Classical and Quantum Fluctuations across Systems and Scales

823. WE-Heraeus-Seminar

16 - 20 December 2024

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 823. WE-Heraeus-Seminar:

Fluctuations are a fundamental manifestation of the microscopic stochastic/quantum dynamics of physical systems. They are present at very different scales and give rise to a plethora of effects, relevant across various research fields. Understanding the origin of fluctuation-induced phenomena is rapidly becoming important not only for fundamental investigations but also for the characterization of experimental setups and for the opportunities and challenges that they offer to modern technologies. The seminar covers a broad range of subjects having fluctuations as a common denominator. It focuses on current challenges encompassing diverse physical systems both in and out of equilibrium, spanning different scales and configurations. It is structured around following themes:

- Gravitation: Early Universe Cosmology; physics of black holes; analogue models of gravity.
- Atomic physics & Metrology: Superfluids; ultracold atoms; metrology; sensing.
- Light-matter interaction: Quantum optics; optomechanics; Casimir, Casimir-Polder & van der Waals forces.
- Statistical Physics: Quantum thermodynamics; nonequilibrium physics; complex systems.

The pronounced interdisciplinary nature of the seminar aims to facilitate the exchange of complementary views, methodologies and expertise, fostering cross-fertilization of ideas among diverse research communities. By convening leading experts working on different area of physics directly related to fluctuations, the Seminar provides the ideal setting to assess the current status of this rapidly developing field and to discuss future developments.

Introduction

Scientific Organizers:

Prof. Dr. Kurt Busch	Humboldt-Universität zu Berlin Institut für Physik, Germany E-Mail: kurt.busch@physik.hu-berlin.de
Dr. Salvatore Butera	University of Glasgow School of Physics and Astronomy, UK E-Mail: salvatore.butera@glasgow.ac.uk
Dr. Francesco Intravaia	Humboldt-Universität zu Berlin Institut für Physik, Germany E-Mail: francesco.intravaia@physik.hu-berlin.de

Administrative Organization:

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Introduction

Venue:

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Registration:

Marion Reisinger (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 15 December 2024

17:00 – 21:00	Registration	
18:30	*BUFFET SUPPER and informal get-together*	

Monday, 16 December 2024

08:00	*BREAKFAST*	
08:45 – 09:00	Dr. Kurt Busch Dr. Salvatore Butera Dr. Francesco Intravaia	**Welcome words**
09:00 – 09:40	Markus Oberthaler	**Observations of Quantum and 'Classical' Fluctuations of Quantum Fields**
09:40 – 10:05	David Clement	**Emergence of non-Gaussian atom correlations in strongly interacting ultracold Bose gases**
10:05 – 10:30	Kevin T. Geier	**Superfluidity and sound propagation in disordered Bose gase3**
10:30 – 11:10	*COFFEE BREAK*	
11:10 – 11:50	Gabriele Ferrari	**False vacuum decay via bubble nucleation in ferromagnetic superfluids**
11:50 – 12:15	Fabio Lingua	**Continuous-variable square-ladder cluster states in a microwave frequency comb**
12:15 – 14:00	*LUNCH*	

Program

Monday, 16 December 2024

14:00 – 14:40	Giovanna Morigi	**Quantum spatial searches**
14:40 – 15:05	Rodrigo Câmara	**Topological Properties of Spin Dynamics and Symmetry-Breaking in Chiral Atomic Systems**
15:05 – 15:30	Oksana Chelpanova	**Semi-classical dynamics of quantum spin chains in the presence of a non-Markovian environment**
15:30 – 16:10	*COFFEE BREAK*	
16:10 – 16:50	Pierre-François Cohadon	**From Gravitational-Wave Detection to Quantum Optomechanics**
16:50 – 17:15	Lilia Woods	**Quantum Friction and Landau-Zener Tunneling in Dissipative Systems**
17:15 – 17:30	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
17:30 – 18:00	*Discussions*	
18:30	*DINNER AND GET TOGETHER*	

Program

Tuesday, 17 December 2024

08:00	*BREAKFAST*	
09:00 – 09:40	Ruth Gregory	**Simulating a Quantum Black Hole?**
09:40 – 10:05	Ian Moss	**Dark matter droplets**
10:05 – 10:30	Nick Proukakis	**Fluctuations in Superfluids & Modelling Challenges: Analogies between Ultracold Atoms and Cosmological Fuzzy Dark Matter**
10:30 – 11:10	*COFFEE BREAK*	
11:10 – 11:50	Silke Weinfurtner	**TBA**
11:50 – 12:15	Friedrich Koenig	**Quasinormal modes of optical solitons**
12:15 – 14:00	*LUNCH*	
14:00 – 14:40	Bei-Lok Hu	**Fluctuations of Quantum Fields and Thermodynamics of Spacetime**
14:40 – 15:05	Scott Robertson	**Particle and entanglement production in an analogue preheating experiment**
15:05 – 15:30	Sascha Lang	**Spontaneous photon production in a tuneable dielectric**
15:30 – 16:10	*COFFEE BREAK*	
16:10 – 16:50	Iacopo Carusotto	**Quantum fluctuations in backreaction phenomena**
16:50 – 17:15	**Poster flashes 1**	
17:15 – 18:30	**Poster Session 1**	
18:30	*DINNER AND GET TOGETHER*	

Program

Wednesday, 18 December 2024

08:00	*BREAKFAST*	
09:00 – 09:40	Udo Seifert	**Stochastic thermodynamics: From concepts to model-free inference**
09:40 – 10:05	Benjamin Lindner	**Linear and nonlinear fluctuation-response relations in non-equilibrium systems - spiking neurons, stochastic oscillators, and particles in an active bath**
10:05 – 10:30	Tuan Pham	**Irreversibility in Non-reciprocal Chaotic Systems**
10:30 – 11:10	*COFFEE BREAK*	
11:10 – 11:50	Massimiliano Esposito	**Macroscopic stochastic thermodynamics**
11:50 – 12:15	Krzysztof Ptaszynski	**Dynamical signatures of discontinuous phase transitions: exponential versus power-law scaling**
12:15 – 14:00	*LUNCH*	
14:00 – 14:40	Eric Lutz	**Fluctuations and stability of quantum heat engines**
14:40 – 15:05	Philipp Strasberg	**Emergent decoherent histories in isolated quantum many-body systems**
15:05 – 15:30	Carsten Henkel	**Hybrid dynamics of quantum systems coupled to a small heat bath**
15:30 – 16:10	*COFFEE BREAK*	
16:10 – 16:50	Miles P. Blencowe	**Mapping gravitational decoherence and entanglement to multimode optomechanics**
16:50 – 17:15	**Poster flashes 2**	
17:15 – 18:30	**Poster Session 2**	
18:30	*HERAEUS DINNER ((social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 19 December 2024

08:00	*BREAKFAST*	
09:00 – 09:40	Lukas Novotny	**Classical and quantum fluctuations probed with a levitated nanoparticle**
09:40 – 10:05	Kimball Milton	**Quantum Vacuum Self-Propulsion and Torque of Inhomogeneous Bodies out of Thermal Equilibrium**
10:05 – 10:30	Daniel Bloch	**Near-Field Thermal and Vacuum Fluctuations at an Interface: Experimental Attempts for a Precise Determination of Surface Resonances**
10:30 – 11:10	*COFFEE BREAK*	
11:10 – 11:50	Ricardo Decca	**New scheme for measurement of short range forces**
11:50 – 12:15	Carles Martí Farràs	**Numerical Evaluation of Casimir-Lifshitz Forces in the Time Domain**
12:15 – 12:20	CONFERENCE PHOTO	
12:20 – 14:00	*LUNCH*	
14:00 – 14:40	Roberto Passante	**Radiation-mediated processes between atoms in external backgrounds or in non-inertial frames**
14:40 – 15:05	Lucia Rizzuto	**Dispersion interactions in quantum or classical external environments**
15:05 – 15:30	Romuald Kilianski	**Algorithmic discovery of repulsive CP forces**
15:30 – 16:10	*COFFEE BREAK*	
16:10 – 16:35	Steven Kim	**Superbunched Radiation of a Tunnel Junction due to Charge Quantization**
18:30	*DINNER AND GET TOGETHER*	

Program

Friday, 20 December 2024

08:00	*BREAKFAST*	
09:00 – 09:25	Omar Jesús Franca Santiago	**Purcell effect in chiral environment**
09:25 – 09:50	William McGregor	**Cavity Decay Rate with Topological Insulators**
09 50 – 10:15	Šimon Gabaj	**Modifying quantum friction with advanced material properties**
10:15 – 10:55	*COFFEE BREAK*	
10:55– 11:20	Jaehyeok Jin	**Auxiliary Field Classical Monte Carlo: Integrating Quantum and Classical Sampling into Bottom-Up Field-Theoretical Modeling**
11:20– 11:45	Viktor Pergamenshchyk	**General hydrodynamic approach for a cold Bose gas**
11:45 – 12:00	Scientific organizers	**Closing words**
12:00	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Saturday; however, a self-service breakfast will be provided on Saturday morning

Posters

Poster Session 1, Tuesday 17 December 2024, 17:15 h

Nils Berhausen	**A microscopic model for a nonlinear dissipative dielectric medium**
Kate Brown	**Mitigating boundary effects in finite temperature simulations of false vacuum decay**
Matthieu Bruneau	**Simulation of atomic diffraction through a nanograting**
Christopher Burgess	**Hyperboloidal methods for the quasinormal modes of non-relativistic systems**
Daniel Derr	**Temporal noise in atom interferometry**
Mairi Gilmour	**Optical wavefront control using atomic arrays**
Christian Miguel Karres	**Spurious effects in quantum-enhanced atom interferometers**
Arman Kashef	**Fluctuation-Dissipation Theorem in open quantum systems: Compatibility with the Lindblad Master equation at thermal equilibrium**
Deniz Defne Köksal	**Graphene-Induced modification of atomic spontaneous emission**
Cristofero Oglialoro	**Quantum Vacuum Correlations in a Modified Analogue Spacetime**
Taylor Ray	**Controlling noise in quantum devices using phononic spectral hole burning**
Lara Marie Tomasch	**Jaynes-Cummings Model for Chiral Cavity Quantum Electrodynamics**

Poster Session 2, Wednesday 18 December 2024, 17:00 h

Ignat Fialkovskiy	**On casimir force in smooth layered systems**
Sebastián Franchino-Viñas	**Local semitransparent boundary conditions and resummations for scalar pair creation**
Ayoub Hadi	**Towards precise measurement of the Casimir-Polder interaction**
Bal Krishan	**Periodic smoothening of largest fluctuation governs finite size scaling exponents of one dimensional growing interfaces**
Youcef Mouffok	**Magnetoelectronic and thermodynamic properties of new quaternary heusler alloys for spintronics applications**
Riza Ogul	**Nuclear cluster formation in intermediate and high energy heavy-ion collisions**
Enrique Puga Cital	**Thermodynamic Trade-Offs in steady-state heat engines with Inertia**
Juan Carlos Rivera Hernández	**Non-reciprocal scattering in a microwave frequency comb**
Gopal Chandra Santra	**Quantum resources in disorder**
Tanja Schoger	**Casimir interaction between two spherical objects - in the classical and quantum regime**
Nicolas Schüler	**Casimir-Polder force in a nonlinear medium**
Emma Wünsche	**Three-atom contributions to Casimir forces**

Abstracts of Lectures

(in alphabetical order)

Mapping gravitational decoherence and entanglement to multimode optomechanics

M. Blencowe and J. Yant

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Recent work has shown that it may be possible to detect gravitationally induced entanglement in tabletop experiments in the not-too-distant future. However, there are at present no thoroughly developed models for this type of experiment where the entangled particles are treated more fundamentally as excitations of a relativistic quantum field, and with the measurements modeled using expectation values of field observables. We propose a thought experiment where one (or two) composite particles (comprising N scalar nucleon field quanta) are initially prepared in a superposition of coherent states within a common three-dimensional harmonic trap. The single composite particle initial superposition state can evolve to a mixed state in the presence of a thermal graviton environment, while the two composite particle initial state can evolve to an entangled state through their mutual gravitational interaction, both operationally probed through particle position detection probabilities. We show that the gravitational decoherence and entanglement dynamics of the scalar quantum field interacting with weak field quantum gravity can be approximately mapped onto a multimode optomechanical system, for which the quantum dynamics can be solved analytically up to a mode summation.

