Center for Astrophysics | Harvard & Smithsonian
ITAMP
60 Garden Street
Cambridge, MA 02138 USA

Institute for Theoretical Atomic Molecular and Optical Physics

A Symposium on Science @ ITAMP

May 16 - 17, 2024

Phillips Auditorium
60 Garden St. Cambridge MA 02138

itamp.harvard.edu

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Contents

Notes

A Note!

Dear Friends:

ITAMP is 35 years old. These have been transformative years for the AMO physics, ushering in not only a renaissance in the field, but also tremendously exciting directions and new opportunities. ITAMP began life as a theoretical center to promote the interest of and facilitate research and training in the broadly-defined areas of AMO physics. It remains true to this mission.

ITAMP has hosted more than 150 workshops, topical groups and symposia, and Winter Graduate Schools in AMO Physics, over this period. Scholars from nearly all sub-disciplines of AMO physics have visited ITAMP; as invited speakers, as short- and long-term scholarly visitors, as participants to its workshops, as fellows, and as students. It is a truly international center for theoretical AMO sciences.

Indulging in celebration and retrospection is a healthy endeavor when planning for the future. This “reunion” is a timely and fresh step in this direction. We will gather to celebrate its fellows, and their impact on the AMO sciences over the last 35 years.

Welcome.

For everyone at ITAMP,
Hossein Sadeghpour

Science @ ITAMP

Schedule

Thursday May 16, 2024

• Welcome	8:30-9:00 AM	Phillips Auditorium
• Science Sessions	9:00-5:30 PM	Phillips Auditorium
• Working Lunch	12:00-2:00 PM	Library
• Poster Session	5:45 PM	Library

Friday, May 17, 2024

• Science Sessions	9:00-5:00PM	Phillips Auditorum
• Working Lunch	12:00-2:00 PM	Library
• Dinner	6:30 PM	Harvard Faculty Club

Bihui Zhu

University of Oklahome

"Exploring quantum correlations in nonequilibrium many-body systems"

Quantum correlations among many particles underlie numerous intriguing properties of quantum systems and serve as a resource for advancing quantum-enhanced technologies. Characterizing and controlling quantum correlations are thus important for the applications of near-term quantum devices. In this talk, I will discuss some recent work investigating quantum correlated phenomena in nonequilibrium settings relevant to several current quantum platforms. In the first part, I will present a way to probe the buildup of quantum spin correlations in a cold-atom ensemble with collective measurement. Next, I will discuss the cooperative behaviors of many spins undergoing strong dissipation and driving, as demonstrated in a recent cavity-QED experiment. Finally, I will show the generation of quantum entanglement in a nonunitary quantum circuit.

Nicole Yunger-Halpern

National Institute of Standards and Technology

"Non-Abelian thermodynamics"

Starting in undergraduate statistical mechanics, physicists study small systems that thermalize by exchanging quantities with large environments. The exchanged quantities —energy, particles, electric charge, etc.—are conserved globally, and the thermalization helps define time's arrow. If quantum, the quantities are represented by Hermitian operators. We often assume implicitly that the operators commute with each other—for instance, in derivations of the thermal state's form [1]. Yet operators' ability to not commute underlies quantum phenomena such as uncertainty principles and measurement disturbance. What happens if thermodynamic conserved quantities fail to commute with each other? This question, mostly overlooked for decades, came to light recently at the intersection of quantum information theory and thermodynamics [2]. Noncommutation of conserved thermodynamic quantities has been found to enhance entanglement [3], decrease entropy-production rates [4], alter the eigenstate thermalization hypothesis [5], and more. This growing subfield illustrates how 21st-century quantum information science is extending 19th-century thermodynamics.

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[3] Majidy, Lasek, Huse, and NYH, Phys. Rev. B 107 045102 (2023).
[4] Upadhyaya, Braasch, Landi, and NYH, arXiv:2305.15480 (2023).
[5] Murthy, Babakhani, Iniguez, Srednicki, and NYH, Phys. Rev. Lett. 130, 140402 (2023).

