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Bound impurities in a one-dimensional Bose lattice gas

arXiv:2402.03070

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Outline

We study **two bosonic mobile impurities** interacting with a **bosonic bath** in **one-dimensional optical lattices**.

1. Impurities in ultracold atom gases
2. Model
3. Ground-state properties
4. Quench dynamics
5. Conclusions

Outline

1. **Impurities in ultracold atom gases**
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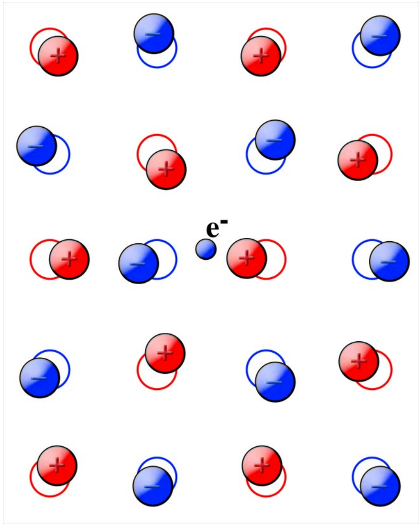
Impurities and quantum mixtures

- The study of **impurities in quantum mediums** has a long history.

- Impurities are usually understood as **dressed quasiparticles** referred to as **polarons**.

- The **experimental** progress realising **ultracold atomic mixtures** offer a unique setting to probe impurities.
  C. Baroni, G. Lamporesi, and M. Zaccanti, arxiv:2405.14562 (2024).

- Impurities are realised with **highly-imbalanced mixtures**.

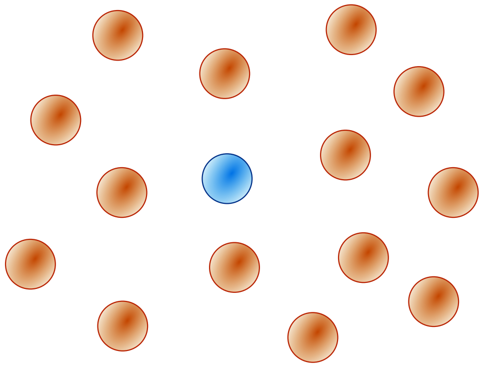


Electrons in a ionic crystal.
L. Landau and S. Pekar, Zh. Eksp. Teor. Fiz **18**, 419 (1948).

Bose polarons and bipolarons

- **Bose polarons**, impurities immersed in a **BEC** gas, were achieved in landmark experiments in 2016.
  N. B. Jørgensen et al., PRL **117**, 055302 (2016). M.-G. Hu et al., PRL **117**, 055301 (2016).

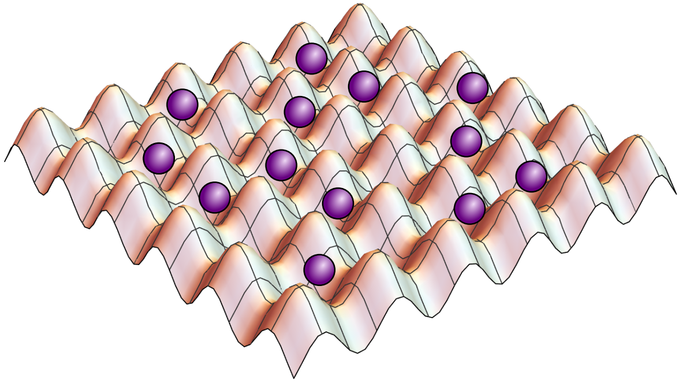
- The study of **two impurities** immersed in a BEC has also received increasing theoretical attention, as they can form bound **bipolarons**.
  A. Camacho-Guardian *et al*., PRL **121**, 013401 (2018).

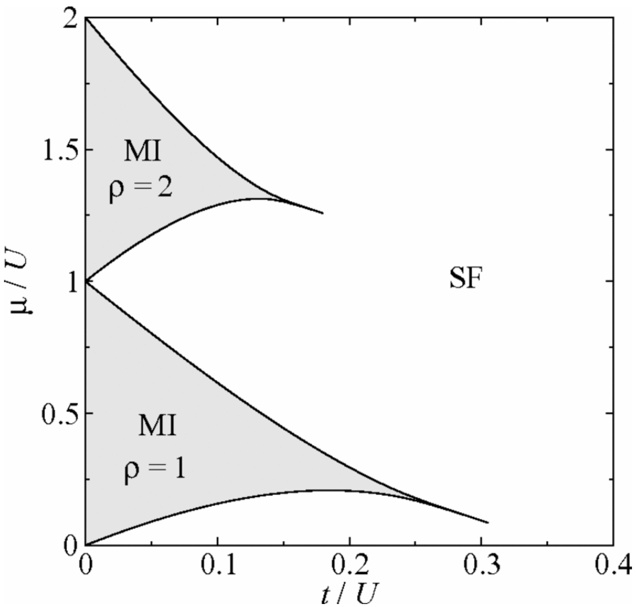


Ultracold atoms in optical lattices

- Ultracold atoms in **optical lattices** offer another interesting setting to study many-body physics.

Gross and I. Bloch, Science **357**, 995 (2017).





Phase diagram of the 1D BH model.
S. Ejima *et al.*, PRA **85**, 053644 (2012).

- **Bosons** in **tight** optical lattices are described by the **Bose-Hubbard model**

$$\hat{H} = -t \sum_{\langle i,j \rangle} \left(\hat{a}_i^\dagger \hat{a}_j + \mathrm{h.c.} \right) + \frac{U}{2} \sum_i \hat{n}_i \left(\hat{n}_i - 1 \right) .$$

t: tunnelling
U>0: boson-boson interaction

- The Bose-Hubbard model shows a **superfluid-to-Mott insulator** phase transition.

J. K. Freericks and H. Monien, EPL **26**, 545 (1994).

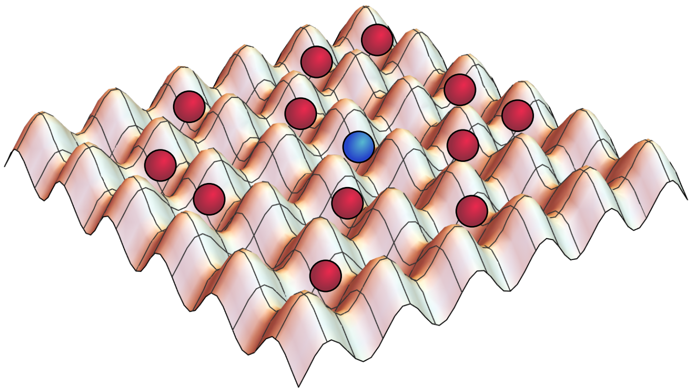
Lattice polarons

- The study of **impurities in optical lattices** has received renewed interest.

