10th Course of the
International School of
Nonequilibrium Phenomena

TOPNESS25

Applications and Theoretical aspects on: Non-Equilibrium Phenomena, Topology, Superconductivity, and Superfluidity

April 27 – May 1 2025

Erice (Italy)

Monday 28/04

Erice

	Speaker	Talk
08:45 – 09:00		***Opening***
09:00 – 09:30	**Braggio**	*Thermoelectric detection in quantum systems*
09:30 – 10:00	**Taddei**	*Thermodynamic uncertainty relations for superconducting hybrid systems*
10:00 – 10:30	**Paladino**	*Current phase relation of short graphene Josephson junctions: dilute impurities and spin-orbit coupling effects*
10:30 – 11:00		**Coffee Break**
11:00 – 11:30	**Simon**	*Magnetic impurities in superconductors: Role of many-body interactions*
11:30 – 12:00	**Salasnich**	*Amplitude, phase, and topological fluctuations in two-dimensional superconductors*
12:00 – 12:30	**Grifoni**	*Friedel oscillations and chiral superconductivity in monolayer NbSe2*
12:30 – 14:00		**Lunch**
14:00 – 14:30	**Ferraro**	*Dynamical blockade of a reservoir for optimal performances of a quantum battery*
14:30 – 15:00	**Traverso Ziani**	*Charging free fermion quantum batteries*
15:00 – 15:30	**Benenti**	*Harnessing dissipation for enhanced performance and precision in quantum thermal machines*
15:30 – 16:00		**Coffee Break**
16:00 – 16:20	**Finocchiaro**	*Hybrid interacting quantum Hall thermal machine*
16:20 – 16:40	**Milloch**	*Halide perovskite artificial solids as a new platform to simulate collective phenomena in doped Mott insulators*
16:40 – 17:10	**Leonforte**	*The conditional mutual information as a detector of topological and non-topological phase transitions for one-dimensional systems*
17:10 – 17:30	**Chang**	*Strong coupling of a superconducting flux qubit to single bismuth donors*
17:30 – 17:50	**Roccati**	*Controlling Markovianity with Chiral Giant Atoms*

Tuesday 29/04

Erice

	Speaker	Talk
09:00 – 09:30	**Amico**	*Coherent effects in driven atomic Josephson Junctions*
09:30 – 10:00	**Chirolli**	*Cooper quartets in interacting hybrid superconducting systems*
10:00 – 10:30	**Grilli**	*The Shrinking Fermi liquid theory for strange metallicity in cuprates*
10:30 – 11:00		**Coffee Break**
11:00 – 11:30	**Bergeal**	*Superconductivity and Rashba spin orbit coupling in KTaO 3 - based 2DEG*
11:30 – 12:00	**Stornaiuolo**	*Magneto-transport in a spin-polarized oxide two-dimensional electron system*
12:00 – 12:30	**Poccia**	*New avenues for artificial 2.5-dimensional superconducting heterostructures*
13:00 – 14:00		**Lunch**
14:00 – 14:30	**Paternostro**	*Non-equilibrium quantum thermodynamics of gravitational collapse models*
14:30 – 15:00	**Carollo**	*Measurement-Induced Phase Transitions Under Information Loss*
15:00 – 15:30	**Perroni**	*Dissipation-driven dynamical and topological phase transitions: from few- to many-body quantum systems*
15:30 – 16:00		**Coffee Break**
16:00 – 16:20	**Blasi**	*Topological Josephson junctions in the integer quantum Hall regime*
16:20 – 16:40	**Capecelatro**	*Andreev non-Hermitian Hamiltonian for Open Josephson junctions from Green's functions*
16:40 – 17:10	**Picó-Cortés**	*Nonequilibrium Josephson and Andreev Transport in the Cotunneling Regime of Quantum Dot Junctions*
17:10 – 17:30	**Vigliotti**	*Non-equilibrium photonic kinetics in a Josephson junction chain*
17:30 – 17:50	**Vianello**	*Finite-temperature entanglement and coherence in asymmetric bosonic Josephson junctions*
20:00 – 22:00		**Social Dinner**

Wednesday 30/04

Erice

	Speaker	Talk
09:00 – 09:30	**Andrei**	*Quantum impurity in interacting environments – three systems, one phase diagram*
09:30 – 10:00	**De Palo**	*Quasi-one dimensional dipolar bosonic systems: from gas to droplets and their fragmentation*
10:00 – 10:30	**Del Pace**	*Topological excitations of atomic Fermi superfluids in arbitrary optical structures*
10:30 – 11:00		**Coffee Break**
11:00 – 11:30	**Giannetti**	*Mott materials: a journey from non-thermal switching to ultrafast coherent control*
11:30 – 12:00	**Lo Franco**	*Proof-of-principle demonstration of quantum effects in nonequilibrium entropy production via quantum photonics*
12:00 – 12:30	**Neilson**	*A new Gross-Pitaevskii approach for exciton superfluids and incompressible supersolids*
12:30 – 14:00		**Lunch**
14:00 – 14:30	**Governale**	*Odd-frequency superfluidity from a particle-number-conserving perspective*
14:30 – 15:00	**Peña Ardila**	*Charged Polarons in atom-ion hybrid systems*
15:00 – 15:30	**Ciccarello**	*Emission of qubits into the bulk or photonic graphene*
15:30 – 16:00		**Coffee Break**
16:00 – 16:20	**Bhattacharyya**	*Majorana fermions in filamentary low dimensional superconductors*
16:20 – 16:40	**Ponticelli**	*Quantum vs thermal fluctuations in two-dimensional superconductos*
16:40 – 17:10	**Spada**	*Exploring Two-Dimensional Bose Gases: From Superfluid Droplets to Supersolids*
17:10 – 17:30	**Sferrazza**	*Square-Root Topology in Quantum Optics*
17:30 – 17:50	**Pascucci**	*Density collective modes in bilayer exciton systems*
		Discussions & Closing Remarks

Sommario

Thermoelectric detection in quantum systems

Monday 28/04
09:00 – 09:30

Alessandro Braggio
CNR-NANO, Istituto di Nanoscienze
NEST, Scuola Normale Superiore Pisa

Type of Contribution: Invited Oral

Thermoelectricity is the capability to generate electrical current from a temperature gradient. We will instead review about some recent applications as detection of different physical mechanism spanning from interactions effects in superconductors [1,2,3], superconducting order parameter symmetries [4], nonlocal detection of topological properties [5,6] and Bogoliubov-Fermi points [7] or even particle-hole breaking in the center of Abrikosov vortices [8]. We will concentrate in the application for quantum Hall systems where nonlocal thermoelectricity can be used to measure the strength of the electron-electron interaction and the heat exchange mediated by it [9]. We will show how those results are possibly relevant for the field of quantum technologies spanning from quantum sensing [10,11,12] to quantum computing applications.

References

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[4] C. Guarcello, A. Braggio, F. Giazotto, R. Citro Phys. Rev. B **108** (2023) L100511
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[6] G. Blasi, F. Taddei, L. Arrachea, M. Carrega, A. Braggio Phys. Rev. B **102** (2020) 241302
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[9] A. Braggio, M. Carrega, B. Sothmann, R. Sánchez, Phys. Rev. Research **6**, (2024) L012049
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[12] C. Guarcello, R. Citro, F. Giazotto, A. Braggio Applied Phys. Lett. **123** (2023) 152601

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Thermodynamic uncertainty relations for superconducting hybrid systems

Monday 28/04
09:30 – 10:00

F. Taddei[1*], F. Maya[2,3,4], M. Governale[5], R. Fazio[4]

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Type of Contribution: Invited Oral

In 2015 Barato and Seifert introduced the thermodynamic uncertainty relation (TUR), which is expressed as an inequality assessing the minimal dissipation (measured by the rate of entropy production) required to generate an output current with minimum relative uncertainty. Here, we are interested in the TUR formulated for electric and thermal transport in the steady-state regime for a system containing superconducting regions.

