FETPROACT-3-2014: Quantum simulation

Project AQuS - Analog quantum simulators for many-body dynamics

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Continuous reporting - Deliverable no. 2.1 Lead beneficiary: TU Wien

Report on set up of quantum simulation platforms, including new means for preparation, initialisation, and driving

The central objective of the AQuS project is to lay the grounds for experimentally feasible analog quantum simulation, focusing on three promising platforms: Ultracold atoms in optical lattices and the continuum as well as cavity polaritons. So far, strong progress was made in all three experimental fields, complemented by extensive support and complementary developments on the theory side.

General objectives and related achievements.

The key objective relating to the present deliverable was to lay the grounds for experimentally feasible analog dynamical quantum simulation. The AQuS project was set up to focus on three promising platforms that have the potential to fully satisfy that aim: Ultra-cold atoms in optical lattices and in the continuum as well as cavity polaritons. With the latter, the task was to explore whether strongly interacting photons can be employed for dynamical quantum simulation. Devices were to be designed to investigate elements of universality in non-equilibrium quantum dynamics which would allow to look for the best suited system belonging to the same universality class. It is essential to put together a toolbox of measurement schemes that allows to efficiently address specific features of the quantum system, such as entanglement of the state and its higher-order correlation functions.

The partners within the AQuS consortium have contributed significantly in developing the envisaged new platforms for analog dynamical quantum simulation based on continuous and lattice atomic gases as well as cavity polaritons. The devices are being developed for measuring universality in non-equilibrium dynamics and to determine scaling properties and thus universality classes.

TU Wien recently has made decisive technological progress in performing experiments on prethermalisation, Generalized Gibbs ensembles, and thermalisation of bosonic quantum gases in one-dimensional (1D) chip-based traps. This lead them to focus on developing new designed potentials within the 1D experimental setup, on the initialisation and driving of many-body systems by optimal control, for creating interesting initial states for analog quantum simulators. TU Wien developed new methods to read the simulator devices and in particular demonstrated the ability to extract high-order correlation functions from the measured full distribution data. They furthermore proceeded with building a new Lithium-based experiment for 1D and 2D analog quantum simulators with strong interactions.

INO-CNR has focused on theoretically studying the preparation, initialisation and driving of polariton-based analog quantum simulators, and on identifying and characterizing novel platforms for analog quantum simulation of many-body dynamics. Specifically, it has contributed to the development of quantum many-body simulator platforms based on ultracold atoms and on optical systems such as cavity polaritons and propagating light.
LPN-CNRS has focused on developing methods for the measurement of the spatially and temporally resolved first- and second-order coherence functions of polariton condensates in different geometries (planar cavity or lattice; two-, one-, and zero- dimensional systems) and ultrafast time resolution (2 ps). In collaboration with colleagues in Antwerp, they have developed a new theoretical framework to explain unexpected observations. According to the theory being developed, the current picture of polariton condensation likely needs to be significantly revised.

LMU-MPQ has successfully developed and characterized a commensurate period-two superlattice which allows the preparation of a charge-density wave (CDW) of ultracold fermionic potassium atoms and the measurement of CDW and spin-density wave (SDW) orders. They furthermore successfully demonstrated the control of the dimensionality of their system. Not only identical experiments were performed in 1D and 2D, but also intermediate situations with highly anisotropic hopping parameters were realized.

UHEI has focused on developing quasi 1D quantum simulation platforms of spinor Bose gases, realizing Spin ½, Spin 1, and Spin 2 systems by means of selected sets of hyperfine levels of Rubidium-87. The make use of spin-changing collisions to create, in a controlled manner, instable evolution and the creation of strong non-linear excitations. They have developed tools to image the spin components separately and to measure a variety of correlation functions of the density and spin operators by combining precise spin rotations with Stern-Gerlach imaging techniques. Moreover, they developed high-precision counting techniques which allow access to fluctuations at the single-particle level.

Description of the work carried out

The AQuS activity of the TU-Wien on Task 2.1 has focused on (i) studying the preparation of designed potentials for the 1d experiment, (ii) initialization and driving of many body systems by optimal control to create interesting initial states for analog quantum simulators and develop methods to read them, and (iii) building a new experiment for 1d and 2d analog quantum simulators with strong interactions.

(i) **Designing potentials by dipole trap painting:** Many of the non-equilibrium and relaxation experiments are currently limited by the longitudinal trap confinement. TU Wien will implement a designed dipole potential for modifying the longitudinal trapping potential, while the chip trap will still be used to realise the transverse trapping and manipulation. They plan to create designed laser fields using a digital mirror device (DMD), which will allow them also to actively modify the longitudinal potential during the experiment.

Such a dipole potential can be used to create, for example, square-well longitudinal confinement, which is of great advantage for the comparison with theoretical models, or any other desired modifications, like adding longitudinal barriers, dimples or lattices. This new addition will greatly enhance the capability of the experiments.

(ii) **Initializing and reading analog quantum simulators:** Following up on the Twin-Atom-Beam experiment [Bücken et al. Nature Phys. 7, 808 (2011)] TU Wien sets out to probe in detail the optical coherence tomography (OCT) excitation to excite a 1D BEC into the first motional transverse trap state. Based on these results, in collaboration with the group of T. Calarco, (Univ. Ulm), a much improved and faster excitation scheme was developed. While with the previously realized sequence the full population inversion of the condensate had been achieved in more than 5 ms, the new excitation takes only 1.2 ms, enabling the manipulation of motional states faster than the onset of the decay through the parametric amplification process [1].
Changing the splitting procedure in our interferometer experiments on pre-thermalization TU Wien was able to create interesting quantum states and studied their non-equilibrium evolution. We used the non-translation invariant phase correlation functions \( C(z_1, z_2) = \langle \exp(i[\varphi(z_1) - \varphi(z_2)]) \rangle \) to directly relate the pre-thermalized state emerging from the specifically designed splittings to the conjectured generalized Gibbs ensemble (GGE) [2]. This ensemble describes the maximum-entropy state to which the system relaxes under the given constraints of the conserved quantities. In their experiment, the phonon mode occupations represent the conserved quantities, and the TU Wien partners were able to extract the occupation numbers from the GGE model of the relaxed pre-thermal state. They verified that the GGE provided a good description by showing that it predicts also higher-order correlation functions (up to 10th order) correctly.

Adding tunnel-coupling to two one-dimensional atomic super-fluids, TU Wien realised a quantum Sine-Gordon model and analysed under which conditions the higher-order phase correlation functions factorise [3]. Non-factorisation of correlation functions allows them to study non-trivial interacting initial states. They could furthermore characterise the essential features of the underlying quantum field theory solely from measurements, identifying the relevant quasi-particles, their interactions, and the topologically distinct vacuum states. This analysis provided a general method to analysing quantum many-body systems through experiments, and a unambiguous way to read analog quantum simulators.

