December 15–19, 2024
Ambrož, Krvavec, Slovenia

BOOK OF ABSTRACTS

NQW

Nonequilibrium Quantum Workshop

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NQW Nonequilibrium Quantum Workshop

December 15 – 19, 2024
Krvavec, Slovenia

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Abstracts

Non-equilibrium Dynamics of Condensed Matter in the Time Domain

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The key insight provided by ultrafast dynamics of condensed matter systems are experimental opportunities to access fundamental excitations caught in action, i.e. observed while they are populated on their intrinsic lifetimes. With femtosecond time resolution at hand dynamic processes determining, e.g., the relaxation and propagation times of non-equilibrium electrons or structural changes induced by external stimuli, which can also change the spin quantum number, are experimentally accessible. In this talk two recent studies will be reported and discussed. First, the propagation of optically excited electrons across an interface between epitaxial metallic layers as well as through one of these layers has been analyzed experimentally by spatially separating pump and probe interaction with the heterostructure sample to its back and front side, respectively. The excited electron is detected on the solid-vacuum interface in time-resolved two-photon photoemission after its propagation through an Fe(001)/Au(001) system. Combining the experimental findings with real-time time-dependent density functional theory and transport simulations, the complete dynamics of the electrons – optical excitation, injection across the interface, and propagation through the Au layer is analyzed microscopically [1]. Second, spin crossover dynamics in condensed layers of Fe(II) complexes are investigated by femtosecond soft x-ray absorption spectroscopy which analyzes the dynamics at fine structure features at the Fe L_3 absorption edge upon resonant optical excitation. In this work an excited intermediate state is identified and assigned. Moreover, the large excitation probability allows to identify effects of molecule-molecule interaction in these films [2]. Both these studies highlight the detailed microscopic insight into excitations that becomes available with the suitable experimental and theoretical concepts and approaches suggesting further development in this direction.

Funding through the Deutsche Forschungsgemeinschaft through the collaborative research center CRC 1242 is gratefully acknowledged.

[1] M. Heckschen et al., PRX ENERGY **2**, 043009 (2023).
[2] L. Kämmerer et al., arXiv:2312.01438 (2023).

Escaping Beam Heating and Electronic Damage Using Ultrashort X-ray Free-Electron Laser Pulses

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Diffraction-before-destruction schemes, enabled by ultrashort X-ray free-electron laser pulses, have led to unrivaled structural refinements using serial femtosecond crystallography. This raises an opportunity to extend the approach to not only outrun structural photoinduced damage but also heating and alterations to electronic orders. First, I will report on an ultralow-temperature vectormagnet setup that has recently become available at the SwissFEL Cristallina endstation, highlighting the advantage of a brilliant, ultrafast X-ray source to access quantum regimes. Second, I will compare the scattering signals of “forbidden” electronic and allowed structural Bragg peaks of elemental silicon, revealing the onset of photoinduced bonding electron reconfigurations on a 10-femtosecond timescale. This suggests limitations for ultrafast X-ray scattering of orders arising from valence electrons, such as charge-density waves in condensed matter, unless even shorter, attosecond X-ray pulses are used.

Interlayer Stacking Order of the 1*T*-TaS_2 Commensurate Charge Density Wave Phase

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The interlayer stacking order and degree of dimerization in the commensurate charge density wave phase in 1*T*-TaS_2 remains highly contested as it becomes increasingly evident that the exact configuration significantly influences the electronic band structure and phonon spectrum. Combining the Hendricks-Teller method with Monte Carlo simulations, we unequivocally reveal the interlayer stacking configuration of the commensurate charge density wave phase in 1*T*-TaS_2 that is benchmarked against experimental X-ray diffraction data. Our results reveal a distribution of monolayers and dimers with a high density of stacking faults. Dynamical mean field theory calculations of this stacking behavior with layered sensitivity show that the insulating ground state is characterized by the coexistence of correlated metal, band and Mott insulating layers, reconciling contradictory conclusions from both theory and experiment on the electronic band structure.

Ultrafast Optical Switching of Magnetic Anisotropy in the Pt/Co/H_2Pc Heterostructure

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The interfaces of 3*d* ferromagnets (FM) with organic molecular semiconductors have attracted significant interest due to their potential applications in the field of spintronics. The hybridization of the surface *d* orbitals of the FM with the *p* orbitals strongly affects the magnetic and electronics properties of both the molecules and the FM at the interface. One of the strongly affected properties is the magnetic anisotropy of the FM [1], which we studied in the Pt/Co/H_2Pc heterostructure. The competing effects of the FM (Co – cobalt) interfaces with the molecular semiconductor (H_2Pc – phthalocyanine) and heavy metal (Pt - platinum) on the magnetic anisotropy have different temperature dependences, leading to the easy-axis of magnetization anisotropy in Co undergoing a temperature transition from in-plane to out-of-plane.

We have investigated the heterostructure Pt(4)/Co(1.4)/H_2Pc(20)/Cu(15) by the means of static and time-resolved polar magneto-optical Kerr effect (MOKE) measurements. Using the static MOKE measurements we traced the temperature dependence of the out-of-plane magnetization loops in Co, which have shown a transition of magnetic anisotropy easy-axis in Co from in-plane to out-of plane in the temperature range of 250 K – 300 K.

We studied the magnetization dynamics (by means of time-resolved MOKE) near the transition temperature of the magnetic anisotropy easy-axis at different applied external magnetic fields. We have observed that after an excitation by an ultrashort (~ 50 fs) laser pulse, the system firstly demagnetizes on the time-scale of ~ 1 ps, followed by an increase of out-of-plane component on the time-scale of 50-500 ps. The largest observed motion of the magnetization out-of-plane was ~ 60 % of the saturation value, showing opportunity to reach total in-plane to out-of-plane reorientation on ~ 100 ps time-scale by further optimization of the heterostructure composition.

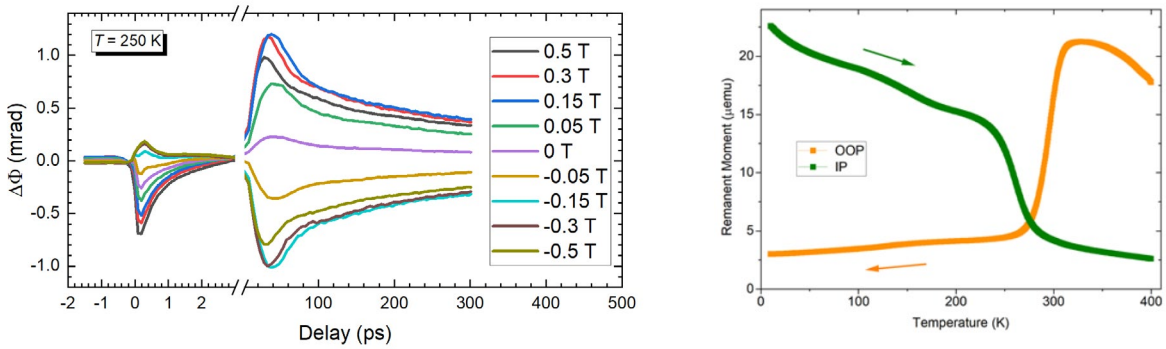

Figure: Transient MOKE near the magnetic anisotropy easy-axis transition at varying external magnetic field (left) and temperature dependence of remanent magnetization orientation.

[1] M. Benini et al., Advanced Materials Interfaces 9, 2201394 (2022).

Multiple carrier generation in a model for Mott photovoltaics

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We investigate multiple carrier generation via impact ionization in a Mott insulator[1,2]. Our study focuses on a model for photovoltaic energy conversion, consisting of one or several correlated layers connected to metallic leads under a finite bias, driven by a periodic electromagnetic field [1,2,3]. The electromagnetic energy is converted into a steady-state current directed towards the higher-potential lead. A kink in the photocurrent as a function of the driving frequency suggests the onset of multiple carrier generation.

We present the characteristics of the photocurrent and power conversion, discussing impact ionisation, multilayer effects and phonon dissipation.

Results are obtained using a steady-state Dynamical Mean Field Theory with an enhanced impurity solver that combines nonequilibrium Green's functions and Lindblad quantum master equations for open quantum systems [4,5].

