

New Avenues for Quantum Simulations In- and Out-of-equilibrium

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Quantum simulation using ultracold atoms and molecules has opened a new research field to probe quantum matter in- and out-of-equilibrium. In fermionic quantum matter, mixed two-dimensional systems boost the pairing energy of holes and have enabled us to observe first signatures of stripe phases in doped systems. In quantum dynamics, probing the full counting statistics of charge transfer allows to explore quantum transport in fundamentally new ways. We test this for the cases of integrable and chaotic quantum dynamics, where for the latter case local subsystems eventually approach a thermal equilibrium state. On the other hand, placing kinetic constraints on the dynamics of the system can drastically hinder such an approach to equilibrium and lead to exceptional regimes where thermalization is suppressed. We discuss recent experiments on such constrained dynamics using ultracold atoms in optical lattices.

Contribution

Invited

Generative AI and Diffusion Models: a Statistical Physics Approach

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Generative AI represents a groundbreaking development within the broader “Machine Learning Revolution,” significantly influencing technology, science, and society. In this colloquium, I will focus on the state-of-the-art “diffusion models”, which are currently used to generate images, videos, and sounds. They are very fascinating algorithms for physicists, as they are very much connected to concepts from stochastic thermodynamics, particularly time-reversed Langevin dynamics. These diffusion models start from a simple white noise input and make it evolve through a Langevin process to generate complex outputs such as images, videos, and sounds. I will show that statistical physics provides principles and methods to characterise this generation process. Specifically, I will discuss how phenomena such as the transition from memorization to generalization and the emergence of features can be understood through the lens of symmetry breaking, phase transitions, and methods used to study disordered systems.

Contribution

Invited

Phase-ordering in systems with long-range interactions

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I will present a thorough discussion of the ordering kinetics of ferromagnetic systems with long-range interactions decaying with distance as r^{-a} , for any a and in any spatial dimension d . I will consider two paradigmatic models: the voter model and the Ising one. The former is solvable in any dimension [1-3]. The latter can be studied analytically in one dimension using scaling arguments [4], or in a continuum (Ginzburg-Landau) approach [5,6]. Besides that, numerical simulations are also available. In general, the kinetics is characterized by the formation and growth of domains. In both models there is an upper critical value a_{SR} of a , such that for $a > a_{SR}$ the model behaves as the corresponding one with short-range interactions (e.g. among nearest-neighbors). In particular, the characteristic size $L(t)$ of the coarsening domains grows as $L(t) \sim t^{1/2}$. There also exists a lower critical value a_{LR} such that some mean-field features (corresponding to $a=0$), specifically the absence of a real coarsening regime, are displayed for a

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Contribution

Oral

Thermal relaxation asymmetry: from single molecules to hydrodynamic fluctuations

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According to conventional wisdom, a macroscopic system placed in an environment with a different temperature relaxes (i.e., warms up or cools down) to the temperature of the surroundings. This relaxation is mediated by the flow of heat that is set only by the temperature difference. However, when rapid changes in temperature push a system far from equilibrium, thermal relaxation becomes asymmetric, which was predicted theoretically and recently confirmed experimentally. That is, under quite general conditions, heating is in fact faster than cooling. I will first introduce the relaxation asymmetry in reversible and detailed-balance violating finite-dimensional systems. Next I will present a rigorous formulation of thermal relaxation in the framework of hydrodynamic fluctuation theory for short- and long-range interacting systems, respectively. I will show that the asymmetry persists in the hydrodynamic limit and that in contrast to finite-dimensions a "true" close-to-equilibrium thermal quench with symmetric heating and cooling at all times does not exist.

Contribution

Invited

The stochastic porous medium equation

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The porous medium equation (PME) is a non-linear diffusion equation that appears ubiquitously in physics, ranging from classical problems, such as surface dynamics below the roughening transition [1], to quantum problems, such as superdiffusion in non-integrable Luttinger liquids [2] and disorder-driven transitions in Weyl semimetals [3].

A stochastic version of the porous medium equation (SPME) has attracted considerable attention in recent years. The presence of non-linearities and noise renders the problem non-equilibrium, similar to the Kardar-Parisi-Zhang equation. However, the universality class is different here, as the equation is conservative. The SPME arises in various contexts, such as the erosion of tilted landscapes [4], continuous models for self-organized criticality [5], critical neural network models of brain dynamics [6], and active matter [7]. Despite this activity, there is no quantitative theory for the SPME even in $d=1$, unlike the KPZ equation.

In my talk, I will present our recent progress in understanding this equation in one dimension. By applying the functional renormalization group, we identified four possible universality classes. We showed that one of them can be mapped onto a special class of random walks. Additionally, we predicted and numerically verified that it exhibits anomalous scaling with non-trivial multiscaling properties.

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Contribution

Oral

Local density bimodality in hard disks confined to a narrow channel

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Two-dimensional (2D) array of hard disks confined laterally within a hard wall channel of the width that commensurates the vertical triangular lattice at close packing, was studied by means computer simulations combined with triangular cell theory (1). We observed that in the range of densities associated with the freezing in bulk 2D hard disks, the confined system exhibits unexpected bimodal distribution of the local density that indicates the crossover from the "gas-like" to "liquid-like" state. To the best of our knowledge such an observation has not yet been reported neither for the bulk nor for confined systems of hard disks. The potential consequences of such a finding are discussed in the terms of structure (2) and collective dynamics (3) properties. We argue that simplicity of a quasi-1D system of hard disks may enable one to get a deeper qualitative and quantitative insight into the variety of phase transformations observed and discussed in the soft condensed matter composed of hard-core molecules.

