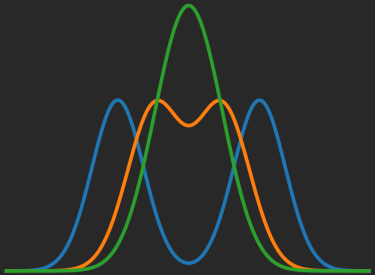
Unitary Renormalization Group Solution of the Single-Impurity Anderson model



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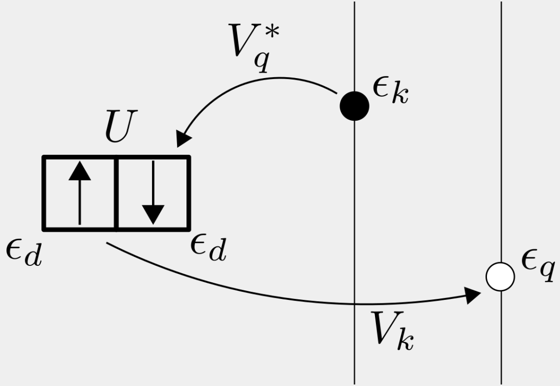
The Single-Impurity Anderson Model

The Single-Impurity Anderson Model

$$\mathcal{H} = \overbrace{\sum_{k\sigma} \epsilon_k \hat{n}_{k\sigma}}^{\text{conduction bath}} + \overbrace{\sum_{k\sigma} \left[V(k) c^\dagger_{k\sigma} c_{d\sigma} + \text{h.c.} \right]}^{\text{hybridisation}} + \overbrace{\epsilon_d \sum_{\sigma} \hat{n}_{d\sigma}}^{\text{impurity site energy}} + \overbrace{U \hat{n}_{d\uparrow} \hat{n}_{d\downarrow}}^{\text{d-d repulsion}}$$



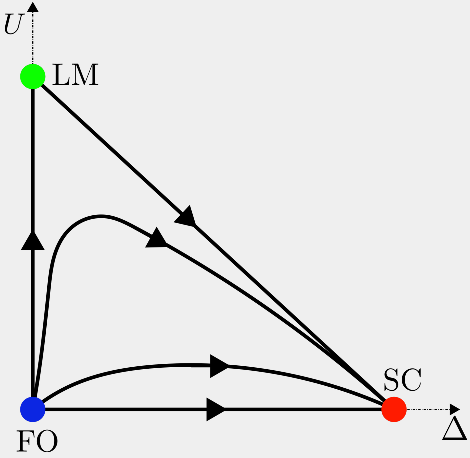
$$\rho(\epsilon) \approx \rho(\epsilon_F)$$

$$\Delta = \rho V^2$$

$$\epsilon_d = -\frac{1}{2} U \text{ (p-h symmetry)}$$

NRG Results - Symmetric Model

- the **free-orbital** fixed point ($U = \Delta = 0$) - unstable
- the **local moment** fixed point ($U = \infty, \Delta = 0$) - saddle point, and
- the **strong-coupling** fixed point ($\Delta = \infty, U =$ finite) - stable.



Krishna-murthy, Wilson, and Wilkins 1975.

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- Is it possible to show the **transfer of spectral weight** along the flow, possibly by tracking the spectral function?
- How does the renormalization affect the **many-particle entanglement** between the electrons?
- Are there any interesting **topological aspects** of the fixed points?

The Unitary Renormalization Group

Unitary Renormalization Group: Overview

The Short Version

Apply *unitary many-body transformations* to the Hamiltonian so as to successively *decouple* high energy states and hence obtain scaling equations.

$$\mathcal{H}(D)$$

$$\Big\Downarrow$$

$$U\mathcal{H}(D)U^\dagger$$

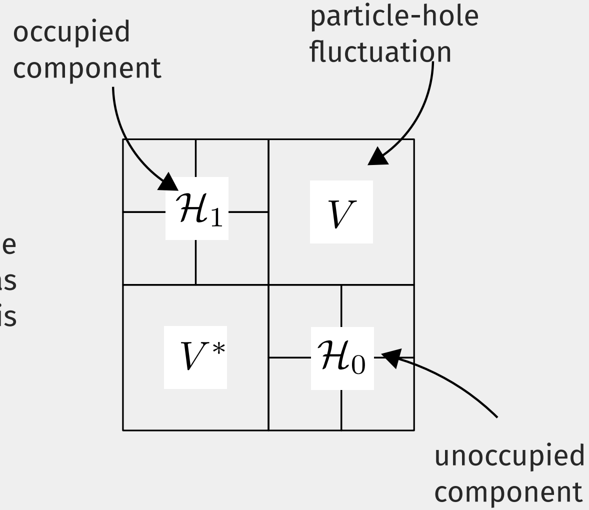
$$\Big\Downarrow$$

$$H(D) + \mathcal{H}'(D - \delta D)$$

Mukherjee and Lal 2020.

