SYMPOSIUMS

Polish-French Symposium II: Advances in Ultracold Matter Physics

31 May 2023 – 02 June 2023
Polish Academy of Sciences Scientific Center in Paris

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The Second Polish-French Symposium on Advances in Ultracold Matter Physics was successfully held at the Scientific Center of the Polish Academy of Sciences in Paris from May the 31st till June the 2nd in 2023. The meeting was co-organized K. Pawłowski, PhD DSc (Center for Theoretical Physics PAS) and E. Witkowska, PhD DSc (Institute of Physics PAS).

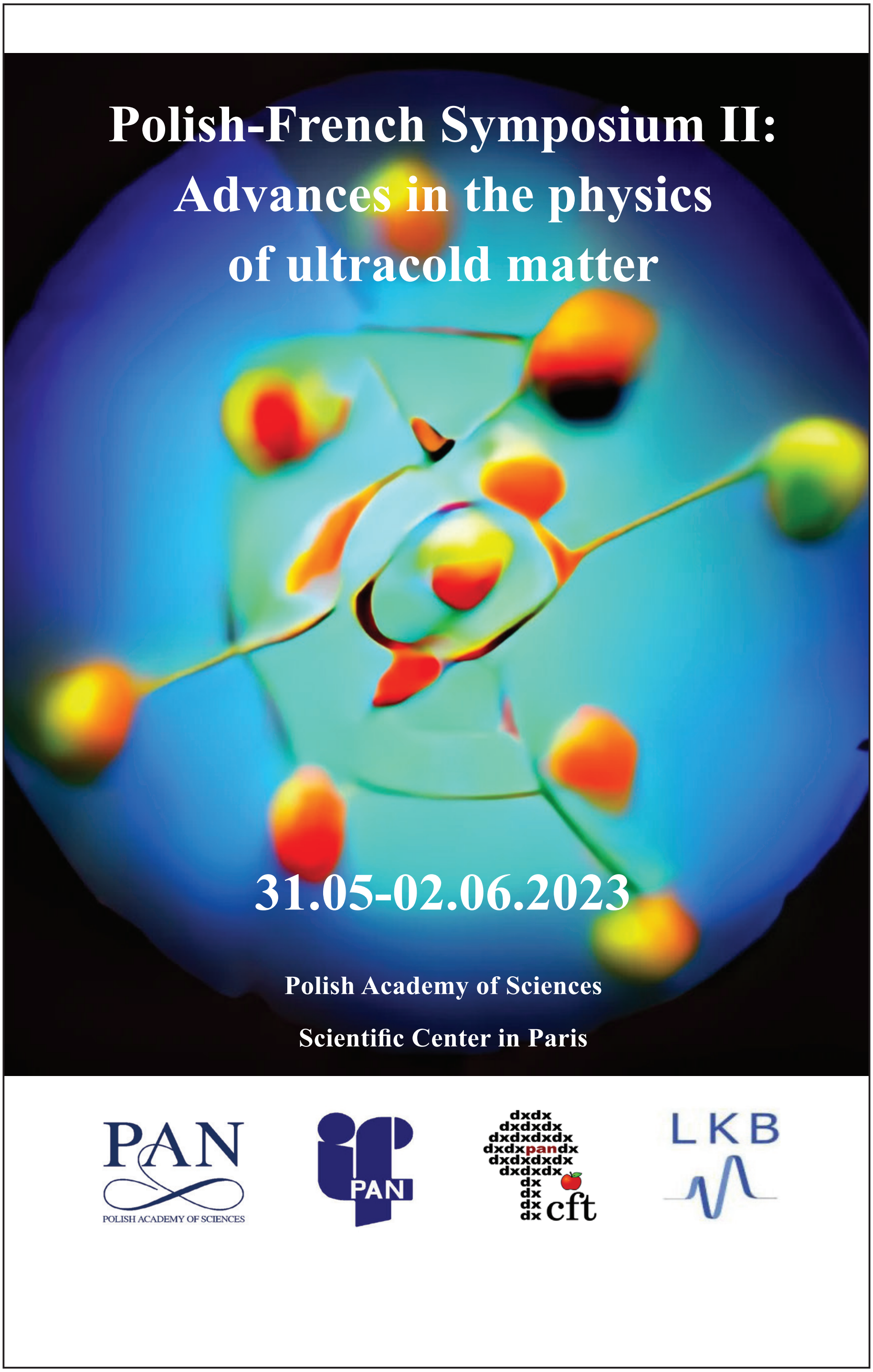
The purpose of the Symposium was to broaden scientific collaboration between high-profile Polish and French scientists working on the physics of ultra-cold gases and their applications in emerging quantum technologies that can revolutionize the fields of computing, encryption, and metrology. The development of these fields is currently supported by European Union due to the Quantum Flagship. The scientific scope of the meeting focused on the recent important theoretical and experimental advances in this field.

The Symposium successfully fostered a vibrant atmosphere for international collaboration, bringing together scientists from not only Poland and France but also from Denmark, Germany, Switzerland, Spain, and Singapore, and such personalities as Maciej Lewenstein, Alice Sinatra, Tilman Pfau, Jan Arlt and Kazimierz Rzążewski.

More than fifty scientists met together over three days to share their developments and new ideas, and to discuss recent advances in the field of physics of ultra-cold gases and beyond. Thirty invited talks were given and more than ten poster presentations. Abstracts of them are available in the *Book of Abstracts* summarizing all presentations and the contribution of the Polish Academy of Sciences.

One of the highlights of the Symposium was the dedication of the first day to celebrate the 80th birthday of Professor Kazimierz Rzążewski, scientists well-known for his contribution to the fields of quantum optics and ultracold quantum gases. His achievements were recognized by the scientific community and resulted in such awards as the Humboldt Foundation Prize, Galileo Medal, and the FNP Prize for 2015 (commonly referred to as the *Polish Nobel Prize*). As a long-time employee and former director of the Center for Theoretical Physics of the Polish Academy of Sciences, Professor Rzążewski has inspired and mentored dozens of researchers.

The event has laid the foundation for ongoing scientific cooperation paving the way for the creation of new contacts and common interests in various areas of the field of ultra-cold atoms. This will lead to the joint investigation of novel concepts in the field and in the longer time scale innovative discoveries and breakthroughs in quantum technologies and beyond.


