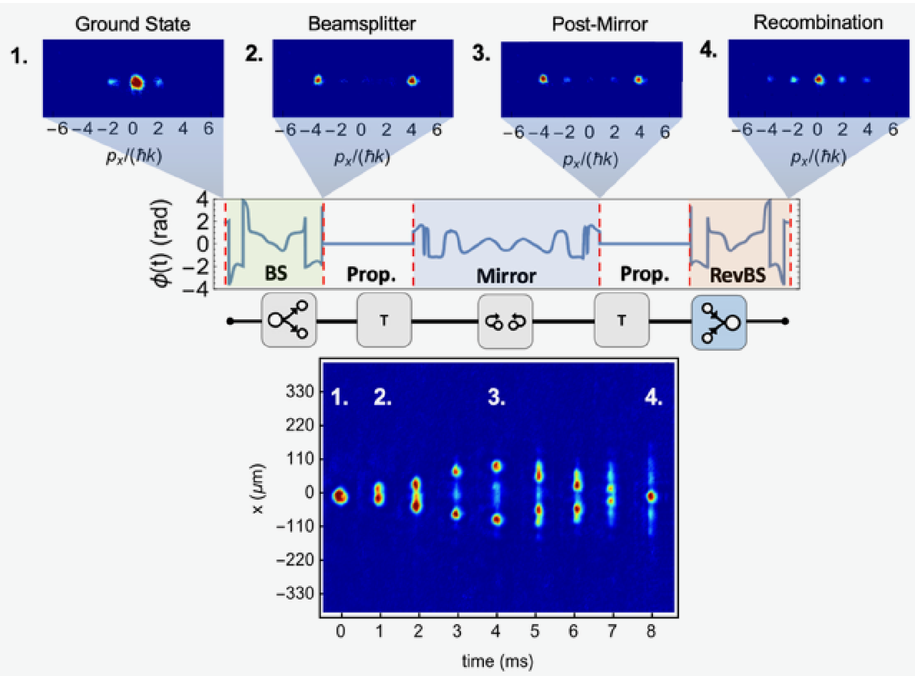
Harnessing AI to Perform Multidimensional Inertial Sensing in an Optical Lattice - Holland, Murray (Keynote Talk)

We are developing a precision atom interferometer based on loading a Bose-Einstein condensate into a three-dimensional optical lattice. By translating this lattice in a controlled manner, we can implement all of the standard operations of atom interferometry: splitting, propagating, reflecting, and recombining a macroscopic quantum wave function. These atom-optic operations act as matter-wave gates: unitary transformations that can be optimized using modern artificial-intelligence techniques. In particular, we employ deep reinforcement learning as a central tool in our experimental design. The gate-set we realize is metrologically universal, analogous to universal gate-sets in quantum computing, and therefore is capable of sensing arbitrary signals. We confirm the designed operations experimentally through in situ imaging of the condensate's spatial evolution within the lattice, as well as through measurements of momentum-state populations after time-of-flight expansion. We further demonstrate applications to several fundamental quantum-sensing circuits, including those used to measure inertial forces, rotation, and gravity gradients. We refer to our sensor as a Bloch-Band Interferometer (BBI) because it manipulates atoms between the lowest Bloch eigenstates in the valence band, where atoms are effectively frozen, and the high-lying Bloch states in the conduction band, where atoms propagate over long distances as effectively free particles. This capability enables us to enclose large interferometric areas in a tiny sensor and thereby achieve high metrological sensitivity, and to do this in multiple dimensions simultaneously. Realizing such large areas requires long interrogation times; to support these durations, we "paint'" tailored optical potentials onto the lattice to emulate a microgravity environment on Earth. In this talk, I will report recent progress on the experiment, as well as developments in the accompanying theory and machine-learning methods.



Murray Holland

Quantum optimal control for atom interferometry

Jack Saywell[1,2], Nikolaos Dedes[1,3], Max Carey[1,2], Joel Abraham[1],
Brynle Barrett[4], Ilya Kuprov[1,5], Tim Freegarde[1*]

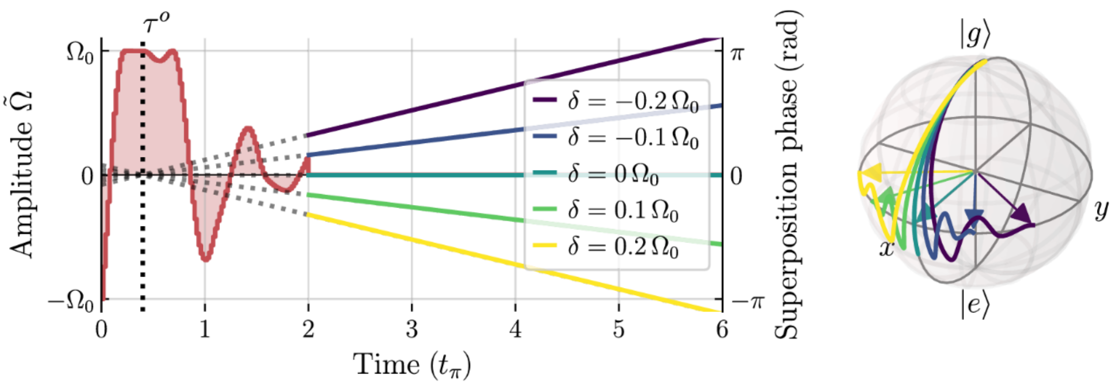
1 *School of Physics & Astronomy, University of Southampton, SO17 1BJ, UK*
2 *Now at Aquark Technologies, Eastleigh SO50 4SR, UK*
3 *Now at Thales RTSI, Reading RG2 6GF, UK*
4 *Department of Physics, University of New Brunswick, E3B 5A3, Canada*
5 *Weizmann Institute of Science, Rehovot 7610001, Israel*
* *tim.freegarde@soton.ac.uk*

In atom interferometry-based sensing and measurement, quantum states are prepared and manipulated by laser pulses that act as the mirrors and beamsplitters of the matterwave interferometer. These pulses define the interferometer geometry, which in turn determines the measurement sensitivity.

If different atoms see different laser intensities at different points within the laser beam, or different frequencies because of their different velocities, the effects of the laser pulses will also differ. This causes variations in state transfer efficiency, superposition phase and phase dispersion, reducing the overall signal-to-noise ratio and scale-factor stability. In general, it is difficult and costly to reduce these variations by further cooling, velocity selection, beam shaping or filtering.

Quantum optimal control allows a spread of quantum state trajectories to be ‘refocused’ in an analogue of aberration-correcting optics by modulating the pulse phase and/or amplitude according to computationally-designed modulation patterns. Pulses and pulse sequences can be optimised for a range of performance objectives and interferometer geometries, including tracking the differing velocities during Large Momentum Transfer.

We shall describe here the principles and techniques of quantum optimal control, with computational simulations and experimental verifications, the importance of pulse design for a well-defined measurement scale factor, the concept of the apparent pulse origin, different choices of fidelity function, and some curious features that emerge from the computational optimizations.



Binary-phase field amplitude (-ve = π phase) during, and superposition phases (various detunings) after, a pulse optimised for scale factor stability, and Bloch sphere trajectories during the pulse.

Experimental Characterization of Optimal Atom Optics Based on Floquet Formalism for Large Scale Atom Interferometers

C. Bigard,[1,*] L. Calmels,[1] S. Beldjoudi,[1] P. Nedeljkovic,[1] B. Allard,[1] and A. Gauguet[1]

[1] *Laboratoire Collisions Agrégats Réactivité (LCAR/FERMI), UMR5589, Université de Toulouse and CNRS 118 route de Narbonne, F-31062 Toulouse, France*

Achieving large momentum transfer with high efficiency is a key requirement for next-generation atom interferometers [1]. Optical lattice-based acceleration techniques provide a promising route toward this goal, enabling coherent manipulation of atomic wave packets over large momentum scales. In particular, the Floquet-based approache [2] (see fig. 1) offers a powerful framework for implementing such dynamics. However, fully exploiting this method requires a detailed understanding of the mechanisms that limit their performance in experimental conditions.

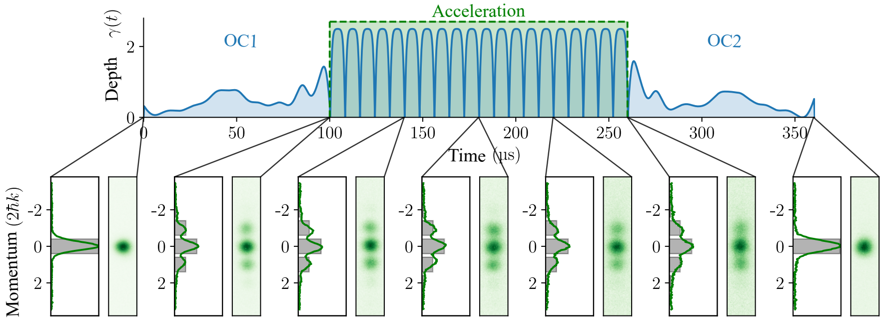


FIG. 1. Principle of Floquet acceleration. The optical lattice is modulated (OC1) to prepare the atomic wave packet in a Floquet state, which is then optimally accelerated by a sequence of lattice pulses before being transferred back into the maximally accelerated state through a final lattice modulation (OC2).

We investigate the limitations of Floquet-based large momentum transfer (LMT) techniques for atom interferometry. While this approach has demonstrated record efficiencies exceeding 99.95% per $\hbar k$, a significant discrepancy

* bigard@irsamc.ups-tlse.fr

remains between theoretical predictions [3] and experimental observations (see fig. 2).

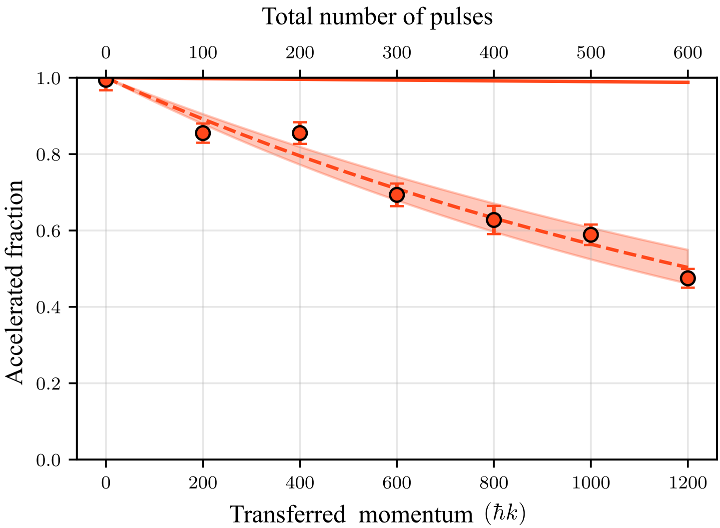


FIG. 2. Loss rate of the Floquet acceleration. The solid orange line is the theoritical efficiency whereas the dashed line is a fit of the experimental data (orange dots).