- These are often called **lattice polarons**, even though optical lattices do not support phonon excitations.

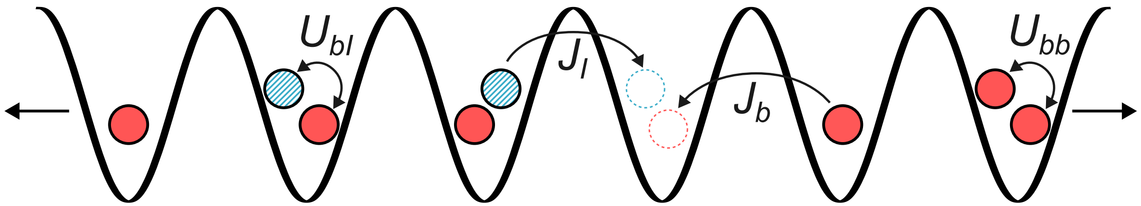
- Several recent works have studied **Bose lattice polarons**.
  V. Colussi, C. Menotti C and A. Recati, PRL **130**, 173002 (2023).
  M. Santiago-García, S. Castillo-López and A. Camacho-Guardian, NJP **26,** 063015 (2024).
  F. Caleffi, M. Capone,I. DeVega and A. Recati, NJP **23**, 033018 (2021).

- Lattice polarons in **fermionic mediums** have also been studied.
  I. Amelio and N. Goldman, Scipost Physics **16**, 056 (2024).



Lattice bipolarons

- **Bipolaron**-like physics in optical lattices with bosonic baths has also attracted significant attention.
  M. Pasek and G. Orso, PRB **100**, 245419 (2019).
  S. Ding, G. A. Domínguez-Castro, A. Julku, A. Camacho-Guardian and G. M. Bruun, SciPost Phys. **14**, 143 (2023).
- Systems with purely **repulsive interactions** can induce the formation of a **bound state between two impurities**.
  K. Keiler, S. I. Mistakidis and P. Schmelche, NJP **22**, 083003 (2020),
- We study **stationary** and **quench-induced dynamics** properties of **two mobile impurities** interacting with a **bosonic bath** and immersed in a **one-dimensional optical lattice**.



Outline

1. Impurities in ultracold atom gases
2. **Model**
3. Ground-state properties
4. Quench dynamics
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Model

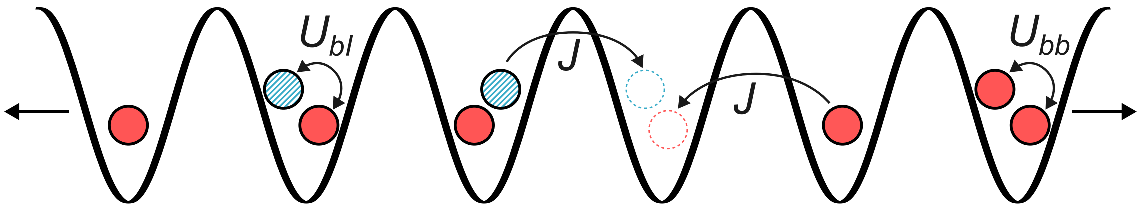
- We consider a **two-component Bose-Hubbard Hamiltonian**

$$\hat{H} = \underbrace{-J \sum_{\sigma=b,I} \sum_{i} \left(\hat{a}^{\dagger}_{i,\sigma} \hat{a}_{i+1,\sigma} + \text{h.c.} \right)}_{\text{Tunnelling}} + \underbrace{\frac{U_{bb}}{2} \sum_{i} \hat{n}_{i,b}(\hat{n}_{i,b} - 1)}_{\text{Boson-boson repulsion}} + \underbrace{U_{bI} \sum_{i} \hat{n}_{i,b} \hat{n}_{i,I}}_{\text{Boson-impurity repulsion}} .$$

b: Bath
I: Impurities

- We study stationary properties with the **exact diagonalisation** (ED) method for a fixed number N_σ of particles of each species.
D. Raventós, T. Graß, M. Lewenstein and B. Juliá-Díaz, JPB **50**, 113001 (2017).

- We consider $M=6,7,8,9$ sites, $N_b=M$ bosons in the bath (**unity filling**) and $N_I=2$ impurities.

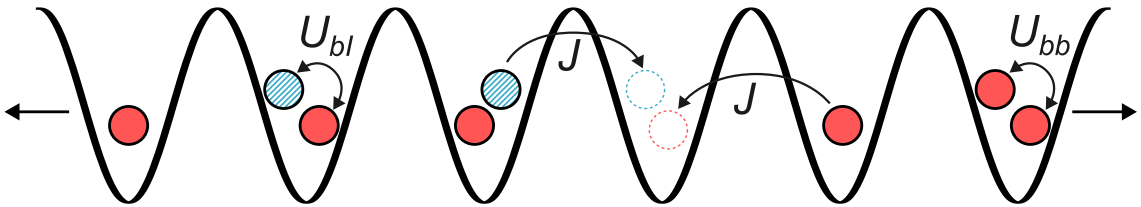


Model

- We consider **periodic boundary conditions** (a ring), which can be achieved in experiment.
  L. Amico, A. Osterloh and F. Cataliotti, PRL **95**, 063201 (2005).

- It has also become possible to realise systems with a **few atoms**.
  D. Blume, RPP **75**, 046401 (2012). Sowiński and M. A. García-March, RPP **82**, 104401 (2019).

- The proposed configuration can be produced with **highly-imbalanced atomic mixtures**.
  N. B. Jørgensen et al., PRL **117**, 055302 (2016).



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Static limit

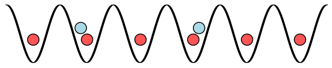
- The ground state in the **static limit** can be examined analytically

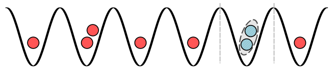
$$\hat{H} = \frac{U_{bb}}{2}\sum_i \hat{n}_{i,b}(\hat{n}_{i,b}-1) + U_{bI}\sum_i \hat{n}_{i,b}\hat{n}_{i,I}.$$

- The **bipolaron energy**: $E_{bp} = E(N_I = 2) - 2E(N_I = 1) + E(N_I = 0).$
  A. Camacho-Guardian *et al*., PRL **121**, 013401 (2018).