On the one hand, we derive bounds to the TUR in the linear-response regime for steady-state transport in two-terminal systems when time reversal symmetry is broken. We find that such bounds are different for charge and heat currents and depend on the details of the system, through the Onsager coefficients, and on the ratio between applied voltage and temperature difference. As a function of such a ratio, the bounds can take any positive values. We calculate such bounds for a hybrid coherent superconducting system using the scattering approach, and the concrete case of an Andreev interferometer is explored [1]. Interestingly, we find that the bound on the charge current is always smaller than 2 when the system operates as a heat engine, while the bound on the heat current is always larger than 2 when the system operates as a refrigerator.

On the other hand, we study how dephasing can lead to the violation of TUR in a hybrid superconducting system consisting of a quantum dot coupled to two superconducting and two normal terminals [2]. A superconducting phase difference φ is applied between the two superconducting leads. The ideal fully coherent situation is compared to two different situations where decoherence sources are introduced. First, we consider the effect of static noise in the phase of the superconductors introduced by averaging over the phase difference φ. Second, we consider the effect of a dephasing probe implemented through one of the normal leads. The violation is weakened or eliminated in both cases when decoherence sources are present.

References

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[2] Franco Mayo, Rosario Fazio, Fabio Taddei, and Michele Governale, in preparation

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Current phase relation of short graphene Josephson junctions: dilute impurities and spin-orbit coupling effects

Monday 28/04
10:00 – 10:30

F. Bonasera, I. Vacante, F. M.D. Pellegrino, G. Falci, E. Paladino

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Type of Contribution: Invited Oral

Despite the structural simplicity of graphene, its mechanical and electronic remarkable properties make this material a versatile starting point for new technologies across a wide range of fields. The recent realizations of graphene-based hybrid systems, such as Josephson junctions, make graphene a promising a platform for new generations of devices for topological quantum computing and quantum sensing. To this aim, accurate control of the electronic properties of graphene Josephson junctions in the presence of disorder is essential.
In this work, we investigate the effects on the equilibrium supercurrent sustained by a ballistic graphene Josephson junction in the short junction limit due to a dilute homogeneous spatial distribution of non-magnetic impurities [1] and due to spin-orbit coupling (SOC) by proximity effect [2].

We find a modification of the current-phase relation with a reduction of the skewness induced by disorder, and a nonmonotonic temperature dependence of the critical current. In the presence of single magnetic impurity, the local density of states at subgap energies allows one to distinguish elastic and inelastic scattering processes and to identify the magnetic nature of the impurity [3]. Moreover we identify combinations of spin-orbit couplings that significantly suppress the supercurrent by opening a gap in the graphene band structure, and combinations which instead enhance it, effectively acting as an effective spin-valley resolved chemical potential. Moreover we find that a strong Rashba SOC produces a GJJ with extremely voltage tunable harmonic content.

References

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Magnetic impurities in superconductors: Role of many-body interactions

Monday 28/04
11:00 – 11:30

M. Uldemolins, [1] A. Mesaros, [1] G. D. Gu,[2] A. Palacio-Morales, [1] M. Aprili, [1] , F. Massee, [1] and Pascal Simon,[1]

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Type of Contribution: Invited Oral

Understanding the interplay between individual magnetic impurities and superconductivity is crucial for bottom-up construction of novel phases of matter such as topological superconductivity and Majorana edge states, as well as to exploit the local response as a probing tool. For decades, the description by Yu, Shiba and Rusinov (YSR) of single spins in a superconductor and its extension to include quantum effects has proven highly successful: the pair-breaking potential of the spin generates sub-gap electron- and hole excitations that are energetically equidistant from zero. By tuning the energy of the sub-gap states through zero, the impurity screening by the superconductor makes the ground state gain or lose an electron, signalling a parity breaking quantum phase transition.

Here, I will present a set of scanning tunneling microscopy (STM) measurements that explicitly invalidate the classical YSR paradigm, and propose an interpretation in terms of a multi-orbital Anderson impurity model [1]. In particular, I will show that in multi-orbital impurities, electronic correlations can conversely lead to a quantum phase transition where the impurity mean occupation changes dramatically, without significant effect of the screening by the superconductor. This finding implies that the YSR treatment is not always valid, and that intra-atomic interactions, particularly Hund's coupling that favours high-spin configurations, are an essential ingredient for understanding the sub-gap states. Our work belongs to a renewed effort to characterize the quantum behavior of magnetic impurities in superconductors by employing toy-models that incorporate many-body correlations [2,3].

References

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Amplitude, phase, and topological fluctuations in two-dimensional superconductors

Monday 28/04
11:30 – 12:00

K. Furutani[1], G. Midei[2], A. Perali[2], L. Salasnich[3]

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Type of Contribution: Invited Oral

We study the amplitude and phase fluctuations of the Ginzburg-Landau quasiorder parameter for superconductors in two spatial dimensions.
Starting from the mean-field critical temperature T_{c0}, we calculate the beyond-mean-field critical temperature T_c by including thermal fluctuations of the quasiorder parameter within the Gaussian level. Moreover, from our beyond-mean-field results, we derive the Berezinskii-Kosterlitz-Thouless critical temperature T_{BKT}, which takes into account topological vortex-antivortex excitations in the phase fluctuations as well as the amplitude fluctuations, to obtain the shifts of transition temperatures.
We elucidate how the Gaussian thermal fluctuations and phase fluctuations associated with vortex excitations affect thermodynamic properties by determining the H-T phase diagram for a type-II superconductor and computing the critical behaviors of the heat capacity, which are experimentally accessible, allowing the characterization of the cascade of different kinds of fluctuations in 2D superconductors.

References
K. Furutani, G. Midei, A. Perali, and L. Salasnich, Phys. Rev. B **110**, 134501 (2024).

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Friedel oscillations and chiral superconductivity in monolayer NbSe2

Monday 28/04
12:00 – 12:30

Julian Siegl,[1] Anton Bleibaum,[1] Wen Wan,[2] Marcin Kurpas,[3] John Schliemann,[1]
Miguel M. Ugeda,[2, 4, 5] Magdalena Marganska,[1, 6] and Milena Grifoni[1]

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Type of Contribution: Invited Oral

In 1965 Kohn and Luttinger proposed a genuine electronic mechanism for superconductivity. Despite the bare electrostatic interaction between two electrons being repulsive, in a metal electron-hole fluctuations can give rise to Friedel oscillations of the screened Coulomb potential. Cooper pairing among the electrons then emerges when taking advantage of the attractive regions. The nature of the leading pairing mechanism in some two-dimensional transition metal dichalcogenides is still debated. Focusing on NbSe2, we show that superconductivity can be induced by the Coulomb interaction when accounting for screening effects on the trigonal lattice with multiple orbitals. Using
ab initio-based tight-binding parametrizations for the relevant low-energy d-bands, we evaluate the screened interaction microscopically, in a scheme including Bloch overlaps. In the direct space, we find long-range Friedel oscillations alternating in sign, a key to the Kohn-Luttinger mechanism. The momentum-resolved gap equations predict two degenerate solutions at the critical temperature Tc, signaling the unconventional nature of the pairing. Their complex linear combination, i.e., a chiral gap with p-like symmetry, provides the ground state of the system. Our prediction of a fully gapped chiral phase well below Tc is in excellent agreement with the spectral function extracted from tunneling spectroscopy measurements of single-layer NbSe2.

References

J. Siegl et al., arXiv:2412.00273v2

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Dynamical blockade of a reservoir for optimal performances of a quantum battery

Monday 28/04
14:00 – 14:30

Fabio Cavaliere[1,2], Giulia Gemme[1,2], Giuliano Benenti[3,4], Dario Ferraro[1,2,*], Maura Sassetti[1,2]

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Type of Contribution: Invited Oral

The development of fast and efficient quantum batteries is crucial for the prospects of quantum technologies. We show that both requirements are accomplished in the paradigmatic model of a harmonic oscillator strongly coupled to a highly non-Markovian thermal reservoir [1]. At short times, a dynamical blockade of the reservoir prevents the leakage of energy towards its degrees of freedom, promoting a significant accumulation of energy in the battery with high efficiency. The possibility of implementing these conditions in LC quantum circuits opens up new avenues for solid-state quantum batteries.