Near-Field Thermal and Vacuum Fluctuations at an Interface: Experimental Attempts for a Precise Determination of Surface Resonances

J.C. de Aquino Carvalho[1], I. Maurin[1], P. Chaves de Souza Segundo[1], A. Laliotis[1], D. de Sousa Meneses[2], S. Hurand[3], T. Martinez[3], O. Rozenbaum[2], D. Bloch[1]

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Quantum and e.m. Near-Field (NF) fluctuations are at the origin of Casimir-type interaction, and of applications playing with NF thermal exchanges. This makes it essential to evaluate experimentally the features of surface resonances, which fully govern the range of extreme NF. Accurate measurements reveal delicate, as measurements on nanostructures are often affected by defects in the nano-realization, instead of being test beds of theory.

High-quality sapphire windows should offer the possibility of an accurate evaluation of surface modes, determined in planar geometry by resonances of the complex response $S(\omega) = [\varepsilon(\omega) -1] / [\varepsilon(\omega) + 1]$ –with ε the (complex) relative dielectric permittivity. Evaluation was performed with 3 competing methods:

(i) Through optical NF measurements of Casimir-Polder (CP) interaction at a Cs(7P)/sapphire interface [1], we extrapolated the temperature-dependent surface resonance, in a situation reverse to the one previously exploited to make CP repulsive and to induce surface quenching [2].

(ii) Through Far-Field (FF) thermal emissivity [3], we remeasured $\varepsilon(\omega,T)$ for sapphire: disagreements found between the two methods were tentatively explained [1] by inaccuracy when extrapolating $\varepsilon(\omega)$ to very remote wings of resonances, in order to determine $S(\omega)$ resonances. As a problem, the extrapolation requires a multi-parameter fitting for emissivity, or equivalently a Kramers-Kronig approach, while the spectral features of emissivity are very unspecific close to surface resonances.

(iii) Lastly, ellipsometry, which is an alternate FF technique directly yielding the complex optical index n_c [with $\varepsilon(\omega)= n_c^2$], fully agrees with FF emissivity.

We will comment on possible origins of the observed discrepancies between NF and FF measurements. Also, the expected NF thermal transfer Cs(7P)$\rightarrow$Cs(6D), induced by surface emission of hot sapphire, has remained unobserved.

The joint research is supported by MITI-CNRS.

References

[1] J.C. de Aquino Carvalho *et al*, PRL **131**, 143801 (2023)
[2] H. Failache *et al*, PRL **83**, 5467 (1999); PRL **88**, 243603 (2002)
[3] J.F. Brun *et al*, J. Appl. Phys. 114, 223501 (2013).

Topological Properties of Spin Dynamics and Symmetry-Breaking in Chiral Atomic Systems

Rodrigo P. Câmara[1] **and Mário G. Silveirinha**[1]

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Fluctuations in the quantum vacuum can induce spontaneous breaking of time-reversal symmetry, leading to time-crystal-like states in chiral atomic systems [1]. In a two-level system interacting with a reciprocal environment, these phenomena are manifested as the dynamic motion of the spin magnetic moment, which can be associated with either an attractor-repeller pair or centers on the Bloch sphere. In this work, we present a theoretical study of the topological properties of the spin flow across the entire Bloch sphere. We demonstrate that the flow can exhibit multiple centers, saddles, and attractor-repeller pairs, depending on the nature of the atomic transitions. Furthermore, we explain how the coexistence of these fixed points is governed by time-reversal symmetry and the Poincaré-Hopf theorem.

References

[1] M. G. Silveirinha, H. Terças, M. Antezza, Phys. Rev. B **108**, 235154 (2023)

Quantum fluctuations in backreaction phenomena

Salvatore G. Butera[2] and Iacopo Carusotto[1]

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In this talk, I will review recent theoretical results on the role of quantum fluctuations in back-reaction phenomena for different quantum emission effects such as dynamical Casimir emission [1,2] and (analog) cosmological particle generation [3].
For the different models considered, I will highlight how the backreaction effect results not only in an effective friction acting on the background excitation, but also in a quick loss of its coherence.
I will finally discuss implications of this result on the validity of the usual semiclassical description of backreaction are discussed and assess experimental observability of the predicted effects in realistic analog model systems based on superconducting circuits and on ultracold atomic clouds.

References

[1] S. Butera and I. Carusotto, Phys. Rev. A **99**, 053815 (2019).
[2] S. Butera and I. Carusotto, Europhys. Lett. **128**, 24002 (2019).
[3] S. Butera and I. Carusotto, Phys. Rev. Lett. **130**, 241501 (2023).

Semi-classical dynamics of quantum spin chains in the presence of a non-Markovian environment

<u>Oksana Chelpanova</u>[1], Hossein Hosseinabadi[1] and Jamir Marino[1,2]

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[2] Department of Physics, University at Buffalo SUNY, Buffalo, New York 14260, USA

Far-from-equilibrium dynamics and the fate of correlations of spin systems coupled to the environment are under active study in many areas of physics, such as spin glass in cavity QED, speen squeezing in metrology, and quantum effects in solid-state physics platforms. In quantum optics/ cavity QED platforms, the Lindblad master equation is a valuable tool to simulate such dynamics, and all-to-all interaction enables a semi-classical approximation to be valid at relevant timescales. In this talk, we present a framework based on the Keldysh path integral that allows us to systematically derive semi-classical dynamics from the Lindblad master equation for such driven-dissipative spin models. We also consider the role of memory effects of the environment, and discuss an instance of dynamics of the spin system in the presence of a non-Markovian bath and limits under which time-local description with the Lindblad master equations is sufficient.

Emergence of non-Gaussian atom correlations in strongly interacting ultracold Bose gases

D. Clément[1]

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A cornerstone in the description of quantum fluids is Bogoliubov theory which explains superfluidity in ensembles of weakly-interacting bosons. This theory treats interaction-induced quantum fluctuations with a linearized approach and predicts the population of modes with opposite momenta. Exploiting the capability to detect individual metastable Helium atoms in momentum space [1], we confirmed this microscopic prediction in a quantum gas experiment [2].

Bogoliubov theory is yet inapplicable when interactions are too strong and non-linear quantum fluctuations can no longer be neglected. Varying the amplitude of a 3D optical lattice [3], we studied momentum correlations in superfluids at strong interactions. We observed that the Bogoliubov pairing is suppressed as interactions become stronger [4]. This departure from the predictions of Bogoliubov theory highlights the role of non-linear quantum fluctuations, which we identified as momentum-correlated clusters of more than two particles, a direct signature of non-Gaussian correlations.

On approaching the phase transition to a Mott insulator state [3], the fraction of atoms in condensate vanishes and fluctuates. In this regime, we observed large and non-Gaussian fluctuations of the condensate atom number [5]. We associate this observation to the non-Gaussian fluctuations of the (condensate) order parameter expected in the critical regime of a continuous phase transition.

References

[1] H. Cayla et al. Physical Review A **97**, 061609(R) (2018).
[2] A. Tenart et al. Nature Physics **17**, 1364 (2021).
[3] C. Carcy et al. Physical Review Letters **126**, 045301(2021).
[4] J.P. Bureik et al. Nature Physics (in press) - arXiv:2401.15340 (2024).
[5] In preparation (2024).

From Gravitational-Wave Detection to Quantum Optomechanics

P.-F. Cohadon

Laboratoire Kastler Brossel, Ecole Normale Supérieure – Université PSL, Sorbonne Université, CNRS, Collège de France, Paris, France

The detection of gravitational waves [1] required four decades of experimental effort to achieve a sensitivity of the order of $h \simeq 10^{-21}$. In 1980, Caves discusses the related quantum limits and demonstrates the existence of the Standard Quantum Limit (SQL) [2], which couples quantum fluctuations of the light field to displacement fluctuations of the mirrors of the interferometer. In doing so, it grants a new status to the mirrors: from simple devices for reflecting light, they become real physical objects. Nobody knows it and nobody calls it that yet, but optomechanics is born.

I will present the different techniques considered to go beyond the SQL, from proof-of-principle table-top experiments to 24/7 operation of squeezed light sources to improve the sensitivity of km-scale gravitational interferometers [3, 4].

I will also explain how the considerable progress recently made in micro/nanofabrication have allowed the emergence of a new field, quantum optomechanics, which consists in coupling mechanical micro- or nanoresonators to light, either in the optical or microwave domain. Emphasis can be put on the quantum state either of the field or of the resonator, which can for example be cooled by radiation pressure [5] close to its quantum ground state [6,7]. This field is very promising for the study of the foundations of quantum mechanics, for example for the study of quantum states and the decoherence of macroscopic mechanical resonators [7,8,9] or for quantum information processing [10]. I will present some recent experiments.

References

[1] The LIGO-Virgo Collaboration, Physical Review Letters **116**, 061102 (2016)
[2] Carlton M. Caves, Physical Review Letters **45**, 75 (1980)
[3] The Virgo Collaboration, Physical Review Letters **123**, 231108 (2019)
[4] The LIGO Scientific Collaboration, Physical Review X **13**, 041021 (2023)
[5] O. Arcizet *et al.*, Nature **444**, 71 (2006)
[6] J. D. Teufel *et al.*, Nature **475**, 359 (2011)
[7] M. Croquette *et al.*, AVS Quantum Science **5**, 014403 (2023)
[8] M. Gely and G. Steele, AVS Quantum Science **3**, 035601 (2021)
[9] B.L. Najera-Santos *et al.*, Physical Review X **14**, 011007 (2024)
[10] B. M. Brubake *et al.*, Physical Review X **12**, 021062 (2022)

New scheme for measurement of short range forces

Ricardo S. Decca

Department of Physics, Indiana University Indianapolis

After briefly reviewing our results obtained using a microelectromechanical oscillator during the past two decades, the progress towards using different methods for measuring interactions between closely spaced bodies will come into play. NV-centers and nanocrystals in an optical trap will be presented. In the latter case different approaches to extract the value of the interaction, particularly when in the quantum limit for the oscillator, will be deployed. The advantages of quantum measurement, but also the issues faced with fluctuating backgrounds and their effects in the system will be discussed, in connection towards a better determination of vacuum fluctuating and gravitational interactions.