Polish-French Symposium II:
Advances in the physics
of ultracold matter
31.05-02.06.2023
Polish Academy of Sciences
Scientific Center in Paris
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PROGRAMME

Wednesday 31/05/2023

08:30–08:50 REGISTRATION

08:50–09:00 WELCOME SPEECH

Special Sessions dedicated to prof. Kazimierz Rzążewski

09:00–10:30 1st Session (chairman K. Sacha)
M. Lewenstein
Dipolar Hubbard and spin systems revisited
M. Gajda
My adventures in physics with Kazik
M. Brewczyk
Searching for cosmic vortices

10:30–11:00 COFFEE BREAK

11:00–12:30 2nd Session (chairman M. Gajda)
K. Rzążewski
The Fock States Sampling method at work
Z. Idziaszek
Quantum simulators with trapped ions and ultracold atoms
J. Arlt
Fluctuations of a Quantum Gas: 28 years of research in a nutshell

12:30–14:00 LUNCH

14:00–15:30 3rd Session (chairman P. Deuar)
M. Trippenbach
Topological states of atoms in a spin dependent optical potential

T. Karpiuk
Bose-Fermi solitons

K. Pawłowski
Quantum droplet and its collective excitations in quasi-1D Bose gas

15:30–16:00 COFFEE BREAK

16:00–17:00 4th Session (chairman Y. Castin)

T. Pfau
Dipolar quantum droplets and supersolids

B. Englert
TBA

17:00–17:15 B. Hryniszyn
New aspects of the ERC grants

19:30 DINNER

Thursday 01/06/2023

09:00–10:30 5th Session (chairman A. Sinatra)

T. Zibold
Observation of the Einstein-Podolsky-Rosen paradox between two Bose-Einstein condensates

I. Frerot
Estimating the quantum Fisher information from a given set of mean values: a semidefinite-programming approach

T. Rosclide
Entanglement dynamics in U(1) symmetric quantum spin lattices: a tale of waves and rotors

10:30–11:00 COFFEE BREAK

11:00–12:30 6th Session (chairman B. Laburthe-Torla)

J. Dziarmaga
From 2D tensor networks to quantum simulations

K. Sacha
Absolutely Stable Discrete Time Crystals
E. Witkowska
Scalable spin squeezing in isotropic Heisenberg spin chains with nearest neighbor interactions

12:30–14:00 LUNCH

14:00–15:30 7th Session (chairman F. Werner)
M. Robert de Saint Vincent
Manipulating the spins of SU(10)-symmetric Fermi gases
Y. Castin
Higgs excitation branch in a pair-condensed Fermi gas / Branche d'excitation de Higgs dans un gaz de fermions condensé par paires
G. Wlazłowski
Towards general-purpose simulation platform for superfluid fermions

15:30–16:00 COFFEE BREAK

16:00–17:00 8th Session (chairman E. Witkowska)
P. Tretlein
Coupling quantum systems with a laser loop
A. Sinatra
Quantum-enhanced multiparameter estimation and compressed sensing of a field

17:00–18:30 POSTER SESSION

Friday 02/06/2023

09:00–10:30 9th Session (chairman T. Roscilde)
H. Perrin
Melting of a vortex lattice in a fast rotating Bose gas
A. Minguzzi
Exact solutions for strongly interacting quantum gases in one dimension

	G. Juzeliunas *Sub-wavelength lattices for ultracold atoms*
10:30–11:00	COFFEE BREAK
11:00–12:30	10th Session (chairman P. Treutlein) B. Labourthe-Tolra *Many-body out-of-equilibrium physics with large spin atoms* D. Petrov *Self-binding of one-dimensional fermionic mixtures with zero-range interspecies attraction* P. Deuar *Thermal properties of squashed quantum droplets*
12:30–14:00	LUNCH
14:00–15:30	11th Session (chairman D. Petrov) J. Reichel *Observing Spin-Squeezed States under Spin-Exchange Collisions for a Second* M. Płodzień *Generation, storage, and validation of metrologically useful many-body entangled states in the analog and digital quantum simulators in the NISQ era* F. Werner *Three-body contact for fermions*
15:30–16:00	COFFEE BREAK
16:00–17:00	12th Session (chairman K. Pawłowski) I. Bouchoule *Relaxation of phonons in the Lieb-Liniger gas by dynamical refermionization* G. Orso *Phase-space methods for atom-cavity systems*

1st Session – Wednesday 9:00-10:30

Maciej Lewenstein
ICFO – The Institute of Photonic Sciences

Dipolar Hubbard and spin systems revisited

In my lecture at the Symposium on the occasion of Doctorate Honoris Causa in Stuttgart I talked about a drug that many of us cannot resist, since the famous paper of Krzysztof Góral, Kazik Rzążewski and Tilman Pfau [1]: Degenerate dipolar gases and dipolar Bose-Einstein condensates [1-3]. Actually, I concentrated then on more recent experimental evidences for condensation of ultracold dipolar excitons [4]. Today's lecture focusses on dipolar gases and dipolar systems in lattices: these are described by extended or non-standard Hubbard model, exhibit strong correlations and lead to many exotic quantum phenomena. But, I will start in fact with the first observation of the checkerboard state of indirect excitons in a 2D lattice [5] – a direct continuation of our work with François Dubin [4].

[1] K. Góral, K. Rzążewski and T. Pfau *Bose-Einstein condensate with magnetic dipole-dipoleforces*, Phys. Rev. A 61, 051601(R) (2000).
[2] L. Santos, G.V. Shlyapnikov, P. Zoller, and M. Lewenstein *Bose-Einstein condensation oftrapped dipolar gases*, Phys. Rev. Lett. 85, 1791 (2000); erratum Phys. Rev. Lett. 88, 139904(2002).
[3] Th. Lahaye, C. Menotti, L. Santos, M. Lewenstein, and T. Pfau *The physics of dipolarbosonic quantum gases*, Rep. Prog. Phys. 72, 126401 (2009).
[4] M. Alloing, M. Beian, D. Fuster, Y. Gonzalez, L. Gonzalez, M. Lewenstein, R. Combescot, M. Combescot and F. Dubin *Evidence for a Bose-Einstein condensate of excitons*, arXiv:1304.4101, EPL 107, 10012 (2014).
[5] C. Lagoin, U. Bhattacharya, T. Graß, R. Chhajlany, T. Salamon, K. Baldwin, L. Pfeiffer, M. Lewenstein, M. Holzmann and F. Dubin *Checkerboard solid of dipolar excitons in a two-dimensional lattice*, Nature 609, pages 485–489 (2022), https://doi.org/10.1038/s41586-022-05123-z, arXiv:2201.03311.

