ICTP SAIFR | International Centre for Theoretical Physics
South American Institute for Fundamental Research

SAIFR/Principia Workshop on Low Dimensional Quantum Gases

March 19-22, 2023

São Paulo, Brazil

Principia Institute

Organized by

Arnaldo Gammal (IFUSP) and Axel Pelster (Technical University Kaiserslautern)

FAPESP ICTP unesp IFT - UNESP INSTITUTO DE FÍSICA TEÓRICA INSTITUTO PRINCIPIA

ICTP South American Institute for Fundamental Research

The ICTP South American Institute for Fundamental Research (ICTP-SAIFR) is a South American regional center in the city of São Paulo created in a collaboration of the Abdus Salam International Centre for Theoretical Physics (ICTP), the Instituto de Fisica Teorica (IFT) of São Paulo State University (UNESP) and the Sao Paulo Research Funding Agency (FAPESP). Its activities include seminars, minicourses, schools and workshops for graduate students and researchers in all areas related to theoretical physics, as well as outreach activities for the general public and for high-school students and teachers. The center has funding for short-term and long-term visitors as well as for postdoctoral and permanent researchers.

Principia Institute - Venue

Principia Institute was created in 2017 as a center for the production and dissemination of scientific knowledge and for connecting science with society. Its activities include a school of talents, intended to attract talented high-school students for further training in Physics, free science courses to general public and also providing the space for hosting international meetings.

The sponsor of the Principia Institute is the Instituto de Física Teórica Foundation, created in 1951 as a non-profit private law entity.

Principia Institute is located at Rua Pamplona, 145, 50 meters away from the hotel Universe Flat.

ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

Workshop on Low Dimensional Quantum Gases

Principia Institute, São Paulo, Brazil

March 19-22, 2023

Originally, this workshop was led by the late Mahir Hussein who regularly organized alternating workshops on Nuclear Physics and on Ultracold Atoms and Chaos. Pursuing his ideals, this São Paulo Workshop deals with ultracold atoms.

Since the experimental discovery of Bose-Einstein condensation in ultracold atomic gases in 1995, there have been several further substantial breakthroughs. Today, systems of ultracold bosonic or fermionic quantum gases allow for a very high level of experimental control. Moreover, they lend themselves to accurate theoretical calculations of their static and dynamic properties, allowing for a detailed quantitative comparison between theory and experiment with high accuracy. Ultracold atomic and molecular matter can be employed to provide idealized realizations of paradigmatically important many-body models considered in various fields, such as atomic and molecular physics, solid-state physics, nuclear physics, and even astrophysics. The high degree of control over the interatomic interactions also allows one to probe quantum fluids in regimes and under conditions hitherto unavailable.

In recent years, attention has focused on these systems in constrained geometries as this leads to stronger correlations among the particles and, thus, to new challenging physics. This upcoming research direction is exemplified most prominently by the recent bubble trap experiments in the Cold Atom Laboratory of the International Space Station. Other prominent examples are provided by the Berezinskii–Kosterlitz–Thouless transition, the simulation of high-temperature superconductivity with fermionic atoms loaded in optical lattices, and the realization of photon Bose-Einstein condensates in dye-filled microcavities. Therefore, we have decided to focus this São Paulo Workshop on low-dimensional quantum gas physics.

Arnaldo Gammal, University of São Paulo, Brazil

Axel Pelster, Rhineland-Palatinate Technical University Kaiserslautern-Landau, Germany

FAPESP ICTP unesp IFT - UNESP INSTITUTO DE FÍSICA TEÓRICA INSTITUTO PRINCIPIA

In Memoriam

Mahir Hussein

* 1944, † 2019

Mahir Hussein was born in Baghdad, Iraq in 1944 [1]. In 1965 he was the first graduate student of the University of Baghdad. During the period of 1967-1971 he pursued his PhD in the US at the Massachusetts Institute of Technology (MIT) under Arthur Kerman. In 1971 he joined the faculty of the University of São Paulo (IFUSP) in Brazil becoming subsequently Associate Professor in 1977 and Full Professor in 1987. With more than 320 papers published in refereed journals and more than 4200 citations he was one of the most productive and important physicists of USP. His main interests were laser driven accelerators, nuclear reactions and exotic nuclei, quantum chaos theory and applications, as well as the theory of Bose-Einstein condensation.

He was the key leading person in a project to install a superconducting solenoid system for the production of radioactive ion beams at the University of São Paulo. He coordinated an effort to purchase solenoids and ancillary systems, leading to what is now known as the Radioactive Ion Beams in Brazil (RIBRAS). He helped his experimental colleagues with his theoretical analysis to understand the results obtained with RIBRAS. The study of the reactions induced by radioactive nuclei in this laboratory shed light on several important issues in nuclear physics and astrophysics.

Hussein received several prestigious awards, among them are:
- 1977-1988: J.S. Guggenheim Fellow at University of Wisconsin-Madison
- 1979-1980: Tinker Visiting Professor at University of Wisconsin-Madison
- 1995: Smithsonian Foundation Fellow at MIT working with Feshbach, Kerman, Moniz and Iachello (Yale) on Foundations of Nuclear Theory
- 1995: Scientific Secretary of the DOE-NSF Nuclear Science Long Range Plan
- 2007-2008: Martin Gutzwiller Fellow at Max-Planck Institute of Physics of Complex Systems, Dresden on Quantum Chaos and Bose-Einstein Condensates
- Member of the Brazilian Academy of Sciences and the World Academy of Sciences as well as Fellow of American Physical Society

From 2007-2019 he chaired the non-conventional Astrophysics group at the Advanced Studies Institute (IEA-USP), where he organized workshops on the topics Bose-Einstein condensation, quantum chaos, nuclear theory and cosmology.

Our meeting was already envisioned by Hussein to take place in 2021 or 2022. It is an honor to continue his efforts in promoting science in different fields. We are sure that he hoped you have an enthusiastic workshop.

[1] N. Alamanos, C. Bertulani and V. Guimarães, *Topical issue on cluster structure and dynamics of nuclei: a tribute to Mahir Hussein*, Eur. Phys. J. A **57**, 196 (2021).