References

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Charging free fermion quantum batteries

Monday 28/04
14:30 – 15:00

Riccardo Grazi, Fabio Cavaliere, Maura Sassetti, Dario Ferraro, Niccolò Traverso Ziani

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Type of Contribution: Invited Oral

The performances of many-body quantum batteries strongly depend on the Hamiltonian of the battery, the initial state, and the charging protocol. In this article we derive an analytical expression for the energy stored via a double sudden quantum quench in a large class of quantum systems whose Hamiltonians can be reduced to 2x2 free fermion problems, whose initial state is thermal. Among the systems for which our results apply, one can find con- ventional two band electronic systems in any dimensionality and quantum spin chains that can be solved through the Jordan-Wigner transformation. In particular, we apply our analytical relation to the quantum Ising chain, to the quantum XY chain, to the cluster Ising and to the long range SSH models. We obtain several results: (i) The strong dependence of the stored energy on the quantum phase diagram of the charging Hamiltonian persists even when the charging starts from a thermal state. Interestingly, in the thermo-dynamic limit, such a strong dependence manifests itself as non-analyticities of the stored energy corresponding to the quantum phase transition points of the charging Hamiltonian. (ii) The dependence of the stored energy on the parameters of the Hamiltonian can, in the Ising chain case, be drastically reduced by increasing temperature; (iii) Charging the Ising or the XY chain prepared in the ground state of their classical points leads to an amount of stored energy that, within a large parameter range, does not depend on the charging parameters; (iv) The cluster Ising model and the long range SSH model, despite showing quantum phase transitions (QPTs) between states with orders dominated by different interaction ranges, do not exhibit super-extensive, i.e. more than linear in the number of sites, scaling of the charging power.

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Harnessing dissipation for enhanced performance and precision in quantum thermal machines

Monday 28/04
15:00 – 15:30

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Type of Contribution: Invited Oral

In contrast to the common sense that dissipation is always detrimental, we show how a quantum thermal machine can leverage a regime of strong dissipation to improve performance and precision. First, we show that the presence of a common environment—which mediates non-trivial correlations in the working medium of a heat engine (two non-interacting quantum harmonic oscillators)—can enhance power and efficiency over an analogous configuration of two independent engines working in parallel. Remarkably, this advantage is striking in the regime of strong dissipation, where independent engines cannot deliver any useful power [1]. Then, after disclosing the intimate connection between the regime of strong dissipation and the synchronization of the two quantum harmonic oscillators, we show how synchronization and non-Markovianity, together with time-reversal symmetry breaking, are necessary ingredients to achieve precise and finite local work current, in violation of the associated thermodynamic uncertainty relations [2].

References

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Hybrid interacting quantum Hall thermal machine

Monday 28/04
16:00 – 16:20

Sara Finocchiaro[1], Dario Ferraro[2], Maura Sassetti[2], Giuliano Benenti[1]

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Type of Contribution: Contributed Oral

We investigate a hybrid thermal machine based on a single closed quantum Hall edge channel forming a quantum dot. It is tunneling coupled with two quantum Hall states at filling factor $\nu = 2$ kept at different temperatures and chemical potentials, playing the role of terminals. The hot one is also driven out-of-equilibrium by means of a periodic train of Lorentzian voltage pulses.
Various working regimes can be explored in this setup, including the engine, the heat pump, and the refrigerator configuration. Remarkably, we identify regions where multiple operational modes can coexist. Moreover, the proposed geometry is ideal to characterize the robustness of these features in the presence of electron-electron interactions.

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Halide perovskite artificial solids as a new platform to simulate collective phenomena in doped Mott insulators

Monday 28/04
16:20 – 16:40

Alessandra Milloch[1,2], Umberto Filippi[3], Liberato Manna[3], Massimo Capone[4] and Claudio Giannetti[1,2]

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Type of Contribution: Contributed Oral

The development of quantum simulators [1], artificial platforms where the predictions of many-body theories of correlated quantum materials can be tested in a controllable and tunable way, is one of the main challenges of condensed matter physics. Here, we introduce artificial lattices made of lead halide perovskite ($APbX_3$, where $X=Cl^-$, Br^-, I^- and A = Cs^+, $CH_3NH_3^+$, $HC(NH_2)^+$) nanocubes [2] as a potential new platform to simulate and investigate the physics of correlated quantum materials.
Upon photoexcitation, these systems exhibit two key phenomena that make them ideal candidates for quantum simulation of correlated solid-state systems: (i) the excitonic Mott transition, which has one-to-one correspondence with the insulator-to-metal transition described by the repulsive Hubbard model in a magnetic field [3], and (ii) the onset of collective superradiant phases [4], which allow to mimic long-range orders emerging from incoherent fluctuations in strongly correlated materials. By means of ultrafast optical spectroscopies, we study the possibility of accessing these different quantum phases by continuously tuning the light excitation intensity. Our results demonstrate the feasibility of realizing a novel quantum simulator that is able to span a parameter range relevant for a broad class of phenomena, such as superconductivity and charge-density waves.

References
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The conditional mutual information as a detector of topological and non-topological phase transitions for one-dimensional systems

Monday 28/04
16:40 – 17:00

Luca Leonforte[1,3], Giovanni Di Fresco[2] and Fabrizio Illuminati[3,4,5]

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Type of Contribution: Contributed Oral

The entanglement of the ground state (GS) can be used to determine the phase and the phase transition of symmetry-protected topological phase (SPTP).
Here, by considering a quantity inherited by quantum information field, the conditional quantum mutual information (QCMI), one can detect the phase transitions and, moreover, one can distinguish between topological phase transitions and the usual symmetry-breaking phase transitions.
Being the QCMI the mutual information between two partitions knowing third partition exists it open the possibility to consider different QCMI for the same ground state.
Thus, we evaluate the QCMI over all possible partitions, both considering open boundary conditions and periodic boundary conditions case, on three different one-dimensional systems the Ising model, the Kitaev chain and the SSH model.
By considering the convenient partitioning scheme of GS, one is able to differentiate the trivial phase from the non-trivial one by using the QCMI. Moreover, one can also differentiate if the transition is topological or symmetry-breaking, and, whether this topological phase admits usual fermions or majorana fermions on the edges. Being the QCMI quantized on these topological models, it can be used as a non-local order parameter characterizing the phase of the ground state.

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Strong coupling of a superconducting flux qubit to single bismuth donors

Monday 28/04
17:00 – 17:20

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Type of Contribution: Contributed Oral

The realization of a quantum computer represents a tremendous scientific and technological challenge due to the extreme fragility of quantum information. The physical support of information, namely the quantum bit or qubit, must at the same time be strongly coupled to other qubits by gates to compute information, and well decoupled from its environment to keep its quantum behavior.
An interesting physical system for realizing such qubits are magnetic impurities in semiconductors, such as bismuth spins in silicon. Indeed, spins in semiconductors can reach extremely long coherence times - of the order of seconds. Yet it is extremely difficult to establish and control efficient gates between distant spins. Here we experimentally demonstrate a protocol where single spins can coherently transfer their quantum information to a superconducting device, which acts as a mediator or quantum bus. This superconducting device allows to connect distant spins on-demand without compromising their coherent behavior.