Mariusz Gajda
Institute of Physics Polish Academy of Sciences

My adventures in physics with Kazik

In this talk, I will focus on several selected problems of atomic physic. Their common feature is a special role which Kazik played in the search for their solution.

Mirosław Brewczyk
University in Białystok

Searching for cosmic vortices

We study a tidal disruption of a white dwarf orbiting a black hole. We model a white dwarf star by a Bose-Fermi droplet and use the quantum hydrodynamic equations to simulate evolution of a black hole-white dwarf binary system. While going through the periastron, the white dwarf looses its mass which, falling onto a black hole, becomes a source of powerful electromagnetic and gravitational radiation. The falling matter itself forms the accretion disk whose complex structure reveals cosmic vortices.

2nd Session – Wednesday 11:00-12:30

Kazimierz Rzążewski
Center for Theoretical Physics, Polish Academy of Sciences

The Fock States Sampling method at work

Thermal fluctuations of Bose-Einstein condensate are of interest ever since E. Schrödinger noticed their dependence on the choice of a statistical ensemble. Widely used the grand statistical ensemble, when applied to an isolated system yielding unphysical results. The problem of fluctuations was a hot topic after the first experiments on BEC. Asymptotic results were obtained and recurrence relations were derived for partition functions in microcanonical and canonical ensembles. The role of weak collisions remains controversial. Recently, the fluctuations were finally measured by the group of Jan Arlt from Aarhus [1, 2]. We are providing theoretical background. In particular, in [2] we argue that the experiment unveiled for the first time microcanonical fluctuations of the condensate. We developed a novel method of computing the statistics of the non-zero temperature properties of the Bose gas, named the Fock States Sampling method, that gives access to both, canonical and microcanonical statistics for up to 100 000 particles. The method is also applicable to the weakly interacting gas trapped in a box. In this case, results for the interaction-induced shifts of the critical temperature will be revisited [3].

[1] M.A. Kristensen, M.B. Christensen, M. Gajdacz, M. Iglicki, K. Pawlowski, C. Klempt, J.F. Sherson, K. Rzążewski, A.J. Hilliard, J.J. Arlt *Observation of Atom Number Fluctuationsin a Bose-Einstein Condensate*, Phys. Rev. Lett.122, 163601 (2019)

[2] M.B. Christensen, T. Vibel, A.J. Hilliard, M.B. Kruk, K. Pawłowski, D. Hryniuk, K. Rzążewski, M.A. Kristensen, and J.J. Arlt *Observation of Microcanonical Atom Number Fluctuations in a Bose-Einstein Condensate*, Phys. Rev. Lett.126, 153601, (2021)

[3] M.B. Kruk, D. Hryniuk, M. Kristensen, T. Vibel, K. Pawłowski, J. Arlt, K. Rzążewski *Microcanonical and Canonical Fluctuations in Bose-Einstein Condensate – Fock state sampling approach*, SciPost Phys. 14, 036 (2023)

Zbigniew Idziaszek
Faculty of Physics, University of Warsaw

Quantum simulators with trapped ions and ultracold atoms

Hybrid systems of laser-cooled trapped ions and ultracold atoms have recently emerged as a new platform for fundamental research in quantum physics. In particular, compound ion-atom systems have been proposed for quantum simulations of condensed matter systems exhibiting strong electron-phonon coupling. The ions forming a periodic lattice, induce a band structure for the atoms, which brings close analogies to natural solid-state systems, with atomic degrees of freedom coupled to phonons of the ion lattice.

In this talk, I will discuss in detail the case of a single ultracold atom interacting with a set of arbitrarily arranged static ionic impurities. In the case of ultracold atoms and ions where interactions are dominated by s-wave collisions the problem admits an analytical solution. Next, I will consider the motion of atoms in the presence of a periodic lattice of equally spaced ionic impurities, in 1D and quasi-1D geometry. In the latter case, the energy spectrum exhibits the presence of multiple overlapping bands resulting from excitations in the transverse direction. At large lattice constants, the energy spectrum resembles the standard Kronig-Penney model with the coupling renormalized due to the scattering in quasi-1D geometry. Finally, I will review results for hybrid systems consisting of a cloud of ultracold fermionic atoms interacting with a periodic lattice of ions, serving as quantum simulators of solid-state systems.

J. J. Arlt
Aarhus Universitet

Fluctuations of a Quantum Gas: 28 years of research in a nutshell

Quantum systems are characterized by the inherent fluctuation of their physical observables. Despite this fundamental importance, the investigation of the fluctuations in interacting quantum systems at finite temperature continues to pose considerable challenges. Many of these challenges were first tackled by Kazimierz Rzazewski in the field of ultracold atoms in 1997 [1] and the Maxwell's demon ensemble was introduced to explain their micocanaonical treatment [2]. Here we report the characterization of atom number fluctuations in weakly interacting Bose-Einstein condensates. Strikingly, we observe fluctuations reduced by 27% below the canonical expectation for a non-interacting gas, revealing their microcanonical nature and validating the Maxwell's demon ensemble. This shows that a microcanonical treatment is indeed required for quantitative predictions of the effect of interactions on the fluctuations. I addition we briefly discuss the investigation of corresponding fluctuations in the terminal part of the system and outline the outstanding questions in the field.

[1] *Fluctuations of Bose-Einstein Condensate,* M. Gajda and K. Rzążewski, Phys. Rev. Lett. 78, 2686 (1997).

[2] *Fourth Statistical Ensemble for the Bose-Einstein Condensate*, P. Navez, D. Bitouk, M. Gajda, Z. Idziaszek, and K. Rzążewski, Phys. Rev. Lett. 79, 1789 (1997).

3rd Session – Wednesday 14:00-15:30

Marek Trippenbach
Faculty of Physics, University of Warsaw

Topological states of atoms in a spin dependent optical potential

We investigate fermionic 6 Li F = 1/2 atoms in a 2D spin-dependent optical lattice potential (SDOLP) generated by intersecting laser beams with a superposition of polarizations. For 6 Li F = 1/2 the effective interaction of an atom with the electromagnetic field contains a scalar and a vector (called as fictitious magnetic field, Bfic) potentials. The Li atoms behave as a quantum rotor (QR) with angular momentum given by the sum of the atomic rotational motion angular momentum and the hyperfine spin. We calculate the band structure of Li atoms in the SDOLP as a function of the laser intensity and an external magnetic field, perpendicular to the lattice plane, in a full band-structure calculation and also in a tight-binding approximation, and the Chern numbers of the SDOLP. We then introduce a blue-detuned potential, which introduces edges to the SDOLP, and then calculate edge states and their spin and spin-current densities. We find both non-topological and topological edge states for the Li atoms in this system.