Step 1:

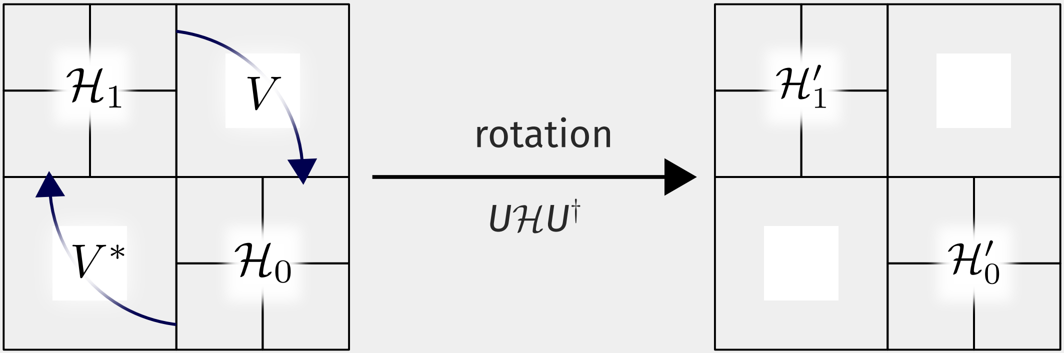
Start with the electrons farthest from the Fermi surface. Write the Hamiltonian as *diagonal and off-diagonal terms* in this basis.



URG: Formalism

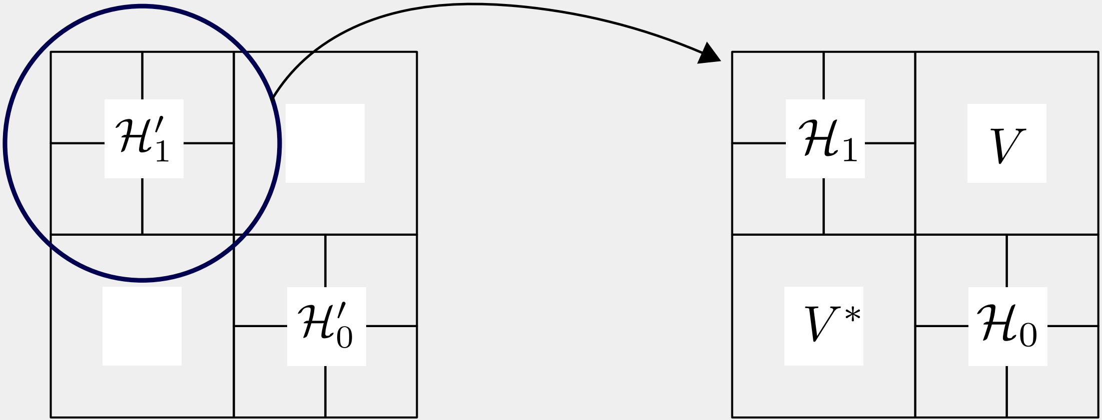
Step 2:

Rotate the Hamiltonian to kill the off-diagonal blocks.



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

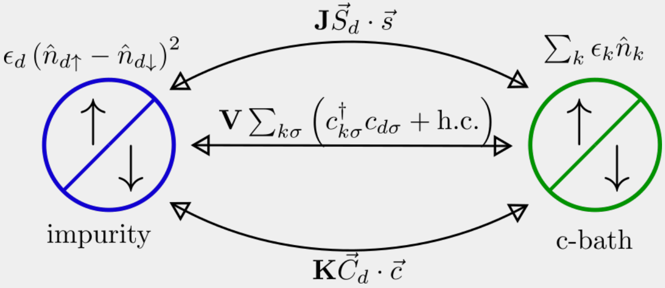
Step 3:
Repeat the process with the new blocks.



Generalized SIAM

Model: Generalized SIAM

$$H = H_{\text{SIAM}} + J\vec{S}_d \cdot \vec{s} + K\vec{C}_d \cdot \vec{c}$$



$$\vec{S}_d \equiv \frac{1}{2}\sum_{\alpha\beta} c^\dagger_{d\alpha}\vec{\sigma}_{\alpha\beta}c_{d\beta}$$

$$\vec{s} \equiv \frac{1}{2}\sum_{\alpha\beta} c^\dagger_{0\alpha}\vec{\sigma}_{\alpha\beta}c_{0\beta}$$

$$\vec{C}_d \equiv \frac{1}{2}\sum_{\alpha\beta} \psi^\dagger_{d\alpha}\vec{\sigma}_{\alpha\beta}\psi_{d\beta}$$

$$\vec{c} \equiv \frac{1}{2}\sum_{\alpha\beta} \psi^\dagger_{0\alpha}\vec{\sigma}_{\alpha\beta}\psi_{0\beta}$$

$$\vec{\psi}_d \equiv \begin{pmatrix} c_{d\uparrow} \\ c^\dagger_{d\downarrow} \end{pmatrix} \qquad \vec{\psi}_0 \equiv \sum_k \begin{pmatrix} c_{k\uparrow} \\ c^\dagger_{k\downarrow} \end{pmatrix}$$

Schrieffer and Wolff 1966.

RG Equations, Their Features and Fixed Points

RG Equations

$$\Delta U = 4|V|^2 \left[\frac{1}{\omega - \frac{1}{2}D + \frac{U}{2} + \frac{1}{2}J} - \frac{1}{\omega - \frac{1}{2}D - \frac{U}{2} + \frac{1}{2}K}\right] + \sum_{k<\Lambda_j} \frac{3}{4}\frac{K^2 - J^2}{\omega - \frac{1}{2}D + \frac{1}{4}J + \frac{1}{4}K}$$

$$\Delta V = \frac{VK}{16}\left(\frac{1}{\omega - \frac{1}{2}D - \frac{U}{2} + \frac{1}{2}K} + \frac{1}{\omega - \frac{1}{2}D + \frac{1}{4}J + \frac{1}{4}K}\right) - \frac{3VJ}{4}\left(\frac{1}{\omega - \frac{1}{2}D + \frac{U}{2} + \frac{1}{2}J} + \frac{1}{\omega - \frac{1}{2}D + \frac{1}{4}J + \frac{1}{4}K}\right)$$

$$\Delta J = -J^2\left(\omega - \frac{1}{2}D + \frac{1}{4}J + \frac{1}{4}K\right)^{-1}$$

$$\Delta K = -K^2\left(\omega - \frac{1}{2}D + \frac{1}{4}J + \frac{1}{4}K\right)^{-1}$$

Passage to Poor Man's Scaling Results

Symmetric SIAM

- $J = 0, K = 0$
- $\omega = -\frac{D}{2}$
- $U = -\frac{\epsilon_d}{2} \ll D$

$$\longrightarrow \quad \delta U = \delta V = 0$$

Haldane 1978; Jefferson 1977.

