Quench-induced dynamics of bound impurities in a one-dimensional Bose lattice gas

FACULTAD DE FÍSICA
PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

Felipe Isaule[1], A. Rojo-Francàs[2], B. Juliá-Díaz[2]

[1] Instituto de Física, Pontificia Universidad Católica de Chile. [2] Facultat de Física & ICCUB, Universitat de Barcelona.

ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA
EXCELENCIA MARÍA DE MAEZTU

I. Background

The study of **optical lattices** with **two impurities** and a **bosonic bath** has received increasing theoretical interest [1-4]. Firstly, the consideration of two impurities enables the formation of **bipolarons**, which have been predicted to form in BECs [5]. Secondly, optical lattices offer a unique setting to study impurities due to the onset of **Mott insulator** phases [6].

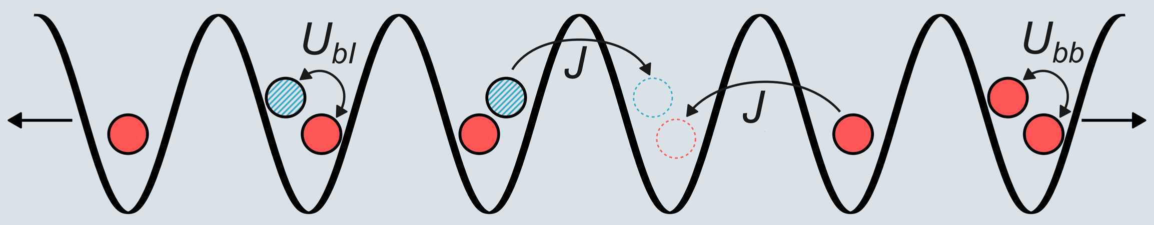


Illustration of the system in consideration. A one-dimensional lattice is filled with a bath of bosons and two bosonic impurities.

We study **two mobile bosonic impurities** immersed in a **one-dimensional lattice** and interacting with a **bosonic bath**. We examine the formation of **bound dimers** of impurities and study the **dynamics** after a **quench of the interactions**.

II. Model

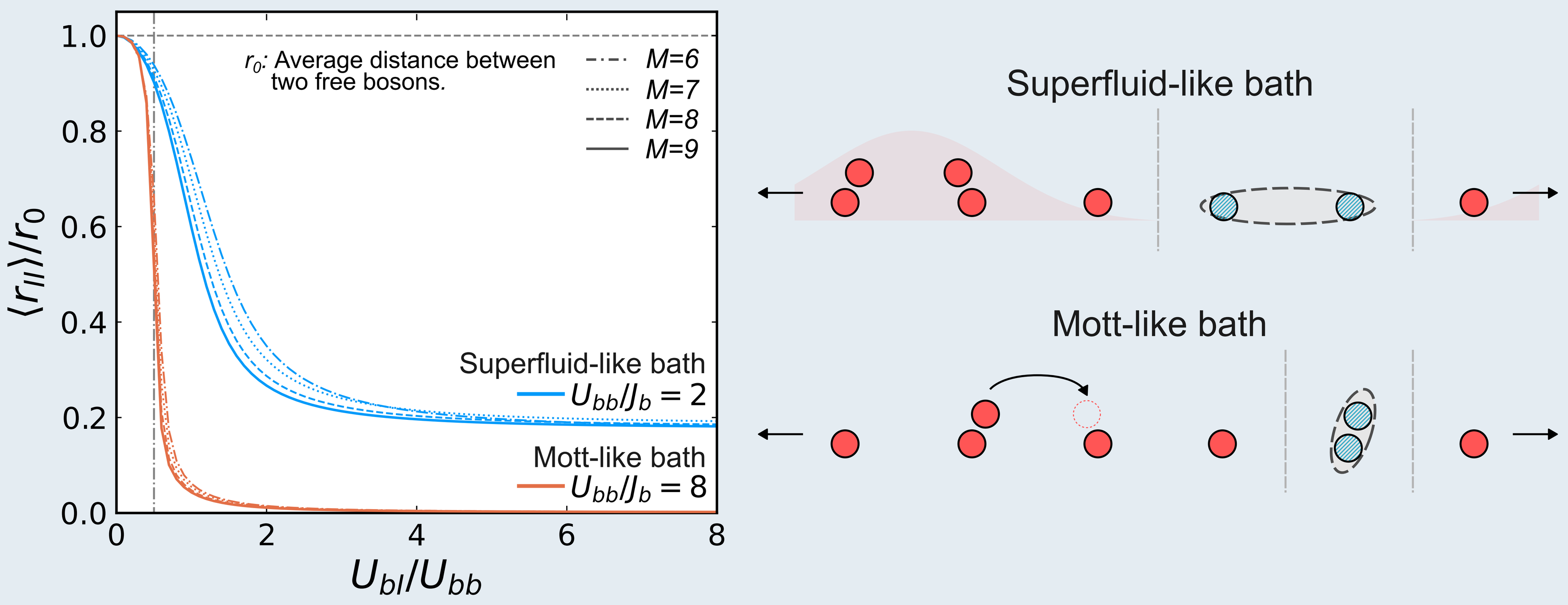
We consider a **two-component Bose-Hubbard Hamiltonian**