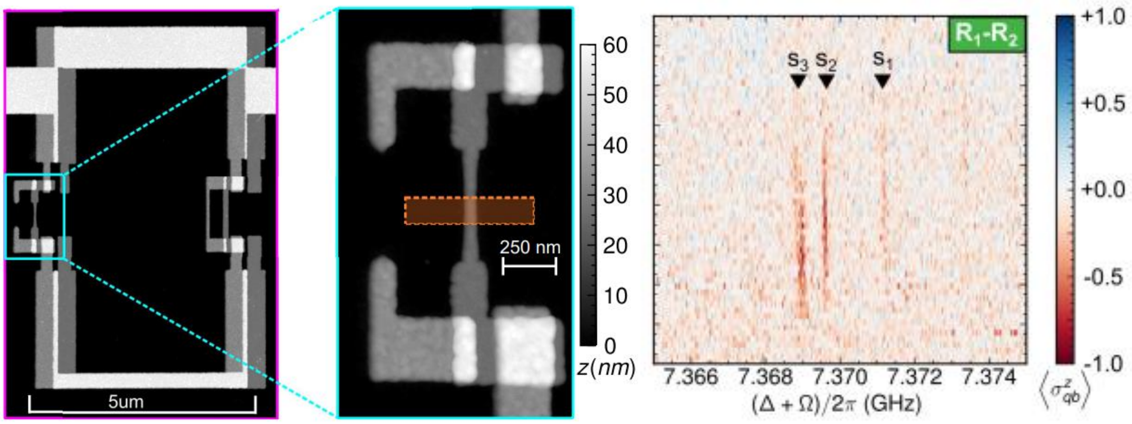

Fig. *(Left) Afm micrograph of a flux qubit with a zoom on the constriction aligned with the region of spin implantation (shown as an orange rectangle). (Right) spectroscopy showing the detection of three single bismuth donors.*

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Controlling Markovianity with Chiral Giant Atoms

Monday 28/04
17:20 – 17:40

Federico Roccati[1]

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Type of Contribution: Contributed Oral

Giant artificial atoms are promising and flexible building blocks for the implementation of analog quantum simulators. They are realized via a multilocal pattern of couplings of two-level systems to a waveguide, or to a two-dimensional photonic bath. A hallmark of giant-atom physics is their non-Markovian character in the form of self-coherent feedback, leading, e.g., to nonexponential atomic decay. The timescale of their non-Markovianity is essentially given by the time delay proportional to the distance between the various coupling points. In parallel, with the state-of-the-art experimental setups, it is possible to engineer complex phases in the atom-light couplings. Such phases simulate an artificial magnetic field, yielding a chiral behavior of the atom-light system. Here, we report a surprising connection between these two seemingly unrelated features of giant atoms, showing that the chirality of a giant atom controls its Markovianity. In particular, by adjusting the couplings' phases, a giant atom can, counterintuitively, enter an exact Markovian regime, irrespectively of any inherent time delay. We illustrate this mechanism as an interference process and via a collision model picture. Our findings significantly advance the understanding of giant atom physics, and open new avenues for the control of quantum nanophotonic networks.

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Coherent effects in driven atomic Josephson Junctions

Tuesday 29/04
09:00 – 09:30

Luigi Amico

Quantum Research Center, Technology Innovation Institute, Abu Dhabi, UAE
Dipartimento di Fisica e Astronomia 'Ettore Majorana', Catania, Italy

Type of Contribution: Invited Oral

Atomic Josephson junctions can be realized by coupling two quasi-two-dimensional atomic clouds with a tunneling barrier. I will consider a driven atomtronic circuit in which the position of the junction is periodically modulated. I will discuss the theory and the experiments that has led led to the observation of the Shapiro steps in the system. By periodically modulating also the barrier height, I will demonstrate that the circuit realizes an atomic Josephson amplifier. This works provide a pathway toward tunable atomtronic circuits with potential applications in quantum sensing.

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Cooper quartets in interacting hybrid superconducting systems

Tuesday 29/04
09:30 – 10:00

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Type of Contribution: Invited Oral

Cooper quartets represent exotic fermion aggregates describing correlated matter at the basis of charge-4e superconductivity and offer a platform for studying four-body interactions, of interest for topologically protected quantum computing, nuclear matter simulations, and more general strongly correlated matter. Focusing on solid-state systems, we show how to quantum design Cooper quartets in a double-dot system coupled to ordinary superconducting leads through the introduction of an attractive interdot interaction. A fundamentally novel, maximally correlated double-dot ground state, in the form of a superposition of vacuum $|0\rangle$ and four-electron state $|4e\rangle$, emerges as a narrow resonance in a many-body quartet correlator that is accompanied by negligible pair correlations and features a rich phenomenology. The system represents an instance of correlated Andreev matter and the results open the way to the exploration of interaction effects in hybrid superconducting devices, and the study of novel correlated states of matter with ingredients available in a quantum solid-state laboratory.

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The Shrinking Fermi liquid theory for strange metallicity in cuprates

Tuesday 29/04
10:00 – 10:30

M. Grilli[1,2*],S. Bhattacharyya[1],S. Caprara[1,2], C. Di Castro[1],G. Mirarchi[1], G. Seibold[3]

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Type of Contribution: Invited Oral

Anomalous metallic properties are observed in optimally and overdoped cuprates, with violation of the Fermi Liquid paradigm. We propose a scenario where, dynamical charge density fluctuations (CDF) with *finite rather short correlation length* mediate a nearly isotropic scattering among the quasiparticles over the entire Fermi surface [1,2] leading to strange-metal behavior. If the damping of these nearly local charge fluctuations increases by decreasing the temperature, the Fermi liquid regime shrinks and the strange metallic behavior is extended to the lowest temperatures, possibly giving rise to a peculiar local quantum criticality [3]. This increase of damping is either due to the decay of CDF into diffusive electron modes [4] or to direct interactions between the CDF possibly leading to the formation of a glassy state [7]. This Shrinking Fermi liquid scenario accounts for both the linear-in-temperature resistivity and the seemingly divergent specific heat [2,4] observed, not only in high-temperature superconducting cuprates, but also in some heavy-fermion metals. This scenario is investigated within a model of overdamped Holstein phonons [5] and it is shown that is has many similarities and some differences with respect to the Marginal Fermi Liquid scenario. The same conclusion is reached from a recent analysis of optical conductivity data [6].

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Superconductivity and Rashba spin orbit coupling in $KTaO_3$-based 2DEG

Tuesday 29/04
11:00 – 11:30

H. Witt[1,2], S. Mallik[1], G. C. Ménard[2],V. Pirogov[2], S. Mandal[2], G. Saïz[2], J. Bréhin[1], L. M. Vicente-Arche[1], I. Boventer[1], A. Gloter[3], L. Benfatto[4], M. Bibes[1] & N. Bergeal[2*]

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Type of Contribution: Invited Oral

The search for Majorana Zero Modes, driven by their potential application for quantum computing, continues to be a challenge. So far, most attempts have been focused on hybrid superconducting-semiconductors nanowires, but other platforms have been suggested. In particular, two-dimensional electron gases (2-DEGs) at oxide interfaces display a unique combination of superconductivity and Rashba spin-orbit coupling, which are the two main ingredients for the realization of topological superconducting states.

After fifteen years of intense work on the $LaAlO_3/SrTiO_3$ interface [1], the recent discovery of a superconducting 2-DEG) in (111)-oriented $KTaO^3$-based heterostructures injected new momentum to the field of oxides interface [2,3]. In this system, the superconducting T_c can be larger than 2K, which is almost one order of magnitude higher than in the $SrTiO_3$ based interfaces. Since Ta is much heavier than Ti, spin-orbit effects are also significantly enhanced as demonstrated recently [4,5]. $KTaO_3$ based 2-DEGs could therefore enable the realization of topological superconductivity, originally proposed for $SrTiO_3$ based 2-DEGs but non-achievable due to the weakness of the relevant energies. In this talk, I will present dc and microwave transport experiments on superconducting 2-DEGs formed at the (111)-oriented AlOx/KTaO3 interface. The temperature dependence of the superfluid stiffness, extracted from the microwave response of the 2-DEG, suggests a nodeless superconducting order parameter with a gap exceeding the prediction of a simple BCS weak-coupling model [6]. I will also introduce recent tunneling spectroscopy measurements in Au/AlOx/(111)-KTaO3, highlighting the superconducting gap's temperature dependence and evolution under a perpendicular magnetic field. Finally, I will report on bilinear magnetoresistance measurements in KTaO3 2-DEGs, providing direct insight into Rashba spin-orbit coupling, Finally, I will provide perspectives on the realization of superconducting devices [7].

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Magneto-transport in a spin-polarized oxide two-dimensional electron system

Tuesday 29/04
11:30 – 12:00

Yu Chen[1], Maria D'Antuono[2,1], Mattia Trama[3], Daniele Preziosi[4], Benoit Jouault[5], Frédéric Teppe[5], Christophe Consejo[5], Carmine Perroni[2,1], Roberta Citro[3,6], Daniela Stornaiuolo[2,1], Marco Salluzzo[1]

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Type of Contribution: Invited Oral

Two-dimensional electron systems (2DES) exhibit a complex interplay between spin-orbit coupling (SOC) and various types of symmetry breaking phenomena. 2DES formed at the interfaces between transition metal oxides, in particular, provide an exceptional platform for studying and the exploiting novel quantum phenomena in the 2D-limit. A major advantage of oxide 2DES is indeed that their physics can be tailored by epitaxially engineering, allowing for the incorporation of several order parameters, such as superconductivity, ferromagnetism and ferroelectricity.

