Exploring the Single-Particle Mobility Edge and Many-Body Localized Phase in a 1D Quasiperiodic Optical Lattice with Ultracold Atoms

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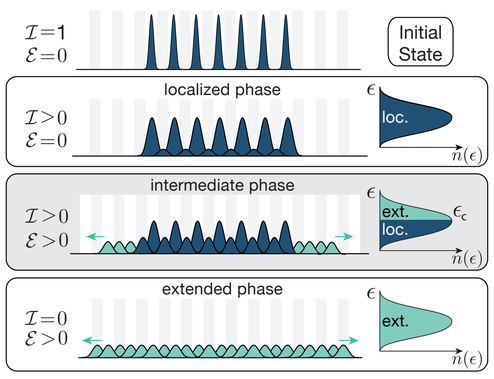
Single-Particle Mobility Edge



Strong detuning: Localized states

Intermediate detuning: Coexistence of localized and extended states
Mobility Edge

Weak detuning: Extended states

Single-Particle Mobility Edge (SPME):
- Critical energy separating localized and delocalized energy eigenstates
- Absent in 1D and 2D **Aubry-André model** (quasi-random disorder)
- First observation of an **exact SPME** in 1D

Experimental Realization

The incommensurate lattice model

$$\hat{\mathcal{H}}_{con} = \underbrace{-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}}_{\text{Kinetic Energy}} + \underbrace{\frac{V_p}{2}\cos(2k_p x)}_{\text{Primary Lattice}} + \underbrace{\frac{V_d}{2}\cos(2k_d x+\phi)}_{\text{Detuning Lattice}}$$

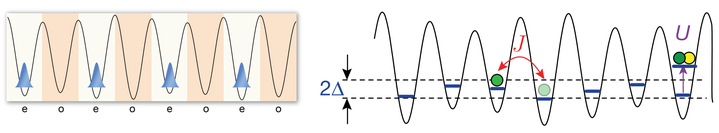
This **continuum Hamiltonian** is valid in all paramter regimes. For a deep primary lattice the tight-binding approximation results in the **Aubry-André-Hamiltonian**:

$$\hat{\mathcal{H}}_{AA} = -J_0\sum_{j,\sigma}(\hat{c}^\dagger_{j+1,\sigma}\hat{c}_{j,\sigma}+\text{h.c.}) + \Delta\sum_{j,\sigma}\cos(2\pi\alpha j+\phi)\hat{n}_{j,\sigma}$$

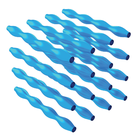
For shallow primary lattices, **corrections** have to be added to account for the appearance of a **single-particle mobility edge**:

$$\hat{\mathcal{H}}_{GAA} = \hat{\mathcal{H}}_{AA} + \hat{\mathcal{H}}'$$

Experimental realization



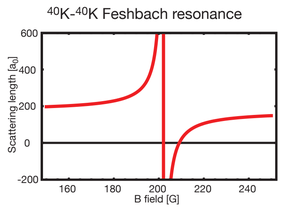
1D Tubes:

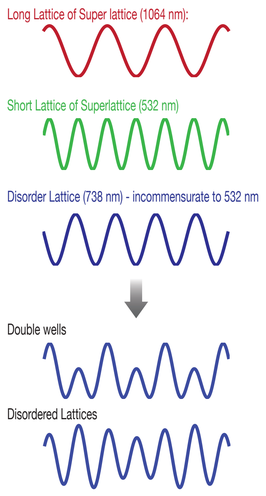


Tunable Interactions $\hat{\mathcal{H}}_U = U\sum_j \hat{n}_{j,\uparrow}\hat{n}_{j,\downarrow}$

atoms in m_F = -9/2 and -7/2 states:

^{40}K-^{40}K Feshbach resonance





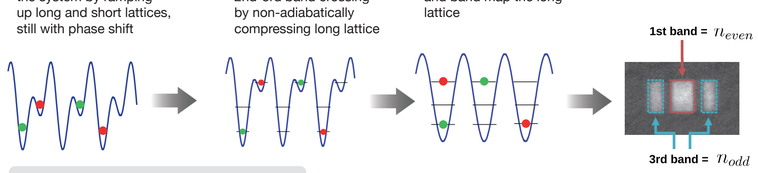
Observables

Imbalance $\mathcal{I} = \dfrac{n_{\text{even}} - n_{\text{odd}}}{n_{\text{even}} + n_{\text{odd}}}$

