Fluctuation-induced Forces

729. WE-Heraeus-Seminar

14 – 17 February 2022

ONLINE

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 729. WE-Heraeus-Seminar:

Fluctuations are ubiquitous in nature, their various kinds being, for example, displayed in water waves, the random motion of (atomic) particles in matter, or in the stochastic behavior of photons in black-body radiation. While often neither of particular interest nor of relevance, fluctuations play a fundamental role if spatially correlated, i.e., when they reach across mesoscopic distances in space. On that level they may give rise to physical forces - so-called fluctuation-induced forces - which have been measured in a large variety of systems and setups at the micrometer scale.

Prominent examples of spatially correlated fluctuations are found in the electromagnetic field, resulting in the celebrated Casimir effect of quantum electrodynamics, and in fluid media near a critical point, causing the so-called critical Casimir effect. While these instances have been shown to comprise interesting equilibrium and non-equilibrium behaviors, out-of-equilibrium situations such as active matter open up even wider avenues due to the general emergence of long-ranged correlations, which, in various cases, have been predicted theoretically. Indeed, relatively few ingredients are required for such fluctuation-induced effects. They thus occur in many different scientific areas, including, e.g. Biology, which renders their study highly interdisciplinary.

This WE-Heraeus Seminar aims at covering the broad range of occurrence of these fluctuation-induced effects, including the impressive recent theoretical and experimental progress. In view of the high degree of interdisciplinarity, this seminar promises to become especially fruitful by bringing together scientists from various research areas, in order to foster cross-fertilization regarding both phenomenology and methodology.

Introduction

Scientific Organizers:

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Program

Program *(CET)*

Monday, 14 February 2022

12:45 – 13:00	Organizers	**Opening**

Chair: Matthias Krüger

13:00 – 13:30	Mauro Antezza	**Casimir Torque and Force on Gratings**
13:30 – 14:00	Giuseppe Bimonte	**Hide It to See It Better: Probing the Influence of Free Charge Carriers on the Thermal Casimir Effect by Iso-Electronic Experiments**
14:00 – 14:25	Francesco Intravaia	**The Viscosity of Vacuum**
14:25 – 14:50	**Speaker Tables + *BREAK***	

Chair: Anna Maciolek

14:50 – 15:10	**Flash Talk Presentations** (2 min)	
15:10 – 15:40	**Poster Session I + *NETWORKING***	

Chair: Marjolein Dijkstra

15:40 – 16:10	Peter Schall	**Critical Casimir Forces Control Colloidal Assembly**
16:10 – 16:35	Robert Evans	**Solvent Mediated Interactions: Is the Critical Casimir Force Special**
16:35 – 17:05	Giovanni Volpe	**Experimental Study of Critical Fluctuations and Critical Casimir Forces**
17:05 – 17:30	**Speaker Tables + *BREAK***	
17:30 – 18:00	Alejandro Rodriguez	**Physical Limits on Fluctuation-Induced Phenomena**

Program *(CET)*

Tuesday, 15 February 2022

Chair: Daniel Dantchev

13:00 – 13:30	Timo Betz	**Exploiting Onsager Regression in Passive Measurements to Reveal Active Mechanics of Living Systems**
13:30 – 14:00	Sergio Ciliberto	**Measurement of the Casimir Force in Binary and Normal Fluids**
14:00 – 14:25	Daniela J. Kraft	**Diffusion and Conformations of Flexible Colloidal Structures**
14:25 – 14:50	**Speaker Tables +** ***BREAK***	

Chair: Matthias Krüger

14:50 – 15:10	**Flash Talk Presentations** (2 min)	
15:10 – 15:40	**Poster Session II +** ***NETWORKING***	

Chair: Thorsten Emig

15:40 – 16:10	Lilia Woods	**Standard and Dirac Materials: Band Structure and Dimensionality Effects in Dispersive Interactions**
16:10 – 16:35	Aleksandra Petkovič	**The Casimir-Like Effect in a One-Dimensional Bose Gas**
16:35 – 17:05	Jeremy Munday	**Controlling the Casimir Effect Through Geometry and Optical Anisotropy**
17:05 – 17:30	**Speaker Tables +** ***BREAK***	
17:30 – 18:00	Yun Liu	**Aggregation and Gelation of Charged Colloidal Particles in Binary Solvents and their Applications**

Program *(CET)*

Wednesday, 16 February 2022

Chair: Clemens Bechinger

13:00 – 13:30	Mehran Kardar	**Ratchet Forces in Active Matter and QED**
13:30 – 14:00	David Dean	**Non Monotonic Casimir Forces in Higher Derivative Field Theories**
14:00 – 14:25	Masami Kageshima	**Complex Mechanical Response of Near-Critical Binary System Studied with Atomic Force Microscopy**
14:25 – 14:50	**Speaker Tables +** ***BREAK***	

Chair: Andrea Gambassi

14:50 – 15:10	**Flash Talk Presentations** (2 min)	
15:10 – 15:40	**Poster Session III +** ***NETWORKING***	

Chair: Francesco Ginelli

15:40 – 16:10	Nicoletta Gnan	**Critical Fluctuations in Active Systems**
16:10 – 16:35	Markus Gross	**Dynamics of the Critical Casimir Force and its Fluctuations**
16:35 – 17:05	Cynthia J. Olson Reichhardt	**Clogging, Dynamics and Reentrant Fluid for Active Matter on Periodic Substrates**
17:05 – 17:30	**Speaker Tables +** ***BREAK***	
17:30 – 18:00	Alexei V. Tkachenko	**Entropic and Informational Forces in Material World**

Program *(CET)*

Thursday, 17 February 2022

Chair: Fred Hucht

12:45 – 13:15	Franco Nori	**Quantum Nonlinear Optics without Photons, how to Excite Two or More Atoms Simultaneously with a Single Photon, and Other Unusual Properties of Ultra-Strongly-Coupled QED Systems**
13:15 – 13:45	Felix Höfling	**Spontaneous Trail Formation in Populations of Auto-Chemotactic Walkers**
13:45 – 14:15	Jean-Baptiste Fournier	**Multibody and Retardation Effects in Field-Mediated Interactions**
14:15 – 14:40	**Speaker Tables +** ***BREAK***	

Chair: Robert Evans

14:40 – 15:10	Jean-François Joanny	**Mixtures of Hot and Cold Particles**
15:10 – 15:35	Alessio Squarcini	**Critical Casimir Interaction between Complex Particles in Two Spatial Dimensions. Exact Results**
15:35 – 16:05	Alberto Parola	**Solvation Forces in Disguise**
16:05 – 16:30	**Speaker Tables +** ***BREAK***	

Chair: Theodore L. Einstein

16:30 – 16:55	Oleg Vasilyev	**Debye vs. Casimir: Controlling the Structure of Charged Nanoparticles Deposited on a Substrate**
16:55 – 17:20	Clemens Bechinger	**Barrier Crossing in a Viscoelastic Bath**
17:20 – 17:30	Organizers	**Closing**
17:30 – 17:50	**Speaker Tables**	
17:50	*END OF THE SEMINAR*	

Posters

Poster Session I, Monday, 14 February, 15:10 h

1	Kiryl Asheichyk	**Brownian Systems Perturbed by Mild Shear: Comparing Response Relations**
2	Bettina Beverungen	**The Casimir-Polder Interaction between Atoms and Cylindrical Structures**
3	Agnese Callegari	**Theoretical and Numerical Study of the Interplay of Casimir-Lifshitz and Critical Casimir Force for a Metallic Flake Suspended on a Metal-Coated Substrate**
4	Luca Cervellera	**Critical Casimir Effect in the Square-Lattice Ising Model with Quenched Surface Disorder**
5	Timo Doerries	**Mobile/Immobile Models with Long Exponential Waiting Times for Biological Applications**
6	Theodore L. Einstein	**Thermal Fluctuations of Steps on Misoriented Surfaces and the Generalized Wigner Surmise**
7	Nima Farahmand Bafi	**Anisotropic Critical Casimir Interaction between Ellipsoidal Particles**
8	Giuseppe Fava	**Strong Casimir Forces in Flocking Active Matter**

Poster Session II, Tuesday, 15 February, 15:10 h

1	Malte Henkel	**Non-Equilibrium Dynamics and Ageing in Quantum Systems**
2	Fred Hucht	**The Square-Lattice Ising Model on the Rectangle**
3	Lukas Hupe	**Collective Dynamics in Populations of Growing Rods**
4	Davide Iacobacci	**Casimir-Polder Shift of Ground-State Hyperfine Zeeman Sublevels of Hydrogen Isotopes**
5	Fatemeh Abbasi	**Neutrophil Mechanotransduction during Durotaxis**
6	Peter Lemmens	**Roton Dynamics and Chiral Fluctuations in Liquid Crystals**
7	Alessandro Magazzu	**Controlling the Dynamics of Colloidal Particles by Critical Casimir Forces**

Poster Session III, Wednesday, 16 February, 15:10 h

1	Saeed Mahdisoltani	**TBA**
2	Piotr Nowakowski	**Casimir-Like Interaction of Inclusions in Lipid Bilayer with Two Order Parameters**
3	Yoav G. Pollack	**Effective Forces in Cellular Soft Matter**
4	Falko Schmidt	**Casimir-Lifshitz Forces vs. Critical Casimir Forces: Trapping and Releasing of flat Metallic Particles**
5	Ariane Soret	**Forces Induced by Quantum Mesoscopic Coherent Effects**
6	Davide Venturelli	**Dynamics of Probe Particles in Near-Critical Fields**
7	Benjamin Walter	**Non-Equilibrium Dynamics of a Colloid Coupled to a Self-Interacting Critical Field**

Abstracts of Lectures

(in alphabetical order)

Casimir torque and force on gratings

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We will discuss recent results: (i) on the theory of the Casimir torque between two gratings rotated by an angle θ with respect to each other [1]; and (ii) on the theory and experiment on the Casimir force between interpenetrating gratings [2]. These findings pave the way to the design of contactless quantum vacuum torsional spring and sensors with possible relevance to micro and nanomechanical devices.