$$\hat{H} = -J \sum_{\sigma=b,I} \sum_{i} \left(\hat{a}^{\dagger}_{i,\sigma} \hat{a}_{i+1,\sigma} + \mathrm{h.c.} \right) + \frac{U_{bb}}{2} \sum_{i} \hat{n}_{i,b} \left(\hat{n}_{i,b} - 1 \right) + U_{bI} \sum_{i} \hat{n}_{i,b} \hat{n}_{i,I} \qquad U_{bb}, U_{bI} > 0$$

where b and I denote the bath's bosons and impurities, respectively. To study stationary properties we employ the **exact diagonalisation** method [7], whereas for the dynamics as a function of **time** t, we **exponentiate** the Hamiltonian [8]. We consider small **periodic lattices** with M sites and loaded with **two impurities** and a bath with M bosons (**unity filling**).

III. Bound Impurities

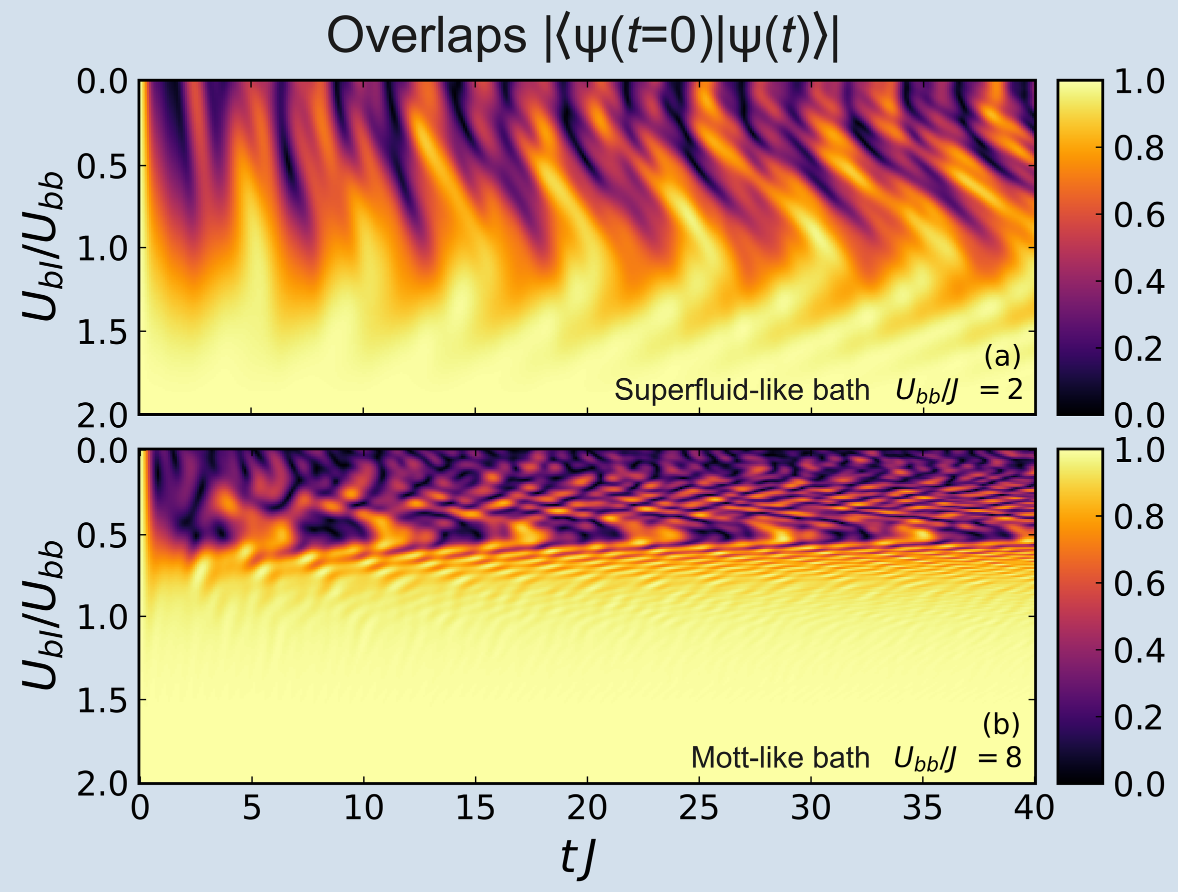
For large U_{bI}/U_{bb}, the bath and impurities **phase separate**, inducing the formation of a **bound dimer** of impurities [4]. This is nicely captured by the **average distance** between impurities.