Tomasz Karpiuk
University in Białystok

Bose-Fermi solitons

In the presentation, I will tell you about the results of two papers from almost twenty years ago on Bose-Fermi solitons. In the first paper we theoretically consider the formation of bright solitons in a mixture of Bose and Fermi degenerate gases. While we assume the forces between atoms in a pure Bose component to be effectively repulsive, their character can be changed from repulsive to attractive in the presence of fermions provided the Bose and Fermi gases attract each other strongly enough. In such a regime the Bose component becomes a gas of effectively attractive atoms. Hence, generating bright solitons in the bosonic gas is possible. Indeed, after a sudden increase of the strength of attraction between bosons and fermions soliton trains appear in the Bose-Fermi mixture. In this work the system we consider is 1D. In the second work we extend our calculations on quasi one dimensional system. Finally I will tell about the results of experimental paper from 2019 confirming our theoretical predictions fifteen years after our predictions.

Krzysztof Pawłowski
Center for Theoretical Physics Polish Academy of Sciences

Quantum droplet and its collective excitations in quasi-1D Bose gas

In my talk, I will summarise my group's efforts in identifying and investigating quantum droplets in the dipolar quasi-1D system. We use a framework which generalizes the LHY correction to the regimes of intermediate and strong short-range interaction, discussed in [1]. In the naive extension of the model to the dipolar interaction, we found that the quantum droplet may exist in the quasi-1D systems. Moreover, among its excitations, there are the dark and grey solitons. The solitonic excitations have unexpected properties – in principle, their width is unlimited [2]. These results can generalized to droplets in the Bose-Bose mixtures [3]. In parallel, we used a many-body approach (DMRG and TDVP) to study the analogous model in the lattice. The main finding here is confirmation of the existence of the liquid phase, which, however, shows unexpected behaviour in the context of the Tonks-Girardeau effect.

[1] Jakub Kopyciński, Maciej Łebek, Maciej Marciniak, Rafał Ołdziejewski, Wojciech Górecki, Krzysztof Pawłowski, SciPost Phys. 12, 023 (2022)

[2] Jakub Kopyciński, Maciej Łebek, Wojciech Górecki, and Krzysztof Pawłowski, Phys. Rev. Lett. 130, 043401 (2023)
[3] Jakub Kopyciński, Luca Parisi, Nick G. Parker, and Krzysztof Pawłowski, Phys. Rev. Research 5, 023050 (2023)

4th Session – Wednesday 16:00-17:00

Tilman Pfau
Physikalisches Institut and Center for Integrated Quantum Science and Technology

Dipolar quantum droplets and supersolids

Dipolar interactions are fundamentally different from the usual van der Waals forces in real gases. Besides its anisotropy the dipolar interaction is nonlocal and as such allows for self organized structure formation, like in many different fields of physics. Although the bosonic dipolar quantum liquid is very dilute, stable droplets and supersolids as well as honeycomb or labyrinth patterns can be formed due to the presence of quantum fluctuations beyond the mean field theory.

B. Englert
National University of Singapore

Adventures with contact interactions

5th Session – Thursday 9:00-10:30

Tilman Zibold
Basel University

Observation of the Einstein-Podolsky-Rosen paradox between two Bose-Einstein condensates

In 1935, Einstein, Podolsky, and Rosen (EPR) conceived a Gedankenexperiment which became a cornerstone of quantum technology and still challenges our understanding of reality and locality today. While the experiment has been realized with small quantum systems, a demonstration of the EPR paradox with massive many-particle systems remains an important challenge, as such systems are particularly closely tied to the concept of local realism in our everyday experience and may serve as probes for new physics at the quantum-to-classical transition. In this work we report an EPR experiment with two spatially separated Bose-Einstein condensates, each containing about 700 rubidium atoms. Entanglement between the condensates results in strong correlations of their collective spins, allowing us to demonstrate the EPR paradox between them. Our results represent the first observation of the EPR paradox with spatially separated, massive many-particle systems. They show that the conflict between quantum mechanics and local realism does not disappear as the system size increases to more than a thousand massive particles. Furthermore, EPR entanglement in conjunction with individual manipulation of the two condensates on the quantum level, as demonstrated here, constitutes an important resource for quantum metrology and information processing with many-particle systems.

Irénée Frérot
Institut Néel, CNRS, Grenoble

Estimating the quantum Fisher information from a given set of mean values: a semidefinite-programming approach

Estimating the quantum resources of many-body systems is a central task of quantum information science. An important issue is to certify relevant properties from only partial knowledge of the many-body state when full-state tomography is unfeasible. Here, we consider the problem of certifying the metrological usefulness of a many-body system (as quantified by the quantum Fisher information associated to unitary transformations) from the knowledge of an arbitrary collection of expectation values. We formulate the problem as a semidefinite programme (SDP), namely as a convex optimization problem for which a well-defined global optimum can be found using standard numerical routines. We apply this approach to probe the metrological ressource of collective spin ensembles, such as those generated by the one-axis-twisting dynamics. Interestingly, the insights provided by our approach lead us to propose very simple interferometry protocols exploiting the full metrological power of the states at all times of the dynamics, including the so-called multiheaded cat states for which such a metrological application had remained elusive.

Tommaso Roscilde
Ecole Normale Supérieure de Lyon

Entanglement dynamics in U(1) symmetric quantum spin lattices: a tale of waves and rotors

Quench dynamics is a fundamental source of many-body entanglement in quantum simulators. Entanglement and correlations are generally believed to establish in the system via the propagation of low-energy quasi-particle excitations at finite momentum, within a light cone dictated by their maximal group velocity. Yet in U(1) symmetric systems an additional group of excitations exists, corresponding to the so-called *zero mode*, i.e. excitations with zero momentum associated with U(1) rotations of the collective spin. These excitations form the so-called Anderson tower of states, with the spectrum of a planar rotor; and therefore their dynamics is akin to that of the paradigmatic one-axis-twisting (OAT) Hamiltonian. In this talk I will discuss how finite-momentum quasiparticles and zero-momentum rotor excitations remain effectively decoupled in a large family of models — including the very relevant case of dipolar spin systems. These models can therefore realize the *OAT cascade* of entangled states, encompassing squeezed states, Schrödinger's cat states and their generalizations.