Contribution

Oral

Out-of-equilibrium localisation in two-dimensional quasiperiodic systems

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Superimposing two square optical lattice potentials creates patterns ranging from conventional periodic ones to exotic quasiperiodic patterns. The topography of the combined potentials depends on the wavelengths of the lattices and the angle between them. Focusing on a case where one lattice potential is much deeper than the other leads to a tight-binding model for ultracold atoms with onsite modulation caused by the shallow lattice. In this talk, I will discuss two types of dynamical localisation phenomena that can emerge in the aforementioned setting.

First, I will theoretically discuss the localisation properties of the many-body interacting two-dimensional quasiperiodic systems mentioned above. In such systems, we demonstrate how a stable many-body localised phase can survive for long times, even in the thermodynamic limit, unlike in randomly disordered systems. Surprisingly, we find that a sub-dimensional network of deterministic lines of weak potential - naturally appearing in these systems - supports transport while keeping localised regions untouched.

Second, I will discuss a single-particle system where the shallow lattice is continuously rotated, thereby inducing an exotic type of periodic driving. Such driving creates spatially varying tunnelling amplitudes that cause dynamical localisation, often accompanied by non-trivial topology. Using the local Chern marker and Bott index, we identify states with non-trivial topological markers that live in ring-shaped regions inside the bulk and are stabilised by strong localisation. Surprisingly, these states result in exotic bulk-localised transport.

Contribution

Oral

The inviscid fixed point of the Burgers--Kardar-Parisi-Zhang equation

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The celebrated Kardar-Parisi-Zhang (KPZ) equation describes the kinetic roughening of stochastically growing interfaces. In one dimension, the KPZ equation is exactly solvable and its statistical properties are known to an exquisite degree. Yet recent numerical simulations investigated the tensionless limit of the KPZ equation or equivalently the inviscid limit of the Burgers equation [1] and unveiled a new scaling, with a critical dynamical exponent $z=1$ differing from the KPZ one $z=3/2$. In this talk, I will show that this scaling is controlled by a fixed point which had been missed so far and which corresponds to an infinite non-linear coupling. This fixed point, called IB (inviscid Burgers) fixed point, can be accessed using the functional renormalization group (FRG), and it is characterized by a $z=1$ exponent [2]. This finding raises the intriguing question of the fate of this new IB fixed point in higher dimensions. I will address this issue, analyzing the multi-dimensional Burgers--KPZ equation using FRG, and show that the IB fixed point exists in all dimensions, and that it controls the large momentum behavior of the correlation functions in the inviscid limit [3]. It turns out that it yields in all dimensions the same super-universal value $z=1$ for the dynamical critical exponent, which is deeply rooted in the symmetries.

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Contribution

Invited

New quantum criticality for the strange metal and Planckian behaviour in high temperature superconductors

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High temperature superconductivity opened two major theoretical problems questioning the BCS theory realm for superconductivity and the omnipresent Landau Fermi Liquid theory: the source and the mechanism of pairing in the first case; the strange metal behavior of the Cuprates with the linear in T resistivity and a divergent specific heat [1] down to the lowest temperatures, the so called Planckian behavior [2], in the second case. I will present a plausible answer to the second problem by introducing a new non equilibrium transition. To this purpose we [3] make use of the newly discovered dynamical charge density fluctuations with short correlation length [4], precursors of the three-dimensional long range charge density waves. We suggest a new paradigm [5-7], controlled by an anomalous quantum critical point, which is in contrast with the standard criticality reached by the space correlation length going to infinity. Here instead, as the temperature goes to zero, the strange criticality with linear in T resistivity and a diverging specific heat are accounted for by the increase of the damping parameter only in the corresponding time dependent Landau Ginzburg equation. When the damping increases by lowering the temperature, the charge density fluctuations relax at longer and longer times giving rise to an anomalous criticality with the formation of a glass of small islands of charge density fluctuations correlated in time not in space.

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Contribution

Oral

Partition Function Zeros of the Frustrated J1-J2 Ising Model on the Honeycomb Lattice

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We study the zeros of the partition function in the complex temperature plane (Fisher zeros) and in the complex external field plane (Lee-Yang zeros) of a frustrated Ising model with competing nearest-neighbor ($J_1 > 0$) and next-nearest-neighbor ($J_2 < 0$) interactions on the honeycomb lattice. We consider the finite-size scaling (FSS) of the leading Fisher and Lee-Yang zeros as determined from a cumulant method and compare it to a traditional scaling analysis based on the logarithmic derivative of the magnetization $\partial \ln \langle |M| \rangle / \partial \beta$ and the magnetic susceptibility χ . While for this model both FSS approaches are subject to strong corrections to scaling induced by the frustration, their behavior is rather different, in particular as the ratio $\mathcal{R} = J_2/J_1$ is varied. As a consequence, an analysis of the scaling of partition function zeros turns out to be a useful complement to a more traditional FSS analysis. For the cumulant method, we also study the convergence as a function of cumulant order, providing suggestions for practical implementations. The scaling of the zeros convincingly shows that the system remains in the Ising universality class for $\mathcal{R}$ as low as -0.22 , where results from traditional FSS using the same simulation data are less conclusive. Hence, the approach provides a valuable additional tool for mapping out the phase diagram of models afflicted by strong corrections to scaling.