[1] E. Manosuakis, Phys. Rev. B 82, 125109 (2010); P. Werner et al., Phys. Rev. B 90, 235102 (2014).
[2] M. Sorantin et al., Phys. Rev. B 97, 115113 (2018); P. Gazzaneo et al. Phys. Rev. B 106, 195140 (2022); Phys. Rev. B 109, 235134 (2024).
[3] F. Petocchi et al., Phys. Rev. B 100, 075147 (2019).
[4] E. Arrigoni et al., Phys. Rev. Lett. 110, 086403 (2013); A. Dorda et al., Phys. Rev. B 89 165105 (2014).
[5] D. Werner et al., Phys. Rev. B 107, 075119 (2023).

Direct signatures of light-driven bands in ultrafast nonlinear optical excitations

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Ultrafast nonlinear optical phenomena in solids have been attracting significant attention as novel methodologies for femtosecond spectroscopy of electron dynamics and control over material properties. In this work, we theoretically explore strong-field nonlinear optical transitions in the prototypical two-dimensional material hexagonal boron nitride (hBN), employing time-dependent density functional theory (TDDFT) and model calculations. Our findings reveal that the *k*-resolved conduction band charge occupations induced by an elliptically polarized laser can be understood within a multi-photon resonant picture—remarkably, however, only when considering the Floquet light-dressed states instead of the undressed matter states. Our work demonstrates that Floquet dressing affects ultrafast charge dynamics even in response to a single pump pulse, and establishes a direct measurable signature of band-dressing in nonlinear optical processes in solids, opening new avenues for ultrafast spectroscopy and valley manipulation.

[1] A. Galler, A. Rubio, O. Neufeld, J. Phys. Chem. Lett. 14, 50, 11298-11304 (2023).

Ultrafast screening of photo-excited charge-transfer insulators with time-resolved X-ray absorption spectroscopy

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Recent pioneering experiments have employed time-resolved X-ray absorption spectroscopy (XAS) to investigate the ultrafast, photo-induced renormalisation of electron interactions in Mott and charge-transfer insulators. However, it remains uncertain which microscopic details can be reliably extracted from current measurements and what additional insights could be revealed by future experimental advancements.

We examine how photo-induced charges modify Hubbard interactions via dynamical screening effects manifesting in the XAS signal. We highlight two key aspects of interpreting XAS modifications when screening processes occur on timescales comparable to valence electron dynamics: (i) Screening in a photo-excited system influences both the position and lineshape of absorption peaks and (ii) the resulting effects generally cannot be captured by a single parameter adjustment. Finally, we compare theoretical predictions with XAS data from NiO to assess the magnitude of bandgap renormalisation. Beyond the band-gap renormalisation, we identify additional photo-induced spectral features, which we interpret as many-body multiplets activated by photo-doped charge carriers.

[1] DG, Eva Paprotzki, Philipp Werner, Martin Eckstein, arXiv:2409.06314.
[2] Tobias Lojewski, DG, et al., arXiv:2305.10145.

Multidimensional coherent spectroscopy of correlated lattice systems

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Multidimensional coherent spectroscopy (MDCS) has been established in quantum chemistry as a powerful tool for studying the nonlinear response and nonequilibrium dynamics of molecular systems. More recently, the technique has also been applied to correlated electron materials, where the interplay of localized and itinerant states makes the interpretation of the spectra more challenging. We use the Keldysh contour representation of effective models and nonequilibrium dynamical mean field theory to study the MDCS signals of prototypical correlated lattice systems. By analyzing the current induced by sequences of ultrashort laser pulses we explore the usefulness of MDCS as a diagnostic tool for excitation pathways and coherent processes in correlated solids. The technique also allows to extract information on the nature and evolution of photo-induced nonequilibrium states.

[1] J. Chen and P. Werner, arXiv:2411.02389 (2024).

Non-destructive imaging of bulk electrical 'hidden' state switching in a 1*T*-TaS_2 cryo-memory device

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To directly monitor the ultrafast, non-volatile switching of cryomemory cells, we conducted a 3D, non-destructive imaging experiment of a 1*T*-TaS_2 device at the Swiss Light Source synchrotron. By combining spatially-resolved micro-beam X-ray diffraction and fluorescence with *in-situ* transport measurements, we detect the insulating equilibrium charge-density wave order and the non-thermal metallic hidden state induced by electrical switching. Our findings reveal that the electrically and optically induced hidden states are not only electronically but also structurally equivalent. Additionally, 3D tomograms expose a narrow switching region beneath and in-between the electrodes, highlighting the roles of both charge injection and out-of-plane strain in the switching process.These insights are crucialfor improving 1*T*-TaS_2 device design and set the stage for non-destructive studies of other phase-change materials using synchrotron light.

Immobile topological quantum matter: fractons

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I will discuss a bourgeoning field of "fractons" — a class of models where quasi-particles are strictly immobile or display restricted mobility. Focusing on just a corner of this fast-growing subject, I will explain how one class of such theories — symmetric tensor gauge theories surprisingly emerge from seemingly mundane elasticity of a two-dimensional quantum crystal. The disclination and dislocation crystal defects respectively map onto charges and dipoles of the fracton gauge theory. This fracton-elasticity duality leads to predictions of fractonic phases and quantum phase transitions to their descendants, that are duals of the commensurate crystal, supersolid, smectic, and hexatic liquid crystals. Extensions of this duality to generalized elasticity theories provide a route to discovery of new fractonic models and their potential experimental realizations.

[1] A. Gromov and Leo Radzihovsky, Colloquium: Fracton matter, Rev. Mod. Phys. **96**, 011001, 2024

Topologically choreographed noise due to ultraslow electrons in metastable Wigner crystal states

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Pinpointing the origin of noise in astronomy is achievable by directing a telescope in the desired direction and measuring the time series of the EM response with a detector that has a suitably broad frequency response. Here, we demonstrate the measurement of electronic motion in real time within a quantum material, revealing distinctly different noise spectra at different positions within an electronically quench-ordered quantum material on the nanometer scale.

The observed electrons are confined within a topologically constrained space, and their motion is recorded using a high-speed scanning tunneling microscope. The dynamics are governed by symmetry and topological principles that choreograph the trajectories of the electrons. Fluctuations in the surroundings play a decisive role, leading to the formation of mesoscopic and microscopic topologically protected confined spaces in which the electrons are moving.

The measurement results manifest themselves as classical density distributions of electronic states whose configuration is determined by quantum probabilities. The electrons exhibit pseudo-periodic trajectories that generate correlated telegraph noise that cannot be explained by conventional quasiparticle interference phenomena.

These observed phenomena provide direct insight into polaronic Wigner glass dynamics. This demonstration of principles paves the way for real-time studies of microscopic dynamics in metastable mesoscopic states of quantum materials.

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Real-time Tunnelling Microscopy: A Novel Method of Imaging Non-equilibrium Dynamics

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Non-equilibrium dynamics is usually studied on ultrafast timescales with the techniques resolving as small as femtoseconds or even hundreds of attoseconds (10^{-15} or 10^{-16} s correspondingly), but working with the spatial-averaged signals. The opposite side of the experimental spectrum features atomically resolving `quasi-static` methods like scanning tunnelling microscopy (STM), electron microscopy and many more, used to study metastable states. Recently, many advances have been made to get spatial imaging techniques down to the `ultrafast` time scales, overlooking the potential insights within the micro- to millisecond range.

In this talk, I will present a novel real-time `Fast-STM` imaging technique—a method that allows the study of dynamics of non-equilibrium states with a temporal resolution of 10^{-5} to 10^{-4} seconds and atomic resolution. Using 1T-TaS_2—a material known for its complex charge density wave properties—as an example, I will demonstrate that Fast-STM reveals both single-electron and collective dynamics on the millisecond timescale. These studies uncover previously unknown charge density wave properties, confirm observations on relaxation processes in the material, and validate the applicability of this new technique for such studies.

Too cold for summer, too hot for winter: The story of fading ergodicity

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I will report about our recent observation of a novel ergodic regime dubbed "fading ergodicity". This is a regime in which a quantum system is still ergodic, however, it also acts as a precursor of the ergodicity breaking phase transition. In other words, "fading" ergodicity is a synonym of the "fading" colors of the leafs that are just about to fall off the tree. We conjecture this regime to be a generic property of quantum systems approaching the ergodicity breaking phase transition, and therefore, one cannot make a system nonergodic without first making the ergodicity fade.

[1] M. Kliczkowski, R. Swietek, M. Hopjan, and L. Vidmar, Physical Review B 110, 134206 (2024).