6th Session – Thursday 11:00-12:30

Jacek Dziarmaga
Jagiellonian Univeristy

From 2D tensor networks to quantum simulations

By avoiding the notorious sign problem, the 2D tensor networks solved some of the long standing problems in the condensed matter physics of strongly correlated systems. They are an efficient description of thermal states and, against the odds, can be used to attempt classical simulation of unitary time evolution. I will discuss examples that make contact with quantum simulations by ultracold atoms or D-wave. These include the 2D (Fermi-)Hubbard model at finite temperature and Kibble-Zurek quenches in the 2D quantum Ising and Bose-Hubbard models.

Krzysztof Sacha
Jagiellonian University

Absolutely Stable Discrete Time Crystals

Discrete time crystals are periodically driven many-body systems that exhibit spontaneous evolution with a period longer than the driving period. Despite the fact that generic periodically driven many-body systems are expected to evolve to an infinite temperature structureless state, discrete time crystals are believed not to heat up. We will demonstrate the possibility of constructing a system that guarantees the absolute stability of discrete time crystals.

Emilia Witkowska
Institute of Physics Polish Academy of Sciences

Scalable spin squeezing in isotropic Heisenberg spin chains with nearest neighbour interactions

I will discuss a method to generate scalable spin squeezing in isotropic Heisenberg spin chains with nearest neighbour interactions. Such spin-squeezed chains can be realized using either bosonic or fermionic ultra-cold atoms in optical lattices. I will show how the addition of the spin-flip coupling or inhomogeneous field induces effective interactions among individual spins allowing the production of scalable spin squeezing. The schemes could be directly implemented experimentally with state-of-the-art techniques.

7th Session – Thursday 14:00-15:30

Martin Robert-de-Saint-Vincent
Laboratoire de Physique des Lasers, CNRS – USPN

Manipulating the spins of SU(10)-symmetric Fermi gases

Ultracold alkaline-earth atoms enable the investigation of the effect of a large spin degree of freedom in interacting fermionic ensembles. I will present our experiments with degenerate Fermi gases of strontium 87. These are held in optical lattices, to realize generalizations of the Fermi-Hubbard model to spins effectively tuneable from 1/2 to 9/2, the actual spin of strontium. In this talk, I will focus on our capabilities for measurement and control of the spins, and connect this to our approach for the study of the antiferromagnetic Heisenberg model of magnetism. The spins of ground-state strontium atoms are of nuclear nature, which in experiments is both a strength, as environmental magnetic noise has little effect, and a complication, as standard spin measurement or manipulation schemes with magnetic gradients are ineffective. I will show nevertheless that a narrow line with large hyperfine structure offers us powerful tools, associated with the engineering of effective spin-orbit coupling. First, we applied adiabatically a three-level coupling involving a dark atomic state, reminiscent of EIT or STIRAP, to transfer momentum in a spin-selective manner [1]. This, we now use for spin measurements; ultimately it enables spin resolved momentum noise correlation spectroscopy. Second, we have demonstrated controlled coherent adiabatic operations in the 10-component spin-manifold, from a deterministically produced, arbitrary spin state. I will connect this to our present effort at controlling the effective atomic spin in experiments using tensor light shifts; and ultimately, by micro-structuring these optical fields, at enabling the growth of measurable quantum correlations and approaching low-energy states of the Heisenberg Hamiltonian [2].

[1] P. Bataille et al., Phys. Rev. A 102, 013317 (2020)
[2] Comparin et al., Phys. Rev. Lett. 129, 113201 (2022)

Yvan Castin
LKB, Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris

Higgs excitation branch in a pair-condensed Fermi gas / Branche d'excitation de Higgs dans un gaz de fermions condensé par paires

The pair-condensed unpolarized spin 1/2 Fermi gases exhibit a collective excitation branch in their broken pair continuum (V.A. Andrianov, V.N. Popov, 1976), sometimes called the Higgs branch. We carried out an in-depth study of it at zero temperature [1]. We start from the eigenenergy equation deduced from the linearized time-dependent BCS theory, which is equivalent to Anderson's RPA, then we carry out its analytical continuation to the lower complex half-plane through its cut line, which is essential to find the collective mode. We compute both the complex dispersion relation and the spectral weights (quasiparticle residues) of the branch.

In the case of so-called BCS superconductors (with charged fermions) where the effect of the crystal lattice is replaced by a short range attractive interaction, but where the Coulomb interaction is taken into account, we restrict ourselves to the limit of weak coupling $\Delta/\mu \to 0+$ (Δ is the order parameter, μ the chemical potential) and wavenumbers $q=O(1/\xi)$ where ξ is the size of a Cooper pair; when the complex energy z_q is expressed in units of Δ and q in units of $1/\xi$, the branch follows a universal law that we determine, insensitive to the Coulomb interaction.

In the case of cold atoms in the BEC-BCS crossover, the fermions are neutral and only a contact interaction remains, but the coupling Δ/μ can take arbitrary values, and we study the branch at any wave number q. (i) In weak coupling, we predict three scales, the one already mentioned $q \approx 1/\xi$, the one $q \approx (\Delta/\mu)$^{−1/3}/ξ where the real part of the dispersion relation admits a minimum and that $q \approx (\mu/\Delta)/\xi \approx k_F$ (k_F is the Fermi wavenumber) where the branch reaches the edge of its domain of existence. (ii) Near the point of chemical potential cancellation on the BCS side, $\mu/\Delta \to 0+$, where $\xi \approx k$F, we find the two scales $q \approx (\mu/\Delta)1/2/\xi$

and $q \approx 1/\xi$. In any case, the branch has a limit of 2Δ and a quadratic start at $q=0$, in accordance with what is expected of a Higgs branch, and should be observable at low q in the response of the gas to a laser Bragg excitation, if one measures the disturbance induced on the modulus of the order parameter rather than on the density [2]. (iii) On the BEC side ($\mu<0$), we also find a Higgs branch of this type (searched in vain by T. Cea, C. Castellani, G. Seibold, L. Benfatto, 2015) but only for $\Delta/|\mu|<0.222$; it should be noted that, in this case, the starting point 2Δ of the branch is strictly below the edge of the broken pair continuum $2(\Delta^2+\mu^2)^{1/2}$, unlike what happens on the side $\mu>0$ (where the edge of the continuum is exactly 2Δ in BCS theory).