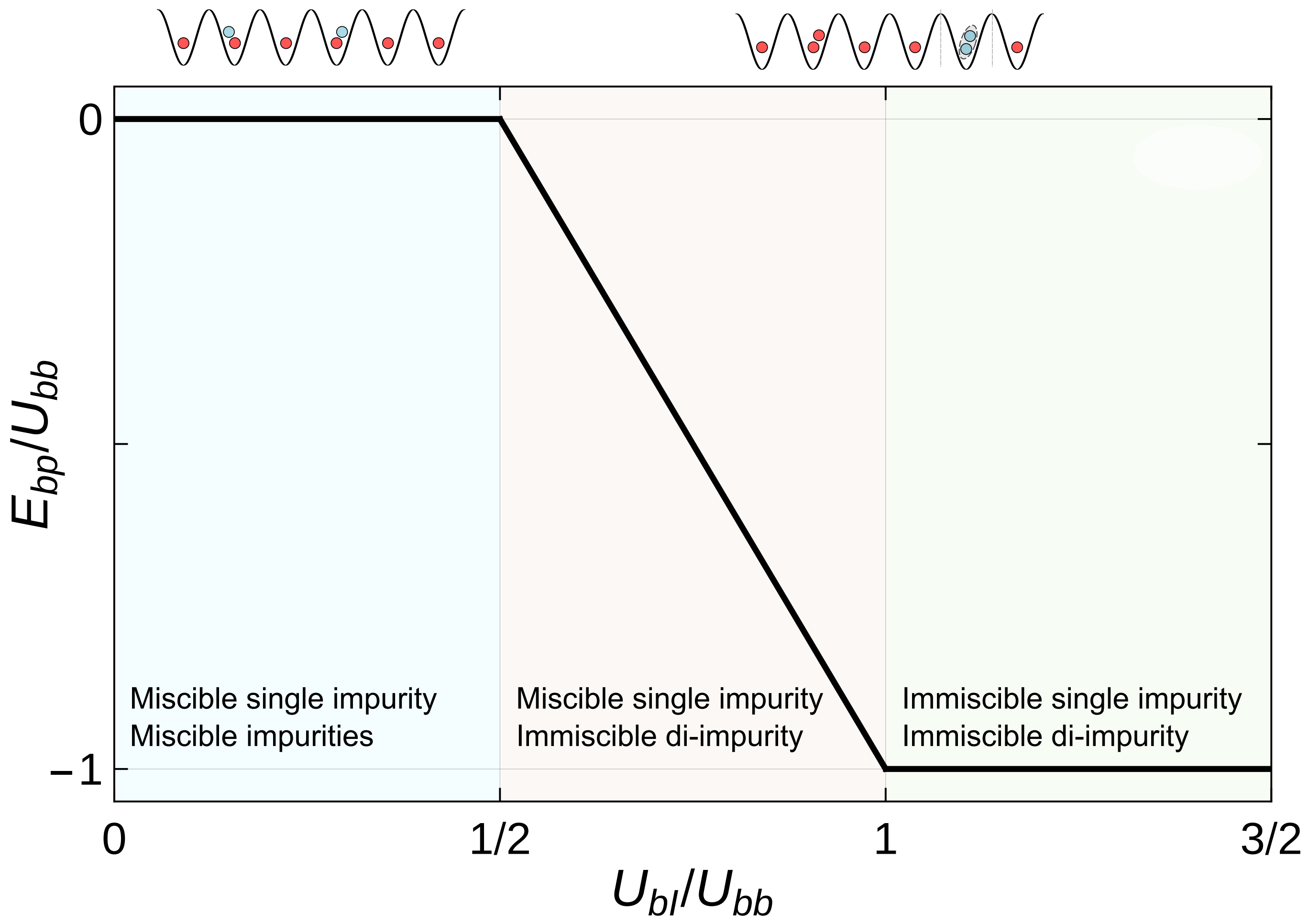
- One obtains:

$$E_{bp} = \begin{cases} 0 & : \; 0 \le U_{bI} < U_{bb}/2 \\ U_{bb} - 2U_{bI} & : \; U_{bb}/2 \le U_{bI} < U_{bb} \\ -U_{bb} & : \; U_{bb} < U_{bI} \end{cases}$$





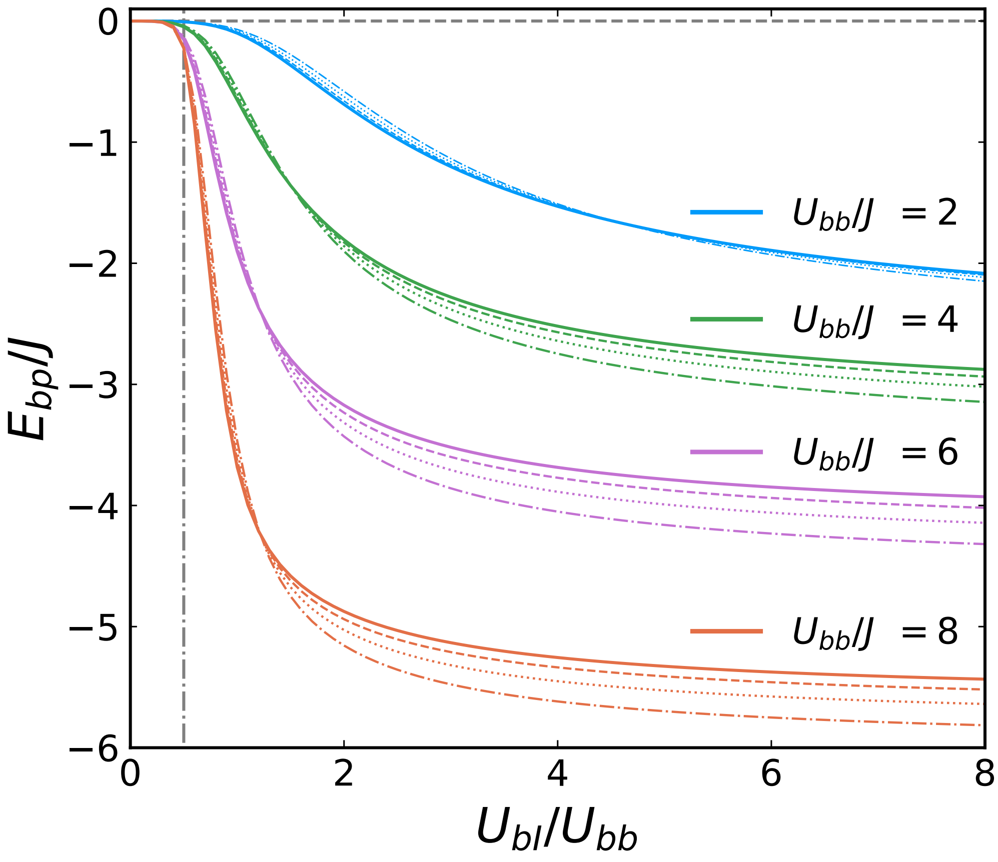
Static limit



- A negative bipolaron energy suggests the formation of **bound states**.