References

[1] Mauro Antezza, H. B. Chan, Brahim Guizal, V.N. Marachevsky, Riccardo Messina, Mingkang Wang, Phys. Rev. Lett. **124,** 013903 (2020)

[2] Mingkang Wang, L. Tang, C.Y. Ng, Riccardo Messina, Brahim Guizal, J. A. Crosse, Mauro Antezza, C.T. Chan, H.B. Chan, Nature Communication **12**, 600 (2021)

Exploiting Onsager regression in passive measurements to reveal active mechanics of living systems

T. Münker[1], G. Knotz[1], R. Jain[1], M. Krüger[1] and T. Betz[1]

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Understanding life is arguably among the most complex scientific problems faced in modern research. From a physics perspective, living systems are complex dynamic entities that operate far from thermodynamic equilibrium. This active, non-equilibrium behavior, with its constant hunger for energy, allows life to overcome the dispersing forces of entropy, and hence drives cellular organization and dynamics at the micrometer scale. Unfortunately, most analysis methods provided by the powerful toolbox of statistical mechanics cannot be used in such non-equilibrium situations, forcing researchers to use sophisticated and often invasive approaches to study the mechanistic processes inside living organisms. Inspired by Onsager's regression hypothesis, we introduce here a Mean Back Relaxation (MBR) observable, which detects active motion in purely passive measurements of particle fluctuations. The MBR, which is based on three-point probabilities, is theoretically and experimentally shown to exhibit markers of non-equilibrium, i.e., of detailed balance breaking dynamics. We furthermore observe an astonishing relation between the MBR and the effective non-equilibrium energy in living cellular systems. This is used to successfully predict the viscoelastic response function and the complex shear modulus from a purely passive approach, hence opening the door for rapid and simple passive mechanics measurements even in active systems.

Hide it to see it better: probing the influence of free charge carriers on the thermal Casimir effect by iso-electronic experiments.

Giuseppe Bimonte

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One of the main unresolved problems in Casimir physics is the role of free-charge carriers in determining the magnitude of the Casimir force between two conducting test bodies. We show that differential experimental setups based on the iso-electronic principle provide the ideal tool to elucidate this problem. We describe several iso-electronic setups specifically aimed at investigating the influence of free-charge carriers in the Casimir effect for metallic, magnetic and semi-conducting test bodies.

Measurement of the Casimir force in binary and normal fluids

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We present here detailed measurements of the Casimir-Lifshitz force between two gold surfaces, performed for the first time in both gas (nitrogen) and liquid (ethanol) environments with the same apparatus and on the same spot of the sample. Furthermore, we study the role of double-layer forces in the liquid, and we show that these electrostatic effects are important. The later contributions were precisely subtracted to recover the genuine Casimir force, and the experimental results are compared with calculations using Lifshitz theory. Our measurements demonstrate that a careful account of the actual optical properties of the surfaces is necessary for an accurate comparison with the Lifshitz theory predictions at short separations of less than 200nm.

We also summarize the observation of a temperature-controlled synchronization of two Brownian-particles in a binary mixture close to the critical point of the demixing transition. The two beads are trapped by two optical tweezers whose distance is periodically modulated. We notice that the motion synchronization of the two beads appears when the critical temperature is approached. In contrast, when the fluid is far from its critical temperature, the displacements of the two beads are uncorrelated. Small changes in temperature can radically change the global dynamics of the system. We show that the synchronisation is induced by the critical Casimir forces. Finally, we present the measure of the energy transfers inside the system produced by the critical interaction.

References

[1] Anne Le Cunuder et al., Phys. Rev. B **98**, 201408(R) (2018)
[2] Ignacio A. Martínez et al., Entropy 19, 77 (2017).

Non-monotonic Casimir forces

David S. Dean

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In this talk I will discuss two examples of systems where thermal or quantum fluctuations lead to fluctuation induced forces which have a non-monotonic behavior that can lead to strong metastability. The first example corresponds to a field theory with higher derivative interactions (examples arise in non-local electrostatics and polymer physics). The second comes from free fermionic systems in the presence of impurities. Despite corresponding to drastically different physics, the two examples show remarkably similar Casimir force phenomenology.

[1] D.S. Dean, B. Miao and R. Podgornik, **Path Integrals for higher derivative actions**,

J. Phys. A 52, 505003 (2019).

[2] D.S. Dean, B. Miao and R. Podgornik, **Thermal Casimir interactions for higher derivative field Lagrangians: Generalized Brazovskii models**, *J. Phys. A: Math. Theor.* **53,** 355005, (2020).

[3] D.S. Dean, P. Le Doussal, S.N. Majumdar and G. Schehr, **Impurities in systems of noninteracting trapped fermions,** SciPost Phys. **10**, 082 (2021).

Solvent Mediated Interactions: is the critical Casimir force special?

R. Evans

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When two ‘large’ objects are immersed in a solvent reservoir an effective potential or solvent mediated interaction arises between these objects. The latter might be macroscopic, say two plates, or mesocopic, say two colloids, or might be two proteins or two nanoparticles.

This talk will give a brief overview of solvent mediated interactions, with some remarks on history and nomenclature, focusing on the case of two parallel plates/walls separated by a distance *L* where the relevant interaction is usually termed the solvation force. This is the excess pressure due to confining the solvent/liquid and is, essentially, the quantity measured by SFA (surface force apparatus) experiments. When the plates are identical, phenomena such as capillary condensation and evaporation, and their criticality, lead to particular signatures in the solvation force and to enhanced density fluctuations. When the walls are opposing, so that one is wet and the other dry, pronounced capillary-wave-like fluctuations occur at mid-point, *L*/2, and have repercussions for the resulting solvation force, including scaling behaviour. Of course, none of these phenomena require a diverging bulk/ reservoir correlation length.

The so-called critical Casimir force is an (important) example of a long-ranged solvent mediated interaction where the physics is driven by a diverging bulk correlation length. We enquire what is special about this case.

Multibody and retardation effects in field-mediated interactions

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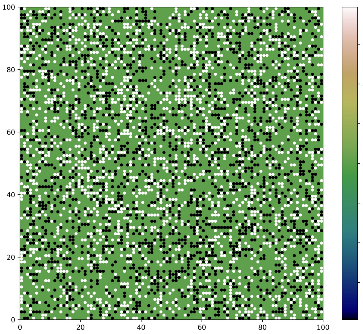
Particles in soft matter interact through the deformation field they create, as in the “cheerios” effect, the curvature-mediated interactions of membrane proteins, or through the Casimir effect. Using a simple model for field-mediated interactions between passive particles, or active particles that switch conformation randomly [1] or synchronously, we derive generic results concerning multibody interactions, activity driven patterns, and retardation effects [2].

References

[1] R. Zakine, J.-B. Fournier and F. van Wijland, *Phys. Rev. Lett.* **121**, 028001 (2018)
[2] J.-B. Fournier, to be published



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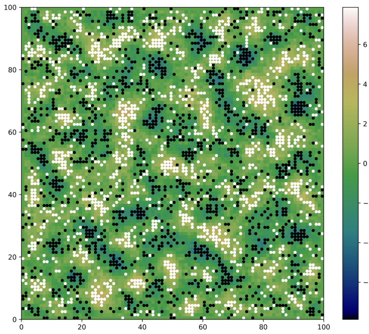

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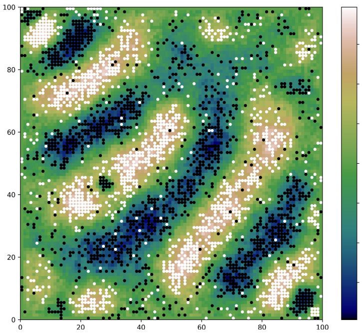

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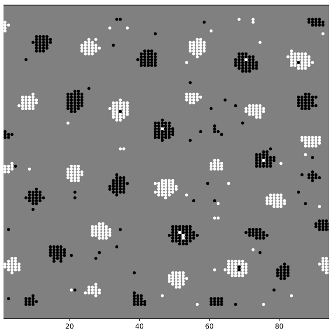

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Barrier crossing in a viscoelastic bath

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We experimentally investigate the hopping dynamics of a colloidal particle across a potential barrier and within a viscoelastic, i.e., non-Markovian bath. We observe two clearly separated time scales in the corresponding waiting time distributions of the particle. While the longer time scale exponentially depends on the barrier height (Kramers-like behavior), the shorter one is similar to the relaxation time of the fluid.

By measuring the effective pseudo potential acting on the particle, we show that this short time scale results from the temporary storage of elastic energy during a crossing event. When released, it strongly increases the probability of a jump back into the initial well. This permanent excitation of the bath strongly increases the hopping rate over potential barriers.

Finally, we show that forcing the relaxation of the particle inside one well strongly suppress this shorter time-scale, validating its non-Markovian origin. Our results are in excellent agreement with a simple model where the particle is elastically coupled to another particle to mimic the effect of the viscoelastic fluid.

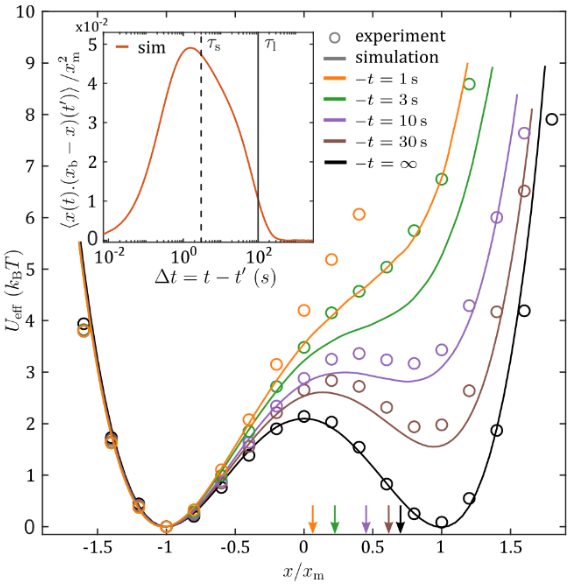

Figure 1: Effective pseudo-potential U_{eff} acting on the particle for experiments (circles) and simulations (lines). After a jump the pseudo-potential is strongly asymmetric, but relaxes towards the double-well after a few seconds.

References

[1] Ginot, F., Caspers, J., Krüger, M., & Bechinger, C. “Barrier crossing in a viscoelastic bath.” Physical Review Letters, **128(2)**, 028001 (2022).

Critical fluctuations in active systems

N.Gnan[1], C. Maggi[2], M. Paoluzzi [3], C. Crisanti [4] and E. Zaccarelli [1]

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The non-equilibrium dynamics of self-propelled particles has attracted great interest in the last decade since it can give rise to intriguing new collective phenomena. The archetypal example is the Motility-Induced Phase Separation (MIPS) [1] that can be understood in terms of active particles that move slower in denser regions, thus triggering an effective attraction that brings the system close to a spinodal decomposition in analogy with gas-liquid coexistence in equilibrium systems.

Critical Casimir forces occurs thanks to the confinement of critical fluctuations between two confining surfaces. Such an effect has been observed in colloidal systems [2] and it is now one of the most exploited techniques to tune interactions between colloids [3].

Given the analogies between the gas-liquid phase separation and the MIPS, a natural question is whether critical “active” Casimir forces can be observed and what is their functional form. To answer to this question, one has first to establish the presence of a second order critical point at the end point of the MIPS and to investigate whether there is a region close to phase separation in which the active critical behavior can be traced back to a specific universality class.