Program for International Workshop
Low Dimensional Quantum Gases
Principia Institute, São Paulo, Brazil, March 19–22, 2023

Sunday, March 19, 2023

09.00 – 10.00 Registration
10.00 – 10.10 Arnaldo Gammal (São Paulo, Brazil):
Opening: Homage to Mahir Hussein
Session 1: Manifolds
10.10 – 11.10 Nathan Lundblad (Lewiston, USA):
Studying ultracold bubbles in orbital microgravity with the NASA Cold Atom Laboratory
11.10 – 11.30 Coffee Break
11.30 – 12.30 Francisco dos Santos (São Carlos, Brazil):
Bose-Einstein condensates and the thin-shell limit in anisotropic bubble traps
12.30 – 14.00 Lunch
14.00 – 15.00 Monica Caracanhas (São Carlos, Brazil):
Superfluid vortex dynamics on curved surfaces (Online)
15.00 – 15.20 Coffee Break
Session 2: Fermions
15.20 – 16.20 Randall Hulet (Rice University, USA):
Spin-charge separation with ultra-cold atoms
16.20 – 17.20 Silvio Vitiello (UNICAMP, Campinas, Brazil):
Ionic polaron in a degenerate Fermi gas

Monday, March 20, 2023

Session 3: Solitons and Turbulence
09.00 – 10.00 Vanderlei Bagnato (São Carlos, Brazil):
Characterization of a far from equilibrium BEC: from turbulence to scalability relations
10.00 – 11.00 Patricia Castilho (São Carlos, Brazil):
Townes soliton in a planar Bose gas
11.00 – 11.20 Coffee Break
11.20 – 12.20 Hugo Terças (Lisboa, Portugal):
Solitonic turbulence in low-dimensional quantum fluids
12.20 – 14.00 Lunch
Session 4: Equilibrium versus Non-Equilibrium
14.00 – 15.00 Anna Minguzzi (Grenoble, France):
Persistent currents in one-dimensional Fermi gases on a ring (Online)
15.00 – 15.20 Coffee Break
15.20 – 16.20 Nick Proukakis (Newcastle, UK):
Criticality, quench dynamics and phase ordering in ultracold gases
16.20 – 17.30 Poster Session I
20:00 *Dinner*

Tuesday, March 21, 2023

Session 5:	**Open Systems**
09.00 – 10.00	Julian Schmitt (University of Bonn, Germany): *Compressibility and the equation of state of a two-dimensional optical quantum gas in a box*
10.00 – 11.00	Marzena Szymanska (University College London, UK): *Novel Non-equilibrium Phenomena in Quantum Fluids of Light*
11.00 – 11.20	Coffee Break
Session 6:	**Supersolids**
11.20 – 12.20	Lauriane Chomaz (University of Heidelberg, Germany): *Exotic many-body states in dipolar quantum Bose gases of magnetic atoms*
12.20 – 14.00	Lunch
14.00 – 15.00	Jordi Boronat (Barcelona, Spain): *Quantum dipoles in two dimensions*
15.00 – 15.20	Coffee Break
15.20 – 16.20	Sadhan Adhikari (São Paulo, Brazil): *Supersolids in Bose-Einstein condensates*
16.20 – 17.30	Poster Session II

Wednesday, March 22, 2023

Session 7:	**Miscellaneous**
09.00 – 10.00	Tobias Frederico (São José dos Campos, Brazil): *Few-boson limit cycles and discrete scale symmetry in integer and non-integer dimensions* (Online)
10.00 – 11.00	Tommaso Macri (Natal, Brazil): *The ubiquity of the quantum boomerang effect in Anderson-localized systems* (Online)
11.00 – 11.20	Coffee Break
11.20 – 12.20	Lauro Tomio (São Paulo, Brazil): *Dynamical vortex production with periodic time-dependent perturbation applied to dipolar and non-dipolar BEC mixtures*
12.20 – 12.30	Axel Pelster (Technical University Kaiserslautern, Germany): *Concluding remarks*
12.30 – 14.00	Snacks and beverages at Principia Institute
14.00 –	Departure

Abstracts of Invited Talks

Supersolids in Bose-Einstein condensates

Sadhan Adhikari

IFT-UNESP

A supersolid is a quantum state, with a periodic crystalline structure as in a solid, that can flow without friction like a superfluid. We will present an account of our study of supersolid formation in a dipolar and in a spin-orbit (SO) coupled Bose-Einstein condensate (BEC) using a mean-field model.

In the case of a dipolar BEC, the crystalline structure in the form of a square or a triangular lattice appears in a plane perpendicular to the polarization direction of dipolar atoms. In this case a beyond-mean-field Lee-Huang-Yang-type repulsive interaction is necessary for stabilizing the supersolid. In the case of a quasi-two-dimensional SO-coupled spin-1 and spin-2 BECs one can also have a periodic crystalline structure in total density in the form of a square or a triangular lattice.

Characterization of a far from equilibrium BEC: from turbulence to scalability relations

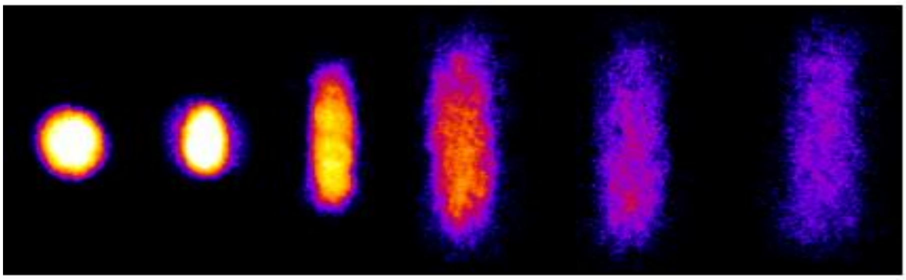
Vanderlei S. Bagnato

University of São Paulo

IFSC- University of São Paulo – Brazil

BME- Texas A&M University - USA

In this presentation we will combine many of the experiments performed in Brazil relating to the production and characterization of a Bose Condensate of Rb atoms, driven far from equilibrium. Excitation of the trapped BEC can be done through a combination of fields that promote time distortion of the trapping potential. These excitations can evolve over time, promoting energy migration from the largest to the smallest scales in a process called cascade. We perform temporal excitations that consist of deformation and slight rotation of the potential, causing the system to evolve to a turbulent regime. Simulations demonstrated generation of solitons, vortices and waves in the sample. Using time of flight techniques, we measure the moment distribution, n(k, t) and from it we obtain the energy spectrum E (k, t). This makes it possible to identify the inertial regions, where E (k, t) is clearly dependent on the power law (inertial region) characteristic of turbulent regime, and to measure the energy flow migrating between the scales and their preservation from the absence of dissipation. Finally, the temporal evolution of the moment distribution allows to verify the presence of a space-time scalability, which indicate the presence of a class of universality in the phenomenon. The problem is investigated on the basis of the theory of the existence of non-thermal fixed points in the system and a discussion around these aspects is offered. This work received support from FAPESP- program CEPID, CNPq and CAPES, all Brazilian agencies and had the participation of L. Madeira, A. Garcia-Orosco, P. Castilho, M. Moreno, L. Machado, G. Telles, H A. J. Middleton-Spencer (visiting student) and P.E.S. Tavares.



