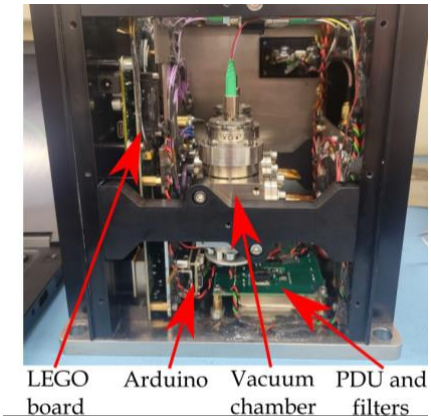
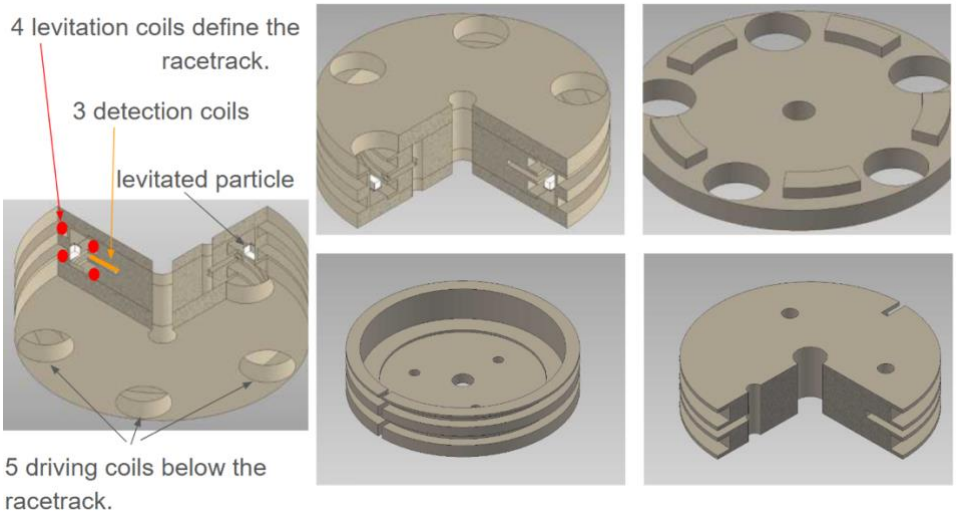
**NEWSLETTER N.6, September 2024**




*OptToSpace payload made by the University of Southampton*




*Second-Generation Gravity Generator in Leiden*

## Summary

## Update of work done

In the past six months, the Trieste group has advanced the theoretical exploration of gravity at the quantum–classical boundary. One line of work shows that if gravity is fundamentally classical and local, its interaction with quantum matter must inevitably produce random diffusion in the motion of probes. This prediction opens up the possibility of detecting gravity-induced diffusion even with classical systems, shifting the focus from highly challenging quantum superpositions to more accessible macroscopic experiments. The formalism leads to precise bounds on the diffusion coefficients required to suppress entanglement, which can be tested in upcoming optomechanical setups. In parallel, the group investigated the Schrödinger–Newton equation, a nonlinear modification of quantum dynamics that embodies a self-consistent classical gravitational potential. While the equation raises concerns of superluminal signalling, it provides a rare testable alternative to quantized gravity. It was demonstrated that by modulating the trapping frequency in levitated mechanical systems, the tiny deviations predicted by the Schrödinger–Newton dynamics can be amplified. This frequency-modulation protocol enhances the detectability of the effect by several orders of magnitude. The analysis shows that state-of-the-art levitated magnetomechanical platforms already provide the conditions needed for such tests. Together, these results chart concrete experimental strategies to probe whether gravity must be quantized or can consistently remain classical.

The Tübingen group continued theoretical work towards coherent superpositions of massive nano-oscillators by using the angular degree of freedom. We looked in detail into the relevant decoherence mechanisms, including gas scattering, photon scattering, eddy currents, resistance losses, and measurement-induced decoherence. We are currently writing the results up in a paper. In parallel we continued our work on finding a measure of quantumness of sources of gravity. We first investigated quantum fluctuations of the total energy for a scalar quantum field theory for different types of states, notably Schrödinger cat states in different bases. Currently we are generalizing this to studying quantum fluctuations of energy density for the same kinds of states.