In this work, we analyze the physical mechanisms responsible for this deviation. In addition to spontaneous emission, we identify pulse-to-pulse fluctuations that break the strict periodicity required by Floquet formalism, as well as slow fluctuations of the lattice depth that induce unwanted coupling between Floquet states.

Our results provide a detailed understanding of the dominant decoherence mechanisms limiting coherent acceleration and establish key requirements for improving the robustness of Floquet-based LMT schemes.

[1] A. Abdalla *et al.*, *arXiv* 2412.14960 (2024).
[2] T. Rodzinka *et al.*, *Nature Communications* **15**, 10281 (2024).
[3] A. Alibabaei *et al.*, *arXiv* 2602.00365 (2026).

Precise, coherent, and robust atom interferometers - Mueller, Holger (Invited Talk)

Atom interferometers have been instrumental in precise measurements of fundamental constants and tests of fundamental laws of physics. But for new tests of the quantum nature of gravity (Carney et al. 2021) and for robust quantum sensing of acceleration and rotation in the field, atom interferometers must have coherences measured in minutes instead of seconds; sizes measured in centimeters instead of meters; and must be robust against vibrations and magnetic fields instead of requiring bulky shielding and vibration isolation. Lattice-hold atom interferometers are a recent addition to the atomic physicists' toolbox to meet those challenges. We will discuss coherence limits in lattice interferometry at the one-minute scale (Panda, M. Tao, et al. 2024), their accuracy in sensing gravity (Panda, M. J. Tao, et al. 2024), and their robustness to environmental effects (Panda et al. 2023).

Carney, Daniel, Holger Müller, and Jacob M. Taylor. 2021. "Using an Atom Interferometer to Infer Gravitational Entanglement Generation." *PRX Quantum* 2 (3): 030330.

Panda, Cristian D., Matthew Tao, James Egelhoff, Miguel Ceja, Victoria Xu, and Holger Müller. 2024. "Coherence Limits in Lattice Atom Interferometry at the One-Minute Scale." *Nature Physics* 20 (June): 1234.

Panda, Cristian D., Matthew J. Tao, Miguel Ceja, Justin Khoury, Guglielmo M. Tino, and Holger Müller. 2024. "Measuring Gravitational Attraction with a Lattice Atom Interferometer." *Nature*, June 26, 1–6.

Panda, C., Ma Tao, Miguel Ceja, Andrew Reynoso, and H. Müller. 2023. "Atomic Gravimeter Robust to Environmental Effects." *Applied Physics Letters*, ahead of print, May 9. https://doi.org/10.1063/5.0163101.

Characterization of atom optics in the quasi-Bragg regime via stroboscopic Raman spectroscopy

J. Gomes Baptista, L. Pagot, S. Merlet, L. A. Sidorenkov, F. Pereira dos Santos
LTE, Observatoire de Paris - Université PSL, Sorbonne Université, Université de Lille, LNE, CNRS
61 avenue de l'Observatoire, F-75014 Paris

The Quasi-Bragg regime offers a good compromise for large-momentum-transfer atom optics, allowing for scaling up the interferometric area, while constraining the population of unwanted states. Separation of momentum states via standard time of flight methods, however, can be challenging when using laser-cooled atoms as a source, rather than ultracold atoms with sub-recoil velocity distribution.

To overcome this limit, we use Raman spectroscopy for stroboscopic sampling of the atomic state evolution in momentum space during the interrogating laser pulses. We quantitatively characterize atom optics employing two-photon ($2\hbar k$) and multi-photon ($6\hbar k$) Bragg transitions, the latter being optionally enhanced with optimal control protocol. We closely match the observed dynamics of the atomic state with simulations. Finally, we perform momentum spectroscopy of the output states in a $6\hbar k$ Bragg gravimeter and discuss application of Raman spectroscopy for single-shot detection of target-state populations.

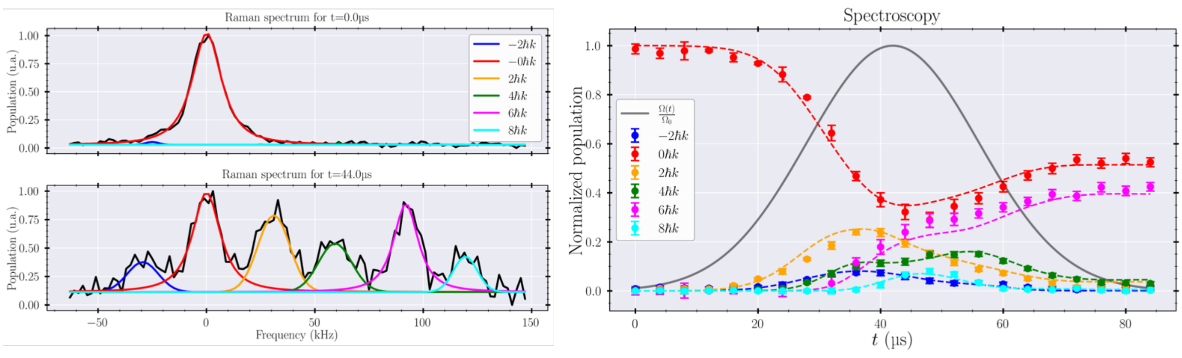


Figure 1: Raman spectra of the momentum states (top left) just before ($t = 0$ μs) and (bottom left) in the middle ($t = 40$ μs) of $6\hbar k$ Bragg mirror interrogation pulse. (Right) Evolution of the populations in significant Bragg states during $6\hbar k$ mirror pulse. The populations (symbols) computed as the fitted areas of the peaks in the measured spectra, similar to those shown in left panels, are compared with results of numerical simulation (dashed lines) based on resolving the Schrodinger equation .

The Super Molasses Trap: cold atoms without magnets

C. H. Camm, J. C. Saywell, M. D. Himsworth, A. A. Dragomir

Aquark Technologies
18 Hathaway Close, Eastleigh, SO50 4SR, UK
e-mail: c.camm@aqrkt.com

Neutral atom trapping has been an integral part of matter wave interferometry systems since their invention. Typically, a sample of cold atoms is produced by a Magneto Optical Trap (MOT) where lasers are employed to provide a velocity selective force, and a magnetic field provides a positional dependent force. The combination of these effects slow down and confine the atoms that enter the beams of light. This ensemble of cold atoms can then be used in a variety of interaction schemes to make different measurements. This has an equally wide variety of applications from including timing, inertial sensing, magnetometry, and RF sensing[1].

Before any sensing scheme is performed, the MOT's magnetic field must be deactivated. This requires extra equipment and creates eddy currents that need to decay before the measurement is performed. Furthermore, any misalignment between the optical and magnetic fields lead to instability in the trapped atom's position. Removing this magnetic field would be very convenient, especially for any miniaturisation and portability requirements. This had previously been thought to be impossible due to an optical Earnshaw violation, however Dragomir [3] discovered a method to trap and cool atoms using *only* an optical field. This new technique was called the Super Molasses Trap (SMT) – named after similar observations from the early days of laser cooling experiments [4].

Aquark technologies has been finding success in developing the SMT and utilising it in our miniaturised and portable platforms. We present our current understanding of the SMT: its experimental realisation, its dynamics and our current theoretical understanding.

Keywords: COLD ATOMS, MOT, MINIATURISATION, SUPERMOLASSES

References

[1] Q. Zhang *et al.*, 'Precision measurements with cold atoms and trapped ions*', *Chin. Phys. B*, vol. 29, no. 9, p. 93203, Sep. 2020, doi: 10.1088/1674-1056/aba9c6.

[2] A. Ashkin and J. P. Gordon, 'Stability of radiation-pressure particle traps: an optical Earnshaw theorem', *Opt. Lett.*, vol. 8, no. 10, p. 511, Oct. 1983, doi: 10.1364/OL.8.000511.

[3] A.-A. Dragomir, 'Cold atoms in your pocket-Enabling technologies', University of Southampton, 2018. [Online]. Available: http://eprints.soton.ac.uk/id/eprint/430425

[4] S. Chu, 'Laser Manipulation of Atoms and Particles', *Science*, vol. 253, no. 5022, pp. 861–866, Aug. 1991, doi: 10.1126/science.253.5022.861.

Experiments at the interface of general relativity and quantum mechanics - Ron Folman and the Atom Chip Group, Ben-Gurion University of the Negev (Invited Talk)

The two pillars of modern physics are the theories of General Relativity (GR) and Quantum Mechanics (QM). After decades of theoretical attempts to unify these two pillars under one theoretical framework (often referred to as quantum-gravity), these pillars remain independent. To some this situation is so unnatural, that they claim it actually hints that at least one of the theories is wrong in some fundamental way. As technology in quantum-optics labs improves, new experiments – working at the interface of these two theories – can be realized. Such experiments will hopefully provide new insights that will eventually allow for the sought-after unification to be finally achieved.

In this talk, I will present three experiments conducted at this interface, two already realized and one planned. The first involves clock interferometry, in which a single clock in a spatial superposition experiences two different proper times due to gravitationally induced red shift [1-3]. The second involves the observation of the consistency of the Einsteinian equivalence principle in the quantum domain [4]. While the first two were realized with atoms, the third involves massive objects, specifically, nano-diamonds [5]. Leaping by ten orders of magnitude in mass relative to the atomic experiments, the third experiment makes use of so-called active mass, where not only the gravitational field of Earth needs to be taken into account.

The experiments are based on Stern-Gerlach interferometry [6]. Time permitting, I will be happy to also address more technical questions. For example, interesting issues concerning decoherence arise [7,8].

[1] Y. Margalit et al., A self-interfering clock as a "which path" witness, Science 349, 1205 (2015).

[2] Zhifan Zhou et al., Quantum complementarity of clocks in the context of general relativity, Classical and quantum gravity 35, 185003 (2018).

[3] Zhifan Zhou et al., Geometric phase amplification in a clock interferometer for enhanced metrology, Science advances 11, adr6893 (2025).

[4] Or Dobkowski, Barak Trok, Peter Skakunenko, Yonathan Japha, David Groswasser, Maxim Efremov, Chiara Marletto, Ivette Fuentes, Roger Penrose, Vlatko Vedral, Wolfgang P. Schleich, Ron Folman, Observation of the quantum equivalence principle for matter-waves, ArXiv:2502.14535 (2025).

[5] Y. Margalit et al., Realization of a complete Stern-Gerlach interferometer: Towards a test of quantum gravity, Science advances 7, eabg2879 (2021).

[6] O. Amit et al., T3 Stern-Gerlach matter-wave interferometer, Phys. Rev. Lett. 123, 083601 (2019).

[7] Y. Japha and R. Folman, Role of rotations in Stern-Gerlach interferometry with massive objects, Phys. Rev. Lett. 130, 113602 (2023).

[8] C. Henkel and R. Folman, Universal limit on quantum spatial superpositions with massive objects due to phonons, Phys. Rev. A 110, 042221 (2024) – Editor's choice.