Distinct eigenstate transitions detected via fidelity susceptibilities

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Recent efforts have focused on understanding how systems approach the ergodicity-breaking transition. Several intriguing properties have already been observed. For example, survival probabilities exhibit scale invariance [1], fluctuations in the Eigenstate Thermalization Hypothesis soften for specific observables, giving rise to fading ergodicity [2], and fidelity susceptibilities develop a maximally divergent peak as the critical point is approached [3]. Nevertheless, a unifying explanation conneting these observations remains to be established. In this presentation, we take a step in this direction by studying two eigenstate transitions in the three-dimensional Anderson model. The first occurs between localization in quasimomentum space and single-particle quantum chaos, while the second occurs between single-particle quantum chaos and localization in position space. We focus on fidelity susceptibilities, observing peaks near both transitions, with maximal divergence and so maximal chaos occurring only near the secondone. We explain this difference, linking the first transition to fading ergodicity,while showing why thesecondonedoes not follow this behavior. Instead, we connect it to the polynomial decay of survival probability.

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[2] M. Kliczkowskiet al. Phys. Rev. B 110, 134206(2024).
[3] M. Pandey et al. Phys. Rev. X 10, 041017(2020).

Stirring the false vacuum via interacting quantized bubbles on a 5564-qubit quantum annealer

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False vacuum decay – the transition from a metastable quantum state to a true vacuum state – plays an important role in quantum field theory and non-equilibrium phenomena such as phase transitions and dynamical metastability. The non-perturbative nature of false vacuum decay and the limited experimental access to this process make it challenging to study, leaving several open questions regarding how true vacuum bubbles form, move, and interact. Here, we observe quantized bubble formation in real time, a key feature of false vacuum decay dynamics, using a quantum annealer with 5564 superconducting flux qubits. We develop an effective model that captures both the initial bubble creation and subsequent interactions, and remains accurate under dissipation. The annealer reveals coherent scaling laws in the driven many-body dynamics for more than 1000 intrinsic qubit time units. This work provides a method for investigating false vacuum dynamics of large quantum systems in quantum annealers.

Scaling theory of many-body ergodicity breaking

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In most non-interacting quantum systems, the scaling theory of localization predicts one-parameter scaling flow in both ergodic and localized regimes [1]. On the other hand, it is expected that in the presence of interactions, at the many-body ergodicity breaking transition, the one-parameter scaling hypothesis breaks down. Here, studying the quantum sun model for many-body ergodicity breaking [2,3], we argue that the two-parameter scaling in the ergodic regime exhibits a simple structure that carries similarities with one-parameter scaling. We introduce a scenario in which the irrelevant corrections amount to substitute the linear dimension L with $L-L_0$, where L_0 is a characteristic ergodisation length, giving rise to the resilient one-parameter scaling at $L \gg L_0$. The finite-size correction introduce an effective one-parameter scaling, where the critical exponent may deviate strongly from the predicted exponent for ergodocity breaking phase transitions. Our theoretical framework may serve as a building block for two-parameter scaling theories of many-body systems.

[1] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979).
[2] J. Šuntajs and L. Vidmar, Phys. Rev. Lett. 129, 060602(2022).
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Typical entanglement entropy of pure states with SU(2) symmetry

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We discuss the effect that the SU(2) symmetry, and the rich Hilbert space structure that it generates in lattice spin systems, has on the average entanglement entropy of highly excited eigenstates of local Hamiltonians and of random pure states [1]. Focusing on the zero total magnetization sector for different fixed total spin, we show that the average entanglement entropy of highly excited eigenstates of quantum-chaotic Hamiltonians and of random pure states has a leading volume-law term whose coefficient depends on the spin density. We provide numerical evidence that the average entanglement entropy is smaller in highly excited eigenstates of integrable interacting Hamiltonians, which lends support to the expectation that the average eigenstate entanglement entropy can be used as a diagnostic of quantum chaos and integrability for Hamiltonians with non-Abelian symmetries. For quantum-chaotic Hamiltonians and for random pure states, we also study the subleading corrections. We find that the nonabelian SU(2) symmetry generates a log volume correction in addition to corrections known to be present in the abelian U(1) case.

[1] R. Patil, L. Hackl, G. R. Fagan, and M. Rigol, Average Pure-State Entanglement Entropy in Spin 1/2 Systems with SU(2) Symmetry, Phys. Rev. B **108**, 245101 (2023).

Scaling of excitation densities following a first-order quantum phase transition on a programmable quantum annealer

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First-order quantum phase transitions are key phenomena in the study of non-equilibrium dynamics within many-body systems, leading to complex behaviors like metastability, coarsening, and nucleation. Slow quenches across transition points are well understood for second-order transitions through the Kibble-Zurek mechanism [1], and recent research has extended this framework to certain first-order transitions as well [2, 3]. Advances in quantum technology now offer new programmable and controllable platforms allowing for experimental investigations of first-order transitions across diverse quantum systems. Here, we examine the scaling of excitation densities in the tilted Ising model when driven across a first-order quantum phase transition using the D-Wave programmable quantum annealer. We employ a protocol where, beginning in the ground state, the longitudinal field in the Ising model is gradually varied through the first-order quantum phase transition. During this evolution, excitations in the form of quantized bubbles emerge at specific parameter values, with their densities following scaling laws akin to the Kibble-Zurek mechanism. We utilize the D-Wave quantum annealer to access large-scale systems of 2000 qubits and long simulation times. Quantum simulation results from the quantum annealer are compared to numerical simulations.

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[3] L.-Y. Qiu, H.-Y. Liang, Y.-B. Yang, H.-X. Yang, T. Tian, Y. Xu and L.-M. Duan. Observation of generalized kibble-zurek mechanism across a first-order quantum phase transition in a spinor condensate. Science Advances, 6(21):eaba7292 (2020).

Device fabrication for a spatially-resolved μARPES study of the current-driven hidden state of 1*T*-TaS_2

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We present a new device fabrication approach for studying the electrically-induced hidden state in 1*T*-TaS_2 via surface-sensitive, techniques such as spatially-resolved angle-resolved photoemission spectroscopy (μARPES). A recent experiment [1] revealed spatially heterogeneous electronic structures in this material using manually shaped bulk samples and hand-painted silver-epoxy contacts with large (500 μm) contact separations. In contrast, our approach uses silicon shadow masks for precise Ti/Au contact patterning, enabling much smaller device dimensions (5 μm). This method allows for *in-situ* exfoliation of electrically contacted thin flakes while preserving a pristine 1*T*-TaS_2 surface, facilitating both μARPES mapping and *in-situ* resistance measurements. I will also review our ongoing experimental efforts, aiming to provide new insights into the spatial formation of the metallic hidden state.

[1] Y. Nitzav et al., arXiv:2407.05535 (2024).

Nearly integrable dynamics and usage of atomic ensembles coupled to light

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Quantum memory for light is a promising application of atomic ensembles. In this case, an optical state is imprinted into a collective atomic excitation on demand. When the ensemble is describable by a continuous medium, there exists a well-known fundamental bound on the storage error, governed by the Maxwell–Bloch equations. However, these equations assume the emission of the atoms into other directions than the mode of interest to be independent. On the other hand, in systems of ordered atomic arrays placed at distances smaller than the light's wavelength, atoms interact with each other strongly, and spatial interference of the emitted light might be exploited to suppress emission into unwanted directions, thereby enabling improved error bounds.

Thus far, techniques to enable better performance have focused on sub-wavelength lattice constants and two-dimensional arrays, whereas super-wavelength configurations might provide simpler experimental routes to realization (e.g., via tweezer arrays). Here, we proposed a method by which three-dimensional atom arrays with super-wavelength lattice constant can be used to realize "selective radiance," where emission into unwanted spatial modes is suppressed to enable better performance of certain quantum optical applications, such as photon storage and photon gates.

Additionally, subwavelength atomic arrays coupled to light show intriguing emergently critical dynamics. We explain the origin of the dynamics to be related to the dynamics of weakly open, nearly integrable systems which are decribable by time-dependent generalized Gibbs ensembles.

[1] C.-R. Mann, F. Andreoli, V. Protsenko, Z. Lenarčič, D. Chang, Selective Radiance in Super-wavelength atomic arrays, arXiv:2402.06439.

[2] I. Ulčakar and Z. Lenarčič, Generalized Gibbs ensembles in weakly interacting dissipative systema and digital quantum computers, arXiv:2406.17033.

