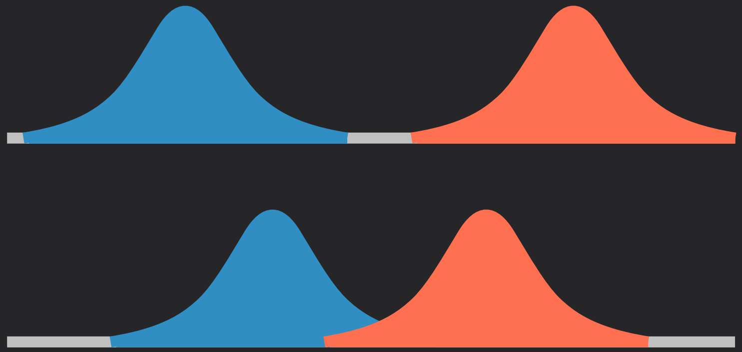
EXACTLY SOLVABLE MODEL OF CORRELATED METAL-INSULATOR TRANSITION

Insights on Non-Fermi Liquid and Mott Insulator

ABHIRUP MUKHERJEE



April 07, 2025

EPQM Seminar

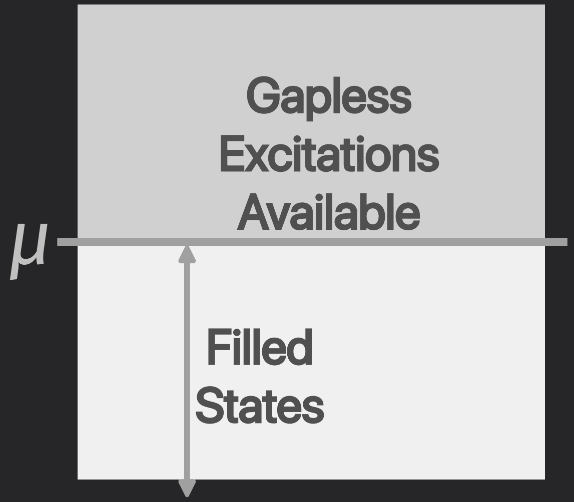
In A Nutshell

- An **exactly solvable** model that displays correlation-driven transition from a **non-Fermi liquid** to a **Mott insulator**.
- Analyse the non-Fermi liquid in this **controlled setting** to understand its features.
- Study a generalisation of this model to obtain **Fermi arcs**

Where Do Mott Insulators and Non-Fermi Liquids Fit in the "Standard Model"?

Mott Insulators Are Different

Half-filled system is **metallic** in absence of interactions.



Dispersion away from band edge is **non-interacting**.

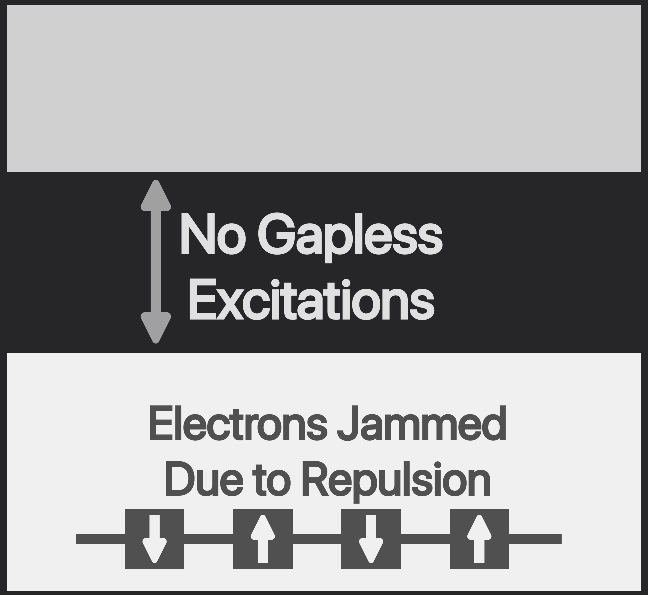
Mott (1968)

Mott Insulators Are Different

Half-filled system is **metallic** in absence of interactions.

Dispersion away from band edge is **non-interacting**.

Add strong **interactions** - Mott Insulator!



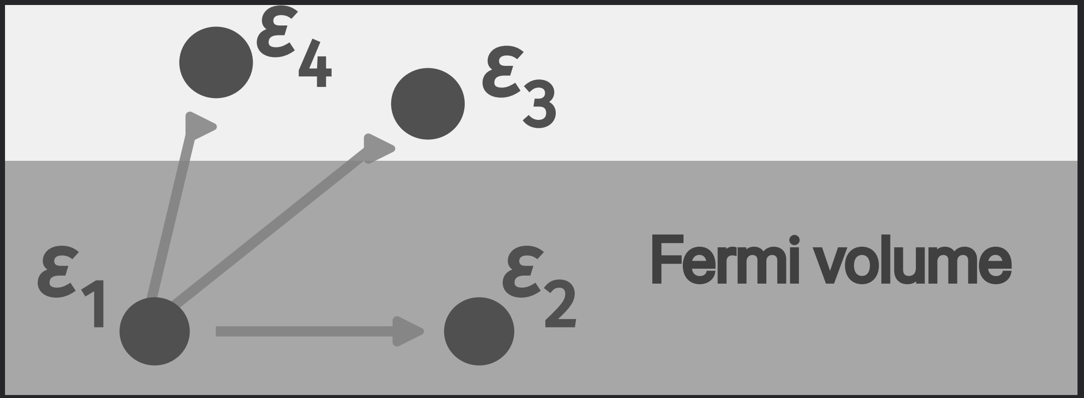
Gap opens inside the band: $\begin{pmatrix} \varepsilon & U \\ U & \varepsilon \end{pmatrix} \to \varepsilon \pm U$

Mott (1968)

Non-Fermi Liquids Are Different

Landau Fermi Liquid Theory (Postulates)

- Theory describing how **metals arise** in interacting systems
- Lack of scattering **phase space** at low-energies
- Fermi surface and low-lying electronic excitations survive (**quasiparticles**).



$$\Gamma \sim \int d\varepsilon_4 d\varepsilon_3 d\varepsilon_2 \delta(\varepsilon - \varepsilon_2 - \varepsilon_3 - \varepsilon_4) \sim \varepsilon^2$$

$$\rho \sim T^2$$

Landau (1958)

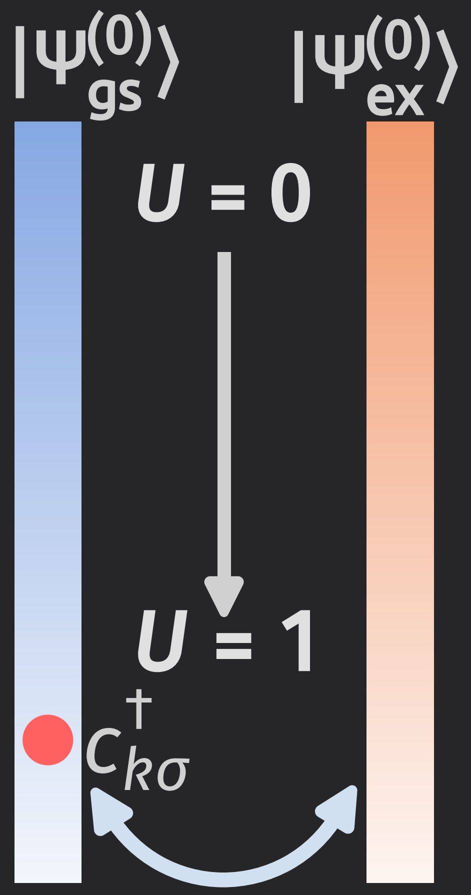
Non-Fermi Liquids Are Different

Landau Fermi Liquid Theory (Quantification)

- **Self-energy** $\Sigma \sim i\omega^2$. Quantifies **decay** rate. Vanishes very fast as $\omega \to 0$: essential for **quasiparticle** picture
- **Quasiparticle residue**: how similar are the true excitations to 1-particle excitations

$$Z = \langle \Psi_{\text{ex}} | c^\dagger_{\boldsymbol{k}\boldsymbol{\sigma}} | \Psi_{\text{gs}} \rangle$$

- $Z = \left(1 - \frac{\partial(\mathrm{Re}\,\Sigma)}{\partial\omega}\right)^{-1}$. Must be **non-zero** for Landau Fermi liquid.