Passage to Poor Man's Scaling Results

Asymmetric SIAM

- $J = 0, K = 0$
- $\omega = -\frac{D}{2}$
- $U \gg D \gg \epsilon_d$

$$\longrightarrow$$

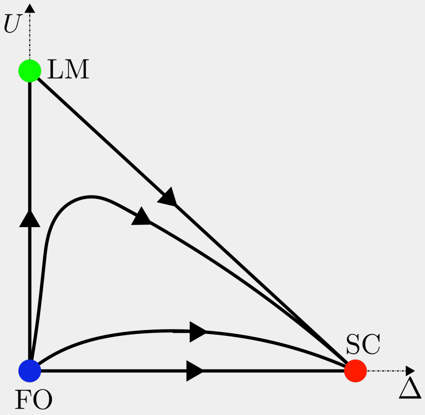
$$\delta U = \delta V = 0$$

$$\delta \epsilon_d = \frac{\Delta}{\pi} \delta \ln D$$

Haldane 1978; Jefferson 1977.

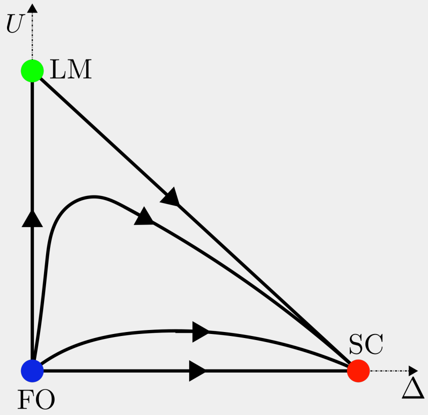
Fixed Points

- $J = K = 0 \longrightarrow \Delta V = 0$
- $J, K, V = 0^{+} \longrightarrow (V^{*}, J^{*}, K^{*}) = \text{large}, U^{*} = 0$
  - **strong-coupling fixed point**

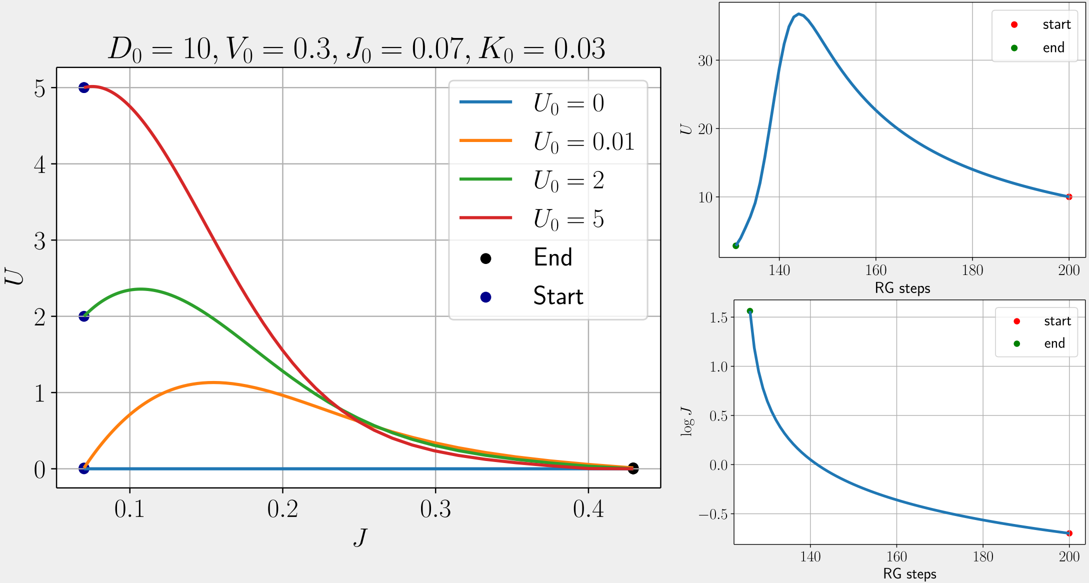


Fixed Points

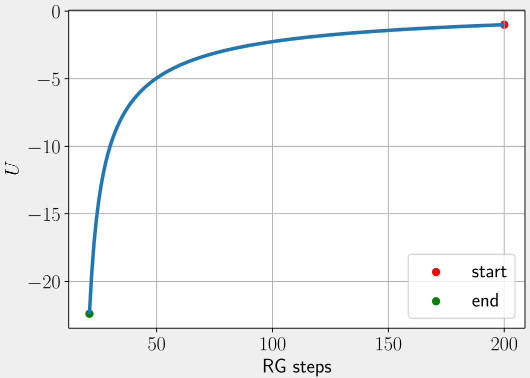
- $J = K = V = 0 \longrightarrow$ all couplings marginal
  - line of fixed points on y-axis
- $U = 0^{+} \longrightarrow$ **local moment fixed point**
  - ground-state is a decoupled impurity spin