By engineering a spin-polarized oxide 2DES with Rashba-like SOC and hexagonal band warping, we demonstrate the first example of an anomalous quantum correction to the magnetoconductance by Dirac-like fermions experiencing competing weak anti-localization and weak localization back-scattering in an oxide 2DES [1], with a phenomenology analogous to that of gapped topological insulators [2]. The results were obtained on the 2DES formed at the interfaces between (111) $LaAlO_3$, $EuTiO_3$, and $SrTiO_3$ single crystal. It is characterized by a trigonal crystal field splitting and ferromagnetism induced by Eu and Ti ions magnetic ordering [3, 4]. The data are explained theoretically in a single band scenario as the combined effects of the Rashba-SOC, of the band-warping induced by the 2DES trigonal symmetry, and of the magnetic gap opening at spin-orbit induced Dirac-like point, giving rise to a non-trivial Berry phase.

These findings open perspectives for the engineering of novel spin-polarized functional 2DES holding promises in spin-orbitronics and topological electronic.

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New avenues for artificial 2.5-dimensional superconducting heterostructures

Tuesday 29/04
12:00 – 12:30

Nicola Poccia[1,2,*]

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Type of Contribution: Invited Oral

New electronics centered on high-temperature superconductor materials, based on the twisting of the crystals are expected to have a notable impact on the fundamental understanding of these systems and the future of quantum technologies. The materials involved are complex ceramics, typically composed of four or five elements, such as $La_{2-x}Sr_xCuO_4$, $YBa_2Cu_3O_{7-x}$ and $Bi_2Sr_2CaCu_2O_{8+x}$, often oxidized owing to an excess of oxygen defects. As of 2025, the fundamental physics of these materials is of interest not solely because of their high critical temperature, close to liquid nitrogen condensation, but primarily because of their complex electronic state, heterogeneously formed by a landscape of puddles, which remains unparalleled in condensed matter physics and still presents many mysteries. Remarkably, more than 30 years of progress in the materials science of these ceramics, also known as cuprate superconductors, has led to a solid grasp of both their weaknesses and their high potential for emerging electronics. The recent reinvigorated possibility of stacking and twisting cuprate superconducting interfaces drives therefore the search for emergent states in complex oxides with forbidden interfaces. Here I will discuss our recent progress in the design, fabrication, and exploration of artificial 2.5-dimensional superconducting heterostructures with a particular attention to the experimental challenges and our point of view on our progress to solve them.

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Non-equilibrium quantum thermodynamics of gravitational collapse models

Tuesday 29/04
14:00 – 14:30

Mauro Paternostro[1,2], Simone Artini[1], Sandro Donadi[2,3], Gabriele Lo Monaco[1]

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Type of Contribution: Invited Oral

I will illustrate an investigation on the entropy production in the Diósi-Penrose (DP) model, one of the most extensively studied gravity-related collapse mechanisms, and one of its dissipative extensions.

To this end, I will analyze the behavior of a single harmonic oscillator, subjected to such collapse mechanisms, focusing on its phase-space dynamics and the time evolution of the entropy production rate — a central quantity in non-equilibrium thermodynamics. The results of such analysis reveal that the original DP model induces unbounded heating, producing dynamics consistent with the Second Law of thermodynamics only under the assumption of an infinite-temperature noise field.

In contrast, its dissipative extension achieves physically consistent thermalization in the regime of low dissipation strength. I will further such study to address the complete dynamics of the dissipative extension, thus including explicitly non-Gaussian features in the state of the system that lack from the low-dissipation regime, using a short-time approach.

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Measurement-Induced Phase Transitions Under Information Loss

Tuesday 29/04
14:30 – 15:00

Alessio Paviglianiti, Giovanni Di Fresco, Alessandro Silva, Bernardo Spagnolo*, Davide Valenti*, Angelo Carollo*

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Type of Contribution: Oral

The behavior of a quantum many-body system undergoing measurements is best understood through an ensemble of quantum trajectories, which can exhibit measurement-induced phase transitions (MIPTs). These transitions, however, cannot be detected using ensemble-averaged observables; instead, they require the ability to distinguish each individual trajectory, making their experimental detection highly challenging. In this study, we investigate how MIPTs are affected when an observer's capacity to distinguish measurement outcomes is reduced. This limitation introduces uncertainty into the system's state, causing observables to reflect a limited subset of trajectories rather than a single one. By analyzing an exactly-solvable Liouvillian model, we explore how long-range spatial correlations are impacted by varying levels of trajectory averaging. We precisely calculate the correlation matrix, Liouvillian gap, and entanglement negativity, revealing that averaging over multiple realizations introduces an effective finite lengthscale. Beyond this scale, long-range correlations are diminished. This indicates that partial trajectory averaging obscures the critical characteristics of individual realizations, effectively masking the distinct signatures of measurement-induced phases.

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Dissipation-driven dynamical and topological phase transitions: from few- to many-body quantum systems

Tuesday 29/04
15:00 – 15:30

C. A. Perroni*, G. Di Bello[1], F. Pavan[1], A. Ponticelli[1,2], V. Cataudella[1,2], G. De Filippis[1,2], A. De Candia[1,2], N. Nagaosa[3], A. Nava[4,5], R. Egger[4], L. Lepori[6], D. Giuliano[5]

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Type of Contribution: oral

Using state-of-the-art numerical approaches, we show that, by quenching the qubits-oscillator coupling in a dissipative two-qubit Rabi model, the system undergoes dynamical quantum phase transitions [1]. These transitions are characterized by kinks in the Loschmidt echo rate function at parameter values close to a thermodynamic quantum phase transition. The two classes of critical phenomena depend on qubit interactions and entanglement, revealing different behaviors of the critical exponent of the first kink of the Loschmidt echo for interacting versus non-interacting qubits [1].
We investigate the nonperturbative effects induced by the environment on the prototype Su-Schrieffer-Heeger chain coupled to local harmonic oscillator baths through either intracell or intercell transfer integrals [2]. Despite the common view, this type of coupling, if suitably engineered, can even induce a transition to topological phases. By using a world-line quantum Monte Carlo technique we determine the phase diagram of the model proving that the bimodality of the probability distribution of the polarization signals the emergence of the topological phase. We show that a qualitative description can be obtained by using an approach based on the cluster perturbation theory providing, in particular, a non-Hermitian Hamiltonian for the fermionic subsystem and insights on the dissipative dynamics [2].
We induce and study a topological dynamical phase transition between two planar superconducting phases [3]. Using the Lindblad equation to account for the interactions of Bogoliubov quasiparticles among themselves and with the fluctuations of the superconducting order parameter, we derive the relaxation dynamics of the order parameter. To characterize the phase transition, we compute the fidelity and the spin-Hall conductance of the open system. Our approach provides crucial information for experimental implementations, such as the dependence of the critical time on the system-bath coupling [4].

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Topological Josephson junctions in the integer quantum Hall regime

Tuesday 29/04
16:00 – 16:20

Gianmichele Blasi, Géraldine Haack, Vittorio Giovannetti*, Fabio Taddei*, Alessandro Braggio*

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Type of Contribution: Contributed Oral

Robust and tunable topological Josephson junctions (TJJs) are highly desirable platforms for investigating the anomalous Josephson effect and topological quantum computation applications. Experimental demonstrations have been done in hybrid superconducting-two dimensional topological insulator (2DTI) platforms, sensitive to magnetic disorder and interactions with phonons and other electrons. In this work, we propose a robust and electrostatically tunable TJJ by combining the physics of the integer quantum Hall (IQH) regime and of superconductors. We provide analytical insights about the corresponding Andreev bound state spectrum, the Josephson current and the anomalous current. We demonstrate the existence of protected zero-energy crossings, that can be controlled through electrostatic external gates. This electrostatic tunability has a direct advantage to compensate for non-ideal interfaces and undesirable reflections that may occur in any realistic samples. TJJs in the IQH regime could be realized in graphene and other 2D materials. They are of particular relevance towards scalable and robust Andreev-qubit platforms, and also for efficient phase batteries.

