ICFO - IMPRS joint workshop 2025

9 - 11 April 2025

ICFO

IMPRS for Quantum Science and Technology
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

MCQST

We are happy to present the final program of the **ICFO-IMPRS Joint Workshop 2025**, marking the **fourth edition** of this collaborative event between our two institutions.

The workshop brings together talented and motivated PhD students working across a broad range of topics in quantum science and technology, with the goal of fostering scientific exchange and strengthening connections between our communities.

In this booklet, you will find detailed information about the activities taking place throughout the workshop. The scientific program includes **nine talks by invited speakers**, offering diverse insights into the latest developments, opportunities, and emerging directions in quantum technologies. Each talk will last approximately 50 minutes, followed by a 10-minute Q&A session. Coffee breaks in between will offer informal spaces for participants to interact and exchange ideas with the speakers and fellow attendees.

In addition, participants will present their research during a **Poster Session**, **and several Short Talk Sessions**. These session offers a valuable opportunity for attendees to explore current work being done within the ICFO and IMPRS communities, and to engage directly with the authors.

The Short Talk Sessions are organized thematically, and each talk will last around 12 minutes, followed by a 3-minute Q&A, allowing students to share their work in a concise, focused format.

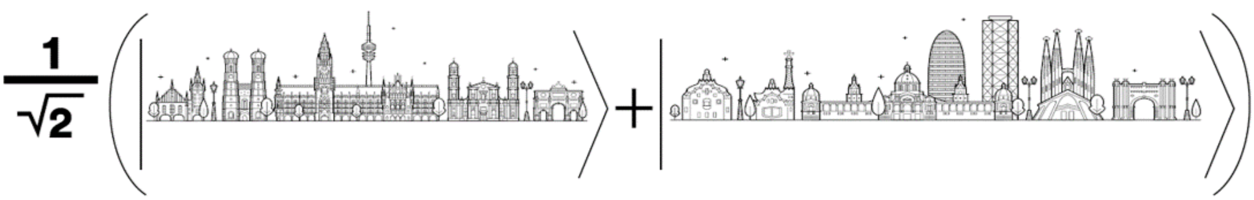
During the first two days, participants will have the chance to join a **hands-on workshop** aimed at providing tools and insights into how cutting-edge technologies can be translated into real-world applications and commercial ventures. This is complemented by an **Industry Session**, featuring a talk from Qilimanjaro Quantum Tech.

Beyond the scientific agenda, a variety of social activities are planned to help participants connect in a relaxed and friendly atmosphere. This year's workshop will also include a **Buddy System** to promote exchange between institutions: each ICFO student is paired with buddies from relevant research groups at IMPRS.

We hope you find the workshop engaging and inspiring, and we're looking forward to seeing everyone in person very soon!

Organizing committee:

Johannes Arceri (IMPRS), Amine Ben Mhenni (IMPRS), Teresa Karanikolaou (ICFO), Harini Raghavan (ICFO), Panagiotis Tselifis (ICFO), Bennet Windt (IMPRS)



Workshop program

April 09th - 11th

Max Planck Institute of Quantum Optics

PROGRAM	WEDNESDAY	THURSDAY	FRIDAY
9:00	Registration	Talk | Prof. Hugues de Riedmatten	Talk | Prof. Darrick Chang
9:20	Opening remarks		
9:30	Talk | Prof. Barbara Kraus		Talk | Prof. Ulrich Schollwöck
10:00		Talk | Dr. Robin Camphausen	
10:30	Talk | Prof. Johannes Knolle		
11:00		Coffee break	Coffee break
11:30	Coffee break	Short talks session A&B	Short talks session A&B
12:00	Short talks session A&B		
12:30		Lunch break	Lunch break
13:00	Lunch break		
14:00		Talk | Prof. Tomasz Smoleński	Talk | Porf. Monika Aidelsburger
14:30	IdeaLab workshop I		
15:00		Coffee break	Talk | Dr. Jad Halimeh
15:30	Coffee break	Industry talk | David Eslava	
16:00	Poster session		Closing remarks
16:30		IdeaLab workshop II	Buddy time | Lab- and Group tours
18:30	Group activities		
20:00		Conference dinner	

Herbert Walther Lecture Hall

09:30 - 10:30

Barbara Kraus (TUM) - *Quantum algorithm for cooling: a simple case study*

We derive a cooling algorithm, which can be utilized for state preparation. We analyse its properties and show that in various scenarios the cooling algorithm outperforms the dissipative state preparation method.

10:30 - 11:30

Johannes Knolle (TUM) - *The Enigmatic Dirac Quantum Spin Liquid*

Quantum fluctuations can inhibit long-range ordering in frustrated magnets and potentially lead to quantum spin liquid (QSL) phases. A prime example is the gapless Dirac quantum spin liquid (DSL) with an emergent U(1) gauge field, which can be described at low energies in terms of emergent quantum electrodynamics in 2+1 dimension (QED3). Despite the availability of several promising triangular lattice candidate materials and recent advances in numerical methods the description of their dynamical response is an outstanding challenge. In this talk, I will first introduce the enigmatic Dirac QSL and show how to obtain QED3 from a spin 1/2 model on the triangular lattice. Second, I will explain our recent theory for the dynamical spin structure factor of the triangular lattice J1-J2 Heisenberg model. We not only find good agreement between recent experiments and rigorous numerics but argue that our theory is a powerful tool for understanding the response of other types of QSLs and their instabilities.

Herbert Walther Lecture Hall

09:00 - 10:00

Hugues de Riedmatten (ICFO) - *Towards quantum repeaters with solid-state quantum nodes*

The distribution of entanglement between the nodes of a quantum network will allow new advances e.g. in long distance quantum communication, distributed quantum computing and quantum sensing. On the ground, quantum information can be distributed across the nodes using single photons at telecommunication wavelengths traveling in optical fibers. To bridge distances much longer than the fiber attenuation length, quantum repeaters can be used. The nodes of a quantum repeater are matter systems that should efficiently interact with quantum light, allow entanglement with photons at telecommunication wavelengths and serve as a quantum memory allowing long-lived and faithful storage of (entangled) quantum bits. In addition, for efficient distribution of entanglement, the nodes should allow multiplexed operation and ideally enable quantum processing capabilities between stored qubits.