Thursday, May 16, 2024

8:30 AM Registration/Refreshments

Session I: Thomas Pohl
9:00 AM Ana-Maria Rey
9:30 AM Annabelle Bohrdt
10:00 AM Break

Session II: Bob Forrey
10:30 AM Nicole Yunger-Halpern
11:00 AM Igor Pikovski
11:30 AM Swati Singh

12:00 PM Working Lunch

Session III: Jake Taylor
2:00 PM Hannes Pichler
2:30 PM Valentin Walther
3:00 PM Break

Session IV: Paola Cappellaro
3:30 PM Chris Laumann
4:00 PM Simos Mistakidis
4:30 PM Colloquium: Misha Lukin

5:45 PM Poster Session

Friday, May 17, 2024
8:30 AM Registration/Refreshments

Session V: Jim Babb
9:00 AM Michael Knap
9:30 AM Richard Schmidt

10:00 AM	Break
Session VI: Phillip Stancil	
10:30 AM	Misha Lemeshko
11:00 AM	Timur Tscherbul
11:30 AM	Rivka Bekenstein
12:00 PM	Working Lunch
Session VII: Peter Rabl	
2:00 PM	Amichay Vardi
2:30 PM	Ceren Dag
3:00 PM	Break
Session VIII: Hossein Sadeghpour	
3:30 PM	Bihui Zhu
4:00 PM	Johannes Feist
4:30 PM	Vasilis Rokaj
6:30 PM	Reception/Dinner at Faculty (by Invitation only)

Valentin Walther

Purdue University

"Rydberg polaritons: from giant molecules to semiconductors"

The strong coupling of light and matter is marked by the formation of polaritons, establishing an efficient exchange of energy between photons and electronic excitations. In this presentation, we explore two complementary sides of the transition to the strong coupling regime.

The first part provides an overview of recent progress on giant diatomic molecules composed of two Rydberg atoms (Rydberg macrodimers), excited from an optical lattice. These molecules feature an intriguing binding mechanism mediated by van der Waals forces. We show how Rydberg macrodimers can be optically coupled to a continuum of free motional states, leading to the formation of multi-atom molecules bound by light.

In the second part, we delve into the world of Rydberg excitons, highly excited bound states of electrons and holes in semiconductors, showcasing their ability to induce significant optical nonlinearities in crystals. Ongoing efforts to push these nonlinearities to the ultimate quantum limit of single photons will also be discussed.

Amichay Vardi

Ben Gurion University

"Chaotic dynamics of coupled Bose-Josephson Junctions: Many-body tunneling and Prethermalization with negative specific heat"

Bosonic Josephson junctions (BJJ) can serve as building blocks for the study of fundamental physics. I will discuss two recent projects involving the chaotic dynamics of coupled BJJ. In the first study, chaos is utilized to stabilize macroscopic cat states and enable the observation of many-body collective tunneling. In the second, we demonstrate non canonical relaxation and a spectacular prethermalizaion effect far way from integrability.

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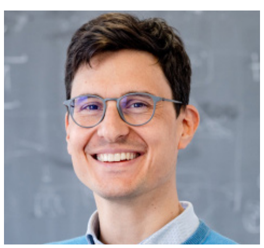

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"Quantum dynamics of ultracold molecules: Addressing the curse of dimensionality problem with quantum algorithms"

I will describe a general-purpose quantum algorithm for solving the time-independent quantum scattering problem on noisy intermediate-scale (NISQ) quantum computers. The algorithm [1] is based on the S-matrix version of the Kohn variational principle, in which the scattering S-matrix is obtained by inverting the Hamiltonian matrix using the variational quantum linear solver (VQLS). We apply the algorithm to single and multichannel quantum scattering problems and show how it can be scaled up to simulate the quantum collision dynamics of large polyatomic molecules, which are currently beyond the reach of classical algorithms.

References:

[1] X. Xing, A. Gomez Cadavid, A. F. Izmaylov, and T. V. Tscherbul, J. Phys. Chem. Lett. 14, 6224 (2023).

Swati Singh

University of Delaware

"Characterizing the quantum properties of ultralight dark matter- an open quantum systems approach"

Obtaining insight into the constituents of dark matter and their interactions with normal, i.e., Standard Model (SM) matter, has inspired a wide range of large and small-scale experimental efforts that harness current technology to look for the feeble interactions between SM matter and DM with unprecedented precision. Several novel experimental approaches involve quantum systems or measurements performed at the limits imposed by quantum mechanics. This is particularly relevant for the case of ultralight bosonic dark matter (UBDM), where dark matter is assumed to be a bosonic field/particle present in high oc- cupation numbers around the earth. While a classical treatment of UBDM and its detectors is well-motivated, future detection strategies would benefit from a quantum treatment of both the field and its interaction with a, perhaps, quantum detector. Here we apply the quantum theory of optical coherence to characterize the statistical properties of the UBDM field and an open quantum system approach to the interaction between the UBDM field and a detector. Our theoretical treatment has implications in uncovering the astrophysical history of the UBDM field, as well as informing quantum metrology-based strategies for its detection.