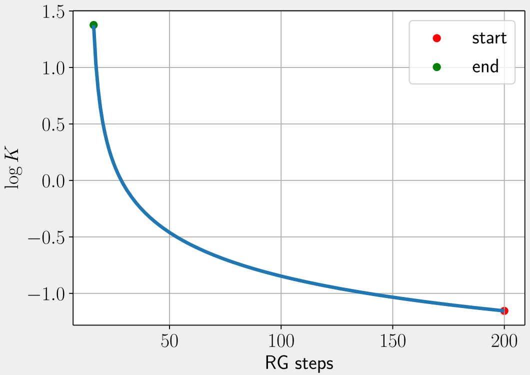


Results: $U > 0, J > K$



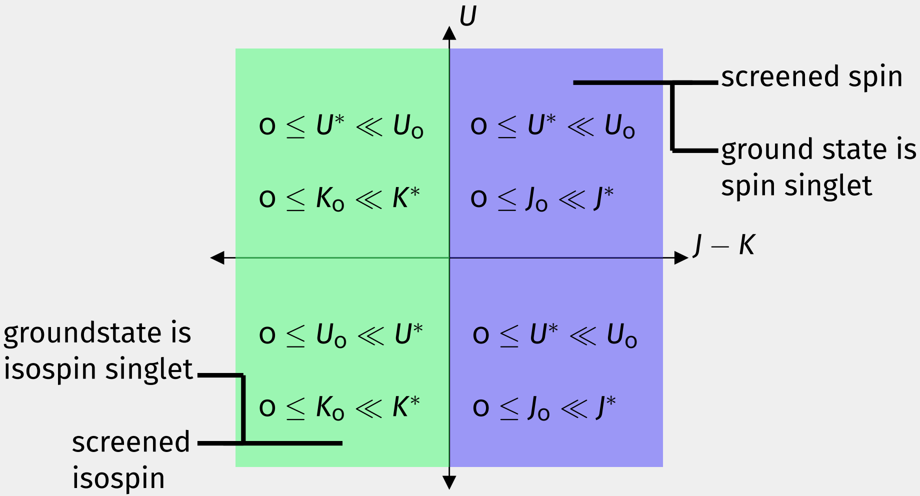
Results: $U < 0, J < K$





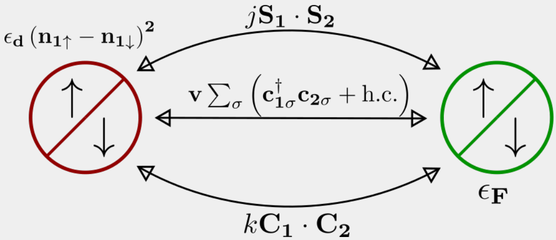
Low energy effective theory and ground state wavefunctions

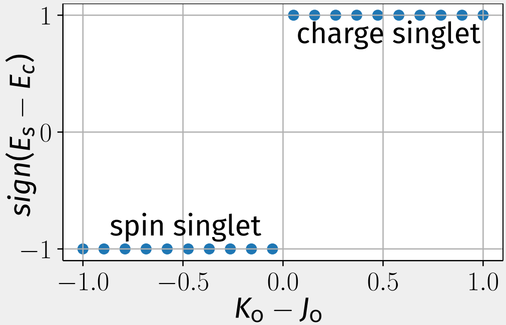
Results: Phase Diagram



Results: Effective Zero-mode Hamiltonian

$$H_{IR} = \epsilon_d^* \left(\hat{n}_{1\uparrow} - \hat{n}_{1\downarrow}\right)^2 + V^* \sqrt{N^*} \sum_\sigma \left(c_{1\sigma}^\dagger c_{2\sigma} + \text{h.c.}\right) + J^* N^* \vec{S}_1 \cdot \vec{S}_2 + K^* N^* \vec{C}_1 \cdot \vec{C}_2$$



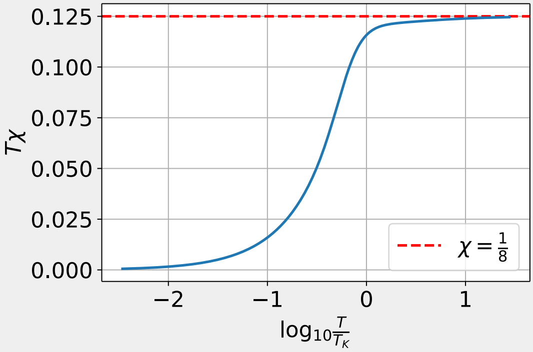


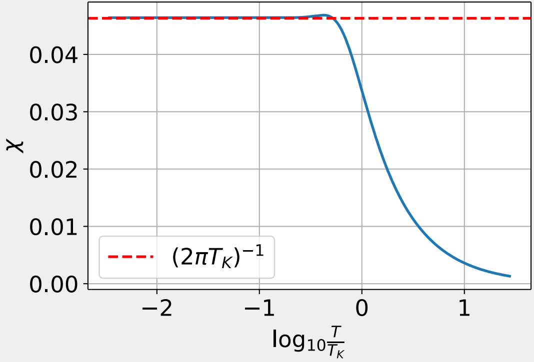
Wilson 1975; Krishna-murthy, Wilson, and Wilkins 1975; Taraphder and Coleman 1991.