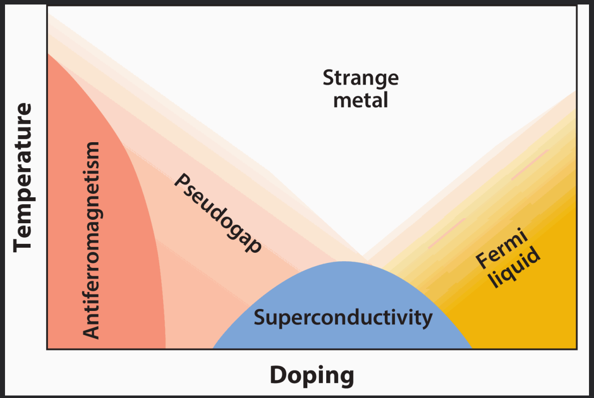


Landau (1958)

Non-Fermi Liquids Are Different

Violations Of Landau Fermi Liquid Theory

- **Tomonaga-Luttinger Liquid**: Interacting electrons in 1D $\longrightarrow$ spin-charge separation!
- **Overscreened** fixed points in Kondo models $\longrightarrow$ fractional entropy, diverging χ, C_v
- **Strange Metal**: Normal state of unconventional SCs in Cu oxides, heavy fermions, pnictides



Custers et al. (2003); Doiron-Leyraud et al. (2009); Emery & Kivelson (1992); Haldane (1981); Keimer et al. (2015)

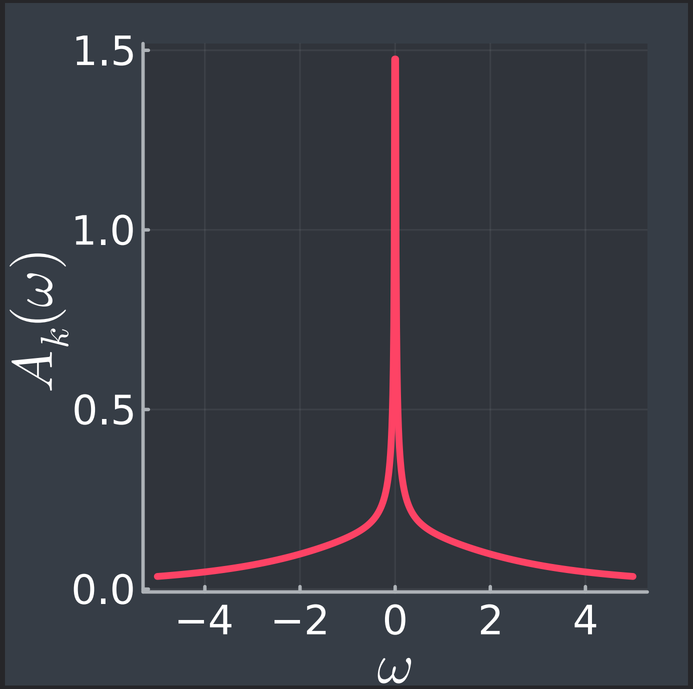
Non-Fermi Liquids Are Different

The Marginal Fermi Liquid

- **Phenomenological** explanation of normal state of cuprates: $\Sigma \sim \omega \log(|\omega|) - i\pi\ |\omega|$
- Quasiparticle residue **vanishes** at Fermi surface

$$Z^{-1} = 1 - \frac{\partial(\mathrm{Re}\ \Sigma)}{\partial \omega} \sim -\log(\omega) \to \infty$$

- Not accessible through **perturbative** corrections of Landau Fermi liquid



Mukherjee & Lal (2020); Varma et al. (1989)

Non-Fermi Liquids Are Different

Main Takeaways

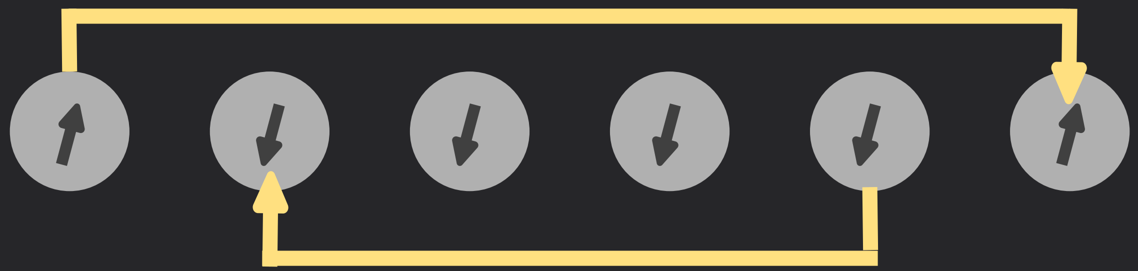
- Landau Fermi Liquid theory requires interacting eigenstates to be **adiabatically connected** to non-interacting eigenstates
- Non-Fermi liquids involve **vanishing quasiparticle residue**, signalling that the states are in fact not adiabatically connected.
- This typically means **non-perturbative** approaches are required to deal with such phases.
- The qualitatively different nature of excitations means that LFL and NFL correspond to **distinct fixed points** in the RG sense.

An Exactly Solvable Model

The Hatsugai-Kohmoto Model

Consider long-ranged interaction in real-space.

$$H = -t \sum_{<i,j>,\sigma} c^\dagger_{i,\sigma} c_{j,\sigma} + \frac{U}{L^d} \sum_{i_1,i_2,r} c^\dagger_{i_1+r,\uparrow} c^\dagger_{i_2-r,\downarrow} c_{i_2,\downarrow} c_{i_1,\uparrow}$$



Switch to momentum space, Hamiltonian **becomes local**!