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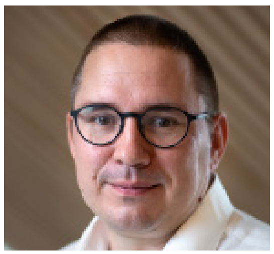

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Richard Schmidt
Heidelberg University

“From Bose-Fermi mixtures to an emerging BEC-BCS crossover in atomically thin semiconductors”

In this talk I will discuss how one can transfer physical concepts and mechanisms originally explored in the context of ultracold atoms to atomically thin materials. Specifically I will focus on our study of a new mechanism to induce superconductivity in atomically thin semiconductors where excitons mediate an effective attraction between electrons. Our model includes interaction effects beyond the paradigm of phonon-mediated superconductivity and connects to the well-established limits of Bose and Fermi polarons. By accounting for the strong-coupling physics of trions, we we show how polaron formation leads to an emerging BCS-BEC crossover in trilayer heterostructures of transition metal dichalcogenides. Even at strong-coupling the bipolarons remain relatively light, resulting in critical temperatures of up to 10\% of the Fermi temperature. This renders heterostructures of two-dimensional materials a promising candidate to realize superconductivity at high critical temperatures set by electron doping and trion binding energies.

Vasilis Rokaj

ITAMP

"Cavity Control of Quantum Matter"

Cavity control of quantum matter has emerged as a possibility to engineer novel phases and desirable material properties [1]. Experiments in cavity QED materials have demonstrated, for example, the breakdown of topological protection in the integer quantum Hall effect [2] and the modification of chemical reactions [3]. In the first part of this talk, I will focus on the quantum Hall effect coupled to a quantum cavity field [4]. Galilean invariance for a homogeneous quantum Hall system implies that the electronic center of mass (CM) decouples from the electron-electron interaction, and the energy of the CM mode, also known as Kohn mode, is equal to the single particle cyclotron transition. We show that strong light-matter hybridization between the Kohn mode and the cavity photons gives rise to collective hybrid modes between the Landau levels and the photons, known as Landau polaritons. We provide the exact solution for these hybrid modes and we demonstrate the weakening of topological protection at zero temperature due to the existence of the lower polariton mode which is softer than the Kohn mode. This provides an intrinsic mechanism for the recently observed topological breakdown of the quantum Hall effect in a cavity [2]. Importantly, our theory predicts the cavity suppression of the thermal activation gap in the quantum Hall transport and connections to recent experiments will be discussed [5]. Then, I will switch to collective phenomena in a system of ultracold ions in a harmonic trap coupled to a homogeneous cavity vacuum field. The cavity field mediates pairwise long-range interactions and enhances the effective mass of the particles. This leads to an enhancement of localization in the matter ground state density, which features a maximum when light and matter are on resonance, and demonstrates a collective behavior with the particle density. The light-matter interaction also modifies the photonic properties of the polariton system, as the ground state is populated with bunched photons. I will conclude by giving an outlook on how the bunched photons can be exploited to generate non-classical states of light through quench dynamics.

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[2] F. Appugliese, J. Enkner, G. L. Paravicini-Bagliani, M. Beck, C. Reichl, W. Wegscheider, G. Scalari, C. Ciuti, J. Faist, Science 375 (6584), 1030-1034 (2022)
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[4] V. Rokaj, J. Wang, J. Sous, M. Penz, M. Ruggenthaler, A. Rubio, Phys. Rev. Lett. 131, 196602 (2023)
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[6] V. Rokaj, S.I. Mistakidis, H. R. Sadeghpour, SciPost Phys. 14, 167 (2023)

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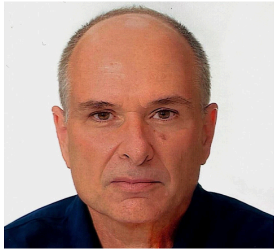

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Ana-Maria Rey

JILA, NIST and U. of Colorado at Boulder

"Observation of itinerant magnetism in polar molecules confined in optical lattices"

Dipolar interactions provide opportunities for the exploration of a wider range of many-body phenomena which remain difficult to manifest and probe in systems with just contact interactions. One such phenomenon falls under the general heading of itinerant quantum magnetism, where magnetic moments (spins) interact with one another with coupling strength J as they hop in a periodic potential at a rate t. Their dynamics is described by the so-called t-J model, a model originally emerging from the large interaction energy expansion of the Hubbard Model, which is believed to describe the fundamental physics behind high Temperature superconductors. In this talk I plan to report on the first realization of a generalized t-J spin model with dipolar interactions using a system of ultracold fermionic molecules with a spin-1/2 encoded in the two lowest rotational states. Our study paves the way for future exploration of itinerant quantum magnetism with the tunability of molecular platforms.