Towards experimental quantum field tomography. The complexity of the states of a many body quantum system prevents standard quantum state tomography. In collaboration with FU Berlin, TU Wien implemented quantum field tomography based on continuous matrix-product states. These states naturally incorporate the locality present in realistic physical settings and are thus prime candidates for describing the physics of locally interacting quantum fields. They implemented this approach in the experiment [4] and partially reconstructed the quantum fields of the far-from-equilibrium states created by coherently splitting a 1D quantum gas. The continuous matrix-product states extracted from the 2\(^{nd}\) and 4\(^{th}\)-order correlation-function data enabled them to describe the measured 6\(^{th}\)-order correlation function. This versatile technique is expected to play an important role in future studies of quantum many-body systems.

(iii) New Li Experiment: In parallel to the above, TU Wien designed a new all-optical lithium experiment for using strongly interacting many-body quantum systems as analog quantum simulators. They established a new laboratory, bought most of the equipment and started building the experiment. The progress was initially delayed because the laboratory where the experiment is being built was not available, due to the promised building work having been significantly delayed. The vacuum, the mechanical mounting, the magnetic field coils and the laser cooling setup for trapping atoms, the experiment control electronics, and the software have now, for most part, been set up. On 25 February 2016, lithium atoms were successfully captured in a magneto-optical trap (MOT). The experiment suffered several further setbacks due to repeated failure of the laser amplifier. High-field magnetic coils for accessing Feshbach resonances and the setup of the high-power trapping laser have been completed. The set-ups of the detection laser and the UV laser for further cooling are in progress. It is expected that the experiment will produce quantum degenerate gases of fermionic lithium atoms and molecular BECs within the next 6 months, and the science chamber and the facilities for it will be integrated into the system. The experiment is expected to be operational within approximately one year, including an absorption-imaging setup for the science chamber.

The AQuS activity of the INO-CNR on Task 2.1 was focused on (i) studying the preparation, initialisation and driving of polariton-based analog quantum simulators, and (ii) identifying and characterizing novel platforms for analog quantum simulation of many-body dynamics.

A central result of line (i) has been the development of a theory of many-body photon states in the presence of a frequency-dependent gain medium (MS7). Publication [5] reports the general theory
and a few simplest applications of it to the non-linear dynamics of single cavity systems and Mott states in small arrays. On-going work is extending this theory to many-cavity arrays to characterize how the frequency-dependent gain can induce non-equilibrium Mott-superfluid transitions. Furthermore, it is applied to photon gases in the presence of synthetic magnetic fields for identifying novel schemes of generating quantum Hall liquids of light. As an unexpected interdisciplinary development, INO-CNR is presently applying this non-Markovian theory – originally developed for polaritons – to explain some unexpected features observed in atom cooling experiments at TU Wien.

From a more phenomenological point of view, INO-CNR has explored how a suitably designed coherent driving allows one to study the physics of the polariton fluid in novel configurations, e.g. strained honeycomb lattices. Here, the strain is responsible for a synthetic magnetic field and, thus, leads to relativistic Landau levels [6] and square lattices with a synthetic magnetic field [7]. An experimental implementation of the idea in [6] is under investigation by the LPN-CNRS node.

In the framework of research line (ii), INO-CNR has explored: (ii-a) quantum fluids of light in cavityless propagating geometries; (ii-b) momentum-space magnetism in cavity with synthetic magnetic fields; (ii-c) synthetic dimensions for quantum gases of atoms and of photons; (ii-d) optically dressed impurities embedded in atomic condensates to simulate quantum emitters interacting with quantum fields.

While the physical ideas underlying (ii-a) were partially known from classical works [e.g. Lai and Haus, Phys. Rev. A 40, 844 (1989)], its power for quantum simulations had not yet been appreciated prior to the INO-CNR works. The general formalism is reported in [8], where the mapping of paraxial propagation of quantum light onto a many-body Hamiltonian is derived and illustrated. The unique feature of this novel platform as compared to other optical systems, e.g., exciton-polaritons, is that it allows to quantum simulate conservative dynamics without being disturbed by the intrinsic losses of cavity systems. Depending on the specific implementation, both continuous-space and lattice geometries can be implemented with comparable ease.

An external collaboration with the experimental group at Heriot-Watt has addressed the promise and the limitations of non-local nonlinearities of thermal origin for the study of many-body physics of propagating fluids of light [9]. Unfortunately, the promise of this specific system appears quite limited, so experimental implementations will have to focus on other materials, e.g. ultracold atomic gases, possibly under a coherent optical dressing.

Inspired by a recent experiment by another group at Heriot-Watt (Mukherjee et al., arXiv: 1604.00689), INO-CNR are now exploring a novel strategy to quantum simulate interacting few-body physics using arrays of coupled linear waveguides. This project is being pushed forward by the post-doc Marco Di Liberto and by the CNR researcher Chiara Menotti who have joined the INO-CNR AQuS team. A manuscript discussing the application of this idea to a pair of strongly interacting bosons in an SSH lattice is in preparation. There, quantum simulation of bound states, of edge bound states, and of the Feshbach resonance mechanism in two-body collision is theoretically illustrated. The potential of this system to quantum simulate electronic dynamics in polymer molecules will also be worth exploring.

The line (ii-b) aims at exploring quantum magnetism in momentum space and has been carried out with the major contribution of the post-doc Tomoki Ozawa who has joined the AQuS team. Starting from the position-momentum-space duality originally introduced in [Price, Ozawa, Carusotto, Phys. Rev. Lett. 113, 190403 (2014)], INO-CNR have investigated observable consequences of the momentum-space magnetic field due to the Berry curvature of the bands. Specifically, spectroscopic protocols to detect momentum-space Landau levels were studied in [7,11], a momentum-space
Harper-Hofstadter model was introduced in [12] for non-interacting particles and weakly interacting bosons and the role of the intrinsically toroidal geometry of the Brillouin zone was highlighted. The resulting momentum-space quantum Hall effect was studied: as the synthetic magnetic field threaded through the torus holes can be tuned by a simply spatial shifting of the minimum of the harmonic trapping potential, one can realize one of the archetypical models of QH physics. This idea was proposed and applied in [13] to the non-interacting case and then to the weakly-interacting boson case. Its far more exciting application to strongly interacting gases is presently in progress: given the effectively toroidal shape of the system in momentum space, fractional states should result in topological degeneracies with many potential applications.

Along similar lines, in (ii-c), INO-CNR has explored the potential of synthetic dimensions to quantum simulate quantum gases in higher dimensions. This idea was already on the market for the atomic case, and the task had been to extend it to novel configurations and, then, to push it forward towards the quantum simulation of 4D systems. The first challenge [14] was based on a novel design based on shaken harmonic traps, which should combine an experimental easy realisation and manipulation, with the long-term promise of obtaining short-range interactions also along the synthetic dimension. The latter research line was instead focussed on the novel quantisation effects of the 4D quantum Hall effect [15,16] and on some subtleties in the measurement of topological invariants via transport experiments [17]. On the other hand, synthetic dimensions for photons were a quite original idea: as a first step, INO-CNR devised a viable photonic configuration which could host the synthetic dimension and the synthetic magnetic field [18]. The role of the driven-dissipative nature of the photon fluid was explored to propose actual experimental protocols to highlight the 4D-QH effect and the quantized response proportional to the 2nd Chern number [18]. A different concept of synthetic dimension for photons was then proposed in [19], with the crucial advantage of automatically giving local interactions in both the physical and the synthetic dimensions, which is of utmost importance in view of quantum simulations of strongly correlated states.