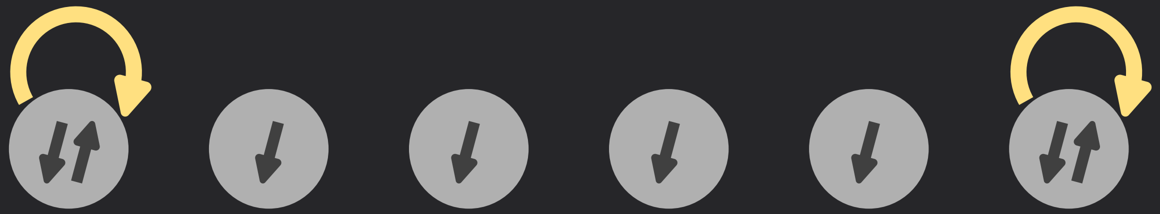
$$c^\dagger_r \sim \sum_k e^{-ikr} c^\dagger_k; \quad H = \sum_{\vec{k}} H_{\vec{k}}; \quad H_{\vec{k}} = \varepsilon_{\vec{k}} \sum_\sigma n_{\vec{k},\sigma} + U n_{\vec{k}\uparrow} n_{\vec{k}\downarrow}$$

Baskaran (1991); Hatsugai & Kohmoto (1992)

The Hatsugai-Kohmoto Model

Contrast with the Hubbard interaction.

$$H_{\text{int}} \sim \sum_i n_{i,\uparrow} n_{i,\downarrow} = \sum_{k_1,k_2,q} c^\dagger_{k_1+q,\uparrow} c^\dagger_{k_2-q,\downarrow} c_{k_2,\downarrow} c_{k_1,\uparrow}$$



- local in real-space, highly **non-local** in k –space
- HK model is $q = 0, k_1 = k_2$ (**zero mode**!) component of the Hubbard
- HKM is easier to solve than Hubbard (KE and PE **do not commute**)

Spectrum

$$H = \sum_{\vec{k}} H_{\vec{k}}; \quad H_{\vec{k}} = \varepsilon_{\vec{k}} \sum_{\sigma} n_{\vec{k},\sigma} + U n_{\vec{k}\uparrow} n_{\vec{k}\downarrow}$$

Each H_k can be diagonalised.

$$|0\rangle : E = 0, \quad |\sigma\rangle : E = \varepsilon_k, \quad |2\rangle : E = 2\varepsilon_k + U$$

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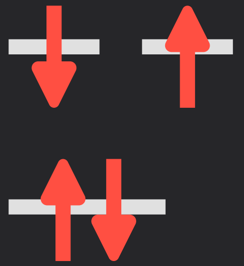

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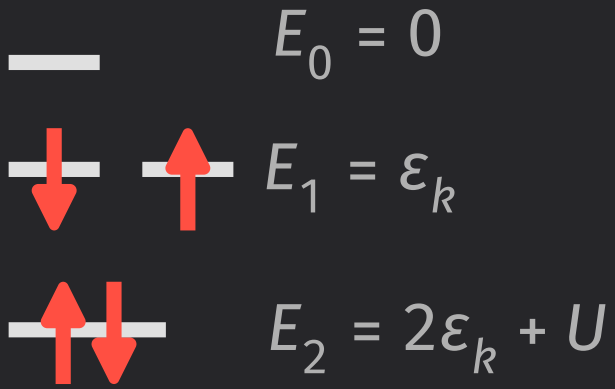

Case Of Half-Filling

$$E(\mu) = E - \mu n_k, \quad \mu = \frac{U}{2}$$

$$E_0 = 0, \quad E_1 = \varepsilon_k - \frac{U}{2}, \quad E_2 = 2\varepsilon_k$$

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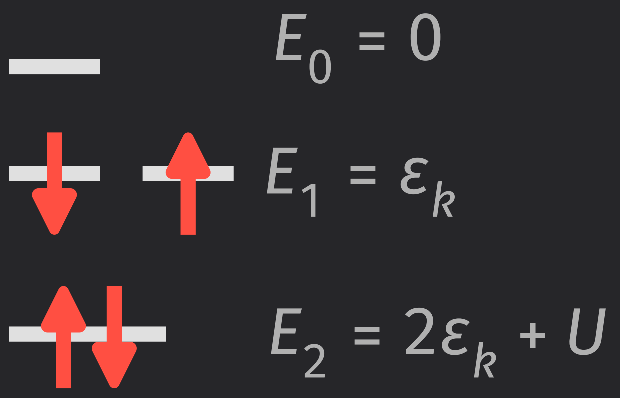

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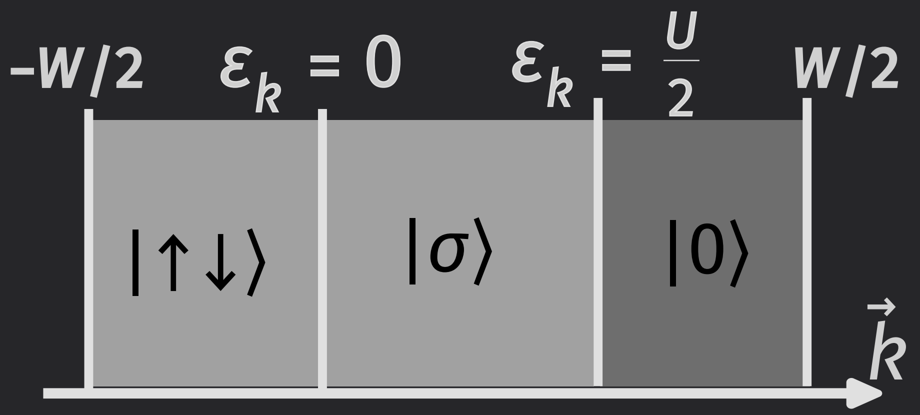


Introduction to Greens Functions

Nature of **excitations** can be studied through Greens function

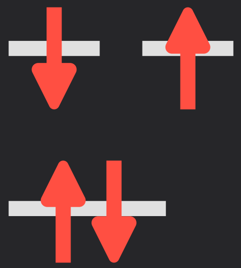
$$G_\nu(t) = -i\theta(t)\langle\{c_\nu(t), c_\nu^\dagger\}\rangle$$

- Non-interacting system: $G_k(\omega + i\eta) = \frac{1}{\omega+i\eta-\varepsilon_k}$
- **Poles** of Greens function $\longrightarrow$ one-particle excitations
- **Zeroes** of Greens function $\longrightarrow$ destruction of one-particle excitations

Exact Single-Particle Greens Function of the HKM

Greens function can be calculated as

$$G_{k\sigma}(\omega) = \frac{P_e(k\sigma)}{\omega - E_X} + \frac{P_h(k\sigma)}{\omega + E_X}$$



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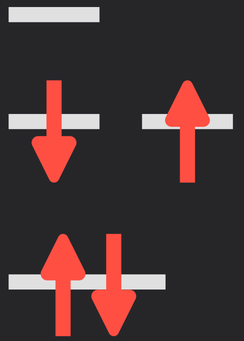
If opposite spin is unoccupied

- Particle addition: $E_X = \varepsilon_k$
- Particle removal: $E_X = -\varepsilon_k$

$$G \to \frac{1 - \langle n_{k\bar{\sigma}} \rangle}{\omega - \varepsilon_k}$$



$E_0 = 0$

$E_1 = \varepsilon_k$

$E_2 = 2\varepsilon_k + U$

$|0\rangle \to |\sigma\rangle$

$|\sigma\rangle \to |0\rangle$

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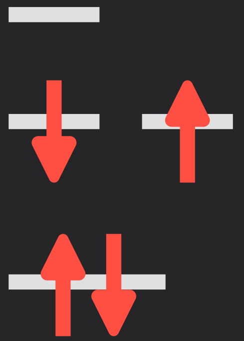
If opposite spin is occupied

- Particle addition: $E_X = \varepsilon_k + U$
- Particle removal: $E_X = -\varepsilon_k - U$

$$G \rightarrow \frac{\langle n_{k\bar{\sigma}} \rangle}{\omega - \varepsilon_k - U}$$