Macroscopic stochastic thermodynamics

Massimiliano Esposito

University fo Luxembourg

Equilibrium thermodynamics emerges from equilibrium statistical mechanics as the most likely behavior of a system in the macroscopic limit. Over the last two decades, significant progress has been made in formulating statistical mechanics for small systems operating far-from-equilibrium. The resulting theory is often called stochastic thermodynamics. I will show that by taking the macroscopic limit of stochastic thermodynamics, one can formulate a nonequilibrium thermodynamics for large systems, typically described by nonlinear deterministic dynamics and macroscopic fluctuations around it [1]. This macroscopic stochastic thermodynamics gives rise to novel fundamental results. For instance, once can bound nonequilibrium steady state fluctuations using the entropy production along deterministic relaxation trajectories [2]. Many classical phenomenological results from macroscopic irreversible thermodynamics are also recovered within well controlled approximations. This theory opens the way to study the energetics of many complex nonlinear phenomena in a broad range of systems, such as chemical reaction networks (CRNs), nonlinear electrical circuits, and Potts models.

References

[1] G. Falasco and M. Esposito, ”Macroscopic stochastic thermodynamics”, arxiv:2307.12406.

[2] N. Freitas and M. Esposito, ”Emergent second law for non-equilibrium steady states”, Nature Communications 13, 5084 (2022).

Numerical Evaluation of Casimir-Lifshitz Forces in the Time Domain

C. Martí Farràs[1], **P. Kristensenr**[2,3], **B. Beverungen**[1], **F. Intravaia**[1], **K. Busch**[1,4]

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[4]Max Born Institute, Berlin, Germany

Fluctuation-induced phenomena, driven by both quantum and thermal fluctuations of the electromagnetic field, lead to intriguing effects that become particularly significant at short length scales. A prominent example is the Casimir effect, typically describing an attractive force between electrically neutral macroscopic objects. Beyond their fundamental interest, understanding these interactions is crucial for advancing and miniaturizing nanostructured devices. However, semi-analytical calculations are limited to a few highly symmetric geometries, underscoring the need for numerical methods capable of exploring more complex configurations. Such methods are essential for characterizing experimental setups and optimizing the design of nanoscale systems. They can flexibly account for arbitrary geometries, realistic material models, and temperature effects. All these aspects are crucial for accurately capturing the complexities of practical applications.

In this work, we present a time-domain finite-element approach based on the discontinuous Galerkin time-domain (DGTD) method. This framework enables accurate evaluation of the electromagnetic response of a system, providing a versatile and efficient scheme for calculating Casimir interactions across a broad range of scales and configurations. We demonstrate that our numerical method not only accurately reproduces independent reference calculations for both local and non-local material models at finite temperature, but also extends effortlessly to less-symmetric geometries where semi-analytical solutions are unavailable.

False vacuum decay via bubble nucleation in ferromagnetic superfluids

C. Baroni, C. Rogora, D. Andreoni, R. Cominotti, A. Zenesini, G. Lamporesi, G. Ferrari

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TIFPA-INFN, Trento, Italy.

Metastability stems from the finite lifetime of a state when a lower-energy configuration is available but only by tunneling through an energy barrier. In classical many-body systems, metastability naturally emerges in a first-order phase transition. A prototypical example is a supercooled vapor. The extension to quantum field theory and quantum many-body systems has attracted significant interest in the context of statistical physics, protein folding, and cosmology, for which thermal and quantum fluctuations are expected to trigger the transition from the metastable state (false vacuum) to the ground state (true vacuum) through the probabilistic nucleation of bubbles. However, the theoretical progress in estimating the relaxation rate of the metastable field through bubble nucleation has not been validated experimentally. Here, we experimentally observe bubble nucleation in isolated and coherently coupled atomic superfluids, and we support our observations with numerical simulations. The agreement between observations and instanton theory confirms our understanding and promotes coherently coupled atomic superfluids as simulators of out-of-equilibrium quantum field phenomena.

References

[1] R. Cominotti et al., Phys. Rev. X. **13**, 021037 (2023).
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[4] C. Rogora et al., Phys. Rev. A **110**, 013319 (2024).

Purcell effect in chiral environments

Claudio Salvador Rapp[1], Janine Christine Franz[1], Stefan Yoshi Buhmann[1] and Omar Jesus Franca Santiago[1]

[1] *Institut für Physik, Universität Kassel, Heinrich-Plett-Straße 40, 34132 Kassel, Germany*

The Purcell effect describes the modification of the spontaneous decay rate in the presence of electromagnetic media and bodies. In this work, we shed light on the dependencies and magnitude of this effect for chiral materials. Using the framework of macroscopic quantum electrodynamics [1,2] and Fermi's golden rule, we study a chiral bulk medium with and without local field corrections, an idealised chiral mirror and a chiral surface. The results imply that the chiral effect is greatest for large transition frequencies, molecules with large optical rotatory strength, and media with a strong cross-susceptibility. In the case of a surface, short distances from the molecule to the interface additionally enhance the effect.

References

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Modifying quantum friction with advanced material properties

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Quantum friction is a non-contact drag force experienced by a neutral polarizable particle when in relative motion to other objects, such as planar structures. The origin of this interaction can be found in the system's electromagnetic fluctuations and in particular within their quantum-mechanical dynamics. Despite its theoretical significance, quantum friction has proved challenging to observe experimentally. This difficult has motivated extensive theoretical investigations into the underlying mechanisms characterizing the interaction, with the aim of pinpointing strategies for controlling its behavior. Studies have highlighted the role of the system's geometry and of the involved material properties for tailoring the interaction. In this talk, we review how these mechanisms influence quantum friction, especially with advanced material properties.

Superfluidity and sound propagation in disordered Bose gases

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In a superfluid, sound can propagate even at zero temperature, driven by fluctuations of the order parameter. This property is at the heart of many fundamental transport phenomena and technological applications. Understanding the robustness of superfluidity to external perturbations is therefore crucial. This talk covers theoretical and numerical results illustrating how the superfluidity and sound propagation in a Bose–Einstein-condensed gas is affected by a spatially fluctuating random potential modeling optical speckles [1]. A key insight is that the disordered potential reduces the speed of sound and introduces damping via mode coupling. These effects are stronger for anisotropic disorder applied in only one spatial direction. To probe the properties of the sound mode, we compute the linear response to a density perturbation in the long-wavelength limit, giving access to the compressibility as well as the sound velocity and its damping. By invoking hydrodynamic theory, knowledge of these quantities can be used to determine the superfluid fraction even well beyond the perturbative regime of weak disorder. However, if the disorder is too strong, the hydrodynamic description fails. A linear-response measurement of the predicted effects is well within the reach of state-of-the-art cold-atom experiments, which may also help clarify the role of quantum fluctuations on the propagation of sound in the presence of disorder.

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Simulating a Quantum Black Hole?

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Horizons can occur in a wide range of physical situations, many of which we can construct in the lab. Most gravity simulators observe features, like super-radiance, that are analysed as a continuum effect in gravity, whereas many interesting "beyond GR" features theorise about the impact of quantised aspects of the black hole.
In this talk, I will describe recent experimental work on a liquid helium giant vortex that naturally has quantisation, and how we hope to explore "black hole" phenomena in a broader context.

Based on [arXiv:2308.10773 [gr-qc]]

with: Patrik Svancara, Pietro Smaniotto, Leonardo Solidoro, James MacDonald, Sam Patrick, and Silke Weinfurtner

Hybrid dynamics of quantum systems coupled to a small heat bath

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It is often assumed that heat baths are infinitely large. We explore examples of systems where this assumption is dropped. One would expect that energy exchange with the system now significantly alters the bath temperature, and this may feed back into the system. In the talk we analyse two quantum systems, one being a one-dimensional Bose-Einstein condensate [1], the other the localised plasmon resonance of a metallic nano-particle [2]. In both cases, we observe in Monte Carlo simulations [3, 4] a transient evolution towards stationarity. In the stationary state, we analyse fluctuations and evaluate different thermodynamic quantities like the internal energy, heat capacity, Bose degeneracy, and plasmon statistics.

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B. L. Hu (胡悲樂) **Fluctuations of Quantum Fields and Thermodynamics of Spacetime***

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My research in the past 40 years can summarily be represented in a 2D phase space with Quantum-Classical on the horizontal axis, and micro-Macro on the vertical. You can tell from the title of my talk that the intention is to **connect the micro features of quantum matter to the macro-structures of spacetime:** matter via quantum field theory, spacetime via general relativity, and micro/macro interface via nonequilibrium statistical mechanics [1]. This stretch may sound wild on surface, but not so surprising if you knew that in my view, **general relativity is in the nature of a hydrodynamic theory** [arXiv:gr-qc/9607070, arXiv:gr-qc/9511077], **valid only in the long wavelength, low energy domain**. GR is a beautiful theory, yet only an effective theory, emergent from **quantum gravity** -- theories describing the microscopic structures of spacetime at the Planck length (10^{-35} m), not unlike thermo- and hydro- to molecular-dynamics. To me, hydrodynamics and thermodynamics not only serve as a set of useful tools, but provide the **correct perspective to ask meaningful questions** about the nature and behavior of spacetime as we know it. My recent work with H. T. Cho, J. T. Hsiang and Y. Xie attempts to **link up the stress energy fluctuations of quantum fields in spacetimes** (with nontrivial topology or curvature) **with their thermodynamic properties**. The former is represented by the **noise kernel**, the stress energy tensor correlator of quantum matter fields, while the latter by the heat capacity and the (adiabatic and isothermal) compressibility. Noise kernel is the centerpiece of **stochastic gravity** [2], a theory for the dynamics of curved spacetimes based on the Einstein-Langevin equation [arXiv:0802.0658] which incorporates fully and self-consistently the **backreaction effects** from the mean values **and** the fluctuations of quantum field stress tensors. **Examining the noise kernel from a thermodynamic perspective** can add a new dimension to our understanding of its physical properties. E.g., heat capacity gives a measure of the fluctuations of the energy density to the mean, acting as a criterion for the validity of the canonical distribution. An intriguing fact coming from the past 3 decades of work [3] is that **the fluctuations of energy density to the mean is close to unity for quantum fields in many different spacetimes**. From a thermodynamic perspective we conjecture that this feature, even for quantum fields in ordinary Minkowski spacetime, is an indication that the balance between spacetime and quantum matter fields has some built-in thermodynamic instability, that their co-existence meets with a **saturation criterion in the "capacity of spacetime" to "hold" the quantum field,** a theme we view as worthy of deeper thoughts.