INO-CNR's work for (ii-d) has extended the concept of analog models of gravity based on atomic condensates (see WP4) to other quantum-field phenomena involving quantum emitters. In particular, in the work [20], they have presented the general formalism underlying this novel example of analog quantum simulator. They also discuss how it can be practically implemented using optically dressed two-level impurities collisionally interacting with the atoms of the condensate in which they are embedded. As first examples of application of this novel quantum simulation platform, they have focused on the Casimir forces and on the quantum friction felt by uniformly moving emitters because of Ginzburg emission.

The LMU-MPQ team has successfully developed and characterized a commensurate period-two superlattice consisting of a frequency-stabilized 532 nm laser (Coherent Verdi) and an amplified 1064 nm fibre laser. The laser frequencies were successfully stabilised on each other using frequency-doubling and offset locks such that the system can now be applied to create a versatile superlattice with controlled relative positions of the two lattices. They have demonstrated the successful preparation of a charge density wave (CDW) of ultracold fermionic potassium atoms (40K) with a fidelity of better than 95%, meaning that less than one in twenty atoms sits on the unwanted sites [21].

At the same time, the method also allows the straightforward and reliable measurement of CDW and spin-density wave (SDW) orders. In the second period, these capabilities will be extended to prepare spin-density waves and multicomponent CDW in Bose-Fermi mixtures. The ability to control the dimensionality has been successfully demonstrated in [22] and [23], where in the latter case not only identical experiments were performed in 1D and 2D, but furthermore also intermediate situations with highly anisotropic hopping parameters were realised. In an independent setup, novel interferometric probes have been developed to characterise the geometric and topological properties
of families of closely spaced bands [24]. These methods combine ideas of strong-gradient dynamics and Wilson lines with Stückelberg interferometry and will be essential to benchmark the quality of topological band structures created by e.g. Floquet engineering.

Publications

The superscript symbols behind the titles indicate the association of the respective publication with the project:

* Work done within the AQuS project (partly co-funded from other sources).
# Work performed before the start of AQuS, towards the objectives of the project, and in general, completed after the submission of the proposal
+ Work not funded directly by AQuS but done in collaborations towards the objectives of AQuS, or before the submission of the proposal

1. **Optimal control of complex atomic quantum systems**
   S. van Frank, 1 M. Bonneau, 1 J. Schmiedmayer, 1 S. Hild, 2 C. Gross, 2 M. Cheneau, 2,3 I. Bloch, 2 T. Pichler, 4 A. Negretti, 5 T. Calarco, 4 S. Montangero 4
   (1Atominstitut, TU Wien, Austria; 2MPIQ, Garching, Germany; 3Institut d’Optique, CNRS, Palaiseau, France; 4IQST, Ulm, Germany; 5ZOQ, Univ. Hamburg, Germany), Nov 2015.
   arXiv:1511.02247 [cond-mat.quant-gas]

2. **On solving the quantum many-body problem**
   T. Schweigler, 1 V. Kasper, 2 S. Erne, 1,2 B. Rauer, 1 T. Langen, 1 T. Gasenzer, 3 J. Berges, 2 J. Schmiedmayer, 1
   (1Atominstitut, TU Wien, Austria; 2ITP, Univ. of Heidelberg, Germany; 3KIP, Univ. of Heidelberg, Germany), May 2015.
   Accepted for publication in Nature, 2017
   arXiv:1505.03126 [cond-mat.quant-gas]

3. **Experimental Observation of a Generalized Gibbs Ensemble**
   T. Langen, 1 S. Erne, 1,2 R. Geiger, 1 B. Rauer, 1 T. Schweigler, 1 M. Kuhnert, 1 W. Rohringer, 1
   I. E. Mazets, 1,4,5 T. Gasenzer, 2,3 J. Schmiedmayer, 1
   (1Atominstitut, TU Wien, Austria; 2ITP, Univ. of Heidelberg, Germany; 3EMMI, GSI, Darmstadt, Germany; 4Wolfgang Pauli Institute, Vienna, Austria; 5Ioffe Physico-Technical Institute, St. Petersburg, Russia), Nov 2014.
   Science 348: 207-21, 2014
   arXiv:1411.7185 [cond-mat.quant-gas]

4. **Towards experimental quantum field tomography with ultracold atoms**
   A. Steffens, 1 M. Friesdorf, 1 T. Langen, 2 B. Rauer, 2 T. Schweigler, 2 R. Huebener, 1 J. Schmiedmayer, 2 C. Riofrio, 1 J. Eisert, 1
   (1FU Berlin, Germany; 2Vienna, Austria), Jun 2014.
   Nature Comm. 6: 7663, 2015
5. **Towards strongly correlated photons in arrays of dissipative nonlinear cavities under a frequency-dependent incoherent pumping**
José Lebreuilly,¹ Iacopo Carusotto,² Michiel Wouters²
(¹INO-CNR BEC and Univ. Trento, Italy; ²Univ. Antwerp, Belgium), Feb 2015.
*C.R. Physique* **17**: 836-860, 2016

6. **How to directly observe Landau levels in driven-dissipative strained honeycomb lattices**
Grazia Salerno, Tomoki Ozawa, Hannah M. Price, Iacopo Carusotto
(¹INO-CNR BEC and Univ. Trento, Italy), Apr 2015.
*2D Mater.* **2**: 034015, 2015
arXiv:1504.04014 [cond-mat.quant-gas]

7. **Momentum-space Landau levels in driven-dissipative cavity arrays**
Andrei C. Berceanu,² Hannah M. Price,¹ Tomoki Ozawa, Iacopo Carusotto¹
(¹INO-CNR BEC and Univ. Trento, Italy; ²Univ. Autonoma Madrid, Spain), Oct 2015.
arXiv:1510.03054 [cond-mat.mes-hall]

8. **Propagation of a quantum fluid of light in a cavityless nonlinear optical medium: General theory and response to quantum quenches**
P.-É. Larré, I. Carusotto
(¹INO-CNR BEC and Univ. Trento, Italy), Dec 2014.
arXiv:1412.5405 [cond-mat.quant-gas]

9. **Superfluid flow and vortex nucleation in room temperature, nonlocal photon fluids**
David Vocke,¹ Kali Wilson,¹ Francesco Marino,² Iacopo Carusotto,³ Brian P. Anderson,⁴ Patrik Öhberg,¹ Daniele Faccio¹
(¹Heriot-Watt Univ., Edinburgh, Great Britain; ²Univ. Firenze, Italy; ³INO-CNR BEC and Univ. Trento, Italy; ⁴Univ. Arizona, USA), Nov 2015.

10. **Topological Varma superfluid in optical lattices**
M. Di Liberto,¹,² A. Hemmerich³,⁴,⁵ and C. Morais Smith¹,⁵
(¹Institute for Theoretical Physics, Centre for Extreme Matter and Emergent Phenomena, Utrecht University, Leuvenlaan 4, 3584CE Utrecht, The Netherlands; ²INO-CNR BEC Center and Dipartimento di Fisica, Universita di Trento, 38123 Povo, Italy; ³Institut für Laser-Physik, Universität Hamburg, Luruper Chaussee 149 22761 Hamburg, Germany; ⁴The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany; ⁵Wilczek Quantum Center, Zhejiang University of Technology, Hangzhou 310023, China), Apr 2016.
arXiv:1604.06055 [cond-mat.quant-gas]
11. **Momentum-space Landau levels in arrays of coupled ring resonators**
Hannah M. Price,1 Andrei C. Berceanu,2 Tomoki Ozawa,1 Iacopo Carusotto1
(1 INO-CNR BEC and Univ. Trento, Italy; 2Univ. Autonoma Madrid, Spain), Mar 2016.