Analogue many-body gravitating quantum systems with a network of dipolar Bose–Einstein condensate

Youssef Trifa[*,a], **Dario Cafasso**[a,b], **Marco Fattori**[a,c,d], **Luca Pezzè**[a,c]

[a] *Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche (INO-CNR), Largo Enrico Fermi 6, 50125 Firenze, Italy*

[b] *Physics Department, University of Naples Federico II, Via Cintia 21, 80126 Naples, Italy*

[c] *European Laboratory for Nonlinear Spectroscopy (LENS), Via N. Carrara 1, 50019 Sesto Fiorentino, Italy*

[d] *Physics Department, University of Florence, Via G. Sansone 1, 50019 Sesto Fiorentino FI, Italia*

ABSTRACT

Operational probes of the interface between quantum mechanics and general relativity in the Newtonian regime share a common description in terms of an effective qubit-qubit coupling [1, 2].

Here, we study the generalization of these approaches to qudit-qudit interaction, with large atomic ensembles. We show that these interactions can be simulated by trapped bimodal Bose–Einstein condensates with long-range coupling, providing a programmable analogue platform to explore gravitating quantum dynamics at accessible time and energy scales. Using qudits allow for a many-body enhancement that facilitates the observation of gravitationally induced entanglement and decoherence, certified by experimentally accessible metrological witnesses.

This talk/poster is complementary to the one proposed by Dario Cafasso, that focuses on the generalization of existing approaches from qubits to qudits for gravitating quantum system, while this talk focuses on the realization of qudit-enhanced protocoles on an analogue quantum simulation platform. More details can be found in our work [3].

REFERENCES

[1] C. Marletto and V. Vedral, Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity, *Phys. Rev. Lett.* **119**, 240402 (2017).

[2] E. Castro-Ruiz, F. Giacomini, and Č. Brukner, Entanglement of quantum clocks through gravity, *Proceedings of the National Academy of Sciences* **114** (2017)

[3] Y. Trifa, D. Cafasso, M. Fattori and L. Pezzè, Analogue many-body gravitating quantum systems with a network of dipolar Bose–Einstein condensates, *arXiv:2602.23319* (2026).

*Presenting author.

Locality, entanglement and quantum sources of gravity - Giacomini Flaminia (Invited Talk)

The interface between gravity and quantum theory has become a lively field of research, substantially driven by the developments of quantum optics technologies. One of the most ambitious experimental goals is the preparation of a massive source in a quantum superposition of spatial locations, enabling tests of gravity in genuinely quantum regimes. Such experiments raise crucial theoretical questions: what insight could they provide on the (quantum) nature of gravity, and which tools and techniques are best suited to interpret them? Information-theoretic methods have proved very useful to analyse these scenarios, with entanglement and the LOCC theorem playing a central role. While these methods are naturally suited to the experimental platforms under consideration, their application to gravity is complicated by the gauge-theoretic nature of the field, which challenges standard notions of subsystems, locality, and information. In this talk, I will argue that concepts and tools of quantum information should be generalised to accommodate gauge theories and gravity.

After reviewing the role played by information-theoretic arguments in current proposals, I will discuss how some of these notions can be reformulated in a gauge-invariant framework. This perspective provides a route toward extending the methodology of quantum information to gravitational scenarios.

The QUPLAS-Gravitation experiment: quantum interferometric and gravitational studies on Positronium. Characterization of the atomic beam.

Francesca Triggiani[1] on behalf of the QUPLAS collaboration

[1] *National Institute for Nuclear Physics (INFN), Section of Milan, Via Celoria 16, 20133 Milan, Italy*

QUPLAS, acronym of QUantum interferometry and gravitation with Positrons and LASers, is a scientific project for the investigation of antimatter through the use of quantum interferometry. This project is divided into several stages and programs [1, 2], among them, the QUPLAS-Gravitation experiment, whose goal is to test the matter-antimatter symmetry. To this end, the experiment aims to analyse, via a laser system, the behaviour of the Positronium in the Earth's gravitational field. The Positronium, defined as the simplest of atoms, is an unstable bound state composed of an electron (e^-) and its antiparticle, the positron (e^+). Given its characteristics, the latter is one of the most suitable candidates for study of the CPT (Charge-Parity-Time) symmetry and Einstein Equivalence Principle (EEP), a violation of which would constitute a key element for the Standard Model Extension (SME) [3]. The preparation of a continuous Ps (Positronium) beam, however, represents an experimental challenge [4, 5].

In this work, described the experiment and its features, we analyse, specifically, the beam production process and the phases that compose it.

References

[1] Ariga A. et al., Nucl. Inst. & Meth. A, 951, 163019 (2020).

[2] Sala S. et al., Sci. Adv., 5, eaav7610 (2019).

[3] Sacerdoti M. et al., Nucl. Inst. & Meth. A, 1071, 170068 (2025).

[4] Giammarchi M., Symmetry, 11, 1247 (2019).

[5] Vinelli G. et al., Class. Quantum Grav., 40, 205024 (2023).

Talk

An Anti-Hydrogen Interferometer for a High Precision Gravity Measurement

Mancini C.[†1, 2], **Tino G.M.**[2, 3, 4], **Christensen A.**[5], **Müller H.**[5]

[1]*Scuola Superiore Meridionale, Largo San Marcellino 10, 80138 Napoli (NA), Italy*
[2]*Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, via Sansone 1, 50019, Sesto Fiorentino (FI), Italy*
[3]*Dipartimento di Fisica e Astronomia, LENS, Università di Firenze, via Sansone 1, I-50019 Sesto Fiorentino (FI), Italy*
[4]*Istituto Nazionale di Ottica del Consiglio Nazionale delle Ricerche (CNR-INO), 50019 Sesto Fiorentino, Italy*
[5]*University of California, Berkeley, Physics Department, 94720, California, USA*

[†]c.d.m@berkeley.edu

Testing the gravitational behavior of antimatter is a central challenge in fundamental physics, with implications for the Einstein Equivalence Principle and the Standard Model. After decades of experimental efforts, the ALPHA collaboration has recently achieved the first observation of the effect of gravity on antihydrogen[1]. Building on the significant progress in antihydrogen production, trapping, and cooling[2], we are now in a position to design and implement, for the first time, a high-precision interferometric measurement of its gravitational acceleration. In this talk I will present the current state of the experiment and the preliminary results on the achievable performance of the interferometer with the present apparatus at ALPHA[3]. While several proposals have been put forward in the past decades[4], recent technological advances have opened new and more realistic experimental pathways. I will present our approach, using Raman pulses driven either by a state of the art Lyman-α laser[5] or by a 2S–3P transition at 656 nm. I will discuss both the technological challenges and the fundamental limitations specific to antihydrogen, together with the strategies developed to overcome them. Despite the relatively low number of atoms (10^4 initially trapped antiatoms per shot), a temperature of 2 mK and a wide spatial distribution, leading to reduced contrast, and with the main systematics due to AC Stark shift and the presence of a strong magnetic field required for trapping, I will show that a measurement of the gravitational acceleration of antihydrogen at the level of $\sigma_g/g \sim 100$ ppm is achievable with the current ALPHA setup after approximately 30 days of integration. These results mark a significant step toward precision tests of gravity with antimatter, opening a new frontier in fundamental physics.

[1]E. K. Anderson et al., *Nature* **691**, 7980 (2023).
[2]R. Akbari et al., *Nature Communications* **16**, 10106 (2025).
[3]C. Mancini, G.M. Tino, A. Christensen and H. Müller, *forthcoming* (2026).
[4]P. Hamilton et al., *PRL* **112**, 121102 (2014).
[5]Y. Oishi et al., *Journal of Physics: Conference Series* **2462** 012026 (2023).

Demonstration of a large area dual-atom-interferometer gyroscope

Jie Gu,[1,2] YinFei Mao,[1,2] Zhan-Wei Yao,[1,3] Anqing Zhang,[1,2] Si-Bin Lu,[1] Run-Bing Li,[1,3,4] Jin Wang,[1,3,4] and Ming-Sheng Zhan[1,3,4]

[1]*Division of Precision Measurement Physics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430071, China*

[2]*University of Chinese Academy of Sciences, Beijing 100049, China*

[3]*Hefei National Laboratory, Hefei 230088, China*

[4]*Wuhan Institute of Quantum Technology, Wuhan 430206, China*

Abstract: In our previous work, a dual-atom-interferometer gyroscope was demonstrated with a total interference area of 2.4 cm^2, achieving a sensitivity of 1.5×10^{-7} rad/s/$Hz^{1/2}$ and a long-term stability of 9.5×10^{-10} rad/s at 23000 s [1]. The atom gyroscope could be self-calibrated by modulating the atomic velocity, and the Earth's rotation rate was measured with a relative uncertainty of 162 ppm [2]. To reduce the influence of vibration, a real-time noise compensation scheme was implemented [3]. In this talk, I will present recent progress on high-precision dual-atom-interferometer gyroscope for inertial measurements [4]. A dual-atom-interferometer gyroscope with a total interference area of up to 21.2 cm^2 was built and demonstrated a rotation sensitivity of 1.3×10^{-8} rad/s/$Hz^{1/2}$. A dynamic angle compensation method was demonstrated to eliminate the influence of the Coriolis effect in the dual-atom-interferometer gyroscope. After compensation, the atom-interference-based sensor presents a rotation stability of 1.9×10^{-10} rad/s at an integration time of 4500 s. This work paves the way for the application of dual-atom-interferometer gyroscopes in the fields of inertial navigation and geophysics.

References

[1] Z. W. Yao, H. H. Chen, S. B. Lu, et al., Phys. Rev. A **103**, 023319 (2021).

[2] H. H. Chen, Z. W. Yao, Z.-X. Lu, et al. Rev. Sci. In strum. **95**, 053201(2024).

[3] Z.-X. Lu, Z. W. Yao, H. H. Chen, et al. Phys. Rev. A **111**, 033305(2025).

[4] J. Gu, Y. F. Mao, Z. W. Yao, et al. in prepartion.

Coherent current oscillations without net particle transfer in weakly coupled matter-wave rings

Axel Pérez-Obiol[1], Juan Polo[2], Luigi Amico[2,3,4]

[1] Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

[2]Quantum Research Centre, Technology Innovation Institute, Abu Dhabi, UAE

[3] Dipartimento di Fisica e Astronomia, Università di Catania, Via S. Sofia 64, 95123 Catania, Italy

[4] INFN-Sezione di Catania, Via S. Sofia 64, 95127 Catania, Italy

axel.perezobiol@uab.cat

Abstract

We investigate the coherent dynamics of persistent currents in weakly coupled matter-wave ring systems, demonstrating oscillations of angular momentum between rings without net particle transfer. The effect originates from a controlled weak link between the rings combined with a slight breaking of left–right and rotational symmetries, which isolates a pair of quasi-degenerate current states and leads to an effective two-mode dynamics. We analyze continuous and lattice ring configurations in the mean-field limit using coupled Gross–Pitaevskii equations, as well as Bose–Hubbard and quantum phase models at finite interactions. In both the weakly interacting and finite-interaction regimes, we observe coherent current oscillations while particle populations in each ring remain nearly constant. The dynamics exhibit distinct signatures depending on the regime: in the mean-field limit, transient density modulations and dark solitons emerge during the transfer, whereas for stronger interactions the density profiles remain nearly homogeneous. We characterize the oscillation periods and their scaling with the inter-ring tunneling, finding different behaviors in the two regimes consistent with their underlying microscopic descriptions. Despite these differences, the mechanism remains robust and can be understood in terms of coherent coupling between two winding-number states. The phenomenon can be implemented with a simple experimental protocol: two initially uncoupled rings are prepared in different current states and subsequently connected through a weak link, triggering the coherent dynamics. The predicted timescales, on the order of seconds, together with the robustness of the effect, indicate that these dynamics are within reach of current cold-atom experiments.