In this talk, I will introduce the concept of quantum repeater and why it is extremely challenging to realize. I will then describe our recent progress towards the realization of quantum repeater nodes with multiplexed ensemble-based quantum memories, using cryogenically cooled rare-earth ion doped solids. I will show how solid-state quantum memories can be entangled with telecom photons using non-degenerate photon pair sources and describe an experiment where this entanglement is distributed over 50 km of fiber in the Barcelona installed fiber network. I will then present our efforts to develop multiplexed quantum memories, in particular the realization of an array of temporally multiplexed quantum memories. Finally, I will then describe our efforts to scale up quantum repeater links. In particular, I will report an experiment demonstrating entanglement between remote multiplexed on-demand solid-state quantum memories, heralded by a telecom photon.

10:00 - 11:00

Robin Camphausen (ICFO) - *Quantum-safe communication for space and fibre*

Current cryptographic protocols employed to safeguard digital data rely on computational hardness assumptions, which may be broken by a sufficiently powerful quantum computer, or potential future classical algorithms. In contrast, the use of quantum resources enables cryptography with provable information-theoretic security, leading to so-called quantum-secure communication. This talk will give an overview of recent advances in the Optoelectronics group at ICFO, in the field of quantum-secure optical communication both for space-based and terrestrial communication networks. Satellite-based quantum communication represents a promising approach for long-distance quantum-secure links, since optical propagation loss in the vacuum of space is essentially zero. Implementation requires the development of components for free-space communication, as well as demanding space qualification to survive exposure to hostile space environments. At ICFO we are deploying a free-space quantum communication testbed, with ~20km of optical path through turbulent atmosphere, in order to simulate aspects of satellite quantum links. We are also developing equipment to be used in space-based quantum communication missions. Fibre-based terrestrial quantum communication, in contrast, can take advantage of substantial already existing classical communication infrastructure. Here, I will show our group's developments towards integrated and field-deployable devices.

14:00 - 15:00

Tomasz Smolénski (University of Basel) - *Optical control of correlated magnetism in moiré materials*

Understanding and controlling strongly correlated many-body spin systems is one of the key challenges in modern condensed matter physics. Among the most promising experimental platforms for these explorations are semiconducting moiré materials (SMMs), which consist of two twisted or lattice-mismatched transition metal dichalcogenide (TMD) monolayers. Owing to their spin-valley-selective optical selection rules and the possibility of incorporating them into charge-tunable devices, SMMs uniquely enable direct optical access to the spin degree of freedom of correlated electrons, whose density can be controlled in-situ using transparent graphene gates. In this talk, I will review our recent ultra-low-temperature magneto-optical investigations of collective electronic magnetism in two different types of SMMs. In the first part, I will focus on angle-aligned, AA-stacked MoSe2/WS2 heterobilayers, where the large detuning between conduction band edges suppresses interlayer hybridization, making this system a realization of an extended Fermi-Hubbard model. Due to the strong, triangular moiré superlattice potential, the electrons forming a Mott insulating state around the unity filling factor in this structure are deeply localized within their moiré lattice sites, rendering their exchange interactions to be vanishingly small. However, as soon as the Mott state is doped with electrons forming doublons, the system begins to exhibit prominent ferromagnetic correlations that are driven by the minimization of doublon kinetic energy via the Nagaoka mechanism [1]. This observation provides direct evidence for this unusual kinetic ferromagnetism in an extended system. In the second part, I will discuss twisted AA-stacked MoTe2 homobilayers, where strong interlayer hybridization of hole orbitals gives rise to flat topological valence bands that support robust ferromagnetic metals as well as fractional and integer Chern insulators at various moiré lattice filling factors [2-5]. I will present our recent results demonstrating that the spin state of these topological many-body magnetic phases can be tuned with light, paving the way for ultrafast control over the topological order parameter.

[1] L. Ciorciaro, T. Smoleński* et al., Nature 623, 509 – 513 (2023).*
[2] J. Cai et al., Nature 622, 63 – 68 (2023).
[3] Y. Zeng et al., Nature 622, 69 – 73 (2023).
[4] H. Park et al., Nature 622, 74 – 79 (2023).
[5] E. Anderson, (…), T. Smoleński, et al., Nature 635, 590 – 595 (2024).

Herbert Walther Lecture Hall

09:00 - 10:00

Darrick Chang (ICFO) - *Emergent phenomena in atom arrays interacting with light*

One of the most exciting directions associated with the rapid advance of quantum science and technologies is the possibility to utilize synthetic quantum systems to realize and explore strongly correlated quantum phenomena. Generally, however, this regime remains challenging to access with quantum atom-light interfaces for two reasons. First, such systems still suffer from significant dissipation, particularly at the level of individual quanta, in the form of spontaneous emission of light into unwanted directions. Second, there is a prevailing strategy to reduce the effects of dissipation, by encoding phenomena within the collective optical response of many atoms, which improves atom-light interaction efficiencies. Unfortunately, this same collective response typically results in collective spin or mean-field descriptions of the physics, which is incompatible with most known strongly correlated phenomena in physics. Within this context, atom arrays with sub-wavelength lattice constant constitute an exciting opportunity to break beyond these boundaries. In these systems, wave interference effects in light emission are strongly enhanced, resulting in highly correlated dissipation. This gives rise to the phenomenon of subradiance, where certain classes of states are highly protected from emission, and which provides a potential mechanism to evade mean-field behavior. Here, we describe our ongoing efforts to identify and understand paradigms by which strongly correlated and emergent phenomena might arise from the natural resources of long-range interactions and collective dissipation in quantum optical arrays. We will focus on two examples, involving the realization of quantum spin liquids in Rydberg atom arrays interfaced with high-finesse cavities, and "evaporative cooling" of many-body spin systems using arrays of atoms coupled to free-space modes.