In this talk I will present recent results on different models of active systems for which we have numerically investigated whether a critical behavior exists. I will show how finite-size scaling analysis provides exhaustive evidence that the critical behavior of these active systems belongs to the Ising universality class [4]. I will discuss how these results suggest to modify the field-theoretical framework to account for the non-equilibrium behavior [5], and how this might impact on critical “active” Casimir forces.

References

[1] M. E. Cates et al., Annu. Rev. Condens. Matter Phys. **6**, 219 (2015)
[2] C. Hertlein et al., Nature **451**, 172 (2008)
[3] T. A. Nguyen et al., Materials **10,** 1265 (2017)
[4] C. Maggi et al., Soft Matter **17**, 3807 (2021)
[5] C. Maggi et al., **arXiv:2108.13971** (2021)

Dynamics of the critical Casimir force and its fluctuations

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In a confined near-critical fluid, long-ranged Casimir forces act on immersed solid particles and surfaces. Here, I will report on some recent advances in the study of the dynamics of the critical Casimir force and of its fluctuations in and out of equilibrium.

In the first part, I will consider a fluid film confined by solid walls, described in terms of a Landau-Ginzburg model with conservative (model B) dynamics. After briefly highlighting the consequences of the global conservation of the order parameter [1], the time evolution of the Casimir force under a temperature quench will be discussed [2]. Next, I will focus on the statics and dynamics of the *fluctuations* of the critical Casimir force, which turn out to have a strongly non-Markovian character [3].

In the second part, I will analyze a simple model for a colloidal particle immersed in a critical solvent. Starting with a system of coupled stochastic PDEs, adiabatic elimination of the fluid degrees of freedom renders an effective Langevin equation for the particle alone, which involves a fluctuation-induced (Casimir) potential as well as a spatially dependent noise and mobility [4].

References

[1] M. Gross, O. Vasilyev, A. Gambassi, S. Dietrich, Phys. Rev. E **94**, 022103 (2016); M. Gross, A. Gambassi, S. Dietrich, Phys. Rev. E **96**, 022135 (2017)

[2] M. Gross, A. Gambassi, S. Dietrich, Phys. Rev. E **98**, 032103 (2018); M. Gross, C. M. Rohwer, S. Dietrich, Phys. Rev. E **100**, 012114 (2019)

[3] M. Gross, A. Gambassi, S. Dietrich, Phys. Rev. E **103**, 062118 (2021)

[4] M. Gross, J. Stat. Mech. (2021) 063209

Spontaneous trail formation in populations of auto-chemotactic walkers

Z. Mokhtari[1], **R. I. A. Patterson,**[2] **and F. Höfling**[1,3]

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[2] *Weierstrass Institute for Applied Analysis and Stochastics, Berlin, Germany*
[3] *Zuse Institute Berlin, Germany*

We study the formation of trails in populations of self-propelled agents that make oriented deposits of pheromones and also sense such deposits to which they then respond with gradual changes of their direction of motion. Based on extensive off-lattice computer simulations aiming at the scale of insects, e.g., ants, we identify a number of emerging stationary patterns and obtain qualitatively the non-equilibrium state diagram of the model, spanned by the strength of the agent–pheromone interaction and the number density of the population [1]. In particular, we demonstrate the spontaneous formation of persistent, macroscopic trails, and highlight some behaviour that is consistent with a dynamic phase transition. This includes a characterisation of the mass of system-spanning trails as a potential order parameter. We also propose a dynamic model for a few macroscopic observables, including the sub-population size of trail-following agents, which captures the early phase of trail formation.

References

[1] Z. Mokhtari, R. I. A. Patterson, and F. Höfling, New J. Phys., in press (2021), DOI: 10.1088/1367-2630/ac43ec.

The viscosity of vacuum

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During the last decades, the study of fluctuation-induced force has grown in relevance in connection to fundamental investigations and quantum-technological applications.

In particular, increasing interest has been devoted to non-conservative fluctuation-induced interactions. Prominent examples are contactless frictional forces between two or more neutral nonmagnetic bodies in relative motion at constant velocity [1,2]. In these systems, even at zero temperature, the quantum electromagnetic field behaves as a viscous medium which hinders the motion of objects moving in vacuum. As with other electromagnetic fluctuation-induced phenomena, this electromagnetic viscosity depends on the temperature, the optical properties and the geometry of all the bodies comprising the system. An accurate theoretical description of this phenomenon can be challenging but often reveals a great richness of interesting physical mechanisms at work behind the scenes [3-6].

In this talk, recent results regarding the electromagnetic vacuum viscosity are discussed. Specifically, an electrically neutral atom which is propelled along the direction of translational invariance of a generic macroscopic electromagnetic environment is considered. Different aspects and scenarios illustrate the interest of the electromagnetic viscosity for fundamental investigations and their connections with other fields of research.

References

[1] F. Intravaia, R. O. Behunin, and D. A. R. Dalvit, Phys. Rev. A **89**, 050101(R) (2014).
[2] F. Intravaia, R. O. Behunin, C. Henkel, K. Busch, and D. A. R. Dalvit, Phys. Rev. A **94** 042114 (2016).
[3] F. Intravaia, R. O. Behunin, C. Henkel, K. Busch, and D. A. R. Dalvit, Phys. Rev. Lett. **117**, 100402 (2016).
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Mixtures of hot and cold particles

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When two types of particles in contact with reservoirs at different temperatures are mixed in solution, they tend to phase separate. If the particle densities are small, the solution can be described by an effective free energy, which is very similar to a Flory free energy for polymer mixtures. Still, this is a non-equilibrium system and there is an energy flux from hot to cold particles.

We show that at higher concentrations the solution is non-reciprocal and no free energy can be defined. This does not prevent the phase separation.

We also discuss the self-diffusion coefficient of a single particle in a dilute solution of particles at a different temperature, ignoring hydrodynamic interactions. The diffusion is enhanced if the particle has a lower temperature than the bath and it is reduced if it has a lower temperature.

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Complex mechanical response of near-critical binary system studied with atomic force microscopy

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In 1978 Fisher and de Gennes predicted that a characteristic force should arise between surfaces placed in near-critical binary liquid mixture as the correlation length ξ increases [1]. Direct detection of this critical Casimir force was first reported by using total internal reflection microscopy (TIRM) [2]. On the other hand, increase in ξ is expected to affect the viscous property of the system. Viscous anomaly of near-critical binary system has drawn interest from 1960's [3,4]. Thus the forces acting on two surfaces placed in near-critical binary system should possess a character of a complex quantity. Based on above consideration application of atomic force microscopy (AFM) to analysis of near-critical system is attempted. By attaching the probing colloid onto an AFM cantilever, it is readily possible to bring it into the region where the gap spacing z is comparable to or smaller than ξ. In addition, by spatially modulating the cantilever it is possible to detect the interaction as a complex response. Here the latter advantage is secured by the magnetic modulation technique introduced into the present home-built AFM apparatus[5]. Figure 1 shows schematic view of experimental setup. A glass colloid is attached onto the cantilever and is magnetically modulated via alternating magnetic field. Figure 2 shows dependence of simultaneously-measured force gradient and viscous drag coefficient on the gap distance z between the colloid and a mica substrate in a mixture of 2,6-lutidine and water at different temperatures below T_c. The both profiles show temperature-dependent variation at short distance range including $z \lesssim \xi$. Details of the experiment and analysis as well as the possibility of future progress will be discussed.

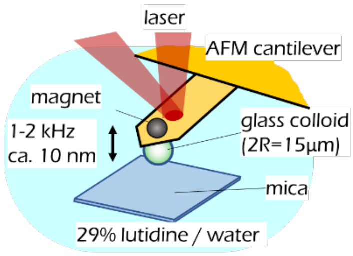

Fig. 1 Schematic view of experimental setup.

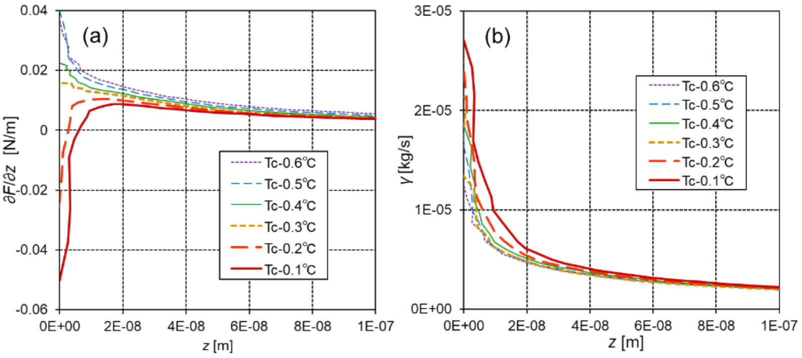

Fig. 2 Dependence of force gradient (a) and viscous drag coefficient (b) on the gap distance z.

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Ratchet Forces in Active Matter and QED

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Symmetry arguments suggest that in the absence of time reversal and invasion symmetries, fluctuations can be rectified to generate ratchet-like forces. Such forces are present in *active matter* (collection of self-propelled particles); where even the pressure has non-trivial dependence on boundaries. Ratchet forces can also arise from non-equilibrium electromagnetic fluctuations, and we inquire if they can be used to construct a heat engine[1].

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Diffusion and conformations of flexible colloidal structures

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Many functional (bio-)molecules such as enzymes, RNA and antibodies possess structural flexibility which provides functionality. For example, different conformations may enhance or inhibit a protein's activity in allosteric regulation and the protein's flexibility may affect diffusion. A rigorous understanding of enzyme function requires quantitative knowledge of the impact of flexibility, however, controlled measurements on the single-molecule level that single out its effect are challenging.

In this talk, I will show how we can create a colloidal model system that features internal degrees of motion and tackle these questions quantitatively. We exploit colloidal joints [1,2], that exploit multivalent interactions [3] to enable the formation of strong and specific but flexible bonds between colloidal particles. I will illustrate the variety of flexible structures that we assembled, from trimers [4] to chains [5], clusters [6] and lattices, and discuss how the flexibility affects their conformations and their diffusive behavior. Our quantitative measurements confirmed long-standing predictions on the diffusion of flexible objects for the first time [4]. Understanding the impact of flexibility opens the door towards using it as a new feature for smart materials, where a change in the microscopic arrangement of subunits affects its macroscopic properties.