12. **Momentum-space Harper-Hofstadter model**
Tomoki Ozawa, Hannah M. Price, Iacopo Carusotto
(1INO-CNR BEC and Univ. Trento, Italy), Nov 2014.
arXiv:1411.1203 [cond-mat.quant-gas]

13. **Quantum Hall effect in momentum space**
Tomoki Ozawa, Hannah M. Price, Iacopo Carusotto,
((INO-CNR BEC and Univ. Trento; Italy)), Feb 2016.
arXiv:1602.07523 [cond-mat.mes-hall]

14. **Synthetic Dimensions for Cold Atoms from Shaking a Harmonic Trap**
Hannah M. Price,1 Tomoki Ozawa,1 Nathan Goldman,2
(1INO-CNR BEC and Univ. Trento, Italy; 2ETH), May 2016.


15. **Four-Dimensional Quantum Hall Effect with Ultracold Atoms**
Hannah M. Price,1 Oded Zilberberg,2 Tomoki Ozawa,1 Iacopo Carusotto,1 Nathan Goldman3
(1INO-CNR BEC and Univ. Trento, Italy; 2ETH; 3Univ. Libre Bruxelles, Belgium), May 2015.
arXiv:1505.04387 [cond-mat.quant-gas]

16. **Towards four-dimensional photonics**
Hannah M. Price,1 Tomoki Ozawa,1 Nathan Goldman,2 Oded Zilberberg,3 Iacopo Carusotto,1
(1Univ. degli Studi di Trento, Italy; 2Univ. Libre de Bruxelles, Belgium; 3ETH Zürich, Switzerland), Mar 2016.

17. **On the measurement of Chern numbers through center-of-mass responses**
H. M. Price,1 O. Zilberberg,2 T. Ozawa,1 I. Carusotto,1 N. Goldman3
(1INO-CNR BEC and Univ. Trento; Italy; 2ETH, Zurich, Switzerland; 3Univ. Libre Bruxelles, Belgium), Feb 2016.
arXiv:1602.01696 [cond-mat.quant-gas]
18. Synthetic dimensions in integrated photonics: From optical isolation to 4D quantum Hall physics*
Tomoki Ozawa,1 Hannah M. Price,1 Nathan Goldman,2 Oded Zilberberg,2 Iacopo Carusotto1
(1INO-CNR BEC and Univ. Trento, Italy; 2ETH; 3Univ. Libre Bruxelles, Belgium), Oct 2015.
arXiv:1510.03910 [cond-mat.mes-hall]

19. Synthetic dimensions with magnetic fields and local interactions in photonic lattices*
Tomoki Ozawa, Iacopo Carusotto
(INO-CNR BEC and Univ. Trento; Italy), Jul 2016.
arXiv:1607.00140 [cond-mat.quant-gas]

20. Casimir forces and quantum friction from Ginzburg radiation in atomic BECs*
Jamir Marino,1,2 Alessio Recati,3,4 Iacopo Carusotto4
(1Institute of Theoretical Physics, TU Dresden, Germany; 2Institute of Theoretical Physics, University of Cologne, Germany; 3Physik Department, TU Muenchen, Garching, Germany, 4INO-CNR BEC and Univ. Trento; Italy), May 2016.

21. Observation of many-body localization of interacting fermions in a quasi-random optical lattice#
M. Schreiber,1,2 S.S. Hodgman,1,2 P. Bordia,1,2 H.P. Lüschen,1,2 M.H. Fischer,3 R. Vosk,3
E. Altman,3 U. Schneider,1,2,4 I. Bloch,1,2
(1LMU München, Germany; 2MPIQ, Garching, Germany; 3Weizmann Inst., Rehovot, Israel; 4Univ. of Cambridge, United Kingdom), Jan 2015.
Science 349: 842, 2015
arXiv:1501.05661 [cond-mat.quant-gas]

22. Emergence of coherence and the dynamics of quantum phase transitions†
S. Braun,1 M. Friesdorf,2 S. S. Hodgman1 M. Schreiber,1 J. P. Ronzheimer,1 A. Riera,2 M.
del Rey,2 I. Bloch,1 J. Eisert,2 U. Schneider,1
(1LMU Munich, Germany; 2FU Berlin, Germany), Mar 2014.
PNAS 112(12): 3641, 2015
arXiv:1403.7199 [cond-mat.quant-gas]

23. Coupling Identical 1D Many-Body Localized Systems†
P. Bordia,1,2 H. P. Lüschen,1,2 S.S. Hodgman,1,2 M. Schreiber,1,2 I. Bloch,1,2 and U.
Schneider1,2,3
(1LMU München, Germany; 2MPIQ, Garching, Germany; 3Univ. of Cambridge, United Kingdom), Sep 2015.
arXiv:1509.00478 [cond-mat.quant-gas]
24. Bloch state tomography using Wilson lines
T. Li, L. Duca, M. Reitter, F. Grusdt, E. Demler, M. Endres, M. Schleier-Smith
I. Bloch and U. Schneider

(1LMU München, Germany; 2MPIQ, Garching, Germany; 3OPTIMAS, Univ. of Kaiserslautern, Germany;
4Grad. School, Mainz, Germany; 5Harvard Univ., Cambridge, USA; 6California Inst., Pasadena, USA;
7Stanford Univ., USA; 8Univ. of Cambridge, United Kingdom), Sep 2015.
Science 352: 1094, 2016

arXiv:1509.02185 [cond-mat.quant-gas]
Both, experimental and theoretical efforts were focused, within a second line of objectives, on working out measures of certification of quantum simulators, aspects of complexity and robustness, as well as exploring the implications of universal properties. The key aim was to find ways how to build trust in quantum simulators. For this, specific analog quantum simulators, including low-dimensional cold gases in lattices and uniform traps, and honeycomb polariton lattices, were certified by comparing observables with available theoretical predictions, up to high-order correlation functions. This helped to build trust for the use of these simulators in extended geometries where no clear theoretical predictions are feasible. An example, where this could be explored are identical experiments on many-body localisation in single and coupled one-dimensional lattice systems.

Much progress was made on the implications of universality for quantum simulators. On the theory side, different avenues have been taken, approaching the scaling properties with analytical field theoretical methods, numerical simulations, and holographic calculations.

General objectives and related achievements.

The key objective relating to the present deliverable was to explore the full potential of the developed platforms for quantum simulation beyond classical reach. An important point was to put forth methods for certification that allow for the rigorous estimation of the devices’ capabilities. Notions of robustness of such quantum dynamical simulators were explored, as well ideas of their computational complexity.