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Auxiliary Field Classical Monte Carlo: Integrating Quantum and Classical Sampling into Bottom-Up Field-Theoretical Modeling

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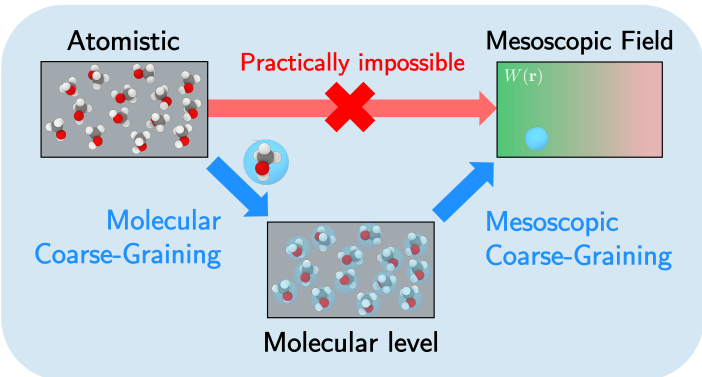
Bottom-up multiscale simulations provide a powerful framework for elucidating the molecular-level mechanisms underlying complex processes across long length and time scales. However, the computational limitations of direct particle-based simulations beyond the molecular scale hinder exploration of mesoscopic phenomena and morphologies. To address this multiscale challenge, we introduce an auxiliary field into classical Monte Carlo sampling, inspired by advancements in Quantum Monte Carlo techniques. Our Auxiliary Field Classical Monte Carlo approach constructs a mesoscopic field formulation by applying the Hubbard-Stratonovich transformation to microscopic interactions, which are derived from multiscale coarse-graining methods. This field-theoretic coarse-graining methodology extends the conventional Hubbard-Stratonovich transformation through the integration of perturbative coarse-graining techniques in reciprocal space. To address numerical phase problems when sampling imaginary values in exponential weights, we utilize Langevin sampling from quantum many-body physics to introduce classical fluctuations for efficient auxiliary field sampling. This novel approach overcomes the limitations of mean-field theory and accommodates a wide range of molecular interactions in condensed matter systems. By combining distinct quantum and classical simulation methodologies, our work significantly expands the range and scope of bottom-up computer simulations.



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Algorithmic discovery of repulsive CP forces

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The ever-progressing miniaturisation of technology makes it impossible to ignore effects arising from the quantum-mechanical description of the world. The forces governing the interactions between molecules, atoms, molecules, and everyday-scale objects belong to the class of phenomena called dispersion forces. The common denominator amongst them is that they are mediated by the quantum vacuum—the lowest energy state of the quantized electromagnetic field.

The particular type of dispersion force of interest to us is the interaction between a neutral atom and a macroscopic metallic surface --- which we refer to as a Casimir-Polder force. A metallic plate near a neutral atom creates an attractive potential, pulling it towards it. The magnitude and direction of the force are then dictated by the object's properties, among them what is most important in our case --- its shape. Despite the seemingly attractive nature of the interaction, we can achieve a repulsive effect by introducing specific geometries. The search for such a structure is limited as CP force can be calculated analytically only for the simplest geometries, motivating us to turn to a computational approach.

We employ a powerful technique of inverse design, operating on the principle of reverse engineering. Given an optimisation goal with a set of constraints, we can match a pre-defined system response with a particular geometry. This reverse problem does not offer a unique solution but one of many that fit our optimization criteria. Therefore, we begin the process with an elementary shape, which the algorithm stretches and moulds in such a way as to produce a repulsive effect on an atom in its vicinity. This method offers the possibility to validate known geometries and provide bespoke alterations in existing structures to produce, tune, or remove the repulsive atom-surface interaction.

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Superbunched Radiation of a Tunnel Junction due to Charge Quantization

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A chaotic light source is characterized by the fact that many independent emitters radiate photons with a random optical phase. The situation is similar when compared to a tunnel junction. There, many independent transport channels are able to emit photons due to a coupling to an electromagnetic environment. However, in a recent experiment it has been observed that a tunnel junction can deviate from the expectation of chaotic light and is able to emit strongly correlated, superbunched photons. Motivated by this, we study the correlation of the radiation and show that the superbunching originates from the emission of multiple photons. We point out that this is only possible due to the quantization of charge.

Quasinormal modes of optical solitons

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Quasinormal modes (QNMs) are essential for understanding the stability and resonances of open systems, with increasing prominence in black hole physics. We present here the first study of QNMs of optical potentials. We show that solitons can support QNMs, deriving a soliton perturbation equation and giving exact analytical expressions for the QNMs of fiber solitons. We discuss the boundary conditions in this intrinsically dispersive system and identify novel signatures of dispersion. From here, we discover a new analogy with black holes and describe a regime in which the soliton is a robust black hole simulator for light-ring phenomena. Our results invite a range of applications, from the description of optical pulse propagation with QNMs to the use of state-of-the-art technology from fiber optics to address questions in black hole physics, such as QNM spectral instabilities and the role of nonlinearities in ringdown.

Spontaneous photon production in a tuneable dielectric

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Relativistic quantum fields and effective field theories for electromagnetism in condensed-matter systems are both subject to non-trivial quantum vacuum fluctuations. In systems with rapidly varying parameters, these fluctuations may be spontaneously converted into real particles. For instance, spontaneous particle creation is expected to occur at the event horizons of astrophysical black holes and in the early inflationary universe. Both situations can be mimicked in table-top experiments, such as in dielectric media with rapidly varying time or space-time dependent effective speeds of light.

In practice, such refractive index modulations are usually created by strong laser pulses and non-linear optical effects, but spontaneous photon creation in dielectrics is commonly studied in linearised theories and for media with explicitly (space-)time dependent material properties. To facilitate a consistent treatment of quantum fluctuations in such non-trivial backgrounds, field and matter degrees of freedom need to be quantised canonically.

We present a recent canoncial approach [1] which has been designed as to account for tuneable dielectrics. In order to obtain a polaritonic dispersion relation, we extend the famous non-absorbing Hopfield model and describe the medium as an ensemble of harmonic oscillators. To include dissipation, we further couple each medium oscillator to an environment field which can carry away energy and information.

To highlight the capabilities of our new model, we will briefly consider spontaneous photon production in a tuneable medium. If time permits, I might also focus on our recent efforts to further extend our model for dissipative linear dielectrics to non-linear media, which would allow refractive index modulations to be described more explicitly.

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Linear and nonlinear fluctuation-response relations in non-equilibrium systems - spiking neurons, stochastic oscillators, and particles in an active bath

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The fluctuations and the response of stochastic systems are not independent but related by fluctuation-dissipation theorems or, equivalently, fluctuation-response relations (FRRs). Originally introduced for systems in thermodynamic equilibrium, generalizations of such relations for non-equilibrium situations have been discussed since the 1970's and are particularly appealing for biological systems. FRRs are useful to (i) prove that a system is outside of equilibrium, (ii) prove that it does not follow Markovian dynamics, (iii) extract parameters and statistics of intrinsic noise sources, (iv) derive analytically statistics of nonlinear stochastic models. In my talk I report progress on several FRRs in systems far from equilibrium.

I discuss a nonlinear FRR for systems that can be perturbed by a step stimulus [1], which can be used as an efficient test of Markovianity. I present a universal description for stochastic oscillators, that results in a simple FRR in terms of a new complex-valued transform of the original oscillator variables [2]. Most importantly, I derive a new class of FRRs for spiking neurons that relate the pronounced fluctuations of spontaneous neural firing to their average response to sensory stimuli, i.e. to the processing of sensory information that is the raison d'etre of neural systems [3]. Most recently, also FRRs for systems driven by shot noise have been derived [4] and will be discussed.

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Continuous-variable square-ladder cluster states in a microwave frequency comb

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Measurement-based quantum computation (MBQC) utilizing continuous-variable (CV) systems offers promising advantages in speed, error correction, and hardware simplicity. The key to MBQC is the control of quantum correlations in the form of graphs or cluster states. While optical frequency combs have demonstrated such correlations, the flexibility and precision of digital signal processing at microwave frequencies present new opportunities.

In this study we demonstrate the realization of square-ladder continuous-variable (CV) cluster states between 95 modes of a microwave frequency comb using a Josephson parametric amplifier (JPA). By injecting vacuum fluctuations into a JPA pumped by three coherent signals, we achieved up to 1dB of nullifiers squeezing, a key metric for verifying the entanglement structure in CV quantum systems. These results demonstrate a significant advancement in generating large-scale entangled states for MBQC in the microwave domain, moving a first step toward a new scalable quantum computing platform.

Emergence of a second law of thermodynamics in isolated quantum systems

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The second law of thermodynamics states that the entropy of an isolated system can only increase over time. This appears to conflict with the reversible evolution of isolated quantum systems under the Schrödinger equation, which preserves the von Neumann entropy. Nonetheless, one finds that with respect to many observables, expectation values approach a fixed value – their equilibrium value, with diminishing fluctuations. This ultimately raises the question: in what sense does the entropy of an isolated quantum system increase over time, and how do we characterise fluctuations therefrom? For classical systems, one introduces the assumption of a low entropy initial state along with the concept of ignorance about the microscopic details of the physical system, leading to a statistical interpretation of the second law. By considering the observables through which we examine quantum systems, both these assumptions can be incorporated, building upon recent studies of the equilibration on average of observables. While the statistical behavior of observable expectation values is well-established, a quantitative investigation of fluctuations in probability, and a connection to entropy increase has been lacking so far. In deriving novel bounds for the equilibration of observables, and considering the entropy of the system relative to observables, we recover a variant of the second law: the entropy with respect to a given observable tends towards its equilibrium value in the course of the system's unitary evolution. These results also support recent findings which question the necessity of non-integrability for equilibration in quantum systems. We further illustrate our bounds using numerical results from the paradigmatic example of a quantum Ising model on a chain of spins. There, we observe entropy increasing up to equilibrium values, as well as fluctuations which expose the underlying reversible evolution in accordance with the derived bounds. If time permits, we will conclude with a discussion of how this formalism can be applied to investigate the irreversible nature of quantum measurements, and their relation to the second law of thermodynamics.

Fluctuations and stability of quantum heat engines

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Stability is an important property of small thermal machines with fluctuating power output. We will present theoretical and experimental results concerning the fluctuation properties of both efficiency and power of quantum heat engines. We will in particular optimize their relative power fluctuations with respect to level degeneracy and level number and find that their optimal performance may surpass those of nondegenerate two-level engines. We further present an experimental investigation of the stability of a quantum Otto engine realized in the large quasi-spin states of Cesium impurities immersed in an ultracold Rubidium bath. We concretely use full-counting statistics of individual atoms to monitor quantized heat exchange between engine and bath at the level of single quanta. We moreover optimize the performance as well as the stability of the quantum heat engine, achieving high efficiency, large power output and small power output fluctuations.