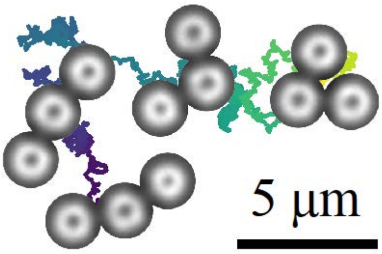

Figure 1: Diffusion trajectory of a flexible trimer in time, with different conformations shown

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Aggregation and gelation of charged colloidal particles in binary solvents and their applications

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The aggregation and gelation behavior of charged silica particles driven by a binary solvent introduced attraction is studied. Surprisingly, we have observed that the aggregation formation at low particle concentration is the very sensitive to the particle size. Large particles tend to aggregate first and precipitate out of solution while smaller sized particles remain mostly in the supernatant.[1-2] As the solvent introduced attraction is a generic phenomenon for particles in a binary solvent, this observation could be used as a generic method for particle purification based on their sizes.[1]

At much higher particle concentrations, this solvent induced attraction could cause the gelation of colloid particles with bicontinuous structures. Unlike the well-studied Bijel systems, the particles with charged surfaces are partitioned completely in the water rich solvent region as the particle surface strongly favors one component of the solvent, i.e., water in our case.[3] Its domain size can be controlled through the temperature ramping rates, and does not need a very fast temperature quenching rate required by Bijel systems. This new gel system is termed as the solvent segregation-driven gel (SeedGel). SeedGel is thermally reversible with precise structure reproducibility.[3] Some SeedGel systems show very amazing optical properties. Despite that it has micrometer sized domains, they are transparent and show a temperature dependent structure color change with dynamic coloration over a wide range of spectrum. Thus, the SeedGel can be used for smart window applications and the optical filters with a precise selection of the wavelength.[4]

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Controlling the Casimir Effect Through Geometry and Optical Anisotropy

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The Casimir effect is a remarkable consequence of quantum electrodynamics and has found applications in physics, chemistry, and even biology. In this talk, I will discuss our work engineering the Casimir effect through both a material's optical properties and its geometry. I will describe experiments where the geometry can greatly modify the strength and power-law of the force [1,2] and how optically anisotropic materials can generate Casimir torques [3]. Finally, I will discuss some of our recent work related to technological applications with switchable Casimir forces and other quantum effects using materials with electrically tunable optical properties.

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Quantum Nonlinear Optics without Photons, how to excite two or more atoms simultaneously with a single photon, and other unusual properties of ultra-strongly-coupled QED systems.

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How to excite two or more atoms simultaneously with a single photon: We consider two separate atoms interacting with a single-mode optical or microwave resonator. When the frequency of the resonator field is twice the atomic transition frequency, we show that there exists a resonant coupling between *one* photon and *two* atoms, via intermediate virtual states connected by counter-rotating processes. If the resonator is prepared in its one-photon state, the photon can be jointly absorbed by the two atoms in their ground state which will both reach their excited state with a probability close to one. Like ordinary quantum Rabi oscillations, this process is coherent and reversible, so that two atoms in their excited state will undergo a downward transition jointly emitting a single cavity photon. This joint absorption and emission process can also occur with three atoms. The parameters used to investigate this process correspond to experimentally demonstrated values in circuit quantum electrodynamics systems.

Quantum nonlinear optics without photons: Spontaneous parametric down-conversion is a well-known process in quantum nonlinear optics in which a photon incident on a nonlinear crystal spontaneously splits into two photons. Here we propose an analogous physical process where one excited atom directly transfers its excitation to a pair of spatially separated atoms with probability approaching 1. The interaction is mediated by the exchange of *virtual* rather than *real* photons. This nonlinear atomic process is coherent and reversible, so the pair of excited atoms can transfer the excitation back to the first one: the atomic analog of sum-frequency generation of light. The parameters used to investigate this process correspond to experimentally demonstrated values in ultrastrong circuit quantum electrodynamics. This approach can be extended to realize other nonlinear interatomic processes, such as four-atom mixing, and is an attractive architecture for the realization of quantum devices on a chip. We show that four-qubit mixing can efficiently implement quantum repetition codes and, thus, can be used for error-correction codes.

A few recent references (mostly 2016-2021) on this topic (ultra-strong coupling cavity QED) are listed below and freely available online at: http://dml.riken.jp/pub/Ultra-strong/

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Solvation forces in disguise

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Effective interactions between particles immersed in a fluid have been the subject of extensive investigations in different regimes: from the Asakura-Oosawa short range attraction present in the ideal gas limit, to the oscillatory behavior induced by repulsive forces. These depletion interactions represent a particular limit of the more general concept of solvent mediated forces, which are known to drive several important phenomena in soft matter, leading either to clustering, colloidal aggregation or dynamical arrest. Solvent mediated forces undergo a significant change when long range correlations are present in the host fluid due to the proximity of a second order phase transition. Targeted experiments show that, on approaching the critical point of a water-surfactant solution, the aggregation of suspended colloidal particles undergoes a remarkable enhancement [1]. This phenomenon, usually attributed to the onset of the critical Casimir effect, appears to be driven by the continuous evolution of the solvation forces already present in the off-critical regime. The universal properties of critical phenomena reflect in the structure of the effective interactions which acquire a scaling form. Density Functional Theory (DFT) is shown to provide a natural framework to describe the transition between critical (Casimir) and non-critical (depletion) regimes. A simple *approximate* DFT allows to express the universal scaling function of the critical Casimir effect in terms of the bulk critical properties [2]. We developed a microscopic approach able to evaluate the solvent-mediated interaction between two plates in a simple fluid, by use of a new density functional based on the hierarchical reference theory, which provides a microscopic description of fluids accurate also in the critical region. The evolution of the effective potential as a function of temperature and density is discussed, emphasizing the smooth transition between the high temperature, entropy-dominated, limit and the critical regime [3].

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The Casimir-like effect in a one-dimensional Bose gas

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I will discuss the fluctuation-induced interaction between two impurities embedded in a one-dimensional weakly-interacting Bose gas. Analytical results for the interaction at arbitrary impurity coupling to the bosons and separation r will be presented. At r □ ξ, where ξ denotes the healing length of the Bose gas, the interaction is well described by the mean-field contribution. It decays exponentially at arbitrary coupling for $r \gg \xi$. At such long distances, however, the effect of quantum fluctuations becomes important, giving rise to a long-ranged quantum contribution to the induced interaction. At longest distances it behaves as $1/r^3$, while at strong coupling we find an intermediate distance regime with a slower decay, 1/r. The quantum contribution in the crossover regime is also calculated.

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Clogging, Dynamics and Reentrant Fluid for Active Matter on Periodic Substrates

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We examine the collective states of run-and-tumble active matter disks driven over a periodic obstacle array. When the drive is applied along a symmetry direction of the array, we find a clog-free uniform liquid state for low activity, while at higher activity, the density becomes increasingly heterogeneous and an active clogged state emerges in which the mobility is strongly reduced. For driving along non-symmetry or incommensurate directions, there are two different clogging behaviors consisting of a drive dependent clogged state in the low activity thermal limit and a drive independent clogged state at high activity. These regimes are separated by a uniform flowing liquid at intermediate activity. There is a critical activity level above which the thermal clogged state does not occur, as well as an optimal activity level that maximizes the disk mobility. Thermal clogged states are dependent on the driving direction while active clogged states are not. In the low activity regime, diluting the obstacles produces a monotonic increase in the mobility; however, for large activities, the mobility is more robust against obstacle dilution. We also examine the velocity-force curves for driving along non-symmetry directions, and find that they are linear when the activity is low or intermediate, but become nonlinear at high activity and show behavior similar to that found for the plastic depinning of solids. At higher drives the active clustering is lost. For low activity we also find a reentrant fluid phase, where the system transitions from a high mobility fluid at low drives to a clogged state at higher drives and then back into another fluid phase at very high drives. We map the regions in which the thermally clogged, partially clogged, active uniform fluid, clustered fluid, active clogged, and directionally locked states occur as a function of disk density, drift force, and activity.

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Physical Limits on Fluctuation-Induced Phenomena

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Much of the continuing appeal and challenge for understanding electromagnetic phenomena stems from the same root: given some scattering objective (enhancing radiation from a quantum emitter, the field intensity in a photovoltaic cell, the radiative cross section of an antenna) subject to physical constraints (material compatibility, fabrication tolerances, or system size) there is currently no method for finding or assessing uniquely best wave solutions [1]. In this talk, we present a theoretical framework based on dual-Lagrange optimization that yields bounds on a wide range of electromagnetic phenomena [2–5]. Results pertaining to fluctuation phenomena are discussed, including spectrally selective limits on Casimir–Polder forces [4], Casimir torques, and near-field heat transfer [5].

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Critical Casimir Forces control Colloidal Assembly

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Critical Casimir forces allow temperature control of colloidal interactions in near-critical solvents. Combined with recent breakthroughs in colloidal particle design, this opens new routes to assemble complex colloidal structures with unprecedented control over their architecture and properties. In particular, patchy particles promise the design of wetting boundary conditions to localize critical fluctuations, possibly inducing directional interactions to assemble “colloidal molecules”, analogues of molecular compounds at the colloidal scale. Such assembly control would offer fascinating applications in the design of new functional materials at micrometer and nanometer length scales.

In this talk, I will show that the combination of patchy particles and critical Casimir interactions enables reversible directional bonding with precise control of the patch-patch interaction strength. Using tetramer particles, we assemble colloidal analogs of well-known sp^3-hybridized carbon compounds such as (cyclo)butane, butyne, cyclopentane, and cyclohexane, and investigate their transition states and reactions. Adsorbed at an attractive substrate, these particles assemble into two-dimensional materials such as graphene. I will show how the critical Casimir interaction control applied to the nanoscale can assemble quantum dots, unfolding its full potential for the fabrication of active films for optoelectronic devices. These results demonstrate the opportunities for applications and exciting new science that can be explored by combining critical Casimir forces with functional nanoparticles.

Critical Casimir interaction between complex particles in two spatial dimensions. Exact results

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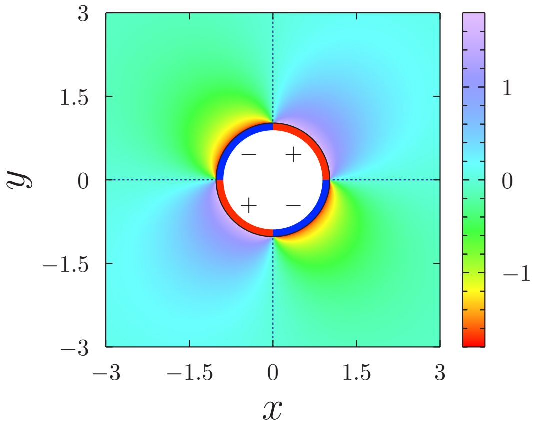
Chemically inhomogeneous colloidal particles immersed in a near-critical binary mixture are subjected to a fluctuation-induced-force known as the critical Casimir effect. By modeling a binary mixture at its demixing critical point by means of the critical Ising model in two dimensions, and exploiting its scaling-limit description in terms of a Conformal Field Theory, we determine the exact density profiles around various particles whose boundaries are formed by patches with different chemical structure and preference of the binary mixture components. The formalism encompasses several interesting configurations, including Janus particles, colloidal quadrupoles (as shown in Figure) and needles with inhomogeneous patches of symmetry breaking boundary conditions. Within the framework of the "Small Particle Operator Expansion" we determine the exact asymptotic behavior of the interaction free energy between these colloids, and colloids confined by a wedge-shaped wall. The leading operator content associated to chemically anisotropic colloidal inclusions is captured by a series of conformal fields which we determine exactly by computing one- and two-point correlation functions of both the order parameter and energy density in the presence of the inclusion. Our theoretical predictions are confirmed by numerical results available in the literature. A discussion about recent developments about the off-critical case is presented.