Density profile evolution of a BEC driven out of equilibrium

Quantum dipoles in two dimensions

Jordi Boronat

Universitat Politecnica de Catalunya

I will review recent results of my group on the properties of dilute quantum gases with dominant dipolar interactions. Our results are obtained using ab-initio Quantum Monte Carlo methods. I will discuss on the formation of stripe phases, the emergence of stable liquids in a bilayer setups and thermal effects.

Superfluid vortex dynamics on curved surfaces

Mônica Andrioli Caracanhas

University of São Paulo

A few theoretical papers have explored the properties of a BEC trapped in a spherically symmetric shell potential [1-3], but recent experimental advances raise the important new question of vortex dynamics on axisymmetric ellipsoidal surfaces. Indeed, shell potentials for ultracold atoms have been generated by superposing quadrupolar and oscillatory magnetic fields [4,5]. The resulting spatially dependent dressed atomic states experience an effective axisymmetric ellipsoidal potential. Experiments performed in the NASA Cold Atom Lab aboard the International Space Station recently produced three-dimensional BECs with no gravity [6], providing now a more realistic possibility to explore bubble trapped BECs [7]. One of the aims of these experiments is the generation of vortices, which can be achieved by rotating the dressed trap or through the spontaneous creation of vortex-antivortex pairs across the condensation transition, namely through the Kibble-Zurek mechanism.

Motivated by these experimental advances, in this work we present a study of vortex dynamics on general axisymmetric compact surfaces with no holes. Specifically, we developed a general method to transform conformally from the axisymmetric surface to a plane, where we use familiar methods based on the hydrodynamic stream function. This transformation yields an additional term in the dynamics of each vortex reflecting the local curvature at its position. Our approach shows that vortices constitute a Hamiltonian dynamical system, with their angular positions on the surface as canonical variables. We checked in detail that the dynamical motion conserves both the total energy and the ``angular momentum", and highlighted the anti-correlation between the vortex speed and the local curvature of the surface.

[1] S. J. Bereta, M. A. Caracanhas, and A. L. Fetter, Superfluid vortex dynamics on a spherical film, Phys. Rev.A 103, 053306 (2021).

[2] A. Tononi and L. Salasnich, Bose-Einstein Condensation on the Surface of a Sphere, Phys. Rev. Lett. 123, 160403 (2019).

[3] K. Sun, K. Padavic, F. Yang, S. Vishveshwara, and C. Lannert, Static and dynamic properties of shell-shaped condensates, Phys. Rev. A 98, 013609 (2018).

[4] Ultracold atoms confined in rf-induced two-dimensional trapping potentials Y. Colombe, E. Knyazchyan, O. Morizot, B. Mercier, V. Lorent, and H. Perrin Europhys. Lett. 67,593 (2004) http://dx.doi.org/10.1209/epl/i2004-10095-7

[5] N. Lundblad, R. A. Carollo, C. Lannert, M. J. Gold, X. Jiang, D. Paseltiner, N. Sergay, and D. C. Aveline, Shell potentials for microgravity Bose-Einstein condensates, npj Microgravity 5 (2019).

[6] D. C. Aveline, J. R. Williams, E. R. Elliott, C. Dutenhoffer, J. R. Kellogg, J. M. Kohel, N. E. Lay, K. Oudrhiri, R. F. Shotwell, N. Yu, and R. J. Thompson, Observation of Bose–Einstein condensates in an Earth-orbiting research lab, Nature 582, 193 (2020).

[7] R. Carollo, D. Aveline, B. Rhyno, S. Vishveshwara, C. Lannert, J. Murphree, E. Elliott, J. Williams, R. Thompson, and N. Lundblad, Observation of ultracold atomic bubbles in orbital microgravity (2021),arXiv:2108.05880.

Townes soliton in a planar Bose gas

Patricia Castilho

Instituto de Física de São Carlos - Universidade de São Paulo

Solitons are well-known structures in one dimensional systems. In two-dimensions they occur only for a specific value of the product of the interaction strength g and atom number N. One example is the Townes soliton obtained as the real, nodeless, and axially symmetric solution of the two-dimensional nonlinear Schrödinger equation. In this work, we present the experimental realization of such a Townes soliton in a two-component planar Bose gas. We explore various interaction strengths, atom numbers and soliton sizes to validade the existence of solitonic behavior for a specific value of gN.

Exotic many-body states in dipolar quantum Bose gases of magnetic atoms

Lauriane Chomaz

University of Heidelberg

Ultracold quantum gases provide a pristine platform to study few-body and many-body quantum phenomena with an exquisite degree of control. The achievement of quantum degeneracy in gases of atoms with large magnetic dipole moments in their electronic ground states has opened up new avenues of research in which long-range anisotropic dipole-dipole interactions play a crucial role. In the case of Bose gases, these interactions compete with the conventional short-range contact interactions, and thanks to so-called Feshbach resonances, this competition can be tuned by changing the strength of the contact forces. In the case of the most magnetic atoms (erbium and dysprosium), fine control of this interaction competition has led to the discovery of novel many-body quantum states. These states include elementary excitations such as the roton modes and equilibrium states such as liquid-like droplets, droplet crystals and supersolids, a paradoxical phase of matter that simultaneously exhibits solid and superfluid orders. A unique mechanism, based on the effect of quantum fluctuations themselves, underlies the stabilisation of these new phases. In my talk, I will review the experimental research progress made in the field of magnetic dipolar gases over the last few years, highlight key results obtained in my former working group in Innsbruck, and finally discuss the future research directions that I am developing in my new research group in Heidelberg, focusing on quantum gases of magnetic atoms in lower dimensional spaces, in and out of equilibrium.