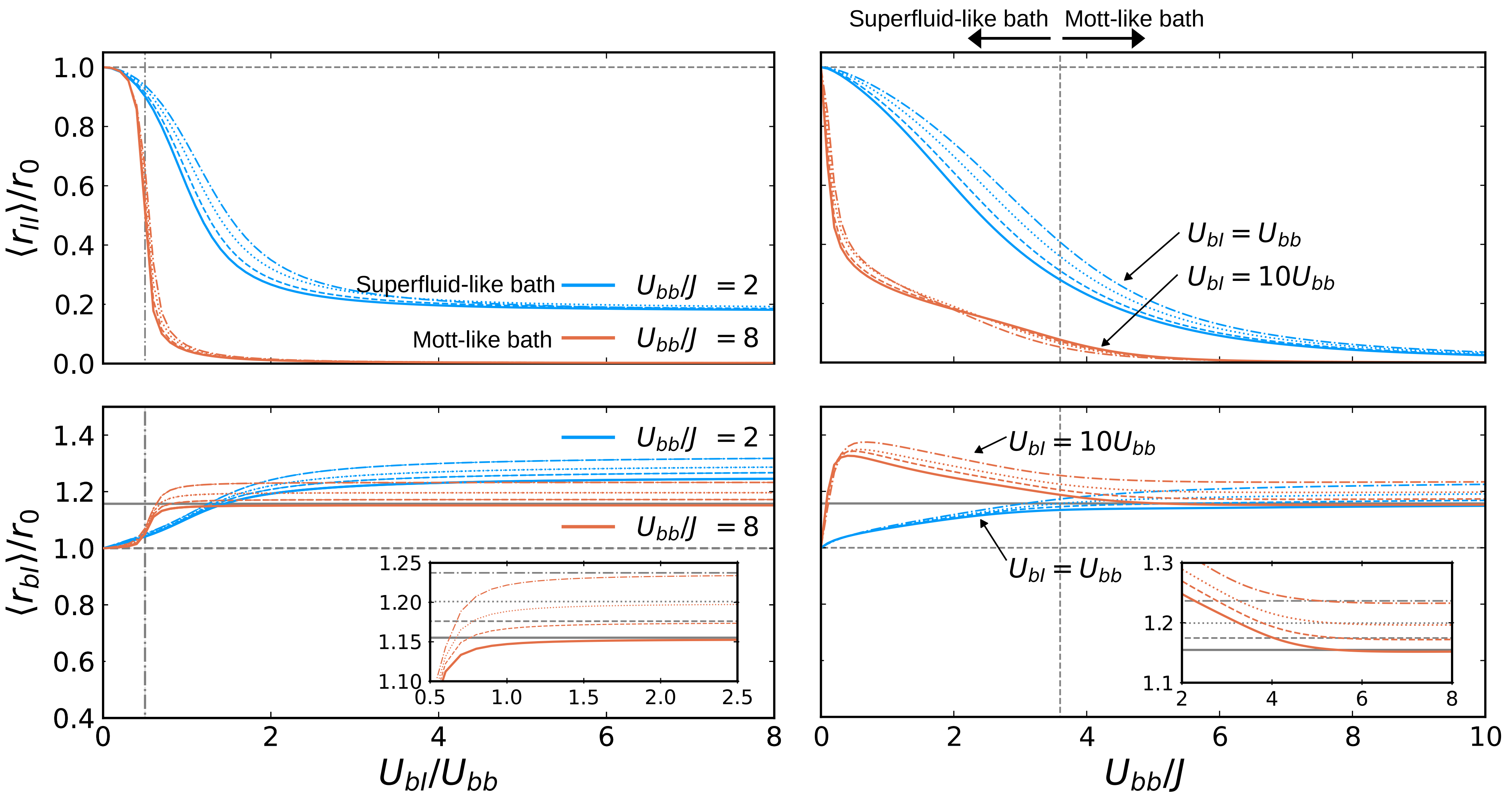
Bipolaron Energy

- Now we examine mobile systems.



- A negative bipolaron energy suggests the formation of **bound states**.

Average distance between particles



- A small $\langle r_{II} \rangle$ signals the formation of a **bound dimer of impurities**.

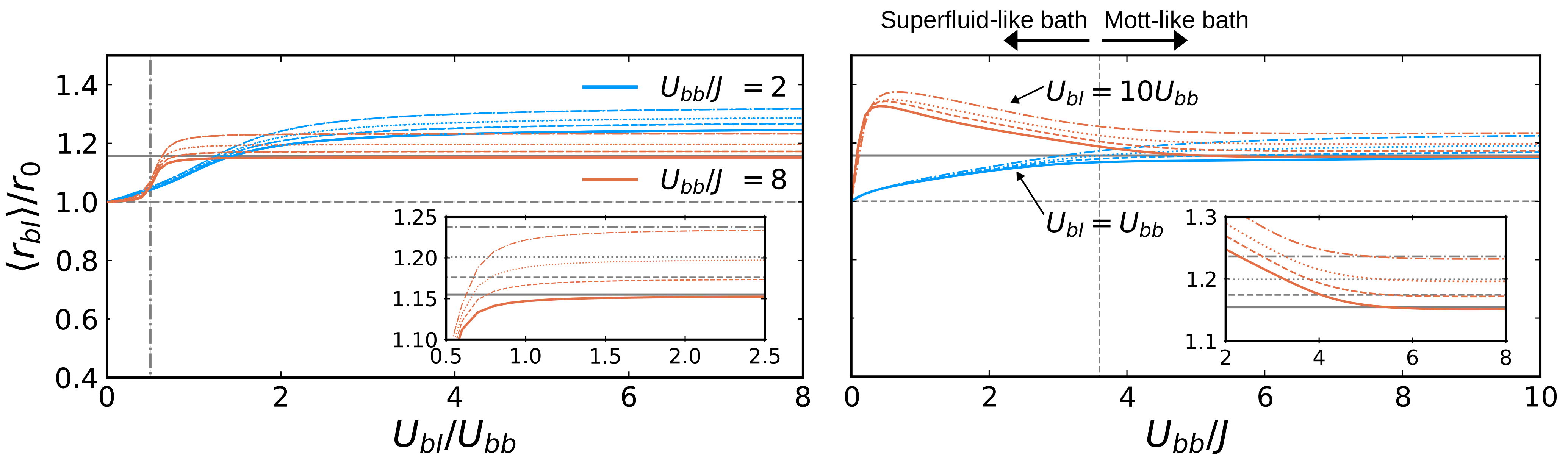
r_0: Average distance between two free bosons.