Contribution

Oral

The Laplacian Renormalization Groups (LRG) unveils the structural organization of heterogeneous networks

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Heterogeneous and complex networks represent the intertwined interactions between real-world elements or agents. Determining the multi-scale mesoscopic organization of clusters and intertwined structures is still a fundamental and open problem of complex network theory. By taking advantage of the recent Laplacian Renormalization Group [1-4] approach, we scrutinize information diffusion pathways throughout networks to shed further light on this issue. Based on inter-node communicability, our definition provides a clear-cut framework for resolving the multi-scale mesh of structures in complex networks, disentangling their intrinsic arboreal architecture. As it does not consider any topological null-model assumption, the LRG naturally permits the introduction of scale-dependent optimal partitions and determines the existence of a particular class of nodes, called "metastable" nodes, that switching regions to which they belong at different scales, are expected to play a central role in the communication between them and, therefore, in managing macroscopic effects of the whole network [5]. [1] P Villegas, T Gili, G Caldarelli, A Gabrielli, Laplacian renormalization group for heterogeneous networks, *Nature Physics* 19 (3), 445-450 (2023) [2] P Villegas, A Gabrielli, F Santucci, G Caldarelli, T Gili, Laplacian paths in complex networks: Information core emerges from entropic transitions, *Physical Review Research* 4, 033196 (2022) [3] A. Gabrielli, D. Garlaschelli, S. Patil, M. A. Serrano, Network Renormalization, <https://arxiv.org/abs/2412.12988>, to appear on *Nature Review Physics* (2025). [4] A. Poggialini, P. Villegas, M.A. Munoz, A. Gabrielli, Networks with Many Structural Scales: A Renormalization Group Perspective, *Phys. Rev. Lett.* 134, 057401 (2025) [5] P. Villegas, A. Gabrielli, A. Poggialini, T. Gili, Multi-scale Laplacian community detection in heterogeneous networks, *Phys. Rev. Res.* 7, 013065 (2025)

Contribution

Invited

Random Quantum Ising Model with Three-Spin Couplings

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We apply a real-space block renormalization group approach to study the critical properties of the random transverse-field Ising spin chain with multispin interactions. First, we recover the known properties of the traditional model with two-spin interactions by applying the renormalization approach for the arbitrary size of the block. For the model with three-spin couplings, we calculate the critical point and demonstrate that the phase transition is controlled by an infinite disorder fixed point. We have determined the typical correlation-length critical exponent, which seems to be different from that of the random transverse Ising chain with nearest-neighbor couplings. Thus, this model represents a new infinite disorder universality class.

Contribution

Oral

Statistical properties of spectra of typical quantum operations and Lindblad generators

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Dynamics of open quantum systems is analyzed under the assumption of discrete or continuous time evolution. We introduce ensembles of random quantum operations and random Lindblad generators, each parameterized by a point in a unit cube. Three axes (q, b, r) of both cubes correspond to the quantumness parameter q , characterizing the process of decoherence and governing the transition from quantum to classical, the parameter b describing breaking of the detailed balance condition, which implies that the spectrum of the operator is real, and the rescaled rank r of the operator. The corner $(1, 1, 1)$ of the 3 -cube represents standard ensembles of generic random quantum operations and random Lindblad generators. Proposed random matrix models allow us to analyze the influence of these three physical parameters for the statistical properties of complex spectra of the corresponding operators.

Contribution

Invited

The MAGIC of Quantum Computing

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Trapped atomic ions are well suited to investigate fundamental questions of quantum physics that require access to and detailed control of individual quantum systems. In addition, this physical platform has set standards for quantum information processing (QIP) for decades. Here, I give a brief introduction to trapped-ion QIP using MAGnetic Gradient Induced Coupling (MAGIC). MAGIC makes coherent qubit control possible using exclusively radio frequency (RF) signals, thus drastically reducing the demands on laser performance for qubit control. It benefits from already accomplished miniaturization and integration of microwave technology, thus circumventing serious hurdles for scaling up trapped-ion quantum computers. Taking advantage of all-to-all coupling in a quantum register can reduce the required circuit-depth of quantum algorithms and can speed up the execution of quantum algorithms. I report on novel 3-qubit gates as elementary algorithmic building blocks. Furthermore, I present a fast two-qubit entangling gate for RF-controlled ions. The speed of this gate is an order of magnitude higher than that of previously demonstrated gates using MAGIC. At the same time, phase-modulation of the driving field decouples hyperfine qubits in $^{171}\text{Yb}^+$ ions from amplitude and frequency noise, increasing the qubits' coherence time by three orders of magnitude. The gate requires only a single continuous RF field per qubit, making it well suited for scaling a quantum processor to large numbers of qubits. Finally, I give a brief account of the experimental characterization of a planar ion trap chip with integrated micro-structured magnets.

Contribution

Invited

Precursor and Bulk Dynamics of Thin Film Spreading

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One of the manifestations of thin film spreading is the phenomenon of a precursor spreading in front of an advancing droplet. The microscopic characteristics of the precursor dynamics are still not fully understood. We study thin film spreading using a driven lattice-gas model of two layers, representing the bulk and the precursor film, first suggested by Abraham et al [1]. By changing the relations between the Hamaker constant (van der Waals interaction), the nearest neighbor interaction (surface tension) and the temperature, we study the effects of these parameters on the scaling exponents describing the spreading of both layers.

We find that the scaling exponents of both layers are neither universal [2] nor monotonic [3], and show that they strongly depend on these parameters, reflecting the competition between the various mechanisms that drive the system. We discuss our results in the context of the well-known Tanner and Lopez laws for bulk dynamics of spreading droplets. We also discuss results recently reported for this problem in band [4] and circular [5] geometries.

