Relevance of electronic interactions at quasiperiodicity-driven localization transitions

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Abstract

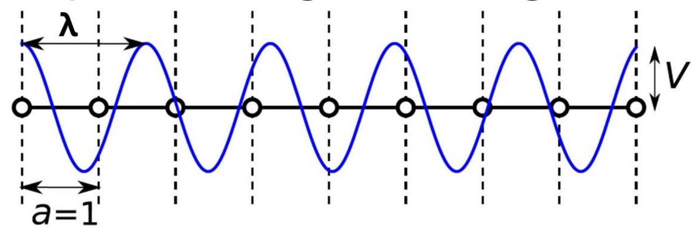
In real materials, disorder can induce (Anderson) insulating phases. Notably, quasiperiodic modulations can also strongly affect wavefunction localization. As the quasiperiodic potential increases, single-particle states can transition from delocalized to critical and finally to localized, with metal-insulator transitions distinct from those seen in disordered systems. The simplest model that captures this transition is the celebrated Aubry-André model, which features a remarkable duality between localized and delocalized states, recently shown to be a generic feature, but somehow hidden, near the transition. For 1D systems of interacting spinless fermions, interactions were found to become irrelevant around the transition, with eigenstates following the hidden duality scenario of the non-interacting limit. This project aims to explore the effects of **spinful interactions** in quasiperiodicity-driven transitions, specifically, whether they become relevant, as in higher-dimensional disorder-driven transitions, or remain irrelevant, as in the spinless case.

Introduction

Quasiperiodic systems:

- Deterministic modulations incommensurate with the lattice
- Possible **experimental realization**: Ultracold atoms and trapped ion experiments, Metamaterials, Moiré Material

Model: 1D system of tight-binding fermions in a quasiperiodic potential

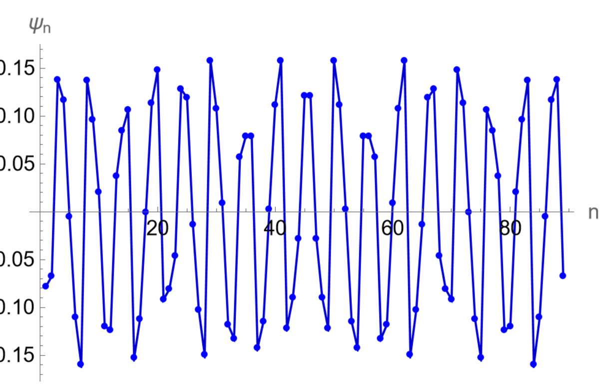


$$\tau = a/\lambda \notin \mathbb{Q}$$

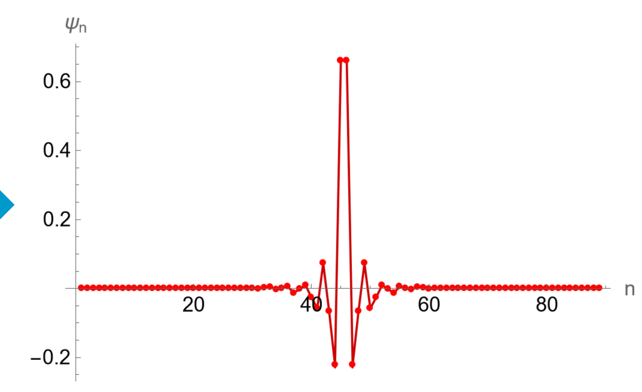
For **non-interacting** fermions ➡ **Aubry-André Model:**

$$H = -t\sum_n (c^\dagger_{n+1}c_n + \text{h.c.}) + V\sum_n \cos(2\pi\tau n + \phi)c^\dagger_n c_n$$

Transition of eigenstates between **extended** and **localized phases**



Increase of quasiperiodic perturbation strength V



- **Remarkable duality** between localized and delocalized states
- Generic feature that hides near transition

For **interacting spinless** fermions:

$$H = -t\sum_{j,\sigma}(c^\dagger_{j+1,\sigma}c_{j,\sigma} + \text{h.c.}) + V\sum_{j,\sigma}\cos(2\pi\tau j + \phi)c^\dagger_{j,\sigma}c_{j,\sigma} + U\sum_j n_{j,\uparrow}n_{j,\downarrow}$$

- **Interactions irrelevant** around the transition driven by V
- **Excitations at transition** behave as **non-interacting:** $P(\{\delta\bar{n}_\alpha\}), K_c \to 1$!