Average distance between particles

- For **large interactions** U_{bb} and U_{bl}, the average distance between the bath and the impurities converges to:

$$r_s^* = r_0 + r_{F,0}/M.$$

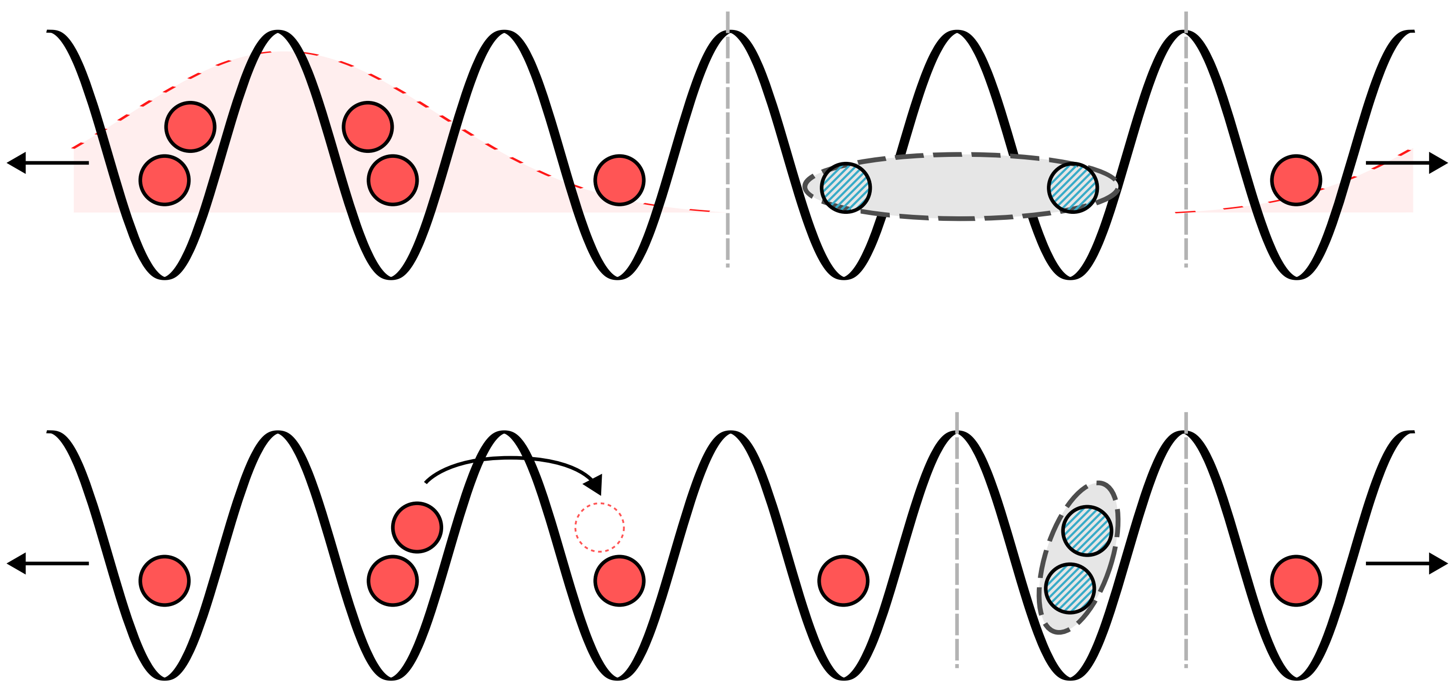
$r_{F,0}$: Average distance between two free fermions of the same spin..



r_0: Average distance between two free bosons.

Bound impurities

- A large bath-impurity repulsion U_{bI} produces a **phase separation**, inducing the formation of **bound impurities**.
- A Mott-like bath supports the formation of **tightly bound dimers**, while a superfluid-like bath supports **shallow dimers**.