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$$|{-\sigma}\rangle \rightarrow |\sigma, -\sigma\rangle$$

$$|\sigma, -\sigma\rangle \rightarrow |{-\sigma}\rangle$$

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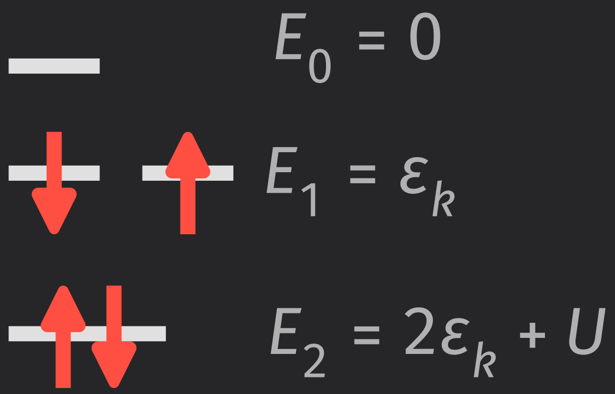

Total Greens Function

$$G_{k\sigma} = \frac{1 - \langle n_{k\bar{\sigma}} \rangle}{\omega - \varepsilon_k} + \frac{\langle n_{k\bar{\sigma}} \rangle}{\omega - \varepsilon_k - U}$$

$$(\varepsilon_k \rightarrow \varepsilon_k - \mu)$$

Correlated Metal-Insulator Transition

The Case Of **Half-Filling**: $2\mu = U, \langle n_{k\sigma} \rangle = \frac{1}{2}$

$$G_{k\sigma} = \frac{1}{2}\left[(\omega - \varepsilon_k + U/2)^{-1} + (\omega - \varepsilon_k - U/2)^{-1}\right]$$

Phillips et al. (2020)

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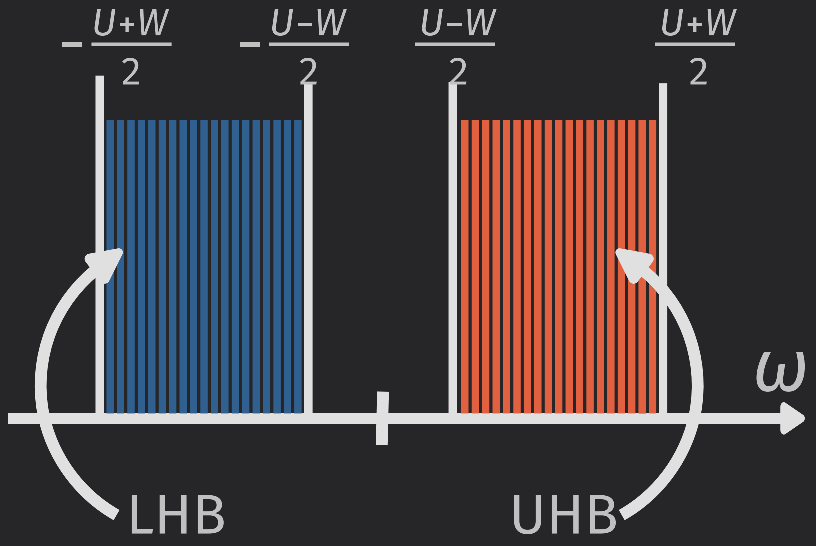
$U > W$ (**Mott Insulator**)



Phillips et al. (2020)

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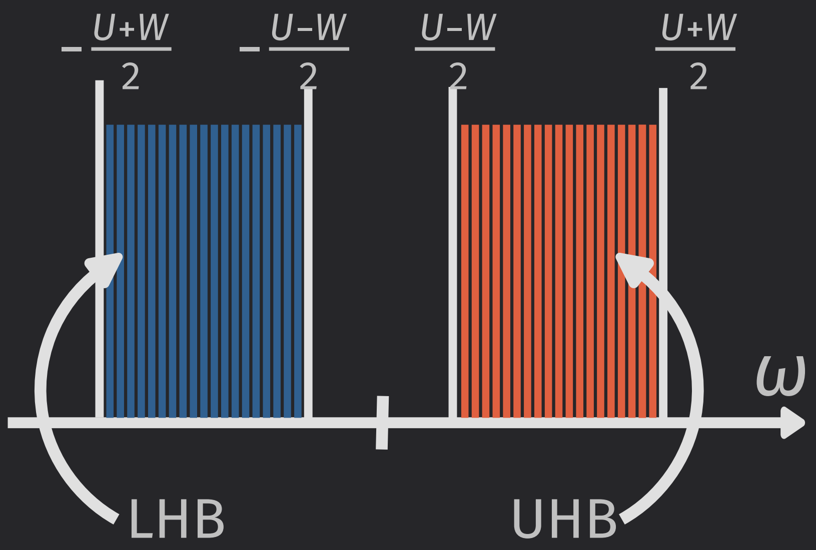
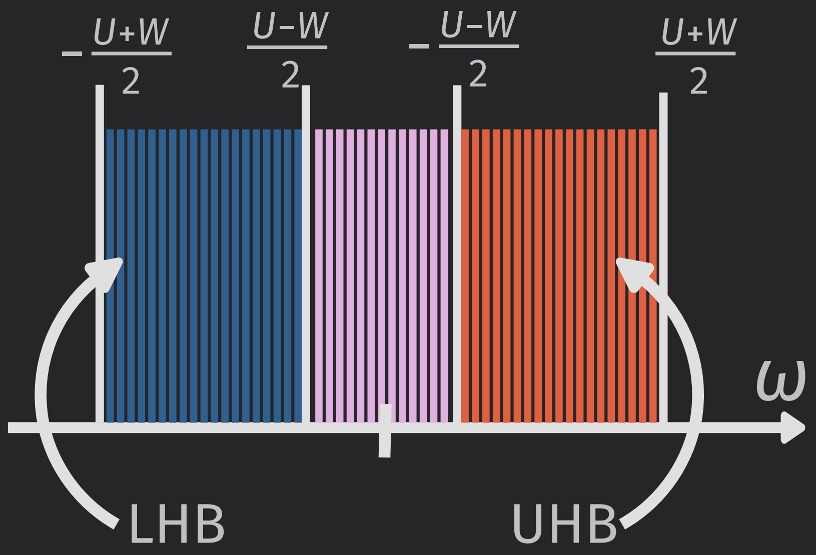


$U < W$ (Metal)



Phillips et al. (2020)

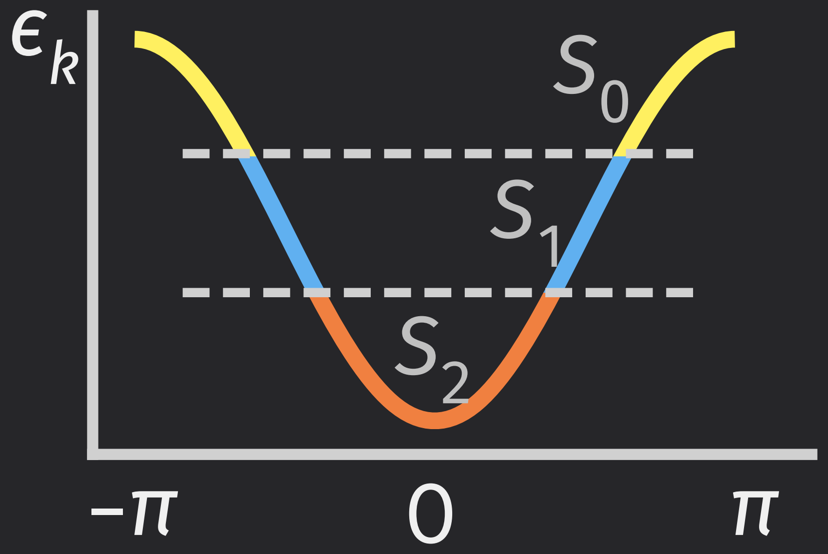
Non-Fermi Liquid Signatures In Metallic Phase