Funding: This work was supported by Ministerio de Ciencia e Innovación, Fondos FEDER, Spain (grant num. PID2024-160393NB-I00).

Interferometry with Bose-Einstein condensates in large elevators - Rasel, Ernst

The talk will report our research on experiments exploiting quantum degenerate gases for atom optics and interferometry in extended free fall of several seconds. Here new perspectives emerge due to the Bremen gravitower and Hannover Einstein Elevator.

Double-Diffraction-Based Accelerometer Using Ultracold Atoms in an Einstein Elevator

Calviac R.[†1], **Marchesini M.**[1], **Le Mener J.**[1], **Beitia Fernández I.**[1], **Metayer C.**[1], **Battelier B.**[1]
[1] *LP2N, Laboratoire Photonique, Numérique et Nanosciences; Université Bordeaux, IOGS, CNRS; 1 rue François Mitterrand, 33400 Talence, France*

[†]romain.calviac@institutoptique.fr

Recently, inertial quantum sensors based on atom interferometry have emerged as powerful tools for high-precision measurements of acceleration and rotation. These devices rely on the coherent diffraction of atoms induced by light pulses during their free-fall evolution over an interrogation time $2T$. As a result, their acceleration sensitivity scales as T^2. However, in ground-based experiments, this scaling is fundamentally limited by the finite size of the apparatus, which constrains the maximum free-fall distance and thus the achievable interrogation time. Consequently, typical sensor heads without atomic fountains are restricted to interrogation times of only a few tens of milliseconds.

A promising approach to overcome this limitation is to operate the sensor in free fall together with the atoms. Such a condition is naturally achieved in space, where the apparent absence of gravity enables, in principle, arbitrarily long interrogation times. This opens the way to unprecedented sensitivities, potentially reaching below $10^{-12}\,\mathrm{g}/\sqrt{\mathrm{Hz}}$ for interrogation times exceeding $1\,\mathrm{s}$[1].

Atom interferometers operated in space are particularly attractive for applications ranging from Earth observation through gravity gradient mapping to fundamental physics tests, such as probing the *Weak Equivalence Principle* (WEP) or detecting gravitational waves[1].

In this configuration, the atomic cloud has no initial velocity, and the interferometer sequence typically relies on double diffraction. However, simulating microgravity ($0g$) conditions on Earth requires dedicated facilities such as drop towers, sounding rockets, or parabolic flights, which limits experimental accessibility and repetition rates. As a result, this interferometric technique has so far received limited experimental investigation.

In this work, we present an experimental study of a Raman ^{87}Rb atom interferometer operating in the double-diffraction regime with an ultracold atomic cloud consisting of a partially condensed cloud of 6×10^4 atoms, with a Bose–Einstein condensate (BEC) velocity dispersion of $1\,\mathrm{nK}$. The study is carried out within the ICE experiment, where the Einstein Elevator provides a unique platform enabling a large number of microgravity ($0g$) realizations in a laboratory environment

Deviations from an ideal parabolic trajectory of the elevator induce residual acceleration fluctuations around $0g$, effectively enabling a shot-to-shot random sampling of the interferometric phase. By repeating the experiment hundreds of times, we reconstruct the characteristic "Batman" probability distribution associated with an oscillating atom interferometer. For long interrogation times (up to $T = 100\,\mathrm{ms}$), this method allows us to estimate the interferometer sensitivity of $4 \times 10^{-7}\,\mathrm{m\,s^{-2}\,shot^{-1}}$ using a Bayesian analysis [4] of the measured probability distribution. This sensitivity is ultimately limited by the maximum duration of the $0g$ phase available in the experiment.

For shorter interrogation times (a few milliseconds), we demonstrate fringe–acceleration correlations[2]. We reconstruct the interferometric phase using the acceleration measured by a classical accelerometer, convolved with the sensitivity function of the double-diffraction interferometer. This provides a clear validation that the system operates in the double-diffraction regime.

Finally, we investigate the contribution and impact of parasitic processes induced by imperfect polarization of the Raman beams. In particular, the absence of initial velocity (and thus Doppler frequency shift) allows additional unwanted transitions during the light pulses, including co-propagating Raman transitions and Bragg diffraction, which can degrade the interferometer performance.

Overall, this work demonstrates the relevance of laboratory-based microgravity platforms for the study of advanced interferometric schemes and provides key insights into the performance and limitations of double-diffraction atom interferometers in zero-gravity conditions. This study paves the way for the CARIOQA European project pathfinder mission[3], which aims to launch an atomic accelerometer onboard a satellite within the next decade.

References

[1] Sven Abend et al. "Technology roadmap for cold-atoms based quantum inertial sensor in space". In: *AVS Quantum Science* 5.1 (Mar. 2023). ISSN: 2639-0213. DOI: 10.1116/5.0098119.

[2] J. Lautier et al. "Hybridizing matter-wave and classical accelerometers". In: *Applied Physics Letters* 105.14 (Oct. 2014). ISSN: 1077-3118. DOI: 10.1063/1.4897358.

[3] T. Lévèque et al. *CARIOQA: Definition of a Quantum Pathfinder Mission.* 2022. DOI: 10.48550/ARXIV.2211.01215.

[4] C. Pelluet et al. "Atom interferometry in an Einstein Elevator". In: *Nature Communications* 16.1 (May 2025). ISSN: 2041-1723. DOI: 10.1038/s41467-025-60042-7.

Interferometry with Bose-Einstein Condensates for inertial sensing using twin lattices

Matter-wave interferometers show great a potential for improving inertial sensing. The absence of drifts recommends them for a variety of applications in geodesy, navigation, or fundamental physics.

Here, ultracold atomic ensembles, featuring a velocity distribution well below the photon recoil velocity, open up new perspectives. In contrast to standard laser cooling methods, they allow to reach better beam-splitting efficiencies and, hence, a higher contrast as well as to reduce systematic uncertainties and biases.

Presently, Bose-Einstein condensates (BECs) provide the means to achieve the lowest expansion energies of few picokelvin. Indeed, the momentum distribution of a BEC can be further narrowed after reaching the regime of ballistic expansion, where all mean field energy is converted to kinetic energy, by the application of the delta-kick collimation technique.

With such ensembles, Bragg processes can be driven with an efficiency of above 95% [1] as well as Bloch oscillations performed without large atomic losses or dephasing [2]. Both enable efficient large momentum transfer in interferometers to enhance their sensitivity for inertial effects. In a so-called twin-lattice atom interferometers more than thousand photon recoils are used to form compact but sensitive atom interferometers [3].

These methods not only bring in reach extremely accurate gravimeters [4] and accelerometers but also gyroscopes. Like the Sagnac effect in ring laser or fiber gyroscopes, the sensitivity of atom interferometers to rotations increases with the space-time area enclosed by the interferometer. In the case of light interferometers, the latter can be enlarged by forming multiple fiber loops. However, the equivalent for matter-wave interferometers remains an experimental challenge. An atom interferometer with scalable area may be formed in a twin lattice combined with a relaunch mechanism to obtain multi loops as well [5]. Due to this scalability, it offers the perspective of reaching unprecedented sensitivities for rotations in comparably compact sensor head setups.

Moreover, atom-chip technologies offer the possibility to generate a BEC and perform delta-kick collimation in a fast and reliable away, paving the way for field-deployable miniaturized atomic devices [6]. Last but not least, the extremely low expansion energies of BECs open up to extend the time atoms spend in the interferometer to tens of seconds. This brings in reach unprecedented sensitivities in space-borne applications such as satellite geodesy.

[1] Ahlers, H. et al. (2016), Double Bragg Interferometry, Phys. Rev. Lett. 116, 173601, doi:10.1103/PhysRevLett.116.173601(2016)
[2] Abend, S., Gebbe, M., Gersemann, M., Ahlers, H., Müntinga, H., Giese, E., Gaaloul, N., Schubert, C., Lämmerzahl, C., Ertmer, W., Schleich, W. P., and Rasel, E. M., Atom-chip Fountain Gravimeter, Phys. Rev. Lett. 117, 203003 (2016)
[3] Gebbe, M., Siemß, J.-N., Gersemann, M., Müntinga, H., Herrmann, S., Lämmerzahl, C., Ahlers, H., Gaaloul, N., Schubert, C., Hammerer, K., Abend, S., Rasel, E. M., Twin-lattice atom interferometry, Nature communications 12(1), 1-7 (2021)
[4] Heine, N., Matthias, J., Sahelgozin, M., Herr, W., Abend, S., Timmen, L., Müller, J. and, Rasel, E.M. A transportable quantum gravimeter employing delta-kick collimated Bose–Einstein condensates, Eur. Phys. J. D 74, 174 (2020)
[5] Schubert, C., Abend, S., Gersemann, M., Gebbe, M., Schlippert, D., Berg, P., and Rasel, E.M., Multi-loop atomic Sagnac interferometry, Scientific Reports 11, 16121 (2021)
[6] Gersemann, M., Gebbe, M., Abend, S., Schubert, C. and Rasel, E. M. (2020), Differential interferometry using a Bose-Einstein condensate, Eur. Phys. J. D 74: 203, doi: 10.1140/epjd/e2020-10417-8 (2020)

Atomic Quantum Technologies for Fundamental Physics

Marilu Chiofalo
Department of Physics, University of Pisa
INFN and VIRGO - Pisa
Women for Quantum

Physics is living an era of unprecedented cross-fertilization among diverse areas of science. In this colloquium, I will first introduce the manifold impact that state-of-the-art ultracold-atomic platforms can have in unveiling foundational aspects of quantum mechanics and general relativity, cosmology and astrophysics. Along this journey, I will take the perspective of three main approaches with potentially remarkable transformative effects, i.e., designing non-classical states of matter for quantum metrology purposes, creating quantum analogues, and engineering quantum simulators.

In the second part of the colloquium, I will briefly present from my research one specific example for each approach, respectively: many-body entangled states for atomic interferometry, analogues of gravitational waves, and quantum time explorations.

Beyond specific contents, I also wish to convey the message that atomic quantum technologies are opening a new scientific era of highly cross-disciplinary research and extended interplay between theoretical and experimental thinking, in fact bringing quantum many-body and AMO physics at center stage in frontier's science. At same time, while their progress will have capillary impact on society, a responsible research and innovation approach to quantum technologies becomes mandatory.

