December 10–14, 2023
Ambrož, Krvavec, Slovenia

# BOOK OF ABSTRACTS

# NQW

## Nonequilibrium Quantum Workshop

December 10 - 14, 2023
Krvavec, Slovenia

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# Constructing nonequilibrium steady states from equilibrium correlation functions

R. Steinigeweg[1]

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State-of-the-art approaches to extract transport coefficients of many-body quantum systems broadly fall into two categories: (i) they target the linear-response regime in terms of equilibrium correlation functions of the closed system; or (ii) they consider an open-system situation typically modeled by a Lindblad equation, where a nonequilibrium steady state emerges from driving the system at its boundaries. While quantitative agreement between (i) and (ii) has been found for selected model and parameter choices, also disagreement has been pointed out in the literature. Studying magnetization transport in the spin-1/2 XXZ chain, we here demonstrate that at weak driving the nonequilibrium steady state in an open system, including its buildup in time, can remarkably be constructed just on the basis of correlation functions in the closed system. We numerically illustrate this direct correspondence of closed-system and open-system dynamics, and show that it allows the treatment of comparatively large open systems, usually only accessible to matrix product state simulations. We also point out potential pitfalls when extracting transport coefficients from nonequilibrium steady states in finite systems.

[1] T. Heitmann et al. arXiv:2303.00430
[2] T. Heitmann et al. Physical Review E 108, 024102 (2023)

# Richardson model description of spin-orbit coupling in superconducting islands

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Richardson model, first introduced in nuclear physics as a simplified model of nucleon pairing, is also an appropriate description of a small superconducting island with fixed charge. Complex systems composed of interconnected superconducting islands and interacting quantum dots can be modelled using Hamiltonians that can be transformed into the matrix-product-operator form with small matrices that can be efficiently solved using the density matrix renormalization group [1,2]. This approach allows to include without any approximations the effects of both the exchange interaction (Kondo screening and Yu-Shina-Rusinov subgap states) and the charge repulsion (Coulomb blockade, capacitive coupling) [3] and thereby provide reference results for this family of Hamiltonians that are more general than regular quantum impurity problems. The theory results match well the experimental measurements on hybrid semi-super devices [3,4].

I will describe how this approach can be extended to incorporate two further phenomena, the spin-orbit coupling and the proximity effect leading to level-dependent pairing strength [5]. The combination of the two leads to a degeneracy of even and odd-parity ground states in the regime where the external magnetic field becomes strong enough to generate an increasing number of quasiparticles in the superconducting levels with the weakest pairing strength. This manifests as equal spacing of even and odd states in the charge stability diagrams.

[1] Luka Pavešič, Daniel Bauernfeind, and Rok Žitko, Phys. Rev. B 104, L241409 (2021)
[2] Luka Pavešič and Rok Žitko, Phys. Rev. B 105, 075129 (2022)
[3] Juan Carlos Estrada Saldaña, Alexandros Vekris, Luka Pavešič, Peter Krogstrup, Rok Žitko, Kasper Grove-Rasmussen & Jesper Nygård, Nat. Commun. 13, 2243 (2022)
[4] Juan Carlos Estrada Saldaña, Alexandros Vekris, Luka Pavešič, Rok Žitko, Kasper Grove-Rasmussen, Jesper Nygård, arXiv:2203.00104
[5] Juan Carlos Estrada Saldaña, Luka Pavešič, Alexandros Vekris, Kasper Grove-Rasmussen, Jesper Nygård, Rok Žitko, arXiv:2306.06001

# Direct characterization of photo- and electrically-induced "hidden" state switching of 1*T*-$TaS_2$

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Brilliant, ultrashort, and coherent X-ray free-electron laser (FEL) pulses allow for investigation of dynamics at the inherent time and length scale of atoms. I will illustrate this capability at the example of recent time-resolved X-ray diffraction data taken in the "hidden" phase of the Van der Waals material 1*T*-$TaS_2$, hinting that out-of-plane restacking suppresses the optically-induced hidden state. Furthermore, I will also present preliminary static micro-beam X-ray diffraction data of electrically switched 1*T*-$TaS_2$ cryomemory cells which indicate that also from a structural point of view the photo- and electrically-induced "hidden" states are closely related.

# Spatial mapping of the electronic structure of 1*T*-$TaS_2$

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As a step towards resolving the spatially-resolved electronic structure of the layered transition metal dichalcogenide 1*T*-$TaS_2$ – and eventually electronically switched cryomemory devices – we have performed angle-resolved photoemission spectroscopy (ARPES). Using a photon energy of 72 eV and the micrometer spot size available at the *spectromicroscopy* beamline of the *Elettra* synchrotron, we measured the band structure and high-statistics Fermi surface of 11, 500 and 600 nm thick flakes. Also, the first-order phase transition from the nearly-commensurate to the commensurate CDW state leads to a prominent splitting of the Ta 4*f* core levels which we have mapped spatially. In addition, using 400 eV soft X-ray ARPES at the *ADRESS* beamline of the *Swiss Light Source* synchrotron, we established the $k_z$ dependence of the band structure of a 110-nm thick flake, which reveals a two dimensionality of the electronic structure.

# Integrals of motion in dipole-conserving models

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The Hilbert space fragmentation, for which the Hamiltonian shatters into exponentially many blocks in the site occupation basis, can result in the breakdown of thermalization. In this presentation, we focus on the pair-hopping (PH) model, a paradigmatic model of the Hilbert-space fragmentation. Furthermore, it can be derived as an effective model of the Stark chain, imposing strict conservation of the dipole moment. Notably, the non-vanishing autocorrelation functions in the PH model, as reported in [1], suggests the existence of local or quasilocal integrals of motion (IOMs). Hence, we propose a numerical algorithm that establishes all IOMs linear in a given set of operators. We employ it to demonstrate that the density modes in the PH model are frozen and become strict IOMs in the thermodynanic limit. Nevertheless, these modes become subdiffusive after incorporating higher-order corrections the PH model. Finally, we make a connection with the Stark model. We demonstrate that although both energy and dipole moment are conserved in the thermodynamic limit [2], the Stark chain supports only one IOM.

[1] P. Sala et al., Physical Review X 10 (2020)
[2] S. Nandy et al., arXiv:2310.01862 (2023)

# Critical quantum dynamics of observables at eigenstate transitions

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It is an outstanding goal to unveil the fingerprints of universal quantum dynamics at eigenstate transitions. Focusing on quadratic fermionic Hamiltonians, we identify physical observables that exhibit critical behavior at the transition. Our result is based on two ingredients: (a) A relationship between the observable time evolution in a many-body state and the transition probabilities in single-particle states, and (b) a scale invariance of transition probabilities, which generalizes the recent result for survival probabilities [1,2]. We then show that these properties give rise to a critical behavior in the quantum quench dynamics of observables, which share the common eigenbasis with the Hamiltonian before the quench. We numerically demonstrate this phenomenon at the localization transition in the three-dimensional Anderson model, for which the critical bahavior can be detected in experimentally relevant observables such as site occupations and particle imbalance [3].

[1] M. Hopjan and L.Vidmar, Phys. Rev. Lett. 131, 060404 (2023)
[2] M. Hopjan and L.Vidmar, arXiv:2309.16005 (2023)
[3] S. Jiricek et al., in preparation

# Laser-induced tunnel ionization and femtosecond nonthermal melting in MgO

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Laser-induced melting plays a crucial role in advancing manufacturing technology and ultrafast science [1-3]; however, its atomic processes and microscopic mechanisms remain elusive due to complex interplays between many degrees of freedom within a timescale of ~100 femtoseconds. We employ MgO as an example to investigate the nonequilibrium mechanisms of laser-driven ultrafast nonthermal melting of wide-gap materials. Our study is based on real-time time-dependent density functional theory (rt-TDDFT) molecular dynamics (MD) simulations. We report here that laser melting is greatly accelerated by tunnel ionization processes. The tunneling processes generate a large number of photocarriers and results in intense energy absorption, instantaneously changing the potential energy surface of lattice configuration. The strong electron-phonon couplings and fast carrier relaxation enable the efficient energy transfer between electrons and the lattice. The modulation of melting thresholds and phase boundary demonstrate the possibility of manipulating phase transition on demand. A shock wave curve is also obtained at moderate conditions ($P < 50$ GPa), extending Hugoniot curve to new regimes. These results account well for the latest ultrafast melting experiments, and provide atomistic details and nonequilibrium mechanism of photoinduced ultrafast phase transitions in wide-gap materials.

[1] S. K. Sundaram et al., Inducing and probing non-thermal transitions in semiconductors using femtosecond laser pulses. Nat. Mater. 1, 217-224 (2002)
[2] C. W. Siders et al., Detection of nonthermal melting by ultrafast X-ray diffraction. Science 286, 1340-1342 (1999)
[3] E. H. Penilla et al., Ultrafast laser welding of ceramics. Science 365, 803-808 (2019)

# Nanoscale polytype transformation

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The transitional metal dichalcogenides crystalize in different polytypes, dictating their charge density wave (CDW) states. It is possible to perform the polytype transformation in situ by either an optical [1] or an electrical pulse [2,3], creating new nanoscale structures and polytypes that sometimes do not exist as bulk materials. We explore the polytype transformed structures of bulk materials 2H-$NbSe_2$ and 4Hb-$TaSe_2$.

Using the electrical pulse from the STM tip, the surface of the 2H-NbSe2 is transformed to the 1T polytype in which we observe rich CDW physics of domains and domain walls, as well as dynamical switching between different charge ordering configurations. The diverse spectroscopic signature of the CDW state shows a similarity to the hidden state of 1T-$TaS_2$ [4].

We also present experiments on 4Hb-$TaSe_2$ which consists of alternating stacking of the 1T and 1H layers. Similar to the 2H-$NbSe_2$ experiments, we show that it is possible to create a nanoscale polytype transformation of the top surface from the 1H to the 1T polytype with the electrical pulse from the STM tip. Although the transformed 1T polytype in both materials adopts the same $\sqrt{13}\times\sqrt{13}$ CDW superlattice, their electronic structure is different. Other materials from the group of 2H and 4Hb polytypes could likely be explored for nanoscale polytype transformations.

[1] J. Ravnik et al. ACS Appl Nano Mater. 2, 3743 (2019)
[2] J. Zhang et al. Science 274, 757 (1996)
[3] F. Bischoff et al. Chem. Mater. 29, 9907 (2017)
[4] D. Cho et al. Nat. Commun. 7, 10453 (2016)

# Electronic Amorphous State of 1T-$TaS_2$: An Order Embedded in the Disorder

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The 1T-$TaS_2$, a peculiar transition metal dichalcogenide with a charge density wave (CDW) at low temperatures, has been studied for the last 10 years since the original discovery of a metastable hidden (H) state in it [1]. Mainly, the research was focused on the properties of this state [2] as well as their possible applications [3]. The H-state can be achieved by driving the material out of equilibrium using an ultrashort laser pulse or a short electrical pulse. Similarly to the H-state, at higher excitation fluences an electronic amorphous (A) state can be reached.

In our scanning tunnelling microscopy studies, we are exploring the coexistence of amorphous, commensurate (C) and hidden CDWs; and the dynamical reconfigurations between them. At the same time, we are showing that in addition to these CDWs, the A-state can locally form embedded `islands` of charge order not observed in any other states of the material. In addition, studies of the dynamics in the A-state are showing possible transitions as well as thermal fluctuations of this ordering.

The observed local behaviour of this system with various emergent states is a good example of topologically-constrained dynamics. As a result, the A-state of 1T-$TaS_2$ provides valuable insight into the correlation between topology and kinetics in many-body quantum states and can be considered an accessible experimental model for studying non-equilibrium quantum dynamics.