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G. Blasi, *et al*., Phys. Rev. Research **5**, 033142 (2023)

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Andreev non-Hermitian Hamiltonian for Open Josephson junctions from Green's functions

Tuesday 29/04
16:20 – 16:40

Roberto Capecelatro[1,2]

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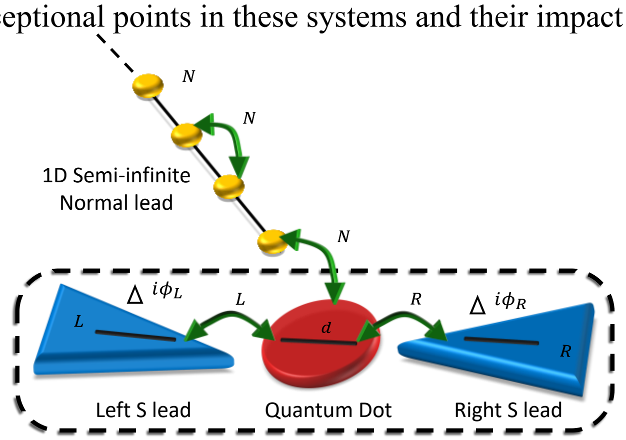
Type of Contribution: Contributed Oral

We investigate the transport properties of open Josephson junctions (JJs) through a minimal effective non-Hermitian (NH) approach derived from the equilibrium Green's function (GF) formalism. Specifically, we consider a JJ with a quantum dot (QD) barrier coupled to a normal metal reservoir. The coupling introduces an imaginary self-energy term in the JJ Hamiltonian which can be naturally accounted for in the NH formalism. We propose a scheme for deriving an effective NH Hamiltonian for the Andreev levels only, which we compute from the singular part of the barrier GF. To establish the range of applicability of this NH model, we benchmark our results for both the dot density of states and the supercurrent against exact GF predictions in different transport regimes. We find that, as a rule of thumb, the Andreev NH description is accurate when the spectral overlap between the Andreev bound states (ABS) and the near-gap continuum states is negligible, i.e., when the ABS energies lie sufficiently far from the superconducting gap relative to their linewidth. We also start applying the Andreev NH approach to study transport in QD junctions involving magnetic fields and spin-orbit interactions when coupled to normal reservoirs. Our goal will be to investigate the effects of decoherence on key phenomena such as 0-π transitions and the Anomalous Josephson effect, as well as to explore the possible presence of exceptional points in these systems and their impact on transport.



Josephson junction

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Nonequilibrium Josephson and Andreev Transport in the Cotunneling Regime of Quantum Dot Junctions

Tuesday 29/04
16:40 – 17:00

Jordi Picó-Cortés, Gloria Platero*, Andrea Donarini, Milena Grifoni

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Type of Contribution: Contributed Oral

We investigate nonequilibrium transport through superconducting nanojunctions using a Liouville space approach [1]. The formalism allows us to study finite-gap effects, and to account for both quasiparticle and Cooper-pair tunneling. With focus on the weak-tunneling limit, we study the stationary dc and ac current up to second order (cotunneling) in the hybridization energy. For the particular case of a strongly interacting quantum dot sandwiched between two superconductors, we identify the characteristic virtual processes that yield the Andreev and Josephson current and obtain the dependence on the gate and bias voltage for the dc current, the critical current, and the phase-dependent dissipative current. In particular, the critical current is characterized by regions in the stability diagram in which its sign changes from positive to negative, resulting in a multitude of $0-\pi$ transitions. The latter signal the interplay between strong interactions and tunneling at finite bias.

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Non-equilibrium photonic kinetics in a Josephson junction chain

Tuesday 29/04
17:00 – 17:20

Anton V. Bubis[1], Lucia Vigliotti[1]*, Maksym Serbyn[1], and Andrew P. Higginbotham[2]

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Type of Contribution: Contributed Oral

With the recent push towards the development of quantum technologies, multimode quantum systems, such as superconducting resonators, have drawn considerable attention. These systems can be generally described as a set of weakly nonlinear bosonic modes, coupled to a thermal bath and subject to a coherent driving. As the number of modes grows and extrinsic decoherence is reduced, it becomes more relevant to understand the inter-modes interaction, which is a potential source of internal decoherence. Among multimode systems, Josephson junction chains raise much interest given their high tunability, and it is therefore of utmost importance to understand their internal multimode dynamics. In this work, we investigate the problem both theoretically and experimentally, focusing on four-wave mixing processes. We consider a long chain, whose plasmonic modes are experimentally probed via multitone microwave spectroscopy. We first assess the framework in the absence of driving, and then move to the out-of-equilibrium regime. Under two coherent drives, we observe cascaded coupling between plasmonic modes, which is reproduced theoretically by applying the input-output theory to multiplets of modes coupled by the nonlinear Hamiltonian. Under incoherent broadband drive, we explore the kinetics of weakly populated modes. We implement numerically a kinetic equation to predict the non-equilibrium steady state of the system, and match the observed scaling of excess decay of the non-driven modes due to internal dynamics. Our work establishes the key role of four-wave mixing nonlinearities in the non-equilibrium response of Josephson junction chains, paving a way for studying far from equilibrium multimode quantum systems.

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Finite-temperature entanglement and coherence in asymmetric bosonic Josephson junctions

Tuesday 29/04
17:20 – 17:40

Cesare Vianello[1], Matteo Ferraretto[2], and Luca Salasnich[1,3,4]

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Type of Contribution: Contributed Oral

We investigate the finite-temperature properties of a bosonic Josephson junction composed of N interacting atoms confined by a quasi-one-dimensional asymmetric double-well potential, modeled by the two-site Bose-Hubbard Hamiltonian. By performing an exact numerical diagonalization, we compute the spectral decomposition of the statistical ensemble of states describing the system, the thermodynamic and entanglement entropies, the population imbalance, the quantum Fisher information, and the coherence visibility. We analyze their dependence on the number of particles, the interaction strength, the energy asymmetry between the two wells, and the temperature, showing in particular that finite temperature and energy asymmetry affect the entanglement and coherence properties of the system in a non-trivial way. The exact numerical results also serve as a benchmark for effective analytical results. We discuss how the system can be described by an effective quantum Hamiltonian over a wide range of interactions. From this we argue that in the strong-tunneling regime, thermal averages of observables having a classical analogue can be computed analytically using a modified Boltzmann weight involving an effective temperature.

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Quantum impurity in interacting environments – three systems, one phase diagram

Wednesday 30/04
09:00 – 09:30

Natan Andrei

Department of Physics
Rutgers University

Type of Contribution: Invited Oral

When a local spin impurity is placed in a metal, modeled as a non-interacting gas of electrons, it is screened by a cloud of electrons around it. What happens when instead the impurity is placed in a superconductor? The traditional answer is that in a 3-dimensional superconductor the impurity is screened by a local bound state. This answer fails in one dimension where quantum fluctuations play an important role, and as I shall show, the answer is more interesting - a rich phase diagram emerges. Then I will place the impurity in an open dissipative environment and will find a similar phase diagram. Similar results are found for an impurity coupled to an interacting spin chain. I will discuss the origin of the similarity.

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Quasi-one dimensional dipolar bosonic systems: from gas to droplets and their fragmentation

Wednesday 30/04
09:30 – 10:00

Stefania De Palo
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Type of Contribution: Invited Oral

Using a variational approximation based on the Lieb-Liniger gas Bethe ansatz wave function, we study a tightly trapped one-dimensional dipolar gas of bosonic atoms for which we derive the equation of state. We test our results by computing the breathing mode, finding very good agreement with available experiments.
We follow the gas liquid transition of the system when the strength of the dipolar interaction becomes sufficiently attractive compared to the contact one allowing the formation of droplets. This is signalled by a steep increase of the breathing mode and a change in sign of the chemical potential. Eventually, on increasing the number of particles in the cloud, the density profile shows the typical droplet flat-top shape.
Upon a sudden release of the trap, varying the number of trapped atoms and the scattering length, the numerical solution of a time-dependent generalized Gross-Pitaevskii equation shows either an evaporation of the cloud, the formation of a single self-bound droplet, or a fragmentation in multiple droplets.