Signature I: Composite Gapless Excitations

$$G_{k\sigma} = \frac{1}{2}\left[(\omega - \varepsilon_k + U/2)^{-1} + (\omega - \varepsilon_k - U/2)^{-1}\right]$$

Momentum states classified into three groups:

- $S_2 : \varepsilon_k < -U/2$:
  Both poles below $\omega = 0$: $\langle n_k \rangle = 2$
- $S_1 : -U/2 < \varepsilon_k < U/2$:
  One pole below $\omega = 0$: $\langle n_k \rangle = 1$
- $S_0 : \varepsilon_k > U/2$:
  No pole below $\omega = 0$: $\langle n_k \rangle = 0$



Phillips et al. (2020)

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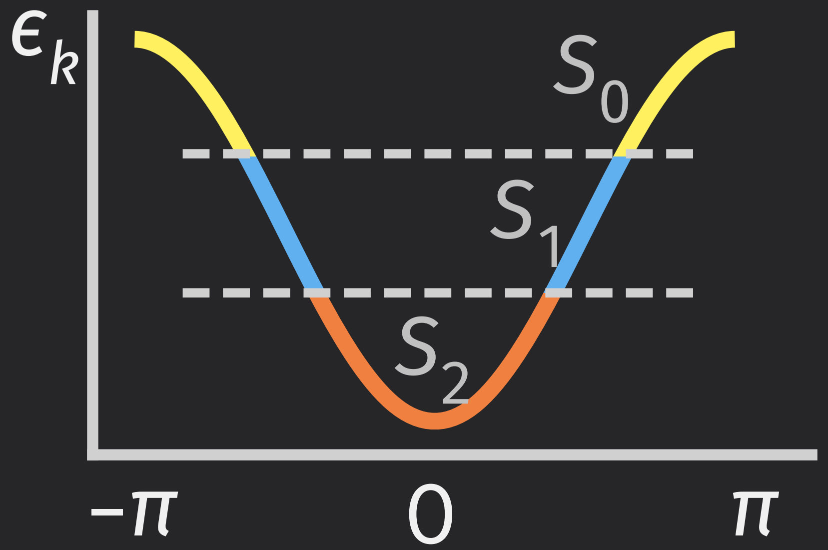


Ground state is a **mixed** state.

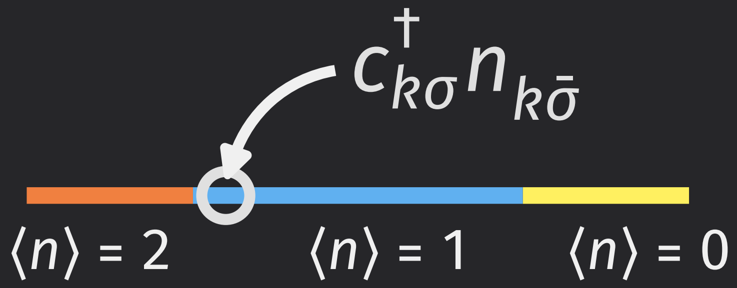
- k –states in S_2 are doubly-occupied.
- k –states in S_1 are half-filled.
- 2^{N_1}-fold degenerate.

Phillips et al. (2020)

Signature I: Composite Gapless Excitations

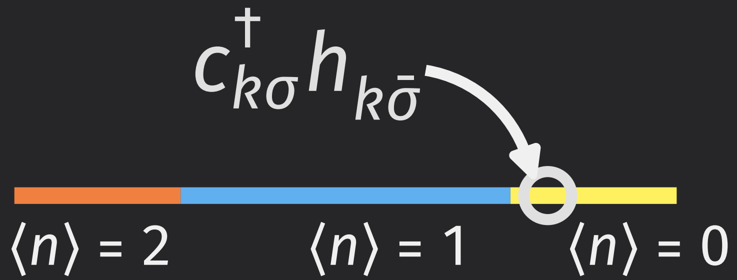
Near $S_2 - S_1$ boundary $(\varepsilon_k = -U/2)$

- Excitation operator: $c^\dagger_{k\sigma} n_{k\bar{\sigma}}$
- Excitation energy is $\varepsilon_k + \frac{U}{2} \to 0^+$



Near $S_1 - S_0$ boundary $(\varepsilon_k = U/2)$

- Excitation operator: $c^\dagger_{k\sigma}(1 - n_{k\bar{\sigma}})$
- Excitation energy is $\varepsilon_k - \frac{U}{2} \to 0^+$



Projectors are needed because the other excitations are gapped.

Baskaran (1991); Phillips et al. (2020); Zhao et al. (2024)

Signature I: Composite Gapless Excitations

Near $S_2 - S_1$ boundary

$$c^\dagger_{k\sigma} n_{k\bar{\sigma}}$$

Near $S_1 - S_0$ boundary

$$c^\dagger_{k\sigma}(1 - n_{k\bar{\sigma}})$$

Excitations are Non-Fermi Liquid In Nature!

- Strong correlations lead to **composite** (hole/double) excitations
- Excitations are **not electronic** (do not satisfy $\{\cdot\}$ relations)
- **Breakdown** of quasiparticle picture, and hence of Fermi liquid theory

Baskaran (1991); Phillips et al. (2020); Zhao et al. (2024)

Signature II: Divergence of Self-Energy

We have at 1/2-filling:

$$G_{k\sigma} = \frac{1}{\omega - \varepsilon_k + \frac{U^2/4}{\omega-\varepsilon_k}}.$$

Self-energy is $\Sigma(\omega) = \frac{U^2/4}{\omega-\varepsilon_k}$

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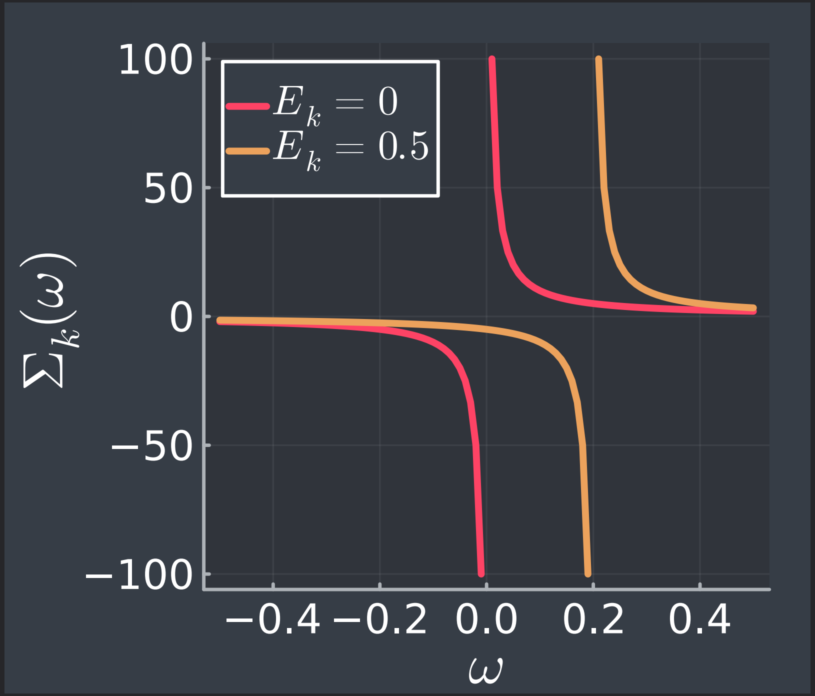
- **Diverges** along $\varepsilon_k = 0$ as $\omega \to 0$
- **Violates** Fermi Liquid Theory
- Leads to zeros of Greens function
- Death of Landau **quasiparticles**