Impurity Susceptibilities and Impurity spectral function

Results: Spin Susceptibility

$$\chi_s = \lim_{B \to 0} \frac{\partial m}{\partial B}$$



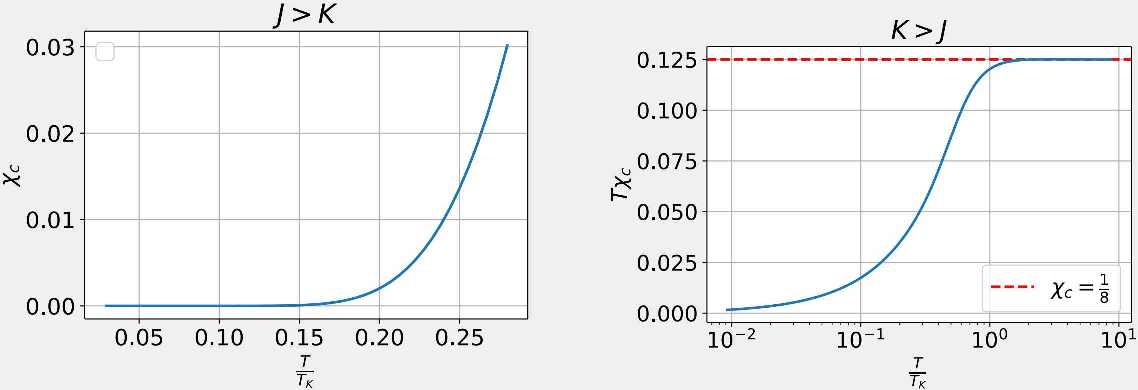


$\chi(T \to 0) = (2j)^{-1}$ $\quad$ $T_K \equiv \frac{2N^*}{\pi}(D^* - 2\omega)$ $\quad$ $(\chi \times T)(T \to \infty) = \frac{1}{8}$

Wilson 1975; Krishna-murthy, Wilson, and Wilkins 1975.

Results: Charge Susceptibility

$$\chi_c = \lim_{\mu \to 0} \frac{\partial N}{\partial \mu}$$

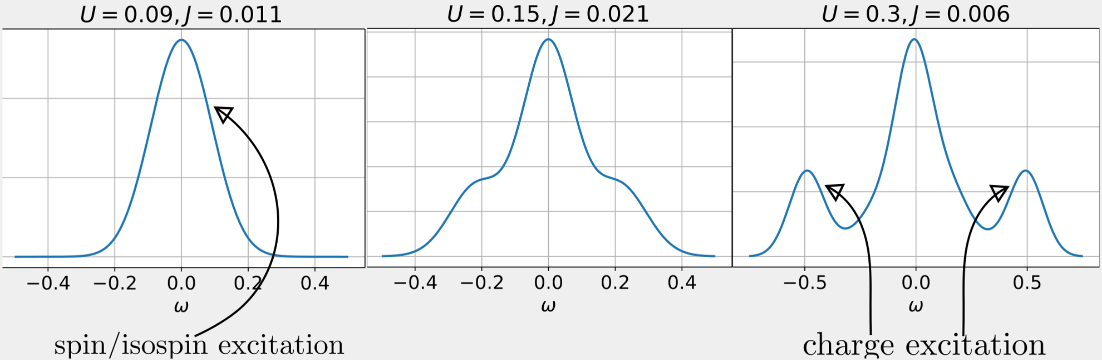


$$(\chi_c \times T)(T \to 0)\Big|_{K>J} = \frac{1}{2k} \qquad (\chi_c \times T)(T \to 0)\Big|_{J>K} = 0 \qquad \chi_c(T \to \infty) = \frac{1}{8}$$

Taraphder and Coleman 1991; Zitko and Bonca 2006.

Results: Impurity Spectral Function

$$\mathcal{A}(\omega) = -\frac{1}{\pi}\mathrm{Im}\ \left[G^{\sigma}_{dd}(\omega)\right] \qquad G^{\sigma}_{dd}(t) = -i\theta(t)\left\langle\left\{c_{d\sigma}(t), c^{\dagger}_{d\sigma}\right\}\right\rangle$$

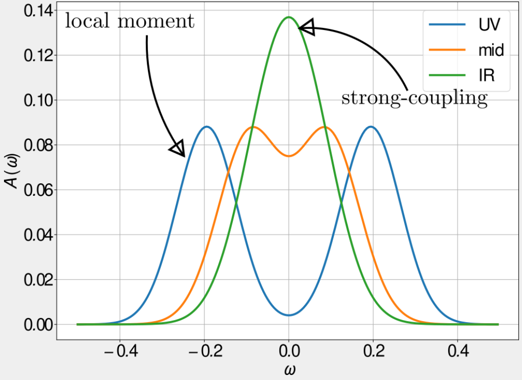


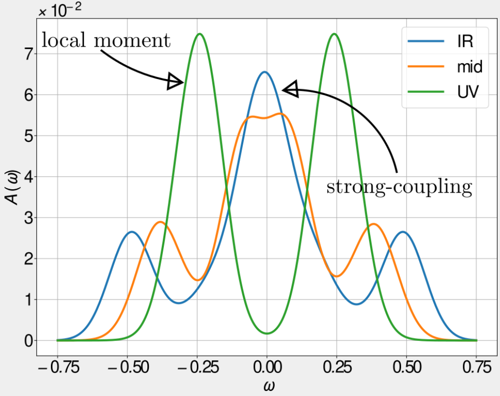
Hewson 1993; Bulla, Costi, and Pruschke 2008.