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Cavity Decay Rate with Topological Insulators

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Non-reciprocal behaviour can be observed in the case of time-reversal symmetry broken topological insulators (TSB-TIs). The symmetry can be broken by applying dopants to the surface or by application of an external magnetic field. This non-reciprocity can be represented by adding an axionic term to the Lagrangian, which is proportional to the scalar product of the electric and magnetic fields and has an associated coupling constant. This term does not obey time-reversal symmetry, so provides a simple way of depicting the non-reciprocity of the TSB-TI. The addition of this term and the consideration of a single atom in a cavity behaving as a dipole implies that the atomic dipole moment will directly interact with both the electric and magnetic fields. This is a non-trivial effect which would not typically be seen in reciprocal media. The results presented will demonstrate how the decay rate of an atom in the cavity (Purcell effect) will differ between the reciprocal and non-reciprocal cases. It will be demonstrated how the non-reciprocity affects the cavity decay rate as a function of position, frequency and permittivity. These investigations are a potential route to measuring the coupling constant for the axionic term in the Lagrangian.

Quantum Vacuum Self-Propulsion and Torque of Inhomogeneous Bodies out of Thermal Equilibrium

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In an earlier paper, we explored how quantum vacuum torque can arise: a body or nanoparticle that is out of thermal equilibrium with its environment experiences a spontaneous torque. But this requires that the body be composed of nonreciprocal material, which seems to necessitate the presence of an external influence, such as a magnetic field. Then the electric polarizability of the particle has a real part that is nonsymmetric. This effect occurs to first order in the polarizability. To that order, no self-propulsive force can arise. Here, we consider second-order effects, and show that spontaneous forces can arise in vacuum, without requiring exotic electromagnetic properties. Thermal nonequilibrium is still necessary, but the electric susceptibility of the body need only be inhomogeneous. We investigate several examples of such a body. The results found are consistent with previous numerical investigations. Here, we account for the skin depth of metal surfaces. We also consider the frictional forces that would cause the body to acquire a terminal velocity, which might be observable. More likely to be important is relaxation to thermal equilibrium, which can still lead to a terminal velocity that might be experimentally verifiable. The source of the propulsive force is the nonsymmetric pattern of radiation from different parts of the body, the higher reflectivity of the metal portion playing a crucial role. As one would expect, a spontaneous torque will also arise on an inhomogeneous chiral object if it is out of thermal equilibrium with the environment. Once a chiral body starts to rotate, it will experience a small quantum frictional torque, but much more important, unless a mechanism is provided to maintain the nonequilibrium state, is thermalization: The body will rapidly reach thermal equilibrium with the vacuum, and the angular acceleration will essentially become zero. For a small inhomogeneous chiral body, a terminal velocity will result, which seems to be in the realm of observability. We are currently exploring how higher-order effects may permit forces and torques on homogeneous bodies.

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Quantum spatial searches

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Efficient retrieval of information is a core operation in the world wide web, is essential for the sustainance of living organism, and is a paradigm for optimization algorithms. Inspired by the food search dynamics of living organisms, we discuss a search on a graph with multiple constraints where the dynamics is a selforganized process resulting from the interplay of coherent dynamics and Gaussian noise. We show that Gaussian noise can be beneficial to the search dynamics leading to significantly faster convergence to the optimal solution [1]. We then analyse quantum searches on a graph that are assisted by long-range interactions and stochastic dynamics and discuss when their efficiency can outperform the one of coherent quantum search protocols [2,3].

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Dark matter droplets

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A new model for dark matter is put forward which consists of uniform droplets of Bose Einstein condensate. In this model, structure forms rapidly, shortly after the hot big bang plasma de-ionises. The model also produces modifications to the expansion rate before droplet formation that affect the measurement of cosmological parameters from Cosmic Microwave Background data. The model could contribute to explaining why observations at high redshift see anomalously high structure formation and predict low values for the Hubble constant.

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Classical and quantum fluctuations probed with a levitated nanoparticle

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We use a levitated nanoparticle to measure fluctuations of the electromagnetic field and the particle's mechanical motion. Using feedback control we cool the particle's center-of-mass motion to its quantum ground state and reduce the fluctuations below the zero-point level. Our goal is to generate macroscopic quantum superpositions by placing the particle into two locations at once. This will allow us to test quantum collapse models and the interface of quantum mechanics and gravity.

Observations of Quantum and ‘Classical’ Fluctuations of Quantum Fields

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The experimental platform of ultracold gases provides a unique opportunity to study a wide range of phenomena in physics. In this talk I will give an overview of how ultracold gases can be used to study physics in the quantum field theoretical limit, thus establishing the concept of quantum field simulators.

As an introduction, I will report our results on the detection of true quantum correlations of continuous variables in a spinor Bose gas using the concept of entanglement witness, more precisely the steering criterion [1]. The same experimental platform also allows the investigation of the physics conjectured for the early dynamics after a heavy ion collision, as studied at CERN, where field fluctuations at different length scales change in time in a scaling way, i.e. the scale dependent fluctuations are described by a universal function and the evolution is captured by a simple rescaling of the length scale and amplitude [2]. The platform also opens a new way to extract quantum effective actions in quantum field theory settings [3].

As a third example of quantum field fluctuations, I will present our study of the particle production of a scalar field living on an expanding spacetime. Assuming the cosmological principle, the metric for large scales is given by the Friedmann-Lemaitre-Robertson-Walker metric. This metric is fully characterized by the sign of the curvature and a general scale factor, both of which are under full control in ultracold gas experiments. I will discuss how particle production i.e. fluctuations of the scalar field, in expanding spacetime can be detected [4] and how it relates to the two-mode squeezing discussed in the context of quantum steering with spinor condensates.

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Radiation-mediated processes between atoms in external backgrounds or in non-inertial frames

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We consider radiation-mediated processes for atoms, such as energy shifts and van der Waals/Casimir-Polder or resonance interactions, in several external backgrounds such as metallic boundaries or external quantum or classical fields, or for a noninertial motion of the atoms. Radiative processes with movable boundaries will be also considered.

We discuss how radiation-mediated interactions are modified due to the presence of the background or of the motion of the atoms and of the boundaries.

We discuss how these effects can be exploited to modify and tailor radiation-mediated interactions between atoms or macroscopic polarizable bodies.

General hydrodynamic approach for a cold Bose gas

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We present the derivation of the hydrodynamics for a cold Bose gas at T = 0 from the microscopic platform based on the many-body Schrödinger equation and general assumptions of the hydrodynamic approach (HA) applicable to any dimension. We develop a general HA for a cold spatially inhomogeneous Bose gas assuming two different temporal and spatial scales and obtain the energy as a functional of both fast inner quantum mode and slow macroscopic mode. The equations governing the fast and slow modes are obtained from this functional by their independent variations. The fast mode is the wave function in the stationary state at local density which can be ground, excited with a nonzero atom momenta, or a superposition of more than one state. The energy eigenvalue (or expectation value) of this local wave function universally enters the hydrodynamic equation for the slow mode in the form of the local chemical potential which incorporates the inner local momentum. For zero inner momenta and particular choices of this eigenvalue as a function of gas density, this equation reduces to the known equations based on the local density approximation. If, however, the inner momenta are nonzero, the equation includes the interaction between these momenta and the slow mode velocity. Relation between this general HA and the standard local density approximation is elaborated. Two effects of the local momenta and their density dependence on the soliton solutions are demonstrated.

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Irreversibility in Non-reciprocal Chaotic Systems

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How is the irreversibility of a high-dimensional chaotic system controlled by the heterogeneity in the non-reciprocal interactions among its elements? In this paper, we address this question using a stochastic model of random recurrent neural networks that undergoes a transition from quiescence to chaos at a critical heterogeneity. In the thermodynamic limit, using dynamical mean field theory, we obtain an exact expression for the averaged entropy production rate – a measure of irreversibility – for any heterogeneity level J. We show how this quantity becomes a constant at the onset of chaos, while changing its functional form upon crossing this point. The latter can be elucidated by closed-form approximations valid for below and slightly above the critical point and for large J.

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Fluctuations in Superfluids & Modelling Challenges: Analogies between Ultracold Atoms and Cosmological Fuzzy Dark Matter

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The ubiquitous nature of the phenomenon of Bose-Einstein condensation [1], experimentally observed in various weakly—interacting gaseous laboratory condensates appears to be also potentially relevant to the modelling of dark matter, critical for understanding structure formation in the Universe. All such systems can be described (in appropriate limits) by a sizeable coherent part, embedded within a fluctuating medium of incoherent particles. In this talk I will briefly outline such models, focussing on the similarities between laboratory and cosmological condensates, contrasting their predictions to corresponding experimental and astrophysical observations, and critically discussing implications and open questions.

The cosmological "Fuzzy Dark Matter"(FDM) model (an alternative to the established particle-based "Cold Dark Matter" (CDM) model) postulates the existence of an ultralight bosonic particle exhibiting galactic-size de Broglie wavelengths, facilitating a wave description: central to this model is the suppression of small-scale gravitational collapse by quantum pressure, which leads to galaxies containing coherent "solitonic cores", surrounded by incoherent particles [2]. While this picture is closely analogous to the centrally-located ultracold atomic condensate, surrounded by a thermal cloud – with the role of the harmonic trap in the cosmological setting mimicked by gravity – there are clear distinctions in the role of fluctuations in such systems. We present a generalized model which includes a fully self-consistent description of both coherent and incoherent degrees of freedom through the coupling of an appropriate stochastic Gross-Pitaevskii equation to a quantum Boltzmann equation and show that such a model reduces either to the standard picture of CDM, or FDM in cosmology [3], or to established stochastic, and kinetic, formalisms in ultracold quantum gases [4].

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Dynamical signatures of discontinuous phase transitions: exponential versus power-law scaling

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There are conflicting reports in the literature regarding the finite-size scaling of the Liouvillian gap and dynamical fluctuations at discontinuous phase transitions, with various studies reporting either exponential or power-law behavior. In our work [1], we clarify this issue by employing large deviation theory. We distinguish two distinct classes of discontinuous phase transitions that have different dynamical properties. The first class is associated with phase coexistence, i.e., the presence of multiple stable attractors of the system dynamics (e.g., local minima of the free energy functional) in a finite phase diagram region around the phase transition point. In that case, one observes asymptotic exponential scaling related to stochastic switching between attractors (though the onset of exponential scaling may sometimes occur for very large system sizes). In the second class, there is no phase coexistence away from the phase transition point, while at the phase transition point itself there are infinitely many attractors. In that case, one observes power-law scaling related to the diffusive nature of the system relaxation to the stationary state.

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Dispersion interactions in quantum or classical external environments

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We investigate the dispersion interaction between two neutral atoms, or between a neutral atom and a boundary, in an external environment. Specifically, we consider the Casimir-Polder interaction between two atoms, interacting with the quantum radiation field, when an external electromagnetic field, prepared in a Fock state or in a coherent state, is present. We discuss how these interactions can be modified by the presence of the external environment and the possibility to observe such effects. The case of the atom-mirror Casimir-Polder interaction in the presence of external quantum fields will be also considered.