The QUB/Palermo team addressed the non-equilibrium thermodynamic behavior of various formulations of quantum Brownian motion (QBM) using the framework of stochastic thermodynamics. While the widely used Caldeira-Leggett master equation exhibits desirable thermodynamic features, such as the fulfilment of a detailed balance, it fails to ensure complete positivity. In contrast, several completely positive and trace-preserving (CPTP) extensions turn out to be thermodynamically controversial. The team has shown that such extensions introduce anomalous phase-space structures that violate detailed balance at the steady state,

leading to non-vanishing entropy production and effective non-equilibrium current of unclear physical origins. These results highlight a fundamental tension between quantum consistency and thermodynamic equilibration in open quantum systems that will have to be resolved when addressing open-system dynamics.

As a follow-up to the seminal thought-experiment for a spin-based test of quantumness of gravity, the QUB/Palermo team was part of a consortium proposing an experiment to test the quantum nature of gravity by checking whether gravity can entangle two micron-sized crystals. A pathway to this is to create macroscopic quantum superpositions of each crystal first using embedded spins and Stern-Gerlach forces. These crystals could be nanodiamonds containing nitrogen-vacancy (NV) centres. The spins can subsequently be measured to witness the gravitationally generated entanglement. This is based on extensive theoretical feasibility studies and experimental progress in quantum technology. The eventual experiment will require a medium-sized consortium with excellent suppression of decoherence including vibrations and gravitational noise. The team was involved in the preparation of a white paper laying down the progress and plans towards realizing this platform.

## Mauro Paternostro has been inducted in the Royal Irish Society

Membership of the Academy is the highest academic honour in Ireland. The RIA currently has approximately 680 members (including 98 Honorary Members), who are elected in recognition of their academic achievements. Paternostro's recognised work in quantum control of large-scale systems has helped unlock development in the field of quantum optomechanics. A theoretical driving force behind ground-breaking experimental efforts, he has trained a generation of scientists pushing the boundaries of the field

## Southapmton's OptToSpace demonstrates levitated mechanics in space

On 23 June 2025, The Exploration Company's Mission Possible capsule flew with 25 hosted payloads (300 kg), validating major systems before re-entry. The University of Southampton's OpToSpace experiment, built by Prof. Hendrik Ulbricht's team, was among the payloads. It tested levitated mechanics in space by trapping and controlling nanoparticles with optical and magnetic techniques. Despite a communications loss during descent, the flight returned valuable data from

the space environment. The project builds on Southampton's ESA Payload Masters win that secured the flight opportunity.

### Second-Generation Gravity Sensors Completed in Leiden

In order to detect the gravitational acceleration that is produced by a small particle at the frequencies where our gravitational sensor is at its most sensitive, the particle that produces the gravity needs to make a periodic motion with an amplitude of 1 or 2 centimetres.

In September 2025 we have completed the design and assembly of the second version of our gravity generator, an important milestone in our project. It consists of four coils that together generate a magnetic field configuration that can levitate a piece of superconductor and let it move on a circular trajectory together. In addition, it includes five drive coils to drive the particle around and three detection coils to monitor the particles motion. The system is optimized for a source mass of 0.1-100milligram.

### Publications

| Authors | Title | Journal | Volume | Page | Year |
|---|---|---|---|---|---|
| Pi, Hailong; Sun, Chuang; Kiang, Kian Shen; Georgescu, Tiberius; Ou, Bruce Jun-Yu; Ulbricht, Hendrik; Yan, Jize | Levitation and controlled MHz rotation of a nanofabricated rod by a high-NA metalens | Microsyst Nanoeng | 11 | 2055 | 2025 |
| Homans, Jack; Simcox, Elliot; Wardak, Jakub; da Palma Barbara, Laura; Fuchs, Tim M.; Mufato, Rafael; Concepcion, Florence; Dragomir, Andrei; Vogt, Christian; Nisbet-Jones, Peter; Bridges, Christopher; Ulbricht, Hendrik | An experimental platform for levitated mechanics in space | Quantum Sci. Technol. | 10 | 2058 | 2025 |
| Gundhi, Anirudh; Ulbricht, Hendrik | Measuring Decoherence Due to Quantum Vacuum Fluctuations | Phys. Rev. Lett. | 135 | 1079 | 2025 |
| Piccione, Nicolò; Bassi, Angelo | Exploring the effects of mass dependence in | Phys. Rev. A | 112 | 2469 | 2025 |