Quantum Sensing in Space for Fundamental Physics and Earth Observation

Gaaloul N. for the MAIUS, CUAS, STE-QUEST and CARIOQA consortia
Leibniz University of Hanover, Institute of Quantum Optics, Hanover, Germany
gaaloul@iqo.uni-hannover.de

Space-borne quantum technologies and more particularly atom-interferometry-based devices are announcing a new era of strategic, intense space exploitation. Indeed, space offers a unique environment characterized by low-noise and low-gravity necessary for a wide spectrum of applications ranging from time and frequency transfer to Earth observation and the exploration of fundamental laws of physics.

Efforts to operate atom physics experiments in these ideal conditions are however challenged by a number of technical limitations as the extreme miniaturization or power consumption requirements for example.

In this contribution, we report about recent advances of pioneering successful space implementations of atom optics experiments[1234] as well as about recent mission concepts based on the use of quantum-gas sensors. Of particular interest for Fundamental Physics, is the satellite mission Space-Time Explorer and QUantum Equivalence Principle Space Test (STE-QUEST)[56] featuring a dual-species atom interferometer operating over tens of seconds, which will address some of the most fundamental and puzzling questions of physics by testing the universality of free fall with an accuracy better than one part in 10^{-17}, searching for different types of Ultra-Light Dark Matter (ULDM) and testing the foundations of quantum mechanics.

Moreover, atomic sensors could also map temporal variations in Earth's gravity field opening the era of Space Quantum Gravimetry. We will report on the CARIOQA satellite mission pathfinder[7], recently endorsed by the European Commission. It is set to lay the groundwork for a space Geodesy mission, utilizing atom accelerometers.

---

[1] D. Becker, *et al., "*Space-borne Bose–Einstein condensation for precision interferometry", *Nature,* **562**, 391 (2018).

[2] M. D. Lachmann, et al., "Ultracold atom interferometry in space", *Nature Comm.* **12**, Article number: 1317 (2021).

[3] D. Aveline, et al., "Observation of Bose–Einstein condensates in an Earth-orbiting research lab" *Nature*, **582**,11 (2020).

[4] N. Gaaloul, et al., "A space-based quantum gas laboratory at picokelvin energy scales", *Nature Communications*, **13**:7889 (2022).

[5] H. Ahlers, et al., "STE-QUEST: Space Time Explorer and QUantum Equivalence principle Space Test", arXiv:2211.15412 (2022).

[6] C. Struckmann, et al., "Platform and environment requirements of a satellite quantum test of the Weak Equivalence Principle at the 10^{-17} level" Phys. Rev. D **109**, 064010 (2024).

[7] T. Lévèque, C. Fallet, J. Lefebve, et al., Proc. SPIE — ICSO 12777, (2023).

FOMO, Poggio All'agnello, September 14-18, 2026

In-trap Collimation for dual-BEC Interferometry in Space

T. Estrampes[1,2†], **G. Müller**[1], **C. Puertas-Gonzale**[1,2], **E. Charron**[2], **M. Meister**[3], **N. P. Bigelow**[4], **N. Gaaloul**[1], **for the CUAS consortium**

[1] *Leibniz University Hannover, Institute of Quantum Optics, Hannover, Germany*
[2] *Paris-Saclay University, ISMO, Orsay, France*
[3] *Ulm University, Institute of Quantum Optics and Center for Integrated Quantum Science and Technology, Ulm, Germany*
[3] *University of Rochester, Department of Physics and Astronomy, Rochester, USA*

† estrampes@iqo.uni-hannover.de

Performing dual-species atom interferometry in space enables high-precision tests of Einstein's Equivalence Principle, benefiting from extended interrogation times in microgravity. However, the achievable sensitivity is limited by the control of the differential center-of-mass (CoM) dynamics as well as by the expansion energies of the atomic mixtures. Here, we report on experiments performed with ^{87}Rb in the Cold Atom Laboratory aboard the International Space Station, addressing these limitations.

We demonstrate a detailed understanding of the atomic dynamics by gauging an atom-chip model against different experimental sequences implemented in the Cold Atom Laboratory aboard the International Space Station. This approach allows us to significantly reduce the residual classical motion of a ^{87}Rb Bose–Einstein condensate (BEC), enabling longer free-expansion times. Such control is essential for long-interrogation-time interferometry, which has previously been limited in this platform because of the CoM motion of the cloud [1].

To address the expansion energy, we propose an in-trap collimation technique based on the controlled excitation of collective modes, compatible with state-of-the-art atom-chip setups. In contrast to the widely used, state-of-the-art Delta-Kick collimation [2], this method keeps the atoms confined at all times, simplifying the control of their classical motion and avoiding technical limitations in the two-species case, such as differential CoM kicks [3]. Implementing this technique, we demonstrate two-dimensional collimation of a condensed ^{87}Rb cloud and achieve expansion times of up to 700 ms, solely constrained by technical limitations.

Finally, we simulate the extension of this method to dual-species mixtures of ^{39}K and ^{87}Rb as displayed in Fig. 1. Our results indicate that, with minor adaptations, comparable collimation performance can be achieved. This opens a promising route toward state-of-the-art expansion energies in mixtures required for next-generation space-based tests of the Equivalence Principle [4].

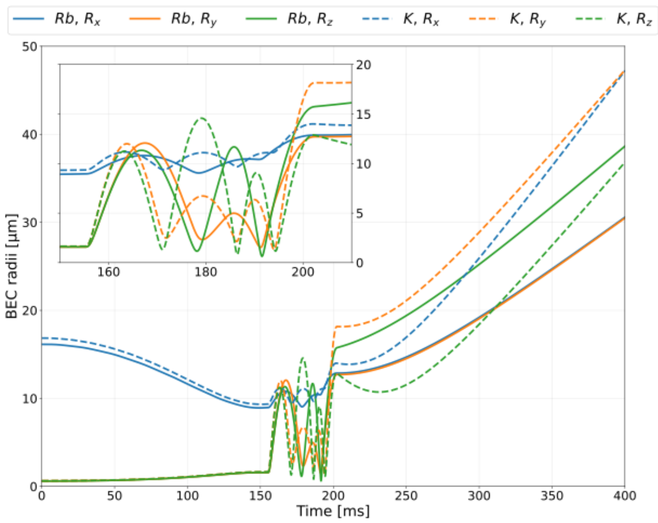


Figure 1: Illustration of the size expansion of a BEC mixture made of potassium and rubidium. Both atomic clouds are transported together during the first 150 ms of the sequence before being collimated for another 50 ms using in-trap lensing to reach sub-30 pK for each species.

References

[1] Space magnetometry with a differential atom interferometer. M. Meister *et al.*, arXiv:2505.23532 (2025)

[2] Collective-Mode Enhanced Matter-Wave Optics. C. Deppner *et al.*, *Phys. Rev. Lett.* **78**, 2088 (1997)

[3] Apparatus for quantum-mixture research in microgravity. B. Piest *et al.*, arXiv:2508.20820 (2025)

[4] STE-QUEST – Space Time Explorer and QUantum Equivalence principle Space Test: The 2022 medium-class mission concept. N. Gaaloul *et al.*, arXiv:2211.15412 (2025)

Carsten Klempt

Entanglement-enhanced atom interferometry - Klempt, Carsten (Keynote Talk)

Interferometers based on ultracold atoms enable absolute measurements of inertial forces with unprecedented precision. However, their resolution is fundamentally limited by quantum fluctuations, and surpassing this limit requires the use of entangled atomic quantum states. I will review current approaches for achieving entanglement-enhanced sensitivities in inertially sensitive atom interferometers. Our method relies on generating entanglement via spin-changing collisions in Bose–Einstein condensates. I will present a characterization of the resulting quantum states with single-particle counting resolution, revealing Hong–Ou–Mandel correlations, genuine multi-particle entanglement, and Heisenberg-limited interferometric sensitivity. We apply these quantum states to demonstrate the operation of an atomic gravimeter that surpasses the quantum limit by −1.7−0.5+0.4 dB. This demonstration is enabled by Bose–Einstein condensates whose expansion is further reduced through delta-kick collimation. The concept is compatible with state-of-the-art atom interferometers and provides a pathway to enhancing the performance of current and future very-long-baseline atom interferometers.

Tailored entangled states for frequency metrology and atom interferometry

Klemens Hammerer (U Innsbruck, IQOQI Innsbruck, U Hannover)

Designing tailored entangled states for diverse metrological settings and applications under realistic noise and experimental constraints remains a central challenge. In frequency metrology limited by spontaneous emission, optimized GHZ and GHZ-like states as well as Gottesmann-Knill-Preskill like “grid states” combined with suitable measurement and estimation strategies enable sensitivity gains beyond the standard quantum limit. In atom interferometry based on Bragg scattering, spin-squeezed states provide measurable enhancements in phase sensitivity when system parameters and input states are jointly optimized.

Correlated Atomic Sensors: Gravitational-Wave Detection and Parameter Estimation from Amplitude Collapse

Enno Giese
TU Darmstadt, Fachbereich Physik, Institut für Angewandte Physik, Darmstadt, Germany

Atomic sensors based on light-matter interactions, such as atomic clocks and atom interferometers, are promising candidates to complement existing gravitational-wave detectors, particularly in the mid-frequency regime. While both rely on interference, they differ fundamentally in their implementation: atomic clocks probe interference between internal states at a single location, whereas atom interferometers exploit spatial superpositions of matter waves. In this contribution, we present a unified framework [1] to describe the response of both platforms to gravitational waves in the laboratory frame, where spacetime perturbations acting on both the light fields and atomic wave packets give rise to effective phase shifts.
We show that atom interferometers exhibit an intrinsic sensitivity to gravitational waves due to their spatial separation. In contrast, atomic clocks are only indirectly sensitive, as interrogation pulses effectively probe distances between spatially separated clocks. We will discuss the conditions under which this mechanism becomes relevant, in particular the requirement of geodesic motion, which is naturally realized in satellite-based scenarios but typically not in terrestrial experiments.
A key challenge for high-precision sensing of such minute phases is noise mitigation, which is commonly addressed through correlation measurements between two sensors, which is key to any proposal for dark-matter or gravitational-wave detection. Inspired by quantum clock interferometry, we introduce Parameter Estimation from Amplitude Collapse (PEAC), a method for phase extraction that does not rely on strict phase stability [2].
We demonstrate that PEAC significantly improves the trueness of phase estimation, substantially reducing bias compared to standard approaches for perfectly correlated signals like ellipse fitting. Moreover, we show that optimal performance is achieved near, but not exactly at, vanishing signal amplitude, where the method reaches a precision comparable to conventional estimators. Overall, we will establish PEAC as a broadly applicable and robust analysis tool for correlated quantum sensors, and outline its potential for enhancing gravitational-wave detection with atomic systems as well as for a wider range of precision-measurement applications.