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Contribution

Oral

Linear and nonlinear waves on a stable torus of fluid

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Curved interfaces such as toroidal drops are ubiquitous in nature, but are unstable, making them difficult to control and study. Using an original technique we create a stable and stationary torus of liquid, deposited on a superhydrophobic substrate allowing for a systematic study of waves along its inner and outer border under curved and periodic conditions. By exciting the torus border and recording the displacements of the two borders, we study the dispersion relation of the torus, yielding a rich spectral structure: gravity-capillary waves, sloshing modes and a center-of-mass mode. We will first show that nonlinear waves in form of solitons can propagate along the torus borders for sufficiently strong forcing. We will then stress the observation of subsonic elevation solitons which are due to a strong influence of periodic boundary conditions through a Korteweg-de Vries equation, giving a non-trivial dependence of the soliton velocity on its amplitude and torus curvature. Finally, we will discuss the observation of a triadic resonance instability between two different dispersion branches, namely the sloshing and gravity-capillary modes. Such nonlinear interactions thus lead to a transfer of energy between the two branches which is fully characterized. For a stronger forcing, additional waves are generated by a cascade of three-wave interactions populating the wave spectrum. Such a three-wave two-branch interaction mechanism is probably not restricted to hydrodynamics and could be of interest in other systems involving several propagation modes.

Contribution

Invited

Effective mass approach to dynamics of non-Markovian systems

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Recent pioneering experiments on non-Markovian dynamics done, e.g., for active matter have demonstrated that our theoretical understanding of this challenging yet hot topic is rather incomplete and there is a wealth of phenomena still awaiting discovery. It is related to the fact that typically for simplification the Markovian approximation is employed and as a consequence the memory is neglected. Therefore, methods allowing to study memory effects are extremely valuable. We demonstrate that a non-Markovian system described by the Generalized Langevin Equation (GLE) for a Brownian particle of mass M can be approximated by the memoryless Langevin equation in which the memory effects are correctly reproduced solely via the effective mass M^* of the Brownian particle which is determined only by the form of the memory kernel. Our work lays the foundation for an impactful approach which allows one to readily study memory-related corrections to Markovian dynamics. Selected examples of the non-trivial influence of latter such as memory-induced absolute negative mobility and current-reversal effects will be briefly discussed.

Contribution

Oral

Capturing instantons within the Functional Renormalization Group

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We investigate the localized excitations (instantons or kinks) in the ϕ^4 theory using Renormalization Group, RG. We do so in the regime of high interest for phase transitions, the vicinity of the lower critical dimension (d_{lc}) at which finite-temperature ordering becomes impossible due to such excitations. These excitations are nonperturbative and thus notoriously difficult to capture using standard field theoretical techniques. Thus, we want to assess whether instantons are captured within low approximation schemes of the Nonperturbative Functional RG (NPfRG).

Even in these lowest approximations of the NPfRG we find strong evidence that it captures instantons in the vicinity of d_{lc} . The hallmark of the approach to the lower critical dimension nonuniform (in field) convergence of the fixed point potential. This is due to a boundary layer forming near the minimum, the width of which shrinks to 0 as d_{lc} is approached. The emergence and shape of this shrinking boundary layer allows us to recover the T_c and gives strong evidence that the critical exponent $1/\nu$ goes to 0 in the limit of d_{lc} regardless of approximation [1, 2].

Unlike specialized methods usually needed to investigate localized excitations (e.g., the Bruce and Wallace droplet approach for the Ising model [3-5]), NPfRG is a general and versatile approach. We hope that our findings can then be applied to other systems dominated by localized, nonuniform excitations, such as hysteresis in the Random Field Ising model [6-7] or even to tunneling problems that occur at the d_{lc} , like Josephson junctions [8].

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Contribution

Oral

Detecting changes in complex networks characteristics in the cryptocurrency market

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This study introduces a methodology for analyzing the evolution of correlation structures within the cryptocurrency market by employing a q -dependent detrended cross-correlation coefficient ($\rho(q,s)$). By extending traditional correlation metrics, this approach selectively captures cross-correlations at varying fluctuation amplitudes and time scales. The methodology incorporates q -dependent Minimum Spanning Trees (q MSTs), which graphically represent the evolving network structures of cryptocurrency correlations. Using minute-by-minute exchange rate data for 140 cryptocurrencies traded on Binance from January 2021 to October 2024, the research applies rolling window analysis to track temporal correlations and network topology changes. Key findings reveal significant structural shifts in the q MSTs around April 2022, coinciding with the Terra/Luna collapse triggered by the cryptocurrency market crash. Initially, the network was highly centralized around Bitcoin (BTC), but later periods saw decentralization, with cryptocurrencies such as Ethereum (ETH), Sandbox (SAND), and others gaining prominence. These structural changes are corroborated by spectral analysis of the correlation matrix, showing decreased dominance of BTC and increased contributions from other assets.

The second result of this analysis is identifying the relationship between the structure of MST networks and the amplitude of the considered fluctuations. Medium-sized fluctuations exhibit stronger correlations compared to the largest ones. Furthermore, MSTs constructed from correlation matrices emphasizing the largest fluctuations are more decentralized than those derived from matrices dominated by medium fluctuations.

Another important finding is the quantitative assessment of differences between various correlation networks based on fluctuation amplitudes using graph distance metrics. This analysis revealed that the most significant differences in correlation structures occur during disruptions, such as intra-crashes affecting the majority of cryptocurrencies. During such events, the largest fluctuations are more strongly correlated, and interestingly, the MST structure emphasizing these fluctuations becomes entirely decentralized. In contrast, the MST derived from matrices dominated by medium correlations exhibits a more centralized structure.

The findings underscore the utility of q MSTs in uncovering fluctuation-dependent correlation structures and their applications across various domains, including finance, biology, and social systems. This approach provides insights into the dynamics of complex, interconnected systems, offering potential for broader applicability beyond cryptocurrency markets.