Few-boson limit cycles and discrete scale symmetry in integer and non-integer dimensions

Tobias Frederico

ITA-Sao Jose dos Campos

The Efimov effect and the associated limit cycles for the correlations between the few-body state observables are presented for integer and non-integer dimensions between two and three for particular cases of three-atom systems formed by Li, Cs and Rb. In particular we discuss the transition to the situation when the Efimov effect disappears by lowering the dimension. Going to more particles the new limit cycles beyond the Efimov one are presented for four-bosons in 3D and beyond it, including examples in non-integer dimensions.

Spin-charge separation with ultra-cold atoms

Randall Gardner Hulet

Rice University

Models of quantum many-body phases of matter may be realized using fermionic ultracoldatoms in place of the electrons, and engineered optical potentials to emulate a crystal lattice. Quantum simulation of this kind takes advantage of the capability to adhere to a theoretical model, while the tunability of model parameters enables quantitative comparison with theory. As an example, repulsively interacting spin-1/2 fermions confined to one-dimensional (1D) tubes, realize a Tomonaga-Luttinger liquid. The low energy excitations are collective, bosonic sound waves that correspond to either spin-density or charge-density waves that, remarkably, propagate at different speeds. Such a spin-charge separation has been observed in electronic materials, but a quantitative analysis has proved challenging because of the complexity of the electronic structure and the unavoidable presence of impurities and defects in electronic materials. In collaboration with our theory colleagues, we made a direct theory/experiment comparison and found excellent agreement as a function of interaction strength [1]. It was necessary to include nonlinear corrections to the spin-wave dispersion arising from back-scattering, thus going beyond the Luttinger model. More recently, we explored the disruption of spin correlations with increasing temperature [2], an effect that destroys spin-charge separation.

1. R. Senaratne*, D. Cavazos-Cavazos* et al, "Spin-charge separation in a 1D Fermi gas withtunable interactions", Science 376, 1305 (2022).

2. D. Cavazos-Cavazos, R. Senaratne, A. Kafle, and R.G. Hulet, "Realization of a spin-incoherent Luttinger liquid", arXiv:2210.06306 (2022).

Studying ultracold bubbles in orbital microgravity with the NASA Cold Atom Laboratory

Nathan Eric Lundblad

Bates College

Exploring the effects of geometry, topology, dimensionality, and interactions on ultracold atomic ensembles has been continually fruitful in the decades since the first observation of Bose-Einstein condensation (BEC). One heretofore unexplored configuration for ultracold ensembles is that of a bubble or shell, where trapped atoms are confined in the vicinity of a spherical or ellipsoidal surface. Such a system could offer new collective modes, topologically-sensitive behavior of quantized vortices, self-interference and shell collapse, as well as the exploration of trapped ultracold systems with mm-scale spatial extent. While techniques for the generation of bubble-shaped traps have been known since 2001, terrestrial gravity has thus far prevented the observation of ultracold bubbles. With the construction of the NASA Cold Atom Lab (CAL) facility and its subsequent delivery in 2018 to the International Space Station (ISS) and commissioning as an orbital BEC user facility, experimental atomic physics schemes that require a sustained microgravity environment are now possible.

I will present recent CAL observations of trapped bubbles of ultracold atoms, including a variety of bubble-trap configurations that are possible with this apparatus. I will also discuss the thermodynamics of ultracold bubbles and review open questions being explored in the ongoing second science run of CAL aboard ISS, which feature improved bubble aspect ratios and filling as well as improved imaging; I will also review upcoming changes to the CAL facility aimed at improved BEC quality, as well as recent progress made with shell structures in terrestrial laboratories.

The ubiquity of the quantum boomerang effect in Anderson-localized systems

Tommaso Macri

UFRN

Anderson localization is a general phenomenon that applies to a variety of disordered physical systems. Recently, a manifestation of Anderson localization for wave packets launched with a finite average velocity was proposed, the quantum boomerang effect (QBE). This phenomenon predicts that the disorder-averaged center of mass of a particle initially moves ballistically, then makes a U-turn, and finally slowly returns to its initial position. The QBE has been predicted to take place in several models with Anderson localization and has been experimentally observed in the paradigmatic quantum kicked rotor model. In this talk, we review these results and suggest an extension of this effect to classical stochastic models.

Persistent currents for ultracold fermions on a ring

Anna Minguzzi

CNRS, Grenoble

We study the persistent currents of an interacting Fermi gas confined in a tightly confining ring trap and subjected to an artificial gauge field. For attractive interactions, we study the currents all through the BCS-BEC crossover. At weak attractions, on the

BCS side, fermions display a parity effect in the persistent currents, i.e. their response to the gauge field is paramagnetic or diamagnetic depending on the number of pairs on the ring. At resonance and on the BEC side of the crossover, we find a halving of the periodicity of the ground-state energy as a function of the artificial gauge field and disappearance of the parity effect,

indicating that persistent currents can be used to infer the formation of tightly-bound bosonic pairs. We analyze then the readout of current states by spiral interferograms, showing that Fermi gases display an intrinsic reduction of coherence. We finally show that the spin-resolved density-density correlator obtained from the expansion of the fermions at long times allows to probe the halving of the periodicity of the persistent currents and also yields information on quasi-off diagonal long range order.

Criticality, quench dynamics and phase ordering in ultracold gases

Nikolaos Proukakis

New Castle University

The emergence of macroscopic coherence in a many-body quantum system is a ubiquitous phenomenon across different physical systems and scales. After reviewing key concepts characterizing such systems (correlation functions, condensation, quasi-condensation), I will then apply them to the study of emerging non-equilibrium features in the dynamical path towards such a highly-coherent state across homogeneous/inhomogeneous 2D/3D geometries:

In particular, this talk focuses on the characteristic examples of symmetry-breaking within the context of the Kibble-Zurek mechanism, coarsening dynamics and equilibration, following a dynamical quench from an incoherent to a coherent state. particular emphasis is placed on emerging universal features in the dynamics of conservative and open quantum systems, and the extent that these can be observed in current experiments with quantum gases, while acknowledging the critical role of dimensionality and inhomogeneities.