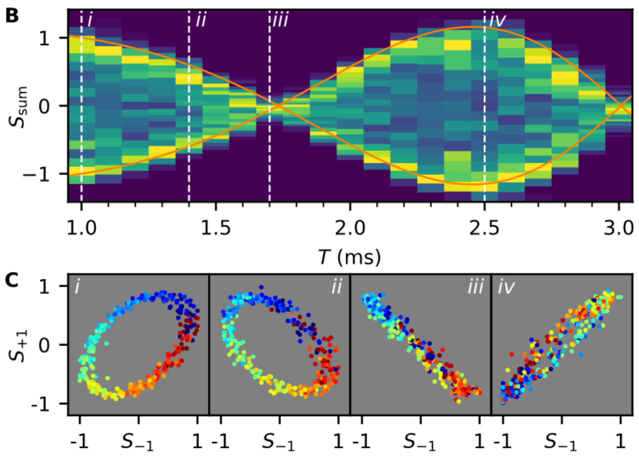


Figure 1:Amplitude collapse of two correlated superposed interference signals extracted from a statistical histogram analysis and bivariate ellipse plots of the respective correlation data. The amplitude collapse is a distinct feature of PEAC. Taken from [2].

[1] S. Schaffrath, D. Störk, F. Di Pumpo & E. Giese, *Unified laboratory-frame analysis of atomic gravitational-wave sensors*, AVS Quantum Science 7, 044402 (2025)
[2] D. Derr, D. Pfeiffer, L. Lind, G. Birkl & E. Giese, *Phase Estimation from Amplitude Collapse in Correlated Matter-Wave Interference,* arXiv:2602.12227 [quant-ph]

Towards Rotational Matter-Wave Interference with Levitated Nanorotors

Florian Fechtel[1], Stephan Troyer[1], Lorenz Hummer[1], Benjamin Stickler[2], and Markus Arndt[1]

[1]University of Vienna, Faculty of Physics & Vienna Doctoral School in Physics & Vienna Center for Quantum Science and Technology, Vienna, Austria
[2]Institute for Complex Quantum Systems and Center for Integrated Quantum Science and Technology, Ulm University, Ulm, Germany

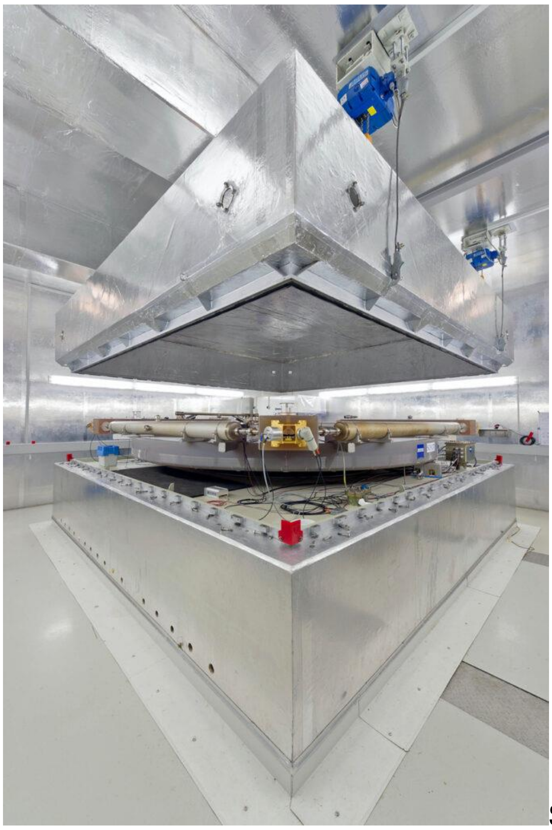
April 15, 2026

Abstract

Levitated nanoparticles are emerging as uniquely powerful platforms for probing quantum mechanics and matter-wave interference at macroscopic mass scales. Particles trapped in an optical tweezer feature exceptionally high quality factors, realizing a near-ideal harmonic oscillator. Among all motional degrees of freedom, rotational motion is of particular interest. Since rotational dynamics are nonlinear and confined to a periodic, compact phase space, they support mesoscopic quantum phenomena such as tunnelling in persistent quantum tennis racket flips and rotational matter-wave interference. The nonlinearity enables interference effects that can be observed without an additional beam splitter. This same nonlinearity inevitably introduces cross-coupling between rotational modes, necessitating motional control over at least two rotational degrees of freedom.

We demonstrate simultaneous ground-state cooling of two librational modes (α and β) of a silica nano-dumbbell (mass 4 GDa) via coherent scattering into a bimodal high-finesse cavity. Each orthogonal cavity mode couples selectively to one librational mode, preventing mode hybridisation and enabling independent cooling of each mode. By selecting nano-dumbbells with nearly degenerate librational frequencies and tuning the cavity birefringence, we achieve simultaneous ground-state cooling of both modes and report an angular alignment with a precision better than 20 µrad — approaching the quantum zero-point fluctuation. Starting from this cooled state, we aim to implement a rotational revival protocol. The orientational ground state corresponds in the angular momentum basis to a coherent superposition spanning a mean occupation $\langle j \rangle \sim 10^4$. Upon non-adiabatic release, the state disperses under free evolution into a superposition of rotational quantum states with classically mutually exclusive angular momenta. At the revival time, collective interference among all components reconstructs the initial alignment. The revival time scales linearly with the particle's moment of inertia, reaching approximately one hour for our cooled nano-dumbbell. Reducing the particle mass to the 10 MDa range brings the revival time into the millisecond regime, rendering rotational matter-wave interference experimentally feasible. We therefore extend these cooling and control techniques to rotors with smaller moments of inertia, paving the way towards rotational quantum revivals at macroscopic mass scales.

Inertial Earth Rotation Sensing utilizing Large Ring Lasers - Schreiber, Karl Ulrich (Invited Talk)


Side view of the ring-interferometer

Ring lasers are now resolving the rate of rotation of the Earth with 8 significant digits. Technically they constitute a Sagnac interferometer, where a traveling wave resonator, circumscribing an arbitrary contour, defines the optical frequencies of two counter-propagating resonant laser beams. Subtle non-reciprocal effects on these laser beams however, cause a variable bias, which reduces the long-term stability. Over the last two years, we have improved the performance of the G ring laser at the Geodetic Observatory Wettzell to the point, that we obtain long-term stable conditions over more than a year. Advances in the modeling of the non- linear behavior of the laser excitation process as well as some small but significant improvements in the operation of the laser gyroscope are taking us now right to the point, where the periodic part of the variable Earth rotation amounting to less than 1 ms in the Length of Day (LoD) can be recovered.

Since a ring laser gyroscope is an inertial sensor, it is sensitive to the precession of the earth rotation axis. This corresponds to a continuous motion of 50 seconds of arc per year. It is the first time that this has been observed by an inertial sensing technique. A laser gyroscope is a local sensor, but we extract a global quantity from it. How accurate are these measurements and where are the persisting error sources? This talk outlines the current state of the art of inertial rotation sensing in the geosciences and points out where the remaining challenges lie. Furthermore, we discuss promising ways for an improved sensor stability.

Global and Multiphase Estimation with Multipartite Qudit Resources - Smerzi Augusto (Invited Talk)

Quantum metrology is usually formulated in the local regime, where Fisher information sets the ultimate precision. In this talk I will discuss global and multiphase estimation, where periodicity, finite data, and measurement incompatibility can become important. I will then show how multipartite qudit entanglement provides a natural resource for these tasks. Using collective SU(d) generators and Young-diagram methods, one can classify high-dimensional entanglement structures and derive Fisher-information bounds that certify useful metrological resources.

Optimized squeezing for accurate differential sensing under large phase noise

Robin Corgier[1,†], Marco Malitesta[2,3,†], Leonid A. Sidorenkov[1], Franck Pereira Dos Santos [1], Gabriele Rosi[3,4], Guglielmo M. Tino[2,3,4,5], Augusto Smerzi[2,5,6], Leonardo Salvi[3,4,5], Luca Pezzè[2,5,6]

[1]LTE, Observatoire de Paris, Université PSL, Sorbonne Université, Université Lille, LNE, CNRS, 61 avenue de l'Observatoire, 75014 Paris, France.

[2] Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche (INO-CNR), Largo Enrico Fermi 6, 50125 Firenze, Italy.

[3] Department of Physics and Astronomy, Universita di Firenze, Via Sansone 1 50019 Sesto Fiorentino, Italy.

[4] Istituto Nazionale di Fisica Nucleare (INFN), Via Sansone 1, 50019 Sesto Fiorentino, Italy.

[5] European Laboratory for Nonlinear Spectroscopy (LENS), Via Nello Carrara 1, 50019 Sesto Fiorentino, Italy.

[6] QSTAR, Largo Enrico Fermi 2, 50125 Firenze, Italy.

Abstract.

Atom interferometers are reaching sensitivities fundamentally constrained by quantum fluctuations. A main challenge is to integrate entanglement into quantum sensing protocols to enhance precision while ensuring robustness against noise and systematics. Here, we theoretically investigate differential phase measurements with two atom interferometers using spin-squeezed states of N atoms, accounting for common-mode phase noise spanning the full 2π range. We estimate the differential signal using model-free ellipse fitting, a robust method requiring no device calibration and resilient to additional noise sources. Our results show that spin-squeezing enables sensitivities below the standard quantum limit (SQL). Specifically, we identify optimal squeezed states that minimize the differential phase uncertainty, scaling as $N^{-2/3}$, thus overcoming the SQL by a factor $N^{1/6}$, while eliminating the bias inherent in ellipse fitting methods. We benchmark our protocol against the Cramér-Rao bound and compare it with hybrid methods that incorporate auxiliary classical sensors. Our findings provide a pathway to robust and high-precision atom interferometry, in realistic noisy environments and using readily available states and estimation methods.

† These authors contributed equally to this work.

Atom gradiometry for the MIGA large scale interferometer

K. Verbeke[1], Y. Meng[1], N. Mandin[1], Q. Cojean[1], J-B. Gerent[1], A. Bertoldi[1], J. Pinon[3], A. Bodeau[3], Q. Beaufils[2], A. Landragin[2], and B. Canuel[1]

[1]LP2N, Laboratoire Photonique, Numérique et Nanosciences, Université Bordeaux–IOGS–CNRS:UMR 5298, rue F. Mitterrand, F–33400 Talence, France
[2]LTE, Observatoire de Paris, Université PSL, Sorbonne Université, Université de Lille, LNE, CNRS, 61 avenue de l'Observatoire, F-75014 Paris, France
[3]LSBB, Laboratoire Souterrain à Bas Bruit, CNRS UAR3538, Avignon Université, La Grande Combe, F-84400 Rustrel, France

The MIGA (Matter-wave laser Interferometric Gravitation Antenna) project [1] aims to open the way towards a new generation of sub-Hz gravitational waves detectors. This gravity antenna is based on large-scale atomic interferometry techniques which are envisioned by a number of international projects not only for gravitational wave detection but also for Dark Matter studies [2]. The MIGA antenna consists in an array of three Rb Atom Interferometers simultaneously interrogated on a baseline of 150 m. Its construction is now being finalized at the LSBB underground laboratory in Rustrel, France.