Results: Spectral Function Renormalization

$$\mathcal{A}(\omega) = -\frac{1}{\pi}\text{Im}\left[G^{\sigma}_{dd}(\omega)\right]$$

$$G^{\sigma}_{dd}(t) = -i\theta(t)\left\langle\left\{c_{d\sigma}(t), c^{\dagger}_{d\sigma}\right\}\right\rangle$$



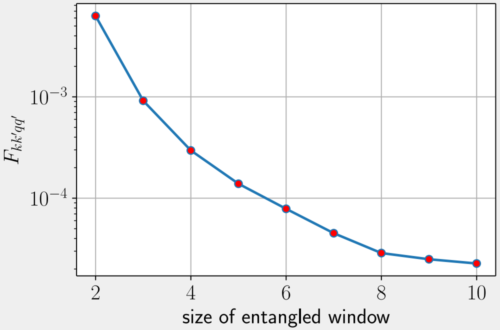


Entanglement measures and Topological Features of low energy theory

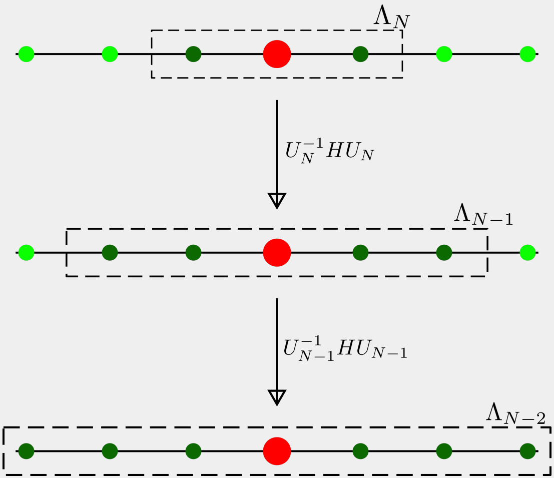
Results: Kondo Cloud Hamiltonian

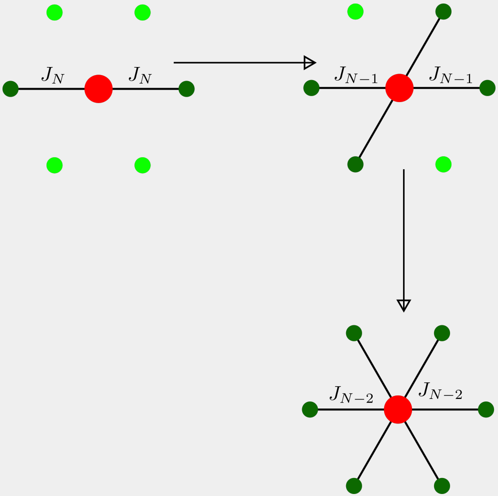
$$H^*(\text{d, cloud}) \xrightarrow{\text{solve for bath Hamiltonian}} H^*_{\text{cloud}}$$

$$H^*_{\text{cloud}} = \overbrace{H^*_0}^{\text{kinetic energy}} + \overbrace{\sum_{kk'\sigma\sigma'} f_{kk'}\hat{n}_{k\sigma}\hat{n}_{k'\sigma'}}^{\text{Fermi liquid-type interaction}} + \overbrace{\sum_{kk'qq'} F_{kk'qq'} c^\dagger_{k\uparrow} c^\dagger_{k'\downarrow} c_{q\uparrow} c_{q'\downarrow}}^{\text{non-Fermi liquid-type interaction}}$$



Results: Reverse RG: Overview



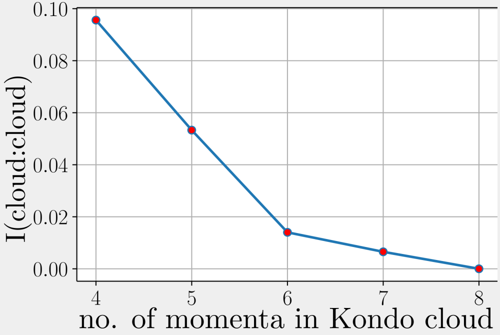


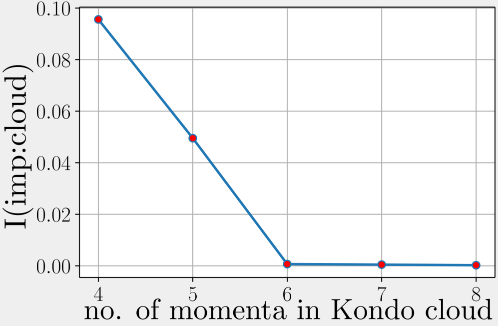
Mukherjee 2020.

Results: Reverse RG: Mutual Information

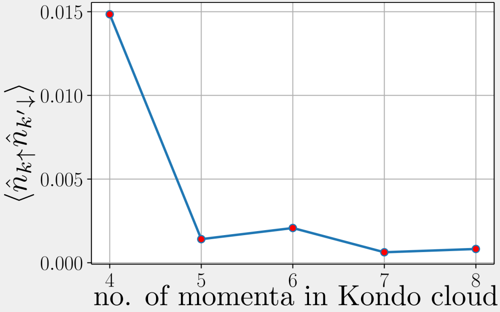
$$I(A:B) = S_A + S_B - S_{AB}$$

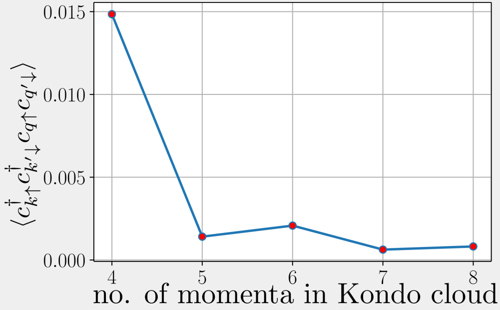
$$S_A = -\mathrm{Tr}\,[\rho_A \ln \rho_A]$$