Nonthermal order by nonthermal disorder

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The quench dynamics of systems exhibiting cooperative or almost competitive orders in equilibrium are explored using Ginzburg-Landau theory plus fluctuations. We show that when the renormalization of the free energy by fluctuations is taken into account, anisotropic stiffnesses and relaxation rates of the order parameters can lead to a stabilization of ordered states at transient free energy minima which are distinct from any (global or local) minima of the equilibrium free energy. This theory demonstrates that nonequilibrium fluctuations play a pivotal role in forming nonthermal orders. As nonthermal order and nonthermal fluctuations mutually stabilize each other over some time, this mechanism could be seen as a nonequilibrium variant of the order-by-disorder phenomenon. We discuss the relevance of these findings for systems with intertwined orders, such as high-temperature superconductors and the kagome metals, as well as for systems that show orbital ordering.

[1] Francesco Grandi, Antonio Picano, Ronny Thomale, Dante M. Kennes, Martin Eckstein, aXiv:2412.02616.

Characterization of non-Markovian features of subsystem dynamics

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Accessing the long-time non-equilibrum dynamics of many-body systems is a hard numerical task. While short time evolution can be efficiently performed, for example, using tensor network, long time behaviour is difficult to capture due to generically high entanglement built during the time evolution. If interested only in local observables, one could extract them from subsystem dynamics. Corresponding evolu.on is non-unitary due to the coupling to the rest of the system. Here, we use Adam Optimization Algorithm to find the time-local, not necessarily completely positive map that best captures the given short-time subsytem dynamics obtained from thermodynamic tensor network calculations. Learned map reveals the nature of coupling to the environment and we are exploring whether these maps could be used to evolve subsystem to longer times that are unaccessible for direct simulation.

[1] Miguel Frias-Perez, Mari Carmen Banuls, Phys. Rev. B 106, 115117 (2022).
[2] Hall, Cresser, Andersson, Phys. Rev. A 89, 042120 (2014).

Resolving Length Scale Dependent Transient Disorder Through An Ultrafast Transition

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The development of materials with specialized and highly efficient properties increasingly relies on complex local structures that stray from the ideal of a perfect crystal. Advancements in electronics technology drive a need for materials that switch between distinct states: either electrical (e.g., memristors, ferroelectrics), magnetic (e.g., ferromagnets, antiferromagnets) or structural (e.g., charge density wave states). A key example is the metal-insulator transition. It is well established that local structure plays a central role in many equilibrium phase transitions driven by the competition of energy and entropy. Some non-equilibrium phase transitions can be triggered on demand using ultrafast laser pulses. Local structure has also been implicated in these transitions, but this is less understood due to a lack of appropriate means to quantify length scale dependent local disorder in these ultra-fast transient states.

The pair distribution function method has propelled structural studies beyond idealized crystal models, enabling atomic structure studies of quantum materials over varying length scales. It has indeed been instrumental in revealing concealed from detection nanoscale behaviors that have been increasingly frequently critical for comprehensive understanding of establishment of quantum phases. Applying this method with ultrafast time resolution has the potential to similarly disrupt the study of structural dynamics and phase transitions. Here, we demonstrate such a measurement of $CuIr2S_4$, an archetypal spin singlet dimer system exhibiting orbitally driven Peierls transition in equilibrium [1], optically pumped from its low temperature Ir-dimerized phase. Dimers are optically removed without spatial correlation, generating a structure whose level of disorder depends strongly on length scale. The re-development of structural ordering over tens of picoseconds is directly tracked over both space and time as a transient state is approached. This measurement demonstrates both the crucial role of local structure and disorder in non-equilibrium processes and the feasibility of accessing this information in quantum materials with state-of-the-art XFEL facilities [2].

[1] E. S. Bozin, W. G. Yin, R. J. Koch, M. Abeykoon, Y. S. Hor, H. Zheng, H. C. Lei, C. Petrovic, J. F. Mitchell & S. J. L. Billinge, Nature Communications 10, 3638 (2019).
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Photo-induced chirality in a non-chiral crystal

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Chirality is a form of symmetry closely related to the physical properties of solids and the chemical and biological activity of molecular systems. However, inducing chirality in a non-chiral material is challenging, because it requires breaking all mirrors and all roto-inversions simultaneously.

In this talk, I will show how nonlinear phononics, a protocol for rationally designing the structure and symmetry of crystals with light,[1,2] can be used to induce chirality of either handedness in the non-chiral piezoelectric material BPO_4.

At equilibrium, two compensated sub-structures of opposite handedness coexist within the unit cell of this material. By resonantly driving either one of two orthogonal, doubly degenerate infrared-active phonon modes with intense mid-infrared light pulses, we were able to displace a second lattice distortion with a positive or negative amplitude, uncompensating the staggered chirality and creating a picosecond-lived structure with either handedness. The optical activity of the transient chiral phases is comparable to the static value of prototypical chiral α-quartz, limited by the strength of the strength of the mid-infrared excitation pulse used in our experiment.

These findings offer new prospects for the control of out-of-equilibrium quantum phenomena in complex materials.

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[2] A. Disa et al. Nature Physics 17, 1087 (2021).
[3] Z. Zeng et al. arXiv 2407.08491 (2024).

Optical signatures of dynamical excitonic condensates

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Excitons, or bound electron-hole pairs, can condense into an excitonic insulator state, similarly to Cooper pairs in superconductors. A non-equilibrium carrier concentration, such as the one transiently induced by photo-doping or sustained by a tuneable bias voltage in bilayers, can create a dynamical excitonic insulator state, yet proving phase coherence in such setups remains challenging.

We examine the condensate phase behavior theoretically and show that optical spectroscopy can distinguish between phase-trapped and phase-delocalized dynamical regimes. In the weak-bias regime, trapped phase dynamics result in an in-gap absorption peak nearly independent of bias voltage, while at higher biases its frequency increases approximately linearly.

Both regimes exhibit pronounced second harmonic responses. In the large bias regime, the response current grows strongly under the application of a weak electric probe leading to negative weight in the optical response, which we analyze relative to predictions from a minimal model for the phase. This work opens new avenues for experimentally probing coherence in excitonic condensates and the detection of their dynamical regimes.

Lindblad dynamics and GGEs in quantum computers

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Identifying use cases with superconducting circuits not critically affected by the inherent noise is a pertinent challenge. Here, we propose using a digital quantum computer to showcase the activation of integrable effects in weakly dissipative integrable systems. Dissipation is realized by coupling the system's qubits to ancillary ones that are periodically reset. We compare the digital reset protocol to the usual Lindblad continuous evolution by considering non-interacting integrable systems dynamics, which can be analyzed using scattering between the Bogoliubov quasiparticles caused by the dissipation. The inherent noise would cause extra scattering but would not critically change the physics. A corresponding quantum computer implementation would illuminate the possibilities of stabilizing exotic states in nearly integrable quantum materials.

[1] I. Ulčakar and Z. Lenarčič, Generalized Gibbs ensembles in weakly interacting dissipative systems and digital quantum computers, arXiv:2406.17033 (2024).

Complexity beyond entanglement - magic of strongly interacting quantum matter

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Quantum resources have entered the many body stage over the last two decades. It is by now widely appreciated that entanglement plays a key role in characterizing physical phenomena, as diverse as topological order and critical behaviour. However, entanglement alone is not informative about state complexity, and in fact, it is only one side of the medal. In this talk, I will flip the coin and tackle quantum state complexity of many-body systems under the lense of non-stabilizerness - also known as magic. Magic quantifies the difficulty of realizing states in most error corrected codes, and is thus of fundamental practical importance. However, very little is known about its significance to many-body phenomena.I will present method(s) to measure magic in tensor network simulations, and illustrate a series of applications to many body systems, including:

a) how state magic and long-range magic behave in conformal field theories - illustrating the limit of the former, and the capabilities of the latter;
b) how magic characterizes phases of lattice gauge theories,
c) both in the context of spin liquids/error correction (toric code), and in the context of theories describing coupling between matter and light (Schwinger model); and
d) how the corner of Hilbert space represented matrix product states is in fact chopped into different complexity blocks, once magic is properly taken into account.

Finally, I will discuss the broader impact of these findings on state complexity - indicating that realizing generic state quantum dynamics may require a very large amount of resources in error correcting quantum computers, but at the same time, providing interesting perspectives on new classes of variational states more powerful than tensor networks.