10:00 - 11:00

Ulrich Schollwöck (LMU) – *Complex time and real materials*

The simulation of correlated real materials remains one of the big challenges of solid-state physics, in particular due to the fact that the physical behaviour is often determined by energy scales which are extremely small compared to the raw scales of the substances. In this talk I will discuss how extending time evolution into the complex plane alleviates entanglement issues to an extent that we may calculate precise Green’s functions, self-energies and spectral functions at very low frequencies (of the order of 0.001 of bandwidth), which is the scale that has to be resolved to understand correlated metals in a realistic setting.

14:00 - 15:00

Monika Aidelsburger (MPQ & LMU) - *Engineering quantum many-body systems atom by atom*

The computational resources required to describe the full state of a quantum many-body system scale exponentially with the number of constituents. This severely limits our ability to explore and understand the fascinating phenomena of quantum systems. Quantum simulation offers a potential route to overcome these limitations. The idea is to build a well-controlled quantum system in the lab, which represents the problem of interest and whose properties can be studied by performing controlled measurements. In this talk I will introduce quantum simulators based on neutral atoms. Recent advances in experimental techniques have led to system sizes and coherence times that challenge even the most powerful classical numerical algorithms. I will also present novel experimental techniques and observables that provide unprecedented insights into the properties of quantum many-body systems, covering topics from topology to fundamental questions regarding the thermalization of isolated quantum systems.

15:00 - 14:00

Jad Halimeh (MPQ & LMU) - *Quantum simulation of far-from-equilibrium dynamics of gauge theories*

I will go over our recent research, which bridges quantum many-body physics and quantum simulation through two main pillars. The first focuses on investigating exotic far-from-equilibrium phenomena in lattice gauge theories, uncovering properties of dynamical phase transitions and criticality. The second aims to develop experimentally feasible schemes to probe such dynamics on state-of-the-art quantum hardware, including cold atoms and molecules, superconducting qubits, and trapped ions. We will go over a series of experiments highlighting the interplay between these two pillars.

B0.32 Lecture Hall

12:00 - 12:15

Teresa Dimitra Karanikolau (ICFO) - *Decoherence in Rydberg-EIT*

Rydberg EIT platforms are particularly interesting for quantum nonlinear optics because they combine the non-dissipative and ideally lossless propagation of photons under EIT with the strong non-linearities induced by the Rydberg interaction. In its simplest form, a single photon propagating under EIT conditions experiences a perfectly transparent atomic medium. However, the presence of an atom excited to a Rydberg state (which can physically arise due to a previous photon stored as a Rydberg spin wave or a second photon co-propagating in the same pulse) can destroy the transparency of the atoms within some "blockade radius," causing scattering of one photon and the inevitable decoherence of the Rydberg spin wave, due to the entanglement between where the photon was scattered and the position of the Rydberg atom. Previously, this decoherence process has been studied within the Maxwell-Bloch model, where scattering from atoms is assumed to occur independently. Our aim is to investigate the validity of this model, by comparing against a full microscopic model where wave interference and multiple scattering are exactly accounted for. As the nature of decoherence impacts applications ranging from photon-photon gates to effective many-body models for strongly interacting photons, it would be interesting to identify any strong deviations from M-B models.

12:15 - 12:30

Ignacio Pérez (ICFO) - *Engineering tunable synthetic fluxes with Raman-coupled Bose mixtures in an accordion optical lattice*

We report on our progress towards an interacting many-body realization of the Harper-Hofstadter model. This model describes charged particles in a lattice subjected to a magnetic field and predicts exotic phases, such as lattice analogues of fractional quantum Hall states, in the presence of interactions. Previous implementations of such strongly interacting systems with neutral cold atoms have been limited to systems with only a few particles. Our experiment features a Raman-coupled bosonic spin mixture loaded into a one-dimensional optical lattice. This configuration forms an effective two-dimensional lattice, where the spin states act as a synthetic dimension. This enables the realization of a ladder system, providing a minimal instance of the Harper-Hofstadter model. The Raman coupling introduces complex tunnelling amplitudes, generating a synthetic magnetic flux through the ladder. A key feature of our system is the interplay between two competing length scales: the lattice spacing and the wavelength associated with the Raman recoil momentum. We present experimental results using optical lattices with tuneable lattice spacing, allowing us to engineer ladder systems threaded by arbitrary synthetic fluxes. The system's spectrum is probed using spin-injection techniques, providing insights into the properties of synthetic flux ladders.

12:30 - 12:45

Lukas Wangler (ICFO) - *Challenging the traditional understanding of cavity QED with many atoms.*

Harnessing the interaction between atoms and an optical cavity to generate long-range interactions is a well-established paradigm of quantum optics. An atom can emit a photon into a cavity mode, which is far detuned from atomic resonance, and subsequently the photon gets absorbed by another atom. This process gives rise to effective atom-atom interactions. The atoms also interact with the modes of the free-space electromagnetic field. Conventionally, interactions with free-space modes are modeled by introducing a spontaneous emission rate for each atom. However, a closer analysis reveals, that the free-space modes also mediate effective interactions between the atoms. We demonstrate that for a large number of atoms, these free-space mediated interactions can dominate over the cavity-mediated interactions and thus challenge the traditional understanding of cavity QED. To explore this, we quantitively study the influence of free-space interactions on the example of cavity-based spin squeezing schemes.

12:45 - 13:00

Amine Ben Mhenni (IMPRS)- *Gate-tunable Bose-Fermi mixture in a strongly correlated moiré bilayer electron system*

Quantum gases consisting of species with distinct quantum statistics, such as Bose-Fermi mixtures, can behave in a fundamentally different way than their unmixed constituents. This makes them an essential platform for studying emergent quantum many-body phenomena such as mediated interactions and unconventional pairing. Here, we realize an equilibrium Bose-Fermi mixture in a bilayer electron system implemented in a WS2/WSe2 moiré heterobilayer with strong Coulomb coupling to a nearby moiré-free WSe2 monolayer. Absent the fermionic component, the underlying bosonic phase manifests as a dipolar excitonic insulator. By injecting excess charges into it, we show that the bosonic phase forms a stable mixture with added electrons but abruptly collapses upon hole doping. We develop a microscopic model to explain the unusual asymmetric stability with respect to electron and hole doping. By studying the Bose-Fermi mixture via monitoring excitonic resonances from both layers, we demonstrate gate-tunability over a wide range in the boson/fermion density phase space, in excellent agreement with theoretical calculations. Our results further the understanding of phases stabilized in moiré bilayer electron systems and demonstrate their potential for exploring the exotic properties of equilibrium Bose-Fermi mixtures.