Progress on this line of research has been very successful. Concerning certification, much progress has been made in finding and implementing new concepts as well as in developing specific theoretical settings where mathematically exact results can be determined. In this way, paths could be paved for developing genuine quantum simulators which in certain situations can be benchmarked with theory and then applied in extended situations such as higher-dimensional geometries where no exact theoretical results are possible.

FU Berlin has developed tools for the certification of continuous-variable many-body states, to be used, e.g., for photonic quantum technologies. They have made progress in clarifying conceptual questions concerning the implementation in the experimental platforms considered in the project. In collaboration with TU Wien, quantum field tomography of ultracold atoms on atom chips, in particular for continuous matrix-product states describing the many-body systems implemented on our platforms has been realised. Cold-atom architectures on the basis of optical lattices have been certified in their functioning in collaboration with LMU-MPQ. In addition, photonic and optomechanical architectures were studied.

New certification tools for polariton quantum devices were developed by LPN-CNRS.
main advances, tools to isolate and characterize edge states in driven-dissipative polariton honeycomb lattices were demonstrated. In addition, techniques to force the system to condense in flat bands were demonstrated, which enhances the effect of disorder and interaction effects.

Further key steps towards the implementation of certification tools were the development of control of dimensionality by LMU-MPQ as well as studies of the dynamics of quantum phase transitions, performed in collaboration with LMU-MPQ.

**LMU-MPQ** could successfully deliver on the proposal to perform experiments in different dimensions which except for the geometry can be considered identical. The achieved parameter-free quantitative agreement with tDMRG calculations performed by FU Berlin cross-validates the experimental results and helps to build trust also in the higher-dimensional experimental data where no classical verification is possible. In a second study, by coupling identical many-body localized systems, ergodic dynamics and therefore a quick decay of the initial charge-density wave and break-down of MBL ensues. In both experiments, the higher-dimensional data provides a very strong benchmark for novel theoretical and numerical techniques.

**UHEI** has developed numerical code to evaluate exact results of quantum many-body dynamics for specific one-dimensional systems (for the transverse-field Ising model and – in collaboration with the Davis group at U Queensland – the Lieb-Liniger model), which can serve as benchmark tools for certifying analog quantum simulators. They have, in addition, started comparisons with semi-classical simulations allowing to identify effects of quantum correlations in the measured observables.

**Description of the work carried out**

Progress on this line of research has been very successful in the relevant period, and Deliverable 3.1 has actually been achieved in time in M12. The tools developed are of key importance for the following steps in work on quantum simulators.

The key aim of this work package is to develop tools to build trust in the functioning of a quantum simulator beyond classical capabilities. For this, the mentioned certification tools are an important ingredient [1]. Task 3.1 is specifically important here.

Work has progressed both on conceptual questions and with respect to implementations in the experimental platforms considered in this project. In particular, quantum field tomography of ultracold atoms on top of atom chips has been realised (FUB, TU WIEN) [2], the many-body problem has been assessed via correlation functions in the same architecture [3,4], including its applications for generalised Gibbs ensembles (TU WIEN) [5], cold atomic architectures of cold atoms in optical lattices have been certified in their functioning (LMU, FUB) [6], and photonic and optomechanical architectures have been considered (FUB) [1,7]. Edge states have been directly observed in driven-dissipative polariton honeycomb lattices as well as condensation in flat bands and complex nonlinear hopping phases (LPN-CNRS in collaboration with INO-CNR) [8,9,10], again opening up new certification tools for quantum devices. The relevant works were often of a collaborative nature, reflecting the highly interactive approach taken in this research consortium. The successful coupling of identical 1D many-body localised systems (LMU) demonstrates that key steps of the continuous control of dimensionality have been taken [11], relating to Task 3.2.

Based on this work, further steps on certifying quantum simulators beyond classical reach can be taken. In fact, some of the works already have that flavour, in particular work on the dynamics of quantum phase transitions (LMU, FUB) [6], in which high-dimensional systems out of equilibrium are considered, out of reach for classical computers.
Publications:

The superscript symbols behind the titles indicate the association of the respective publication with the project:

* Work done within the AQuS project (partly co-funded from other sources).
# Work performed before the start of AQuS, towards the objectives of the project, and in general, completed after the submission of the proposal
+ Work not funded directly by AQuS but done in collaborations towards the objectives of AQuS, or before the submission of the proposal

1. **Reliable quantum certification for photonic quantum technologies**#
   L. Aolita,¹ C. Gogolin,¹ M. Kliesch,¹ J. Eisert,¹
   (¹FU Berlin, Germany), Jul 2014.
   *Nature Comm., 6: 8498, 2015*

2. **Towards experimental quantum field tomography with ultracold atoms**#
   A. Steffens,¹ M. Friesdorf,¹ T. Langen,² B. Rauer,² T. Schweigler,² R. Huebener,¹
   J. Schmiedmayer,² C. Riofrio,¹ J. Eisert,¹
   (¹FU Berlin, Germany; ²Vienna, Austria), Jun 2014.
   *Nature Comm., 6: 7663, 2015*

3. **On solving the quantum many-body problem***
   T. Schweigler,¹ V. Kasper,² S. Erne,¹,² B. Rauer,¹ T. Langen,¹ T. Gasenzer,³ J. Berges,²
   J. Schmiedmayer,¹
   (¹Atominstitut, TU Wien, Austria; ²ITP, Univ. of Heidelberg, Germany; ³KIP, Univ. of Heidelberg, Germany), May 2015.
   Accepted for publication in *Nature*, 2017
   arXiv:1505.03126 [cond-mat.quant-gas]

4. **Continuous matrix product state tomography of quantum transport experiments***
   G. Haack,¹ A. Steffens,² J. Eisert,² R. Huebener,²
   (¹Geneva, Switzerland; ²FU Berlin, Germany), Apr 2015.

5. **Experimental Observation of a Generalized Gibbs Ensemble***
   T. Langen,¹ S. Erne,¹,² R. Geiger,¹ B. Rauer,¹ T. Schweigler,¹ M. Kuhnert,¹ W. Rohringer,¹
   I.E. Mazets,¹,4,5 T. Gasenzer,²,³ J. Schmiedmayer,¹
   (¹Atominstitut, TU Wien, Austria; ²ITP, Univ. of Heidelberg, Germany; ³KIP, Univ. of Heidelberg, Germany; ⁴Wolfgang Pauli Institute, Vienna, Austria; ⁵Ioffe Physico-Technical Institute, St. Petersburg, Russia), Nov 2014.
   *Science 348: 207-21, 2014*
   arXiv:1411.7185 [cond-mat.quant-gas]
6.  **Emergence of coherence and the dynamics of quantum phase transitions**
   S. Braun,¹ M. Friesdorf,² S. S. Hodgman¹ M. Schreiber,¹ J. P. Ronzheimer,¹ A. Riera,² M. del Rey,² I. Bloch,¹ J. Eisert,² U. Schneider,¹ (¹LMU Munich, Germany; ²FU Berlin, Germany), Mar 2014.
   **PNAS 112(12): 3641**, 2015
   arXiv:1403.7199 [cond-mat.quant-gas]