Particle and entanglement production in an analogue preheating experiment

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Preheating is a post-inflationary phase in cosmology where particles are excited by parametric resonance. As they are seeded by vacuum fluctuations, the particles are produced in entangled pairs.

An analogue preheating experiment involving a modulated quasi-1D Bose-Einstein condensate (BEC) was realized in [1], and while production of quasiparticle pairs was indeed observed, their entanglement was not. In [2], weak dissipation of the excitations was phenomenologically introduced and shown to be able to prevent the generation of entanglement. Fully nonlinear numerical studies of the modulated gas based on the Truncated Wigner Approximation (TWA) were then conducted [3], confirming that phonon-phonon interactions can induce an effective dissipation acting against the parametric resonance and degrading or indeed destroying the induced entanglement. In [4], the dominant interaction channel for small occupation numbers in 1D quasi-BEC was identified as Beliaev-Landau scattering between the resonant mode and the thermal population. The associated dissipation rate was analytically derived and checked against TWA simulations.

In this talk, I will recount the above history and describe the dynamics at play, emphasizing the subtle interplay between growth and dissipation that leads to distinct regimes of particle and entanglement production. Implications for experimental optimization will also be discussed.

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Stochastic thermodynamics: From concepts to model-free inference

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Stochastic thermodynamics provides a universal framework for analyzing nano- and micro-sized non-equilibrium systems [1]. Prominent examples are single molecules, molecular machines, colloidal particles in time-dependent laser traps and biochemical networks. Thermodynamic notions like work, heat and entropy can be identified on the level of individual fluctuating trajectories. They obey universal relations like the fluctuation theorem.

Thermodynamic inference as a general strategy uses consistency constraints derived from stochastic thermodynamics to infer otherwise hidden properties of non-equilibrium systems [2]. As a paradigm for thermodynamic inference, the thermodynamic uncertainty relation discovered in 2015 provides a lower bound on the entropy production through measurements of the dispersion of any current in the system [3]. Likewise, it quantifies the cost of temporal precision for biomolecular processes and provides a model-free bound on the thermodynamic efficiency of molecular motors and microscopic heat engines. Generalizations allow us to apply it to time-dependently driven systems like the unfolding of proteins under mechanical force. Waiting time distributions between observable events yield even better bounds on entropy production and the topology and driving affinity of the underlying network [4].

In this talk, I will introduce the main concepts and illustrate them with representative examples.

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Emergent decoherent histories in isolated quantum many-body systems

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This talk reviews recent progress in our understanding of emergent decoherent histories from “first principles” (i.e., without the use of ensembles or approximations to the Schrödinger dynamics, akin to pure-state statistical mechanics) [1-5]. I start by briefly reviewing the formalism of decoherent histories and why they are important to make sense of a unitarily evolving quantum Universe, followed by a general explanation why one expects slow and coarse observables of many-body systems to decohere. Then, I present results suggesting that generic (non-integrable) quantum many-body systems are characterized by an exponential suppression of interference effects whereas integrable system might display only a powerlaw suppression (as a function of the particle number of the system). If time permits, I also explain how arrows of time can emerge in a time-symmetric Multiverse, I address the structure of the Multiverse as revealed by (long) (de/re)coherent histories (a hitherto unappreciated phenomenon), and/or I elucidate the relation between decoherent histories and environmentally induced decoherence.

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Quantum Friction and Landau-Zener Tunneling in Dissipative Systems

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Friction in atomistic systems is usually described by the classical Prandtl-Kontorova model suitable for capturing the dragging force of a particle in a periodic potential. Here we consider the quantum mechanical version of this problem with a revised model that is very similar to the Landau-Zener theory in linear chains. The time evolution of the system is captured with the Liouville-von Neumann equation through the density matrix of the system. The dynamics is controlled by the interplay between the strength of the potential, distance separation, velocity, and strength of coupling with an external dissipative bath. The computed energy population dynamics, the geometric phase, and the dissipative rates help us understand various frictional regimes from a microscopic perspective.

Abstracts of Posters

(in alphabetical order)

A microscopic model for a nonlinear dissipative dielectric medium

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With the help of nonlinear optics and the technique of electro-optic sampling, it has recently become feasible to access quantum fluctuations in dielectric media experimentally. On the theory side, recent experiments have been successfully described in an extended macroscopic QED framework [1]. Related proposals suggest observing spontaneous photon creation (e.g., in analogue experiments on cosmological particle creation or Hawking radiation) in nonlinear media with explicitly time or space-time dependent properties. To account for particle creation in tuneable dielectrics, one commonly resorts to microscopic models which represent the medium as a collection of harmonic oscillators. Unlike the corresponding macroscopic approaches, microscopic models can be quantised canonically, but they often neglect dissipation.

To bridge the gap between the existing macroscopic and microscopic approaches, we are currently incorporating non-linear effects into a recent microscopic model for linear dielectrics with dissipation [2]. In this presentation, I will report on first preliminary results of this new project. To account for the nonlinearity, we replace the usual harmonic medium oscillators with anharmonic oscillators. Apart from that, we also replace the established dipole coupling between the oscillators and the electromagnetic field with a non-linear coupling. Dissipation will be included by coupling the medium oscillators to a scalar environment field. The resulting model accounts for a number of nonlinear optical effects, including second harmonic generation, as well as sum- and difference-frequency generation.

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Mitigating boundary effects in finite temperature simulations of false vacuum decay

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Cold atomic gases have proven a valuable medium in which to study early universe phase transitions such as first order false vacuum decay, where a system escapes a metastable state via the nucleation of bubbles. Two-dimensional systems offer an ideal compromise between experimental difficulty and analogy strength, but the latter is threatened by boundary effects. It has previously been found [1] that the inclusion of an optical box trap causes bubbles to preferentially nucleate along the trap boundaries. Here, we show that this unwanted boundary activity can be suppressed by modifying the trap geometry to include a trench. We demonstrate this using finite-temperature simulations of both pseudo-spin-1/2 and spin-1 gases.

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Simulation of atomic diffraction through a nanograting

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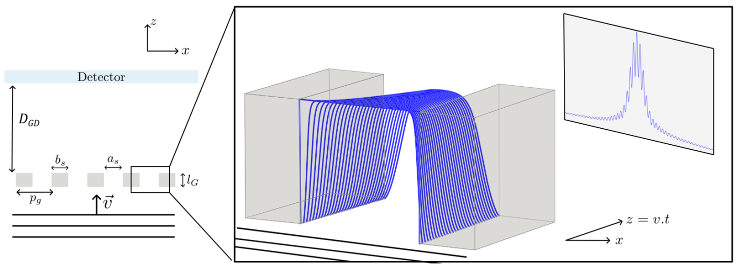
Tremendous advancements in the field of cold atoms have transformed atomic interferometry into a versatile, precise and powerful tool for inferring tiny forces or developing atomic clocks.

This contribution focuses on theoretically modelling an experiment involving the diffraction of cold argon atoms through a transmission nanograting. The observed diffraction pattern is intrinsically related to the short-range dispersion forces between the atoms and the material, known as the Casimir-Polder (C-P) forces. These forces prevailing at the nanoscopic scale make accurate measurement and modeling crucial, for example, to explore non-Newtonian short-range gravitational effects and advance nano-device technology.

In this context, we have developed a quantum numerical model, combined by quantum electrodynamics (QED) calculations. It leads to the validation of the observed data, and to the outperform of current state-of-the-art techniques[1]. Our metrological analysis addresses statistical and systematic effects—including nanograting geometry, finite size effects, and slit width opening angles—leading to the determination of an atom-surface potential strength parameter $C_3 = 6.87 \pm 1.18$ meV.nm^3.

This value is primarily constrained by the knowledge of the nanograting geometry. To enhance sensitivity to the complete 2D C-P potential within the nanograting slits, we are implementing a scanning angle method, which involves varying the incidence angles between the atomic jet and the nanograting. To advance beyond recent work, we are currently extending our 1D numerical model to a 2D framework and developing new 2D QED calculus. This extension aims to improve the precision of C-P potential measurements and explore new short-distance interactions.

This work is supported by DLR funds from the BMWK (50WM2450A QUANTUS-VI).



Propagation of a matter wave function through a single slit and the resulting diffraction pattern from the nanograting[2]

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Hyperboloidal Methods for the Quasinormal Modes of Non-Relativistic Systems

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The quasinormal modes (QNMs) of an open system are dissipative modes that encode characteristic information about the system, with implications, e.g., in observational astrophysics and optics. The so-called compactified hyperboloidal method has recently found wide use in the numerical computation of QNM frequencies, but it has hitherto been available only in the relativistic context. We generalize this hyperboloidal method by extending it into the non-relativistic domain, with diverse applications ranging from fibre optical solitons to post-Einsteinian gravity [1, 2]. In the gravitational context, the modeling of non-relativistic QNMs will be especially important for predicting signatures of Lorentz violations arising in quantum gravity models [3]. We discuss the programme of black hole spectroscopy, and how non-relativistic QNM methods may facilitate observational tests of a range of quantum gravity models at future gravitational wave observatories.

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Temporal Noise in Atom Interferometry

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Atom interferometers are versatile instruments for measuring inertial forces and conducting high-precision experiments. For instance, differential setups can be used to test various facets of the Einstein equivalence principle [1], detect gravitational waves, or search for physics beyond the Standard Model [2]. Whilst differential setups effectively suppress laser phase noise through single-photon transitions [3], other significant noise sources, such as gravitational gradients and temporal fluctuations in gravity, remain challenging.

Our work presents atom interferometers as detectors for dark matter [4], an approach which can be readily generalised to gravitational-wave detection. With these results at hand we show our approach to an investigation of temporal noise from various sources in atom interferometry. To do this, we bring all phase contributions in an atom interferometer on an equal footing, allowing direct comparison with the laser phase. By incorporating knowledge of local noise profiles, a more accurate phase analysis seems feasible, thereby enhancing the overall sensitivity. We review current differential setups [5] and analyse temporal noise across multiple sources.

Our findings have implications for high-precision measurements, particularly in areas of fundamental physics, by offering a deeper understanding of the interplay between different temporal noise sources.

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On Casimir Force in Smooth Layered Systems

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We investigate the Casimir-type pressure in electromagnetic systems characterised by dielectric permittivity smoothly varying along one of the coordinates, $\epsilon = \epsilon(x)$. The Casimir energy is expressed through the scattering data on the system [1], which is constructed in a N-plate pairwise constant approximation, following the ideas of [2]. The limit $N \to \infty$ (with thickness of each plate going to zero) restores continuous system.

We find that the naive interpretation of Casimir force as a derivative in respect to the position of k-th interface yields trivially vanishing result in the continuum limit. Other approaches to the interpretation of the results are discussed. Apart from applications in real systems, we assess the possibilities of using this technique in 'Casimir cosmology' [3].

As a by-product we express the scattering matrix of the system as an ordered exponent type object satisfying a linear matrix equation. It permits asymptotic investigation along the lines of [4].