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| | spontaneous collapse models | | | | |
| Amaral, Dorian W. P.; Uitenbroek, Dennis G.; Oosterkamp, Tjerk H.; Tunnell, Christopher D. | First Search for Ultralight Dark Matter Using a Magnetically Levitated Particle | Phys. Rev. Lett. | 134 | 1079 | 2025 |
| Pfeifer, Christian; Rätzel, Dennis; Braun, Daniel | Gravitational attraction of ultrarelativistic matter: A new testbed for modified gravity at the Large Hadron Collider | Phys. Rev. D | 111 | 2470 | 2025 |
| Ahrens, Felix; Ji, Wei; Budker, Dmitry; Timberlake, Chris; Ulbricht, Hendrik; Vinante, Andrea | Levitated Ferromagnetic Magnetometer with Energy Resolution Well Below $\hbar$ | Phys. Rev. Lett. | 134 | 1079 | 2025 |
| Muffato, R.; Georgescu, T. S.; Homans, J.; Guerreiro, T.; Wu, Q.; Chisholm, D. A.; Carlesso, M.; Paternostro, M.; Ulbricht, H. | Generation of classical non-Gaussian states by squeezing a thermal state into nonlinear motion of levitated optomechanics | Phys. Rev. Research | 7 | 2643 | 2025 |
| Altamura, Davide Giordano Ario; Vinante, Andrea; Carlesso, Matteo | Improved bounds on collapse models from rotational noise of the Laser Interferometer Space Antenna Pathfinder mission | Phys. Rev. A | 111 | 2469 | 2025 |
| Bose, Sougato; Fuentes, Ivette; Geraci, Andrew A.; Khan, Saba Mehsar; Qvarfort, Sofia; Rademacher, Markus; Rashid, Muddassar; Toroš, Marko; Ulbricht, Hendrik; Wanjura, Clara C. | Massive quantum systems as interfaces of quantum mechanics and gravity | Rev. Mod. Phys. | 97 | 1539 | 2025 |
| Crognaletti, Giulio; Bartolomeo, Giovanni Di; Vischi, Michele; Viteritti, Luciano Loris | Equivariant Variational Quantum Eigensolver to detect phase transitions through energy level crossings | Quantum Sci. Technol. | 10 | 2058 | 2025 |

## Dissemination activities

In the last 6 months, QuCoM members delivered the following seminars and talks:

Collapse Models
Event: School of Quantum Foundations: Speakable and Unspeakable. Speaker: Angelo Bassi. Place: MEDILS, University of Split (Croatia). Date: 22 August 2025

Introduction to Optomechanics
Event: School of Quantum Foundations: Speakable and Unspeakable. Speaker: Matteo Carlesso. Place: MEDILS, University of Split (Croatia). Date: 19 August 2025

Combatting vibrations at ultra low temperatures: challenges and possibilities
Event: Ultra low temperature conference. Speaker: Tjerk Oosterkamp. Place: Lancaster University, Lancaster. Date: 18 August 2025

Metafisica sperimentale: il caso delle disuguaglianze di Bell
Event: ScienzaNuova 2025 Speaker: Angelo Bassi Place: Akademie Meran, Merano (Italy) Date: 22 July 2025

Creation of a Black Hole Bomb instability in an electromagnetic system
Event: Workshop: A look at the interface between gravity and quantum theory. Speaker: Marion Cromb. Place: San Vito di Cadore , Italy. Date: 24 July 2025

Measuring the gravitational near-field of the LHC beam
Event: Physics beyond collider seminar series. Speaker: Daniel Braun. Place: CERN, Geneva. Date: 15 July 2025

Creation of a Black Hole Bomb instability in an electromagnetic system
Event: Conference: GR24 & Amaldi16. Speaker: Marion Cromb. Place: Scottish Exhibition Center, Glasgow, UK. Date: 14 July 2025

Causal influence in QM
Event: RQI North 2025. Speaker: Daniel Braun. Place: University of Napoli. Date: 27 June 2025

Probing Quantum Collapse with Rotational Dynamics
Event: 15th annual conference on Relativistic Quantum Information (North). Speaker: Davide Giordano Ario Altamura. Place: Università degli studi Federico II Napoli. Date: 23 June 2025

Levitated Mechanical Detectors of Dark Matter
Event: School Fundamental Problems in Quantum Physics 2025. Speaker: Hendrik Ulbricht. Place: Trieste, Italy. Date: 18 June 2025