Bose-Einstein condensates and the thin-shell limit in anisotropic bubble traps

Francisco Ednilson A. dos Santos

Universidade Federal de São Carlos

The use of cold atoms to create Bose-Einstein condensates (BECs) has led to the development of numerous models, including the bubble trap-shaped potential, which has garnered significant interest. While the relationship between the physical parameters and the resulting manifold geometry in the thin-shell limit for the anisotropic bubble trap has yet to be fully understood, this work aims to address this gap in knowledge. We demonstrate how the parameters of the system must be manipulated in order to prevent collapse in the thin-shell limit, resulting in a dimensional compactification and an effective 2D Hamiltonian that can be applied to current bubble trap experiments. Additionally, we provide examples of our theory by solving the Hamiltonian for certain cases.

Compressibility and the equation of state of a two-dimensional optical quantum gas in a box

Julian Schmitt

University of Bonn

Quantum gases of atoms, exciton-polaritons, and photons provide a test bed for many-body physics under both in- and out-of-equilibrium settings. Experimental control over their dimensionality, potential energy landscapes, or the coupling to reservoirs offers wide possibilities to explore phases of matter, for example, by probing susceptibilities, as the compressibility. For gases of material particles, such studies of the mechanical response are well established, in fields from classical thermodynamics to cold atomic quantum gases; for optical quantum gases, they have so far remained elusive. In my talk, I will discuss experimental work demonstrating a measurement of the compressibility of a two-dimensional quantum gas of photons in a box potential, from which we obtain the equation of state for the optical medium. The experiment is carried out in a nanostructured dye-filled optical microcavity. We observe signatures of Bose-Einstein condensation at large phase-space densities in the finite-size system. Upon entering the quantum degenerate regime, the density response to an external force sharply increases, hinting at the peculiar prediction of a highly compressible Bose gas. In other recent work, we have demonstrated a non-Hermitian phase transition of an open photon Bose-Einstein condensate, which is revealed by an exceptional point in the fluctuation dynamics.

Novel Non-equilibrium Phenomena in Quantum Fluids of Light

Marzena Szymanska

University College London

Driven-dissipative quantum fluids of light, experimentally realised in for example semiconductor microcavities, circuit or cavity QED systems, provide a unique testbed to explore new non-equilibrium quantum phenomena. I will review recent progress in this field. In particular, we show that polariton quantum fluid can exhibit a non- equilibrium order, where superfluidity is accompanied by stretched exponential decay of correlations [1]. This celebrated Kardar-Parisi-Zhang (KPZ) phase has not been achieved before in any system in 2D, and even 1D realisations have not been conclusive. I will then discuss how these systems can undergo other unconventional phase transitions and orders [2,3], and display flow properties connected but distinct from conventional superfluidity. Finally, when placed in strained honeycomb lattice potentials, polariton fluids can condense into a rotating state, the lowest Landau level, forming a vortex array and spontaneously breaking time reversal symmetry [4].

[1] A. Zamora et al, PRX 7, 041006 (2017); PRL 125, 265701 (2020); A. Ferrier et al,

PRB 105, 205301 (2022)

[2] G. Dagvadorj et al, arXiv:2208.04167, PRL to appear (2023)

[3] G. Dagvadorj et al, PRB 104, 165301 (2021)

[4] C. Lledo et al, SciPost 12, 068 (2022)

Solitonic turbulence in low-dimensional quantum fluids

Hugo Terças

Instituto Superior Técnico, Universidade de Lisboa

Soliton hydrodynamics is an appealing tool to describe strong turbulence in low-dimensional systems. Strong turbulence in quasi-one dimensional spuerfluids, such as Bose-Einstein condensates, involves the dynamics of dark solitons and, therefore, the description of a statistical ensemble of dark-solitons, i.e. soliton gases, is necessary. In this work, we propose a phase-space (kinetic) description of dark-soliton gases, introducing a kinetic equation that is formally similar to the Vlasov equation in plasma physics. We show that the proposed kinetic theory can capture the dynamical features of soliton gases and show that it sustains an acoustic mode, a fact that we corroborate with the help of direct numerical simulations.

Dynamical vortex production with periodic time-dependent perturbation applied to dipolar and non-dipolar BEC mixtures

Lauro Tomio

IFT-UNESP

Recent studies on the dynamical production of stable vortices and quantum turbulence, with non-dipolar and dipolar coupled condensates, confined by a pancake-like trap perturbed by time-dependent periodic interactions, are reported. Two different models are assumed for the periodic time-dependent perturbations being applied to the coupled system. To generate the dynamics, with turbulence and vorticity, in one of the models we rely on a stirring procedure, which is applied to non-dipolar systems. In another model, in which we investigate the critical velocities for nucleation of vortex dipoles and clusters, we consider a dipolar coupled system under linearly and circularly moving Gaussian obstacles.

Ionic polaron in a degenerate Fermi gas

Silvio A Vitiello

Unicamp

Properties of an ionic polaron in a degenerate Fermi gas are presented. Long-range interactions between the ion and the gas atoms are considered by applying the diffusion Monte Carlo method. The effective mass of the polaron is found to be significantly larger than that of the uncharged polaron. The radial distribution function of the gas atoms around the ion indicates that the ion creates a local density maximum. The quasiparticle residue, which characterizes the coherence of the polaron, is also affected by the long-range interaction. The study examines the interaction energy between two polarons, as well as the polaron energy as a function of the interaction strength.