Contribution

Oral

Measurement induced transition in long-range system

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The interplay of coherent and incoherent dynamics has a rich and long history in the context of quantum physics. At the basic quantum mechanical level, it is responsible for a plethora of few body effects, of particular relevance to quantum optical systems. Over the last two decades, boosted by impressive progress in both solid state and atomic experiments, this interplay has found vast application in the context of many-body phenomena as well. A particularly successful framework in this respect has been the identification of new phases of matter associated with the non-equilibrium steady states of local Liouville dynamics. In parallel to these developments, a series of recent works has introduced a new perspective that, instead of focusing on the properties of the average steady state, studies the many-body properties at the level of single quantum trajectories. In this context, it has been shown how the competition between quantum measurements and coherent dynamics (either analog or digitally generated) can give rise to transitions that manifest themselves in specific observables that are not properties of the averaged state - such as von Neumann entropies, negativities, or two-time correlation functions. In the talk I will review our recent contributions to this topics

Contribution

Invited

When frustration is a feature: quantum applications of topologically frustrated spin chains

Alberto Catalano¹

¹University of Padua

The physics of topological frustration has recently harnessed a lot of interest because of at least two main reasons. From a theoretical standpoint, these systems seem to defy the predictions of Landau's theory: while being introduced by an opportune choice of the boundary conditions, it has been shown that topological frustration can deeply modify the phase diagram of 1D quantum spin chains, e.g. by inducing novel phase transitions or destroying order parameters. Beyond theoretical implications, topologically frustrated (TF) spin chains exhibit compelling technological potential due to their long-range correlations and spectral properties. Therefore, in this talk I will discuss two interesting scenarios within this context. I will at first show that TF spin chains are excellent candidates for the development of robust quantum energy storage devices, i.e. quantum batteries, resilient against external decoherence. Finally, I will focus on the deep connection between the ground-states of these systems and W states, a class of highly entangled non-stabilizer states, which further highlights the relevance of these systems in the realm of quantum simulations and computation.

Contribution

Invited

Ostwald ripening - an unfinished story

Michael Wilkinson¹

¹Open University

As well as being a classic problem in statistical physics, Ostwald ripening may be important in atmospheric science because it provides a non-collisional route for the growth of water droplets in clouds.

The process was the subject of a subtle analysis in a classic paper by Lifshitz and Slyozov, which is widely accepted as a correct theory for growth in the long-time limit. In this talk I shall explain why that theory is incomplete. I present numerical results showing that there is an essential instability in the process, and give a theoretical explanation. This instability does not have a large effect on the long-time limit of the droplet growth, but it does imply that the Lifshitz-Slyozov theory is not exact.

I shall present some results on simplified versions of the Ostwald ripening process, for which it is possible to analyse the instability in some detail. I also discuss the relevance of Ostwald ripening to understanding the growth of water droplets in rainfall.

Ostwald ripening remains a significant open problem.

Contribution

Oral

Sub-symmetry protected topological states

Hrvoje Buljan¹

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A hallmark of symmetry-protected topological phases are topological boundary states, which are immune to perturbations that respect the protecting symmetry. It is commonly believed that any perturbation that destroys such a topological phase simultaneously destroys the boundary states. However, by introducing and exploring a weaker sub-symmetry requirement on perturbations, we find that the nature of boundary state protection is in fact more complex. We demonstrate that the boundary states are protected by only the sub-symmetry, using Su-Schrieffer-Heeger and breathing Kagome lattice models, even though the overall topological invariant and the associated topological phase can be destroyed by sub-symmetry preserving perturbations [1]. By precisely controlling symmetry-breaking in photonic lattices, we experimentally demonstrate such sub-symmetry protection of topological states. Our results apply beyond photonics and could be used to explore the properties of symmetry-protected topological phases in the absence of full symmetry in different physical contexts.

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Contribution

Invited

Kinetic theory of weakly perturbed integrable models

Miłosz Panfil¹

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Integrable systems are characterized by an infinite number of conserved charges and stable quasi-particle excitations. When integrability is broken, interactions between quasi-particles are introduced, opening the way for a novel kinetic theory that incorporates both integrable and non-integrable processes. In this talk I will review recent advances in the development of such a kinetic framework, which provides new insights into a range of non-equilibrium phenomena. These include the thermalization of homogeneous systems, the emergence of the Navier-Stokes equations, and the generalization of the famous BBGKY hierarchy.

Contribution

Oral

Universality of Top Rank Statistics for Brownian Reshuffling

Zdzislaw Burda¹, Mario Kieburg²

¹AGH University of Krakow, Faculty of Physics and Applied Computer Science, ²University of Melbourne, School of Mathematics and Statistics

We study the dynamical aspects of the top rank statistics of particles, performing Brownian motions on a half-line, which are ranked by their distance from the origin. For this purpose, we introduce an observable that we call the overlap ratio $\Omega(t)$, whose average is the probability that a particle that is on the top- n list at some time will also be on the top- n list after time t . The overlap ratio is a local observable which is concentrated at the top of the ranking and does not require the full ranking of all particles. It is simple to measure in practice. We derive an analytical formula for the average overlap ratio for a system of N particles in the stationary state that undergo independent Brownian motion on the positive real half-axis with a reflecting wall at the origin and a drift towards the wall. In particular, we show that for $N \rightarrow \infty$, the overlap ratio takes a rather simple form $\langle \Omega(t) \rangle = \text{erfc}(a \sqrt{t})$ for $n \gg 1$ with some scaling parameter $a > 0$. This result is a very good approximation even for moderate sizes of the top- n list such as $n=10$. Moreover, as we show, the overlap ratio exhibits universal behavior observed in many dynamical systems including geometric Brownian motion, Brownian motion with a position-dependent drift and a soft barrier on one side, the Bouchaud-Mézard wealth distribution model, and Kesten processes.