Herbert Walther Lecture Hall

12:00 – 12:15

Albert Rico (UAB) - *Dimensional advantage in quantum communication*

The benefits of quantum communication over classical communication can be seen in terms of enhanced security and the scalability of the carrier system. In this talk, we will focus on the latter: we present a communication protocol between Alice and Bob where correlated events occur with zero probability, while anticorrelated events occur with maximal probability. We will demonstrate that this protocol can be realized using a quantum system of operational dimension d, whereas a classical implementation would require at least dimension 2d. This research is hybrid in nature: the classical dimension is established through polynomial optimization, while the quantum dimension is determined by an explicit setup that is currently under experimental preparation. Additionally, we will discuss our observations on the protocol's robustness against noise.

12:15 – 12:30

Anubhav Kumar Srivastava (ICFO) – *Topological quantum thermometry*

An optimal local quantum thermometer [1] has a particular energy level structure with a single ground state and highly degenerated excited states manifold, with an energy gap proportional to the estimated temperature. We show [2] that such a spectrum can be engineered in a system of spinless fermions confined in a one-dimensional optical lattice described by the experimentally realizable topological Rice-Mele model at specific lattice fillings, resulting in a close-to-optimal sensitivity of the system to the temperature changes. We characterize the system's sensitivity to temperature changes in terms of quantum Fisher information. We also study the thermalisation dynamics of the proposed topological thermometer coupled with another quantum many-body system.

[1] Correa, Luis A., et al. "Individual quantum probes for optimal thermometry." Physical review letters 114.22 (2015): 220405.
[2] Srivastava, Anubhav Kumar, et al. "Topological quantum thermometry." arXiv preprint arXiv:2311.14524 (2023).

12:30 – 12:45

Marc Langer (Walter Schottky Institute) - *Optimal matchgate circuits for fermionic Gaussian states*

Fermionic Gaussian states (FGS), and the related matchgates, play an important role in the study of various phenomena. Despite being able to represent highly entangled states, they are still tractable on classical computers. A naturally arising question is how to optimally create such states, for instance when using matchgate circuits acting on product states. In this work, we present an algorithm for explicitly constructing such circuits that provably yields the minimal number of gates. Our techniques furthermore allow us to characterize which states can be represented exactly with a low depth matchgate circuit. We finally highlight some potential applications of these results, including approximate state preparation, disentangling algorithms and classical simulation methods.

Short talks *Session A* Thursday 10th

B0.32 Lecture Hall

11:30 - 11:45

Guillem Müller-Rigat (ICFO) - *Testing the Hilbert's space dimension of many-body quantum states*

We formalise a Bell dimension witness tailored to systems of arbitrary size. We demonstrate how metrological resources, in the form of spin-nematic squeezed states as produced in Bose Einstein condensates, optimally violate said witness. Our results motivate unprecedented Bell experiments to test dimensional-constrained correlations in the many-body regime. Work with A. Aloy, M. Fadel, M. Lewenstein and J. Tura.

11:45 - 12:00

Isabel Nha Minh Le (IMPRS) - *Employing tensor networks and Riemannian quantum circuit optimization for fermionic Hamiltonian simulation*

Simulating fermionic systems is relevant for many fields like quantum chemistry or condensed matter physics. Trotterization is a simple and common tool to approximate the time evolution on a quantum computer. However, accurate simulations for long times are restricted by the resulting deep quantum circuits. The goal of this work is to increase accuracy under constant depth, utilizing only classical resources before employing any quantum device for simulation. We start from a fermionic swap network that implements a Trotter step using a brickwall circuit layout. To further increase the accuracy of the initial circuit, Riemannian optimization is employed to optimize the two-qubit gates under unitary constraints. The reference time evolution operator can efficiently be expressed as a matrix product operator for short enough times t. By interpreting the quantum circuit as a tensor network, a suitably chosen cost function and the corresponding gradient can be evaluated using tensor network methods. Executing the optimized circuit repetitively on a quantum device enables simulation times t^'≫t. We apply our method to molecular Hamiltonians and the 1D Fermi-Hubbard for 60 spin orbitals and t=0.3.

12:00 - 12:15 **Benjamin Schiffer (IMPRS)** - *Experimental realization of a Shortcut to Adiabaticity in a Neutral Atom Quantum Computer*

TBA

12:15 - 12:30 **Juliette Tudoce (ICFO)** - *Exploring the Interface of Sound Reverberation and Quantum Behaviors*

This research investigates the interplay between quantum optics theory and the theoretical properties of sound resonance, with a focus on their potential applications in artistic creation. By examining wave-particle duality in cavities and quantum interference patterns, the study seeks to establish a theoretical framework linking quantum behaviors to sound reverberation in controlled environments. The goals are threefold: (i) to bridge quantum interference and reverberation theoretically, (ii) to elucidate the real-world behavior of sound reverberation using insights from quantum interference patterns, and (iii) to develop simulations of quantum-inspired sound reverberation for integration into artistic processes. This work aspires to create novel avenues for collaboration between quantum science and the arts, offering both theoretical advancements and practical tools for creative expression.

Short talks *Session B* Thursday 10th

Herbert Walther Lecture Hall

11:30 – 11:45 **Harini Raghavan (ICFO)-** *Functionalized mm-scale vapor cells for alkali-metal magnetometry*

Miniaturized high sensitivity optically pumped magnetometers (require simultaneously small volumes, temperature control, magnetic field control, and low magnetic noise. This presents interlinked challenges when designing vapor cells for OPMs. We report a dual chamber 4 x 4 x

1.5 mm^3 low noise functionalized vapor cell (and its use in a single beam OPM). The FVC, made at wafer scale by MEMS techniques, incorporates surface metallization for both heating and thermal monitoring, while also maintaining a low thermal magnetic noise. We discuss also the zero field operation of the OPM, in which we observe a magnetic sensitivity of about 18 fT /√Hz. This FVC design is a step toward mass producible OPMs for applications in sectors including medical imaging, space and geophysical.