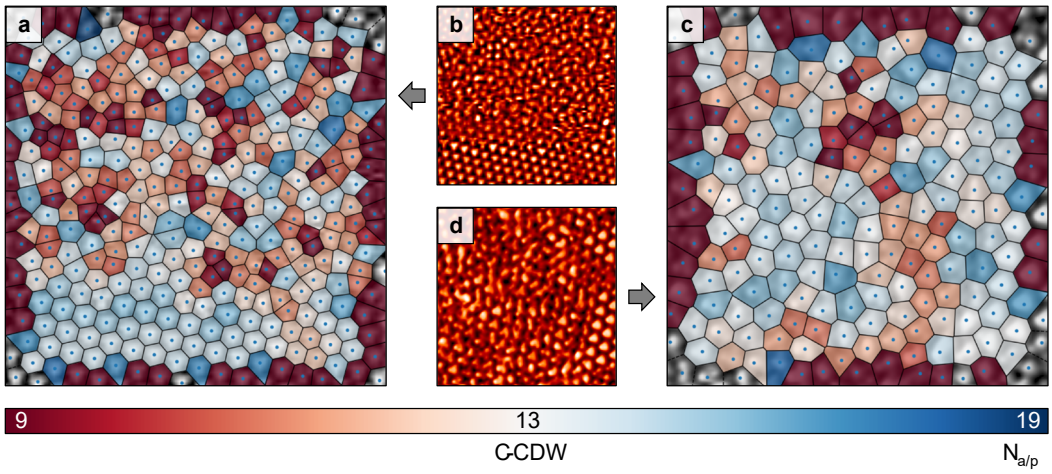


**Fig. 1.** A-state of 1T-$TaS_2$ measured with STM with a high **(a)** and normal **(c)** CDW density. **a, c)** Positions of the CDW peaks (points) and corresponding Voronoi tessellations (filled polygons). The colourmap is defined by Na/p – the number of atomic positions occupied by a single peak of CDW with red corresponding to the most dense CDW order. Na/p=13 corresponds to the commensurate CDW in 1T-$TaS_2$. **b, d)** Original STM images showing the border between the A and the H states.

[1] L. Stojchevska et al. Science 344, 177–180 (2014)
[2] I. Vaskivskyi et al. Sci. Advances 1, e1500168 (2015)
[3] A. Mraz et al. Nano Lett. 22, 4814-4821 (2022)

# Monday, December 11, 2023

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# Trajectories through emergent metastable states in 2D correlated electron systems

D. Mihailovic[1,2,3]

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Non-equilibrium states of matter have become of great fundamental and practical interest in recent years because of their wide importance in diverse areas of physics. With the rapid development of new time-resolved techniques, the temporal dynamics of competing processes and interactions were recently elucidated in a wide variety of complex condensed matter systems. However, the physics of metastable mesoscopically non-periodic quantum textures emerging from phase transitions has been largely experimentally inaccessible till now: current state of the art time-resolved methods using x-rays, electron diffraction, photoemission, THz and optical spectroscopy all average over multiple transition outcomes. Moreover, they cannot resolve irregular nonperiodic nanoscale structures, but some progress has been made in the use of scanning tunneling microscopy. Here I will outline experimental and theoretical progress in the study of emergent phenomena in metastable states, concentrating on well-known systems that offer insights into complex physics of multicomponent non-equilibrium electronic systems, such as charge fractionalization, jamming and topologically arrested kinetics.

# Possible hidden phases in photo-doped Mott insulators

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Doping charge carriers into Mott insulators provides a pathway to produce intriguing emergent phenomena. In equilibrium systems, doping can be chemically controlled. On the other hand, photo-doping, where particles are excited across the Mott gap, provides an alternative way. Compared to chemical-doping, photo-doping creates a wider variety of charge carriers, which may lead to the emergence of fascinating nonequilibrium states. In particular, when the gap is large, the lifetime of photo-carriers is exponentially enhanced, leading to quasi-steady states after intraband cooling of photo-carriers.

In this talk, we explore possible hidden phases that arise as quasi-steady states of photodoped Mott insulators using the quasi-equilibrium approach [1]. Within this approach, we treat the photo-doped state as an equilibrium state of an effective model for a given photo-doping level. We apply the idea to the 1D extended Hubbard model. In the first part [1], we present our numerical results obtained with the infinite time-evolving block decimation. We show the emergence of the so-called η-pairing phase and the string charge-density-wave phase, and discuss their physical properties. In the second part [2], we reveal the analytical aspects of these photo-doped states. We show that the corresponding wave function in the large on-site interaction limit can be expressed as $|\Psi\rangle = |\Psi_{\mathrm{charge}}\rangle|\Psi_{\mathrm{spin}}\rangle|\Psi_{\eta-\mathrm{spin}}\rangle$, which indicates the separation of spin, charge and η−spin degrees of freedoms. Here η−spin represents the type of the photo-carriers, i.e. doublons and holons. This state is analogous to the celebrated Ogata-Shiba state of the doped Hubbard model in equilibrium. The expression provides us useful insight into the properties of the photo-doped states. Our results demonstrate that the emergent degrees of freedom activated by photo-doping can lead to peculiar types of quantum states absent in equilibrium.

[1] Y. Murakami, S. Takayoshi, T. Kaneko, Z. Sun, D. Golež, A. J. Millis, P. Werner, Comm. Phys. 5, 23 (2022)
[2] Y. Murakami, S. Takayoshi, T. Kaneko, A. Läuchli, P. Werner, Phys. Rev. Lett. 130, 106501 (2023)

# Flavours of openness

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I will introduce and review different aspects of open quantum systems dynamics, providing some background and motivation for the 2023 NQW talks with a flavour of openness.

# Non-equilibrium transport and quantum information jet in the Hubbard model

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In this presentation, I focus on the impact of interaction and symmetries on non-equilibrium charge and spin transport in the Hubbard model. The structure of non-equilibrium dynamics is found to change dramatically upon increasing interaction [1-4]. In usual quench experiments, a relatively standard Fermi liquid-like behavior appears for small interactions, while phenomena such as composite particle formation along with negative temperature states emerge for larger interactions [1].

The properties of the infinite temperature state depend crucially on symmetries. At half-filling, he SU(2) Hubbard model exhibits global $SU_c(2)\otimes SU_s(2)$ symmetry, and there Kardar-Parisi-Zhang (KPZ) scaling is observed in charge and spin correlations and transport [2]. Away from half-filling, however, the $SU_c(2)$ charge symmetry is reduced to $U_c(1)$, while the $SU_s(2)$ symmetry for the total spin is retained. Consequently, transport in the charge sector becomes ballistic, while KPZ scaling is preserved in the spin sector. The anomalous diffusion coefficient is found to scale as 1/U at large U.

In the presence of localized particle loss at the end of a semi-infinte chain, we observe a ballistic current front propagation with strongly renormalized front velocity, and a hydrodynamic current density profile. Operator entanglement is found to propagate faster than the depletion profile, preceding the latter [3], and a mutual information jet appears that propagates with a velocity independent of U. While the slow front can be captured by a cellular automaton model and carries classical correlations, the fast mutual information front appears to have a quantum-mechanical nature, and persists at infinite temperature and interaction.

[1] M.A. Werner, C.P. Moca, M. Kormos, Ö. Legeza, B. Dóra, G. Zaránd, Spectroscopic evidence for engineered hadron formation in repulsive fermionic SU(N) Hubbard Models, Phys. Rev. Research 5, 043020 (2023)
[2] C.P. Moca, M.A. Werner, A. Valli, T. Prosen, G. Zaránd, Kardar-Parisi-Zhang scaling in the Hubbard model, Phys. Rev. B, in print [arXiv:2306.11540]
[3] C.P. Moca, M.A. Werner, Ö. Legeza, T. Prosen, M. Kormos, G. Zaránd, Simulating Lindbladian evolution with non-abelian symmetries: Ballistic front propagation in the SU(2) Hubbard model with a localized loss, Phys. Rev. B 105, 195144 (2022)
[4] P. Penc, C.P. Moca, T. Prosen, G. Zaránd, M.A. Werner, Quantum-information jet in the infinite temperature Hubbard model, unpublished

# Nonequilibrium dynamics and transport in Holstein models

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Understanding the properties of real materials requires the incorporation of multiple degrees of freedom into the theoretical modeling. In this research, we focus on the coupling of electrons to phonons. We developed a comprehensive matrix-product-states based schemes that allows to compute spectral functions [1], optical conductivity [2] and thermal conductivity [3] of one-dimensional Holstein chains, both for the polaron case and half filling, and at finite temperatures. These techniques work well in the small-polaron regime and in intermediate regimes where phonon frequency, electron-phonon coupling and elecronic hopping matrix elements are of the same scale.

In order to access the adiabatic regime of phonon frequencies much smaller than the electronic bandwidth, we combine matrix-product-state and Krylov-space methods with the multritrajectory Ehrenfest technique, called MPS-MTE and Lanczos-MTE [4]. The latter treats phonons classically and samples over initiial conditions set by the phonons‘ initial quantum state. The resulting hybrid techniqes rely on a propagation of electronic many-body states that depend on the time-dependent classical coordinates and momenta. We verify the correct implemenation by studying the decay of charge-density wave order analyzed in [5] and then apply the MPS-MTE method to the problem of a many-body localized system coupled to classical phonons. We observe a delocalization induced by this coupling.

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[1] D. Jansen, J. Bonča, and F. Heidrich-Meisner Phys. Rev. B 102, 165155 (2020)
[2] D. Jansen, J. Bonča, and F. Heidrich-Meisner, Phys. Rev. B 106, 155129 (2022)
[3] D. Jansen and F. Heidrich-Meisner, Phys. Rev. B 108, L081114 (2023)
[4] H. Menzler, S. Mondal, and F. Heidrich-Meisner, in preparation.
[5] M. Ten Brink et al. J. Chem. Phys. 156, 234109 (2022)

# Critical Full Counting Statistics in Integrable Spin Chains

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# The pairing symmetry in the quasi-one-dimensional superconductors $A_2Mo_3As_3$ (A=Rb, Cs)

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The $A_2Mo_3As_3$ (A = K, Rb, Cs) compounds are built of assembled $Mo_3As_3$ chains and are thus the potential realisations of quasi-one-dimensional metals. Various experiments on these materials hint to the Tomonaga-Luttinger liquid (TLL) physics from which superconductivity with a relatively high critical temperatures of $T_c \approx 10.5$ K emerges. However, TLL and its relevance to emerging superconductivity are not yet resolved for $A_2Mo_3As_3$ due to their multiband nature.

Here we report a combined $^{75}$As nuclear quadrupole resonance (NQR), $^{87}$Rb and $^{133}$Cs nuclear magnetic resonance (NMR) and muon spin relaxation (μSR) study of $Rb_2Mo_3As_3$ and $Cs_2Mo_3As_3$ powders. The alkali metal spin-lattice relaxation rates show a characteristic power-law temperature dependence over a broad temperature range, which is a hallmark of the TLL dynamics dominated by the two-quasi-one-dimensional bands. Detailed analysis reveals that these compounds may be in an unusual state of effective attractive interactions, which opens up intriguing possibilities for the unconventional pairing symmetries of the superconducting state. To address the superconducting state we, in addition to $^{75}$As and alkali metal relaxation rate studies, employ also the ‚transverse-field μSR. The temperature dependence of the muon relaxation rate, σ, is in the superconducting state due to the field distribution created by the vortex lattice and is compared against s-, p- , and d-wave scenarios. The penetration depth $\lambda = 669$ nm and the coherence length $\zeta = 3.4$ nm are also determined.