Magic spreading under quantum many-body dynamics

Xhek Turkeshi, Emanuele Tirrito, Piotr Sierant

Magic state resources, also known as the non-stabilizerness, quantify the beyond-Clifford operations necessary for universal quantum computing and are related to complexity of representing states of quantum many-body systems on classical computers. How rapidly are magic resources generated by generic many-body dynamics under constraints of locality? What can we say about non-stabilizerness of time-evolved state in the limit of long-time evolution under many-body Hamiltonians?

In this talk, I will address these questions by discussing non-stabilizerness of Haar-random states, and its relation with non-stabilizerness of eigenstates of ergodic many-body systems [1]. Subsequently, I will discuss the problem of magic spreading in brick-wall random unitarycircuits [2], which combine principles of locality and unitarity, serving as a minimal model of ergodic many-body dynamics. A replica trick enables the investigation of non-stabilizerness dynamics for systems of up to N = 1024 qudits. Our main finding is that magic resources equilibrate on timescales logarithmic in system size N, akin to anticoncentration and Hilbert space delocalization measures, but differently from entanglement entropy.

[1] X. Turkeshi, A. Dymarsky, P. Sierant, Pauli Spectrum and Magic of Typical QuantumMany-Body States, arXiv:2312.11631
[2] X. Turkeshi, E. Tirrito, P. Sierant, Magic spreading in random quantum circuits,arXiv:2407.03929

Tuning slow dynamics in a family of quantum East models: Insights from Fock-space graphs

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In the field of thermalization in closed quantum systems, we use eigenstate thermalization to characterize ergodic systems while instances of fully nonergodic systems would be many-body localization, if stable. Recently, a rich behavior has been found in systems with dynamical or kinetic constraints, which exhibit weak erghodicty breaking. Many such quantum models are inspired by classical spin glass physics, with the quantum East model a prominent example [1]. This models exhibits a region of nonergodic dynamics as signalled by nonthermal long-time values of density autocorrelations for many initial states, at least on finite systems. This is traced back to the existence of localized states [2] and presumably clusters of states weakly hybridized with the rest of all states [3], in the computational basis.

Using the computational basis, i.e., the eigenbasis of local density operators, we construct the Fock-space graph for the quantum East model. The associated Hamiltonian gives rise to ergodic dynamics, hence the nonergodicty is driven by the diagonal detuning of nodes. Simply speaking, such detuning leads to delayed decay of density autocorrelations in the sense of perturbation theory. We introduce measures to capture the hierarchy of detuned nodes inspired from graph theory and then define a family of quantum East models gnerated by different detuning protocols. By computing density autocorrelationss and eigenstate entanglement entroyp, we propose a connection of graph theoretical measures and the degree of nonergodicty [4].

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[2] Pancotti et al. Phys. Rev. X **10**, 021051 (2020).
[3] Badbaria et al. arXiv:2407.12909.
[4] Menzler, Bañuls, Heidrich-Meisner, in preparation.

Critical dynamical exponent in short-range quadratic Hamiltonians

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We investigate the spreading of a particle described by quadratic Hamiltonian with short-range hopping in lattices of various dimensions. We find that the critical transport is achieved when the Thouless time, defined as time of saturation of the mean-square displacement, approaches the typical Heisenberg time, related to the Hausdorff fractal dimension of eigenspectrum. For the critical transport, we find a simple relation between the dynamical exponent z and the fractal dimension of the eigenspectrum d_s. As an example, we consider lattices with Fibonacci-potential in one, two and three dimensions. Our study reveals that the superdiffusive transport in two dimensions and the diffusive transport in three dimensions cannot be critical and it clarifies known results for e.g. the Anderson or Aubry-André models [1].

[1] M. Hopjan and L.Vidmar, in preparation.

Quantum versus classical dynamics in closed and open spin systems

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We present a comprehensive comparison of spin and energy dynamics in quantum and classical spin models on different geometries, ranging from one-dimensional chains, over quasi-one-dimensional ladders, to two-dimensional square lattices [1,2]. In particular, we focus on the dynamics at formally infinite temperature and consider the correlation functions of local densities, where the time evolution is generated either by the (linear) Schrödinger equation in the quantum case, or by the (nonlinear) Hamiltonian equations of motion in the classical case. While, in general, a quantitative agreement between quantum and classical dynamics cannot be expected, our large-scale numerical simulations for spin-1/2 systems with up to N=36 lattice sites defy this expectation. Specifically, we observe a remarkably good agreement for all geometries, which is best for the nonintegrable quantum models in quasi-one or two dimensions, but still satisfactory in the case of integrable chains, at least if transport properties are not dominated by quasilocal conserved charges. Our findings indicate that classical simulations provide a meaningful strategy to analyze the dynamics of many-body quantum models, even in cases where the spin quantum number S=1/2 is small and far away from the classical limit $S \to \infty$. Finally, we discuss how this finding can be used to obtain Lindblad quantum dynamics from correlation functions of classical spin chains [3].

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Room-temperature non-volatile switching in a charge density wave material

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Control over the novel quantum states that emerge from non-equilibrium conditions is of both fundamental and technological importance. Metastable charge density wave (CDW) states are particularly interesting as their electrical manipulation could lead to ultra-efficient memory devices. However, the ability to use electrical pulses for non-volatile resistance switching involving CDW states is exceedingly rare and has been limited to cryogenic temperatures. In this work, we investigate a recently discovered layered semiconductor that exhibits competition between distinct CDW orders that were shown to be susceptible to optical manipulation [1,2,3]. We report that electrical pulses can be used for excitation to novel, yet stable electronic states over a broad temperature range between 6 K and 400 K. We find that switching is driven primarily by an electrical field and is fully reversible via a thermal erase procedure. Our experiments show that the pathway for switching is both fast and non-thermal. The resistance of the new electronic state is tuneable with the electrical pulse voltage, so the electronic device acts as a memristor. Our work opens the door for the room temperature electrical control of the CDW order. Furthermore, low-voltage, fast, and non-thermal operation reported here holds great promise for novel memory devices and neuromorphic computing applications.

[1] D. Wu et al. Phys. Rev. Materials 3, 024002 (2019)
[2] B. Q. Lv et al. Phys. Rev. Lett. 128, 036401 (2022)
[3] Q. Liu et al. Nat. Commun. 15, 8937 (2024)

Charge Density Wave Stacking and Metastable Energy Landscapes in $EuTe_4$

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The rare-earth telluride EuTe4 is a layered compound exhibiting charge density wave (CDW) order and a remarkable unconventional hysteretic transition with a temperature range of over 400 K [1]. The origin of the transition, which lies entirely within the incommensurate CDW phase of $EuTe_4$, has recently been the subject of heavy debate [2]. New experimental findings also suggest $EuTe_4$ to be a promising candidate for ambient condition non-volatile all-optical control through the manipulation of its electronic polar states [3].

We present a theoretical study of the CDW mechanism and the associated hysteresis in $EuTe_4$. Through the construction of a tight-binding lattice model based on Fermi surface nesting, we obtain peaks in the susceptibility response, consistent with (one of) the experimentally observed wave vector(s) [2]. We recover the V-shaped trimer formations within individual layers by incorporating lattice distortions via Peierls coupling. We show that interlayer stacking generically leads to stable excited states and the exploration of the energy landscape for the various multilayer configurations uncovers a plethora of near-degenerate metastable states. The symmetry analysis of these states, in relation to experimental measurements of second harmonic generation (SHG), indicates that polar order layer stacking dynamics plays an important role in the exotic properties of $EuTe_4$.

[1] D.Wu et al., Phys. Rev. Materials 3, 024002 (2019).
[2] B. Q. Lv et al., Phys. Rev. Lett. 128, 036401 (2022).
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Long-living prethermalization in nearly integrable spin ladders

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Relaxation rates in nearly integrable systems usually increase quadratically with the strength of the perturbation that breaks integrability. We show that the relaxation rates can be significantly smaller in systems that are integrable along two intersecting lines in the parameter space. In the vicinity of the intersection point, the relaxation rates of certain observables increase with the fourth power of the distance from this point, whereas for other observables one observes standard quadratic dependence on the perturbation. As a result, one obtains exceedingly long-living prethermalization but with a reduced number of the nearly conserved operators. We show also that such a scenario can be realized in spin ladders.