7.  **Observation of non-Markovian micro-mechanical Brownian motion**
   S. Groeblacher,¹ A. Trubarov,² N. Prigge,² G. D. Cole,¹ M. Aspelmeyer,¹ J. Eisert,² (¹Vienna, Austria; ²FU Berlin, Germany), May 2013.
   **Nature Comm. 6: 7606**, 2015

8.  **Edge states in polariton honeycomb lattices**
   M. Milicevic,¹ T. Ozawa,² P. Andreakou,¹ I. Carusotto,² T. Jacqmin,¹ E. Galopin,¹ A. Lemaître,¹ L. Le Gratiet,¹ I. Sagnes,¹ J. Bloch,¹ and A. Amo ¹
   (¹LPN/CNRS, Marcoussis, France; ²INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, Povo, Italy ), Aug 2015.
   **2D Mater 2: 034012**, 2015
   arXiv:1504.05761 [cond-mat.mes-hall]

9.  **Bosonic Condensation and Disorder-Induced Localization in a Flat Band**
   F. Baboux,¹ L. Ge,²,³ T. Jacqmin,¹ M. Biondi,⁴ E. Galopin,¹ A. Lemaître,¹ L. Le Gratiet,¹ I. Sagnes,¹ S. Schmidt,⁴ H. E. Türeci,⁵ A. Amo,¹ and J. Bloch¹,⁶
   (¹LPN/CNRS, Marcoussis, France; ²Department of Engineering Science and Physics, CUNY, New York, USA; ³The Graduate Center, CUNY, New York, USA; ⁴ETH Zurich, Switzerland; ⁵Princeton University, New Jersey, USA; ⁶Université Paris-Saclay, Palaiseau Cedex, France), Feb 2016.
   arXiv:1505.05652 [cond-mat.mes-hall]

10. **Interaction-induced hopping phase in driven-dissipative coupled photonic microcavities**
    S.R.K. Rodriguez,¹ A. Amo,¹ I. Sagnes,¹ L. Le Gratiet,¹ E. Galopin,¹ A. Lemaître,¹ and J. Bloch¹,²
    (¹LPN/CNRS, Marcoussis, France; ²Ecole Polytechnique, Palaiseau, France), Feb 2016
    arXiv:1602.07114 [physics.optics]

11. **Coupling Identical 1D Many-Body Localized Systems**
    P. Bordia,¹,² H. P. Lüschen,¹,² S.S. Hodgman,¹,² M. Schreiber,¹,² I. Bloch,¹,² and U. Schneider¹,²,³
    (¹LMU München, Germany; ²MPIQ, Garching, Germany; ³Univ. of Cambridge, United Kingdom), Sep 2015.
    arXiv:1509.00478 [cond-mat.quant-gas]
First report on universality classification and implementation procedures

In the center of attention are the implications of universal properties for quantum simulators. Indeed, specifically notions of universality in non-equilibrium evolution promise to significantly enhance the applicability of analogue quantum simulators. The deliverable is concerned with a first report providing evidence for this enhancement.

Indeed, this potential could convincingly be fleshed out. In the focus of attention was the observation of scaling in the dynamics of a strongly quenched quantum gas [1], the identification of a non-thermal fixed point in a holographic superfluid [2], and the anomalous scaling at non-thermal fixed points of Burgers' and Gross-Pitaevskii turbulence, concerned with universal dynamics in open systems such as realised with polariton condensates [3] (UHEI). This work was complemented by other work on non-equilibrium dynamics that considers scaling laws (FUB). Steps have been undertaken to develop understanding of integrable long-time dynamics for models where exact computations are possible [5].

This initial work invites further studies, in particular in cold atomic and polaritonic architectures and platforms for quantum simulations. These ramifications will be explored. In summary, the central goals concerning the present deliverable were perfectly well fulfilled in time by M12.

In the experiment [1], we demonstrated the experimental ability to detect scaling and measure scaling exponents of, in this case, correlation lengths and times scaling in the dimensionless tuning parameter measuring the distance to the critical point. The experiment formed a first step towards further developments we are presently implementing and testing in spinor Bose gases. In [1] we moreover reported on our theoretical results that for quenches only a little closer to the critical point than so far implemented, the experiment should be able to access non-perturbative universal crossover behaviour reminiscent of Ising-type dynamics.

In [2], we presented a first study of non-thermal fixed points and universal dynamics of a relativistic field model within the AdS-CFT duality framework. We were able to evaluate the complex Einstein field equations numerically and demonstrate the emergence of turbulent excitations at the surface of the AdS bulk space. These excitations were shown to be related to non-thermal fixed point scaling similarly as in a pure field-theoretic calculation done before [e.g. B. Nowak et al., Phys. Rev. A 85: 043627, 2012]. This AdS-CFT analysis has supplied us with expertise and numerical code to be developed further to include (a) back-action of the black-hole horizon into the bulk, to take into account the influence of the thermal-like component of the system (b) use the duality relation to develop a dual quantum simulator of gravity models.

In [3] we developed a first approach to non-thermal fixed points and universality in non-equilibrium evolution which is based on functional renormalisation group methods. We concentrated on the Burgers and Kardar-Parisi-Zhang models and found scaling relations which allowed to make predictions on universal scaling laws of Gross-Pitaevskii sound-wave turbulence. This is of importance for the development of the theory of universal dynamics of open and driven-dissipative systems such as the polariton-based systems developed in the LPN-CNRS labs. We have extended these studies, including extensive simulations, to exhibit the role of dissipative forces as compared
to forces originating from the direct interaction of non-linear defect-type excitations (solitons, vortices) of the field. The results are prepared for publication at present.

For [5] we have further developed, in collaboration with the group of Matt Davis, Queensland, numerical techniques to compute the long-time evolution and equilibration of the one-dimensional Bose gas with contact interactions. This will be of importance within our aims to develop benchmark techniques on the basis of exactly solvable models. Its results are most interesting in view of the question to what extent 1D quantum gases can be observed to thermalise instead of approaching non-thermal states characterized by Generalized Gibbs Ensembles, see also Task 4.2.

Publications:

1. **Observation of scaling in the dynamics of a strongly quenched quantum gas**
   E. Nicklas,1 M. Karl,1 M. Höfer,1 A. Johnson,2 W. Muessel,1 H. Strobel,1 J. Tomkovic,1 T. Gasenzer,1 and M. K. Oberthaler1
   (1KIP, Univ. of Heidelberg, Germany; 2Laboratoire Charles-Fabry, Palaiseau, France), Sep 2015.
   arXiv:1509.02173 [cond-mat.quant-gas]

2. **Non-Thermal Fixed Point in a Holographic Superfluid**
   C. Ewerz, T. Gasenzer, M. Karl, and A. Samberg
   (1ITP & KIP, Univ. of Heidelberg, Germany and EMMI Darmstadt, Germany), Oct 2014.
   *JHEP* **05**: 070, 2014

3. **Anomalous scaling at non-thermal fixed points of Burgers' and Gross-Pitaevskii turbulence**
   S. Mathey, T. Gasenzer, and J.M. Pawlowski
   (1ITP and CQD, Univ. of Heidelberg, Germany and EMMI Darmstadt, Germany), May 2014.

4. **Quantum many-body systems out of equilibrium**
   J. Eisert,1 M. Friesdorf,1 C. Gogolin2
   (1FU Berlin, Germany; 2ICFO, Spain), Feb 2014.