Contribution

Oral

Critical exponents at the Nishimori point

Gesualdo Delfino¹

¹SISSA - Trieste

Systems with strong quenched disorder and frustration represent a famously difficult problem of statistical physics. Their critical properties in physical dimensions have been analytically inaccessible and are extensively studied numerically since decades. We consider the Nishimori point at which the ordered, disordered and spin glass phases meet and show how properties of the Nishimori line lead to the exact identification of the correlation length and crossover critical exponents. This is the first time that exact non-mean-field exponents are obtained in three dimensions. Our results also reveal the first realization of exact super-universality (independence of some exponents on the symmetry parameter) in three dimensions and open the way to the understanding of this emergent phenomenon of random criticality.

Contribution

Oral

Central limit theorems, large deviations and the renormalization group

Adam Rancon¹

¹Université de Lille

The Ising model at criticality is a paradigmatic example of random variables displaying strong correlations at all scales. While in the high and low temperature phases the collective properties of the system are described by the standard (Gaussian) central limit theorem, the critical point separating the two phases is captured by a scale invariant and universal asymptotic probability distribution. From a physicist point of view, the emergence of such probability distribution is understood using the renormalization group, which effectively describes the behavior of coarse-grained random variables.

In this talk, I will give a pedagogical overview of these concepts, using the probability distribution of the order parameter as an example of a non-trivial observable that can be computed using a functional version of the renormalization group. I will show that large deviations are universal, while very large deviation are non-universal. Furthermore, I will discuss how corrections-to-scaling can be rephrased in the language of large deviations as a generalized Cramer's series.

Contribution

Invited

General hydrodynamic approach for a cold Bose gas

Victor Pergamenshchik¹

¹Center for Theoretical Physics, Warsaw, Poland

We present the derivation of the hydrodynamics for a cold Bose gas at $T = 0$ from the microscopic platform based on the many-body Schrödinger equation and general assumptions of the hydrodynamic approach (HA) applicable to any dimension. We develop a general HA for a cold spatially inhomogeneous Bose gas assuming two different temporal and spatial scales and obtain the energy as a functional of both fast inner quantum mode and slow macroscopic mode. The equations governing the fast and slow modes are obtained from this functional by their independent variations. The fast mode is the wave function in the stationary state at local density which can be ground, excited with a nonzero atom momenta, or a superposition of more than one state. The energy eigenvalue (or expectation value) of this local wave function universally enters the hydrodynamic equation for the slow mode in the form of the local chemical potential which incorporates the inner local momentum. For zero inner momenta and particular choices of this eigenvalue as a function of gas density, this equation reduces to the known equations based on the local density approximation. If, however, the inner momenta are nonzero, the equation includes the interaction between these momenta and the slow mode velocity. Relation between this general HA and the standard local density approximation is elaborated. Two effects of the local momenta and their density dependence on the soliton solutions are demonstrated.

V. M. Pergamenshchik, Phys. Rev. A, 110, 033308 (2024)

Contribution

Oral

Non-universality of aging during phase separation of the two-dimensional long-range Ising model

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We investigate the aging properties of the phase-separation kinetics in the paradigmatic two-dimensional conserved Ising model with power-law decaying long-range interactions $\sim r^{-(2+s)}$. By means of large-scale Metropolis Monte Carlo simulations, enabled by a novel algorithm for long-range interacting systems, we investigate deep quenches from the disordered state to a finite temperature well below T_c . For all values of s , physical aging with a power-law decay of the two-time autocorrelation function $C(t, t_w) \sim (t/t_w)^{-\lambda/z}$ is observed. The autocorrelation exponent λ displays a complex dependence on s : For the corresponding nearest-neighbor model (recovered in the limit of large s) a value of $\lambda=3.500(26)$ is determined. In the long-range regime $s < 1$ the values of λ are all compatible with $\lambda=4$. In between, where also the equilibrium critical exponents show a non-trivial s -dependence, a continuous crossover is visible for $1 < s < 2$ with non-universal, s -dependent values of λ .

Contribution

Oral

Dispersive interaction of an optical frequency comb with atoms in a cavity

Ticijana Ban¹

¹Institute of Physics, Centre for Advanced Laser Techniques

In this talk, I will introduce one of the most exciting platforms for advancing quantum technologies based on cold atoms. In our laboratory, we utilize lasers to cool atoms to temperatures close to absolute zero, creating the foundation for developing quantum simulators and optical atomic clocks.

I will specifically focus on the results of our experiment in which cold atoms interacts with an optical frequency comb (OFC) inside a high-finesse Fabry-Perot cavity in the dispersive regime. In the linear dispersive regime, we observe a collective frequency shift of multiple cavity modes in the spectrum of the transmitted OFC. In the nonlinear regime, we study bistability in the transmission of a single comb mode. These results introduce a new approach to controlling light-matter interactions with multiple OFC modes in cavity-enhanced setups, paving the way for the implementation of recent proposals in cavity cooling [1], quantum annealing [2, 3], and quantum simulations [4].

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Contribution

Invited

Analog of the Carnot engine for intracellular diffusivity fluctuations

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It has experimentally been observed that intracellular diffusivity slowly fluctuates locally under the exponential law for normal and anomalous diffusion, see, e.g., Refs. [1,2]. A formal analogy of such a fluctuating diffusivity to thermodynamics has been developed in Ref. [3]. A key there is to see that the exponential law formally takes the “canonical distribution” at the statistical level: the diffusivity, which is proportional to local temperatures of living cells [4], is identified with the analog of the system energy. Consequently, not only the analogs of the quantity of heat and work as well as the internal energy but also that of the Clausius inequality have been established.

Here, an analog of the heat engine constructed in Ref. [5] is discussed based on the formal analogy. This heat-like engine consists of two kinds of processes to be realized by compression/expansion of the cell and the change of temperature, constituting a cycle. In the processes, the diffusivity follows the exponential law while the average diffusivity or the average local temperature is kept fixed. The efficiency of the engine during the cycle, which quantifies how much the diffusivity change as the analog of work is extractable, is found to formally coincide with that of Carnot's.

