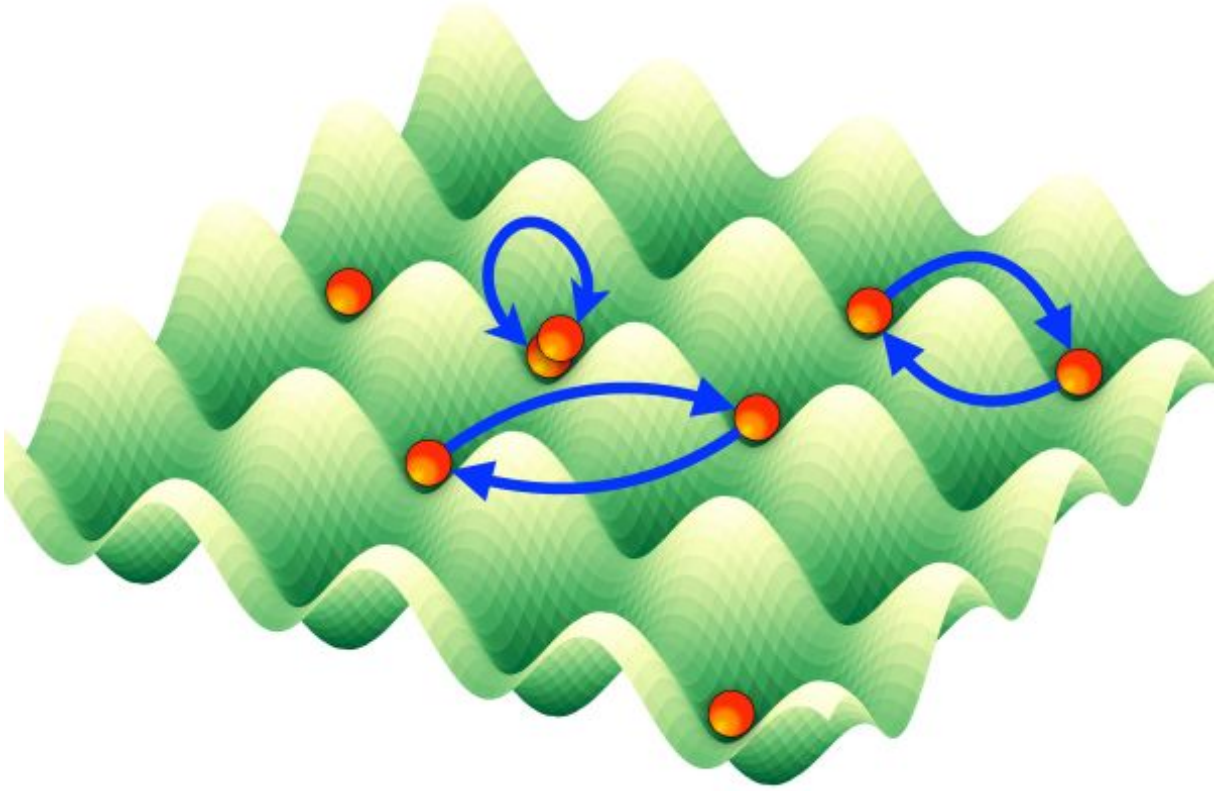
ICFO



Quantum simulation with interacting ultracold atoms: recent progress and future perspectives

Researchers provide an updated review of non-standard Bose-Hubbard models, a theoretical framework typically used to describe quantum simulators using ultracold atoms with various kinds of interactions. The review compiles recent results in the field and discusses how intriguing states of matter and quantum mechanical effects can emerge in these systems.

March 28, 2025

Atomic quantum simulators are emerging quantum technologies that have demonstrated tremendous potential to unveil novel quantum mechanical phenomena. Typically, the experimental platform for these simulators involves bosonic atoms at ultracold temperatures. By creating a grid of light with powerful lasers, called an optical lattice, the atoms arrange in space following a periodic pattern, occupying different lattice sites. However, rather than remaining isolated from one another, the atoms can interact in many different ways: they can