Les gaz de fermions de spin 1/2 non polarisés condensés par paires présentent une branche d'excitation collective dans leur continuum de paire brisée (V.A. Andrianov, V.N. Popov, 1976), appelée parfois branche de Higgs. Nous en avons effectué une étude poussée à température nulle [1]. Nous partons de l'équation aux énergies propres déduite de la théorie BCS dépendant du temps linéarisée, ce qui équivaut à la RPA d'Anderson, puis nous en effectuons le prolongement analytique au demi-plan complexe inférieur à travers sa ligne de coupure, ce qui est indispensable pour trouver le mode collectif. Nous calculons à la fois la relation de dispersion complexe et les poids spectraux (résidus de quasi-particule) de la branche.

Dans le cas des supraconducteurs (à fermions chargés) dits BCS où l'effet du réseau cristallin est remplacé par une interaction attractive à courte portée, mais où l'interaction de Coulomb est prise en compte, nous nous restreignons à la limite de couplage faible $\Delta/\mu \to 0^+$ (Δ est la paramètre d'ordre, μ le potentiel chimique) et aux nombres d'onde $q=O(1/\xi)$ où ξ est la taille d'une paire de Cooper; quand l'énergie complexe z_q est exprimée en unités de Δ et q en unités de $1/\xi$, la branche suit une loi universelle que nous déterminons, insensible à l'interaction de Coulomb. Dans le cas des atomes froids dans le croisement CBE-BCS, les fermions sont neutres et il ne reste qu'une interaction de contact mais le couplage Δ/μpeut prendre des valeurs arbitraires, et nous étudions la branche à tout nombre d'onde q. (i) En couplage faible, nous prédisons trois échelles, celle déjà mentionnée $q \approx 1/\xi$, celle $q \approx (\Delta/\mu)^{-1/3}/\xi$ où la partie réelle de la relation de dispersion admet un minimum et celle $q \approx (\mu/\Delta)/\xi \approx k_F$ (k_F est le nombre d'onde de Fermi) où la branche atteint le bord de son domaine d'existence. (ii) Près du point d'annulation du potentiel chimique du côté BCS, $\mu/\Delta \to 0+$, où $\xi \approx k_F$, nous trouvons les deux échelles $q \approx (\mu/\Delta)^{1/2}/\xi$ et $q \approx 1/\xi$. Dans tous les cas,la branche est de limite 2Δ et de départ quadratique en $q=0$, en accord avec ce que l'on attend d'une branche de Higgs, et devrait être observable à faible \$q\$ dans la réponse du gaz à une excitation de Bragg par laser, si l'on mesure la perturbation induite sur le module du paramètre d'ordre plutôt que sur la densité [2]. (iii) Du côté CBE ($\mu<0$), nous trouvons aussi une branche de Higgs de ce type (cherchée en vain par T. Cea, C. Castellani, G. Seibold, L. Benfatto, 2015) mais seulement pour $\Delta/|\mu|<0{,}222$; il est à noter que, dans ce cas, le point de départ 2Δ de la branche est strictement en dessous du bord du continuum de paire brisée $2(\Delta^2+\mu^2)^{1/2}$, au contraire de ce qui se passe du côté $\mu>0$ (où le bord du continuum vaut exactement \$2\Delta\$ dans la théorie BCS).

[1] Y. Castin, H. Kurkjian, *Branche d'excitation collective du continuum dans les gaz defermions condensés par paires : étude analytique et lois d'échelle/Collective excitation branch of the continuum in pair-condensed Fermi gases: analytical study and scaling laws*, Comptes Rendus Physique 21, 253 (2020).

[2] Y. Castin, *Spectroscopie de Bragg et mode du continuum de paire brisée dans un gaz defermions superfluide/Bragg spectroscopy and broken pair continuum mode in a superfluid Fermi gas*, Comptes Rendus Physique 21, 203 (2020).

Gabriel Wlazłowski

Faculty of Physics, Warsaw University of Technology

Towards general-purpose simulation platform for superfluid fermions

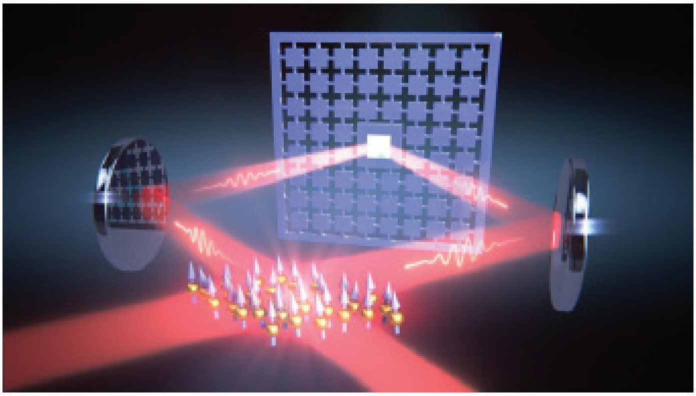
Numerical simulations are an important ingredient of modern research. In the field of Bose-Einstein condensates, the Gross–Pitaevskii equation (GPE) is a workhorse that facilitates the interpretation of experimental data for various setups. The counterpart of GPE for superfluid fermions are mean-field Bogoliubov-de Gennes (BdG) equations. Formally, their applicability is limited to weak couplings, while the experiments typically operate for strong couplings (around the unitary limit). The density functional theory (DFT) can be a remedy for this disparity. It is a versatile method describing with very good accuracy the static, dynamic, and thermodynamic properties of many-body Fermi systems in a unified framework, while keeping the numerical cost at the same level as the mean-field approach. I will summarize developments of the DFT dedicated to ultracold atomic gases across BCS-BEC crossover, together with its open-source numerical implementation (W-SLDA Toolkit). Selected applications of the method to various experimental setups will be presented.

8th Session – Thursday 16:00-17:00

Philipp Treutlein
University of Basel

Coupling quantum systems with a laser loop

Many of the breakthroughs in quantum science and technology rely on engineering strong Hamiltonian interactions between quantum systems. Typically, strong coupling relies on short-range forces or on placing the systems in high-quality electromagnetic resonators, which restricts the range of the coupling to short distances. In this talk I will show how a loop of laser light can generate Hamiltonian coupling over a distance [1] and report experiments using this approach to strongly couple a nanomechanical membrane oscillator and an ultracold atomic spin ensemble across one meter in a room-temperature environment [2]. We observe spin-membrane normal mode splitting, coherent energy exchange oscillations, two-mode thermal noise squeezing, and dissipative coupling with exceptional points [2]. We furthermore realize an optical coherent feedback loop and use it for cooling of the membrane vibrations [3,4]. Our experiments demonstrate the versatility and flexibility of light-mediated interactions, a powerful tool for quantum science that offers many further possibilities and is readily applicable to a variety of different systems.



