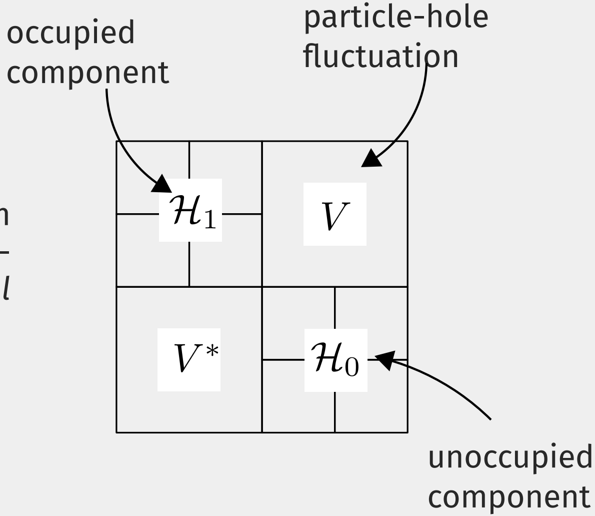
.

$k_1 \equiv$ IR state (Fermi surface)



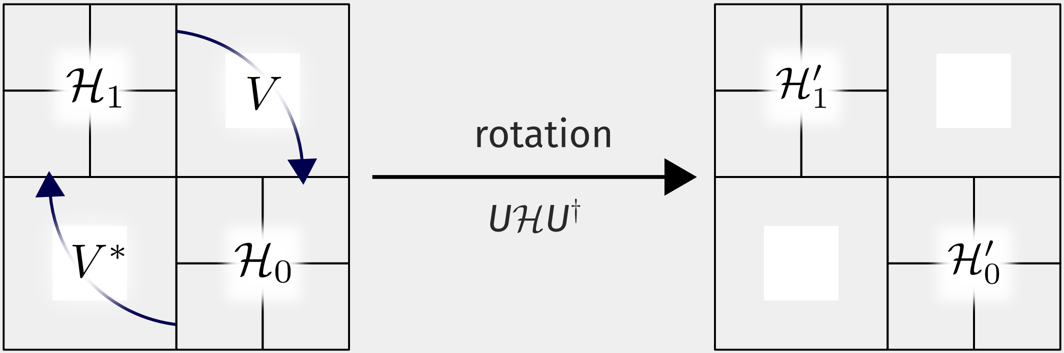
**Step 1: Select a UV-IR Scheme**

Start with the electrons farthest from the Fermi surface. Write the Hamiltonian as *diagonal and off-diagonal terms* in this basis.



**Step 2:**

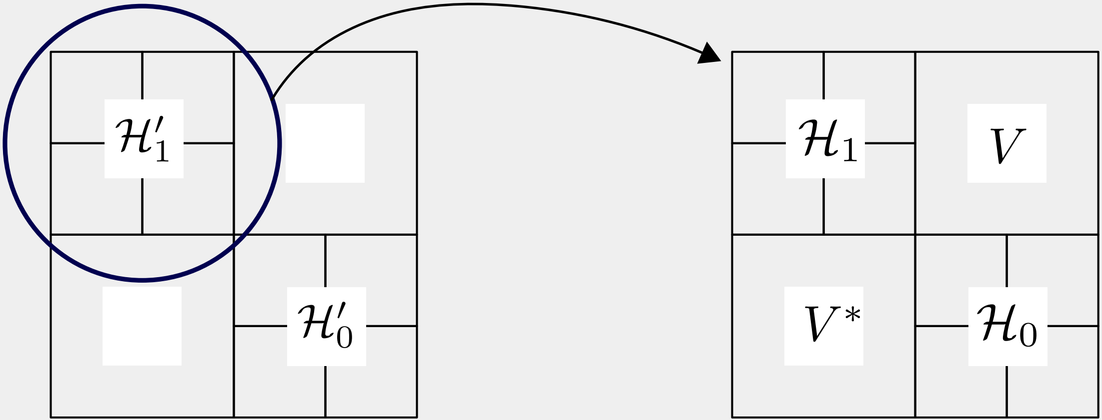
Rotate the Hamiltonian to kill the off-diagonal blocks.




$[\mathcal{H}, \hat{n}] \neq 0$

$[\mathcal{H}, \hat{n}] = 0$

**Step 3:**
Repeat the process with the new blocks.



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- Presence of finite-valued fixed points
- Spectrum-preserving transformations
- Tractable low-energy effective Hamiltonians