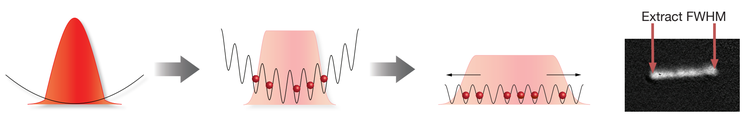
Expansion $\mathcal{E}$ = FWHM

Imbalance Detection $\mathcal{I}$

- Stop dynamics by freezing the system by ramping up long and short lattices, still with phase shift
- Remove disorder, traverse 2nd-3rd band crossing by non-adiabatically compressing long lattice
- Remove short lattice and band map the long lattice



Expansion Measurement $\mathcal{E}$



Compensate anti-trapping potential of the blue-detuned lattice with dipole trap

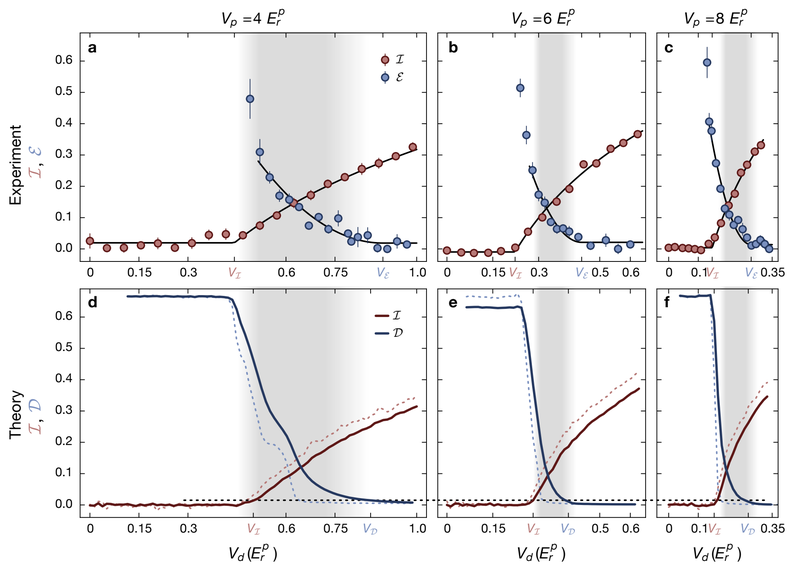
Non-Interacting Results

Physical observables

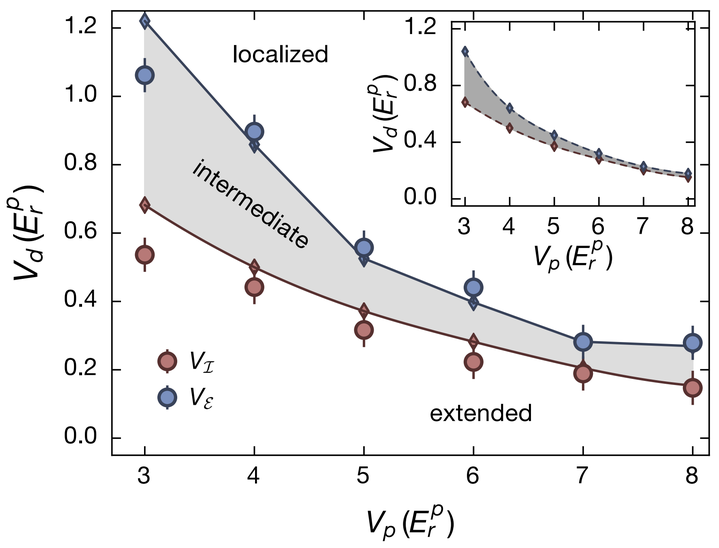
Density Imbalance $\mathcal{I}$:
- **sensitive to first localized state emerging at disorder strength $V_{\mathcal{I}}$**
- measured at **200 tunneling times** due to finite imbalance lifetime