5. **A coordinate Bethe ansatz approach to the calculation of equilibrium and nonequilibrium correlations of the one-dimensional Bose gas**
   J. C. Zill,1 T. M. Wright,1 K. V. Kheruntsyan,1 T. Gasenzer,2,3 and M. J. Davis1,4
   (1U Queensland, Brisbane, Australia; 2KIP, Univ. of Heidelberg, Germany; 3EMMI Darmstadt, Germany; 4JILA, UC Boulder, U.S.A.), Apr 2016.
   arXiv:1601.00434 [cond-mat.quant-gas]
Motivated by the current strong interest in disordered systems, both LMU-MPQ and FU Berlin have focussed their plans on strongly correlated transport and long-time evolutions of quantum systems after a quantum quench primarily around the dynamics in the presence of disorder. LMU-MPQ could for the first time experimentally demonstrate the existence of Many-Body Localized states (MBL), where the presence of disorder breaks ergodicity and gives rise to localized states even in the presence of interactions [1,2]. Drawing heavily on abilities developed in WP2, they could observe the evolution of an initial charge density wave (CDW) and demonstrate that, despite the Hamiltonian not distinguishing between even and odd sites, parts of the initial CDW order persist for long times in the presence of strong interactions, thereby directly signalling non-ergodic behaviour [1]. By using the technique of dimensional crossovers, LMU-MPQ could further demonstrate that even in the nominally 1D case the residual, exponentially suppressed tunnel coupling between the 1D systems is the dominant decay channel [2].

Motivated by joint discussions, FU Berlin could establish a novel link between quantum information theory and notions of condensed matter. They demonstrated that the existence of local constants of motion, often taken as the defining property of MBL, together with a generic spectrum, is sufficient to rigorously prove information propagation [3]: These systems can be used to send a signal over arbitrary distances, in that the impact of a local perturbation can be detected arbitrarily far away. Furthermore, and again inspired by experimental work by LMU-MPQ, they analysed additional experimentally accessible witnesses that directly probe distinct features of MBL [4], distinguishing it from its Anderson counterpart, and are of direct relevance for the ongoing work at LMU-MPQ. The witnesses constructed build upon a body of recent theory work performed at the FU Berlin, but are constructed in a way that they make use of information only that is obtainable from measurements available with present technology. For example, while the scaling of entanglement entropies in time may be characteristic for MBL logarithmic in time, such entanglement entropies are not accessible for large system sizes. One ingredient in the proposed witnesses are density-density-correlators from parity of particle number measurements, which are seen to carry comparable characteristic information. These discoveries open the doors to study novel quantum long-time dynamics, since the typical long-time cut-off for quantum behaviour due to thermalization is absent in an ideal MBL system.

In an independent experiment, LMU-MPQ could also demonstrate another hallmark of non-thermaling many-body dynamics following a quantum quench, namely the emergence of non-ground-state coherence in a melting Mott insulator of 1D hard-core bosons [5], thereby demonstrating ballistic transport in a strongly interacting system. This study combined the use of in-situ and time-of-flight imaging in order to capture the full dynamics of the quantum gas.

The physics of information propagation within a strongly correlated many-body system was also a central part in another joined work between FU Berlin and LMU-MPQ, where the emergence of coherence during slow quenches through a quantum phase transition was studied [6]. The observed dynamics goes both beyond the picture of free quasiparticles and is distinct from the scaling (or Kibble-Zurek) regime expected for very slow ramps, and demonstrates the ability to reveal the full
complexity of the studied models. In 1D, the dynamics observed experimentally at LMU-MPQ agrees quantitatively with essentially exact matrix-product simulations performed at FU Berlin, thereby cross-validating both approaches. It is key to this experiment that it can be viewed as a significant step towards a fully-fledged quantum simulator. For 1D systems, the functioning of the experiment to capture the dynamics of quantum phase transitions can be efficiently benchmarked using tensor network methods (or exact diagonalization for small systems), confirming all predictions made. Yet, the experiment is very similar also in higher dimensions, when no known sufficiently accurate efficient classical simulation method is available for this type of problem. In this sense, one can view the higher dimensional system as performing a quantum simulation that outperforms classical simulations on supercomputers.

Publications:

1. **Coupling Identical 1D Many-Body Localized Systems**
   (°LMU München, Germany; ¨MPIQ, Garching, Germany; †Univ. of Cambridge, United Kingdom), Sep 2016.
   *Phys. Rev. Lett.* **116:** 140401, 2016
   arXiv:1509.00478 [cond-mat.quant-gas]

2. **Observation of many-body localization of interacting fermions in a quasi-random optical lattice**
   M. Schreiber,° S.S. Hodgman,° P. Bordia,° H.P. Lüschen,° M.H. Fischer,³ R. Vosk,³ E. Altman,³ U. Schneider,° I. Bloch,°
   (°LMU München, Germany; ¨MPIQ, Garching, Germany; †Weizmann Inst., Rehovot, Israel; ‡Univ. of Cambridge, United Kingdom), Jan 2015.
   *Science* **349:** 842, 2015
   arXiv:1501.05661 [cond-mat.quant-gas]

3. **Local constants of motion imply information propagation**
   M. Friesdorf,¹ A. H. Werner,¹ M. Goihl,¹ J. Eisert,¹ W. Brown,¹
   (¹FU Berlin, Germany), November 2015.

4. **Experimentally accessible witnesses of many-body localisation**
   M. Goihl,¹ M. Friesdorf,¹ A. H. Werner,¹ W. Brown,¹ J. Eisert,¹
   (¹FU Berlin, Germany), January 2016.

5. **Dynamical Quasicondensation of Hard-Core Bosons at Finite Momenta**
   L. Vidmar,¹ J.P. Ronzheimer,² M. Schreiber,² S.S. Hodgman,² F. Heidrich-Meisner,¹ I. Bloch,² and U. Schneider²,⁵
   (¹ASC, LMU München, Germany; ¦Dep. of Physics, LMU München, Germany; ²MPIQ, Garching, Germany; ³Univ. of Pittsburgh, USA; ⁵Univ. of Cambridge, United Kingdom), Oct 2015.
   *Phys. Rev. Lett.* **115:** 175301, 2015
   arXiv:1505.05150 [cond-mat.quant-gas]
6. **Emergence of coherence and the dynamics of quantum phase transitions**
   S. Braun,¹ M. Friesdorf,² S. S. Hodgman ¹ M. Schreiber,¹ J. P. Ronzheimer,¹ A. Riera,² M. del Rey,² I. Bloch,¹ J. Eisert,² U. Schneider,¹
   (¹LMU Munich, Germany; ²FU Berlin, Germany), Feb 2015.
   *PNAS 112(12): 3641*, 2015
   arXiv:1403.7199 [cond-mat.quant-gas]

7. **Equilibration via Gaussification in fermionic lattice systems**
   M. Gluza,¹ C. Krumnow,¹ M. Friesdorf,¹ C. Gogolin,² J. Eisert,¹
   (¹FU Berlin, Germany; ²ICFO, Spain), January 2016.