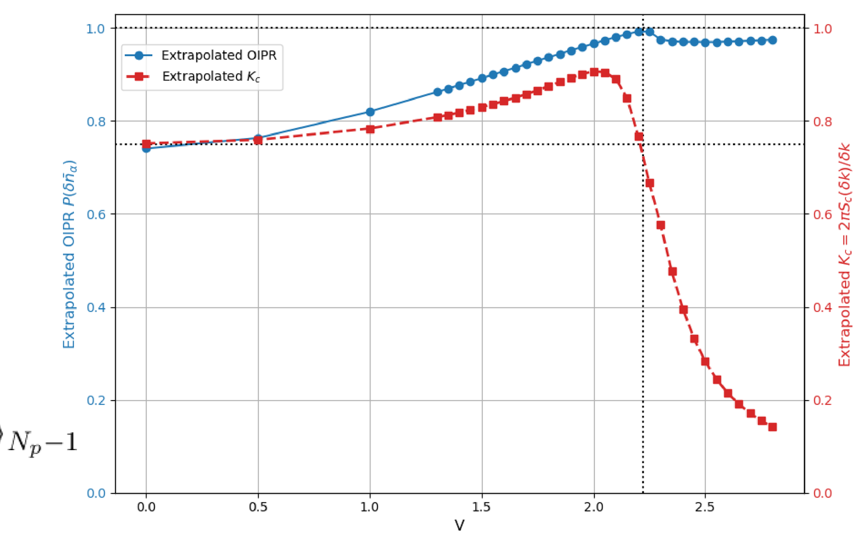
Non-interacting limit
- $P(\{\delta\bar{n}_\alpha\}) = 1$
- $K_c = 1$

Luttinger Parameter

$$K_c = 2\pi \lim_{k\to 0} S_c(k)/k$$

Occupation Inverse Participation Ratio

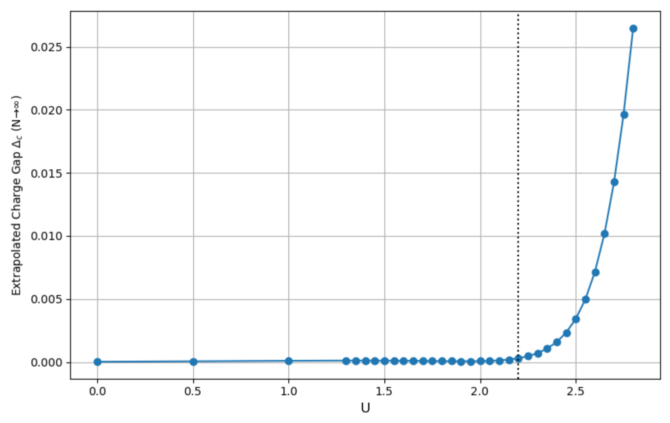
$$P(\{\delta\bar{n}_\alpha\}) = \frac{\sum_\alpha |\delta\bar{n}_\alpha|^4}{(\sum_\alpha |\delta\bar{n}_\alpha|^2)^2} \qquad C^{ij}_e = \langle c^\dagger_i c_j\rangle_{N_p} - \langle c^\dagger_i c_j\rangle_{N_p-1} \qquad C_e|\alpha\rangle = \delta\bar{n}_\alpha|\alpha\rangle$$

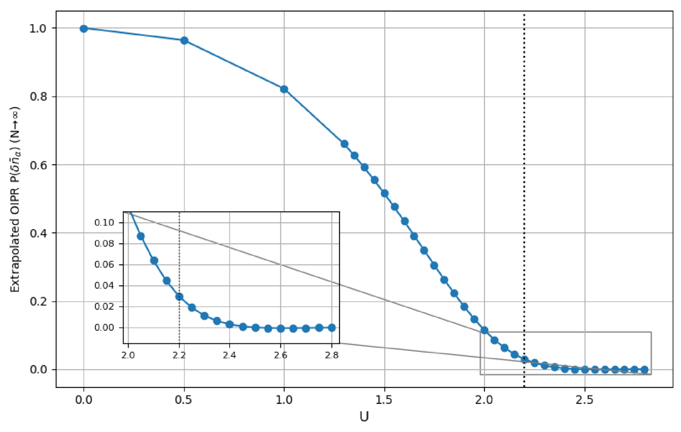


Complementary study: Spinless Model changing U

Ordered transition:
Luttinger Liquid (gapless) to Charge-Density-Wave (gapped)

➡ **Excitations near the transition** are **highly interacting:** $P(\{\delta\bar{n}_\alpha\}) \to 0$!