11:45 – 12:00 **Panagiotis Tselifis (ICFO)-** *Selective heating of atoms in subwavelength array coupled to an optical nanofiber*

Neutral atoms trapped in a 1D lattice surrounding an optical nanofiber constitute an established platform for researching atom-light interactions. Although the number of trapped atoms is large (N>1000), such lattices suffer from imperfect filling, due to collisional blockade. An interesting regime would be to achieve near perfect filling. In that case, strong interference enables "selective radiance," wherein scattering losses of light into free space are suppressed, leading to vastly improved efficiencies in applications and new fundamental phenomena. Here, we explore the possibility of "selectively heating" single atoms, while keeping longer atomic chains (N~10) intact, by exploiting collective resonances and linewidths of the latter. Our study pushes our current understanding of the physics of trapped atoms in deep subwavelength lattices, as it relies on the interplay of collective internal and external atomic degrees of freedom, beyond the laser heating and cooling theory for single atoms.

12:00 – 12:15 **Daniel Molpeceres (IMPRS)** **-** *Numerical optimizations for cooling algorithms*

In this talk, I will do a brief recap on the basic notions of cooling algorithms, and focus on how the interplay between system and bath can be exploited. More specifically, I will focus on the cooling of a free-fermion model, and how numerical optimization of the free parameters in the algorithm can lead to greatly enhanced cooling power, even in the presence of noise.

12:15 – 12:30 **Philipp Stammer (ICFO) -** *On the photon number and energy conserving subspaces in non-linear quantum optics*

TBA

B0.32 Lecture Hall

11:45 - 12:00

Antariksha Das - *Cavity-Enhanced On-Demand Solid-State Quantum Memory*

Long-lived and efficient photonic quantum memories are key constituents of quantum repeaters for long-distance quantum communications. Rare earth ion-doped crystals are arguably ideal candidates for building such optical quantum memories as they offer excellent coherence properties, long storage times, and high multiplexing capabilities. However, the storage efficiency tends to decay with longer storage times, limiting their utility for practical implementations. Here, we present a cavity-enhanced on-demand atomic frequency comb (AFC) spin-wave quantum memory using a Pr3+: Y2SiO5 crystal embedded in an impedance-matched cavity. We achieve a device efficiency of 40 % for weak coherent pulses and explore the impact of the impedance-matched cavity on noise levels. Additionally, we investigate the quantum memory performance for different bandwidths and control pulse power.

12:00 - 12:15

Javier Jordán Parra (i2CAT) - *Quantum Satellite research line and activities developed at i2CAT*

The Quantum Satellite research line and activities performed at i2CAT will be presented. Will contain briefing of topics, activities and results done about: A#1. QKD satellite modelling, design and evaluation A#2. QKD System based on LEO Satellite - PERTE aeroespacial A#3. Novel architecture and protocols for Quantum Networks: Quantum RINA A#4. Satellite Quantum Networks A#5. Deploy 6G Quantum Cryptography Laboratory

12:15 - 12:30

Alexander Ulanowski - *Optically addressable spins in erbium-doped materials*

Optically addressable spins are emerging as a promising platform for distributed quantum information processing. Among these, erbium dopants stand out due to their telecom transition, which is compatible with fiber-optic transmission, and their favorable optical and spin coherence properties. In our experiments, we use high-Q optical resonators which allow us to resolve single spins in several host crystals. In YSO, a well-established material for rare-earth dopants, we demonstrate coherent control of more than 360 individual dopants in a Fabry-Perot cavity, a high-fidelity optical single-shot readout and a hyperfine coherence time exceeding 0.2 seconds. Erbium-implanted silicon, a relatively novel material platform, also exhibits promising optical and spin properties. In a nano-photonic resonator, we achieve a readout fidelity of 87(1) % and a spin coherence time up to 48(2) µs, exceeding the Purcell-enhanced optical lifetime of 1 µs. Furthermore, the coupling of the erbium electron spin to nearby nuclear spins may enable additional qubit registers with long-coherence times. Being fully compatible with nano-photonic devices, our approach paves the way to scalable, long-range quantum networks.

Short talks *Session B* Friday 11th

Herbert Walther Lecture Hall

11:45 – 12:00

Pavel Popov (ICFO) - *Non-perturbative signatures of fractons in the twisted multi-flavor Schwinger model*

Gauge-field configurations with non-trivial topology have profound consequences for the physics of Abelian and non-Abelian gauge theories. Over time, arguments have been gathering for the existence of gauge-field configurations with fractional topological charge, called fractons. Ground-state properties of gauge theories can drastically change in presence of fractons in the path integral. However, understanding the origin of such fractons is usually restricted to semi-classical argumentation. Here, we show that fractons persist in strongly correlated many-body systems, using the multiflavor Schwinger model of quantum electrodynamics as a paradigm example. Through detailed numerical tensor-network analysis, we find strong fracton signatures even in highly discretized lattice models, at sizes that are implementable on already existing quantum-simulation devices. Our work sheds light on how the non-trivial topology of gauge theories persists in challenging non-perturbative regimes, and it shows a path forward to probing it in table-top experiments.

12:00 – 12:15 **Claudio Iacovelli (ICFO)-** *Encoding a topological gauge theory on an ring-shaped Bose gas*

Topological gauge theories constitute a framework for understanding strongly-correlated quantum matter in terms of non-interacting, composite degrees of freedom. We propose a scheme to realize a one-dimensional topological gauge theory, the chiral BF theory, on a ring geometry. This realization can be achieved with an optically-dressed Bose gas in a ring-shaped trap. In this system, the topological properties of the underlying chiral BF theory manifest through a magnetic flux variable which is density-dependent. The proposal enables to observe the interplay between the topology of the theory and that of the space.