A loop of laser light couples the vibrations of a nanomechanical membrane to the spin of a cloud of ultracold atoms

[1] T.M. Karg, B. Gouraud, P. Treutlein and K. Hammerer *Remote Hamiltonian interactions mediated by light*, Phys. Rev. A 99, 063829 (2019).

[2] T. M. Karg, B. Gouraud, C.T. Ngai, G.-L. Schmid, K. Hammerer and P. Treutlein *Light-mediated strong coupling between a mechanical oscillator and atomic spins one meter apart*, Science 369, 174 (2020).

[3] G.-L. Schmid, C.T. Ngai, M. Ernzer, M. Bosch Aguilera, T.M. Karg and P. Treutlein *Coherent feedback cooling of a nanomechanical membrane with atomic spins,* Phys. Rev. X 12, 011020(2022).

[4] M. Ernzer, M. Bosch Aguilera, M. Brunelli, G.-L. Schmid, T.M. Karg, C. Bruder, P.P. Potts and P. Treutlein *Optical coherent feedback control of a mechanical oscillator,* Phys. Rev. X(2023), accepted for publication, arXiv:2210.07674

Alice Sinatra

Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris

Quantum-enhanced multiparameter estimation and compressed sensing of a field

We show that a significant quantum gain corresponding to squeezed or over-squeezed spin states can be obtained in multiparameter estimation by measuring the Hadamard coefficients of a 1D or 2D signal. The physical platform we consider consists of two-level atoms in an optical lattice in a squeezed-Mott configuration, or more generally by correlated spins distributed in spatially separated modes. Our protocol requires the possibility to locally flip the spins, but relies on collective measurements. We give examples of applications to scalar or vector field mapping and compressed sensing.

9th Session – Friday 9:00-10:30

Hélène Perrin
CNRS and Univ. Sorbonne Paris Nord

Melting of a vortex lattice in a fast rotating Bose gas

Weakly interacting quantum gases offer a very convenient platform for the study of superfluid dynamics. One of the many intringuing properties of superfluids is their behavior in the presence of an imposed rotation. At zero temperature, the ground state of the rotating gas supports a triangular vortex lattice, the vortex density being set by the rotation frequency. As temperature increases, however, the triangular lattice is expected to be gradually destroyed, by displacement of the vortex centers and eventually strong phase fluctuations. In my talk, I will present our experimental observations as we rotate a rubidium quantum gas in a very smooth oblate potential. We observe the progressive melting of the vortex lattice at large rotation frequency and finite temperature. We compare our findings to theoretical predictions by Gifford and Baym.

Anna Minguzzi
Laboratoire de Physique et Modélisation des Milieux Condensés (LPMMC)

Exact solutions for strongly interacting quantum gases in one dimension

Strongly repulsive Bose and Fermi gases under external confining potential are amenable to exact solutions by generalized Girardeau mappings. We have used those solutions to understand the equilibrium and dynamical properties of bosons, fermions and mixtures. I will specifically focus on the spectral function for lattice bosons and on the spin-mixing dynamics of two-component Fermi gases in harmonic traps.

Gediminas Juzeliūnas
Institute of Theoretical Physics and Astronomy, Vilnius University

Sub-wavelength lattices for ultracold atoms

Traditionally, optical lattices are created by interfering two or more light beams, so that atoms are trapped at minima or maxima of the emerging interference pattern depending on the sign of the atomic polarizability [1]. The characteristic distances over which such lattice potentials change are limited by diffraction and thus cannot be smaller than half of the optical wavelength λ. The diffraction limitation can be overcome and subwavelength lattices can be created using coherent coupling between atomic internal states [2-9]. In particular, recent experiments demonstrated deeply subwavelength lattices using atoms with N internal states Raman-coupled with lasers of wavelength λ [7]. The resulting unit cell was N times smaller compared to the usual λ/2 periodicity of an optical lattice.

In the present talk we will discuss various ways to produce subwavelength lattices and effects manifesting in these lattices. In particular, we will present our recent work on periodically driven subwavelength lattices [8], as well on two-dimensional subwavelength lattices affected by the synthetic magnetic flux [9]. Ongoing research on many-body effects in subwavelength lattices will also be mentioned.

[1] I. Bloch, Nature Physics 1, 23 (2005).
[2] M. Łącki et al., Phys. Rev. Lett. 117, 233001 (2016).
[3] F. Jendrzejewski et al., Phys. Rev. A 94, 063422 (2016).
[4] Y. Wang et al, Phys. Rev. Lett. 120, 083601 (2018).
[5] E. Gvozdiovas, P. Račkauskas, G. Juzeliūnas, SciPost Phys. 11, 100 (2021).
[6] P. Kubala, J. Zakrzewski and M. Łącki, Phys. Rev. A 104, 053312 (2021).
[7] R.P. Anderson et al, Physical Review Research 2, 013149 (2020).
[8] D. Burba, M. Račiūnas, I.B. Spielman and G. Juzeliūnas, Phys. Rev. A 107, 023309 (2023).

10th Session – Friday 11:00-12:30

Bruno Laburthe-Tolra
CNRS – Paris 13 University

Many-body out-of-equilibrium physics with large spin atoms

Our experimental projects at the Laser Physics Institute (North Paris University) aim at characterizing entanglement for many-body systems made of large spin atoms. In the talk, I will describe the advances on our chromium experiment. Using this experiment, we have investigated the spin dynamics and quantum thermalization of a macroscopic ensemble of S = 3 spins initially prepared in a pure coherent spin state. The experiment uses an unit-filled array of 10 thousand atoms in a three dimensional optical lattice. Atoms interact at long distance under the effect of magnetic dipole-dipole interactions, realizing the spin-3 XXZ Heisenberg model with long-range couplings. We have investigated the build-up of quantum correlations in this many-body system. For this, we measured collective properties such as the total population in the seven different Zeeman states, or the collective spin length. We found that the measurement of magnetization fluctuations provides direct quantitative estimates for two-body correlations. We furthermore performed bi-partite measurements making use of a super-lattice to independently measure even and odd lattice sites. This allowed to demonstrate that atom-atom correlations in our many-body interacting system are anisotropic. I will finally discuss advances on how to control magnetic field fluctuations, and possibilities to demonstrate entanglement.