Signature II: Divergence of Self-Energy

How Does A Diverging Self-Energy Leave The System Metallic?

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How Does A Diverging Self-Energy Leave The System Metallic?

Greens functions for composite excitations do not have self-energy!

$$d^\dagger_{k\sigma} = c^\dagger_{k\sigma} n_{k\sigma}, \quad G_d = \frac{1}{\omega - \varepsilon_k - \frac{U}{2}}$$

$$h^\dagger_{k\sigma} = c^\dagger_{k\sigma}(1 - n_{k\sigma}), \quad G_h = \frac{1}{\omega - \varepsilon_k + \frac{U}{2}}$$

These can therefore propagate with **long lifetimes**.

Is This A Realistic Model of Interacting Electrons?

Stability Under Small Perturbations

$$S = S_{\text{FL}} + U \int c^{\dagger}_{k\uparrow} c^{\dagger}_{k\downarrow} c_{k\downarrow} c_{k\uparrow} +$$

$$u \int c^{\dagger}_{k_1+q,\uparrow} c^{\dagger}_{k_2-q,\downarrow} c_{k_2,\downarrow} c_{k_1,\uparrow}$$

Phillips et al. (2020); Zhao et al. (2023)

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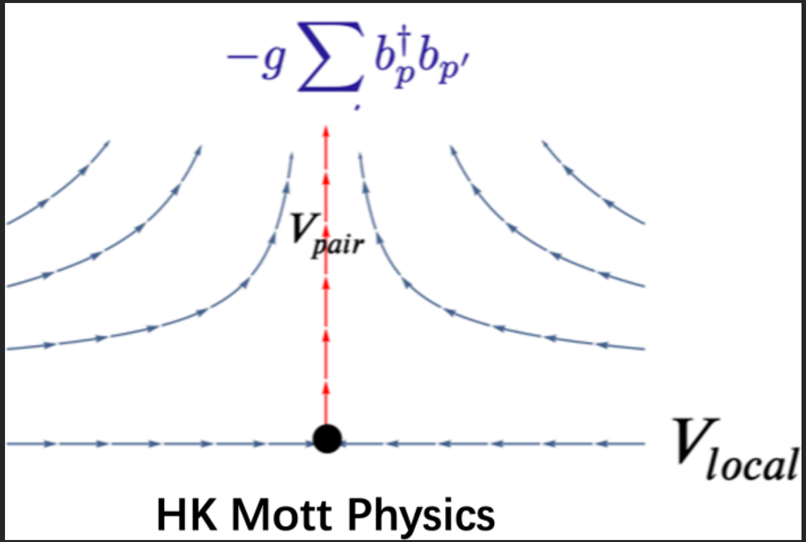
- HK interaction strongly **relevant** under RG flow
- **Stable** under local interaction terms
- Displays superconducting instability



Phillips et al. (2020); Zhao et al. (2023)

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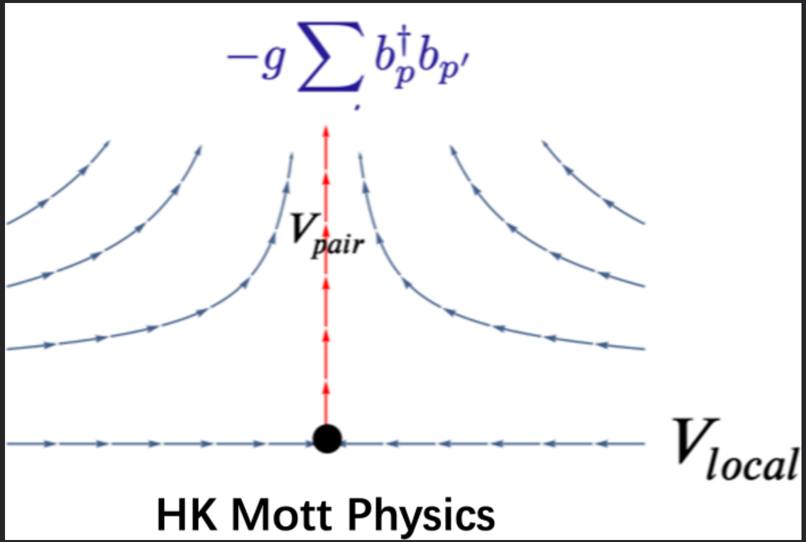

Key Point: HK interaction is the **source of Mottness** in Hubbard model.

Phillips et al. (2020); Zhao et al. (2023)

Link With The 2D Hubbard Model

Alternative form of HK interaction:

$$U \sum_k n_{k\uparrow} n_{k\downarrow} \sim -J \sum_k \boldsymbol{S}_k \cdot \boldsymbol{S}_k$$

Baskaran Model

$$\sum_k \varepsilon_k n_{k\sigma} + \left(\sum_k \boldsymbol{S}_k \right)^2 - J \sum_k \boldsymbol{S}_k \cdot \boldsymbol{S}_k$$

- Spin-charge separation of NFL
- Gapped spinon excitations

Baskaran (1991); Mukherjee & Lal (2020)

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- Spin-charge separation of NFL
- Gapped spinon excitations