A small **tightly-bound dimer** is formed in Mott-like baths, while a large **shallow dimer** is formed in superfluid-like baths.

IV. Quench-dynamics of the overlaps

We prepare an **initial state with a dimer formed** for U_{bI}/U_{bb}=2, and perform a **quench** to a **smaller** value of U_{bI} at t=0. We examine the **time-evolution** of the **overlaps** between the initial and evolved state.

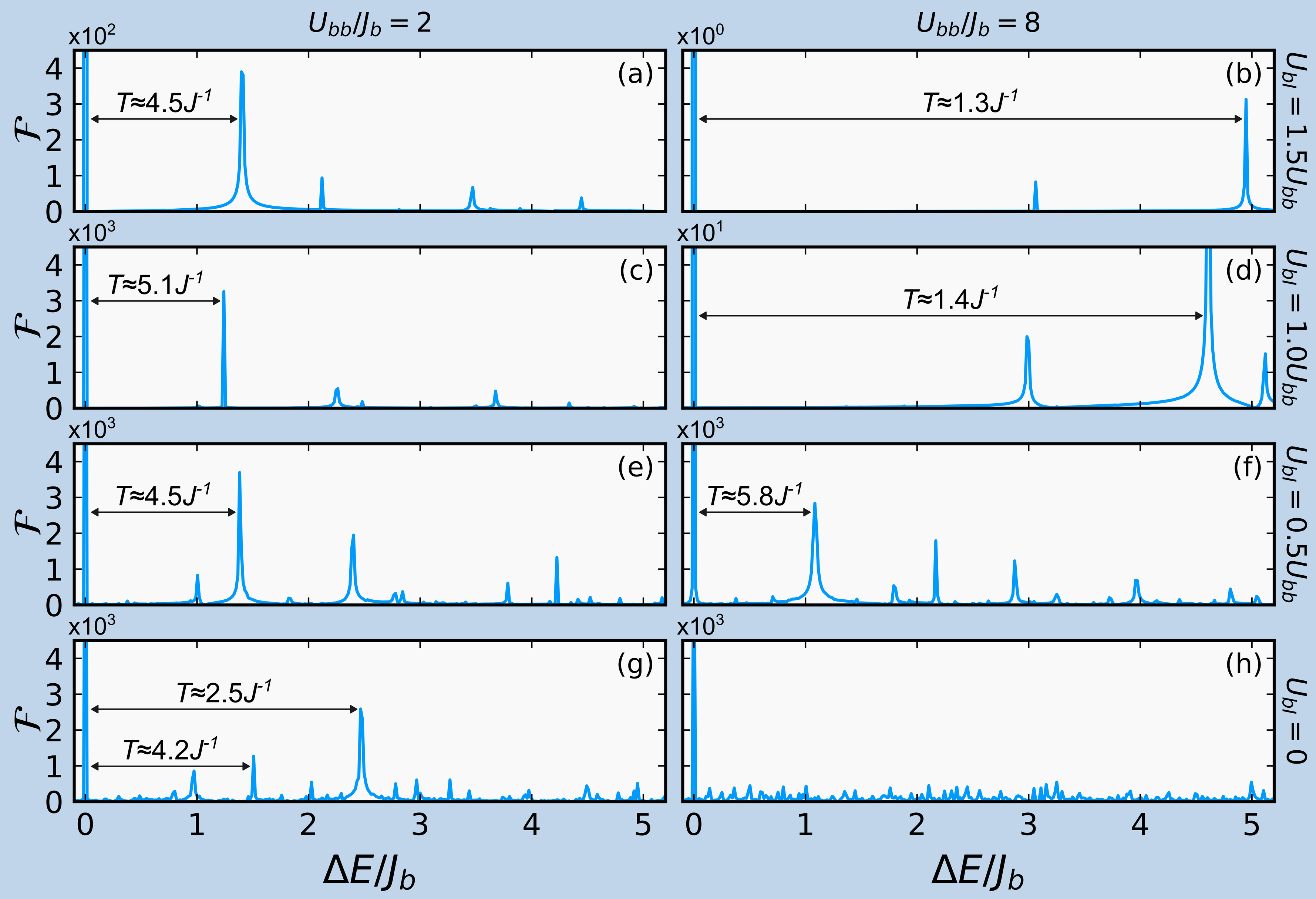


We observe a **periodic** onset of **collapses** and **revivals** of the dimer state. Also, in superfluid-like baths the dimers still show revivals for **large quenches** of U_{bI} to **zero**, while these disappear in Mott-like baths.

Interestingly, the **period of oscillations** reaches a **maximum** around the **phase separation strength** U_{bI}/U_{bb}≈0.5.

V. Fourier Analysis

To understand the oscillation patterns, we perform a **Fourier analysis** of the time evolution. For M=7 we obtain:



The peaks provide the **observed periods** of oscillations, including the maxima [panels (c) and (f)]. We find that the peaks correspond to **phase-separated excitations** where the dimers have a **larger size**. These excitations drive the oscillations after the interaction quenches.

F.I. acknowledges funding from ANID through FONDECYT Postdoctorado No 3230023. B.J-D and A.R-F acknowledge funding from Grant No. PID2020-114626GB-I00 by MCIN/AEI/10.13039/5011 00011033 and "Unit of Excellence María de Maeztu 2020-2023" award to the Institute of Cosmos Sciences, Grant CEX2019-000918-M funded by MCIN/AEI/ 10.13039/501100011033. We acknowledge financial support from the Generalitat de Catalunya (Grant 2021SGR01095). A.R.-F. acknowledges funding from MIU through Grant No. FPU20/06174. We thank J. Martorell for useful discussions.