Igor Pikovski

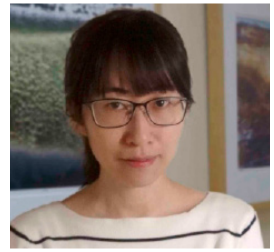
Stevens Institute of Technology

"Detecting single gravitons with quantum sensing"

In this talk I will outline a recent result from our group that demonstrates how signatures of single-graviton-exchange can be observed in laboratory experiments [1]. We show that for massive quantum acoustic resonators, absorption of single gravitons from background gravitational waves can be resolved through continuous quantum sensing of quantum jumps, and correlations to LIGO detections. Our results show that single graviton signatures are within reach of experiments. In analogy to the discovery of the photo-electric effect for photons, I will discuss how such signatures can provide the first experimental hints of the quantization of gravity.

References:

[1] G. Tobar, S. Manikandan, T. Beitel, I. Pikovski. "Detecting single gravitons with quantum sensing." Arxiv:2308.15440 (2023)



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"Probing long-range topological entanglement in quantum simulators"

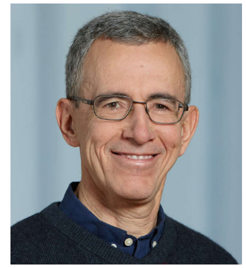
Quantum simulators offer new ways of preparing topologically ordered phases of matter. Probing the long-range entanglement structure associated with topological order is however challenging. Conventionally this is done via measurements of the entanglement entropy of subsystems. However, with standard approaches this is exponentially costly in subsystem size, such that the detection of topological entanglement across long distances becomes unfeasible. In this talk I propose a new protocol to overcome this challenge and extract universal long-range entanglement efficiently. I illustrate this scheme for various string-net models representing both abelian and non-abelian topologically ordered phases, and discuss how it could be implemented with neutral atom tweezer arrays.

Simos Mistakidis

Missouri University of Science and Technology

“Universality classes of strongly ferromagnetic spinor superfluids”

Scale invariance and self-similarity in physics provide a unified framework to classify phases of matter and dynamical properties of near- and far-from-equilibrium many-body systems. To address universality, we monitor the non equilibrium dynamics of a two-dimensional ferromagnetic spinor gas subjected to quenches of the quadratic Zeeman coefficient. This allows to dynamically cross the underlying second-order magnetic phase transitions triggering spin-mixing. Within the short time-evolution we observe the spontaneous nucleation of topological defects (gauge or spin vortices) which annihilate through their interaction giving rise to magnetic domains for longer timescales where the gas enters the universal coarsening regime. This is characterized by the spatiotemporal scaling of the spin correlation functions and structure factor allowing to measure corresponding scaling exponents which depend crucially on the symmetry of the order parameter and belong to distinct universality classes. Our experimental observations are in excellent agreement with the predictions of the truncated Wigner method accounting both for quantum and thermal fluctuations in the initial state. These results represent a paradigmatic example of categorizing far-from-equilibrium dynamics in quantum many-body systems and reveal the interplay of topological defects for the emergent universality class.



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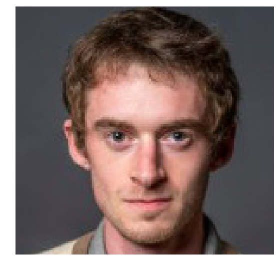

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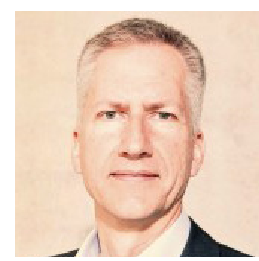

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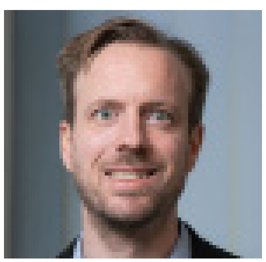

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Misha Lukin

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"Rydberg blockade and the new frontier of quantum information and computing"

We will discuss how the early work at the ITAMP in the 1990s and 2000s created a theoretical foundation for the recent exciting developments that redefined the cutting edge frontier of quantum information science and quantum computing. Several generations of ITAMP postdocs and visitors have made and are making major contributions to this frontier.