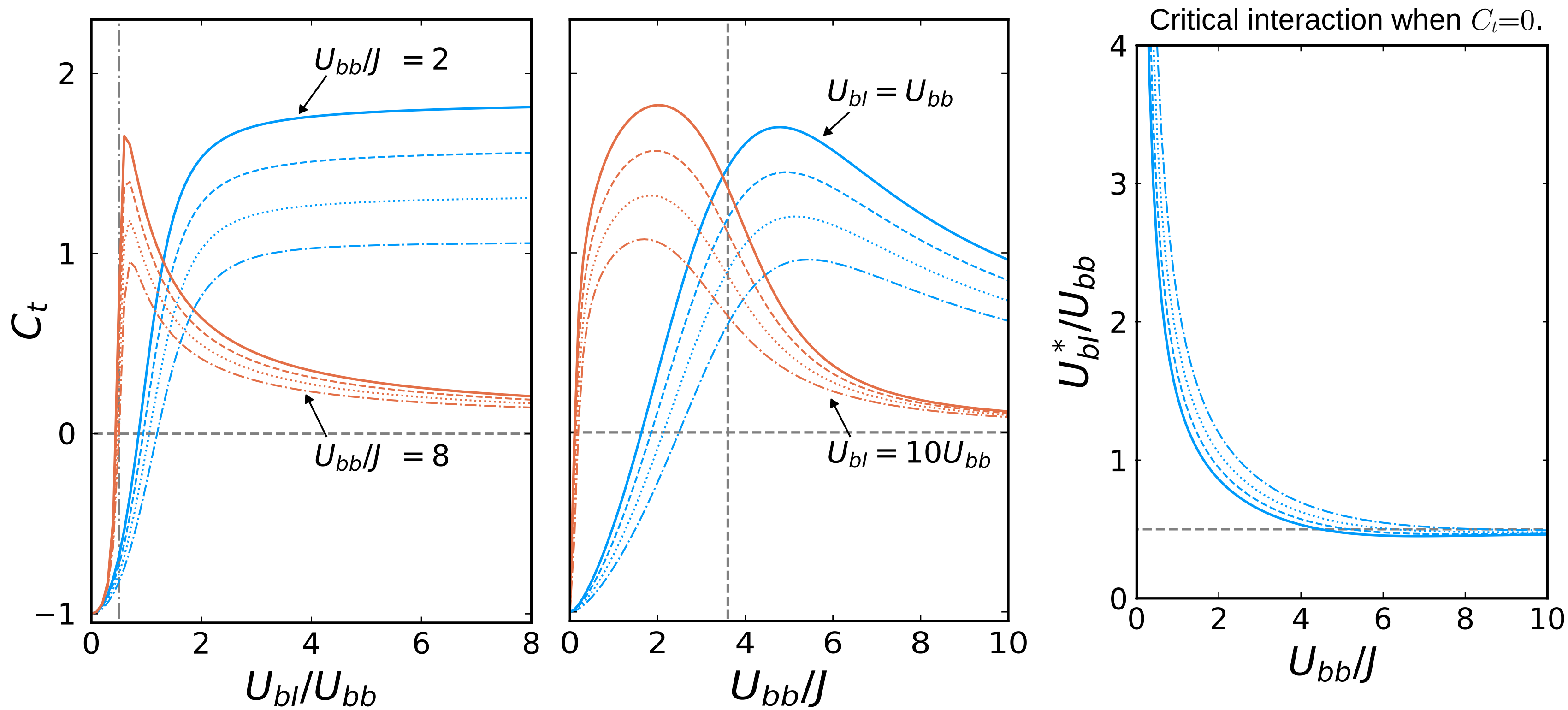


Tunnelling of dimers

- To further characterise the formation of dimers, we examine the **tunnelling correlator**

C. Menotti and S. Stringari, PRA **1**, 045604 (2010).

$$C_t = \langle \hat{a}^\dagger_{i,I} \hat{a}^\dagger_{i,I} \hat{a}_{i+1,I} \hat{a}_{i+1,I} \rangle - \langle \hat{a}^\dagger_{i,I} \hat{a}_{i+1,I} \rangle^2.$$



- Dimers form for $U_{bI} > U_{bb}/2$.

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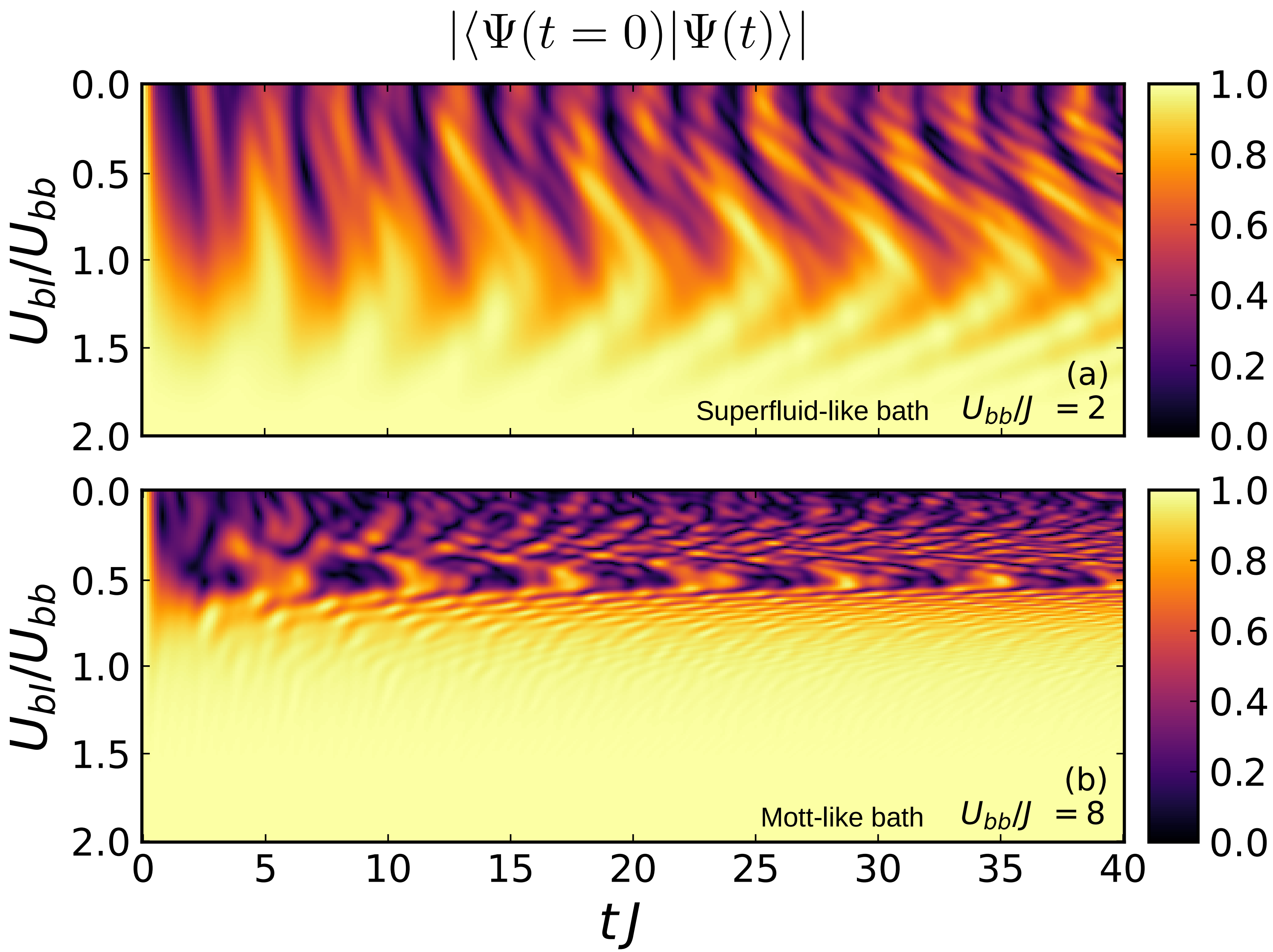
Quench-induced dynamics