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Local semitransparent boundary conditions and resummations for scalar pair creation

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In the study of quantum fields under the action of external fields, it is custom to employ idealized boundary conditions, such as Neumann or Dirichlet. We propose instead a more realistic scenario, in which we replace them by local semitransparent boundary conditions, i.e. spacetime dependent conditions. We impose them on a quantum scalar field by coupling it to an appropriately localized background field. In particular, after a resummation we are able to compute the first terms in the expansion of the effective action around a homogeneous configuration of the background field, as well as the corresponding probability of pair production. Based on [1,2,3].

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Optical Wavefront Control using Atomic Arrays

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A common issue when dealing with interactions between standard materials and light in the optical range is that the magnitude of the magnetic response of many of these materials is often a few orders less than that of the electric response. To achieve an operational Huygens surface, where a combination of magnetic and electric dipoles can combine in such a way to allow for total control of a wavefront emitted from the surface, a significant magnetic character must be accessible. Within the literature this has been achieved using a 2D atom array with sub wavelength spacing by Ruostekoski [1], such that sub-radiant and super-radiant modes are accessible, proving the array to be useful as a quantum memory and flexible optical component.

Presented work takes a focus on the Huygens surface aspect, expanding on current literature to prove such a system could be used to generate more complex optical states, such as higher order skyrmions, and be used as an in situ configurable quantum state preparation device, specifically noting how these states can be prepared with regards to specific array parameters and detuning values, as well as presenting the transmission and reflection characteristics of the array over a wide range of detuning to examine the response even out with these Huygens regions of operation.

Fluctuations in the positions of the atoms due to temperature and zero-point fluctuations have been explored in the literature and found to potentially impact surface performance. A longer term goal of this project is to explore the effect of collective behaviour on fluctuations in atomic position, looking at the impact of enhanced recoil energies due to collective effects [2].

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Towards precise measurement of the Casimir-Polder interaction

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In quantum field theory, the vacuum of the electromagnetic (EM) field represents its ground state, characterized by zero-point energy and quantum fluctuations [1]. Geometric constraints on this vacuum energy lead to phenomena like the Casimir-Polder (CP) effect [2], which plays a significant role in nanotechnology and has the potential for probing new physics [3, 4, 5]. Precise control of the CP force will enable improved measurement and evaluation of quantum electrodynamics (QED) predictions, such as repulsive CP forces and quantum friction, as well as tightening constraints on theoretical models of dark matter, the charge-parity (CP) problem, and string theory [6, 7]. However, current CP force measurements are limited to a 5-10% precision range.

In this context, we developed a setup in which slow atomic pulses diffract through a nanograting. The prolonged proximity of slow atoms to the surface amplifies the CP interaction's effect on the diffraction pattern, enabling precise extraction of the CP potential [8]. Our quantum model accurately describes low atomic velocities and near-surface effects [9]. This setup achieved statistical errors below 1% in the measurement of the CP potential with 95% confidence. Extensive statistical analysis, including likelihood ratios, goodness-of-fit tests, and Monte Carlo simulations, revealed a strong correlation between the nanograting geometry and the measured CP interaction strength (C3), with systematic errors around 17.2% [10]. To mitigate these geometric influences, we are enhancing our setup to allow tomographic measurements by varying the incident angle, aiming to decouple the nanograting geometry from C3.
This tomographic approach is expected to improve sensitivity to the CP potential form and provide robust experimental support for the QED formulation, potentially challenging alternative theoretical models.

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Spurious Effects in Quantum-Enhanced Atom Interferometers

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Quantum-enhanced atom interferometry (AI) is an active area of research in the field of high-precision metrology [1]. Pushing the phase uncertainty below the standard quantum limit (SQL) using many-body entanglement introduces a new era to the realm of quantum sensing.

Sub-SQL atom interferometers have been studied mostly utilising (pseudo) spin squeezing in cold atomic ensembles [2, 3]. There already exist partial realisations with spin squeezed atomic clouds [4, 5]. To advance in experimental realisations of sub-SQL sensing, it is crucial to consider and analyse the effects of velocity selectivity [6] that reduce an atom interferometer's phase sensitivity due to initial momentum distributions of finite width.
We have shown that particle loss as well as non-balanced beam splitters – both effects induced by velocity selectivity – reduce the phase sensitivity of a Mach-Zehnder-Interferometer (MZI). For that, we implemented a fully second quantised description of the MZI making the characterisation of these effects straight forward. This allows for a quantitative analysis of the competition between these perturbations and quantum enhancement in AI.

In summary, the second quantised formalism for the MZI provides a method for optimising a given setup regarding input states, i.e. their robustness to loss and noise. These results will be of particular benefit for proposals that employ large-momentum-transfer [7] and multi-diamond [8] techniques, as sensitivity-degrading effects become a significant limiting factor for these architectures.

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Fluctuation-Dissipation Theorem in Open Quantum Systems: Compatibility with the Lindblad Master Equation at Thermal Equilibrium

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Here, we study the circumstances in which the fluctuation-dissipation theorem (FDT) in open quantum systems at equilibrium can be reconciled with the Lindblad Master Equation (LME) formalism. The conventional FDT derivation, which assumes unitary dynamics, is complicated by the dissipative and irreversible processes inherent in open quantum systems, which are characterized by non-unitary evolution as a result of coupling with an external environment. We concentrate on the derivation of an FDT in the equilibrium regime, using the Markovian dynamics and weak system-environment coupling assumptions to determine the conditions under which the FDT is still valid. Future research on applying the fluctuation-dissipation framework to nonlinear response in open quantum systems will build upon this analysis.

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Graphene-Induced Modification of Atomic Spontaneous Emission

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Graphene's remarkable electronic properties have sparked widespread interest in recent years, particularly for its potential applications in fundamental research and technologies focusing on light-matter interaction. In this study, we investigate how a graphene monolayer modifies the spontaneous emission rates of a nearby atom. Our formalism relies on a description of graphene's properties in terms of a (2+1)-Dirac model. Through a combination of numerical and analytical investigations, we provide a detailed description of the emission rate as a function of the atom-graphene separation and the atom's initial state. Our findings reveal peculiar changes in the emission spectrum, suggesting implications for atom-photon coupling in quantum optics and nanophotonics. Additionally, we propose that spontaneous emission could serve as a probe for testing specific properties of graphene, opening avenues for experimental validation.

Periodic smoothening of largest fluctuation governs finite size scaling exponents of one dimensional growing interfaces

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In solid-on-solid growth models for growing interfaces, a single parameter control on largest fluctuation of the growing interface, termed as periodic smoothening, which translates to reducing the magnitude of largest height fluctuation with a fixed frequency during interface growth is found to produce a continuum of finite size scaling exponents by varying the control parameter. For interfaces in Gaussian universality class, the only well defined exponent, the growth exponent (β), is found to vary continously whereas for interfaces in Edwards-Wilkinson (EW) and Kardar-Parisi-Zhang (KPZ) universality classes, roughness (α) and dynamic (z) exponents vary continously while the growth exponent (β) remains unchanged. The later scenario is identical to weak universality which allows continous variation of some critical exponents keeping others fixed[1].

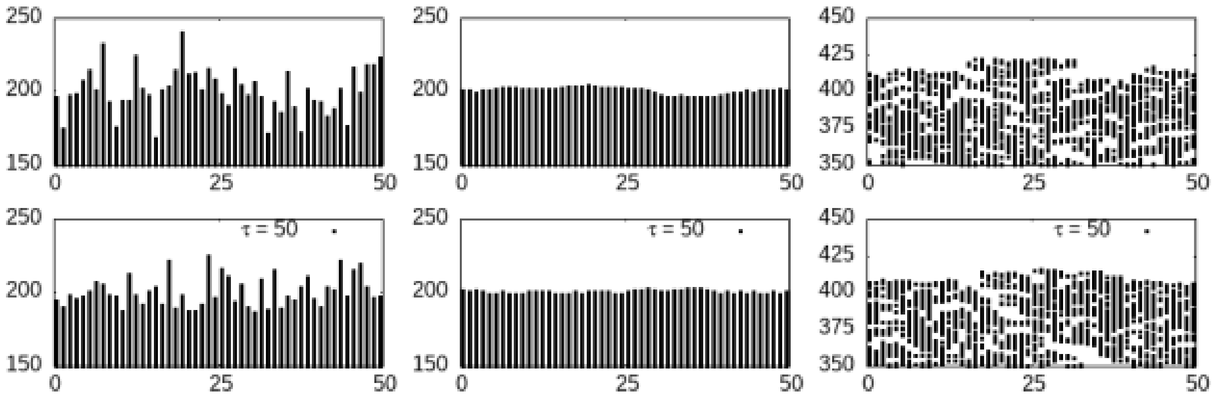

Figure: Snapshot of growing interfaces without periodic smoothening (top) and with periodic smoothening of largest (negative) fluctuation with a period τ=50 (bottom). Left: Random deposition (RD) model. Center: RD with surface relaxation model. Right: Ballistic deposition model. Each of these interfces are formed on a substrate of length L=50 after depositing 10000 particles.

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Magnetoelectronic and thermodynamic properties of new quaternary heusler alloys for spintronics applications

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The aim of our study using the full potential augmented plane wave method (FP-LAPW) based on density functional theory (DFT) bymean generalized gradient approximation GGA implemented in the WIEN2K package. magnetoelectronic and thermodynamic properties of the quaternary half heusler alloys as smart materials for spintronics applications is to predict new class of materials by studying elastic properties to insure their stability, optoelectronic properties to predict their kind of conductivity and mangetoelectronic properties to confirm their magnetic propeties as promising candidates for future spintronics applications,

KEYWORDS: quaternary half heusler alloys, spintronics, wien2k, magnetoelectronic properties

Quantum Vacuum Correlations in a Modified Analogue Spacetime

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A surprising feature of quantum mechanics is its prediction of non-zero fluctuations in the ground state of electromagnetic fields. Although many macroscopic effects have been linked to these fluctuating vacuum fields, only recently has it become possible to measure them directly using electro-optic sampling.
This method is based on the interaction of a classical field, e.g. a strong laser pulse, with the quantum vacuum fluctuations within a nonlinear crystal. This makes it possible to retrieve the signatures of the quantum vacuum from the resulting, subsequently altered, field [1]. In a slightly more sophisticated setup of two co-propagating classical fields, it is even possible to access the two-point correlation function of the vacuum field at distinct spacetime regions. This enables the investigation of the spacetime structure of the vacuum fluctuations.
In this work, we employ the formalism of macroscopic quantum electrodynamics to theoretically describe field propagation in nonlinear dispersive media and predict the signatures of the quantum vacuum as well as its spacetime structure in the electro-optic sampling signal [2].
We show how additional external fields might modify the spacetime structure of the correlation function of the quantum vacuum fluctuations by locally changing the index of refraction. We discuss the changing refractive index in the context of a nontrivial analogue spacetime, where light propagation in dispersive media can be influenced similarly to a curved spacetime.