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Topological excitations of atomic Fermi superfluids in arbitrary optical structures

Wednesday 30/04
10:00 – 10:30

G. Del Pace*[1,2,3], M. Frómeta Fernández[2,3], N. Grani[1,2,3], D. Hernández-Rajkov[2,3], G. Roati[2,3]

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Type of Contribution: Invited Oral

The ability to precisely sculpt the geometry of ultracold atoms provided by spatial light modulators has opened in recent years to the possibility to precisely engineer ad hoc architectures to study specific excitations of quantum matter with an unprecedented level of control. In this talk, I will review our recent experimental results on the study of topological excitations in atomic Fermi superfluids in tunable optical potentials.
In a bulk geometry, we create arbitrary configurations of quantum vortices to investigate their dissipation mechanism. In the minimal configuration of a vortex dipole, i.e. a vortex-antivortex pair, with the antivortex pinned at the center of the trap, we track the orbiting trajectory of the mobile vortex to extract the mutual friction coefficients, ruling the dissipative dynamics of vortex motion.
In a ring geometry, topological excitations produce long-lived and quantized persistent currents, which we excite with the phase imprinting technique and directly measure with an interferometric probe, analogous to heterodyne detection. With these tools we excite current with a winding number as high as 9 and study their stability in a clean ring, in the presence of a localized impurity and when the ring is cut by a number of identical tunneling barriers. In all cases, the current decay happens via vortex emission, which decrease the current winding number. However, the coherence properties of the Josephson junction realized in the presence of the tunneling barriers yields to a counter-intuitive stabilization of the current upon increasing the number of junctions, namely increasing the number of barriers in the ring.
Our results highlight how the ability to design the potential of atomic superfluids opens for not only new investigation on fundamental properties of quantum matter and its excitations, but also for the implementation of atomtronics circuits with controlled currents.

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Mott materials: a journey from non-thermal switching to ultrafast coherent control

Wednesday 30/04
11:00 – 11:30

Alessandra Milloch, Claudio Giannetti

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Type of Contribution: Invited Oral

Achieving the full understanding and control of the insulator-to-metal transition in Mott materials is key for the next generation of electronics devices, with applications ranging from ultrafast transistors, volatile and non-volatile memories and artificial neurons for neuromorphic computing. We will review the state-of-the-art knowledge of the Mott transition, with specific focus on the paradigmatic Mott insulator V_2O_3. We will emphasize the current attempts in controlling the Mott switching dynamics via the application of external voltage and electromagnetic pulses and we will discuss how the recent advances in time- and space-resolved techniques are boosting the comprehension of the firing process and the role of topological defects of the order parameter. The nature of the voltage/light-induced Mott switching is inherently different from what is attainable by the slower variation of thermodynamic parameters, thus offering promising routes to achieving the reversible and ultrafast coherent control of conductivity in Mott nanodevices.

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Proof-of-principle demonstration of quantum effects in nonequilibrium entropy production via quantum photonics

Wednesday 30/04
11:30 – 12:00

Qing-Feng Xue,[1] Xu-Cai Zhuang,[1] De-Yang Duan,[1] Ying-Jie Zhang,[1] Wei-Bin Yan,[1] Yun-Jie Xia,[1] Rosario Lo Franco,[2,*] and Zhong-Xiao Man[1]

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Type of Contribution: Invited Oral

Entropy production is a key concept underpinning the second law of thermodynamics and quantifying irreversibility, imposing strict limits on the possible transformations in thermodynamic processes.

In this talk, we report the experimental observation, through an all-optical platform, of the splitting of entropy production in an open quantum system into two distinct parts: one associated with populations and another with coherences [1]. This observation agrees with prior theoretical predictions [2]. The coherence-related part reflects a purely quantum contribution, absent in classical systems. By controlling the bath temperatures and the initial coherences of the system, we first evaluate the total entropy production arising from both populations and coherences. Then, by fully removing the system's coherences, we determine the contribution linked solely to populations. The difference between these two measurements allows us to isolate the coherence-related term. This decomposition demonstrates that quantum irreversibility can, in principle, be mitigated by properly managing these two components of entropy production.

Our experiment shows the capability of the designed optical setup to provide a proof-of-concept for observing entropy production at the quantum scale, by effectively encoding both system-bath interaction time and bath temperatures into the parameters of optical elements. Thus, quantum photonics and linear optics technologies offer a versatile and effective platform for simulating and exploring quantum thermodynamic processes.

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A new Gross-Pitaevskii approach for exciton superfluids and incompressible supersolids

Wednesday 30/04
12:00 – 12:30

David Neilson[1*], Andrey Chaves[2], Sara Conti[1], Milorad Milosevic[1], Luis Pena Ardila[3]

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Type of Contribution: Invited Oral

Recent reports of signatures of superfluidity [1,2,3] of dipolar excitons have drawn a lot of attention to excitonic bilayer semiconductor systems in which electrons and holes are confined in separate layers so the excitons are long-lived and spatially indirect. In an earlier variational calculation, we predicted a transition in this system from a superfluid to an incompressible supersolid with single site occupancy [4].
We investigate the superfluid and supersolid ground states with a time-independent Gross-Pitaevskii approach for electron-hole double-layer excitonic systems. The exciton- exciton interaction is dipole-like long-range, and everywhere repulsive. The pure repulsion contrasts with ultracold dipolar gases [5] where the effective interaction contains attractive as well as repulsive parts. We construct a new Gross-Pitaevskii formalism that (i) excludes energies of self-interaction of the excitons on single occupancy sites [6] and (ii) takes into account strong two-particle correlations. The Gross-Pitaevskii equation at $T=0$ is solved over a wide range of experimentally accessible values of the parameters: the separation of the electron-hole layers and the exciton density. Both superfluid ground states and incompressible supersolid ground states are found.
We further investigate formation of vortices in the exciton superfluid and supersolid. Since superfluids are quasi-neutral, the stabilization and observation of vortex matter is used to decisively establish the existence of coherent condensation [7] and to characterize a superfluid to supersolid transition [8]. We determine the characteristics, the interaction, and the vortex lattice properties which all depend on the exciton dipole moments and exciton density. An interesting picture emerges: a density pileup and saturation of the vortex core size is observed at the transition to the supersolid. At the transition, the vortices are sufficiently compact to completely fit within single unit cells of the incompressible supersolid.

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Odd-frequency superfluidity from a particle-number-conserving perspective

Wednesday 30/04
14:00 – 14:30

K. Thompson[1], U. Zülicke[1,2], J Schmalian[3], M. Governale[1], and J. Brand[4]

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Type of Contribution: Invited Oral

We investigate odd-in-time (or odd-frequency) pairing [1] of fermions in equilibrium systems within the particle-number-conserving framework of Penrose, Onsager and Yang [2,3], where superfluid order is defined by macrosocopic eigenvalues of reduced density matrices [4]. We show that odd-frequency pair correlations are synonymous with even fermion-exchange symmetry in a time-dependent correlation function that generalises the two-body reduced density matrix [5]. Macroscopic even-under-fermion-exchange pairing is found to emerge from conventional Penrose-Onsager-Yang condensation in two-body or higher-order reduced density matrices through the symmetry-mixing properties of the Hamiltonian. We identify and characterise a transformer matrix responsible for producing macroscopic even fermion-exchange correlations that coexist with a conventional Cooper-pair condensate, while a generator matrix is shown to be responsible for creating macroscopic even fermion-exchange correlations from hidden orders such as a multi-particle condensate. The transformer scenario is illustrated using the spin-imbalanced Fermi superfluid [6] as an example. The generator scenario is demonstrated by the composite-boson condensate arising for itinerant electrons coupled to magnetic excitations [7]. Structural analysis of the transformer and generator matrices is shown to provide general conditions for odd-frequency pairing order to arise in a given system. Our formalism facilitates a fully general derivation of the Meissner effect for odd-frequency superconductors that holds also beyond the regime of validity for mean-field theory.