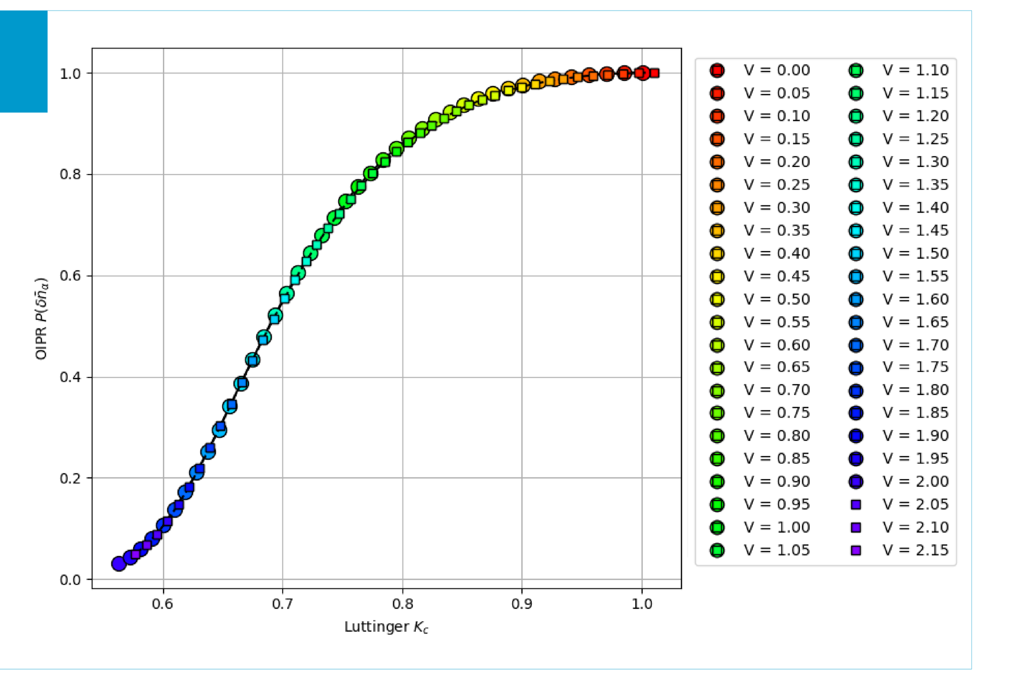




- **Luttinger Liquid –** low energy behavior depends only on velocity u_c and Luttinger parameter K_c

Single-particle quantity $P(\{\delta\bar{n}_\alpha\})$ depends **only** on K_c ➡ $P = P(K_c)$

Next step: Find an analytical expression for $P(K_c)$!



Model and Motivation

For **interacting spinful** fermions (electrons) ➡ **Aubry-André Hubbard Model:**

$$H = -t\sum_j (c^\dagger_j c_{j+1} + \text{h.c.}) + V\sum_j \cos(2\pi\tau j + \phi)c^\dagger_j c_j + U\sum_j n_j n_{j+1}$$

- Exhibits a localization transition driven by quasiperiodic modulation strength V
- **Its properties and nature remain unexplored!**

Can **localization transitions** driven by quasiperiodicity always be described by a **non-interacting theory**?

or

Do **spinful interactions** alter the **nature** of the transition?

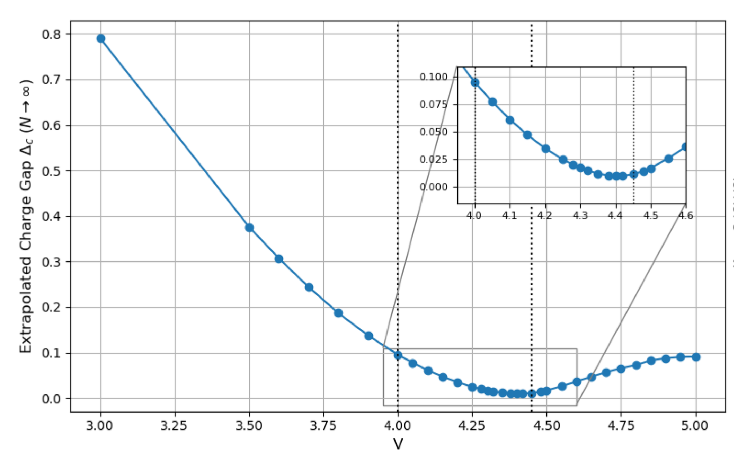
Methods

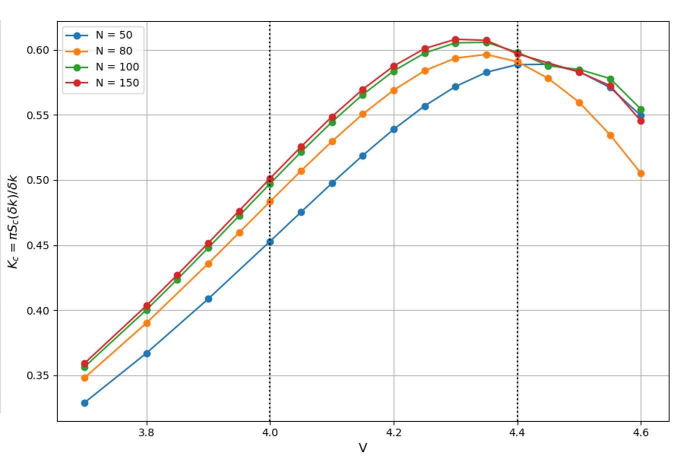
Density Matrix Renormalization Group (DMRG)

- **Numerical variational method** that determines the ground state of many-body Hamiltonians, using a **Matrix Product State** (MPS) representation
- Overcomes exponential growth of total Hilbert space with system size → determination of quantum states with **polynomial complexity**

Preliminary results

- Transition Mott insulator (gapped) – Luttinger Liquid (gapless) – Anderson insulator (gapped)





Localization transition seems to be **interactive:** $K_c \neq 1$ (its non-interactive value) near criticality

⬇

Interactions seem to **be relevant** around the transition driven by V!

Next step: Improve **model and metrics convergence** to achieve higher system sizes!

Find out more...

- About this project:
- About us:

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