F. Isaule, A. Rojo-Francàs, B. Juliá-Díaz
arXiv:2402.03070
Accepted in Scipost Physics Core

[1] M. Pasek and G. Orso, PRB **100**, 245419 (2019).
[2] K. Keiler, S. I. Mistakidis, and P. Schmelcher, NJP **22**, 083003 (2020).
[3] S. Ding et al., SciPost Phys. **14**, 143 (2023).
[4] V. Yordanov and F. Isaule. J. Phys. B **56**, 045301 (2023).
[5] A. Camacho-Guardian *et al.*, PRL **121**, 013401 (2018).
[6] I. Bloch, J. Dalibard and W. Zwerger, Rev. Mod. Phys. **80**, 885 (2008).
[7] D. Raventós *et al.*, J. Phys. B **50**, 113001 (2017).
[8] R. B. Sidje, ACM Transactions on Mathematical Software **24**, 130 (1998).
[9] T. Sowiński and M. A. García-March, Rep. Prog. Phys. **82**, 104401 (2019).
[10] C. Baroni, G. Lamporesi, and M. Zaccanti, arXiv:2405.14562 (2024).
[11] L. Amico, A. Osterloh and F. Cataliotti, PRL **95**, 063201 (2005).
[12] L. W. Cheuk *et al.*, Science **353**, 1260 (2016).
[13] M. F. Parsons *et al.*, Science **353**, 1253 (2016).

VI. Outlook

We have studied **two bosonic impurities** immersed in a small **one-dimensional lattice Bose bath**. We have examined the **dynamics** after an **interaction quench** and found an intriguing onset of **collapses** and **revivals** of the **bound impurities**.

The studied model could be produced experimentally with a **few-body** [9] and **highly-imbalanced mixture** [10] in **ring configurations** [11], while the revivals could be observed with measurements of atomic **correlations** [12,13].