[1] Ž. Gosar et al., Phys. Rev. B 101, 220508(R) (2020)
[2] Ž. Gosar et al., J. Phys. Chem. Solids 181, 111478 (2023)

# TBD

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# Ultrafast Electronic Domain Fluctuations Detected in a Nonequilibrium X-Ray Speckle Visibility Experiment

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Since the advent of X-ray free electron lasers, a standard method to study metal-insulator transitions is in a nonequilibrium pump-probe diffraction experiment to disentangle how different order parameters evolve at ultrafast timescales. However, this technique is blind to domain fluctuations of the order parameter that may play a critical role in driving these nonequilibrium transitions. To directly couple to these domain fluctuations at ultrafast timescales requires coherent X-ray probes following a laser excitation. Here we employed a novel coherent X-ray technique that uses a split-and-delay line in a pump-probe-probe experimental scheme to measure ultrafast domain fluctuations for the first time. This experiment was carried out at the X-ray Correlation Spectroscopy (XCS) beamline of the Linac Coherent Light Source (LCLS) where we accessed the speckle pattern of a resonant charge order peak in $Fe_3O_4$ to quantify domain fluctuations with 1-picosecond temporal resolution. A complementary, standard X-ray pump-probe experiment on the same charge order peak was carried out at the Bernina end station of SwissFEL to reveal ultrafast melting of the electronic order parameter. Together these two experiments reveal the nonequilibrium evolution of the charge order at picosecond and nanometer length scales.

# False vacuum decay in the transverse field Ising model on a quantum annealer

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This presentation deals with using quantum annealing for observing false vacuum decay in the transverse field Ising model. False vacuum decay is one of the central ideas in quantum field theory. It describes a scenario where a system in a metastable false vacuum state transitions to the true vacuum state. The transition happens by creation of bubbles of true vacuum that expand over the whole system. The timescales and the dynamics of this phenomenon are difficult to observe and describe analytically. The process of transition is analogue to first order phase transitions in condensed matter physics. Metastable states with analogous dynamics can be observed on measurable timescales. An example of such a system is the transverse field Ising model, where false vacuum decay appears in nonequilibrium dynamics following a sudden change in the direction of the external field. Numerical studies have shown the existance of a set of parameters for which false vacuum decay can be observed. Transverse field Ising model is implemented in the D-Wave quantum annealer. Measurements on this device are used to simulate the dynamics of the transverse Ising model. In general, results of simulations show decay dynamics that do not match the theoretical description of the false vacuum decay exactly. This implies additions effects on the dynamics. In the specific limit of low transverse fields and high longitudinal fields the measured dynamics approach the theoretically expected dynamics. Possible explanations for the observed deviations include the open nature of the system in the quantum annealer, the slow change of the field direction and poor validity of the approximations used for theoretical predictions for magnitudes of fields used in the simulations.

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[2] M. S. Turner et al. Nature 298, 633 (1982)
[3] P. Calabrese et al. Journal of Statistical Mechanics: Theory and Experiment 2012, P07016 (2012)
[4] M. Kormos et al. Nature Physics 13, 246 (2016)
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[6] G. Lagnese et al. Phys. Rev. B 104, L201106 (2021)
[7] O. Pomponio et al. SciPost Phys. 12, 061 (2022)

## Tuesday, December 12, 2023

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|---|---|---|
| | **Chair:** | |
| 9:00 - 9:30 | **Daniele Fausti:** Cavity-Mediated Thermal Modulation of the Metal-to-Insulator Transition in 1T-$TaS_2$ | 26 |
| 9:30 - 10:00 | **Martin Eckstein:** Light-matter hybrids made from strongly correlated electron systems | 27 |
| 10:00 - 10:15 | **Federico Cilento:** Ultrafast Dynamics of the Charge Density Wave in Kagome Metals | 28 |
| 10:15 - 10:45 | *COFFEE BREAK* | |
| | **Chair:** | |
| 10:45 - 11:15 | **Michael Sentef:** Light-Matter Control of Quantum Materials | 29 |
| 11:15 - 11:45 | **James McIver:** Ultrafast control of topological transport in quantum materials | 30 |
| 11:45 - 12:00 | **Sourav Nandy:** Emergent dipole moment conservation and subdiffusion in tilted chains | 31 |
| 12:00 - 13:15 | *LUNCH* | |
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| | **Chair:** | |
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| 17:00 - 17:30 | **Philipp Werner:** Photo-induced nonthermal metals | 33 |
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| 20:00 - 20:15 | **Jernej Mravlje:** $Ta_2NiSe_5$: excitonic or not? | 37 |
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# Cavity-Mediated Thermal Modulation of the Metal-to-Insulator Transition in 1T-TaS2

D. Fausti[1]

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This seminar will focus on the potential of cavity electrodynamics in shaping material properties, opened by on our recent investigation into cavity-mediated thermal control of the metal-to-insulator transition in 1T-TaS2, which demonstrated the feasibility of reversible cavity manipulation of a phase transition in a correlated solid-state material.

By immersing the charge density wave material 1T-TaS2 into cryogenic tunable terahertz cavities, we unveil a remarkable shift between conductive states. This transition, triggered by a substantial alteration in sample temperature, is controlled by mechanical adjustments of the distance between cavity mirrors and their alignment.

The discussion will extend to unpublished data on vibrational strong coupling within higher frequency cavities, emphasizing the position-dependent coupling strength that underscores the influence of the mode structure on the observed effects.

Our findings rationalized in a scenario reminiscent of the Purcell effects, wherein the spectral profile of the cavity significantly shapes the energy exchange between the quantum material and the external electromagnetic field unfolds promising opportunities for tailoring the thermodynamics and macroscopic transport properties of quantum materials through strategic engineering of their electromagnetic surroundings. The seminar will discuss some perspectives for cavity control of material functionalities in correlated complex quantum materials.

# Light-matter hybrids made from strongly correlated electron systems

M. Eckstein[1]

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Enhancing the light-matter coupling in cavities provides an intriguing avenue to control properties of matter, from chemical reactions to transport and thermodynamic phase transitions. In this talk, I discuss two mechanisms in which quantum light can influence extended condensed matter systems, in particular strongly correlated electron systems: (i) The hybridization of light and matter can affect first-order metal insulator transitions, because light selectively modifies the free energy of the metallic phase . This mechanism has been discussed in relation to the cavity-controlled metalinsulator transition in 1T-TaS2 [1]. While it most likely is not the relevant mechanism in this case, we discuss other situations where it can be decisive. (ii) We discuss the possibility to induce photon mediated long-range interactions between spin and orbital degrees of freedom [2], which rely on the nonlinear light matter interaction (Raman scattering or two-photon absorption and emission).

[1] Jarc et al., Nature 622, 487 (2023)
[2] Fadler et al., arXiv:2311.01339

# Ultrafast Dynamics of the Charge Density Wave in Kagome Metals

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The Charge Density Wave (CDW) order, descending from a metallic parent state, offers an intriguing playground to study the interplay of structural and electronic degrees of freedom in complex materials. Recently, this phenomenology has been discovered also in Kagome metals. With dispersive and correlation features including topological Dirac-like itinerant states, van-Hove singularities, correlated flat bands, and magnetic transitions at low temperature, kagome metals are located in the interesting regime where both phonon and electronically mediated couplings are significant. In particular, the van-Hove singularities, which are intrinsic to the kagome tiling, have been conjectured to play a key role in mediating the CDW instability. However, to date, the origin and the main driving force behind this charge order is elusive. Here, we use the topological bilayer kagome metal $ScV_6Sn_6$ as a platform to investigate this puzzling problem, and combine time-resolved optical spectroscopy, to unveil the ultrafast dynamics of its CDW phase, with angle-resolved photoelectron spectroscopy and density functional theory [1]. We identify the structural degrees of freedom to play a fundamental role in the stabilization of charge order. In particular, we find $ScV_6Sn_6$ to feature a charge density wave order that predominantly originates from phonons, as odd with other recent findings on other kagome metals like those from the $AV_3Sb_5$ (A = K, Rb, Cs) family, where the CDW originates from an electronic instability. As we shed light on the lattice-mediated low-temperature ordered phase, our findings pave the way for a deeper understanding of ordering phenomena in CDW kagome metals.

[1] M. Tuniz et al., arXiv:2302.10699

# Light-Matter Control of Quantum Materials

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Advances in time-resolved pump-probe spectroscopies have enabled us to follow the microscopic dynamics of quantum materials on femtosecond time scales. This gives us a glimpse into the inner workings of how complex, emergent functionalities of quantum many-body systems develop on ultrafast time scales or react to external forces. The ultimate dream of the community is to use light as a tuning parameter to create new states of matter on demand with designed properties and new functionalities, perhaps not achievable by other means. In this talk I will discuss recent progress in controlling and engineering properties of quantum materials through light-matter interaction [1,2]. I will highlight work on Floquet engineering — the creation of effective Hamiltonians by time-periodic drives — on sub-cycle time scales [3,4] combining theory and pump-probe experiments at the limits of energy and time resolution. I will then showcase recent theories on inducing superconductivity with light by employing enhanced light-matter interaction in the near-field involving polaritonic excitations [5,6].

[1] A. de la Torre et al., Rev. Mod Phys. 93, 041002 (2021)
[2] F. Schlawin, D. M. Kennes, M. A. Sentef, App. Phys. Rev. 9, 011312 (2022)
[3] M. Schüler and M. A. Sentef, https://doi.org/10.1016/j.elspec.2021.147121
[4] S. Ito et al., Nature 616, 696-701 (2023), https://www.nature.com/articles/s41586-023-05850-x
[5] C. J. Eckhardt et al., arXiv:2303.02176
[6] S. Chattopadhyay et al., arXiv:2303.15355

# Ultrafast control of topological transport in quantum materials

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Quantum materials exhibit remarkable non-equilibrium phenomena when driven by the strong fields in femtosecond laser pulses. Recent years have seen a surge of interest in using ultrafast light-matter interaction to create and manipulate photon-dressed Floquet-Bloch states as a strategy for controlling material properties. This excitement is fueled by the predictive power of Floquet theory, which has been used, for example, to correctly predict the formation of topological edge modes in periodically-driven systems that exhibit no topological properties in equilibrium. Many of these proposals have been verified in quantum simulation settings, but are only just beginning to be explored in solids.

In this talk, I will present results on the electrical transport properties of quantum materials driven by mid-infrared laser pulses, probed using an ultrafast optoelectronic device architecture. The talk will primarily focus on recent results obtained on the Weyl semimetal Td-$MoTe_2$, where a rectified, helicity-dependent injection current that scales linearly with the applied laser field was observed. This scaling violates the perturbative description of nonlinear optics/transport, which demands a quadratic field scaling for current rectification to occur. The results can be explained using Floquet theory, which predicts that the observed linear scaling arises from the stimulated emission that accompanies the hybridization of Floquet-Bloch states.

# Emergent dipole moment conservation and subdiffusion in tilted chains

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I plan to talk regarding the transport dynamics of an interacting tilted (Stark) chain, based on our recent work [1]. In this work, we have shown that the crossover between diffusive and subdiffusive dynamics in such a system is governed by F√L, where F is the strength of the field, and L is the wave-length of the excitation. While the subdiffusive dynamics persist for large fields, the corresponding transport coefficient is exponentially suppressed with F so that the finite-time dynamics appear almost frozen. Our work explains the crossover scale between the diffusive and subdiffusive transport by bounding the dynamics of the dipole moment for arbitrary initial state. We also prove its emergent conservation at infinite temperature. Consequently, the studied chain is one of the simplest experimentally realizable models for which numerical data are consistent with the hydrodynamics of fractons.

[1] S. Nandy, J. Herbrych, Z. Lenarčič, A. Głódkowski, P. Prelovšek, M. Mierzejewski, (2023), arXiv:2310.01862 [condmat.str-el].