Expansion $\mathcal{E}$:
- **sensitive to first delocalized state emerging at disorder strength $V_{\mathcal{E}}$**
- measured at **3000 tunneling times** due to extremely slow dynamics in the presence of disorder

If $V_{\mathcal{I}} \neq V_{\mathcal{E}}$ shows existence of a SPME

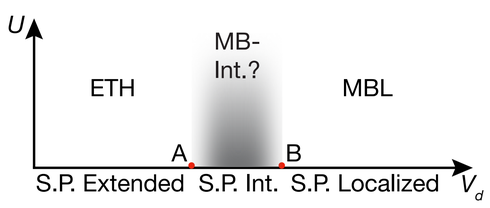


- Phase diagram clearly exhibits **intermediate regime between localized and extended states** => **Single-Particle Mobility Edge**
- Good agreement between experiment and **tube-averaged** (solid lines) exact diagonalization (ED) calculations
- Extraction of $V_{\mathcal{I}}$ and $V_{\mathcal{E}}$ via heuristic fit functions to the data points
- Vanishing mobility edge for large primary lattice depth (mapping to **tight-binding Aubry-André Hamiltonian** for $V_p \geq 8E_r^p$)

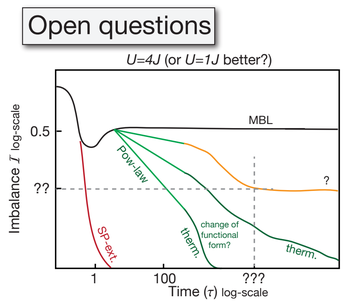


Interacting results

Conjectured Phase Diagram



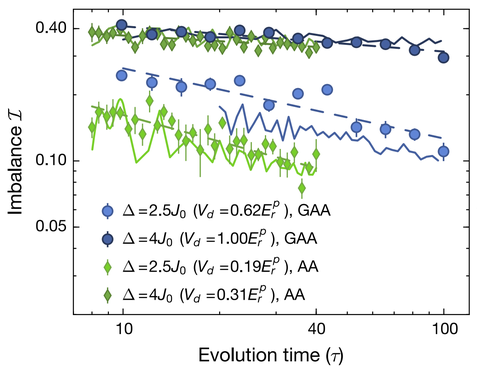
Open questions



- MBL in a model with SPME?
- Does an SPME survive **finite interactions** and does a **many-body mobility edge** (MBME) exist?
- What are the **timescales** involved?
- What would the **experimental signatures** of an MBME be? Which **disgnostics** are required?

Existence of MBME **open debate in theory**:
- Phys. Rev. B **92**, 064203 (2015): "MBME due to symmetry-constrained dynamics and strong interactions"
- Phys. Rev. B **93**, 014203 (2016): "Absence of MBME"

Experimental investigation



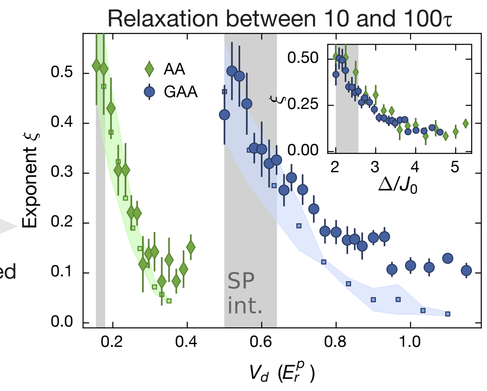
MBL phase

Imbalance decay (power-law?)

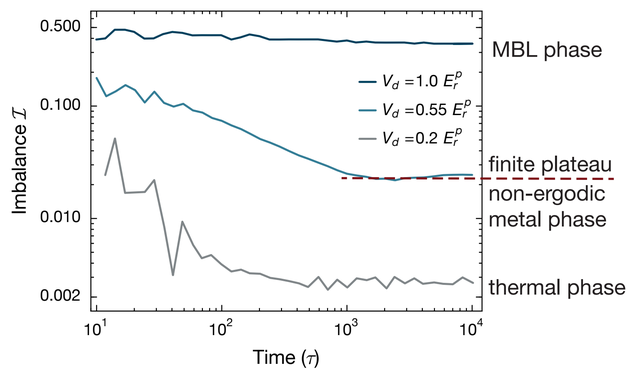
By comparing the **GAA model** (SPME) and the **AA model** (no SPME), we can look for differences in the relaxation dynamics.