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Contribution

Oral

Renormalization group and probability theory

Ivan Balog¹, Adam Rançon², Bertrand Delamotte³, Lovro Šaravanja¹

¹Institute of Physics, Zagreb, ²Universite de Lille, ³Sorbonne Universite

The question of understanding the probabilistic interpretation [1] of the renormalization group (RG) has been a topic of ongoing research for decades, dating back to the inception of the field in the 1970s. Recently [2], we have developed a new method that utilizes the effective average action formalism to devise a flow equation for the rate function $I(m)$. This function determines the scaling function of the critical distribution of the order parameter $P(m)$, with $I(m) = -\ln(P(m))$. We show that I is a universal function, characterized by the parameter $\zeta = \xi/L$, which describes the approach to criticality. We have validated our method through Monte Carlo simulations, which demonstrate a close alignment of the rate functions for different ζ values with those determined from the RG method. Furthermore, our analysis shows that for all cases when $\zeta > 1$, the shape of the rate function is largely similar, yet not identical, to the shape of the fixed point (dimensionless) effective potential, featuring concavity near the origin. We also discuss extensions of our work to momentum-dependent quantities and its implications.

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Contribution

Poster

Ising model of binary election with a split society phase

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¹Institut Ruđer Boskovic

In modern democracies the outcome of elections and referendums is often remarkably tight. To explain this phenomenon we propose a simple model of binary elections based on an Ising model of voters with ferromagnetic coupling of the neighbors and an additional weak antiferromagnetic coupling of every voter to the opinion poll. The model exhibits a new split society phase which properties seems to resemble those observed in some real binary elections: the voters are geographically separated into two groups (domains) with opposite opinions, the total result is close to 50%-50%, and an interface between the domains is located along the lines where the coupling between neighboring voters is reduced (like borders of cities, natural barriers, or historical borders between countries). We discuss the physical properties of our model and study the conditions necessary for the system to be in the split society phase. By analyzing the results of binary elections in various countries we are able to roughly estimate the values of the parameters describing our model.

Contribution

Poster

Double square-well model of polymerizing hard spheres

Miha Luksic¹, Yuriy Kalyuzhnyi¹

¹University of Ljubljana, Faculty of Chemistry and Chemical Technology

We propose a model of polymerizing hard spheres with double square-well bonding potential. The model is represented by the equimolar two-component hard-sphere mixture with hard spheres of the same size σ . In addition to the hard-sphere repulsion particles of different species interact with double square-well potential with two binding minima located at distances 0 . The structure of aggregates formed due to the presence of two narrow square-wells depends on the values of the bonding distances L_s and L_l . For L_s, L_l the particles can form only dimers with two bonding length, for L_s and $\sigma/2$ each particle can form either one bond of the length L_s or two bonds of the length L_l , thus the aggregates formed will be represented by the dimers with bonding distance L_s and chains with the bonding distance L_l . For the larger values of L_s , i.e. $\sigma/2$ the chains with two different bonding distances, L_s and L_l , will appear. Further increase of the bonding distances will cause formation of the structures with more complicated topology. Theoretical description of the model is carried out using extension of resummed thermodynamic perturbation theory for associating fluids with central force binding interaction [1,2]. We calculate thermodynamic and aggregation properties of the model and results compare against corresponding computer simulation results. Very good agreement was observed. Our analysis demonstrate highly nontrivial aggregation behavior of the model due to competition of bonding at two different distances, i.e. L_s and L_l . With appropriate choice of the potential model parameters (the depths and widths of its wells) two scenarios of the temperature dependence of the type of clusters formed was observed. According to the first one upon decreasing the temperature the system first form dimers with bonding length L_s . Further decrease of the temperature destroys dimers and form instead linear chains with bonding length L_l . According to the second scenario the system first form linear chains, which are destroyed in favor of dimers upon additional temperature decrease. This unusual behavior offers a possibility to manipulate the type of the clusters formed via external stimuli. Upon either increasing or decreasing the temperature the system can be driven to form the ordering observed in liquid crystals.

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Contribution

Poster

Interplay between local and non-local frustration in the 1D ANNNI chain

Gianpaolo Torre¹, Alberto Catalano^{1, 2, 3}, Sven Benjamin Kožić¹, Fabio Franchini¹, Salvatore Marco Giampaolo¹

¹Institut Ruđer Bošković, ²Università di Padova, ³INFN sezione di Padova

Frustration arises when local energy constraints cannot be simultaneously minimized. In 1D spin chains with nearest-neighbor interactions, frustration is introduced via a ring geometry with periodic boundary conditions and antiferromagnetic interactions. This topological frustration (TF) modifies key system properties, such as energy gap closure, long-range correlations, and the behavior of order parameters.

In this work, we explore the interplay between topological frustration induced by boundary conditions and local frustration from competing next-to-nearest neighbor interactions using the 1D ANNNI model. We focus on entanglement entropy (EE) as a measure of quantum correlations. In the antiphase, we observe a violation of the area law, with the EE decomposing into two contributions: one independent of TF and another extensive contribution arising from TF, suggesting that the ground state hosts two excitations. This is confirmed by considering two fermionic excitations over the vacuum of a quadratic theory. Furthermore, in the thermodynamic limit, we found that these local and topological contributions to EE decouple.

Contribution

Poster

Computing Quantum Resources using Tensor Cross Interpolation

Sven Benjamin Kožić¹, Gianpaolo Torre¹

¹Ruđer Bošković Institute

Quantum information quantifiers are essential for analyzing strongly correlated systems, making efficient numerical methods crucial. We introduce a general framework for computation of quantum resources using Tensor Cross Interpolation (TCI) algorithms, independent of the system or quantifier. To validate our method, we compute the non-Stabilizerness Rényi Entropy (SRE) and Relative Entropy of Coherence (REC) for 1D and 2D ferromagnetic Ising models with minimal modifications.