- Similar model emerges from 2D Hubbard Model, **Mott liquid**

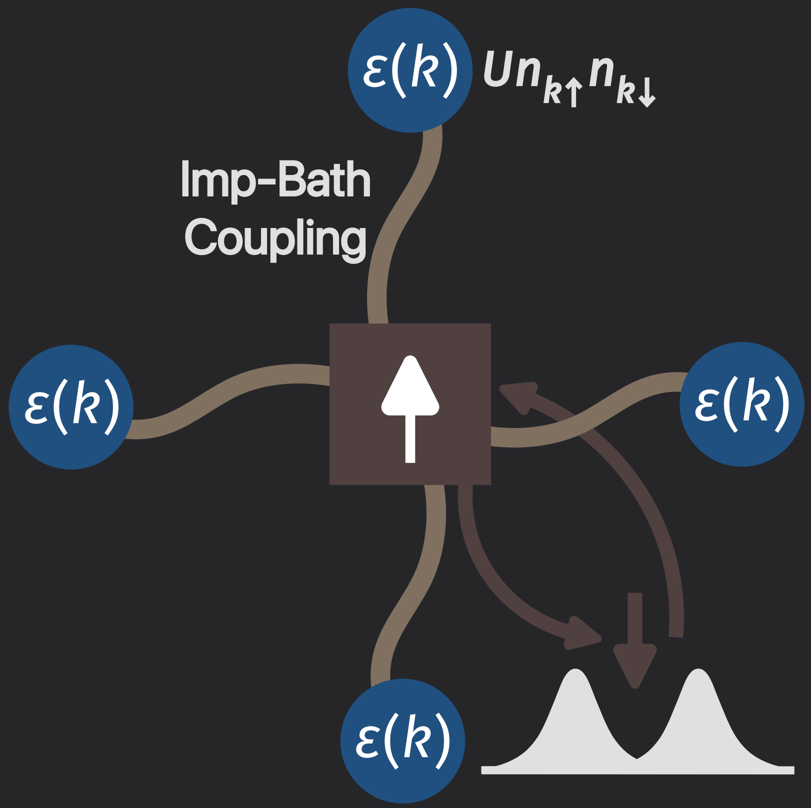
$$-\sum_k \boldsymbol{S}_k \cdot \boldsymbol{S}_{-k} + \sum_k \boldsymbol{C}_k \cdot \boldsymbol{C}_{-k}$$

$$S^z = n_{k\uparrow} - n_{k^T\uparrow}, C^z = n_{k\uparrow} + n_{k^R\uparrow} - 1$$

Baskaran (1991); Mukherjee & Lal (2020)

Avenues for Futher Investigation

Kondo Screening in Hatsugai-Kohmoto Model



Consider local moment hybridising with HK Model

$$H = H_{\text{Kondo}} + H_{\text{HKM}}$$

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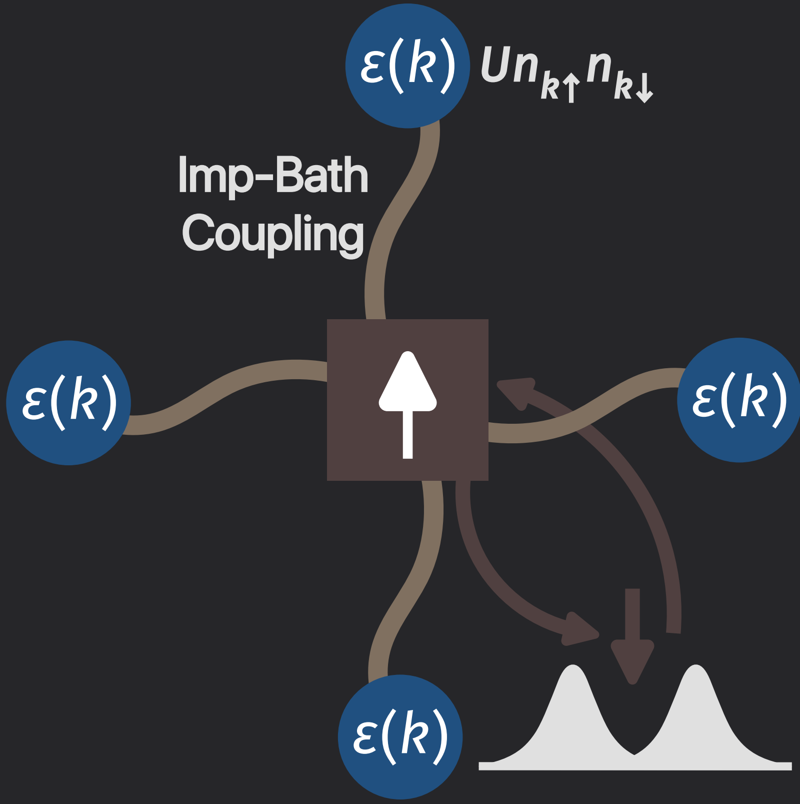

Consider local moment hybridising with HK Model

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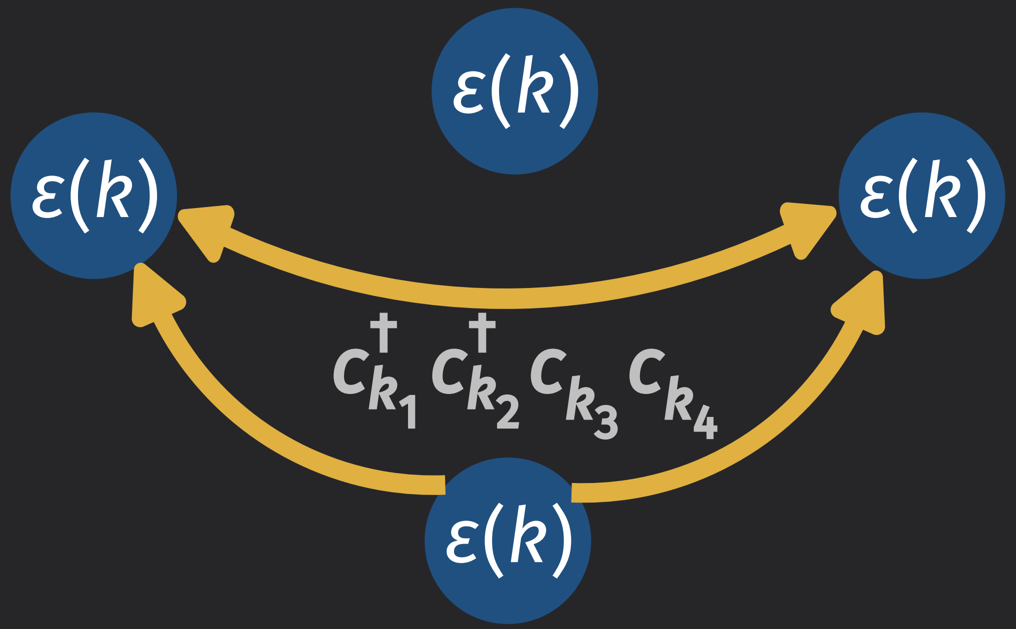
How does **absence** of quasiparticles affect Kondo screening?

Toy Model for Thermalisation and Many-Body Scars



Consider HK Model perturbed by Hubbard interaction

$$H = H_{\text{HKM}} + P_\nu H_{\text{Hub}} P_\nu$$

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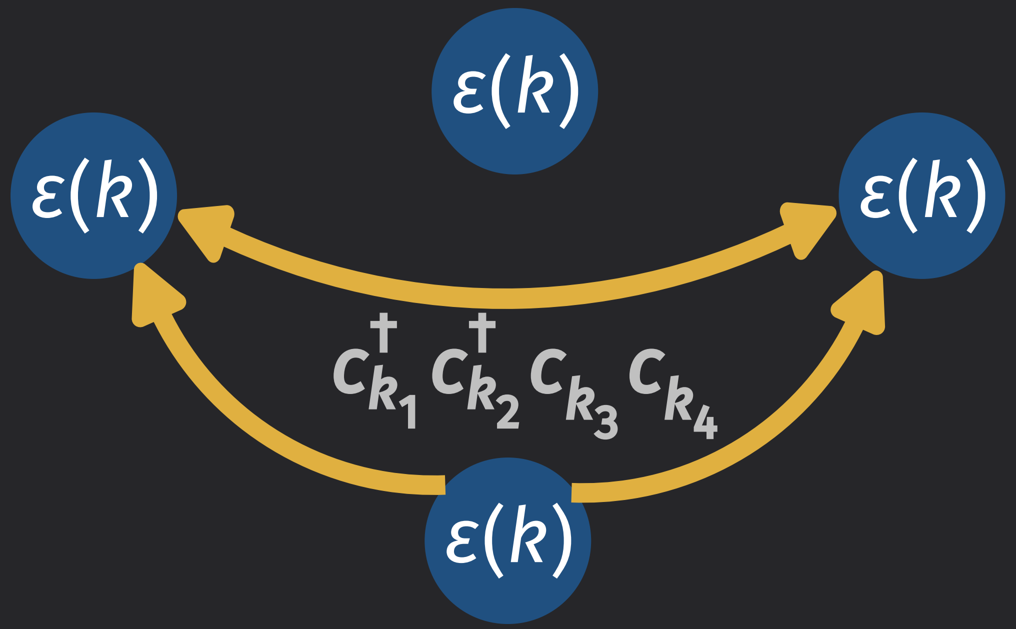