hop from one lattice site to another nearby site, they can feel attraction or repulsion from their nearest neighbors in the lattice, and they can even interact with atoms placed further away through so-called long-range interactions, among others.
The richness and malleability of these systems allow researchers to simulate more complex systems, which might be impossible to access directly, and to explore new states of matter that may not even exist in nature, making artificial creation in the laboratory the only way to observe them.
Fortunately, several theoretical models, the non-standard Bose-Hubbard models (BHMs), can faithfully capture all the intricacies of the aforementioned systems. Investigating non-standard BHMs in the context of atomic quantum simulators is therefore crucial for advancing the field, both from theoretical and experimental perspectives.
The realization of optical lattices in the 2000s triggered the early expansion non-standard BHMs research, which has kept developing rapidly ever since. Nevertheless, ten years have passed since the last review on the topic, during which many significant advances have been made. Today, extraordinary progress in the experimental engineering and theoretical characterization of non-standard BHMs has rendered the previous review outdated.
Now, a joint collaboration between the Indian Institute of Technology Indore, the Institute for Condensed Matter Physics and Complex Systems (Politecnico de Torino), the Institute for Quantum Optics and Quantum Information (Innsbruck), the University of Innsbruck, the Institute of Theoretical Physics (Jagiellonian University), the Mark Kac Center for Complex Systems Research (Jagiellonian University), and **ICFO and ICREA Prof. Dr. Maciej Lewenstein**, has provided an updated review, published in Reports on Progress in Physics. In this work, they have **collected some of the most recent and exciting results on the investigation of non-standard Bose-Hubbard models**, focusing on their application for atomic quantum simulators.
Tackled both from a theoretical and experimental perspective, the researchers discuss how intriguing states of matter and quantum mechanical effects can emerge in these systems, outline recent experimental setups using ultracold atoms and describe the obtained results, and speculate on future developments. i¿½We believe that **this review poses the ground towards many more scientific achievements that the future will bring**i¿½, the researchers sa
. Some of the key advances include accounting for dissipative on-site effects (how energy
s lost in the system due to interactions) in the theoretical description, making it more accurat
; the experimental implementation of long-range interactions and the subsequent explorati
n of their effect on atomic dynamics, leading to new insights into quantum many-body physic
; and achieving higher control of inter-atomic interaction
. i¿½The amount of recent results is impressivei¿½, the authors share, believing that this
ealth of successful research i¿½demonstrates the central importance that non-standard
Hubbard models had, have and will have in order to understand fundamental laws of nature a
pearing in condensed matter and, as recently realized, high energy physics and

quantum chemi

Reference:
Titas Chanda, Luca Barbiero, Maciej Lewenstein, Manfred J. Mark and Jakub Zakrzewski, Recent progress on quantum simulations of non-standard Bose-Hubbard models. Reports on Progress in Physics (2025).
DOI 10.1088/1361-6633/adc3a7

Acknowledgements:
L.B. acknowledges financial support within the DiQut Grant No. 2022523NA7 funded by European Union - Next Generation EU, PRIN 2022 program (D.D. 104 - 02/02/2022 Ministero dell'Universita e della Ricerca). M.L. acknowledges support from: ERC AdG NOQIA; Ministerio de Ciencia y Innovation Agencia Estatal de Investigaciones (PGC2018-097027-B-I00/10.13039/501100011033, CEX2019-000910-S/10.13039/501100011033, Plan National FIDEUA PID2019-106901GB-I00, FPI, QUANTERA MAQS PCI2019-111828-2, QUANTERA DYNAMITE PCI2022-132919, Proyectos de I+D+I i¿½Retos Colaboracioni¿½ QUSPIN RTC2019- 007196-7); MICIIN with funding rom European Union NextGenerationEU(PRTR-C17.I1) and by Generalitat de Catalunya; Fund cio Cellex; Fundacio Mir-Puig; Generalitat de Catalunya (European Social Fund FEDER and C RCA program, AGAUR Grant No. 2021 SGR 01452, QuantumCAT U16-011424, co-funded by RDF Operational Program of Catalonia 2014-2020); Barcelona Supercomputing Ce ter MareNostrum (FI- 2022-1-0042); EU Horizon 2020 FET-OPEN OPTOlogic (Grant No 8997 4); EU Horizon Europe Program (Grant Agreement 101080086 - NeQST), ICFO Inte nal i¿½QuantumGaudii¿½ project; European Union's Horizon 2020 research and in ovation program under the Marie-Sk?odowska-Curie grant agreement No 101029393 (STRE CH) and No 847648 (i¿½La Caixai¿½ Junior Leaders fellowships ID100010434: LCF/BQ/PI 9/11690013, LCF/BQ/PI20/11760031, LCF/BQ/PR20/11770012, LCF/BQ/PR21/1184 013). L. B. acknowledges financial support within the DiQut Grant No. 2022523NA7 funded by European Union - Next Generation EU, PRIN 2022 program (D.D. 104 - 02/02/20 2 Ministero dell'Universit?a e della Ricerca). M.J.M. acknowledges financial su port from a NextGeneration EU Grant AQuSIM through the Austrian Research Promotion gency (FFG) (No. FO999896041), and the Austrian Science Fund (FWF) Cluster of Excel ence QuantA (10.55776/COE1). This research was also funded by National Science Centre (P land) under the OPUS call within the WEAVE programme 2021/43/I/ST3/01142 (J.Z.). A partia support by the Strategic Programme Excellence Initiative at Jagiellonian University as well as that within the QuantEra II Programme that has received funding from the European Uni n's Horizon 2020 research and innovation programme under Grant Agreement No 101017 33 DYNAMITE (M.L. and J.Z.).