Poster Overview

1. **Paramjeet Banger** (Indian Institute of Technology-Ropar, India): *Effective potentials in rotating spin-orbit coupled BECs*
2. **Mateus Biscassi** (Universidade Federal de São Carlos, Brazil and INPHYNI – Université Côte D'Azur, France): *From Classical to Quantum Loss of Coherence Probed by Intensity Correlations in a Large Atomic Cloud*
3. **Pedro Henrique Cook Cunha** (Institute of Physics of São Carlos, Brazil): *Quantum Rayleigh-Taylor instability in two dimensional Bose gases*
4. **Robert Guzman** (Universidad de la Frontera, Chile): *Complex vector light fields propagation in atomic systems*
5. **Leandro Machado** (Instituto de Física de São Carlos, Brazil): *Excitation of Bose-Einstein condensates with temporal resolution in separate zones*
6. **Lucas Madeira** (University of São Paulo – São Carlos, Brazil): *Core structure of two-dimensional Fermi gas vortices in the BEC-BCS crossover region*
7. **Áttis Vinícius M. Marino** (Instituto de Física de São Carlos, Brazil): *Observables' evolution of a trapped quantum gas*
8. **Sheilla de Oliveira Marques** (Universidade Federal de São Carlos, Brazil): *Effective potentials on bubble-traps*
9. **Lucas Mendicino** (Universidad de Buenos Aires, Argentina): *Towards deep laser cooling of the internal an external motion of trapped nano-particles*
10. **Leon Mixa** (Universität Hamburg, Germany): *Enhancing quantum fluctuations in strongly entangled cavity BEC systems*
11. **Muriel** (Universidad de Buenos Aires, Argentina):
12. **John Alejandro Montilla Ortega** (Universidad del Valle, Colombia): *Use of the basis of spin coherent states and quadrupolar states in the description of spin-1 lattice bosons*
13. **Vinicius Zampronio Pedroso** (Utrecht University, the Netherlands): *Chiral superconductivity in the doped triangular-lattice Fermi-Hubbard model in two dimensions*
14. **Sabari** (IFT-UNESP, Brazil): *Dynamics of vortices in the Dipolar Bose-Einstein condensate*
15. **Abhik Kumar Saha** (Indian Association for the Cultivation of Science, India): *Dynamical phase diagram of a one-dimensional Bose gas in a box with a tunable weak link: From Bose-Josephson oscillations to shock waves*
16. **Leonardo Brito da Silva** (University of São Paulo, Brazil): *Stability of the Bose-Einstein condensate mixtures on the bubble*
17. **Jonata Santos Soares** (IFUSP, Brazil): *Bose gases in a cylinder in canonical ensemble*
18. **Renan da Silva Souza** (UFSCar, Brazil): *Excitations of the disordered Bose-Hubbard model*
19. **Santiago Zamora** (Universidade Federal do Rio Grande do Norte (UFRN), Brazil): *Classical Analog of the Quantum Boomerang effect*

Effective potentials in rotating spin-orbit coupled BECs

Paramjeet Banger

Indian Institute of Technology, Ropar

An important research direction opened up in the field of quantum degenerate gases with the experimental realization of artificial gauge fields and spin-orbit (SO) coupling between the spin and the linear momentum of electrically neutral bosons. We theoretically study the stationary-state vortex lattice configurations of rotating spin-orbit- and coherently-coupled spin-1 Bose-Einstein condensates (BECs) in quasi-two-dimensional harmonic potentials. We explore the combined effects of rotation, spin-orbit, and coherent couplings on the spinor system from the single-particle perspective, which is exactly solvable for one-dimensional coupling, under specific coupling and rotation strengths. We illustrate that a boson in these rotating spin-orbit-coupled condensates is subjected to effective toroidal, symmetric double-well, or asymmetric double-well potentials. In the presence of mean-field interactions, using the coupled Gross-Pitaevskii formalism at moderate to high rotation frequencies, the analytically obtained effective potential minima and the numerically obtained coarse-grained density maxima position are in excellent agreement. The effects of rotation are further elucidated by computing the spin expectation per particle for the ferro- and the antiferro-magnetic BECs.

From Classical to Quantum Loss of Coherence Probed by Intensity Correlations in a Large Atomic Cloud

Mateus Biscassi

Departamento de Física - Universidade Federal de São Carlos and INPHYNI - Université Côte D'Azur

In this work we study the transition between two light scattering regimes in a cold atomic cloud and investigate the loss of coherence effects that unravel the physical mechanisms present on the system dynamics. This is done through theoretical simulations in parallel with experimental measurements of the light scattered by an atomic cloud, that show the transition from classical to quantum loss of coherence mechanisms.

Quantum Rayleigh-Taylor instability in two dimensional Bose gases

Pedro Henrique Cook Cunha

São Carlos Institute of Physics

Hydrodynamic instabilities are present in a wide variety of everyday phenomena. Ocean waves, the organization of water droplets into a spider's web, and the mushroom clouds resulting from volcanic eruptions are all examples of such instabilities. In the case of quantum fluids, quantum hydrodynamic instabilities, analogous to those of classical fluids, are related to the superfluid properties of these systems. An example in this direction is the quantum Rayleigh-Taylor instability that can be systematically studied in ultracold gas systems thanks to the high level of control and detection of these systems. In this direct PhD project, we propose to excite the quantum analogue of the Rayleigh-Taylor instability in a two-dimensional (2D) degenerate Bose gas and the subsequent study of the dynamics of the excitations arising from this instability. For this purpose, a new experimental system will be built combining the latest technologies used in this type of experimental system in order to enable the creation of two-dimensional gases with tunable interaction and subject to arbitrary potentials and perturbations, guaranteeing the necessary conditions for the unprecedented observation of the Rayleigh- Taylor in this context.

Complex vector light fields propagation in atomic systems.

ROBERT GUZMAN

DEPARTAMENTO DE FISICA, UNIVERSIDAD DE LA FRONTERA

Complex vector fields are light states where the polarization pattern is in-homogenously distributed across the spatial mode. Preparation of these states is possible thanks to the use of geometric and dynamic phase as well spin–orbit effects of light fields. In this work we explore some aspects of the propagation of complex vector light states through atomic systems. In particular we are interested in how the light- matter interactions affect the topological charge of the light states.

Excitation of Bose-Einstein condensates with temporal resolution in separate zones

Leandro Machado

Instituto de Física de São Carlos

Bose-Einstein condensates (BECs) produced with trapped atoms, are very well controlled quantum systems. In the literature, studies on equilibrium BEC are well-consolidated. On the other hand, when we consider BECs in the non-equilibrium regime, there is still a lot to be understood. The dynamics of out of equilibrium quantum systems, are at the frontier of knowledge. BECs are extraordinary physical systems to study quantum aspects of many-body physics. The evolution of these systems, when externally excited, present interesting properties due to its quantum character, like the collective modes and the generation of quantized vortices (1). Even more, for strongly excited samples, BECs may reach the quantum turbulence regime (2). Our physical system is characterized by a BEC sample confined in a harmonic oscillator trap and its externally excited by an oscillatory magnetic field that introduce perturbations and nonlinearities. Our group has several works in this direction, but always using the same approach to excite the BEC samples, that is, using a single pulse. Now, we are interested in studying these systems with separate zones excitations instead of just a single pulse. This proposal of excitation is motivated by Norman F. Ramsey experiment (3), which introduced the separate oscillatory field method to promote atomic transitions between hyperfine states of atoms and it had important applications in atomic clocks and modern interferometry. Similarly to the Ramsey's experiment, we expect that interference phenomenon should appear in our quantum many-body system. From recent results, we already noted interference phenomenon in the collective modes evolution, like Ramsey fringes. For strongly excited samples using the Ramsey-like excitation, we expect to be able to analyze the persistence of coherence in these samples, indicating if the system becomes more disordered or not with application of perturbations. Thus, the proposal of this work is the development of theoretical models and the elaboration of computer simulations that will reproduce the experiments that are currently being carried out. These theoretical studies will allow us to better understand the behavior of this system, and its response to external excitations.