Misha Lemeshko

Institute of Science and Technology Austria

"Angular momentum of small molecules: quasiparticles and topology"

I will present our recent findings on small molecules kicked by laser pulses. First, I will describe a technique that allows to probe highly excited molecular states in the presence of an environment, such as superfluid 4He, and a corresponding theory based on angulon quasiparticles that is capable of describing such states, in good agreement with experiment.

Second, I will show how that even the simplest of existing molecules - closed-shell diatomics not interacting with one another - host topological charges when driven by periodic far-off-resonant laser pulses. A periodically kicked molecular rotor can be mapped onto a "crystalline" lattice in angular momentum space. This allows to define quasimomenta and the band structure in the Floquet representation, by analogy with the Bloch waves of solid-state physics. In such a momentum space we predict the occurrence of Dirac cones with topological charges, protected by reflection and time-reversal symmetry. These Dirac cones -- and the corresponding edge states -- are broadly tunable by adjusting the laser strength and can be observed in present-day experiments by measuring molecular alignment and populations of rotational levels. This paves the way to study controllable topological physics in gas-phase experiments with small molecules as well as to classify dynamical molecular states by their topological invariants.

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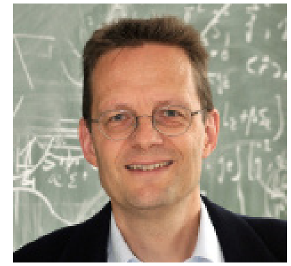

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Rivka Bekenstein

Hebrew University

“Experimental simulations of Post-Newtonian Schrodinger dynamics with optical nonlocal nonlinearities“

We experimentally simulate post-Newtonian gravitational dynamics of wavefunctions by probing nonlinear evolution of optical beams within a nonlocal nonlinear medium. As opposed to our previous research [1] our current experiment goes beyond Newtonian self-gravity by considering first-order relativistic corrections [2]. In this new table-top system we observe new solitonic solutions, and novel beam evolution under a nonlinear “mexican-hat”-type potential. A brief overview of our work towards a setup for realizing quantum metasurfaces [3] in a solid-state based system will be given.

References:

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Michael Knap

Technical University of Munich

“Quantum Simulation of Tunable Bose-Fermi Mixtures with Transition Metal Dichalcogenide Heterostructures”

Heterostructures of two-dimensional Transition Metal Dichalcogenides (TMDs) are emerging as a promising platform for investigating exotic correlated states of matter. Here, we discuss how to engineer Bose-Fermi mixtures in these systems by coupling inter-layer excitons to doped charges in a trilayer structure. Using a solid-state Feshbach resonance, interactions between the carriers can be controlled by an external electric field. These tunable interactions give rise to unexpected transport phenomena at intermediate temperatures. At low temperatures the system can even become unstable toward topological p+ip superconductivity. This demonstrates the potential for TMD heterostructures for realizing and controlling exotic correlated quantum many-body states in previously unaccessible regimes.

Chris Laumann

Boston University

"Imaging superconductors under pressure using a nanoscale quantum sensor"

Pressure alters the physical, chemical and electronic properties of matter. By compressing a material between two opposing brilliant cut diamonds, the diamond anvil cell enables tabletop experiments to reach pressures more than a million times that of atmospheric pressure. Since its development over half a century ago, it has enabled experiments to directly access pressure as a thermodynamic tuning parameter and has had a dramatic impact on quantum science, chemistry and materials physics. Among these impacts, a tremendous amount of recent attention has focused on the discovery of superconductivity in a class of hydrogen-based materials. When compressed to megabar pressures, these so-called super-hydrides are believed to exhibit the highest known critical temperatures, and have led to a nascent field that is equal parts exciting and controversial. Part of this controversy stems from the nature of the tool itself: especially at high pressures, it is tremendously challenging to extract local information from within a diamond anvil cell.