Bethe-Peierls approximation in the era of quantum computers

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Tensor networks have been foundational tools in our understanding of many-body physics of one-dimensional systems. In this talk I will discuss efforts to move away from one-dimensional tensor networks towards networks of arbitrary structures. I will discuss how well established tools from statistical mechanics have propelled recent algorithmic advances and how these tools have been employed to efficiently simulate recent large scale quantum computations.

Impact of Coherent Phonons on Time-Resolved Optical Properties of WTe_2

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The study of transient, far-from-equilibrium states in complex materials can reveal detailed insights into their microscopic properties, especially when multiple observables are considered. In particular, a key question concerns the possibility to track and control atomic lattice displacements [1].

In this work, we investigate the ultrafast dynamics of non-centrosymmetric tungsten ditelluride (WTe_2) by simultaneous time-resolved reflectivity (TR-R) and time-resolved second-harmonic generation (TR-SHG) measurements, performed as a function of the absorbed pump fluence. This twin probe approach, encompassing both linear and nonlinear optical responses, provides a robust framework for analyzing electronic and lattice dynamics in WTe_2.

We performed TR-R and TR-SHG measurements along the two orthogonal in-plane axes of the orthorhombic unit cell, revealing two main phonon modes: a shear phonon mode at ~0.24 THz, indicative of uniform in-plane atomic shifts and visible in both TR-R and TR-SHG signals, and a mode at ~2.4 THz, detected solely in the TR-SHG signal.

A significant (~90°) phase shift in the shear mode is observed in both TR-R and TR-SHG signals and along the two crystallographic directions as a function of pump fluence, suggesting that this phase shift arises from a fluence-dependent change of the phase of the atoms. These findings provide new perspectives for describing on the interactions between coherent phonons and the electronic and lattice properties of complex materials, underscoring the critical role of selecting appropriate experimental observables to extract quantitative information on material properties [2]. Remarkably, we proved that pump fluence can be used as a simple tool to largely modify and tune the initial oscillation phase of the coherent displacements.

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Debye relaxation and ac response of pinned vortex state in superconductors

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Theory of linear microwave response of thin films of type-II superconductors in the mixed state is developed taking into account random spatial fluctuations of the parameters of the system, such as the order parameter, diffusion coefficient, or film thickness. In the regime of collective pinning *ac* response of the system exhibits strong frequency dispersion, arising from nonequilibrium vortex core quasiparticles. The corresponding contribution to the *ac* conductivity is controlled by the inelastic relaxation time, and may exceed the usual Bardeen-Stephen conductivity by orders of magnitude. It is caused by the Debye-type inelastic relaxation. Recently such a phenomenon was observed in NbN and MoGe thin films [1]. Debye mechanism of *ac* losses may be responsible for strong effects of electromagnetic noise upon dc conductivity in the mixed state at low temperatures [2].

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Time resolved RIXS of graphite

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In this presentation, a study conducted on highly oriented pyrolytic graphite using time-resolved resonant inelastic X-ray scattering (trRIXS) will be discussed. Near-UV laser pulses were utilized to excite the system, resonantly targeting the π-π* states near the **M** saddle. The transient electronic structure was probed with FEL pulses tuned to the carbon K-edge, revealing significant renormalization of the RIXS spectra and of the valence band. Key features include the emergence of phonon sidebands and the strong coupling of σ* states to E_{2g} phonons.

These results will be contextualized in light of previous theoretical and experimental findings, highlighting the role of electron-phonon interactions in driving the observed ultrafast dynamics.

Nonequilibrium *GW* calculations based on quantics tensor trains

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One of the challenges in diagrammatic simulations of nonequilibrium phenomena in lattice models is the large memory demand for storing momentum-dependent two-time correlation functions. This problem can be overcome with the recently introduced quantics tensor train (QTT) representation of multivariable functions. Here, we demonstrate nonequilibrium GW simulations with high momentum resolution, up to times which are long enough to study excitation and thermalization processes. The self-consistent calculation on the three-leg Kadanoff-Baym contour employs only QTT-compressed functions, with input functions also generated directly in the QTT form. Our work shows the practical usefulness of this new approach to diagrammatic many-body calculations.

Thouless approach to transport in disordered and nearly integrable spin chains

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The sensistivity of model systems to flux or twisted boundary condition can serve as a tool to distinguish the transport, being either ballistic, normal dissipative or insulating, as first employed 50 years ago in the studies of localization problem. We first consider the relation between level sensitivity R and spin diffusion in spin chains with quasiperiodic potential [1] where Thouless criterion explains the drift with the system size of the crossover to nonergodic/localized regime. In integrable easy-axis Heisenberg chain [2] we show that the apparent spin diffusion is anomalous, since the variation of R with the level spacing is closer to ballistic systems, than to normal dissipative ones. The introduction of finite perturbation reduces R, leading to a pronounced minimum at the crossover to the normal regime, satisfying the random-matrix-theory universality. Moreover, extrapolating to large systems the variation of spin conductivity/diffusivity appears to exhibit a discontinuous jump with the perturbation strength.

[1] P. Prelovšek, J. Herbrych, and M. Mierzejewski, Phys. Rev. B 108, 035106 (2022)
[2] J. Pawlowski, M. Mierzejewski, and P. Prelovšek, in preparation.

Quantum Many-Body Scars in Dual-Unitary Circuits

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Dual-unitary circuits are a class of quantum systems for which exact calculations of various quantities are possible, even for circuits that are nonintegrable. The array of known exact results paints a compelling picture of dual-unitary circuits as rapidly thermalizing systems. However, in this Letter, we present a method to construct dual-unitary circuits for which some simple initial states fail to thermalize, despite the circuits being "maximally chaotic," ergodic and mixing. This is achieved by embedding quantum many-body scars in a circuit of arbitrary size and local Hilbert space dimension. We support our analytic results with numerical simulations showing the stark contrast in the rate of entanglement growth from an initial scar state compared to nonscar initial states. Our results are well suited to an experimental test, due to the compatibility of the circuit layout with the native structure of current digital quantum simulators.

[1] Leonard Logaric, Shane Dooley, Silvia Pappalardi, and John Goold, "Quantum many-body scars in dual uni- tary circuits," (2024), Physical Review Letters.

Ultrafast Band Structure Dynamics in Bulk VSe_2

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Complex materials encompassing different phases of matter can display new photoinduced metastable states differing from those attainable under equilibrium conditions. These states can be realized when energy is injected in the material following a non-equilibrium pathway, unbalancing the unperturbed energy landscape of the material. Guided by the fact that photoemission experiments allow for detailed insights in the electronic band structure of ordered systems, here we study bulk 1T-VSe_2 in its metallic and charge-density-wave phase by time- and angle-resolved photoelectron spectroscopy. After near-infrared optical excitation, the system shows a net increase of the density of states in the energy range of the valence bands, in the vicinity of the Fermi level, lasting for several picoseconds. We discuss possible origins as band shifts or correlation effects on the basis of a band structure analysis. Our results uncover the possibility of altering the electronic band structure of bulk 1T-VSe_2 for low excitation fluences, contributing to the understanding of light-induced electronic states.

Can Quantum Computers Do Nothing?

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Quantum computing platforms are subject to contradictory engineering requirements: qubits must be protected from mutual interactions when idling ('doing nothing'), and strongly interacting when in operation. If idling qubits are not sufficiently protected, information can 'leak' into neighbouring qubits, become non-locally distributed, and ultimately inaccessible. Candidate solutions to this dilemma include patterning-enhanced many-body localization, dynamical decoupling, and active error correction. However, no information-theoretic protocol exists to actually quantify this information loss due to internal dynamics in a similar way to e.g. SPAM errors or dephasing times. By reframing quantum computers as true, many-body, interacting, disordered systems in their own right, we can exploit tools from many-body and information theory to address this issue. In this work, we develop a scalable, flexible, device non-specific protocol for quantifying this bitwise idle information loss based on the exploitation of tools from quantum information theory. We implement this protocol in over 3500 experiments carried out across 4 months (Dec 2023 - Mar 2024) on IBM's entire Falcon 5.11 series of processors. After accounting for other sources of error, and extrapolating results via a scaling analysis in shot count to zero shot noise, we detect idle information leakage to a high degree of statistical significance. This work thus provides a firm quantitative foundation from which the protection-operation dilemma can be investigated and ultimately resolved.