12:15 -12:30 **Lucia Valor Menéndez (IMPRS)-** Cavity QED models of non-Abelian gauge theories

Lattice gauge theories constitute an important tool in studying the fundamental interactions of matter within particle physics and have a wide range of applications in condensed matter physics and quantum information theory. While classical numerical methods can be used to simulate many properties of Abelian and non-Abelian gauge theories efficiently, the intrinsic quantum nature of these theories makes other relevant physical phenomena hard to reproduce. Quantum simulators offer a promising approach to address these challenges, with successful simulations of Abelian theories in different quantum platforms demonstrating their potential in the last decades. Despite these advances, quantum simulation of non-Abelian theories remains challenging. Recent research efforts aimed at the analog simulation of these gauge theories have predominantly focused on atomic quantum platforms like ultracold atoms and trapped ions. Here, we propose a minimal model for a SU(2) lattice gauge theory, implementable as an analog simulation on superconducting quantum hardware. We study properties of the system and explore its experimental implementation. Our work contributes to the exploration and understanding of non-Abelian gauge theories and offers a new and rich implementation to study lattice gauge theories using superconducting qubits.

B0.32 Lecture Hall

Giulia Sionis (ICFO)

Towards Quantum Processing Nodes with Single Rare-Earth ions in nanoparticles

In the current effort to develop Quantum Networks, a promising candidate for light-matter interfaces are rare-earth ions, for their remarkable optical and spin coherence properties, suitable energy structures and lifetimes, and controllable dipole-dipole interactions. Doped into inorganic crystals, they become a highly versatile platform, as they can function at once as single photon sources, quantum memories and quantum processing nodes allowing quantum gates between qubits. In this experiment, we employ Pr3+:Y2O3 and Er3+:Y2O3 nanoparticles embedded in a high-finesse fiber-based microcavity as a candidate for a quantum network node. Nanoparticles allow for high ion densities to enable strong dipolar interactions between individual ions while preserving spectral distinguishability, enabling individual addressing via their inhomogeneous broadening. However, the same long lifetimes that ensure excellent coherence also result in weak spontaneous emission. This drawback is overcome through the Purcell effect by integrating the ions into an open-access fiber Fabry–Perot microcavity, which enhances emission rates, restores photon indistinguishability, and allows dynamic control over cavity resonance. We explore both Pr and Er ions, since the option of having two ion species in the same platform could offer many advantages. Pr ions provide in principle stronger interactions that can be leveraged for quantum processing, while the Er ions' transition at telecom frequencies is very useful for quantum communication purposes. In this poster, we will present the system and describe our current experimental efforts towards the realization of quantum nodes with single rare-earth ions, including the generation of single photons with tunable waveform. Prior results of the project are the dynamic control of the Purcell enhancement of a small ensemble of Er ions emission and the detection of a single Er ion (Casabone et al. 2021, Deshmukh 2022, Deshmukh et al. 2023).

Lena Schumacher (ICFO)

Quantum Satellite research line and activities deveoped at i2CAT

We present an experimental setup, in which we want to combine cavity-enhanced efficient single-photon generation with deterministic atom-photon entanglement generation to realize a quantum repeater protocol using atomic Rydberg ensembles.

Atomic Rydberg-blockaded ensembles allow the realization of efficient quantum memories, single-photon sources or the creation of entanglement between light and atomic excitations, which shows their versatile capabilities in the field of quantum communication. Recently, we have used a Rydberg ensemble to generate single photons from the collective Rydberg excitation with an efficiency of up to 15% per trial [1]. We also demonstrated single photon filtering for non-classical light, using the strong non-linearity of such a system [2]. Motivated by theoretical proposals about Rydberg ensemble-based quantum repeaters [3, 4], we went one step further and rebuilt the complete experimental setup to obtain a state-of-the-art quantum network node. Raman cooling will be employed to cool the fully blockaded Rydberg ensemble to a temperature of ~1µK and thus improve the systems coherence time. A new vacuum system with ultralow reflection coatings allows to effectively enhance the clouds optical depth by placing it inside of an external triangular cavity with Finesse 140, boosting the efficiency of the single photon generation significantly. We will deterministically create time-bin entanglement between the ensemble and single photons, similarly to what has been reported in [5]. For this, we will use a partial excitation of two different Rydberg states to create a superposition of two collective Rydberg excitations. Repeatedly applying a readout and re-excitation pulse sequence will either create an early or late photon, which is entangled with the corresponding Rydberg state. In our poster, we will present the new experimental setup, discuss our motivation and share recent data. This project will establish atomic Rydberg ensembles as 'stand-alone' quantum network nodes and further advance the field of quantum communication. [1] L. Heller, J. Lowinski, K. Theophilo, A. Padron-Brito, and H. de Riedmatten," Raman Storage of

[1] Quasideterministic Single Photons Generated by Rydberg Collective Excitations in a Low-Noise Quantum Memory", Phys. Rev. Applied 18, 024036 (2022).
[2] J. Lowinski, L. Heller, F. Hoffet, A. Padron-Brito, K. Theophilo, and H. de Riedmatten," Strongly Nonlinear
Interaction between Nonclassical Light and a Blockaded Rydberg Atomic Ensemble", Phys. Rev. Lett. 132,
053001 (2024).
[3] Y. Han, B. He, K. Heshami, C. Li, and C. Simon," Quantum repeaters based on Rydberg-blockade-coupled
Atomic ensembles", Phys. Rev. A 81, 052311 (2010).
[4] B. Zhao, M. Mueller, K. Hammerer, and P. Zoller," Efficient quantum repeater based on deterministic
Rydberg gates", Phys. Rev. A 81, 052329 (2010).
[5] P. Sun, Y. Yu, Z. An, J. Li, C. Yang, X. Bao, and J. Pan," Deterministic Time-Bin Entanglement between a
Single Photon and an Atomic Ensemble", Phys. Rev. Lett. 128, 060502 (2022).

Joe Wragg (ICFO)

Action Spectroscopy for Tracking State-Specific Energy Transfer in 2D Semiconductors

While it's long been accepted that the role of momentum dark excitons in the photoresponse of transition metal dichalcogenides (TMD's) is critical, their weak optical signature inhibits their study through conventional means. Here we expose the room temperature contributions of both bright and dark excitons to the behaviour of a TMD, WSe2, from monolayer to multilayer to bulk. To do so, we present dual action spectroscopy, a photocurrent and luminescence detected Fourier-transform excitation spectroscopy scheme to microscopically map the energy landscape of WSe2. While bright excitons naturally dominate the luminescence response of the material, dark excitons dominate the current response. Notably, the dark KK' exciton is more accessible than the ground state KΛ, while current maps reveal a disparity in the diffusivity of the two states. This work provides the basis for a new current-detected approach to study the dynamics of dark exciton states across different materials.