About the operational distinction of different unravelings
Event: Fundamental Problems in Quantum Physics 2025. Speaker: José Luis Gaona Reyes. Place: University of Trieste. Date: 18 June 2025

Are There Quantum Jumps?
Event: 100 Years of Quantum Mechanics. Speaker: Angelo Bassi. Place: Helgoland (Germany). Date: 10 June 2025

Bell's inequality
Event: invited seminar. Speaker: Angelo Bassi. Place: University of Trieste. Date: 26 May 2025

Levitated Mechanical Detectors of Dark Matter
Event: Round Table Workshop on New Avenues in Particle Cosmology. Speaker: Hendrik Ulbricht. Place: Winchester, UK. Date: 21 May 2025

Ways to test the quantum nature of gravity
Event: Quantum 2025. Speaker: Angelo Bassi. Place: Torino. Date: 21 May 2025

Testing Quantum Mechanics in Space
Event: ZARM Workshop on Quantum Systems in Free Fall. Speaker: Tim Fuchs & Jack Homans & Hendrik Ulbricht. Place: University of Bremen, Germany. Date: 8 May 2025

Cryogenic magnetic levitation for future gravity experiments using small source masses
Event: QuCoM meeting Palermo. Speaker: Dennis Uitenbroek. Place: University of Palermo, Italy. Date: 07 May 2025

Measuring decoherence due to quantum vacuum fluctuations
Event: QuCoM meeting. Speaker: Anirudh Gundhi. Place: University of Palermo. Date: 07 May 2025

Nanoparticle Interferometer and State Expansion
Event: QuCoM Palermo meeting. Speaker: Jakub Wardak. Place: University of Palermo, Italy. Date: 6 May 2025

State expansion and State Preparation using Non-linearities in Levitated Mechanics
Event: QuCoM Palermo meeting. Speaker: Rafael Muffato. Place: University of Palermo, Italy. Date: 6 May 2025

Classical Gravity can entangle quantum systems
Event: QuCoM meeting. Speaker: Matteo Carlesso. Place: University of Palermo. Date: 06 May 2025

Levitated Mechanics Experiments for Fundamental Physics in Lab and in Space
Event: QuCoM Palermo meeting. Speaker: Hendrik Ulbricht. Place: University of Palermo, Italy. Date: 5 May 2025

Developments and flight opportunities for levitated mechanics payloads
Event: ESA workshop on Fundamental Physics in Space. Speaker: Hendrik Ulbricht. Place: ESTEC, Noordwijk, The Netherlands. Date: 29 April 2025

100 Years of Quantum Mechanics
Event: INSPYRE 2025. Speaker: Angelo Bassi. Place: LNF-INFN Frascati. Date: 7 April 2025

Moreover, in the frame of QuCoM activities, the following workshop and seminars were organized:

1. **A look at the interface between gravity and quantum theory – 2025 edition** (23/7/2025 – 25/7/2025)

The third edition of workshop gathered young researchers working on topics at the interface between gravity and quantum mechanics. The topics ranged from models describing non-standard coupling between gravity and matter, to recent proposals of experimental setups for studying the nature of gravity via table-top experiments. PhD students and PostDocs were given the opportunity to present their research activity and interact with their colleagues, and share motivations, techniques and perspectives, in a friendly and informal environment. A great amount of time was dedicated to discussions and perspectives.

2. **Fundamental Problems in Quantum Physics 2025** (17/6/2025 – 19/6/2025)

Fifth school on quantum foundations dedicated to Prof. GianCarlo Ghirardi. Quantum mechanics is extremely successful in predicting experimental results and has a vast range of applications. Nonetheless, many unanswered questions remain. The school introduced Master and PhD students to the still outstanding problems in our understanding of quantum foundations. To give a deep look into the foundations of quantum mechanics, lectures were given by experts in the field. An extensive time was dedicated to selected contributed talks.

3. **QuCoM Steering Committee meeting in Palermo** (06/05/2025 – 07/05/2025)

The QuCoM consortium met in person at the University of Palermo on 6–7 May 2025. Partners reviewed project progress, shared results, and aligned on upcoming deliverables. The program featured invited talks and contributed presentations across levitodynamics, precision sensing, and

quantum foundations. The Steering Committee convened to confirm key decisions and coordinate next steps.