Results: Reverse RG: Correlations



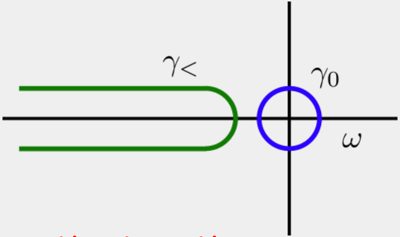


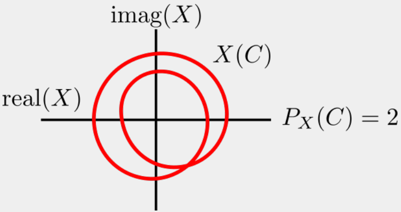
Results: Luttinger's Theorem

$$\underbrace{N}_{\text{total no. of particles}} = \underbrace{P_{\mathrm{Det}\,G_d}(\Gamma_<) + \frac{1}{2}P_{\mathrm{Det}\,G_d}(\Gamma_0)}_{\text{no. of poles of imp. Greens func.}} + \underbrace{V_L}_{\text{no. of poles of cbath Greens func}}$$

$$P_X(C) \equiv \frac{1}{2\pi i}\oint_C dz \frac{\partial \ln X}{\partial z} = \text{no. of poles of } X \text{ enclosed by curve } C$$

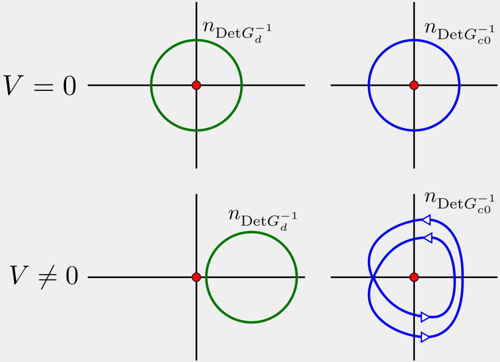
$$= \frac{1}{2\pi i}\oint_{X(C)} \frac{dX}{X} = \text{winding number of } X(C) \text{ around the origin}$$





Seki and Yunoki 2017.

Results: Luttinger's Theorem



$n_{\mathrm{Det}\ G_d^{-1}} = 1$

$n_{\mathrm{Det}\ G_d^{-1}} = 0$

$$V_L = V_L^0 + 1$$

Martin 1982.

Results: Local Fermi Liquid

$$H^* = \overbrace{J^* \vec{S_d} \cdot \vec{s} + K^* \vec{C_d} \cdot \vec{c} + V^* \left(c^\dagger_{d\sigma} c_{0\sigma} + \text{h.c.} \right)}^{\text{solve exactly}} + \overbrace{t \sum_{\langle i,j \rangle} c^\dagger_{i\sigma} c_{j\sigma}}^{\text{treat as perturbation}}$$

$$\Big\downarrow \; 4^{\text{th}} \text{ fourth order pert.}$$

$$E_1^{(4)} = -\frac{16t^4}{3J^{*3}}, \; E_2^{(4)} = -\frac{16t^4}{9J^{*3}}$$

$$H^* \sim J^* \vec{S_d} \cdot \vec{s} + K^* \vec{C_d} \cdot \vec{c} + V^* \left(c^\dagger_{d\sigma} c_{0\sigma} + \text{h.c.} \right) + \overbrace{\frac{t^4}{J^{*3}} \hat{n}_{1\uparrow} \hat{n}_{1\downarrow}}^{\text{local Fermi liquid}}$$

Nozières 1974.

Results: Wilson Ratio (T = 0)

thermal average: $\langle \hat{n}_{1\uparrow}\hat{n}_{1\downarrow}\rangle \xrightarrow[\text{}]{\text{mean field approximation}} \langle \hat{n}_{1\uparrow}\rangle \langle \hat{n}_{1\downarrow}\rangle$

$$\epsilon_{k\sigma} = \epsilon_k^0 + \sum_q f_{kq} \left\langle n_{q\bar{\sigma}} \right\rangle$$

- $f_{\uparrow\uparrow} = 0$
- $\chi_c(T \to 0) = 0$

$\longrightarrow$

- $C_v(T \to 0) = \rho_{\mathrm{imp}} T$
- $\chi_s(T \to 0) = 2\rho_{\mathrm{imp}}$

$$R = \frac{\chi_s}{\frac{C_v}{T}} = 2$$

Hewson 1994.

Results: Relation between R and ΔV_L

- particle-hole symmetry
- strong-coupling fixed-point
- $T = 0$

$\longrightarrow$

$$\frac{\chi_s}{C_v/T} = 1 + U\rho_{\text{imp}}(0)$$

$$\rho_{\text{imp}}(0) = (\pi\Delta)^{-1}\sin^2\delta(0)$$

$$R = 1 + \sin^2\delta(0)$$

Coleman 2015; Hewson 1993; Phillips 2003.

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- Friedel's sum rule
- scattering theory results

$$\longrightarrow \quad \frac{2}{\pi}\delta(0) = \tilde{N} = \Delta V_L$$

Coleman 2015; Hewson 1993; Phillips 2003.