# Shaken, not stirred: a recipe for ultrafast magnetic switching via phononic resonances

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Strong light-matter interaction constitutes the bedrock of all photonic applications, empowering material elements to create and mediate interactions of light with light. Among others, phononamplified interactions were shown to bring a specific twist into this, in the infrared (IR) frequency range. Thus, phono-magnetic effects are the low-frequency analogues of inverse Faraday and Cotton-Mouton effects [1,2] where phonons, not electrons, mediate the interaction between light and spins. In this case, light couples to the spins indirectly by exciting coherent vibrations of the crystal lattice (phonons) that transfer angular momentum to the magnetic ions [3,4]. The optically driven chiral phonons in materials with strong spin-orbit coupling were shown to produce giant effective magnetic fields that exceed those previously seen by several orders of magnitude [5]. The mechanism allows for bidirectional control of the induced magnetization through phonon chirality that in turn can be controlled by the polarization of the laser pulse.

Here we show that through the resonant excitation of circularly-polarized optical phonons in paramagnetic substrates, one can permanently reverse the magnetic state of the substrate-mounted heterostructure [6]. To provide resonant excitation of the optical phonon modes, we use pulses from FELIX (Free Electron Lasers for Infrared eXperiments, Nijmegen, The Netherlands). Single pulses of IR/THz light with photon energy ranging between 25 meV and 124 meV (wavelength 10-50 μm) are typically used. With the handedness of the phonons steering the direction of magnetic switching, such effect offers a selective and potentially universal method for exercising ultrafast non-local control over magnetic order.

Moreover, a different behaviour, characterized by displacive modification of magnetic potentials, can be observed when exciting materials at phonon frequencies with linearly-polarized light. The magnetic switching was shown to create very peculiar quadrupolar domain patterns [7], confirming the mechanism. The mechanism appears to be very universal, and is shown to work in samples with very different crystallographic symmetry and magnetic properties, including weak ferromagnets [8] and antiferromagnets [9], but also completely different systems such as ferroelectrics. Using single-shot time resolved microscopy, we demonstrate that the dynamics of the domain formation proceeds via a strongly inhomogeneous magnetic state resulting in a self-organization of magnon-polarons [10]. This we could arguably relate to the spin-wave instabilities that appear due to the very large amplitude of precessional magnetic motion in the switching process.

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[2] A. M. Kalashnikova et al, Phys. Rev. Lett. 99, 167205 (2007)
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[4] D. M. Juraschek, M. Fechner, A. V. Balatsky, N. A. Spaldin, Phys. Rev. Mater. 1, 014401 (2017)
[5] D.M Juraschek, T. Neuman, & P. Narang, Phys. Rev. Res. 4, 013129 (2022)
[6] C.S. Davies, F.G.N. Fennema, A. Tsukamoto, I. Razdolski, A.V. Kimel, A. Kirilyuk, arXiv:2305.11551 (2023)
[7] A. Stupakiewicz et al, Nature Phys. 17, 489 (2021)
[8] T. Janssen, M. Gidding, C. S. Davies, A. V. Kimel, and A. Kirilyuk, Phys. Rev. B 108, L140405 (2023)
[9] P. Stremoukhov et al, New J. Physics 24, 023009 (2022)
[10] M. Gidding, T. Janssen, C.S. Davies, and A. Kirilyuk, Nature Commun. 14, 2208 (2023)

# Photo-induced nonthermal metals

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Several insulating materials can be switched by laser pulses into transient metal states with apparently nonthermal properties [1-4]. Often, this has been interpreted as a nonthermal closing of a Mott gap. An alternative mechanism is the generation of in-gap states by the nonthermal population of multiplets (e. g. singlet-triplet excitations in dimerized systems), or the nonthermal reshuffling of charge between orbitals. I will present recent nonequilibrium dynamical mean field theory studies of model systems, which provide insights into the nature of photo-induced nonthermal metal states in 1T-$TaS_2$ [5] and rare earth nickelates [6], and realistic simulations of the photo-induced dynamics in $VO_2$ [7], which clarify the excitation and charge reshuffling processes leading to the nonthermal monoclinic metal phase.

[1] M. Ligges et al. Phys. Rev. Lett. 120, 166401 (2018)
[2] J. Dong et al., arxiv:2210.11052 (2022)
[3] V. R. Morrison et al., Science 346, 445 (2014)
[4] D. Wegkamp et al., Phys. Rev. Lett. 113, 216401 (2014)
[5] F. Petocchi et al., Phys. Rev. B 107, 165102 (2023)
[6] P. Werner et al., Phys. Rev. B 107, 035157 (2023)
[7] J. Chen, et al., arxiv:2310.18195 (2023)

# Entanglement phase transition under continuously monitored dynamics in many-body localized systems

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Localization, which is typically induced by disorder, is an exotic phenomenon where a quantum state fails to spread over the entire Hilbert space. Recently, measurement is utilized as another mechanism to localize a quantum state in nonunitary quantum circuits and continuously monitored systems, which exhibit novel quantum phenomena dubbed measurement-induced phase transitions (MIPTs). However, while both the disorder and the measurement localize the wave function and suppress the entanglement spreading, it is still not clear whether they exhibit the same localization properties.

In this talk, we study the localization properties of continuously monitored dynamics and associated MIPTs in disordered quantum many-body systems on the basis of the quantum trajectory approach [1]. By calculating the fidelity between random quantum trajectories, we demonstrate that the disorder and the measurement can lead to dynamical properties distinct from each other, although both have a power to suppress the entanglement spreading. In particular, in the large-disorder regime with weak measurement, we elucidate that the fidelity exhibits an anomalous power-law decay before saturating to the steady-state value. Furthermore, we propose a general method to access physical quantities for quantum trajectories in continuously monitored dynamics without resorting to postselection. It is argued that this scheme drastically reduces the cost of experiments. Our results can be tested in ultracold atoms subject to continuous measurement.

[1] K. Yamamoto and R. Hamazaki, Phys. Rev. B 107, L220201 (2023)

# Entanglement transition and monogamy effects in non-Markovian systems

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In the last few years there has been great interest in the dynamics of monitored quantum many-body systems. The interplay between unitary evolution and dissipative dynamics leads to many effects, including measurement induced phase transitions of the entanglement scaling. While earlier works all considered Markovian dissipative processes, lately there has been growing interest in non-Markovian dissipation and the effect of memory on entanglement transitions [1].

I will present recent results and developments on the study of entanglement in non-Markovian systems [2]. In particular, I will focus on a free fermions ladder model, where one of the chains is the system of interest and the other chain (bath chain) is subjected to Markovian projective measurements. The global dynamics is Markovian and can be studied through standard Montecarlo quantum jumps methods, but because of the internal dynamics of the bath chains, the reduced dynamics on the system chain is non-Markovian. The introduction of this ancillary chain allows to study the entanglement transition in the presence of memory effects. The studied model exhibits a variety of phases, including transition a from area-law to CFT phase and different regimes where the monogamy of entanglement produces strong counter-intuitive effects.

[1] G. Chiriacò et al., Phys. Rev. B 108, 075151 (2023)
[2] M Tsitsishvili et al., arXiv:2307.06624

# Probing Dynamical Resonances In A 5564 Qubit Quantum Annealer

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Understanding the dynamics of complex, strongly interacting many-body systems is crucial in the field of quantum science and engineering. Recent advancements in controlling programmable many-body systems have provided insights into nonequilibrium states, often inaccessible to classical simulations [1-3]. This talk explores the concept of dynamical resonances, which are radically distinct magnetization dynamics occurring only within a very narrow parameter regime, in the transverse field Ising model realized on a quantum annealer. One example that emerges in such a resonant regime are quantum many-body scars, which are rare, non-thermalizing eigenstates that challenge our understanding of quantum thermalization and ergodicity [4-6].

We will delve into the theoretical and experimental aspects of dynamical resonances, discussing their relevance in the context of quantum annealing [7,8]. In particular, we focus on their emergence in the ferromagnetic transverse field Ising model, examining how these elusive quantum phenomena might manifest in state-of-the-art quantum annealers equipped with up to 5564 qubits. The aim of this investigation is to shed light on the properties and dynamics of dynamical resonances, potentially leading to the largest non-equilibrium quantum simulation to date.

This talk will encompass theoretical predictions, experimental setup, methodologies, and preliminary results. We will also touch upon the broader implications of understanding dynamical resonances, as they hold the potential to steer entanglement dynamics in complex many-body systems, opening new avenues in quantum science and engineering.

[1] A.M. Kaufman et al. Science, 353, 794-800 (2016)
[2] M. Schreiber et al. Science 349, 842–845 (2015)
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[4] E. J. Heller Phys. Rev. Lett. 53, 1515–1518 (1984)
[5] H. Bernien et al. Nature 551, 579–584 (2017)
[6] C. J. Turner et al. Nat. Phys. 14, 745–749 (2018)
[7] A.D. King et al. Nature 617, 61–66 (2023)
[8] A.D. King et al. Nat. Phys. 18, 1324–1328 (2022)

# $Ta_2NiSe_5$: excitonic or not?

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$Ta_2NiSe_5$ has long been considered as a prominent candidate for realization of the excitonic condensation that was invoked to explain the opening of the gap in the photoemission and to rationalize the existence of short time scales in pump-probe experiments. A structural transition that coincides with the putative excitonic transition leads to eternal chicken-egg debate addressing the dominant mechanism of the transition. We consider a realistic 6 orbital model and discuss its instabilities in Hartree-Fock calculations including the relevant $B_{2g}$ Raman active phonon. The model realizes excitonic transition with experimentally expected symmetry only provided the electron-phonon coupling is taken into account. From time-dependent calculations we evaluate also two-particle response corresponding to Raman and optical spectra. The key feature of the calculated response is a prominent phase mode, and the extent to which it survives in the structurally distorted ground state may help settling the debate.

# Current-induced excitonic condensation in bilayer systems

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Excitons are correlated electron-hole pairs in multi-band electron systems, which can condense and form ordered phases of matter called excitonic insulators. These are expected to display novel and technologically highly relevant features like superfluid energy transport. While it is experimentally challenging to identify real materials hosting equilibrium excitonic order, out-of-equilibrium protocols open up an independent route to stabilize excitonic condensates.

Ma et.al. [1] proposed a gated semiconductor bilayer architecture, in which an applied voltage bias allows for the continuous creation of interlayer excitons by means of an induced electrical current. We model the setup starting from the quasi-stationary situation [2] within the static Hartree-Fock and second order Born approximations. We compare results from dynamical mean-field theory to simulations in one spatial dimension to shed light on the strong impact of dimensionality on the formation of the excitonic state. To go beyond the quasi-stationary case, we discuss results of time-dependent simulations of a driven four-band model in one spatial dimension, which is coupled to a bosonic bath.

[1] Ma, L. et al. Nature 598, 585–589 (2021)
[2] Ming Xie and A.H. MacDonald, PRL 121, 067702 (2018)

## Wednesday, December 13, 2023

| | | |
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# Long-living prethermalization in nearly integrable spin ladders

J. Pawłowski,[1] M. Panfil,[2] J. Herbrych,[1] M. Mierzejewski[1]

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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.

# Breakdown of Hilbert space fragmentation

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Description of the relaxation or thermalization of the strongly correlated system close to the integrable point remains a challenge. Although the fate of such systems is ultimately an ergodic dynamic, the road to it could take an extremely long time and can display some exotic (type of integrability breaking-dependent) behavior. On the one hand, many extremely long-time scales - reminiscent of integrals of motions - prevent numerical simulations from reaching an unbiased conclusion on such systems. On the other hand, the nonintegrability hinders the analytical approaches. Recently, a new family of ergodicity-breaking systems was found where the Hilbert space is fragmented into exponentially many parts due to constraints on the possible dynamics. Taking the t-Jz model as an example, we will show how one can control the degree of Hilbert space fragmentation, i.e., the number of disconnected subspaces. We will discuss how various time scales emerge from the breakdown of fragmentation and how they affect the relaxation of such systems.