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Entropic and informational forces in material world

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Entropic forces play a prominent role in statistical physics, especially in the context of soft condensed matter. They are responsible for crystalline and liquid crystalline ordering of particles with hard-core repulsion, elasticity of polymers, pressure in gases, hydrophobic interactions, and many other phenomena. I will start my talk with some unusual examples of entropic forces. One of them deals with empty perovskites, a class of ionic solids that exhibits several anomalous properties, e.g. negative thermal expansion, and colossal softening under pressure [1]-[2]. These effects can be traced to the underlying "Floppy Network"- like architecture of these materials, and the entropic elasticity associated with that. In effect, this "hard" matter system has much in common with "soft" ones, such as polymeric gels.

While maximization of entropy may induce interparticle forces or dictate the overall organization of a material, a suppression of informational entropy on the level of constituent building blocks opens a route towards building sophisticated structures with programmable functionalities. This is best exemplified by key-lock interactions in biology that are responsible for much of the complexity of the living world. I will give a brief overview of how "informational forces", i. e. interactions between highly variable and mutually selective building blocks are being employed for creating the next generation of smart materials [3]-[5]. The key ideas inspired by biology are folding, self-assembly and templating. Each of them represents a specific way of transduction of the information needed for construction of a specific output structure. This information-theoretical view naturally leads to a question, whether the underlying complexity may be self-generated. This, in turn, connects our progress in understanding the organization of matter based on informational forces to the problem of the origin of life [6]-[7].

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Debye vs. Casimir: controlling the structure of charged nanoparticles deposited on a substrate

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Deposition and assembly of nanoparticles are the essential steps in the fabrication of next-generation optoelectronic devices, e.g. those based on quantum dots. However, our limited understanding of the interactions at the nanoscale hinders the development of reproducible morphologies and their integration in large-scale industrial processes. In this talk, we shall discuss the deposition of nanoparticles on flat and unpatterned substrates mediated by the interplay of critical Casimir attraction and Debye-screened electrostatic repulsion through immersion in a binary liquid mixture intermixed with salt. With experiments and simulations, we shall show how this assembly process can be biased towards forming 2D layers or 3D islands and how to tune the morphology of the deposited mesostructures. For nanoparticles and substrates favouring the same fluid component, we find with Monte Carlo simulations that the critical Casimir interactions between nanoparticles become drastically reduced at a substrate. In particular, the interactions can become a few k_BT weaker and their decay length a few orders of magnitude smaller than in bulk, which affects the structure of the deposited nanoparticles. With molecular dynamics simulations and experiments, we reveal that the nanoparticles can self-assemble into crystalline clusters, forming mesostructures resembling cluster fluids and spinodal morphology. The simulations also predict the formation of fractal-like nanoparticle gels and bicontinuous phases. These results demonstrate the potential of the critical Casimir interactions to control the deposition and structure of nanoparticles as building blocks for future optoelectronic and photonic devices.

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Experimental study of critical fluctuations and critical Casimir forces

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Critica Casimir forces (CCF) are a powerful tool to control the self-assembly and complex behavior of microscopic and nanoscopic colloids. While CCF were theoretically predicted in 1978 [1], their first direct experimental evidence was provided only in 2008, using total internal reflection microscopy (TIRM) [2]. Since then, these forces have been investigated under various conditions, for example, by varying the properties of the involved surfaces or with moving boundaries. In addition, a number of studies of the phase behavior of colloidal dispersions in a critical mixture indicate critical Casimir forces as candidates for tuning the self-assembly of nanostructures and quantum dots, while analogous fluctuation-induced effects have been investigated, for example, at the percolation transition of a chemical sol, in the presence of temperature gradients, and even in granular fluids and active matter. In this presentation, I'll give an overview of this field with a focus on recent results on the measurement of many-body forces in critical Casimir forces [3], the realization of micro- and nanoscopic engines powered by critical fluctuations [4, 5], and the creation of light-controllable colloidal molecules [6] and active droploids [7].

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Standard and Dirac materials: band structure and dimensionality effects in dispersive interactions

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The exchange of electromagnetic excitations of two objects when they are brought together results in a dispersive ubiquitous force whose sign and magnitude depend on the materials properties and geometry of the interacting objects. At short separations, when the exchange is instantaneous the interaction is in the van der Waals regime and it is determined by exponentially decaying surface modes. The van der Waals interaction is important for the stability of layered materials and the organization and complex behavior of biological systems, including lipids, membranes, and proteins, among other areas. Here we examine how the interplay between the electronic band structure and dimensionality affect van der Waals interactions within the Random Force Approximation. The polarization properties of materials with parabolic (standard systems) and linear (Dirac materials) dispersions in 1D, 2D, and 3D are also obtained. The quantum mechanical and thermal regimes are considered in detail showing various scaling laws. Characteristic distances signaling the onset of thermal fluctuations are also determined, which indicate that in structures with reduced dimensionality thermal effects become prominent at much reduced length scales when compared with 3D systems. The so-obtained results for the van der Waals interactions in standard and Dirac materials give comprehensive understanding of quantum mechanical and classical effects in dispersive interactions in the non-retarded regime.

Abstracts of Posters

(in alphabetical order)

Neutrophil mechanotransduction during durotaxis

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In Vivo, cells experience complex tissue environments with various chemical and physical features. 3D confinement is one of the major physical obstacles for cells in their natural environment. Neutrophils are among the most abundant immune cells in our body, which have to cope with various physical constrictions on their way from entering the blood stream, reaching the infection site, and accomplishing their vital mission. In addition to confinement, the stiffness of the microenvironment is another mechanical feature these rapidly moving cells are exposed to. Due to their long way from cell generation to their target site, neutrophils experience various tissue stiffness, from 1 kPa (bone marrow) to 20 MPa (bone). Previous studies have demonstrated that these cells are responsive to their microenvironment stiffness by adjusting their adhesion and spreading, and also the stiffness of the endothelial layer affects leukocytes decision about where to start transendothelial migration. Based on this knowledge we decided to combine confinement and stiffness change and investigate the impact of 3D stiffness gradient on cell behaviour and migration, a fact called durotaxis. We hypothesized that stiffness gradient might be a triggering factor of neutrophil migration toward the infection site. We confine neutrophils in between 2 layers of polyacrylamide hydrogels with 2 different stiffness and keep this distance stable for the desired period of time to investigate cell mechanotransduction during durotaxis (shifting from soft to stiff) from different points of view. Our preliminary results regarding the neutrophil durotaxis show a surprising and transient force peak on the soft substrate during cell shifting.

Brownian systems perturbed by mild shear: comparing response relations

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We present a comprehensive study of the linear response of interacting underdamped Brownian particles to simple shear flow. We collect six different routes for computing the response, including the symmetry-based approaches and the extension of the Green-Kubo relation to underdamped cases, which shows two unexpected additional terms. These six computational methods are applied to investigate the relaxation of the response towards the steady state for different observables, where interesting effects due to interactions and a finite particle mass are observed. Moreover, we compare the different response relations in terms of their statistical efficiency, identifying their relative demand on experimental measurement time or computational resources in computer simulations.

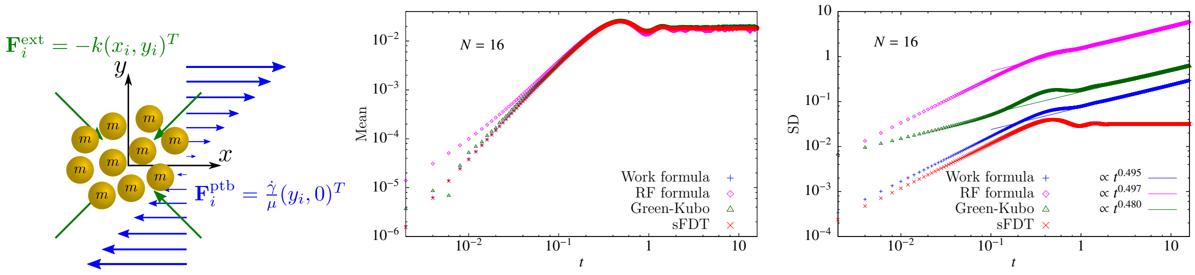

Figure 1: **Left:** The considered system: interacting underdamped Brownian particles confined in a harmonic potential and perturbed by shear flow. **Center:** The linear response for $\sum_i x_i y_i$ as a function of time computed using different response relations (note the agreement between the curves). **Right:** The standard deviation of the response (note the difference between the curves).

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The Casimir-Polder interaction between atoms and cylindrical structures

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A prototypical example of fluctuation-induced forces in the context of quantum electrodynamics is the Casimir-Polder force, which describes the interaction between a neutral atom and one or several macroscopic objects. Since it becomes especially relevant at short distances, this effect has received increasing attention with regard to nanotechnological applications in the past years. One possible avenue to tailor the interaction is through the object's geometry. Indeed, in comparison to a planar surface, more complex geometries introduce additional length scales into the system that induce a qualitative change in the behavior of the force.

Here, we consider the problem of the Casimir-Polder interaction for atoms close to cylindrical structures, i.e. translationally invariant structures in one direction. A key ingredient in our calculation is the electromagnetic Green tensor, which encodes the geometry as well as the material properties of the macroscopic object. This information can be leveraged to identify the system's intrinsic characteristics, including relevant length scales, and draw a connection to the behavior of the force. We evaluate the Casimir-Polder interaction and discuss it with respect to the system's properties. Additionally, analytical calculations of several asymptotic cases are considered. This serves both as a validation of our results while at the same time offering a deeper insight into the underlying physics.

Theoretical and numerical study of the interplay of Casimir-Lifshitz and critical Casimir force for a metallic flake suspended on a metal-coated substrate

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Casimir-Lifshitz forces arise between uncharged metallic objects because of the confinement of the electromagnetic fluctuations. Typically, these forces are attractive, and they are the main cause of stiction between microscopic metallic parts of micro- and nanodevices. Critical Casimir forces emerge between objects suspended in a critical binary liquid mixture upon approaching the critical temperature, can be made either attractive or repulsive by choosing the appropriate boundary conditions, and dynamically tuned via the temperature.