8. **Diagnosing topological edge states via entanglement monogamy**
   K. Mechanetzidis,¹ J. Eisert,² M. Cirio,³ C. Lahtinen,² J. Pachos,¹
   (¹Leeds, UK; ¹FU Berlin, Germany; RIKEN, Japan), November 2015.

9. **Continuous matrix product state tomography of quantum transport experiments**
   G. Haack,¹ A. Steffens,² J. Eisert,² R. Huebener,²
   (¹Geneva, Switzerland; ²FU Berlin, Germany), April 2015.
INO-CNR has made progress in the study of quantum simulators of quantum field theories in configurations of interest for gravitational and high-energy physics, in particular Hawking emission effects from analog black holes as well as Casimir and Ginzburg effects in the presence of quantum emitters interacting with the quantum field. INO-CNR's study of analog Hawking radiation is now being extended to the case of two-component Bose gases, which accurately models experiments at UHEI and TU Wien. Quite remarkably, we anticipate that theory developed to describe polariton fluids under a frequency-dependent pumping developed as Task 2.1-MS7 may be used to theoretically understand some unexpected features of atom cooling experiments at TU Wien.

The INO-CNR activity on quantum simulation of systems of gravitational and cosmological interest has addressed both the atomic and the polaritonic cases. On the atomic side, a strong effort has been devoted by INO-CNR to the study of the so-called black hole lasing phenomenon corresponding to a dynamical instability in a two-horizon system when an inner white hole horizon is associated to an external black hole one. While the importance of this configuration from the gravity point of view is mostly speculative, it is nowadays central in the experimental study of analog models. An experiment at Technion claiming observation of such black hole laser instability [J. Steinhauer, Nature Phys. 10, 864 (2014)] has triggered a lot of theoretical questions, first on the long-time fate of the pair of horizons, then on the actual interpretation of the experimental data. The former issue was investigated in [1]: depending on the system parameters, the system can either evaporate away the horizons restoring a fully sub-sonic configuration, or it can reach a periodically oscillating steady-state in which a regular train of solitons keeps being emitted. Based on this analysis, we have exploited the analogy with standard lasing to give a more precise definition of black hole lasing. To this purpose, the combined experience of INO-CNR in both optics and analog models turned out to be crucial.

The second issue was tackled in the numerical work [2]: while the original interpretation of the author is fully confirmed by our study, our simulations also allowed us to familiarize ourselves with the experimental set-up. This is of great utility in view of the more challenging study of the following experiment which claimed observation of spontaneous quantum Hawking radiation [J. Steinhauer, arXiv:1510.00621]. In particular this last experiment is interfering in a significant way with the original research plans of the AQuS project: on one hand this work has of course spoiled any scientific priority by the AQuS consortium, on the other hand we expect it will revive the international interest on analog models. In this respect, the on-going activity of INO-CNR is to investigate the Hawking phenomena in the novel configuration of a two-component Bose gas: such a configuration is a good model for the spinor condensate of UHEI and for the coupled gases of TU Wien and is therefore of great relevance for the AQuS consortium. A first manuscript in this direction is in the course of being written.

From the polariton side, we have proceeded with a detailed theoretical analysis of acoustic black holes in the fluid configurations under investigation at LPN-CNRS described in H. S. Nguyen, et al., Phys. Rev. Lett. 114, 036402 (2015). The main outcome of this activity is work [3], performed by the INO-CNR post-doc Pjotrs Grisins in collaboration with our LPN-CNRS colleagues. Here we
reported s theoretical Gross-Pitaevskii calculations showing the possibility of observing stimulated Hawking radiation in a pump-and-probe set-up and then truncated Wigner calculations providing a complete understanding of the quantum fluctuation effects and the resulting density correlation functions.

On the experimental side, LPN-CNRS has realised a configuration involving two counterpropagating fluids, which could lead to the formation of successive acoustic horizons for the polariton fluid [4]. First results show the formation of soliton trains and a novel kind of bistability controlled by the phase of the injected fluid.

To assess the feasibility of building holographic quantum simulators for quantum gravity, based on AdS/CFT dualities, we started by performing a detailed numerical analysis of a holographic model for the dynamics of a 2D superfluid. The main results of this activity are reported in [5]. Here we find that the late-time dynamic properties of the holographic model display the same universal features, in terms of dynamic scaling behaviour and vortex dynamics, as conventional models for superfluid Bose gases, such as the Gross-Pitaevskii model. In the course of the activity leading to work [5], we developed a highly efficient and versatile numerical toolkit for simulating the dynamics of a variety of holographic models. Using this toolkit, we have taken first steps in developing holographic-dual models specifically adapted to the 1D systems of the UHEI/TU Wien platforms.

Publications:

1. **Time-dependent study of a black-hole laser in a flowing atomic condensate**
   J. R. M. de Nova, 1 S. Finazzi, 2 I. Carusotto 2
   (1Univ. Complutense, Madrid, Spain; 2INO-CNR BEC and Univ. Trento, Italy), Sep 2015.

2. **Numerical study of a recent black hole lasing experiment**
   M. Tettamanti, 1 S. L. Cacciatori, 1, 2 A. Parola, 1 I. Carusotto 3
   (1Dipartimento di Scienze e Alta Tecnologia, Universita' dell'Insubria, Como, Italy, 2INFN, Milano, Italy, 3INO-CNR BEC and Univ. Trento; Italy), Mar 2016.
   arXiv:1603.04702 [cond-mat.quant-gas]

3. **Theoretical study of stimulated and spontaneous Hawking effects from an acoustic black hole in a hydrodynamically flowing fluid of light**
   Pjotrs Grisins, 1, 2 Hai Son Nguyen, 3 Jacqueline Bloch, 4, 5 Alberto Amo, 4 Iacopo Carusotto 2
   (1DQMP, University of Geneva, Switzerland; 2INO-CNR BEC Center and Universita' di Trento, Povo, Italy; 3Institut des Nanotechnologies de Lyon, Ecully, France; 4Centre de Nanosciences et de Nanotechnologies, CNRS, Univ. Paris-Sud, Universite' Paris-Saclay, Marcoussis, France; 5Physics Department, Ecole Polytechnique, Palaiseau, France), Jun 2016.
   arXiv:1606.02272 [cond-mat.quant-gas]
4. **Phase-controlled bistability of a dark soliton train in a polariton fluid**
   Valentin Goblot, Hai Son Nguyen, Iacopo Carusotto, Elisabeth Galopin, Aristide Lemaître, Isabelle Sagnes, Alberto Amo, Jacqueline Bloch
   (Centre de Nanosciences et de Nanotechnologies, CNRS, Univ. Paris-Sud, Universite' Paris-Saclay, Marcoussis, France; Institut des Nanotechnologies de Lyon, Ecully, France; INO-CNR BEC Center and Universita' di Trento, Povo, Italy; Physics Department, Ecole Polytechnique, Palaiseau, France), Jul 2016.
   arXiv:1607.03711 [cond-mat.quant-gas]

5. **Non-Thermal Fixed Point in a Holographic Superfluid**
   C. Ewerz, T. Gasenzer, M. Karl, and A. Samberg
   (ITP & KIP, Univ. of Heidelberg, Germany and EMMI Darmstadt, Germany), Oct 2014.
   **JHEP 05: 070, 2014**