Dmitry Petrov
Université Paris-Saclay, CNRS, LPTMS

Self-binding of one-dimensional fermionic mixtures with zero-range interspecies attraction

For sufficiently large mass ratios the attractive exchange force caused by a single light atom interacting with a few heavy identical fermions can overcome their Fermi degeneracy pressure and bind them into an $N + 1$ cluster. Using the few-body approach based on the Skorniakov and Ter-Martirosian equation, we determine the energies and the critical mass ratios for the emergence of the tetramer, pentamer, and hexamer. For large N, we solve the problem analytically by using the mean-field theory based on the Thomas-Fermi approximation. The system becomes bound when the heavy-to-light mass ratio exceeds a critical value, which grows as N^3 at large N. Then, by using a mean-field approach valid for large N, we find that $N + 1$ clusters can attract each other and form a self-bound charge density wave, the properties of which we fully characterize.

Piotr Deuar
Institute of Physics Polish Academy of Sciences

Thermal properties of squashed quantum droplets

I will report on some preliminary results on Bose-Bose droplets at significantly nonzero temperature. We have studied the thermal states and approach to thermal equilibrium of quantum Bose-Bose droplets in squashed 2d and 1d geometries with the help of an appropriately modified classical field (SGPE – stochastic Gross-Pitaewvskii equation) method. We find a critical temperature below which droplets can coexist with a thermal background, and find a scaling behaviour of the *droplet fraction* with droplet density and temperature. It also appears that there are several distinct thermal phases in evidence depending on the parameter regime.

11th Session – Friday 14:00-15:30

Jacob Reichel
Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris

Observing Spin-Squeezed States under Spin-Exchange Collisions for a Second

Marcin Płodzień
ICFO – The Institute of Photonic Sciences

Generation, storage, and validation of metrologically useful many-body entangled states in the analog and digital quantum simulators in the NISQ era

Because of challenges in fault-tolerant quantum computing, the main goal for quantum technologies in the next decade is to generate, characterize, and validate massively correlated quantum states. Non-classical correlations, namely entanglement and Bell correlations, are fundamental properties of the quantum many-body systems and crucial resources for emerging quantum technologies. To fully exploit many-body Bell correlations, we need an experimental protocol to generate such quantum states and a method for classifying the depth of many-body Bell correlations. This talk will discuss our recently proposed protocols for generating and classifying metrologically useful many-body entangled and many-body Bell correlated states in the quantum simulators based on the ultra-cold quantum gases in the optical lattices. Next, we will discuss perspectives of using hybrid quantum-classical machine learning techniques to generate such many-body Bell correlated states on the parametrized quantum circuits in the Noisy Intermediate-Scale Quantum devices.

Felix Werner
Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris

Three-body contact for fermions

We consider the resonant Fermi gas, that is, spin 1/2 fermions in three dimensions interacting by a two-body short-range potential of large scattering length a2. A key quantity is the two-body contact C2, which determines numerous observables, such as the number of nearby fermion pairs, the tail of the single-particle momentum distribution, or the derivative of the energy with respect to a2 [1]; furthermore, the two-body loss rate is given by C2 times the imaginary part of 1/a2 [2]. We introduce the three-body contact C3, which determines the number of nearby fermion triplets, the large-momentum tail of the center-of-mass momentum distribution of nearby fermion pairs, and the correction to the zero-range model's energy coming from the finite range of the two-body interaction and/or an additional three-body interaction; furthermore, the three-body loss rate is given by C3 times the imaginary part of a3. Here, a3 is defined by the subleading asymptotic behavior of the zero-energy three-body scattering state at distances intermediate between the interaction range and |a2| [3].

We then compute C3 to leading order in the non-degenerate limit for the homogeneous gas, using a wavefunction approach at $a2 = \infty$, and a diagrammatic approach at $a2 < 0$. In the Feynman diagram technique, the anomalous power-law behavior of three-body correlations at short distance emerges — after cancellation between two-body correlations due to fermionic antisymmetry — from a non-trivial algebraic decay of the three-body propagator at large momenta [4].

[1] S. Tan, Ann. Phys. 323, 2952 (2008); ibid. 323, 2971 (2008)
[2] E. Braaten and L. Platter, Phys. Rev. Lett. 100, 205301 (2008)
[3] F. Werner and X. Leyronas, arXiv:2211.09765
[4] X. Leyronas and F. Werner, in preparation

12th Session – Friday 16:00-17:00

Isabelle Bouchoule
Laboratoire Charles-Fabry

Relaxation of phonons in 1D Bose gases by dynamical refermionization

Giuliano Orso
University Paris Diderot – Paris 7

Phase-space methods for atom-cavity systems

We report recent numerical results on the steady state properties of weakly interacting bosons coupled to an optical cavity, obtained by extensive simulations of phase-space trajectories. The different phase transitions are investigated within the finite-size scaling procedure, and the associated critical points are estimated.

Posters

Poster Session Thursday 17:00-18:30

1. Krzysztof Gawryluk, University in Białystok
Mechanism for sound dissipation in a two-dimensional degenerate Fermi gas

2. Tanausú Hernández Yanes, Institute of Physics Polish Academy of Sciences
Spin squeezingin open Heisenberg spin chains

3. Jakub Kopyciński, Center for Theoretical Physics Polish Academy of Sciences
Ultrawidedark solitons in Bose gases with competing interactions

4. Maciej Bartłomiej Kruk, Institute of Physics Polish Academy of Sciences
BEC Fluctuations Using Fock State Sampling Method

5. Maciej Lewkowicz, University in Białystok
Supersolidity of dipolar Bose-Einstein condensates induced by coupling to fermions

6. Maciej Marciniak, Center for Theoretical Physics Polish Academy of Sciences

7. Youssef Trifa, ENS de Lyon
Scalable squeezing generation in large-S dipolar spin Hamiltonian

8. Buğra Tüzemen, Center for Theoretical Physics PAS

9. Piotr Grochowski, University of Innsbruck / IQOQI Innsbruck
Encoding logical qubits inmotional degrees of freedom

10. Marek Tylutki, Faculty of Physics, Warsaw University of Technology
TBA