Experiments show that repulsive critical Casimir forces can be used to prevent stiction due to Casimir-Lifshitz forces. In a recent work, a microscopic metallic flake was suspended in a liquid solution above a metal-coated substrate [1]. By suspending the flake in a binary critical mixture and tuning the temperature we can control the flake's hovering height above the substrate and, in the case of repulsive critical Casimir forces, prevent stiction.

Here, we present the model for the system of the metallic flake suspended above a metal-coated substrate in a binary critical mixture and show that repulsive critical Casimir forces can effectively counteract Casimir-Lifshitz forces and can be used to control dynamically the height of the flake above the surface. This provides a validation of the experimental results and a base to explore and design the behavior of similar systems in view of micro- and nanotechnological applications.

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Critical Casimir effect in the square-lattice Ising model with quenched surface disorder

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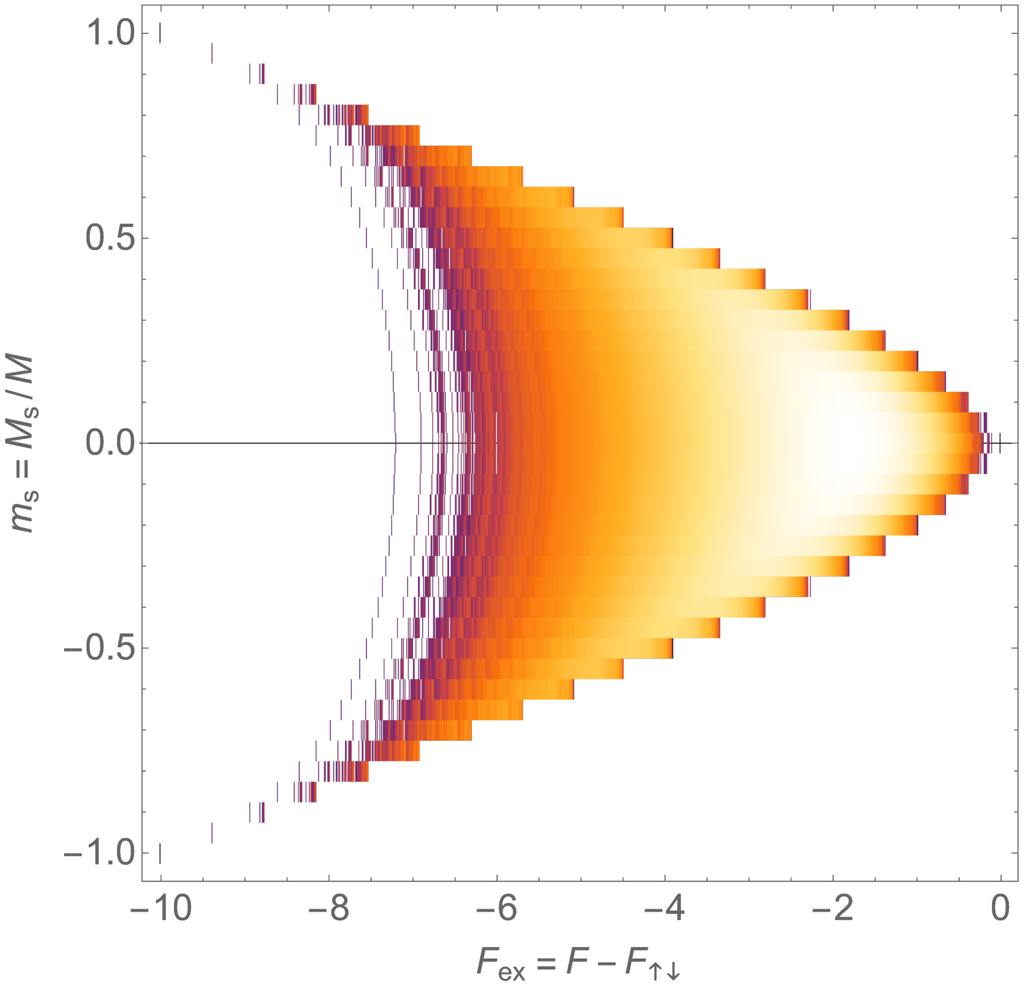
For the square-lattice Ising model, the critical Casimir potential and force can be calculated exactly for many geometries and boundary conditions. From a recent exact solution for the cylinder with length L, circumference M, and with arbitrary random boundary conditions at one boundary, we determine the full density of thermodynamic states $\tilde{\omega}(\delta F, M_s)$, with residual free energy δF and boundary magnetization M_s at criticality. From this quantity we can derive the disorder averaged Casimir potential for different aspect ratios and disorder ensembles.



Density of thermodynamic states $\tilde{\omega}(F_{ex}, M_s)$ for $M = 40$ and $L \to \infty$

Mobile/immobile models with long exponential waiting times for biological applications

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Tau proteins diffuse and stabilise microtubules by transiently binding to them [1]. This resembles the mobile/immobile model known from geoscience [2,3]. We focus on the case where the mean binding time is a lot longer than the mean mobile time. With an equilibrium fraction of initially mobile tracers the process is known to generate Fickian yet non-Gaussian diffusion [4]. The MSD is proportional to t at all times. We calculate the MSD for initially immobile tracers, where we find ballistic diffusion at short times. When all tracers are initially mobile, the full concentration behaves like the mobile fraction of the equilibrium case (striped area in the figure). In this case the MSD has a transient plateau and the PDF is a Laplacian with fixed scale parameters.

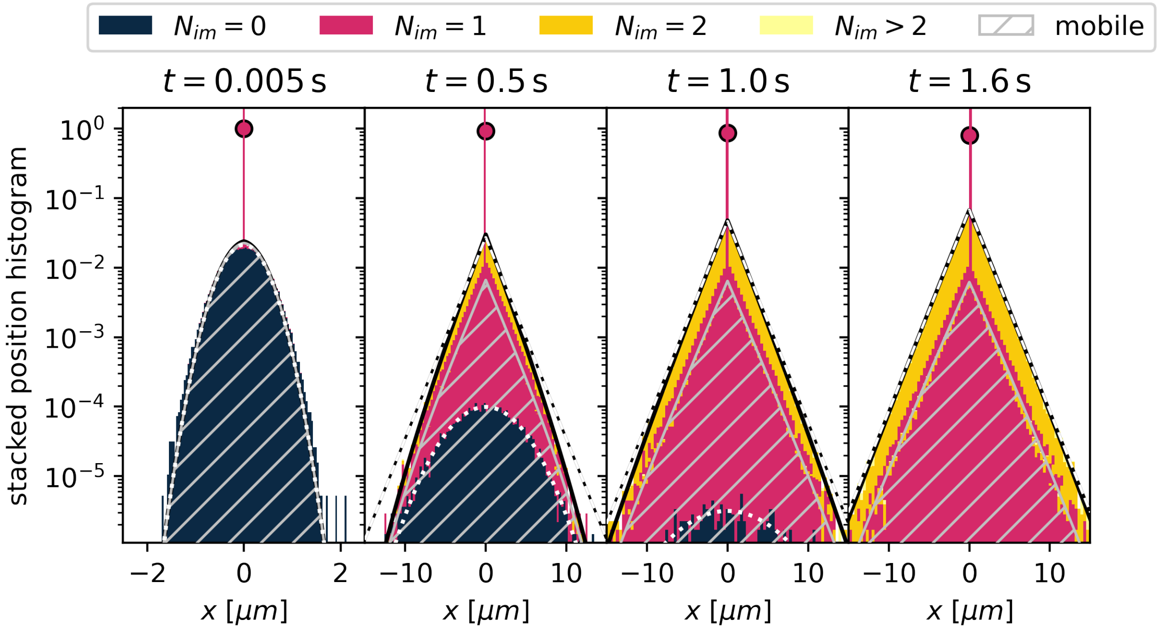

Figure: Concentration profiles for equilibrium initial conditions, where the number of immobilisations N_{im} is colour-coded.

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Thermal Fluctuations of Steps on Misoriented Surfaces and the Generalized Wigner Surmise

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Another well-studied physical example of fluctuation-induced long-range forces is the entropic repulsion between steps on a misoriented ("vicinal") crystal surface.[1] (The misorientation angle corresponds to a thermodynamic density!) Viewed from above, the equilibrium configurations of these steps fluctuating in 2D correspond to the world lines of spinless fermions in (1+1)D. Thus, the distribution of terraces widths (distances s between adjacent steps perpendicular to their mean direction, [\hat{**x**} in "Maryland notation"]) corresponds to the distribution of instantaneous separations of the 1D fermions, collected over quantum time. The particle mass is essentially the stiffness of the steps, determined by the kink energy (energy cost of a unit deviation of a step along \hat{**x**}). There is also an elastic repulsion between steps, which, as the entropic case, decays as s^{-2}. Hence, their contributions can be written g/s^2, where g is not the simple sum of the strengths of the two repulsions. In mean field, the single-particle distribution can be found from the Schrödinger equation for a particle in a box.[2] More generally, the system can be mapped to the venerable Calogero-Sutherland model,[3] which is exactly solvable for the "inverse temperatures" $\beta = 1, 2, 4$, with β simply related to g. The particle separations amazingly correspond to the energy spacings in the Wigner-Dyson model, for which random matrix theory provides useful results.[4] The distribution of terrace widths can be well approximated by the Wigner surmise form, with a rise $\propto s^{\beta}$ and a gaussian decay in s. Since physical values of g are unlikely to correspond to the special values of $g = [-1/4], 0, 2$, we have used the Wigner expression for arbitrary non-negative values of g. Comparison with Monte Carlo simulations and more importantly with experimental data—from Univ Maryland (ED Williams, JE Reutt-Robey groups), FZ-Jülich (H. Ibach, M. Giesen), and several other groups (E Bartel, L. Barbier, JJ Métois, JE.Ortega, et al.)—for various crystalline samples confirm that this approach captures the essential physics of the problems and provides the best way to extract g from data.[5,6] Several subtleties arise in confronting experiments with theory.

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Anisotropic critical Casimir interaction between ellipsoidal particles

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We study the effective interaction between ellipsoidal particles immersed in a critical fluid [1]. The total potential of interaction is inferred from analyzing configurations of particles observed in the experiment. To this end, we have generalized a model–free method [2] to obtain anisotropic interactions. We investigate how the potential depends on the temperature and aspect ratio of the particles and we identify the contribution from the critical Casimir interaction. The results allow for better understanding of the experimentally observed formation of 2D clusters of particles.