# Dynamical universality of charged single-file systems and integrable spin chains

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We introduce and discuss dynamical universality of charge fluctuations in charged single-file systems. The full counting statistics of such systems out of equilibrium generically undergoes first and second order dynamical phase transitions, while equilibrium typical fluctuations are non-Gaussian and given by a universal distribution. Similar phenomenology of dynamical criticality is observed in equilibrium in the easy axis and isotropic regimes of an integrable spin chain. While the easy axis regime does not satisfy a single-file kinetic constraint, it nevertheless supports the non-Gaussian distribution of the charged single-file universality class. Fluctuations at the isotropic point are also anomalous and distinct from those of the Kardar-Parisi-Zhang universality class.

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[2] Ž. Krajnik et al. arXiv:2208.01463 (2022)
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[4] Ž. Krajnik et al. Phys. Rev. Lett. 128, 090604 (2022)

# Optical control of magnetism thru strongly non-equilibrium phases

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The ability to switch magnets between two stable bit states is the main principle of digital data storage technologies since the early days of the computer. Since our demonstration of magnetization reversal by a single 40 femtosecond laser pulse, the manipulation of spins by ultra-short laser pulses has developed into an alternative and energy efficient approach to magnetic recording. Though originally thought to be due to an optically induced effective field, later studies demonstrated that the switching occurred via a strongly non-equilibrium state, exploiting the exchange interaction between the spins. Recent work also show how magnetic textures like skyrmions are generated via a non-equilibrium phase.

While for a long time, all-optical switching (AOS) was exclusively observed in ferrimagnetic alloys, more recent work demonstrated AOS in a broad range of ferromagnetic multilayer materials, albeit that in those examples a large number of pulses were required. By studying the dynamics of this switching process, we have discovered that this switching is a 2-step process, which led us to the subsequent demonstration that highly efficient AOS can be achieved by using pairs of femto/pico-second laser pulses. By combining optical laser excitation with in situ magnetic force microscopy we recently found that the nucleation and switching process evolves via a stochastic network of domains.

As new ICT technologies, such as Artificial Intelligence, is leading to a dramatic increase of the energy cost of computing, the development of radically new physical principles that combine energy-efficiency with high speeds and high densities is crucial for a sustainable future. One of those new principles is neuromorphic computing, that is inspired by the notion that our brain uses a million times less energy than a supercomputer while, at least for some tasks, it even outperforms the latter.

In this talk, I will discuss the state of the art in ultrafast manipulation of magnetic bits and present some first results and new ideas to implement brain-inspired computing concepts in magnetic materials.

**Acknowledgement(s):** Support from the Dutch Research Council (NWO) and the European Research Council ERC grant agreement no.856538 (3D-MAGiC) is acknowledged.

# TBD

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# The correlated random anisotropy model of the Co-organic composite films

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We propose the correlated random anisotropy model that describes thin ferromagnetic films hybridized with organic molecular layers. The asymmetry of the molecules leads to the random in-plane anisotropy induced at the surface of the magnetic film. We show that this strongly modifies the magnetic anisotropy of the whole cobalt layer which magnitude critically depends on the correlation radius of random anisotropy (fig. a). When this radius is small even strong induced anisotropy can be neglected. However, with the increase of correlation radius, the effect of molecules starts to dominate the magnetic properties. It results in the colossal increase of the coercive field, modification of the hysteresis loop shape (fig. b), and breaking of the Raleigh law at low fields.

Physically, the effect results from the modification of pseudoground states in the magnetic film. At a low correlation radius the state can be described by standard domain wall picture, while at larger correlation radiuses a correlated spin glass state emerges.

## Acknowledgements

We acknowledge the support of the EC projects INTERFAST (H2020-FET-OPEN-965046).

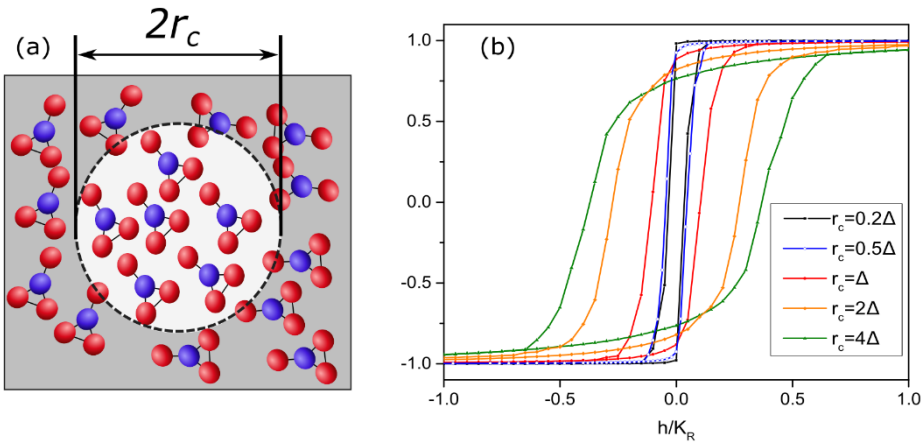


**Fig. 1. a)** The correlation radius $r_c$ of molecule-induced anisotropy. **b)** Hysteresis loops for different values of $r_c$.

# Ultrafast Magnetometry of (Light-Induced) Superconductors

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Driving certain cuprates and organic materials has been shown to induce THz optical properties reminiscent of superconductivity far above the equilibrium transition temperature. However, the magnetic response of these non-equilibrium states remains unexplored. This study investigates whether these states exhibit a Meissner effect, expelling external magnetic fields, and examines their response to changing magnetic fields on sub-picosecond time scales.

Our methodology involves studying the ultrafast magnetic response of these materials in static and time-dependent magnetic fields using the Faraday effect in a magneto-optical crystal adjacent to the sample. This provides sub-picosecond time resolution for reconstructing the position-dependent magnetic properties.

Beginning with the investigation of the destruction of superconductivity below Tc, we explore signs of the light-induced appearance of superconductivity far above Tc. Our study examines the temperature and magnetic field dependence of these phenomena, offering new insights into the non-equilibrium dynamics of these systems.

Furthermore, we discuss how this method could be extended to probe the dynamics of other laser-driven strongly correlated materials. This research sheds light on the unique properties of non-equilibrium states and their potential applications in the field of condensed matter physics.

# Emergent spin phenomena from hyperfine interaction of localized electrons and nuclear spins

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Many modern devices are based on the operations with spins. They require the preparation of the initial state: with spin polarization or at least with spin correlations. There is a limited number of conventional methods to achieve this: application of ferromagnetic materials, current to spin conversion due to spin-orbit interaction and static polarization in high magnetic fields. We show the existence of another way to achieve spin polarization in non-magnetic solid-state devices. It requires small magnetic fields, hyperfine interaction between electron and nuclear spins and small exchange interaction between electron spins. All the interaction energies are considered small compared to temperature, but the mechanism requires non-equilibrium conditions.

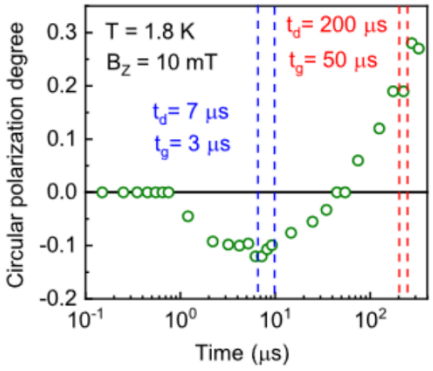


**Fig. 1.** The dependence of circular polarization of luminescense in (In,Al)As/AlAs quantum dots as function of the delay after initial unpolarized excitation pulse.

The physics of dynamic spin polarization involves the interplay of non-equilibrium spin phenomena and effect of the magnetic field on spin relaxation provided by hyperfine interaction of electron and nuclear spin. Such interplay occurs in many organic semiconductors and leads to quite strong room temperature "organic" magnetoresistance related to the correlated spin state [1].

The spin polarization appears due to the interplay of "organic magnetoresistance" physics with weak exchange interaction of electron and holes localized at different molecules [2]. Very similar phenomena exist also in quantum dots where it manifests itself as strong circular polarization of luminescence observable in 10mT magnetic fields at temperatures below 10K [3,4]. The circular polarization has a very complex non-monotonous dependence on the time delay after the initial excitation (Fig. 1) and on the applied magnetic field.

[1] A.V. Shumilin, Phys. Rev. B 101, 134201 (2020)
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# Manipulating exciton binding by floquet engineering in Fermi Hubbard ladder

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Strong excitations of correlated quantum materials give rise to various non-thermal phases which are not present in their equilibrium counterpart. Recently, it was shown that the one-dimensional Fermi Hubbard Model features charge density wave and η-pairing phases upon photo-doping. In this study, we explore the non-equilibrium behavior of the Fermi Hubbard ladder and employ the Schrieffer-Wolff transformation to map it to a simplified t-J-like model, providing an effective equilibrium description of the photo-doped states. Our investigation highlights the significance of applying an electric field along the rung to the hopping term. This floquet manipulation allows to increase the spin and η-exchange coupling along the rung independent of the hopping term. Moreover, the magnitude of hopping decreases as a result of the drive. These combined effect tends to localize the excitons close to each other and thus enhance its binding energy. To characterize the ground state of the system, we employ relevant correlators and make notable observations. We show that at certain drive frequencies, the ground state encompasses a strongly bound holon-holon/doublon-holon pair along the rung, alongside inter-chain singlets. Additionally, we propose experimental setups to test our theory.

# Influence of Metal/Organic-Molecules Interface on Magnetic Anisotropy in Co Thin Films: A Time-Resolved MOKE Investigation

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We investigated by means of the ultrafast time-resolved magneto-optical Kerr effect (MOKE) spectroscopy [1] the effect of the interface between organic molecular semiconductors and cobalt on the magnetic anisotropy of polycrystalline Co thin films. Comparison of the effect was measured on interfaces of Co with: nonmagnetic metal (Al), metalorganic complexes tris(8-hydroxyquinoline)gallium (Gaq3) and M-phthalocyanines (M=Cu, Co) as well as Buckminster-fullerene (C60) molecules.

In general, the transient MOKE signals were found to exhibit damped coherent spin wave oscillations (CSWO) with frequencies up to several tens of GHz. Detailed analysis of the spin-wave temperature and magnetic field dependences allowed us to compare the influence of different molecular interfaces.

We found that the thin Co films interfaced with molecular layers display strong hardening of the CSWO frequency at low T with a rather sharp transition in the 150 K - 170 K range. Interfaces with different molecules show qualitatively and quantitatively similar behavior despite different molecular shapes. The hardening is attributed to increase of the interface induced anisotropy due to the hybridization between the molecular-orbitals and the Co d-orbital derived interface states [2]. We also found that the CSWO are more damped at low T, which we attribute to an increase of magnetic anisotropy inhomegeneity.

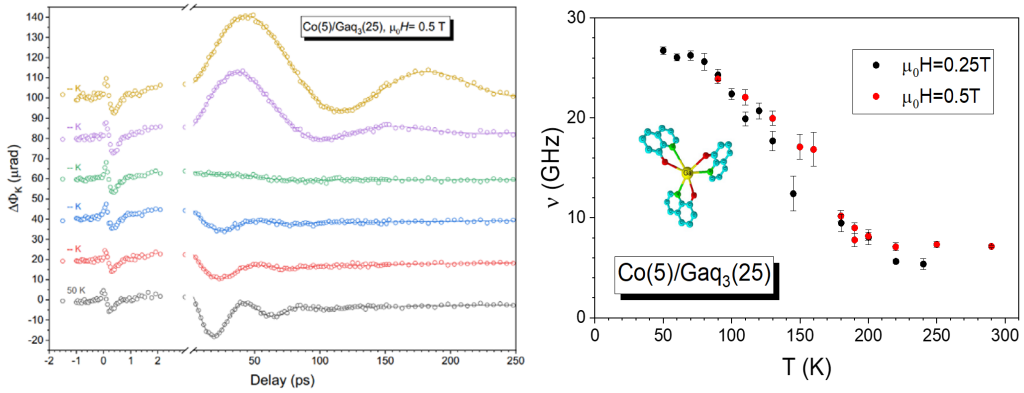


**Fig. 1.** Coherent spin-wave oscillations **(left)** and the temperature dependence of their frequency **(right)** in a tris(8-hydroxyquinoline)gallium interfaced Co film.