- We prepare an **initial state** $\mathit{\Psi}_0$ from the ground state for chosen interactions U_{bb}/J and U_{bI}/U_{bb}.
- We choose a large U_{bI}/U_{bb} so a **dimer is formed**.
- We perform sudden **quenches** at $t{=}0$ to a lower value of U_{bb}/J or U_{bI}/U_{bb}.
- We follow the time evolution by numerical exponentiation

$$|\Psi(t)\rangle = e^{i\hat{H}t}|\Psi(t=0)\rangle.$$

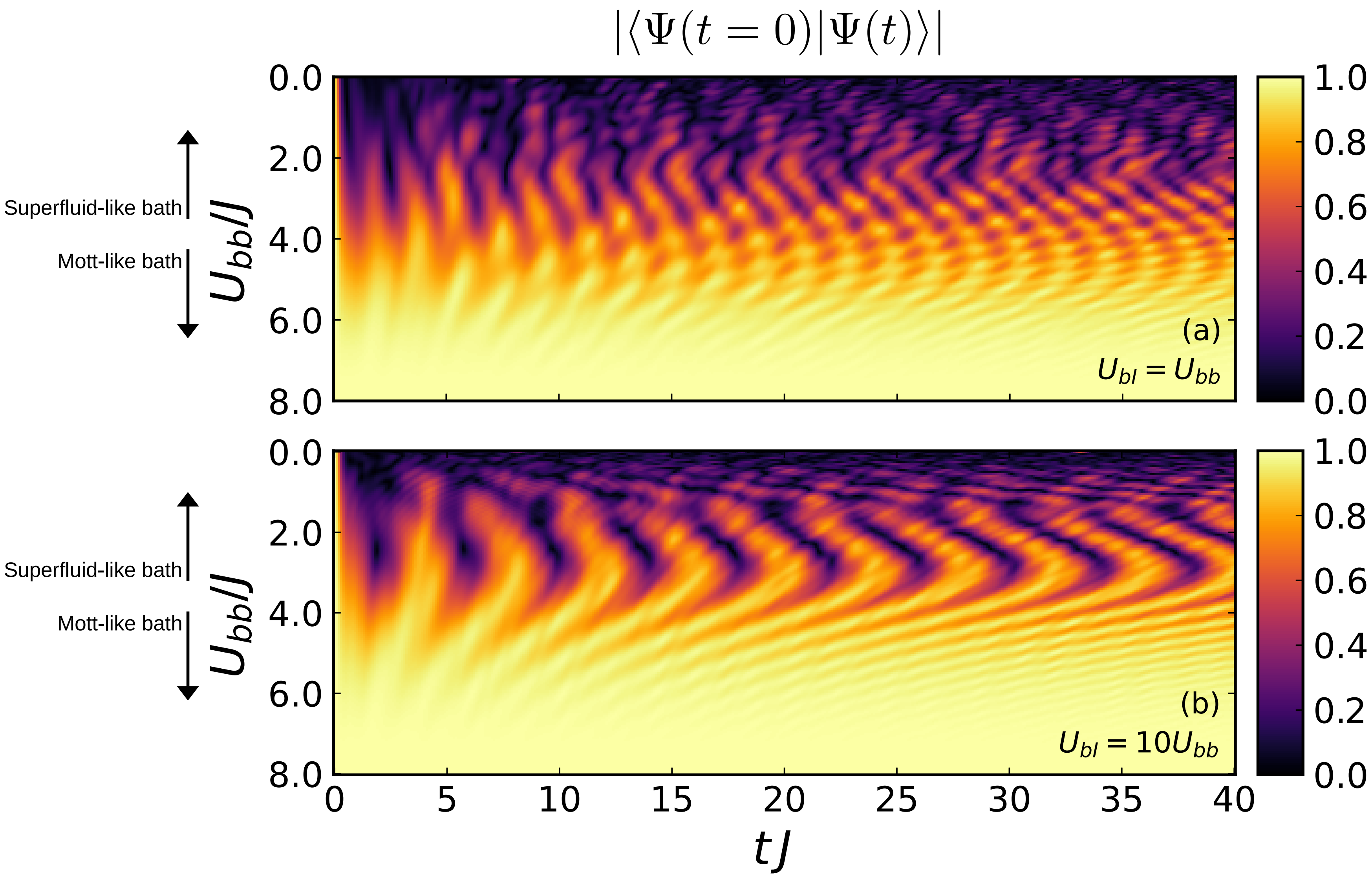
- We consider lattices with $M{=}7$.

Overlaps: Quench in U_{bI}



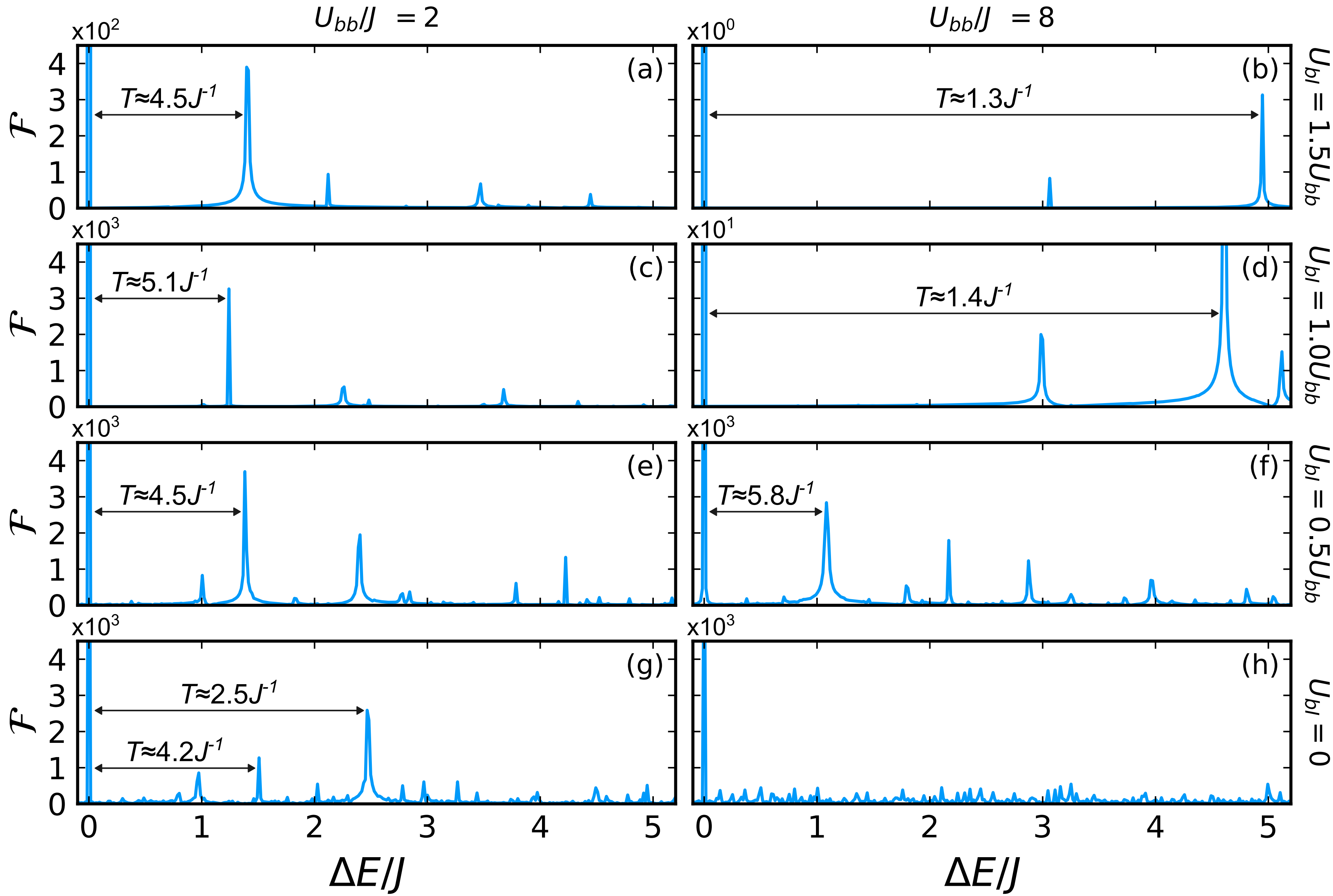
- The system shows **collapses** and **revivals** of the dimer states.
- The **periods reach a maximum** around the interaction when C_t=0 .