No accelerated relaxation from single-particle extended states on experimentally accessible timescales

Time scales limited by **inter-tube coupling** and residual **photon scattering.**
Use numerics to explore longer lifetimes



Theoretical investigation



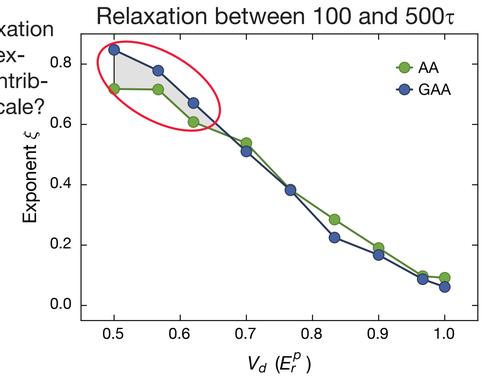
MBL phase

finite plateau
non-ergodic metal phase

thermal phase

MBME plausible, but no direct evidences

Difference in relaxation dynamics -> Do extended states contribute on this timescale?



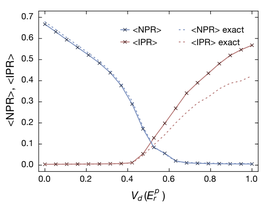
Theory

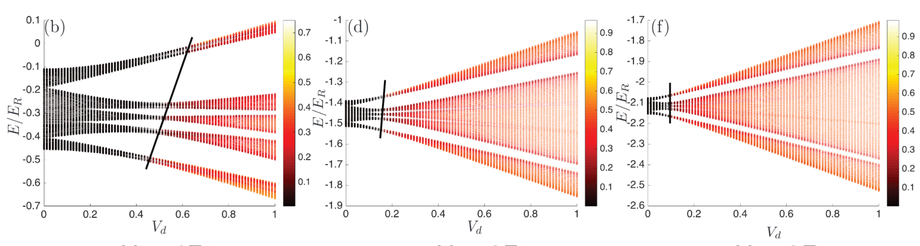
$$\text{NPR} = \left(L\sum_m |u_m^{(i)}|^4\right)^{-1}$$

$$\text{IPR} = \frac{\sum_m |u_m^{(i)}|^4}{\left(\sum_m |u_m^{(i)}|^2\right)^2}$$

	Localized	Extended
IPR	finite	0
NPR	0	finite

Energy bands split up in the presence of detuning lattice. For different energies the **IPR depends on the detuning lattice strength**. This gives rise to a **coexistence of localized and extended states** in the intermediate regime





$V_p = 4E_r^p$ $V_p = 6E_r^p$ $V_p = 8E_r^p$

Mobility edge present in shallow 1D lattice, but disappears in **tight-binding limit** where Hamiltonian maps to **Aubry-André Hamiltonian**

Conclusions

In a nutshell, we find the following intriguing results:

1. Realization of a **lattice model with SPME** and mapping out of the corresponding **phase diagram**
2. **MBL** present in a system with SPME, but only in a regime where all single-particle eigenstates are localized.
3. Single-particle extended states do not serve as an efficient bath for localized states on experimentally accessible timescales.

For the future:
4. Extend experimentally acessible timescales
5. Find better **diagnostics** for the possible many-body intermediate phase

References

1. Schreiber et al., Science 349, 842–845 (2015) (MBL observation)
2. Lüschen et al., arXiv:1709:03478 (2017) (SPME observation)
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5. Bordia et al., PRL 116, 140401 (2016) (Coupling of MBL systems)
6. Lüschen at al., PRX 7, 011034 (2017) (Photon scattering)
7. Ronzheimer et al., PRL 110, 205301 (2013) (Expansion in lattices)