[1] M. van Kampen et al., Phys. Rev. Lett. 88 (2002) 227201
[2] T. Moorsom et al., Phys. Rev. B. 101 (2020) 060408

# Chirped amplitude mode in photo-doped superconductors

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When a continuous symmetry is spontaneously broken, two types of collective modes emerge: phase and amplitude mode fluctuations of the order parameter. The latter is a massive excitation living at the edge of the gap. Recently, signatures of the amplitude mode were observed in photo-doped superconductors using third-harmonics generation in the terahertz regime, which opened the field of nonlinear light-amplitude mode coupling.

We will show that a weak photo-excitation in superconductors leads to a long-lived prethermal phase with a reduced order parameter and superimposed amplitude oscillations. As we increase the intensity of the pump pulse, the amplitude mode oscillations exhibit chirping; namely, the frequency slows down as a function of time. The chirping gets amplified as we approach the nonthermal critical point - an excitation at which the intensity of the light is large enough to destroy the superconducting order. We identify signatures of the chirped amplitude mode in photo-induced current after a monocycle or Gaussian pulse and propose a transmission line circuit experiment to detect the phenomena. In the last part, we will present recent theoretical advances based on the compressed representation of quantum propagators, which allow the analysis of time scales relevant for the collective mode dynamics.

# A renormalization group analysis of the Anderson model in infinite dimensions

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In this talk, I will present a renormalization group analysis of the problem of Anderson localization on Regular Random Graphs (RRGs). I will first review and extend the finite-dimensional analysis of Abrahams, Anderson, Licciardello, and Ramakrishnan in terms of spectral observables, and discuss how to take the large-d limit. I will then motivate that the infinite-dimensional case, relevant also in the context of Many-Body Localization, recovers the Anderson model on RRGs. In this case, the renormalization group β-function necessarily involves two parameters, but the one-parameter scaling hypothesis is recovered for sufficiently large system sizes. I will also discuss how to understand this change in behavior in terms of the geometrical properties of the graphs. The talk will be based on arXiv:2306.14965 and ongoing work.

# A note on weak eigenstate thermalization and normalization of operators

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While the eigenstate thermalization hypothesis (ETH) is well established for quantum-chaotic interacting systems, its validity for other classes of systems remains a matter of intense debate. Focusing on quadratic fermionic Hamiltonians, we here argue that the weak ETH is satisfied for few-body observables in many-body eigenstates of quantum-chaotic quadratic (QCQ) Hamiltonians. In contrast, the weak ETH is violated in two cases: (a) for sums of few-body observables in all quadratic Hamiltonians, and (b) for few-body observables in localized quadratic Hamiltonians. We argue that these properties can be traced back to the validity of single-particle eigenstate thermalization, and we highlight the subtle role of normalization of operators. Our results suggest that the difference between weak and no ETH in many-body eigenstates allows for a distinction between single-particle quantum chaos and localization. We test to which degree this phenomenology holds true for integrable systems such as the XYZ and XXZ models.

# Thursday, December 14, 2023

| | **Chair:** | |
|---|---|---|
| 9:00 - 9:30 | **Andrew George Green:** Phase Transitions in the Classical Simulability of Open Quantum Systems | 54 |
| 9:30 - 10:00 | **Till Domröse:** Light-induced hexatic state observed by ultrafast nanobeam diffraction | 55 |
| 10:00 - 10:15 | **Anze Mraz:** Switching of the nanocryotron-driven charge configuration memristor in real time | 56 |
| 10:15 - 10:45 | *COFFEE BREAK* | |
| | **Chair:** | |
| 10:45 - 11:15 | **Tomaz Mertelj:** Unconventional photo-induced charge-density-wave dynamics in 2H-$NbSe_2$ compared to the conventional in 1T-$VSe_2$ | 57 |
| 11:15 - 11:30 | **Manuel Tuniz:** Manipulation of the charge-density-wave in $VTe_2$ by femtosecond light pulses | 58 |
| 11:30 - 11:45 | **Iris Ulčakar:** Iterative construction of conserved quantities in dissipative nearly integrable systems | 59 |
| 11:45 - 12:00 | **Jože Gašperlin:** The interplay of lattice dynamics, stacking effects and Mott physics in charge-density-wave systems | 60 |
| 12:00 - 12:15 | **Closing:** NQW 2023 | |

# Phase Transitions in the Classical Simulability of Open Quantum Systems

A.G. Green[1]

[1]*University College London, UK*

We introduce a Langevin unravelling of the density matrix evolution of an open quantum system over matrix product states, which we term the time-dependent variational principle-Langevin equation. This allows the study of entanglement dynamics as a function of both temperature and coupling to the environment. As the strength of coupling to and temperature of the environment is increased, we find a transition where the entanglement of the individual trajectories saturates, permitting a classical simulation of the system for all times. This is the Hamiltonian open system counterpart of the saturation in entanglement found in random circuits with projective or weak measurements. If a system is open, there is a limit to the advantage in simulating its behaviour on a quantum computer, even when that evolution harbours important quantum effects. Moreover, if a quantum simulator is in this phase, it cannot simulate with quantum advantage.

# Light-induced hexatic state observed by ultrafast nanobeam diffraction

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[3]*Institute of Experimental and Applied Physics, Kiel University, Germany*
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Quantum materials are characterised by enhanced correlations between their microscopic degrees of freedom that favor the occurence of exciting physical properties that are tunable by optical excitation, including the formation of charge-density waves (CDWs). The investigation of the dynamics following such an optical quench is available in ultrafast transmission electron microscopes (UTEMs), versatile tools that combine nanometer spatial with femtosecond temporal resolution (Fig. 1a) [1,2].

Here, we investigate the transformation between the nearly-commensurate (NC) and the incommensurate (IC) CDW phase in the layered quantum material 1T-TaS2 [3,4]. Therein, selective contrast enhancement by means of ultrafast dark-field microscopy allows us to follow the spatially heterogeneous suppression of the NC phase on the nanoscale, particularly at interphase boundaries [3]. In a complementary approach, the establishment of three-dimensional IC CDW order is accessible by means of ultrafast electron diffraction [4]. Specifically, the high-coherence electron source of the Göttingen UTEM [2] enables collimated diffractive probing of nanometer-sized, spatially homogenous sample regions with high reciprocal-space resolution (Fig. 1c).

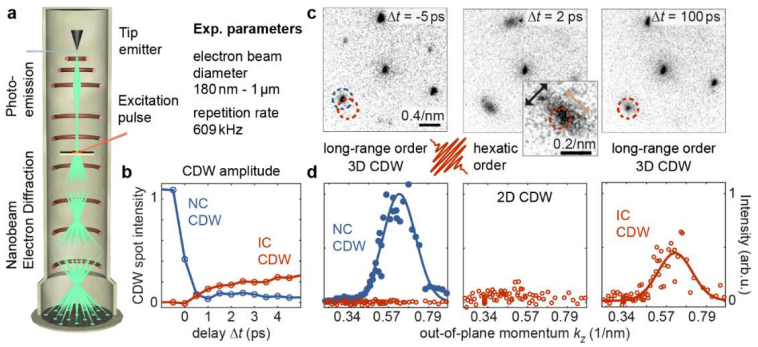


**Fig. 1. a)** UTEM schematics. **b)** Evolution of the CDW spot intensity of the IC (red) and the NC phase (blue). **c)** Characterisation of in-plane disorder. Transient hexatic order is encoded in the azimuthally broadened diffraction spots (brown arrow). **d)** CDW rocking curves. We find similar spot broadening also along the out-of-plane direction, indicative of a dimensional crossover.

Based on a tomographic reconstruction of the CDW diffraction spot shape during the dynamics, we identify an initial loss of interlayer correlations (Fig. 1d). Along the in-plane directions, this dimensional crossover is corroborated by a suppression of translational, but intact orientational order, paralleling the phenomenology of a hexatic phase [5]. We conclude that, in close analogy, the phase transition observed here unfolds via a network of topological point defects and a transient hexatic state.

Our results show how optical excitation can induce low-dimensional behaviour in functional materials. In the future, we expect ultrafast nanobeam electron diffraction to further enhance the investigation of non-equilibrium dynamics in the presence of spatial heterogeneity.

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[2] A. Feist et al., Ultramicroscopy 176, 63-73 (2017)
[3] Th. Danz, T. Domröse, C. Ropers, Science 371, 371-374 (2021)
[4] T. Domröse et al., Nat. Mater. (2023)
[5] D. Nelson, B. Halperin, Physical Review B 19, 2457-2484 (1979)

# Switching of the nanocryotron-driven charge configuration memristor in real time

A. Mraz,[1,2] R. Venturini,[1,3] D. Svetin,[1,2] I. Vaskivskyi,[1,2] T. Lotrič,[1] B. Brezec,[1] M. Merljak,[1] D. Kazazis,[4] J. Ravnik,[4] S. Gerber,[4] Y. Ekinci,[4] V.V. Kabanov,[1] D. Mihailovic[1,2]

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To improve the field of superconducting computer systems, a low-power, fast and durable memory device that is compatible with the single-flux-quantum (SFQ) logic is needed [1,2]. Here we report on recent progress in the development of a so-called parallelotron (pTron) [3] device that comprises a superconducting three-terminal amplifying nanowire cryotron (nTron) [4] and a charge configuration memristor (CCM) [5,6] based on 1T-$TaS_2$. Besides the current-voltage characteristics and read operation, we also record switching of the device in real time when the switching pulse is applied to the control terminal. Measured results show great matching to model predictions, demonstrating the validity of the model and its potential usefulness for future optimization of the device's parameters. We briefly discuss the effect of noise on the switching capabilities of the pTron device.

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# Unconventional photo-induced charge-density-wave dynamics in 2*H*-$NbSe_2$ compared to the conventional in 1*T*-$VSe_2$

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We investigated temperature dependent ultrafast near-infrared transient reflectivity dynamics in coexisting superconducting (SC) and charge density wave (CDW) phases of layered 2*H*-$NbSe_2$ using NIR and visible excitations. With visible pump-photon excitation (400 nm) we find a slow high-energy quasiparticle relaxation channel which is present in all phases. In the CDW phase, we observe a distinctive transient response component. The component is marked by the absence of coherent amplitude mode oscillations and a relatively slow, picosecond rise time, which is different than in most of the typical CDW materials, such as 1*T*-$VSe_2$.

In the SC phase, another tiny component emerges that is associated with optical suppression of the SC phase. The transient reflectivity relaxation in the CDW phase is dominated by phonon diffusive processes with an estimated low-T heat diffusion constant anisotropy of ~ 30. Strong excitation of the CDW phase reveals a weakly non-thermal CDW order parameter (OP) suppression. Unlike CDW systems with a larger gap, where the optical OP suppression involves only a small fraction of phonon degrees of freedom, the OP suppression in 2*H*-$NbSe_2$ is characterized by the excitation of a large number of phonon degrees of freedom and significantly slower dynamics.