In this talk, I describe a new approach to directly "see" the physics inside the science chamber of a diamond anvil cell at ultra-high pressures. The basic idea is deceptively simple: We directly integrate a thin layer of sensors into the surface of the diamond anvil that is actually applying the pressure. We demonstrate the ability to perform diffraction-limited imaging of both stress fields and magnetism, with the latter allowing us to image the magnetic field expulsion associated with superconductivity. Applying our techniques to cerium hydride, we observe the dual signatures of superconductivity: diamagnetism characteristic of the Meissner effect and a sharp drop of the resistance to near zero. By locally mapping both the diamagnetic response and flux trapping, we directly image the geometry of superconducting regions, showing marked inhomogeneities at the micron scale.

Annabelle Bohrdt

University of Regensburg

"Simulating strongly correlated systems: combining quantum simulation with machine learning"

Using different quantum simulation platforms, the physics of various two-dimensional quantum many-body systems can be explored, ranging from (long-range) interacting spin systems to Fermi-Hubbard models. Simultaneously, methods from artificial intelligence have reached an impressive level of performance, e.g. in natural language processing. In the context of correlated systems in particular, neural quantum states have emerged as a new tool to efficiently represent quantum many-body states. There are two main use cases for such a representation: 1.) given an (experimental) realization, one can efficiently reconstruct the quantum many-body state of the system by training a neural network on the measured data. 2.) The second main application of neural quantum states is to apply variational Monte Carlo to learn a desired state, such as the ground state of a system, or the time evolution under a given Hamiltonian. I will present some of our recent efforts to study ground states of strongly correlated quantum systems, such as t-J type systems and fractional quantum Hall states. Finally, I will combine reconstruction from data with learning from Hamiltonians: by first training on experimental data from a Rydberg atom tweezer array, we initialize the neural quantum state closer to the ground state of the true Hamiltonian. By then switching to variational Monte Carlo and minimizing the Hamiltonian energy in the second stage of training, we find a speedup in convergence time, as well as a significantly improved energy even for less-powerful neural network state architectures. This showcases how limited datasets from experiments can be combined with numerical methods in a hybrid approach to yield more accurate results than either experiment or numerics could provide on its own.

Ceren Dag

ITAMP

"Many-body quantum chaos and scars"

Spectral form factor (SFF), defined as the Fourier transform of two-level spectral correlation function, is known to follow random matrix theory (RMT) revealing spectral rigidity in quantum chaotic systems. I will first present the experimental observation of this physics on a superconducting quantum processor [1]. Then I will discuss how quantum many-body systems exhibit a generic early-time deviation from RMT in a number of paradigmatic and stroboscopically-driven 1D cold-atom models giving rise to universal scaling functions of SFF in this early-time regime [2]. A notable exception to quantum chaos is the quantum scarring, which consists of two phenomena today: (i) Quantum scars, introduced within the context of single-particle quantum billiard models, are quantum eigenstates with an enhanced probability density around an unstable periodic orbit embedded in a chaotic phase space. (ii) Quantum many-body scars are a few low-entropy eigenstates in an otherwise chaotic many-body spectrum, and can weakly break ergodicity resulting in robust oscillatory dynamics. I will discuss the distinct properties of these two phenomena emphasizing their different origins. Finally, I will show that quantum scars can show up in many-body systems too. In other words, many-body dynamics could follow unstable periodic orbits in chaotic phase spaces, which generalizes the quantum scars to many-body setting [3,4].

References:

[1] arXiv:2403.16935.
[2] Communications Physics 6 (1), 136 (2023).
[3] Physical Review Letters 132 (2), 020401 (2024).
[4] arXiv:2401.06848.

Johannes Feist

Universidad Autónoma de Madrid

"Using cavities to modify material properties"

The use of cavity quantum electrodynamical effects, i.e., of vacuum electromagnetic fields, to modify material properties has rapidly gained popularity and interest in the last decade. A canonical example of this is strong light-matter coupling, reached when the interaction of material excitations with confined light modes overcomes dissipation effects and the two parts hybridize to form mixed light-matter eigenstates, so-called polaritons. These polaritons inherit properties of both light and matter excitations and additionally display fundamentally new phenomena. The large available range of possible material systems and cavity architectures opens a rich playground for novel functionalities. I will discuss several topics related to this overall field, including the modification of photophysics and photochemistry in organic molecules, some fundamental results and pitfalls for the modification of low-energy excitations, and recent progress on few-mode field quantization in complex nanophotonic structures, i.e., strategies to obtain cavity-QED-like models for arbitrary cavity geometries and materials.