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Nuclear cluster formation in intermediate and high energy heavy-ion collisions

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(In collaboration with A. S. Botvina, N. Buyukcizmeci, M. Bleicher, W. Trautmann)

Properties of a physical system can be classified as equilibrium (EOS) and non-equilibrium (transport coefficients) properties. The balance between attractive and repulsive forces determines the equilibrium state of cold nuclear matter at baryon density ρ_0. When the average nucleon density is lower than ρ_0 the attractive nuclear forces dominate, which gives rise to growing density fluctuations and clusterization of nucleons. Simulations of nuclear cluster formation heavily rely on models of density fluctuations to predict how and nuclear clusters will form and evolve over time. Due to the similarities of nuclear and stellar matter, this is corresponding to formation of astrophysical object like neutron stars, galaxies and etc in astrophysical events. Formation of nuclear clusters (hot nuclei) can be described by combining the dynamical models (QMD-Quantum Molecular Dynamics) and statistical models (SMM-Statistical Multifragmentation Model). The statistical models can describe the fragment yields emitted from the collisions. For example, the mass and charge distributions of intermediate mass fragments can be approximated by a power-law fitting parametrization. The behavior of power law parameter τ may be associated with a phase transition in finite systems. There are numerous peculiarities in this transition region, such as a plateau-like behavior of the caloric curve, large fluctuations of the temperature and of the number of the produced fragments, scaling laws for fragment yields, and other phenomena expected for critical behavior [1].

On the other hand, the non-equilibrium properties, such as transport coefficients can be desribed by dynamical models through the kinetic equations such as Boltzmann’s equation and its extended versions like Landau, Vlasov, BUU and etc. We refer to BBU which describes the evolution of the one-body phase-space density under the influence of a mean field, with two-body collision term. Another kind of transport model, the so called QMD model is formulated in terms of nucleon coordinates and momenta under the action of a many-body Hamiltonian. In heavy-ion collisions, transport theory of the initial stage of the collisions of projectile and target nuclei is governed by the transport properties of nuclear matter. We will discuss some examples of anayses of the experiments such as FAZIA, ALADIN, FRS, FRIB etc, at high energy heavy-ion collisions (see, for example, Refs. [2-4].

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Thermodynamic Trade-Offs in Steady-State Heat Engines with Inertia

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The Thermodynamic Uncertainty Relation (TUR) defines a seemingly fundamental trade-off between precision and dissipation in non-equilibrium systems. Building on this, the universal trade-off further constrains system performance, revealing that power, efficiency, and stability in power output cannot all be optimized simultaneously. Although the TUR and the universal trade-off have been well-established for overdamped systems, recent research highlights the limitations of the TUR in underdamped dynamics. In this study, we investigate two distinct steady-state heat engine models that surpass the limits of the TUR in these conditions. However, despite this violation, both systems still adhere to the universal trade-off.

Controlling noise in quantum devices using phononic spectral hole burning

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While quantum physics may enable powerful new forms of computation, noise has stifled our ability to realize this in practical applications. This noise is produced in part by so-called two-level tunneling states (TLSs).

TLSs are hypothesized to be atoms or a group of atoms that can occupy either of two configurations within a material. Similar to how an electron within an atom can jump between orbitals when stimulated by a photon, TLSs can jump between their two energy configurations by absorbing or emitting a microwave or a phonon. This process contributes to unwanted noise in the system, which is a problem for upcoming in nascent quantum technologies that seek to utilize long-lived microwave excitations (e.g., superconducting qubits).

However, two remarkable properties may enable the noise produced by TLSs to be controlled: (1) they simultaneously interact with microwaves and phonons, and (2) their absorption can be “saturated,” or sharply reduced when driven by electromagnetic or mechanical waves.

The two-time correlation function and corresponding power spectrum for the deviation of a TLS dipole moment provide information about the noise generated in the system, and the optical Bloch equations give information about the quantum dynamics of these systems including effects from the driving acoustic field and phonons inherent to the system. Using these insights, we aim to predict how electromagnetic noise produced by TLSs can be controlled using intense mechanical waves.

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Non-reciprocal scattering in a microwave frequency comb

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Achieving non-reciprocity without relying on bulky, magnetic-based circulators presents a major challenge for scalable quantum computing architectures. This work explores the use of a Josephson Parametric Amplifier (JPA) as a non-reciprocal device. While JPAs are highly effective in amplifying quantum signals without introducing back-action, their intended mode of operation is typically reciprocal. We define non-reciprocity in terms of the scattering asymmetry between input/output frequency modes. Pumping the JPA with multiple low—and high-frequency pumps and carefully tuning their phase and amplitude can enable non-reciprocity. We explore different non-reciprocal regimes ranging from a two-mode isolator, and a three-mode circulator to a general non-reciprocal scattering between n=81 frequency modes.

Quantum Resources in Disorder

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Understanding how physical systems deviate in the presence of disorder is a fundamental problem in many-body physics and quantum information science. Addressing these effects often requires extensive numerical averaging over multiple samples, which raises the question of whether novel quantum resources change due to such averaging. In this work, we analytically demonstrate that the emergence of Markovian or non-Markovian dynamics depends on the symmetry of the *single-body* disordered Hamiltonian and the probability distributions of the disorder. This method can be further used in quantum computing platforms involving qubits and qudits for error simulation and mitigation. On the other extreme are strongly interacting models, described by random matrices, where we look for their resource contents. By changing the span of disorder in power-law decaying random matrices, we explore how quantum resources such as entanglement and non-stabilizerness manifest. The scaling laws and critical points of phase transitions vary depending on whether the system follows a power-law random banded matrix model or a Rosenzweig-Porter model and whether we examine ground or bulk states in the energy spectrum. In summary, we investigate how disordered Hamiltonians uniquely harness multiple quantum resources, opening new pathways for utilizing disordered physics in quantum information tasks such as quantum control, quantum simulation, and quantum computing.

Casimir interaction between two spherical objects - in the classical and quantum regime

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Casimir has shown in his seminal work from 1948 that vacuum fluctuations of the electromagnetic field can lead to an attractive force between two perfect reflector plates. However, for non-zero temperatures also thermal photons contribute to the Casimir force. Our study investigates the Casimir effect resulting from the thermal fluctuations, focusing on the experimentally relevant setup involving two spherical objects.
We studied two systems in this limit: metallic spheres in vacuum and a dual setup consisting of dielectric spheres in an electrolytic solution. Thermal fluctuations dominate for metallic spheres at distances above the thermal wavelength, while it was demonstrated in an experiment [1] that the thermal contribution becomes dominant for dielectric spheres in electrolytes at much smaller distances. This makes the Casimir force also relevant for colloidal and biophysical systems. We derived analytical and semi-analytical expressions for the Casimir free energy [2,3], respectively, for the two systems, which are accurate enough for most practical applications, with no need to go through numerical computations.
While the Casimir interaction in the previously mentioned systems is always attractive, we were also interested in setups where two objects repel each other due to the Casimir force. We thus studied an idealized system of two perfect electromagnetic conductor (PEMC) spheres, where we found that for specific configurations, the sign of the force can be switched by changing the system temperature [4]. Our findings may serve as a guide to explore Casimir repulsion in more realistic materials for a geometry commonly used in experiments.

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Casimir-Polder force in a nonlinear medium

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The discovery of the Casimir effect in 1948 [1] has, among others, created a new research field involving vacuum forces and fluctuations. The Casimir effect gives rise to the attractive Casimir force [2] between two neutral polarizable bodies in vacuum as well as to the Casimir-Polder force between a particle and a polarizable macroscopic body. In our work, we theoretically investigate the interaction between two electric dipoles to obtain the Casimir-Polder force. In order for the force to arise purely from electric contributions, we introduce a nonlinear interaction between the particle and the body, which may for instance stem from embedding the entire setup in a nonlinear medium. Using macroscopic quantum electrodynamics [3,4], we analytically calculate the resulting energy correction in third order perturbation theory as well as the Casimir-Polder force between an atom in its ground state and the field.

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Jaynes-Cummings Model for Chiral Cavity Quantum Electrodynamics

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We examine the effects of chirality on the interaction of a two-level quantum system with a single mode of the quantised electromagnetic field inside a chiral cavity [1].
The Jaynes-Cummings-model acts as a starting-point to develop a more general model [2]. For that, we consider the effects of chirality on the field and calculate chiral standing waves inside the chiral cavity. We also take into account the properties of chiral molecules and their electric and magnetic dipole moments. We then use our findings to study the resulting modified coupling constants, Rabi oscillations and the eigenenergies of the system.
Our results imply an increase in coupling for matching handedness of the field and molecule and a decrease for non-matching handedness. The Main Result is shown in Figure 1.

Additionally, the next step is to study the force acting on the molecule, as well as observing a system when two modes of opposite handedness are present inside the cavity.

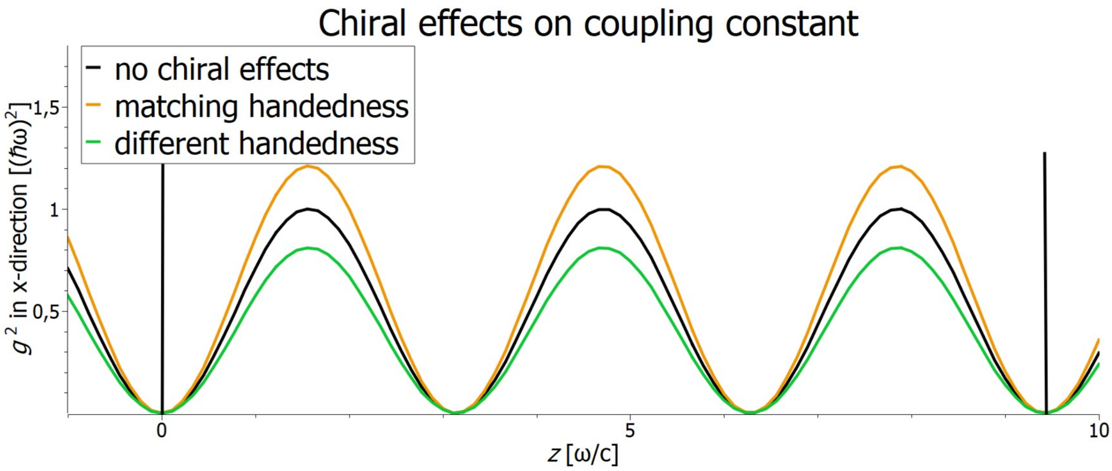

Figure 1: Chiral effects on the coupling constant *g*.

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Three-atom contributions to Casimir forces

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We want to investigate Casimir forces between rough parallel plates with electric properties. For the reduced symmetry associated with realistic roughness, it is necessary to use approximate methods. Using a Born series it is possible to expand the Casimir force into a power series in the polarisabilities of constituent atoms of the plates [1]. The expansion can be interpreted as the sum of many-body contributions: the first term contains two-atom contributions, the second term three-atom interactions, and so on. The two-atomic contributions are known to lead to the well-known Hamaker expression. We aim to study the impact of three-atom contributions as well.

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