Nuria Rego Falagán (ICFO)

Towards hybrid entanglement between a solid-state quantum memory and an atomic ensemble

This research is part of a long-term project to achieve hybrid entanglement between disparate quantum systems: a cold atomic ensemble and a rare-earth ion-doped crystal. This is a key step towards building hybrid quantum networks, essential for the realization of the future quantum internet. We implement the DLCZ protocol to generate photon pairs creating light-matter entanglement, with one of these photons converted to the telecom C-band via difference frequency generation in a periodically poled lithium niobate (PPLN) waveguide. This converted photon will interfere with a photon generated via spontaneous parametric down-conversion (SPDC) by the solid-state system, requiring active frequency stabilization to ensure photon indistinguishability. Currently, we focus on optimizing photon generation and improving the efficiency of the quantum frequency conversion process to improve the overall system performance. The experimental setup and latest experimental progress will be presented in the poster.

Damiano Aliverti (IMPRS)

Are single electrons subsystems?

Entanglement is a fascinating feature of the quantum world and serves as a key resource for quantum information processing. While its foundation is well-established in the context of distinguishable particles, the concept of entanglement for identical particles is still subject to misconceptions and controversial views. To settle this issue, we first clarify that identical particles do not define proper

subsystems: the algebra of observables of single particles cannot be faithfully embedded into the one of the total systems, resulting in a violation of the axioms defining subsystems. Accordingly, no notion of entanglement and more general types of correlation between identical particles exists that is genuine, i.e., valid independent of the underlying quantum state. Yet, there exist specific non-generic wave functions which allow one to label the identical particles through disjoint spatial regions or generally orbital subspaces.

Alberto Cavallar (IMPRS)

Towards finite energy quantum simulation of the 2D Fermi-Hubbard model

TBA

Ludvik Cigna (IMPRS)

On the Theory and Functionality of Local Disentangling Algorithms

Controlling entanglement is pivotal for the advancement of quantum technologies. In this context, disentangling algorithms have attracted significant attention due to their potential to address challenges in quantum state preparation, compression, complexity estimation, and quantum control. In our work, we introduce a unified and mathematically rigorous framework for disentangling based on local measurements, which is particularly suitable for current NISQ devices. This framework provides a generalization to multi-qubit disentangling and offers practical speed-ups compared to previous heuristic approaches, building on a recent solution to the relaxed quantum marginal problem. We further analyze the convergence behavior and the evolving structure of states during the algorithm, starting from Haar-random states.

Denise Cocchiarella (IMPRS)

Low-Temperature Thermal States via Tensor Networks

We introduce a tensor network method for approximating thermal equilibrium states of quantum many-body systems at low temperatures. In contrast to standard (thermofield double matrix product state) algorithms, our ansatz is constructed from the zero-temperature limit, the ground state, which can be simply found with a standard tensor network approach. This method allows us to efficiently compute thermodynamic quantities and entanglement properties. We demonstrate our approach within a tree tensor network ansatz, although it can be extended to other tensor networks, and present results illustrating its effectiveness in capturing the finite-temperature properties in the 1D and 2D scenario.

Marianna Crupi (IMPRS)

Realistic error model for efficient noise characterization

Current quantum devices are known to be affected by a different variety of errors, therefore finding an efficient protocol to extract the most complete and accurate characterisation of those errors is crucial for the future development of quantum technologies. Existent methods for efficient process tomography, such as randomized benchmarking or shadow tomography, can only efficiently compute specific quantities of the process, leaving out other potentially relevant ones.

To resolve this issue, we propose a model for noise tomography for which the complete characterisation of the process is efficient by construction. Under the assumption that the errors in the device are well represented by our model, our protocol is efficient in time and sample complexity and exhibits a scaling of O(n). Our model is device and noise model independent and can be readily applied to characterise correlated and coherent errors in 2D architectures of current quantum computers. We support our theoretical findings with numerical experiments and simulations.

Aaron Schäpers (IMPRS)

Novel approaches for laser stabilization

Ultra-stable lasers are at the heart of scientific endeavors in both applied and fundamental physics. Their frequency precision is an essential requisite for high-fidelity operations in optically controlled qubits, makes them a key component of optical atomic clocks [Ludlow 2015] and allows to test the theoretical foundations of physics. To increase a laser's natural frequency stability for high-precision experiments, it is actively stabilized to an external frequency reference. The state of the art in this field is attained with Fabry-Pérot cavities under optimized laboratory conditions [Matei 2017], implying extensive control of external parameters like temperature, pressure, and vibrations. However, many applications require ultra-stable lasers outside of laboratory conditions, e.g., field-employable quantum network nodes, transportable atomic clocks, and space-based tests of fundamental physics. In this context, we will explore two new types of frequency references for laser stabilization that are compatible with field conditions. The first approach uses a resonator formed by two Bragg grating mirrors in an optical fiber. A proof-of-concept experiment of our group [Merkel 2021] revealed a promisingly low sensitivity of the resonance frequency to vibrations as well as temperature and pressure variations, but the limits of this technique are yet to be tested. The second frequency reference to be explored are erbium-doped ring resonators in silicon chips. Their frequency sensitivity to resonator length fluctuations can be dramatically improved when the group velocity of light is reduced by spectral hole burning in the inhomogeneous absorption line of the dopants [Horvath 2022], making this platform an interesting candidate for highly compact and stable frequency references. [Horvath 2022]: S. Horvath et al., „Slow light frequency reference cavities—proof of concept for reducing the frequency sensitivity due to length fluctuations“, New J. Phys. 24 033034 [Ludlow 2015]: D. Ludlow et al., „Optical atomic clocks”, Rev. Mod. Phys. 87, 637 [Matei 2017]: D. G. Matei et al., „1.5 µm Lasers with Sub-10 mHz Linewidth“, Phys. Rev. Lett. 118, 263202 [Merkel 2021]: B. Merkel et al., „Laser stabilization to a cryogenic fiber ring resonator," Opt. Lett. 46, 444-447

Josef Willsher (IMPRS)

Dynamics of the U(1) Dirac spin liquid

TBA

Kaidi Xu (IMPRS)

Quantum simulation of Z2 lattice gauge theory

Quantum simulation of lattice gauge theory is an intriguing playground for studying non-equilibrium many-body dynamics and its implications in high-energy physics. We will demonstrate the implementation of a 1+1D and 2+1D Z2 LGT theory with mass-resonance term on a quantum processor. The exotic dynamics that weakly break the ergodicity are studied by both classical and quantum simulation. The error mitigation schemes and the robustness of local gauge symmetry against different noise channels will also be discussed.