Core structure of two-dimensional Fermi gas vortices in the BEC-BCS crossover region

Lucas Madeira

São Carlos Institute of Physics, University of São Paulo

The study of cold Fermi gases has proven to be a very rich research field, and investigating low-dimensional systems has become an active area in this context. The two-dimensional (2D) Fermi gas has particularly attracted much interest since its experimental realization. A purely attractive potential in 2D always supports a bound state, and the ability to vary the interaction strength over the entire BEC-BCS crossover regime offers rich possibilities for studying these systems. The presence of quantized vortices is an indication of a superfluid state. With the recent progress on the 2D Fermi gases, it seems natural to extend the theoretical study of vortices to these systems. In this work, we employed Quantum Monte Carlo methods, which are many-body calculations well-suited to tackle strongly-interacting systems, to compute properties of a single vortex in a 2D Fermi gas. We considered the ground state to be a disk with hard walls and zero total angular momentum, and the vortex excitation corresponds to each fermion pair having one unit of angular momentum. We calculated the vortex excitation energy, density profiles, and vortex core properties related to the current. We found a density suppression at the vortex core on the BCS side of the crossover and a depleted core on the BEC limit. Reference: L. Madeira, S. Gandolfi, K.E. Schmidt, Phys. Rev. A 95, 053603 (2017)

Observables' evolution of a trapped quantum gas

Áttis Vinícius M Marino

Instituto de Física de São Carlos

From a computer simulation of a Bose-Einstein Condensate (BEC) trapped by a harmonic potential, initially containing a pair of doubly charged anti-parallel vortices, the temporal evolution of a number of observables of interest was extracted. These observables help to outline a more complete understanding of the evolution of the system under these conditions, such as the emergence of a turbulent regime excited by the interaction of quantum vortices. The analysis of the evolution of the momentum distribution and energy spectrum shows that, from a certain instant onwards, a turbulence regime is established characterized by the presence of cascades of energy and particles, evidenced by the presence of regions of the spectrum that obey power laws of known scales. Vinen's ultraquantum turbulence regime, observed in experiments carried out in liquid helium and characteristic of superfluids, was also detected in the simulation as a result of the interaction of vortices. Through the directional analysis of the momentum distribution, in which the spectra limited to specific solid angles and directions are compared, it is shown that the isotropy of the momentum distribution is reached as soon as the turbulent regime starts, despite the strong spacial anisotropy of the system geometry. Furthermore, by performing a separation of the kinetic energy spectra into their rotational and compressive components, it is observed that the evolution of the system triggers the transport of compressive energy into rotational energy. Extracting the fluxes of energy and particles through the classes of momenta from the simulation, an oscillatory behavior, characteristic of the breathing mode of the system, is obtained. In particular, the particle flux presents a positive and practically constant region in the range of momenta in which the Vinen turbulence regime is identified, indicating the presence of a direct cascade of particles.

Effective potentials on bubble-traps

Sheilla de Oliveira Marques

Universidade Federal de São Carlos

Motivated by recent progress in the experimental realization of Bose-Eintein condensation (BEC) in a bubble trap, we investigate the behavior of a Bose gas on a curved manifold. The simplest geometrical form that approximately describes this type of trap is a spherical one, for which we have computed the low-lying excitation modes. To this end, we have performed a dimensional reduction of the Gross-Pitaevskii (GP) equation, which leads to an effective two-dimensional GP equation for the condensate wave function. On the other hand, a more appropriate manifold to describe a bubble trap is an ellipsoid. For this case, the two-dimensional GP equation turns out to have an effective potential, referred to as geometrical potential, which results in a non-uniform ground state along the surface. Moreover, external asymmetries of the experiments become relevant in this case. We compare how these two aspects affect the ground state of the BEC on the ellipsoid.

Towards deep laser cooling of the internal an external motion of trapped nano-particles

Lucas Mendicino

Universidad de Buenos Aires

We present our road-map and advances towards cooling the internal and external degrees of freedom of a levitated nano-particle via laser methods. We study cooling of rare-earth doped nano-crystals trapped in quadrupole Paul trap and discuss the benefits, challenges and progress in this field and in our lab.

Cooling the bulk of crystals dopped with Ytterbium has been achieved for centimeter-sized as well as for nano-sized objects to temperatures in the range of 100 K. This minimum temperature is the result of competing heating and cooling mechanisms. Heating processes are mainly determined by the presence of impurities in the crystals in ppm concentrations as well and by inhomogeneous broadening of the dopants in the crystal. This spurious heating could be limited in small nano-particles if both the dopants and the impurities could be spectrally addressed individually to enhance cooling and avoid heating. On the other hand, cooling power is limited by the fine linewidth of the dopant transition, which could be broadened by co-doping with atoms with resonant levels and faster transitions, such as in the Er-Yb up-conversion pair.

We also study laser cooling of the center of mass of a rare-earth doped nano-crystal, via the Doppler mechanism. We conclude that unless an efficient mechanism is found to increase the coupling of the dopant to the driving field, cooling rates are too low to compete even with electrical noise or black body radiation heating rates.

Finally we will share our advance in building an ultra high-vacuum compatible system to trap and cool nano-particles in a linear Paul trap with a blade design. We have tested a laser induced acoustic desorption loading mechanism and are setting up an electrical center-of-mass feedback cooling system as a first stage before laser cooling.