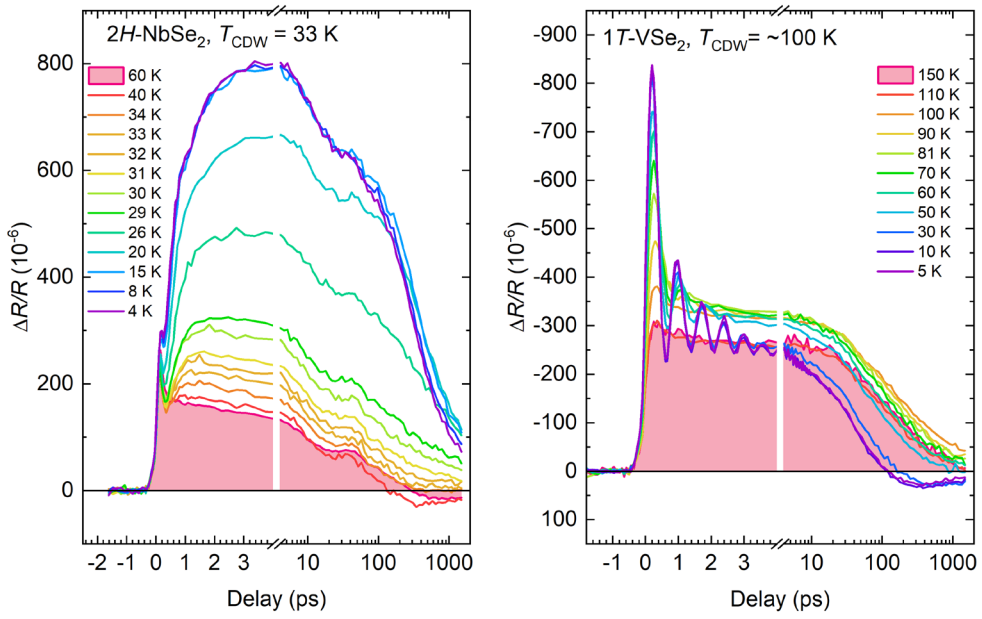


**Fig. 1.** Temperature dependent transient reflectivity in 2*H*-$NbSe_2$ and 1*T*-$VSe_2$.

# Manipulation of the charge-density-wave in $VTe_2$ by femtosecond light pulses

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By combining time and angle-resolved photoemission spectroscopy (tr-ARPES) and broadband time-resolved optical spectroscopy (TR-OS) we investigate the effect of an optical excitation on the electronic and structural properties of the charge-density wave (CDW) system $VTe_2$. Recently, the modification of the material's electronic structure induced by CDW formation has been discussed because the strongly orbital-dependent changes may give rise to a topological change in specific bands [1].

In our contribution, we show by means of TR-OS measurements the possibility to optically excite the amplitude mode (AM) of the CDW phase and therefore couple to the CDW condensate [2]. Moreover, by studying the partial closing of the CDW gap our tr-ARPES experiments unveil a major role played by the lattice degrees of freedom in the stabilization of the CDW phase in $VTe_2$.

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[2] Tuniz, M. et al. arXiv:2305.03528 (2023)

# Iterative construction of conserved quantities in dissipative nearly integrable systems

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Integrable systems offer rare examples of solvable many-body problems in the quantum world. Due to the fine-tuned structure, their realization in nature and experiment is never completely accurate, therefore effects of integrability are observed only transiently. One way to surpass that is to couple nearly integrable systems to baths and driving: these will stabilize integrable effects up to arbitrary time, as encoded in the time dependent, and eventually, the stationary state of form of a generalized Gibbs ensemble. However, the description of such driven dissipative nearly integrable models is challenging and no exact analytical methods have been proposed so far. Here we develop an iterative scheme in which integrability breaking perturbations (baths) determine the most necessary conserved quantities to be added into a truncated generalized Gibbs ensemble description. Our scheme significantly reduces the complexity of the problem, paving the way for thermodynamic results.

[1] I. Ulčakar and Z. Lenarčič, arXiv:2310.03809 (2023)

# The interplay of lattice dynamics, stacking effects and Mott physics in charge-density-wave systems

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The transition metal dichalcogenide 1T-TaS2 is a layered compound that exhibits a series of increasingly commensurate charge density wave phases with decreasing temperature, including a low-temperature insulating phase. For a single 1T-TaS2 layer, with an odd number of electrons per Star-of-David cluster, the insulating behaviour may be attributed to Mott localisation. However, the stacking arrangement of multiple layers can lead to doubling of the unit cell, where the nature of the insulating state is ambiguous [1, 2]. Furthermore, the various possible stacking terminations lead to surface states with non-trivial interplay between band-insulating and Mott-insulating behaviour. [3].

We propose a minimal model, motivated by the Peierls transition, to investigate the influence of these degrees of freedom. The model describes a (semi-bulk) stack of coupled one-dimensional chains at half-filling. Charge-density-wave order is introduced through Peierls electron-lattice coupling in the transverse direction, and treated at the mean-field level. We present the equilibrium phase diagram of the model, demonstrating regions where, as a result of layer stacking, the trimerized phase is stabilized instead of the expected dimerized phase. We identify a narrow band crossing the Fermi level and opening of the Mott gap due to on-site electron-electron interactions.

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# Posters

# Superconductivity in the epitaxially grown 1T-$TaS_2$: The effect of strain and substrate ion diffusion

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The 1T-$TaS_2$ has been studied for the last few years due to its peculiar electronic properties, including the charge density wave (CDW) transition at low temperatures and metastable states. Under high hydrostatic pressure, with doping or intercalation, this material can form a superconducting phase. Thin crystals of 1T-$TaS_2$ deposited on different substrates exhibit transitions at temperatures rather different from the bulk crystals, which is usually attributed to a substrate-induced strain effect.

While the bulk crystals are relatively easy to synthesize, for the real-life application of the material, well-defined thin samples are required. Usually, such samples are obtained by mechanical exfoliation from the bulk crystals, but molecular beam epitaxy (MBE) in principle allows growth of films with controlled thickness without introducing any exfoliation-related effects to the material.

In the present work, we are using the MBE method to grow 1T-$TaS_2$ films of different thicknesses on $(LaAlO_3)_{0.3}(Sr_2TaAlO_6)_{0.7}$ substrates. While the grown films are confirmed (using X-ray diffraction) to be 1T polytype, the transition to commensurate CDW is suppressed. At the same time, resistivity, magnetoresistance and critical current measurements show metallic behaviour with an onset to a superconducting state below $T_c$=3.8 K. We show that this effect is caused by a strongly amplified out-of-plane compressive strain introduced by the differential tensile in-plane stain during the after-growth cooling. Additionally, La and Sr are found in trace quantities, resulting in doping of the epitaxial films.

Provided that ion diffusion can be controlled, our experiments show that tensile substrate strain can be used to fine-tune the material to achieve the desired properties which gives an accessible alternative to the hydrostatic pressure for studying strain effects in 2D materials.

# Conditional no-jump dynamics of non-interacting quantum chains

[* In preparation]

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Non-equilibrium open quantum systems continue to raise many physical challenges. In this respect, we may quote the transport phenomena in driven quantum chains, where a nonunitary dynamics arises from the coupling with external reservoirs, e.g. Lindblad baths [2]. The quantum trajectory techniques represent a simple tool to access the Lindblad dynamics by stochastic averages over single trajectories evolving in time as pure states [3]. The evolution of each trajectory is generated by a non-Hermitian effective Hamiltonian and it is perturbed by the so-called quantum jumps appearing stochastically in time. The quantum jumps may be pictorially seen as the action of some detectors monitoring the exchange of particles between the system and the external environment.

The complete statistics of jumps occurring in time is captured by the theory of Full Counting Statistics [4-6]. Connected to these concepts, the no-jump probabilities and the waiting-time distributions represent a powerful theoretical probe for the interplay between non-Hermitian dynamics and jump events [1,7]. We address the study of these quantities for non-interacting quantum chains and inhomogeneous jump rates, generalising results for non-ideal monitoring efficiencies.

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# Table-top EUV polarimeter for probing ultrafast magnetization dynamics

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The High Harmonic Generation process, which occurs in noble gasses under illumination by laser radiation of energy densities on the order of 10^14 W/cm^2, allows for the generation of EUV light in a laboratory setting. Spectral characteristics of such sources are immensely usefull in the study of, for example, multi-component magnetic systems, since concurrent observation of the magnetization dynamics of different constituent atoms' spins is possible.

Studying element-specific magnetization dynamics is key to understanding the process of ultrafast demagnetization in a variety of materials, and such experiments allow for testing the various models proposed to explain this effect in ferromagnets – a question on which consensus has still not been reached [1, 2]. The interplay of different elemental spis has also been shown to be crucial in materials exhibiting exotic effects, such as sing-shot switching of magnetization in ferimagnets [3, 4]. Generally, element-specific magnetization dynamics are studied either with Magnetic Circular Dichroism of Magneto Optical Kerr Effect (MOKE), usually in a single projection, most commonly in Transverse MOKE (T-MOKE). However, by limiting oneself to only one projection, interpretation of experimental data can be difficult since the reconstruction of the full trajectory of the excited spins is impossible, and in the case of T-MOKE, no information about the imaginary part of the dielectric constant can be obtained.

Currently, a table-top HHG source offering novel capabilities is being commissioned at the Complex Matter Department at Jožef Stefan Institute. The setup will enable us to perform ultrafast resonant pump-probe experiments in the Polar- and Longitudinal-MOKE geometries without any mechanical readjustments of the setup, while to study the T-MOKE response only a simple exchange of the external magnet will be necessary. The setup allows for measuring both the Kerr rotation and the Kerr ellipticity, features high spectral resolution, the possibility of cooling the sample, and shortened acquisition times compared to most existing machines of this type.

Motivation for the development of the setup, its capabilities and the design considerations necessary to achieve them, the current stage in the commissioning process, and some preliminary results will all be presented.

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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 [Phys. Rev. Lett. 131, 060404 (2023) and arXiv:2309.16005], 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 single-particle 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 one-dimensional Aubry–André model, we demonstrate that the transition probabilities exhibit scale-invariant 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.

# Nontrivial damping of quantum many-body dynamics in the spin-1/2 XXZ chain

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Understanding how the dynamics of a given quantum system with many degrees of freedom is altered by the presence of a generic perturbation is a notoriously difficult question. Recent works predict that, in the overwhelming majority of cases, the unperturbed dynamics is just damped by a simple function, e.g., exponentially as expected from Fermi's golden rule. While these predictions rely on random-matrix arguments and typicality, they can only be verified for a specific physical situation by comparing to the actual solution or measurement. Crucially, it also remains unclear how frequent and under which conditions counterexamples to the typical behavior occur. In this poster, we discuss this question from the perspective of projection-operator techniques, where exponential damping of a density matrix occurs in the interaction picture but not necessarily in the Schrödinger picture. We show that a nontrivial damping in the Schrödinger picture can emerge if the dynamics in the unperturbed system possesses rich features, for instance due to the presence of strong interactions. This suggestion has consequences for the time dependence of correlation functions. We substantiate our theoretical arguments by large-scale numerical simulations of spin transport in a perturbed spin-1/2 XXZ chain, where nearest-neighbor interactions are treated as a perturbation to the integrable reference system.

[1] T. Heitmann et al. Physical Review E 104, 054145 (2021)
[2] M. Kempa et al. In preparation

# Optical manipulation of bipolarons in a system with nonlinear electron-phonon coupling

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Research in the field of driven quantum materials is at the forefront of modern solid-state physics. The development of new laser sources enabled a new chapter in the field[1] where we can selectively excite collective degrees of freedom, like lattice, magnetic and electronic excitations, to generate new emergent states of matter[2,3]. Among most prominent examples are optical manipulation of magnetic order[4-6], lightinduced non-equilibrium metal–insulator transitions[7-9], and optically enhanced transient states displaying superconducting signatures[2,10,11].