Johannes Arceri (IMPRS)

Interplay of topology and disorder in driven honeycomb lattices

One of the most fascinating properties of topological phases of matter is their robustness to disorder [1]. While various methods have been developed to probe the geometric properties of Bloch bands with ultracold atoms [2], most fail in the presence of disorder due to their reliance on translational invariance. Here, we demonstrate that topological edge modes can be employed to detect a disorder-induced phase transition between distinct topological phases in a Floquet-engineered two-dimensional optical honeycomb lattice.

[1] J. Zheng, et al., Floquet top. phase transitions, Phys. Rev. B (2024)
[2] N. R. Cooper, J. Dalibard, and I. B. Spielman, Topological bands, Rev. Mod. Phys. (2019)

Jona Nägerl (DAMTP Cambridge University)

Applications of Complex-valued Networks for dense associative memory networks

Complex-valued associative memory networks have been explored as models for storing and retrieving patterns based on similarity under partial or noisy conditions. Building on this foundation, we investigate systems of coupled oscillators based on the Stuart-Landau model, leveraging their phase and amplitude dynamics to represent and retrieve memory states. This approach explores modifications of the model for potential enhancements in robustness and capacity.

Industry Session & Workshop

Herbert Walther & B0.32 Lecture Hall

Dr David Eslava

Quilimanjaro

Qilimanjaro is a quantum computing company developing full-stack solutions with a strong focus on coherence and near-term usability. Our approach combines algorithm development with hardware design, with a particular bet on fluxonium qubits—promising a path to longer coherence times and more scalable architectures.
Our vision is to enable useful quantum computing by focusing on analog and hybrid quantum systems tailored to real-world applications. We work closely with research and industry partners to bridge the gap between experimental platforms and practical deployments.
A key milestone is the deployment of a quantum computer based on superconducting qubits at the Barcelona Supercomputing Center (BSC)—a unique integration of quantum hardware into an HPC environment, opening the door to hybrid quantum-classical workflows.
In this session, we'll present Qilimanjaro's technological roadmap, our work with fluxonium qubits, and how we're building towards practical quantum advantage through coherent, application-driven systems.

IdeaLab Workshop

Have you ever wondered how your research could benefit society beyond the academic realm? This workshop will provide you with the tools to explore the commercial potential of cutting-edge technologies.

Join a team and dive headfirst into the exciting world of technology transfer:

- Analyse Real-World Technologies: Delve into the practical applications of innovative technologies.
- Develop a Business Perspective: Learn to identify the market opportunities.
- Present your Findings: Practice communicating your solution and its benefits.

Whether you're a seasoned researcher or just starting your scientific journey, this workshop is your chance to gain valuable insights into the world of technology transfer.

Workshop Venue April 9th- April 11th

Max Planck Institute of Quantum Optics

Max Planck Institute of Quantum Optics
Hans-Kopfermann-Straße 1, 85748 Garching

Workshop Dinner April 10th

Max Emmanuel Brauerei

To round off the second day, we warmly invite all participants to join us for the Workshop Dinner on April 10th at:

Max Emanuel Brauerei
Adalbertstraße 33, 80799 Munich

https://max-emanuel.de/

We will leave together at **7:15 PM from Garching Forschungszentrum subway station**, heading directly to the restaurant via public transport. If you prefer to make your own way there, feel free to join us directly at the venue.

It will be a great opportunity to unwind, continue conversations from the day, and enjoy some traditional Bavarian food and drinks in good company!

Motel One

Motel One Munich Parkstadt Schwabing

Anni-Albers-Straße 10, 80807 Munich

Double or room with breakfast included

From airport to the hotel

You can take the **Lufthansa Express Bus** (https://www.airportbus-muenchen.de/en) from **Munich Airport** to **Schwabing/Nordfriedhof**, then walk **10 min** to the hotel (**~40 min total**, 12€ for a single ticket)

Alternatively, take the **S8 S-Bahn** (direction **Herrsching**) to **Johanneskirchen**, switch to **Bus 50** to **Gertrud-Grunow-Straße**, and walk **10 minutes** (**~1 hour total**, 14,30€ for a single ticket M-5 covering 5 zones)

Sharing a taxi or Uber might also be an option, if people arrive at the airport in groups (~20 min & 80€ in total)

From the hotel to the workshop venue

From the hotel to the venue (Max Planck Institute of Quantum Optics): Walk **10 min** to **Nordfriedhof** U-Bahn station, take the **U6** to **Garching Forschungszentrum**, then walk another **10 min** to MPQ (**~35 min total**)

B&B Hotel

B&B Hotel München-Garching

Daimlerstraße 3, 85748 Garching bei München

Single room with breakfast included

From airport to the hotel

From the airport to the hotel with public transport take the **S8 S-Bahn** (direction **Herrsching)** to **Ismaning**. At Ismaning, transfer to **Bus X202** to **Garching-Hochbrück**. The hotel is a short walk from there (~30 min total, 10,20€ for a day ticket M-3 covering 3 zones)

From the hotel to the workshop venue

A taxi or Uber will take ~15 min and cost approx. 50-60€

From the B&B hotel to the workshop venue (MPQ), travel from Garching-Hochbrück to Garching Forschungszentrum wih the U6 subway, which is ~5 min and costs 2€ for a short ride (2 stops= Kurzstrecke)