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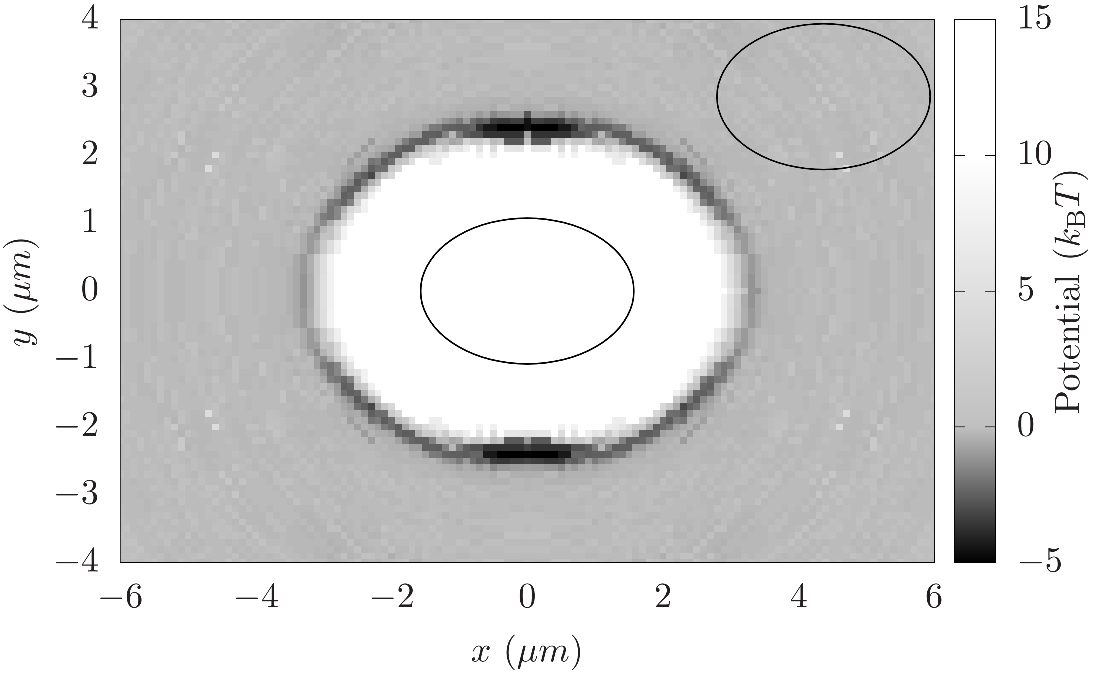

Plot of the potential of interaction of ellipsoidal particles in parallel configuration for $T = T_\mathrm{c} - 0.5\mathrm{K}$. The first particle is in the center of the plot and the color code shows how the potential of interaction depends on the position of the center of the second particle.

Strong Casimir-like Forces in Flocking Active Matter

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Flocking – the collective motion exhibited by certain active matter (AM) systems capable of spontaneously breaking their rotational symmetry – is a ubiquitous phenomenon, observed in a wide array of different living systems and on an even wider range of scales. Examples range from fish schools and flocks of birds to bacteria colonies and cellular migrations, down to the co-operative behavior of molecular motors and biopolymers at the subcellular level.

The bulk flocking state, as described by the celebrated Toner & Tu (TT) theory, is characterized by a strongly fluctuating ordered phase endowed by long-ranged massless correlations. While our knowledge of the bulk behavior of free collective motion is now fairly complete, at least when the surrounding fluid may be safely neglected (the so-called "dry approximation"), much less is known regarding the collective behavior of confined flocking AM. This is a problem of great relevance for many experimental realizations, either synthetic or biological, where confinement by hard boundaries is practically unavoidable.

While it has been argued that the hydrodynamic bulk fluctuations should be left unchanged by the local interaction with hard boundaries confining the TT fluid in the direction(s) transversal to collective motion, little is known about the behavior of fluctuations near such boundaries.

In this work we describe for the first time genuinely long-ranged forces that arise confining flocking AM between flat reflecting boundaries – either elastic or inelastic – in the direction(s) transversal to collective motion. Direct numerical simulations and analytical results show that non-equilibrium fluctuations induce an unusually strong Casimir-like force, characterized by a rather slow algebraic decay. We also argue that this behavior, while directly controlled by an inhomogeneous density profile in the transversal direction, is ultimately related to the scaling of transversal velocity fluctuations with the confinement size L.

Non-equilibrium dynamics and ageing in quantum systems

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The collective and purely relaxational dynamics of quantum many-body systems after a quench at temperature $T=0$, from a disordered state to various phases is studied through the exact solution of the quantum Langevin equation of the spherical and the O(n)-model in the limit $n\rightarrow\infty$. The stationary state of the quantum dynamics is shown to be a non-equilibrium state. The quantum spherical and the quantum O(n)-model for $n \rightarrow \infty$ are in the same dynamical universality class. The long-time behaviour of single-time and two-time correlation and response functions is analysed and the universal exponents which characterise quantum coarsening and quantum ageing are derived. The importance of the non-Markovian long-time memory of the quantum noise is elucidated by comparing it with an effective Markovian noise having the same scaling behaviour and with the case of non-equilibrium classical dynamics.

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The square-lattice Ising model on the rectangle

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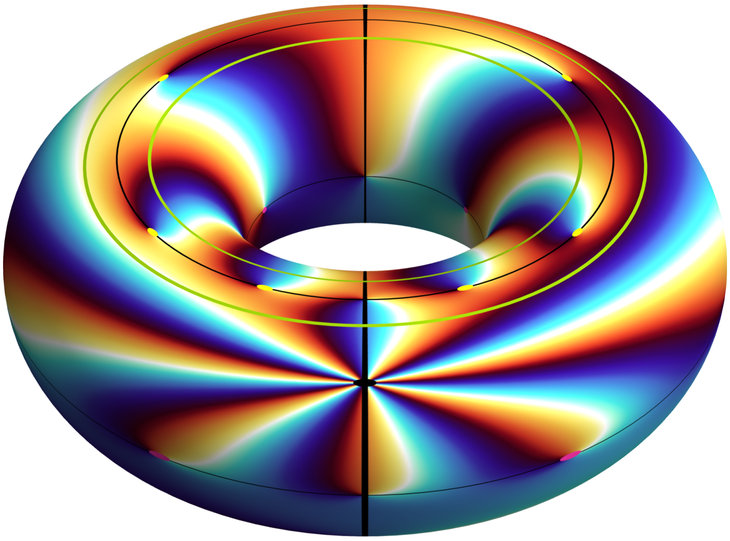
For the square-lattice Ising model, the universal critical Casimir potential and force scaling functions can be calculated exactly for many geometries and boundary conditions. We present a recent exact solution of the square lattice Ising model on the $L \times M$ rectangle, with open boundary conditions in both directions [1], in terms of the determinant of a $M/2 \times M/2$ Hankel matrix $\mathbf{H}$. The $M-1$ independent matrix elements of $\mathbf{H}$ are Fourier coefficients of a certain symbol function, which is given by the ratio of two characteristic polynomials. These polynomials are associated to the different directions of the system, encode the respective boundary conditions, and are directly related through the symmetry of the considered Ising model under exchange of the two directions. This representation is a major simplification of earlier results [2, 3].

The resulting Casimir scaling functions are dominated by logarithmic terms caused by corner contributions.



Complex structure of the symbol function of $\mathbf{H}$ for $M = 6$ and $L = 5$, wrapped onto the complex torus [1].

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Collective dynamics in populations of growing rods

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Recent research shows that in confined populations of growing and dividing rods, such as microcolonies of bacteria, a complex interplay between growth activity, fluctuating inter-particle forces and boundary effects can lead to emergent collective dynamics, including global flow of cellular matter and alignment due to the nematic symmetry of local mechanical interactions.

Here, we use a new versatile framework for agent-based simulations to explore these effects in systems with different geometries containing two-dimensional spherocylinders. We observe the emergence of orientational order in rectangular channels and analyse its dependence on both microscopic parameters of the rods and the geometry of the confinement. Further observations of complex orientation patterns in open polygonal domains hint at a link between shear rate anisotropy and orientation. We plan to extend our research to include birth-death induced fluctuations and the resulting forces.

Casimir-Polder shift of ground-state hyperfine Zeeman sublevels of hydrogen isotopes in a micron-sized metallic cavity at finite temperature

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A fundamental problem in atomic physics is the interaction of atoms with radiation fields. The atom's coupling with quantum fluctuations of the electromagnetic (em) field causes the spontaneous decay of excited states, and leads to the famous Lamb shift. Studies carried out over the past 70 years or so revealed that atomic level positions are corrected by two further effects that were not considered in the original Lamb shift.

On one hand, it was realized that at finite temperature, in addition to the virtual photons that are responsible of the Lamb shift, real photons give rise to a temperature-dependent correction of atomic levels. A different and interesting situation is that of an atom in a confined geometry. Since the presence of material boundaries modifies the spectrum of the modes of the em field, the lifetimes and energies of the atom's excited states are shifted. The additional correction to the energy levels resulting from the presence of one or more material surfaces (possibly at finite temperature) is referred to as the Casimir-Polder (CP) shift.

In [1], we computed the frequency shift of ground-state hyperfine transitions of an H atom placed in a metallic cavity at finite temperature. We found that the resonant Casimir- Polder interaction of the atom's magnetic moment with the fluctuating magnetic field existing in the cavity causes a significant shift of hyperfine transitions, and it also leads to a very large increase of their widths, as compared to an atom in free-space exposed to black-body radiation at the same temperature as the cavity. By considering cavities made of different metals and held at different temperatures, we established that larger frequency shifts are obtained in cavities made of metals having a large conductivity, most notably Ag and Al at low temperatures. The predicted shifts for H atoms placed at a distance of a hundred nanometers from the walls of a Ag cavity at a temperature of 70 K can be as large as 90 Hz,
while their widths are of the order of a few kHz. The obtained shift could be measurable with presently available techniques of magnetic resonance.

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Roton Dynamics and Chiral fluctuations in Liquid Crystals

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Liquid crystals are a playground and table top for the study of exotic phases and fluctuations. They also establish the basis for a range of functional materials and applications. This is due to the interplay of short range repulsion, long range dipolar interactions, as well as large and anisotropic polarizabilities. The discovery of topological defects induced by curved interfaces and strain fields has recently renewed our interest in these materials.

The study of liquid crystals gained another momentum with the application of a novel spectroscopic tool, inelastic light scattering using photon fields with varying phase and polarizations [1]. Circular dichroism and Raman optical activity are used to characterize chiral degrees of freedom. However, only recently we could analyze the phase front of scattered Raman photons in semimetals and molecular liquids with this respect.