We provide an exact time evolution for two electron system coupled non-linearly to lattice distortions and driven by external laser pulse, which homogeneously excites dipolar active lattice modes. We show that electronic binding can be dramatically enhanced or reduced depending on the pulse protocol. The electron binding (repulsion) remains enhanced due to modified bipolaronic self-trapping leading to a long-lived (metastable) state even after the pulse has been switched off. We show that the binding takes place only for negative values of non-linear electron-lattice couplings, which is in contrast with previously applied approximation predicting a sign independent binding. Finally, we show that the metastable state slowly decreases if Einstein phonons acquire a finite bandwidth, still, the double occupancy remains elevated in comparison to its value before the appliaction of the pulse.

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# Important role of phononic dispersion in bipolaronic systems

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The interaction between electrons and lattice vibrations, a phenomenon known as electron-phonon (EP) interaction, is a subject of extensive research in solid-state physics. This interaction significantly influences the physical properties of a diverse range of materials[1-3]. To gain a fundamental understanding of systems where EP interaction plays a crucial role, researchers have extensively investigated the Holstein model (HM)[4]. Although the HM is conceptually simple, it lacks an exact analytical solution. Consequently, researchers have employed a wide array of numerical methods to explore its static and dynamic properties.

HM simplifies EP interactions by focusing on short-range interactions between charge carriers and lattice distortions, assuming that long-range interactions are effectively screened. The strength of this short-range coupling depends on the relative displacements between the atom hosting the charge carrier and its neighboring atoms. There have been relatively few studies that explore short-range coupling to acoustic phonons[5] since acoustic phonons primarily involve inphase motion of neighboring atoms, resulting in negligible relative displacements and weak electron-phonon coupling. As a result, HM typically disregards acoustic phonons. In contrast, optical phonons describe antiphase atomic motion, leading to substantial relative displacements and, consequently, much stronger electron-phonon coupling. A common approximation is to include optical phonons in HM as dispersionless Einstein phonons. This choice is motivated not only by the notion that it provides a reasonable approximation when the phonon bandwidth is small compared to the average phonon

frequency but also by the additional complexities that phonon dispersion introduces into both analytical and numerical treatments of the model. As a result, there are relatively few research papers[6-8] dedicated to studying HM with dispersive optical phonons. These studies have revealed that phonon dispersion has a profound impact on polaron properties, affecting quantities such as the effective mass[6], the optical conductivity[7], and the spectral function[8]. However, it is important to note that these works primarily investigate the influence of dispersion on polaron properties and do not delve into the interactions between polarons.

In contrast, our study focuses on the effect of phononic dispersion in a system consisting of two electrons strongly coupled to optical phonons. To account for the Coulomb interaction between charge carriers, we introduce a Hubbard term to the Holstein model, resulting in the Holstein-Hubbard model (HHM). Our investigation focuses on assessing the impact of phononic dispersion on various aspects of the system, including static properties like effective mass and binding energy, as well as dynamic processes observed in the spectral function.

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# Constructing nonequilibrium steady states from equilibrium correlation functions in generic nonintegrable systems

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State-of-the-art approaches to extract transport coefficients of many-body quantum systems broadly fall into two categories: (i) they target the linear-response regime in terms of equilibrium correlation functions of the closed system; or (ii) they consider an open-system situation typically modeled by a Lindblad equation, where a nonequilibrium steady state emerges from driving the system at its boundaries. While quantitative agreement between (i) and (ii) has been found for selected model and parameter choices, also disagreement has been pointed out in the literature. Studying magnetization transport in the spin-1/2 XXZ chain, we here demonstrate that at weak driving the nonequilibrium steady state in an open system, including its buildup in time, can remarkably be constructed just on the basis of correlation functions in the closed system. We numerically illustrate this direct correspondence of closed-system and open-system dynamics. This poster particularly complements R. Steinigeweg's talk by recent results for generic nonintegrable systems, where the spin-1/2 XXZ chain is modified by integrability-breaking pertubations.

[1] T. Heitmann et al. arXiv:2303.00430
[2] T. Heitmann et al. Physical Review E 108, 024102 (2023)
[3] M. Kraft et al. In preparation

# Probing stability of false vacuum with quantum quenches

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Metastability is a state of equilibrium that is inherently unstable, yet persists over extended periods due to energy barriers hindering transitions to more stable configurations. It is a fascinating concept that pervades numerous scientific disciplines. Detecting whether a system is in a stable (true vacuum) or metastable state (false vacuum) is often a difficult task since the lifetime of a metastable state can be prohibitively long. Our work focuses on investigating vacuum stability through a genuine non-equilibrium real-time method. We demonstrate that, by analyzing in the Fourier space the time evolution after a quantum quench, we can differentiate between the two vacuums of the quantum transverse field Ising chain. The effect is observable at much shorter time scales than the typical time scale of the decay process. Inspired by the potential simulation of out-of-equilibrium dynamics in quantum field theories using atomic systems, we then show how, by tuning the parameters to the scaling limit, our results are consistently connected with the ones predicted by the field theory.

[1] G.Lagnese, F. M. Surace, S. Morampudi, F. Wilczek arXiv:2308.08340v1

# High-harmonic generation in semi-Dirac and Weyl semimetals with broken time-reversal symmetry: Exploring merging of Weyl nodes

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In this talk, I will discuss high-harmonic generation in a model that realizes a transition from a broken time-reversal symmetry Weyl-semimetal to a semi-Dirac regime, i.e. a gapless semimetal with dispersion that is parabolic in one direction and conical in the other two. The induced anomalous high harmonics (i.e. in the current in a direction perpendicular to the electric field) are high in particular in the semi-Dirac regime. For Weyl semimetals, I will show that anomalous high harmonics are due to excitations at momenta where the dispersion is not strictly linear and that in the linearized low energy theory the anomalous response is harmonic only.

# Impact of coherent phononons on the linear and non-linear time-resolved optical properties of Tellurium

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The way a transient far-from-equilibrium state of matter affects the macroscopic optical properties of the sample under scrutiny can provide, upon proper modelling, a wealth of information about the microscopic properties of the atoms that constitute the material. For this reason, the possibility to access the problem from multiple viewpoints can in principle considerably ease this task. Here we report on the study of the coherent and incoherent ultrafast dynamics of non-centrosimmetric tellurium, as revealed by acquiring simultaneously the time-resolved reflectivity and the time-resolved second-harmonics-generation as a function of the pump fluence.

The coherent oscillations associated to the A1 phonon mode exhibits a damped cosinusoidal behavior as a function of pump-probe delay, superimposed on a slowly decreasing background. The second harmonics generation signal exhibits a similar time-dependent behavior. However, a careful spectral analysis reveals distinct dynamics of the two time-resolved probes, concerning the oscillation frequency and the damping parameter. A careful analysis of the incoherent and coherent dynamics reveals that the atomic lattice displacements modulate differently the linear (reflectivity) and nonlinear (second-harmonics) optical properties. Particularly, the frequency of the A1 optical phonon mode, at the same pump pulse fluence, is found to be higher in the second harmonic signal compared to the reflected probe signal. Conversely, the damping of the oscillations exhibits an opposite behavior.

These observations cannot be explained by simply invoking a different probing depth of the two probes, hence sensing a different effective fluence. Conversely, the possibility that a larger probing depth detects a faster dephasing is an option. As a result, by combining two complementary probes, it becomes possible to disentangle the information of coherent phonon dephasing from that of coherent phonon decay or diffusion. Additionally, the observation that a large reduction of second-harmonics generation after Te photoexcitation occurs, indicative of the transient realization of a more centrosimmetric phase, explains the fact that, at least at moderate fluence, no anharmonic effects are detected, that were instead observed only at larger pump fluences.

These findings and approach will contribute to improve the understanding of coherent phonons and hold promise for further exploration of their coupling to the electronic and lattice properties of complex materials. In particular, the quantification of the fact that the same photoexcited state displays different dynamics when analyzed by different probes allows to select the most proper information when these experimental observables are used to compute quantitative information about the properties of the sample under investigation.

# Similarity between a many-body quantum avalanche model and the ultrametric random matrix model

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In the field of ergodicity-breaking phases, it has been recognized that quantum avalanches can destabilize many-body localization at a wide range of disorder strengths. This has in particular been demonstrated by the numerical study of a toy model, sometimes simply called the "avalanche model" or the "quantum sun model" [1], which consists of an ergodic seed coupled to a perfectly localized material. In this paper, we connect this toy model to a well-studied model in random matrix theory, the ultrametric ensemble. We conjecture that the models share the following features. 1) The location of the critical point is predicted sharply by analytics. 2) On the localized side, both models exhibit Fock space localization. 3) There is a manifold of critical points. On the critical manifold, the eigenvectors exhibit nontrivial multifractal behaviour that can be tuned by moving on the manifold. 4) The spectral statistics is intermediate between Poisson statistics and random matrix statistics, also tunable on the critical manifold. We confirm these properties numerically.

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# Theory of Non-Hermitian Fermionic Superfluidity on a Honeycomb Lattice: Interplay between Exceptional Manifolds and Van Hove Singularity

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Recent advancement in the experimental techniques of ultracold atoms has allowed us to control physical parameters feasibly and associated quantum state preparations in many-body physics. As a practical tool for quantum simulation, rich phenomena in condensed matter physics have been successfully performed by using an optical lattice. Moreover, ultracold atoms in an optical lattice have broadened their research area to the preparation of unconventional lattice structures, such as honeycomb [1] and kagome lattices [2]. In particular, fermionic superfluidity, which is one of the most fascinating many-body phenomena, has been investigated on such unordinary optical lattices. These studies have opened a new area to investigate many-body physics in controllable setups. On the other hand, it is of particular importance to identify how dissipation affects the quantum coherence of many-body states because any physical system cannot avoid the effect of the environment [3]. Recent experimental progress in ultracold atoms has realized unprecedented many-body phenomena in open quantum systems. Motivated by these experiments, much attention has been drawn to the non-Hermitian (NH) quantum many-body systems. Remarkably, NH BCS theory has been proposed [4], and many theoretical investigations have been conducted so far to explore unconventional NH fermionic superfluid phase transitions associated with exceptional manifolds, which are the special singularity where both the eigenvalues and the eigenvectors are degenerate. While it is crucial to study how exceptional manifolds change conventional condensed matter physics, a unified understanding of their impact on NH quantum many-body phenomena still remains a challenging issue.

In this study [5], we investigate the non-Hermitian fermionic superfluidity subject to dissipation of Cooper pairs on a honeycomb lattice, for which we analyse the attractive Hubbard model with a complex-valued interaction. Notably, we demonstrate the emergence of the dissipation-induced superfluid phase that is anomalously enlarged with a cusp on the phase boundary. We find that this unconventional phase transition originates from the interplay between exceptional lines and van Hove singularity, which has no counterpart in equilibrium. Furthermore, we find that the infinitesimal dissipation induces the nontrivial superfluid solution at the critical point. Our results can be tested in ultracold atoms with photoassociation techniques by postselcting special measurement outcomes with the use of quantum-gas microscopy, and stimulate the curiosity for non-Hermitian many-body physics induced by exceptional manifolds in open quantum systems.

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# Finite-temperature properties of the easy-axis Heisenberg model on frustrated lattices

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Motivated by recent experiments on a compound displaying Ising-like short-range correlations on the triangular lattice[1], we study the anisotropic easy-axis spin-1/2 Heisenberg model on the triangular and kagome lattice by performing numerical calculations of finite-temperature properties, in particular of static spin structure factor and of thermodynamic quantities, on systems with up to 36 sites. On the triangular lattice, the low-temperature spin structure factor exhibits long-range spin correlations in the whole range of anisotropies, whereas thermodynamic quantities reveal a crossover upon increasing the anisotropy, most pronounced in the vanishing generalized Wilson ratio[2] in the easy-axis regime. In contrast, on the kagome lattice, the spin structure factor is shortrange, and thermodynamic quantities evolve steadily between the easy-axis and the isotropic case, consistent with the interpretation in terms of a spin liquid.

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