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- particle-hole symmetry
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$$R = 1 + \sin^2\delta(0)$$

- Friedel's sum rule
- scattering theory results

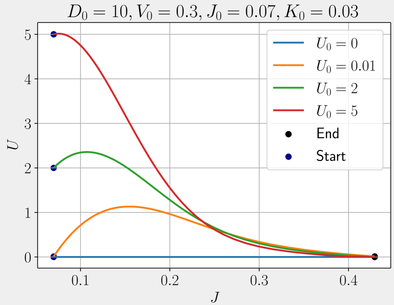
$$\longrightarrow \quad \frac{2}{\pi}\delta(0) = \tilde{N} = \Delta V_L$$

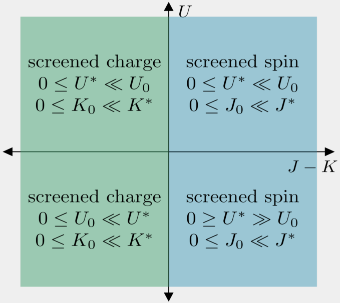
$$R = 1 + \sin^2\left(\frac{\pi}{2}\Delta V_L\right)$$

$$\Delta V_L = 1 \longrightarrow R = 2$$

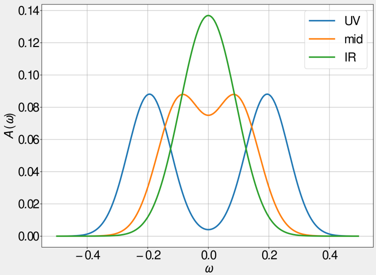
Coleman 2015; Hewson 1993; Phillips 2003.

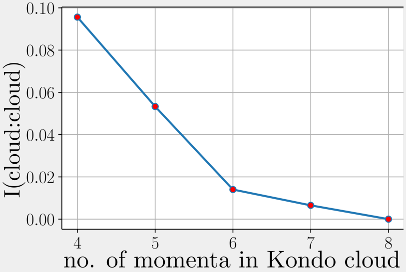
Summary of Results





$$H_{cloud} = H_0 + H_{FL} + H_{NFL}$$





$$R = 1 + \sin^2 \pi \Delta V_L = 2$$

$$\underset{\substack{\downarrow \\ \mathrm{SC}}}{V_L} = \underset{\substack{\downarrow \\ \mathrm{LM}}}{V_L^0} + 1$$

Future Directions

What's Next?

- Analytical expression for temperature-dependent Wilson ratio

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- Separating the contributions of various parts of the Kondo cloud to the spectral function

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- Analytical expression for temperature-dependent Wilson ratio
- Separating the contributions of various parts of the Kondo cloud to the spectral function
- Suggested by the generalized double-bracket form of URG, we can try to see if URG can be used as an optimizer.

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- Analytical expression for temperature-dependent Wilson ratio
- Separating the contributions of various parts of the Kondo cloud to the spectral function
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- extensions to the Kondo and Anderson lattices, and hence to the problem of heavy Fermions

Thanks for your attention!

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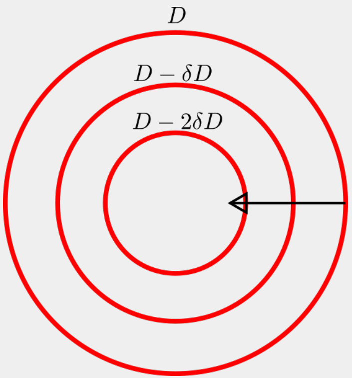
URG: Relation to Poor Man's Scaling

$$H = H_0 + \underbrace{V_+ + V_-}_{\text{off-diagonal terms we want to remove}}$$



Philosophy of Poor Man's scaling:

- Successively eliminate high-energy energy shells
- Write high energy excitations as second-order correction to low-energy scatterings
- Typically perturbative

Anderson 1970.

URG: Relation to Poor Man's Scaling

$$H = H_0 + \underbrace{V_+ + V_-}_{\substack{\text{off-diagonal terms} \\ \text{we want to remove}}}$$

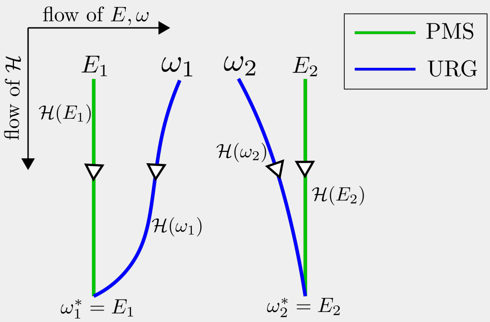
E = exact eigenvalue

ω = URG quantum fluctuation scale

$$\Delta H_{\text{PMS}} = V_- \frac{1}{E - H_0} V_+ + V_+ \frac{1}{E - H_0} V_-$$

$$\Big\downarrow E \to \omega$$

$$\Delta H_{\text{URG}} = V_- \frac{1}{\omega - H_0} V_+ + V_+ \frac{1}{\omega - H_0} V_-$$



URG: Relation to Continuous Unitary Transformation RG

$$H = \overbrace{H_d}^{\text{diagonal part}} + \overbrace{H_X}^{\text{off-diagonal part}}$$

$$\Delta H_{\text{CUT}} = \Delta l \left[\left[H_d(l), H_X(l) \right], H(l) \right]$$

$$V_{kq}(l) = V_{kq}(0) e^{(\epsilon_k - \epsilon_q) l}$$

- off-diagonal terms decay exponentially
- those that connect larger energy differences decay fastest

Głazek and Wilson 1993; Wegner 1994.

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$$\Delta H_{\text{URG}} = \overbrace{\left[\left[H_d, \frac{1}{\omega_1 - \omega_0} \left(\hat{\omega} - H_d \right)^{-1} H_I \right], H \right]}^{\Delta H_0} - H^I$$

$$\Delta H_0 \xrightarrow{\left(\hat{\omega} - H_d\right)^{-1} \sim -H_d^{-1}} \Delta\lambda \times \left[\left[H_d, H_I \right], H \right]$$