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Charged Polarons in atom-ion hybrid systems

Wednesday 30/04
14:30 – 15:00

Luis A. Peña Ardila

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Type of Contribution: Oral

Charged quasiparticles dressed by the low excitations of an electron gas constitute one of the fundamental pillars for understanding quantum many-body effects in some materials. Quantum simulation of quasiparticles arising from atom-ion hybrid systems may shed light on solid-state uncharted regimes. Here, we will discuss ionic polarons created as a result of charged dopants interacting with a Bose-Einstein condensate [1] and a polarized Fermi gas [2]. Here, we show that even in a comparatively simple setup consisting of charged impurities in a weakly interacting bosonic medium and an ideal Fermi gas with tunable atom - ion scattering length, the competition of length scales gives rise to a highly correlated mesoscopic state in the bosonic case; in contrast, a molecular state appears in the Fermi case. We unravel their vastly different polaronic properties compared to neutral quantum impurities using quantum Monte Carlo simulations. Contrary to the case of neutral impurities, ionic polarons can bind many excitations, forming a nontrivial interplay between few and many-body physics, radically changing the ground-state properties of the polaron.

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Emission of qubits into the bulk or photonic graphene

Wednesday 30/04
15:00 – 15:30

Francesco Ciccarello

University of Palermo, Italy

Type of Contribution: Invited Oral

We study emission properties of qubits coupled to a 2D honeycomb lattice of coupled resonators, a setup by now within reach in circuit-QED platforms. We show that, by combining non-local coupling ("gian atom") with an engineered syntethic electric field, a qubit in the bulk can emit chiral light orthogonal to the electric field without the need for breaking time reversal symmetry of the lattice.
We additionally study qubits coupled to the latttice edge. We show that, for suitable edge geometry (e.g. zigzag or bearded) vacuum Rabi oscillations, long-range excitation transfer and long-range dipole-dipole dispersive interactions can occur.
the need for breaking time reversal symmetry of the lattice. We additionally study qubits coupled to the latttice edge. We show that, for suitable edge geometry (e.g. zigzag or bearded) vacuum Rabi oscillations, long-range excitation transfer and long-range dipole-dipole dispersive interactions can occur.

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Majorana fermions in filamentary low dimensional superconductors

Wednesday 30/04
16:00 – 16:20

S. Bhattacharyya[1*], M. Alessandrini[1], M. Grilli[1,2], B. van Heck[1]

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Type of Contribution: Contributed Oral

Several 2D superconductors turns out to have an inhomogeneous filamentary structure surrounded by a metallic matrix. Since a sizeable Rashba spin orbit coupling is often present in these systems, a magnetic field along the superconducting filaments may induce a topologically non trivial electronic state [1]. Then, Majorana Zero Modes (MZM) may appear at the endpoints of these filaments, which are, however, embedded in a metallic environment. It is therefore of interest to determine the decay processes and timescales of the MZM due to the surrounding metal. At the level of minimal models, the simplest one to look at is one with MZM tunnel-coupled to a 1d/2d tight-binding metallic lattice. We performed a semi-analytic Lindblad analysis on this model and found that it reveals non-trivial, slower decay rates for expectation values of certain parity operators of the zero modes, which may be further verified using `exact' numerics [2]. A more microscopic model involves one or more Kitaev chains coupled to a surrounding 2d metal. A numerical study of this more realistic model clarifies the role of disorder in promoting slower decay rates.[3]

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Quantum *vs* thermal fluctuations in two-dimensional superconductors

Wednesday 30/04
16:20 – 16:40

Andrea Ponticelli[1,2], Francesco G. Capone[1,2], Vittorio Cataudella[1], Giulio De Filippis[1], Antonio De Candia[1], Carmine A. Perroni[1]

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Type of Contribution: Contributed Oral

In this work, we investigate the role of quantum fluctuations on the attenuation of superconductivity in two-dimensional superconductors. The two-dimensional quantum XY (QXY) model in the phase representation is extensively studied via Path Integral Quantum Monte-Carlo techniques. A phase diagram of temperature vs. quantum coupling is carried out in all the regimes showing that there is no evidence of a reentrant phase transition. We also show that the predicted Halperin and Nelson critical behaviour for resistance is fully reproduced in the QXY model up to quantum coupling values close to the critical value. In addition, linear response transport properties at finite frequencies are investigated in both regions, superconducting and normal.

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Exploring Two-Dimensional Bose Gases: From Superfluid Droplets to Supersolids

Wednesday 30/04
16:40 – 17:00

Gabriele Spada

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Type of Contribution: Contributed Oral

Two-dimensional (2D) Bose gases offer a captivating platform for exploring exotic quantum phases, from superfluid droplets to supersolids, where interactions, quantum statistics, and thermal fluctuations interplay, with Berezinskii–Kosterlitz–Thouless (BKT) transitions shaping their rich phase diagrams. Using path-integral Monte Carlo simulations, we study attractive Bose mixtures at finite temperatures, revealing the formation of superfluid droplets through a pronounced first-order transition from gas to liquid. This transition features a sudden superfluid onset, due to BKT physics, together with a localized jump in the density. The behavior is stabilized by the quantum scale anomaly, which tunes the critical interaction strength. Remarkably, quasi-2D and pure 2D models show striking consistency in their equations of state. Turning to 2D soft-disk bosons, we combine Hartree-Fock and Monte Carlo methods to chart a detailed phase diagram, identifying a robust supersolid phase at low temperatures that bridges a uniform superfluid and an insulating quasi-crystal. As the temperature rises, this supersolid loses superfluidity via a BKT transition, followed by the melting of density modulations, with subtle evidence suggesting an intermediate hexatic phase. These findings underscore the pivotal role of BKT transitions in dictating superfluidity's emergence and decay in 2D Bose gases, illuminating interaction-driven quantum phenomena and opening experimental avenues to probe these elusive states in reduced dimensions.

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Square-Root Topology in Quantum Optics

Wednesday 30/04
17:00 – 17:00

Giovanni Luca Sferrazza, Francesco Ciccarello*

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Type of Contribution: Contributed Oral

The seemingly simple mathematical operation of taking the square root has profound implications for uncovering new physical phenomena with the Dirac equation being a prominent example. Recently, it has been shown that the square-root procedure can be a powerful tool to reveal topological properties that lie beyond the conventional classification of topological insulators, opening new frontiers in condensed matter physics. We extend the concept of square-root topology to quantum optics by investigating atoms coupled to a photonic analogue of a square-root topological insulator. We will delve into the topological protection of atom-photon bound states and the nature of photon-mediated interactions in this novel and exotic setting. These systems, which are within reach of cutting-edge experimental platforms such as circuit QED, offer a novel setting to uncover new mechanisms for robust light-matter interactions and topological quantum phenomena.

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Density collective modes in bilayer exciton systems

Wednesday 30/04
17:20 – 17:40

Filippo Pascucci, Sara Conti, David Neilson, Andrea Perali*, Jacques Tempere**

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Type of Contribution: Contributed Oral

Recent discoveries of new bidimensional materials have renewed the attention of researchers about the superfluidity of indirect excitons in systems comprising a conductive layer of electrons close to a conductive layer of holes. Despite extensive experimental efforts, conclusive evidence of exciton superfluidity remains elusive due to challenges in traditional probing methods, partly because of the neutral nature of excitons.

We investigate the behaviour of density collective modes in the normal and superfluid phases of the bilayer exciton system to identify alternative fingerprints of exciton superfluidity. We derive the dressed density response functions through the Random-Phase-Approximation considering a self-consistent screened interlayer and intralayer interaction.
In the normal state, stable acoustic and optic density collective modes exist outside the particle-antiparticle continuum.
In the exciton superfluid phase screening effects lead to an energy gap in the single-particle excitation spectrum consistently larger than the Fermi energy.
We show that such a large energy gap suppresses the propagation of stable density collective modes as the system transitions from the normal to the superfluid exciton phase.

Experimental observation of the disappearance of the acoustic and optic brunches would serve as an unambiguous fingerprint of exciton superfluidity in bilayer systems.

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