Poster session

Universal distributions of overlaps from unitary dynamics in generic quantum many-body systems

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We study the preparation of a quantum state using a circuit of depth t from a factorized state of N sites. We argue that in the appropriate scaling limit of large t and N, the overlap between states evolved under generic many-body chaotic dynamics belongs to a family of universal distribution that generalizes the celebrated Porter-Thomas distribution. This is a consequence of mapping replicas in the space to a model of dilute domain walls. Our result provides a rare example in which analysis at an arbitrary number of replicas is possible, giving rise to the complete overlap distribution. Our general picture is derived and corroborated by the exact solution of the random phase model and an emergent random matrix model given by the Ginibre ensemble. Finally, numerical simulations of two distinct random circuits show excellent agreement, demonstrating universality.

Exploring quantum resources in random parameterized quantum circuits

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Parameterized quantum circuits (PQCs) are one of the building blocks of the Variational Quantum Algorithms, hybrid algorithms which consist of a quantum circuit, a cost function, and a classical optimization method [1]. The quantum part of the problem, the PQC, can be studied by the characterization of its properties as a random quantum circuit, obtained sampling the circuit parameters according to a particular probability distribution [2, 3]. The so obtained random circuit will not only represent the averaged properties of the architecture of the original PQC, but will also provide a framework to study the characteristics of possible random scrambling systems based in quantum circuits with the provided structure. In this work, we studied how restrictions on the architecture of the quantum circuit, as the topology of the qubits connections, freedom on the parameterization, and presence of indefinite causal order, influence the generation of uniformly distributed pure states quantified with the expressibility [2] and the generation of entanglement measured by the Scott [4] and Concurrence [5] quantifiers. In the part of the study where we compare topologies, it waspossible to observe that the topology of the circuit (i.e., the connectivity considered) is highly influential to the generation of entanglement, which is then reflected in the generation of uniformly distributed states. Circuits generating entanglement standard deviations closer to the analytic values for the real uniform distribution (Haar case) have a steeper increase of the expressibility in higher dimensional systems [3]. In a simpler setting of 2 qubits circuits, we studied how the presence of indefinite causal structures can benefit the generation of uniformly distributed random states in comparison with regular definite causal circuits. To understand the results, we applied a parameterized Quantum Switch [5] to represent the class of indefinite causal structured circuits. The results for the comparison with the Quantum Switch shown that indefinite causal ordered circuits have higher values and a steeper increase of expressibility when compared to causally ordered ones with similar gate structure. This result constrasts with the previous observation, where the entanglement in smaller dimensions is not the most important factor, but here the indefinite causal order plays an important role [5]. In this sense, we explored how different quantum resources, more specifically entanglement and indefinite causal order, can be applied to generate random circuits based on parameterized gates.

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Critical quantum dynamics of observables at eigenstate transitions

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Based on the dynamics of survival probability in a quantum quench protocol, the intriguing critical phenomena of scale invariance was recently pointed out for eigenstates transitions, providing a promising tool to detect the boundaries of thermalizing behavior in closed quantum systems. In this work we generalize single-particle survival probability to transition probabilities between singleparticle states in the eigenbasis of the Hamiltonian before a quantum quench. Studying two paradigmatic quadratic Hamiltonians, i.e. the three-dimensional Anderson model and the onedimensional Aubry–André model, we demonstrate that the transition probabilities exhibit scaleinvariant mid- and late-time dynamics in a similar fashion as the survival probability. Futher, we show that under the dynamics governed by quadratic Hamiltonians, one-body observables in a many-body sector are given as linear combinations of single-particle transition probabilities. As the main result of this work, we then demonstrate that scale invariance occurs also for generic observables like the particle imbalance in a quench from an initial Hamiltonian that shares the observables eigenbasis.

Fading ergodicity in the models of ergodicity breaking transition

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Eigenstate thermalization hypothesis (ETH) represents a breakthrough in many-body physics since it allows the linking of thermalization of physical observables with the applicability of random matrix theory (RMT) [1-4]. Recent studies were also extremely fruitful in exploring possible counterexamples to thermalization, ranging, among, from integrability, single-particle chaos, many-body localization, many-body scars, to Hilbert-space fragmentation. In all these cases the conventional ETH is violated. However, until recently, it remained elusive how the conventional ETH breaks down when one approaches the boundaries of ergodicity, and whether the range of validity of the ETH coincides with the validity of RMT-like spectral statistics. In our recent work, we bridged this gap and set up a novel scenario of the ETH breakdown in many-body quantum systems, dubbed fading ergodicity regime, which establishes a link between the conventional ETH and nonergodic behavior [6]. We provided numerical and analytical arguments for its validity for the quantum sun model of ergodicity-breaking phase transition [7]. We also conjectured that one may not observe the breakdown of ergodicity without entering the region where ergodicity fades. Here, we provide more evidence that the breakdown of the conventional ETH is not associated with the breakdown of RMT-like spectral statistics. We further follow the same phenomenology to illustrate the conjecture's relevance for other models exhibiting the ergodicity breaking transition.

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Signature of preformed pairs in angle-resolved photoemission spectroscopy

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We use density matrix renormalization group (DMRG) and variational exact diagonalization (VED) to calculate the single-electron removal spectral weight for the Hubbard-Holstein model at low electron densities. Tuning the strength of the electron-phonon coupling and of the Hubbard repulsion allows us to contrast the results for a liquid of polarons versus a liquid of bipolarons. The former shows spectral weight up to the Fermi energy, as expected for a metal. The latter has a gap in its spectral weight, set by the bipolaron binding energy, although this is also a (strongly correlated) metal. This difference suggests that angle-resolved photoemission spectroscopy could be used to identify liquids of pre-formed pairs. Furthermore, we show that the one-dimensional liquid of incoherent bipolarons is well approximated by a 'Bose sea' of bosons that are hard-core in momentum space, occupying the momenta inside the Fermi sea but otherwise non-interacting. This new proposal for a strongly-correlated many-body wavefunction opens the way for studying various other properties of incoherent (non-superconducting) liquids of pre-formed pairs in any dimension.

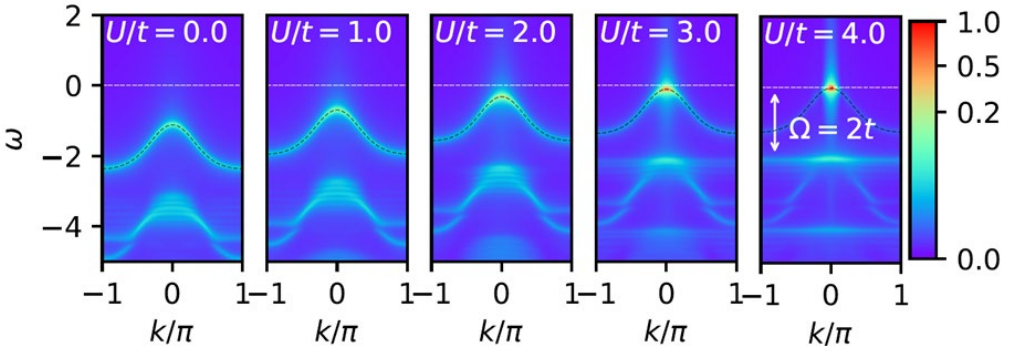

Figure 1: Spectral weight $A(k,\omega)$ for a system with N_e=2 electrons at fixed t=1, Ω=2, λ=1 and increasing U=0, ..., 4 (left to right panels) computed with VED. The white horizontal dashed line marks the chemical potential $\mu=E_P(0)- \Delta/2$ while the black dashed line shows the inverted polaron dispersion, $-E_P(k)$ (up to an overall shift). As U increases, the N_e=2 GS evolves from a bipolaron (spectra display a 'gap' between the lowest binding energy feature and μ) to two unbound polarons (spectral weight starting at μ).