In chiral liquid crystals, the characteristic length scale (twisting length) is tuned to the wavelength of the incident light. This leads to a resonant coupling of the phase of the Laguerre-Gaussian beams to chiral fluctuations [2]. We observe a finite energy Lorentzian for small momenta and a quasi-elastic, Gaussian fluctuation spectrum for large momenta [3]. We attribute the latter to Roton quasiparticles in analogy to the quantum liquid, suprafluid helium. Molecular dynamic studies show that including non-local interactions reverses the slope of the phonon dispersion, leading to a Roton minimum. It is therefore a rather general phenomenon of complex matter. Interestingly our studies show that the Roton feature couples to handedness of the photon field, while the Gaussian fluctuations couple to their chirality. We will compare these features to the properties of functional materials and quantum liquids.

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Controlling the dynamics of colloidal particles by critical Casimir forces

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Density fluctuations of the composition of a binary critical mixture emerge when its temperature is in proximity of the critical point. If these fluctuations are confined between two objects (e.g., two colloids), they give rise to Critical Casimir forces (CCFs) [1]. The interest in the CCFs has blossomed in recent years because of their promising applications in nanoscience and nano-technology to manipulate objects, to assemble devices [2] and to drive machines [3]. These applications of CCFs can be possible thanks to their piconewton strength, nanometric action ranges, which match the requirements of nanotechnology. Furthermore, CCFs can be finely tuned as a function of temperature, and present a strong dependence on the surface properties of the confining objects [4].
In our experiments we use micro-particles, dispersed in a critical mixture of water and 2,6-lutidine at the critical lutidine mass fraction $C_L^c = 0.286$, corresponding to a lower critical point at the temperature $T^c \simeq 34$ $T^c \cong 34°$ C [5]. We use holographic optical tweezers to manipulate and hold our particles at fixed position in the bulk of the critical mixture. Then we set increasing values of the mixture temperature to investigated, by blinking optical tweezers, how CCFs affect the free dynamics of a couple of colloidal particles in the bulk of a critical solution [6].

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Casimir–like interaction of inclusions in lipid bilayer with two order parameters

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We present a simple, exactly solvable model of biological lipid bilayer with two order parameters describing spatial configuration and chemical composition of the membrane. Despite of its simplicity, the system shows quite a rich behavior, including two distinct critical regimes and a Fisher–Widom line. We study the Casimir–like interaction between inclusions on such a membrane. The inclusions are defined as the points where the spatial position of the membrane is fixed; this is mimicking the interaction of biological lipid bilayer with immersed proteins (see the picture below). Depending on how these inclusions interact with the membrane, three different behaviors of the Casimir–like force are possible. They differ in the strength and the decay lengthscale of the interaction.

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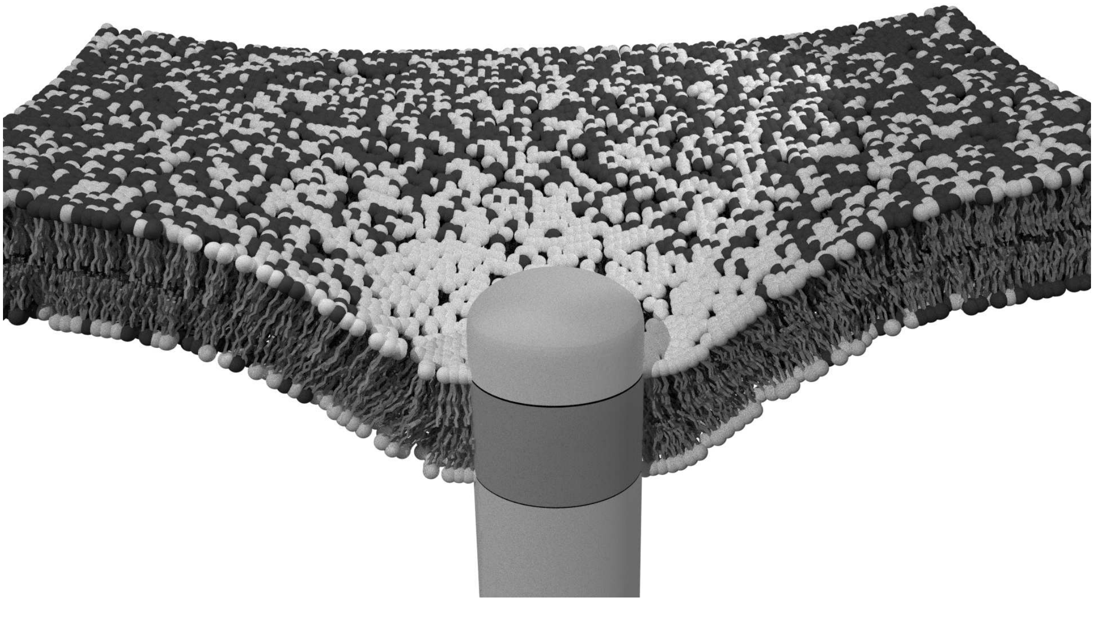

Effective forces in cellular soft matter

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Active particles break time-reversal symmetry and objects immersed in such an active fluid can experience effective statistical forces originating from the active medium. While many such examples have been shown for motile self-propelled particles, our own work explores effective forces emerging from a proliferating cellular active medium[1]. In contrast to the motile matter examples, we find evidence that quasi-long-range forces can act between passive bodies that are fully symmetric. This important feature together with the ability to tune the forces and possibly even switch them between attractive and repulsive, suggest novel possibilities for self-assembly systems dominated by growth..

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Casimir-Lifshitz forces vs. Critical Casimir forces: Trapping and releasing of flat metallic particles

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Casimir forces in quantum electrodynamics emerge between microscopic metallic objects because of the confinement of the vacuum electromagnetic fluctuations occuring even at zero temperature. Their generalization at finite temperature and in material media are referred to as Casimir-Lifshitz forces. These forces are typically attractive, leading to the widespread problem of stiction between the metallic parts of micro- and nanodevice.

Recently, repulsive Casimir forces have been experimentally [1-2] realized but their use of specialized materials stills means that the system can not be controlled dynamically and thus limits further implementation to real-world applications. Here, we experimentally demonstrate that repulsive critical Casimir forces, which emerge in a critical binary liquid mixture upon approaching the critical temperature, can be used to prevent stiction due to Casimir-Lifshitz forces. We show that critical Casimir forces can be dynamically tuned via temperature, eventually overcoming Casimir-Lifshitz attraction. We study a microscopic gold flake above a flat gold-coated substrate immersed in a critical mixture. Far from the critical temperature, stiction occurs because of Casimir-Lifshitz forces. Upon approaching the critical temperature, however, we observe the emergence of repulsive critical Casimir forces that are sufficiently strong to counteract stiction. By removing one of the key limitations to their deployment, this experimental demonstration can accelerate the development of micro- and nanodevices for a broad range of applications.

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Forces induced by quantum mesoscopic coherent effects

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We study an athermal, non equilibrium system, using classical light propagating in a scattering medium. In the multiple scattering regime, spatially long ranged intensity fluctuations arise from mesoscopic coherent effects. These fluctuations can be described by an effective Langevin equation, which allows to understand the fluctuations as resulting from a non equilibrium light flow. Inspired by the similarity with non equilibrium hydrodynamics, we identify radiative forces induced by the intensity fluctuations, which constitute the first example of mechanical forces induced by coherent effects.

We also derive an uncertainty relation for the coherent light fluctuations. Thermodynamic uncertainty relations unveil useful connections between fluctuations in thermal systems and entropy production. We extend these ideas to zero temperature quantum mesoscopic physics where fluctuations are due to coherent effects and entropy production is replaced by a cost function. The cost function arises naturally as a bound on fluctuations, induced by coherent effects – a critical resource in quantum mesoscopic physics.

Dynamics of probe particles in near-critical fields

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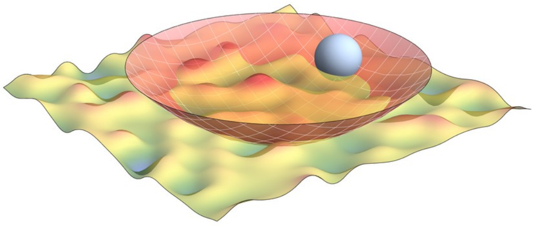

Studying the motion of colloidal particles in contact with thermally fluctuating environments provides a tool to probe the rheological properties of soft-matter systems. While past studies have mostly focused on the behavior of tracer particles passively carried by a fluctuating solvent, in recent years increasing attention has been paid to scenarios in which the particle and the solvent affect each other dynamically. If the medium is a fluid near a critical point, which displays long-range spatial correlations and long relaxation times, then field-mediated forces must play a prominent role on the resulting dynamics of the tracer particle.

Here we analyze the simple setup in which a probe particle trapped in a harmonic potential is linearly coupled to a scalar Gaussian field, and they both undergo an overdamped Langevin dynamics. Consider first the relaxation of the particle towards the center of the trap after it is released far from its equilibrium position [1]. One finds long-time algebraic tails in the average displacement of the colloid, whose decay exponents are only determined by the spatial dimensionality of the system and the dynamical critical exponent of the field. Both linear response analysis and adiabatic elimination schemes fail to predict this behavior.

Consider now two such particles confined in two spaced apart harmonic potentials and coupled to the same field [2]. When an external periodic driving is applied to one such particle, a non-equilibrium periodic state is eventually reached where the motion of the two beads synchronizes due to the field-mediated effective interaction, a phenomenon already observed in experiments performed on colloidal particles immesersed in a binary mixture close to the critical point of the demixing transition [3]. We characterize the nonlinear response of the second particle far from the adiabatic regime where the field can be assumed to relax instantaneously.

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Non-equilibrium dynamics of a colloid coupled to a self-interacting critical field

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We discuss the non-equilibrium dynamics of a Brownian particle linearly coupled to a fluctuating field at criticality, modelling colloidal diffusion in complex liquids. This microrheological model can be applied to study the rich phenomenology of transport in disordered media, such as biological cells or tissues, or spin glasses.

We approach this problem by constructing a non-equilibrium field theory describing the joint stochastic evolution of the colloid and the field as a perturbation theory valid for weak coupling strengths. Through systematic perturbative expansion, this method allows us to extend known results for Gaussian fields at equilibrium to the case of self-interacting fields out of equilibrium, predicting several dynamic observables of the colloid.

Moreover though, by inverting the newly found relations between the field fluctuation's statistics and their impact onto the colloid's stochastic evolution, we can use a measurement of the latter to infer information about the surrounding field and its critical properties, such as critical exponents. In so doing, this provides an experimental protocol to study the critical properties of fields via colloids, which is useful in situations where the field itself is difficult to observe experimentally.