A testbed platform is located at the LP2N laboratory (Talence, France) where a reduced scale version of the antenna is up and running with two currently independent atom interferometers. Such a platform allows to speed up the development of the final apparatus and to investigate systematic effects limiting its sensitivity.

We will present this testbed apparatus composed of two atomic interferometers (AI) sharing a common interrogation laser. We will first detail the independent performances of each source, typically producing $N=10^6$ atoms cooled at $T\approx 2\mu K$ with a 1.6 second cycling time. A single retro-reflected interrogation laser, with a waist diameter of 2.4 cm and which is time-modulated, is used to generate standard three pulses atom interferometers with a total interrogation time up to 20 ms. The interferometers operates in the Quasi-Bragg regime with a contrast up to 50%. We will report on the first gradiometric measurements of the setup, in which the two spatially separated AIs are simultaneously interrogated by the interrogation laser, a configuration that effectively rejects common noise sources. We conclude by presenting the gradiometer transfer function and open the discussion on future experimental goals.

References

[1] B. Canuel et al. "Exploring gravity with the MIGA large scale atom interferometer". In: *Sci. Rep.* 8.1 (2018), p. 14064. DOI: 10.1038/s41598-018-32165-z. URL: https://doi.org/10.1038/s41598-018-32165-z.

[2] Abdalla A. et al. "Terrestrial Very-Long-Baseline Atom Interferometry: summary of the second workshop." In: *EPJ Quantum Technol* 12.42 (2025). DOI: https://doi.org/10.1140/epjqt/s40507-025-00344-3.

Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)

Jan Rudolph[1, 2]

[1] *Department of Physics, Stanford University, Stanford, California 94305, USA*
[2] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

The Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100) is a next-generation quantum sensor under construction at Fermilab. It aims to explore fundamental physics using clock atom interferometry across a 100-meter vertical baseline [1]. It will serve as a prototype gravitational wave detector in the unexplored frequency range between 0.01 and 3 Hz, search for ultra-light dark matter in the 10^{-22} – 10^{-15} eV mass range, and test quantum mechanics on macroscopic time and length scales. I will outline the sequence design for the large momentum transfer atom optics that unlock the desired sensitivities for these science goals. Additionally, I will present the current status of the instrument, including challenges and innovations related to the detector design.

[1] M. Abe, *et al.* (MAGIS Collaboration), Quantum Science and Technology **6** (2021)

AION: A prototype differential atom interferometer for fundamental physics

Richard Hobson, Alice Josset, Dillen Lee, Thomas Walker, Ludovico Iannizzotto Venezze, Leonie Hawkins, Charles F A Baynham, Oliver Buchmueller

Gravitational waves and dark matter are among the most compelling frontiers in fundamental physics, motivating proposals for Very Long-Baseline Atom Interferometers (VLBAIs) such as AION, MAGIS, AICE, and AEDGE. In this talk, I give an overview of one such project, AION, for which we have recently built the first "mini" prototype of a VLBAI using the Sr-87 clock transition. I present the latest results from the AION Sr-87 interferometer, showing operation at the Standard Quantum Limit, immunity to laser phase noise, and sensitivity to artificially injected coherent oscillatory signals—analogous to dark matter and gravitational waves—across a broad frequency range. Finally, I describe prospects for new clock interferometry techniques and the development of larger VLBAI detectors.

Photon-Mediated Interactions for Novel Matterwave Interferometers and Clocks - Thompson, James K. (Invited Talk)

Photons bouncing back and forth many times between highly reflecting mirrors provides a novel way to mediate interactions between laser-cooled atoms held between the mirrors. Such photon-mediated interactions provide a unique set of tools for both quantum simulation and sensing. In this talk, I will discuss our efforts to sculpt these interactions in order to expand the palette of cavity-mediated interactions that can be a realized, including exchange interactions [1, 2], many-body gap protection [1-3], XYZ interactions [4], 3 & 4-body interactions [5], and dissipative interactions [6-7]. I will high light our work in the context of enhanced matterwave interferometers [2-5, 8] and optical clocks [9].

[1] Norcia et al, *Science* 361 259 (2018)

[2] Luo et al, *Science* **384** 551 (2024)

[3] Niu et al, *Phy. Rev. Lett.* **134** (11) 113403 (2025)

[4] Luo et al, *Nature Physics* **21** 916 (2025)

[5] Luo et al, *Science* **390** 925(2025)

[6] Schafer et al, *Nature Physics* **21** 902 (2025)

[7] Song et al, *Science Adv.* **11**, eadu5799 (2025)

[8] Greve et al, *Nature* **610** 472-477 (2022)

[9] Robinson et al, *Nature Physics* **20** 208-213 (2024)

Probing quantum mechanics with nanoparticle matter-wave interferometry

S. Pedalino[1,2], B. Ramírez-Galindo[1,2], R. Ferstl[1,2], K. Hornberger[3], S. Gerlich[1] and M. Arndt[1]

[1]*Faculty of Physics, University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria*
[2]*University of Vienna, Vienna Doctoral School in Physics, Boltzmanngasse 5, 1090 Vienna, Austria*
[3] *Faculty of Physics, University of Duisburg-Essen, Duisburg, Germany*

Exploring the transition between quantum mechanics and classical physics remains a central challenge in physics. At its heart lies the superposition principle: while it underpins modern quantum theory and many emerging technologies, its consequences appear to fade from view as systems become larger and more complex. **Matter-wave interferometry** provides a particularly direct way to probe this boundary by preparing the center-of-mass motion of **massive particles in spatial superposition states** and reading out quantum coherence through interference.

In this contribution, we present matter-wave interference of 8 nanometer large **sodium nanoparticles** containing more than **7,000 atoms**, with masses exceeding **170,000 Da**. The particles propagate in **Schrödinger-cat-like** motional superposition states and reach a macroscopicity of **μ = 15.5** [1], improving on previous matter-wave interferometry benchmarks by an order of magnitude in this metric. These results extend spatial superposition to substantially larger masses and to a qualitatively new material class for high-mass quantum experiments.

To achieve this, we introduce an experimental platform [2] that extends matter-wave interference to **large metal clusters** [3], establishing a qualitatively new material class for high-mass quantum experiments. The approach provides a clear route to prepare and probe delocalized center-of-mass states of nanoparticles and to study how coherence persists, or breaks down, as system size and complexity grow.

Beyond fundamental tests, the strong phase sensitivity of matter-wave fringes enables **precision sensing**: small phase shifts translate into accurate measurements of particle properties. Applied to mass-selected metal clusters, this opens access to **magnetic** [4], **electric** [5], and **optical** [6] response parameters, providing insights relevant to cluster physics and potential applications in nanotechnology and materials science.

[1] S. Pedalino, B. E. Ramírez-Galindo, R. Ferstl, K. Hornberger, M. Arndt, and S. Gerlich, **Nature 649, 866–870 (2026)**
[2] S. Pedalino,B. Ramírez Galindo, T. de Sousa, Y. Y. Fein, P. Geyer, S. Gerlich and M. Arndt. *Quantum Sensing, Imaging, and Precision Metrology* (**Vol. 12447, pp. 100-109**) (2023)
[3] S. Pedalino, T. de Sousa, Y. Y. Fein, S. Gerlich, and M. Arndt, **Physical Review A 106 (2), 023312 (2022)**
[4] Y. Y. Fein, P. Geyer, F. Kiałka, S. Gerlich, and Markus Arndt, **Phys. Rev. Res. 1, 033158 (2019)**
[5] Y. Y. Fein, S. Pedalino, A. Shayeghi, F. Kiałka, S. Gerlich, M. Arndt, **Phys. Rev. Lett. 129*, 123001* (2022)**
[6] Y. Y. Fein, A. Shayeghi, L. Mairhofer, F. Kiałka, P. Rieser, P. Geyer, S. Gerlich, and M. Arndt, **Phys. Rev. X 10, 011014. (2020)**

Cavity-mediated momentum squeezing for time-domain atom interferometry below SQL

Nicolò Montalti,[1,*] Panagiotis Christodoulou,[1]
Jacob Fricke,[1] Tobias Donner,[1] and Tilman Esslinger[1]
[1] *ETH Zürich, Otto Stern Weg 1, 8093 Zürich*

Time-domain atom interferometry currently provides the most accurate determinations of the fine-structure constant α through the measurement of atomic recoil frequencies. However, beyond systematic uncertainties, the sensitivity of traditional methods is fundamentally limited by the standard quantum limit (SQL). To overcome this constraint, we demonstrate a method for generating momentum-squeezed pairs of atoms using a ^{87}Rb Bose-Einstein condensate in a high-finesse optical cavity (Fig. 1). By seeding the cavity with an external laser, we can transition the dynamics from a parametrically amplified quantum regime to classical Kapitza-Dirac scattering. Leveraging these squeezed states, we implement an SU(1,1) Talbot-like active interferometer that enables sub-shot-noise measurements of the atomic recoil. This approach opens a route toward more precise determinations of fundamental constants and stringent tests of their consistency with the standard model.

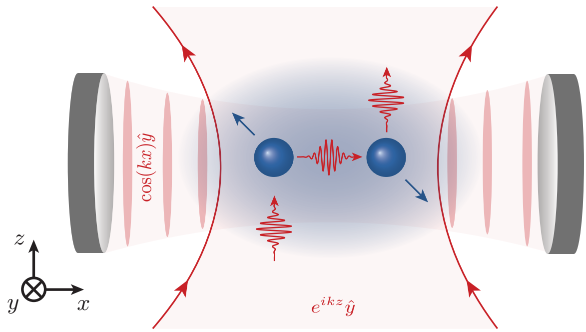


FIG. 1. A ^{87}Rb BEC is positioned in a high-finesse optical cavity and transversally pumped. A pump photon is scattered into the cavity mode and subsequently reabsorbed by a second atom. Upon re-emission of the photon into the pump field, the process leaves behind a number-squeezed pair of atoms with correlated momenta, in analogy to optical parametric down-conversion.

* nmontalti@ethz.ch

Quantum Sensing for Rail Positioning

Andrew David White
Centre for Cold Matter, Imperial College London, South Kensington Campus, London, SW7 2AZ

A. Ainsworth, D. Bahra, R. Shah, A. Cimbri, A. Kaushik, J.P. Cotter
Centre for Cold Matter, Imperial College London, South Kensington Campus, London, SW7 2AZ

Global Navigation Satellite Systems (GNSS) are critical to our daily lives, supporting many sectors including transport, finance, and defence. In fact, 10% of the EU's GDP is enabled by GNSS [1], as such, a GNSS outage would cause significant financial and societal damage. Consequently, new methods that support the continuity of critical national infrastructure are under development. In areas where GNSS cannot be relied upon, inertial navigation can be used as an alternative to accurately position vehicles. However, for many applications, the drift in the classical accelerometers and gyroscopes that underpin inertial navigation systems limits the position accuracy that can be achieved. Quantum enhanced inertial sensors offer an attractive alternative with the potential to deliver much lower drift rates and therefore facilitate more precise inertial navigation over longer periods of time. With more accurate positioning systems the London Underground rail network, which is 45% below the surface [2], would be able to increase capacity and reliability.