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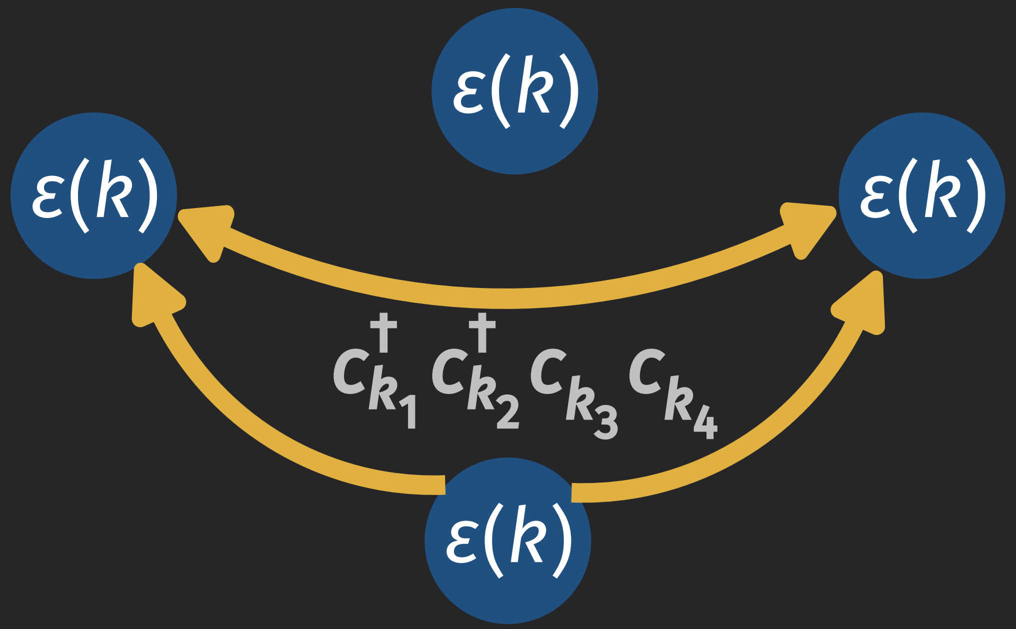
- H_{Hub} allows **thermalisation** of k –states

Toy Model for Thermalisation and Many-Body Scars

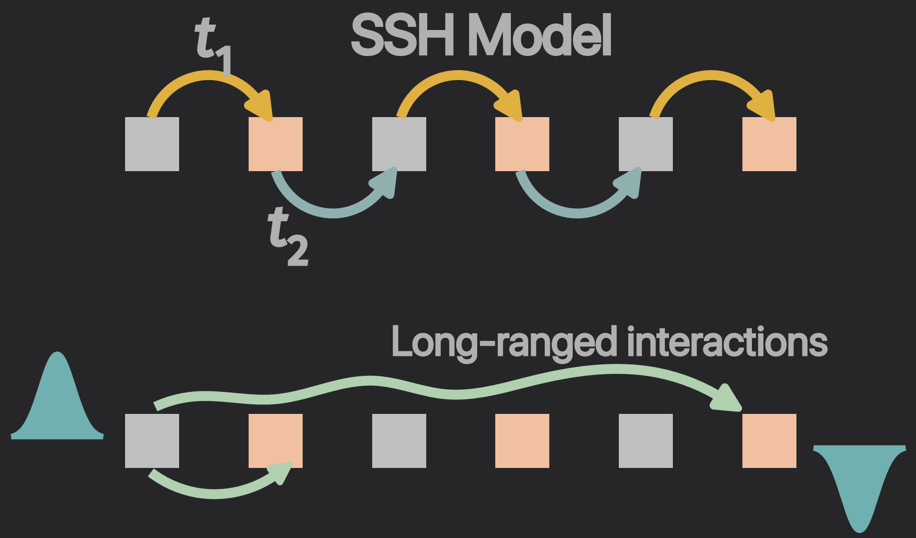


Consider HK Model perturbed by Hubbard interaction

$$H = H_{\mathrm{HKM}} + P_\nu H_{\mathrm{Hub}} P_\nu$$

- H_{Hub} allows **thermalisation** of k –states
- P_ν will preserve certain sectors. **Scars**?

Effect of Hatsugai-Kohmoto Interaction on Edge Modes of SSH Chain

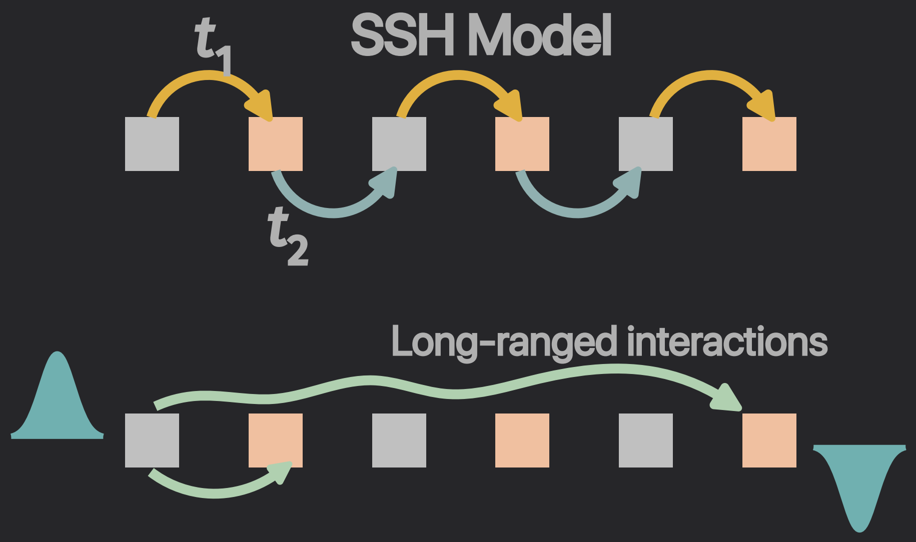


Add long-ranged HKM interactions to SSH chain.

$$H_{\mathrm{SSH}} = -t_1 c_1^\dagger c_2 - t_2 c_2^\dagger c_3 + \ldots$$

$$H = H_{\mathrm{HKM}} + H_{\mathrm{SSH}}$$

Effect of Hatsugai-Kohmoto Interaction on Edge Modes of SSH Chain



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$$H = H_{\mathrm{HKM}} + H_{\mathrm{SSH}}$$

- Fate of topological **edge modes**?

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