Overlaps: Quench in U_{bb}



- The system shows **collapses** and **revivals** of the dimer states.
- The **periods reach a maximum** around the **superfluid-Mott transition region**.

Fourier Analysis: Quench in U_{bI}



- The oscillations are driven by **phase-separated excitations**.

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Conclusions

- We have studied **stationary properties** and **quench-induced dynamics** of two impurities immersed in a 1D Bose lattice gas.
- We have characterised the formation of **bound dimers of impurities**.
- We revealed an intriguing onset of **collapses and revivals** after a quench of the interactions.
- We found that the **oscillations** are driven by **phase-separated excitations**.
- <u>Future work:</u>
    - Consider fermionic baths.
    - Study Rabi (driven) impurities.
    - Employ other theoretical techniques.

Conferences en Chile

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3rd Workshop on Molecular Quantum Technology - MQT 2024

December 9 to 13

https://www.miroptics.cl/quantum-optics-2024-chile/

December 16 to 20

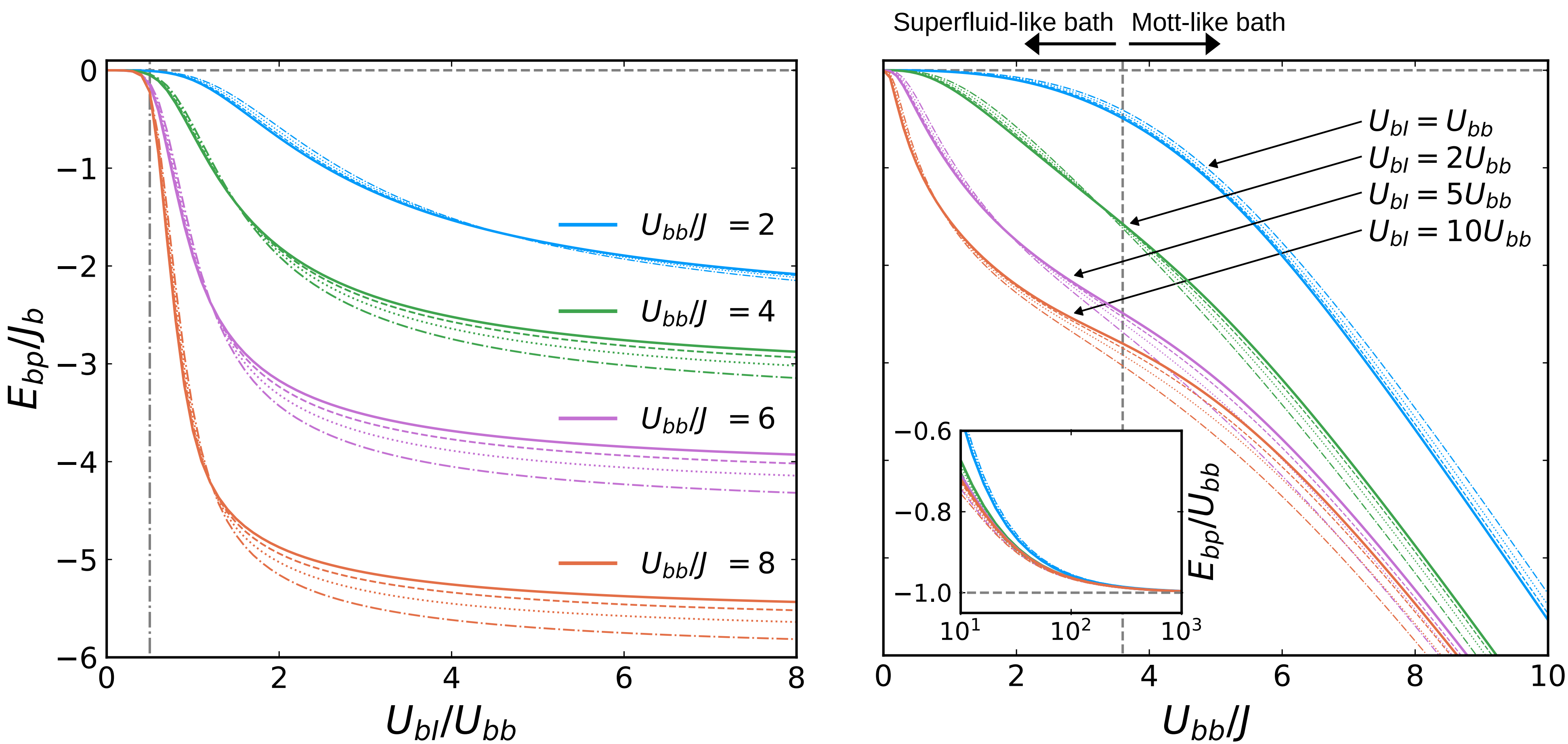
https://mqt2024.org/

Puerto Varas

Thank you!

Bipolaron Energy

- Now we examine mobile systems.



- A negative bipolaron energy suggests the formation of **bound states**.

Average distances: Quench in U_{bI}