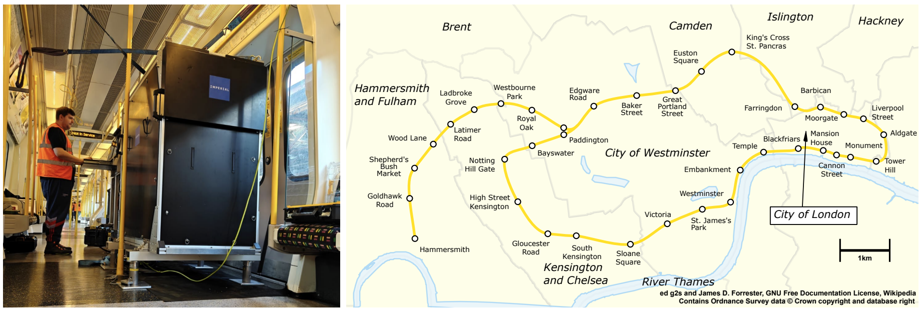


Fig. 1 Quantum enhanced accelerometer deployed on the London Underground rail network and the route of the train under London.

At Imperial College London we are developing quantum enhanced inertial sensors, using cold atom interferometry, that can be deployed in a rail environment and have recently begun live testing on the Transport for London underground network. We will present an overview of the sensor and discuss recent developments to translate quantum sensors into a robust and reliable technology for rail positioning.

References

[1] European commission, "EU SPACE Programme Overview". Available at https://defence-industry-space.ec.europa.eu/eu-space-programme-overview_en (Accessed March 2026)
[2] Transport for London (TFL), Available at https://tfl.gov.uk/ (Accessed January 2025)

Airborne strapdown quantum gravimeter

Y. Bidel[1], S. Darmon[1], A. Maïnos[1], A. Bresson[1], N. Zahzam[1], C. Blanchard[1], M. Cadoret[2], L. Faure[3], F. A. Wahab de la Fuente[4], B. Kaczmarczuk[5], Q. Beaufils[5], F. Pereira Dos Santos[5], T. E. Jensen[5]

[1] DPHY, ONERA, Université Paris-Saclay, France
[2] LCM, CNAM, France
[3] EXAIL, France
[4] SENER Aeroespacia, Spain
[5] Laboratoire Temps Espace, Observatoire de Paris, Université PSL, Sorbonne Université
[6] Department of Space Research and Space Technology, Technical University of Denmark, Denmark

Airborne gravimetry is a powerful tool for regional gravity mapping. It fills a gap between satellite techniques, which have a low spatial resolution, and traditional ground measurements, which can only be performed on the ground in accessible areas. Atom interferometry has already revolutionized airborne gravimetry by providing, for the first time, a sensor capable of performing absolute gravity measurements, i.e., a sensor that does not suffer from drift and does not need to be calibrated [1] [2] [3] [4]. Here, we report the development of a second-generation airborne quantum gravimeter, which aims to be smaller and more precise. To this end, we developed an instrument that does not require a gyrostabilized platform, reducing the volume and mass from 486 L and 200 kg to 27 L and 48 kg. The rotational operating range has been improved by hybridizing the atom accelerometer with classical accelerometers and gyroscopes. We also studied techniques and methods to improve accuracy in dynamic. We tested this strapdown gravimeter on a hexapod simulating aircraft motion and obtained a measurement precision of 0.15 mGal, which is twice as good as that obtained with the gyrostabilized gravimeter. These results pave the way for the use of quantum gravimeters in smaller aircraft and even drones, and also to improve the precision of airborne gravity measurements.

[1] Y. Bidel, N. Zahzam, A. Bresson, C. Blanchard, M. Cadoret, A. V. Olesen, and R. Forsberg, Absolute airborne gravimetry with a cold atom sensor, Journal of Geodesy **94**, 20 (2020).
[2] Y. Bidel et al., Airborne Absolute Gravimetry With a Quantum Sensor, Comparison With Classical Technologies, Journal of Geophysical Research: Solid Earth **128**, e2022JB025921 (2023).
[3] T. E. Jensen, B. Dale, A. Stokholm, R. Forsberg, A. Bresson, N. Zahzam, A. Bonnin, and Y. Bidel, Airborne gravimetry with quantum technology: observations from Iceland and Greenland, Earth System Science Data **17**, 1667 (2025).
[4] J. Wang et al., Cross-Validated Airborne Gravimetry With Dual Atomic Absolute Gravimeters, IEEE Transactions on Instrumentation and Measurement **75**, 1 (2026).

Figure 1 – Airborne cold atom gravimeter. (left: laser and electronic system, right : sensor head and Inertial Measurement Unit mounted on a vibration isolation platform.

Yannick Bidel

New frontiers in quantum simulation and sensing via cavity mediated interactions - Ana Maria Rey - JILA, NIST and University of Colorado, Boulder, CO 80309-0440, USA - Email: arey@jilau1.colorado.edu (Keynote Talk)

Atoms and photons are the fundamental building blocks of our universe. Their interactions rule the behavior of our physical world but at the same time can be extremely complex, especially in the context of many-body quantum systems. Understanding and harnessing them is one of the major challenges of modern quantum science. In recent years, ultracold atomic systems have emerged as a pristine platform for the exploration of atom-light interactions. I will discuss the potential of atomic systems loaded in optical cavities as a resource to enhance the energy scales needed to observe complex many-body behaviors by harnessing infinity range interactions mediated by photons that can couple a large set of internal levels. I will show how cavity systems can help us not only to shed light on behaviors of iconic Hamiltonians describing real materials but also to engineer broader classes of Hamiltonians with multi-body interactions too complex to emerge naturally. Furthermore, I will explain how they can facilitate the generation of quantum entanglement and overcome physical constraints currently limiting the performance of state-of-the-art atomic clocks and interferometers.

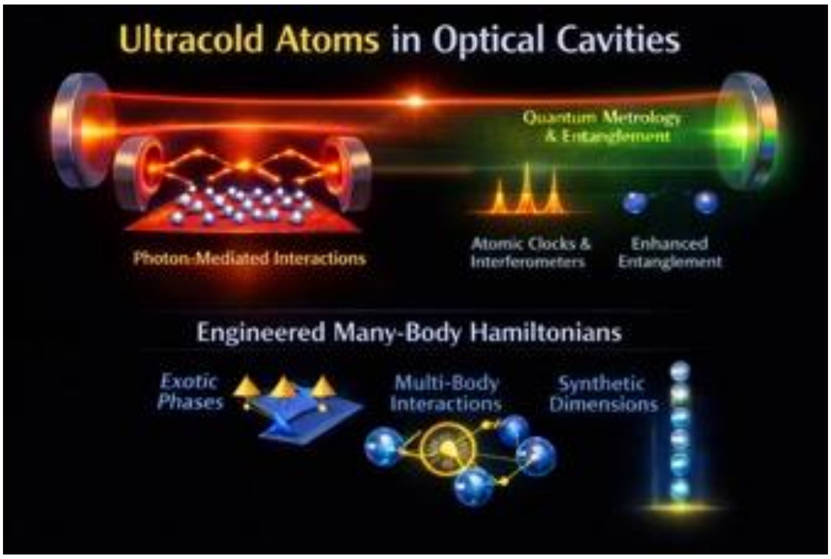


Figure: atoms in optical cavities are a unique platform for advancing quantum simulation and sensing.

Precision measurements of Casimir-Polder potential and prospects with material transmission gratings

Bruneau M.[1,2], De Girolamo E.[1,2], Routier G.[2], Fabre N.[2], Ducloy M.[2], Bouton Q.[2], Gaaloul N.[1], Impens F.[3], Dutier G.[2]

[1]Institut für Quantenoptik, Leibniz Universität Hannover, Germany,
[2]Laboratoire de physique des lasers, Université Sorbonne Paris Nord, Villetaneuse, France,
[3]Federal University of Rio de Janeiro, Rio de Janeiro, Brazil.

Measuring Casimir-Polder potential - the atom surface interaction - remains challenging over the years simply due to the nanometer scale involved. The use of a slow atomic beam crossing a transmission grating with typical 100 nm slits is an appropriate tool to constrain atom surface distances and built a text book experiment. Model the atomic diffraction picture requires assembling the full wave function diffraction and exact Casimir-Polder potential. A constant effort has been made on calculating the wave function propagation inside the grating that leads to a novel situation where the potential accuracy is expected to drop down from 17% [1] to few percents.

A novel tomography-like experimental method coupled to the complete modeling leads us to unprecedented understanding of atomic diffraction through transmission gratings for future experimental scenario. A first theoretical proposal based on a multi order atomic interferometer shows a significant accuracy enhancement of the usual Mach-Zehnder design based on constructive quantum interferences between diffraction orders. In a different way, quantum reflection is a good candidate for Casimir-Polder intermediate range measurements [2]. And finally, physics beyond standard model can be probed at the current state of the art with such an atomic set up in the sub-micrometer scale near surfaces.

[1] J. Lecoffre, A. Hadi, M. Bruneau, C. Garcion, N. Fabre, E. Charron, N. Gaaloul, G. Dutier, and Q. Bouton, "Measurement of Casimir-Polder interaction for slow atoms through a material grating", **Physical Review Research 7**, 013232 **(2025)**

[2] J. Fiedler, F. Spallek, A. Vega, E. K. Osestad, Q. Bouton and G. Dutier, "Quantum reflection effects in the diffraction of matter waves", **Europhysic Letter 151,** 25003 **(2025)**

Fast atom diffraction through single-layer graphene

Christian Brand[1], Carina Kanitz[1], Jakob Bühler[1], François Aguillon[2], Vladimír Zobač[3], Toma Susi[3], Philippe Roncin[2] and Maxime Debiossac[1]

[1]German Aerospace Center (DLR), Institute of Quantum Technologies
[2]Institut des Sciences Moléculaires d'Orsay (ISMO), Centre national de la recherche scientifique (CNRS)
[3]University of Vienna, Faculty of Physics

Quantum experiments with ultra-cold clouds of atoms have become the work horse in matter-wave interferometry. Complementary to that, we explore the opposite part of the energy spectrum, using atoms at kiloelectronvolt energies. This led to the recent demonstration of atom diffraction through single-layer graphene in our group [1]. In the experiments, the combination of short and strong atom-lattice interactions opens the door to a rich field of physics to be explored. In the case of helium, we observe a new diffraction regime where the thermal movement of the lattice atoms induces dephasing of the grating structure. This effect is not present for atomic hydrogen, where the interaction potential with the material is considerably weaker. Interestingly, diffraction through 2D materials is not limited to neutral atoms, but is also observed for ions [2]. Fast atom diffraction in transmission thus opens new vistas for materials research and sheds light onto novel physical phenomena.

[1] Kanitz *et al.*, Science **389**, 724-726 (2025)
[2] Kanitz *et al.*, in preparation