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Positive Operator Valued Measures Neural Networks for Open System Dynamics

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We employ a recently proposed numerical approach to model open systems dynamics. This method uses positive operator valued measures (POVM) [1] to describe the quantum state as a probability distribution over a set of measurements, which can be approximated by a neural network. Then a time dependent variational principle (TDVP) is applied to project state dynamics over the neural network ansatz [2]. We target the dynamics of arrays of trapped atoms in an optical tweezer lattice with photo-mediated dipole-dipole interaction and correlated dissipation [3] . When prepared out-of-equilibrium, under certain conditions, such a system exhibits a short-time fast decay followed by a slow power-law relaxation. We assess if the numerical technique can depict long-range interacting open systems for extended time evolution, where the nor-trivial regime appears. We address the possibility of upscaling such methodology to larger system sizes as a potential complement for more standard tensor network techniques, which are not efficient for long-range interacting and two-dimensional setups

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Local Density of States Correlations in the Lévy-Rosenzweig-Porter random matrix ensemble

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We present an analytical calculation of the local density of states corre-lation function $\beta(\omega)$ in the L´evy-Rosenzweig-Porter random matrix ensemble at energy scales larger than the level spacing but smaller than the bandwidth. The only relevant energy scale in this limit is the typical level width Γ_0. We show that $\beta(\omega \ll \Gamma_0) \sim W/\Gamma_0$ (here W is width of the band) whereas $\beta(\omega \gg \Gamma_0) \sim (W/\Gamma_0)(\omega/\Gamma_0)^{-\mu}$ where μ is an index characterising the distribution of the matrix elements. We also provide an expression for the average return probability at long times: $\ln[R(t \gg \Gamma_0^{-1})] \sim -(\Gamma_0 t)^{\mu/2}$. Numerical results based on the pool method and exact diagonalization are also provided andare in agreement with the analytical theory.

Entanglement entropy of many-body systems with particle number conservation

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Quantum entanglement in quantum many-body phyiscs is crucial in understading non-equilibrium dynamics and thermalization of closed systems, i.e., systems that are completely isolated from the environment. We can examine the bipartite entanglement entropy of quantum lattice systems of interacting bosons. The average entanglement entropy of highly excited eigenstates of a quantum chaotic Hamiltonian follows a volume law, described by Page's curve [1]. It has been shown in the hard-core boson limit that the presence of particle number conservation, the volume law term will depend on the average number of particles per lattice site [2]. The volume law leading term can be retrieved using a ”mean-field” approach [3]. Using this approach we can explore soft-core bosons by generalizing the Bianchi-Dona distribution [4]. We manage to determine the volume law term of the average entanglement entropy for soft-core bosons using a generating function of the grand canonical ensemble at infinite temperature and a ”mean-field” approach.

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Roles of electron-phonon and electron-electron interactions in $SrVO_3$

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The spectral and transport properties of strongly correlated metals, such as SrVO3 (SVO), are widely attributed to electron-electron interactions, with lattice vibrations (phonons) playing a secondary role. Here, using first-principles electron-phonon and dynamical mean field theory calculations, we show that electron-phonon interactions play an essential role in SVO: they govern the electron scattering and resistivity in a wide temperature range down to 30 K, and induce an experimentally observed kink in the spectral function. In contrast, the electron-electron interactions control quasiparticle renormalizations and low temperature transport, and enhance the electron-phonon coupling. We clarify the origin of the near quadratic temperature dependence of the resistivity by analyzing the electron-electron and electron-phonon limited transport regimes. Our work disentangles the electronic and lattice degrees of freedom in a prototypical correlated metal, revealing the dominant role of electron-phonon interactions in SVO.

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High order strong-coupling expansion for X-ray absorption under dynamical screening

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Time-resolved X-ray absorption spectroscopy (trXAS) is a promising experimental technique to shed light on the electronic structure of photo-excited solids, such as the ultrafast photo-induced renormalization of the electron interaction U in Mott and charge transfer insulators. To theoretically model trXAS in charge transfer insulators, non-equilibrium DMFT+GW calculations have been used [1]. These calculations reveal that both the shift and the modification of the X-ray lineshape following photo-excitation can provide insights into the nature of screening and the transient modification of electronic interactions.

Accurately computing trXAS spectra in the context of dynamical screening constitutes a significant computational challenge. A promising approach is the strong-coupling expansion of the screened density-density interaction [2], which has primarily been applied with in the lowest order thus far. In this talk, I present a novel computational scheme for efficiently evaluating higher order contributions to the strong-coupling expansion [3]. This method employs a decomposition of the screened interaction into exponential mode functions, significantly reducing computational complexity to O(N log N). I will discuss the effect of dynamical screening on X-ray absorption spectra and the real-time strong-coupling expansion based on the mode decomposition within a simplified Holstein impurity model.

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Polynomially filtered exact diagonalization in quantum many body systems

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Polynomially filtered exact diagonalization (POLFED) is a time and memory-efficient method for extracting the spectrum at the targeted the energy of the spectrum, developed by [1]. Exact diagonalization becomes challenging for system sizes larger than L=18. Lanczos method can be used to target eigenvalues at lower/upper parts of the spectrum. Shift and invert method was invented to overcome obstacles of Lanczos method. POLFED is the improvement of the shift-and-invert method, it stands out by preserving the sparsity of the hamiltonian, low memory usage, and its simplicity of application. With POLFED we can reach system sizes as large as L=24, and L=20 on a modest laptop. The study of systems thermalization properties can be challenging since thermalization is defined in thermodynamic limit but we can only access the number of particles of order 10, with POLFED helps us to reach larger system sizes.

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Fabrication of advanced 1T-TaS_2 electronic devices

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1T-TaS_2 is renowned for its complex phase diagram, characterized by multiple charge density wave phases and a hidden metastable state. This work investigates the influence of fabrication processes on the properties of 1T-TaS_2 samples and comparing free-standing samples to those in contact with a substrate. We aimed to minimize fabrication-induced effects by exploring alternative preparation methods that preserve the material's intrinsic transport properties.

Our study further examined the behaviour of 1T-TaS_2 as sample thickness was reduced, evaluating consistency with previous findings. Special attention was given to how fabrication methods impact the hidden metastable state, which plays a critical role in potential applications. A more stable metastable state could enhance the practical viability of 1T-TaS_2, particularly for memristor technologies.

Hilbert space geometry and quantum chaos

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The quantum geometric tensor (QGT) characterizes the Hilbert space geometry of the eigenstates of a parameter-dependent Hamiltonian. In recent years, the QGT and related quantities have found extensive theoretical and experimental utility, in particular for quantifying quantum phase transitions both at and out of equilibrium. Here we consider the symmetric part (quantum Riemannian metric) of the QGT for various multi-parametric random matrix Hamiltonians and discuss the possible indication of ergodic or integrable behaviour. We found for a two-dimensional parameter space that, while the ergodic phase corresponds to the smooth manifold, the integrable limit marks itself as a singular geometry with a conical defect. Our study thus provides more support for the idea that the landscape of the parameter space yields information on the ergodic-nonergodic transition in complex quantum systems, including the intermediate phase.

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Time local F-ansatz for the auxiliary master equation approach

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Describing long-lived photodoped states in Mott insulators is challenging due to the need to address exponentially separated timescales. The time-local-F ansatz (TLFA) provides insights into such states. In a previous paper [1, 2], it was shown that the time evolution using the TLFA with the non-crossing approximation (NCA) agrees well with the corresponding real-time spectra. Furthermore, for a given distribution function obtained through this procedure, we compared the steady-state spectral functions calculated by the numerically exact quantum Monte Carlo algorithm, the NCA, and the auxiliary master equation approach (AMEA). AMEA has been shown to capture the gap more accurately than NCA, with the Monte Carlo results serving as the benchmark. While the Monte Carlo approach is numerically accurate, it is computationally expensive, whereas AMEA is substantially faster. Motivated by this, we implemented the TLFA directly in AMEA, potentially enabling more accurate long-term time evolution compared to NCA. In our poster, we present preliminary results of our implementation.

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Temperature dependent Raman spectra and THz emission of Co/C_{60} heterostructures

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The organic-metal hybridized interfaces are of wide interest for studying fundamental phenomena and functional properties [1,2]. The interface states play a crucial role by potentially strongly affecting the injected carriers spin polarization [3-5]. We have analyzed the Raman spectra and spintronic terahertz emission of Co/C_{60} thin films, investigating the temperature-induced phase transition in C60 and possible ultrafast spin-polarized injection/transport into/across C_{60} molecular layer. We found that the temperature dependence of Raman spectra is associated to rotational freezing [6] below 220 K (during heating) for the Co/C_{60} samples. For the H_g and A_g Raman modes in Co/C_{60}($x_{C_{60}}$>=12nm), a hysteretic behavior is observed in the temperature dependence of the frequency v_0 and linewidth γ. In addition, the observed THz transients are T-independent and show no delay with increased $x_{C_{60}}$. They correspond to a combination of the $x_{C_{60}}$-dependent pinhole contribution and $x_{C_{60}}$-independent intrinsic Co contributions and are in a significant portion not related to the C_{60}-layer spin-polarized carrier transport.

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