Enhancing quantum fluctuations in strongly entangled cavity BEC systems

Leon Mixa

Universität Hamburg

Cavity-BEC systems with strong coupling between the atomic and cavity sector provide extraordinary possibilities for observing details in their Dicke phase transition through the cavity loss channel. By microscopic derivation starting from the systems field Hamiltonian, we uncover the atomic quantum fluctuations around the condensate. These quantum fluctuations are then captured in exact fashion as the bath of a system-bath description of the cavity-BEC. We find analytic expressions of the spectral densities governing the Landau and Beliaev damping. This enables unprecedented insight as we investigate their influence on the strongly entangled system.

We discuss in detail, how to control the faceted bath in particular concerning the sub-ohmic quantum fluctuations. Furthermore, we present the influence on the system and its Dicke phase transition with regard to the critical point, universality class and temperature dependence. This also allows us to discuss the experimental accessibility of the quantum fluctuations.

Thermometry in ion crystals

Muriel

Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires

The high degree of control that trapped ion platforms offer can be exploited to simulate quantum and classical systems. One area of particular interest is the study of transport phenomena in the vibrational degrees of freedom of an ion crystal, which requires estimating the local temperature of the crystals. In this work we present our advances in single ion thermometry in a Paul trap. We implement two methods to estimate the ion temperature: Doppler broadening and CPT spectroscopy, and study the effects excess micromotion has in these experiments.

Use of the basis of spin coherent states and quadrupolar states in the description of spin-1 lattice bosons

JOHN ALEJANDRO MONTILLA ORTEGA

Universidad del Valle

The high degree of control provided by ultra-cold atom experimental techniques has led to the development of quantum simulators, bringing one-dimensional systems to the laboratory. In one dimension, fluctuations tend to be collective and propagate over long distances due to the inevitability of collisions. Therefore, theoretical frameworks that use collective fluctuations have been developed to describe these systems. The present work aims to explore a theoretical development within a functional field theory, using Schwinger boson mapping in the construction of an ansatz to represent the state of the system on the basis of bosonic spin coherent states. The perspective of the work is to use this representation of the state in conjunction with variational techniques to characterize the magnetic phases of spin-1 bosons trapped in a one-dimensional periodic potential in the strongly interacting and correlated phase of the Mott insulator.

Chiral superconductivity in the doped triangular-lattice Fermi-Hubbard model in two dimensions

Vinicius Zampronio Pedroso

Utrecht University

The triangular-lattice Fermi-Hubbard model has been extensively investigated in the literature due to its connection to chiral spin states and unconventional superconductivity. Previous simulations of the ground state of the doped system rely on quasi-one-dimensional lattices where true long-range order is forbidden. Here we simulate a 12x12 triangular lattice using state-of-the-art Auxiliary-Field Quantum Monte Carlo. Upon doping a non-magnetic chiral spin state, we observe evidence of chiral superconductivity at filling n=5/6 supported by long-range order in Cooper-pair correlation and a finite value of the chiral order parameter. With this aim, we first locate the transition from the metallic to the non-magnetic insulating phase where we see competition between chiral and magnetic orders. Our results pave the way towards a better understanding of strongly correlated lattice systems with magnetic frustration.

Dynamics of vortices in the Dipolar Bose-Einstein condensate

Sabari

IFT-UNESP

In this talk, I will discuss about the formation and dynamics of the vortices in the dipolar Bose-Einstein condensates. For this purpose, we solve a two-dimensional, nonlocal Gross-Pitaevskii equation numerically. First, I calculate the critical velocity for the nucleation of vortices in the dipolar BECs for different possible cases. We show that the dipole-dipole interaction plays a significant role in determining the critical rotation frequency for vortex formation. We also discuss the impacts of the different strengths of the dipole-dipole interaction in the vortex formation process. Further, we demonstrate the vortex lattice for a large rotation frequency.

Dynamical phase diagram of a one-dimensional Bose gas in a box with a tunable weak link: From Bose-Josephson oscillations to shock waves

Abhik Kumar Saha

INDIAN ASSOCIATION FOR THE CULTIVATION OF SCIENCE

We study the dynamics of one-dimensional bosons trapped in a box potential in the presence of a barrier creating a tunable weak link, thus realizing a one-dimensional Bose-Josephson junction. By varying the initial population imbalance and the barrier height, we evidence different dynamical regimes. In particular, we show that at large barriers a two-mode model captures accurately the dynamics, while for low barriers the dynamics involves dispersive shock waves and solitons. We study a quench protocol that can be readily implemented in experiments and show that self-trapping resonances can occur. This phenomenon can be understood qualitatively within the two-mode model.

Stability of the Bose-Einstein condensate mixtures on the bubble

Leonardo Brito da Silva

University of São Paulo

Bose-Einstein condensates (BEC) confined in spherical geometries are currently feasible with the achievement of bubble trap confinements in cold atom experiments performed in microgravity conditions aboard the International Space Station. We simulate this system by a perfect spherical two-dimensional shell surface and study analytically and numerically the dynamic stability of BEC binary-mixture systems, taking into account the intra- and interspecies interaction effect on different initial conditions. We perform our studies by observing Bogoliubov de-Gennes (BdG) spectrum and also the dynamics simulation driven by the Gross-Pitaveskii (GP) equation.

Bose gases in a cylinder in canonical ensemble

Jonata Santos Soares

Instituto de Física da Universidade de São Paulo

The recursive canonical method is a great approach to study the Bose gases in finite systems. Here we'll apply it idea in a cylindrical confinement in a non-interacting case calculating the condensed fraction and ground-state fluctuations.

Excitations of the disordered Bose-Hubbard model

Renan da Silva Souza

We investigate the effect of disorder upon the excitations of the Mott insulating state at zero temperature described by the Bose-Hubbard model. Using a field-theoretical approach we obtain a resummed expression for the disorder ensemble average of the spectral function. Its analysis shows that disorder leads to an increase of the effective mass of both quasi-particle and quasi-hole excitations. Furthermore, it yields the emergence of damped resonance states, which exponentially decay during propagation in space. We argue that such resonance states correspond to excitations of the Bose-glass phase.

Classical Analog of the Quantum Boomerang effect

Santiago Zamora

Universidade Federal do Rio Grande do Norte (UFRN)

A particle with finite initial velocity in a disordered potential comes back and in average stops at the original location. This phenomenon dubbed ‘quantum boomerang effect’ (QBE) has been recently observed in an experiment simulating the quantum kicked-rotor model [PhysRevX.12.011035]. Here we investigate the classical analog of the quantum boomerang effect.