Contribution

Poster

Stabilizer Entropy and entanglement complexity in the Sachdev-Ye-Kitaev model

Jovan Odavić¹

¹University of Naples Federico II

The Sachdev-Ye-Kitaev (SYK) model is of paramount importance for the understanding of both strange metals and a microscopic theory of two-dimensional gravity. In this poster presentation, we show the results of the interplay between Stabilizer Renyi Entropy (SRE) and entanglement entropy in both the ground state and highly excited states of the SYK4+SYK2 model interpolating the highly chaotic four-body interactions model with the integrable two-body interactions one. The interplay between these quantities is assessed also through universal statistics of the entanglement spectrum and its anti-flatness. We find that SYK4 is indeed characterized by a complex pattern of both entanglement and non-stabilizer resources while SYK2 is non-universal and not complex. Additionally, we discuss the fragility and robustness of these features depending on the interpolation parameter. The poster presentation is based on: <https://arxiv.org/abs/2502.03093>

Contribution

Poster

Kinetic equality for susceptibility out of equilibrium

Takaaki Monnai¹

¹Seikei university

The signal to noise ratio characterizes the operating principle of small systems such as the model-independent upper bounds of the precision of observables given by the square mean to variance ratio.

In this presentation, we show a rigorous and general kinetic susceptibility equality (KSE) out of equilibrium [1]. We explain that KSE is a universal relation for the precision of observables and the action to the dynamical activity. KSE is derived from a model-independent informational equality that connects the susceptibility of observables to Fisher information. We also show that as special cases KSE reproduces the kinetic uncertainty relation, its multivariate extensions, and a sort of fluctuation dissipation relation for observables and the action.

[1] Takaaki Monnai, Phys. Rev. E 110, L062101 (2024)

Contribution

Poster

Phase behavior of patchy colloids confined in patchy porous media

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A simple model for functionalized disordered porous media is proposed and the effects of confinement on self-association, percolation and phase behavior of a fluid of patchy particles are studied [1]. The media are formed by randomly distributed hard-sphere obstacles fixed in space and decorated by a certain number of off-center square-well sites. The properties of the fluid of patchy particles, represented by the fluid of hard spheres each bearing a set of the off-center square-well sites, are studied using an appropriate combination of the scaled particle theory for the porous media, Wertheim's thermodynamic perturbation theory, and Flory-Stockmayer theory. To assess the accuracy of the theory a set of computer simulations have been performed. In general, predictions of the theory appeared to be in good agreement with the computer simulation results. Confinement and competition between the formation of bonds connecting the fluid particles, and connecting fluid particles and obstacles of the matrix, gave rise to a re-entrant phase behavior with three critical points and two separate regions of the liquid-gas phase coexistence.

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Contribution

Poster

Critical and tricritical behavior of the $d=3$ Blume-Capel model: Results from small-scale Monte Carlo simulations

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We investigate the location of the critical and tricritical points of the three-dimensional Blume-Capel model by analyzing the behavior of the first Lee-Yang zero, the density of partition function zeros, and higher-order cumulants of the magnetization. Our analysis is conducted through Monte Carlo simulations, intentionally using only small system sizes. We demonstrate that this approach yields excellent results for studying the critical behavior of the model. Our findings indicate that at the tricritical point, where logarithmic corrections are anticipated, the numerical results align closely with the theoretical exponents describing these corrections. These expected values are then employed to accurately determine the coordinates of the tricritical point. At the model's critical point, the corrections correspond to those of the three-dimensional Ising model criticality, which we also use to precisely ascertain the critical temperature at zero crystal field. Additionally, we utilize more traditional thermodynamic quantities to validate the self-consistency of our analysis.

Contribution

Poster

Two point entanglement and correlations in the 2D Hubbard modell

Anna Kauch¹, Frederic Bippus¹, Gergo Roósz², Karsten Held¹, Fakher Assaad³

¹TU Wien, ²HUN-REN Wigner FK Budapest, ³University of Würzburg

We calculate all two-point correlators in the two-dimensional Hubbard model at finite temperature. We use a diagrammatic extension of the dynamical mean field theory (DMFT), the so-called dynamical vertex approximation to obtain the correlations. The main advantage of the dynamical vertex approximation over the original DMFT, is that it describes correlations on all length scales.

Using the correlators, one can reconstruct the reduced density matrix of any two sites. We analyze the dependence of the mutual information and the entanglement negativity on the distance and relative position of the two sites.

Contribution

Poster

Emergence of the 3D diluted Ising model universality class in a mixture of two magnets

Juan Jesús Ruiz-Lorenzo¹, Maxym Dudka^{2, 3, 4}, Mariana Krasnytska^{2, 3, 5}, Yuriy Holovatch^{2, 3, 6, 7}

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Usually, the impact of structural disorder on the magnetic phase transition in the 3D Ising model is analyzed within the framework of quenched dilution by a non-magnetic component, where some lattice sites are occupied by Ising spins, while others are non-magnetic. This kind of quenched dilution, according to the Harris criterion, leads to a change in the critical exponents that govern the asymptotics in the vicinity of the phase transition point. However, the inherent reason for the emergence of a new, random Ising model universality class is not the presence of a non-magnetic component but the disorder in a structure of spin arrangement. Within the renormalization group approach it can be shown for instance for a random mixture of two Ising-like magnets that differ in spin length s and concentration c [1]. Supporting this outcome we set up extensive Monte Carlo simulations. In doing so, we analyze the effect of structural disorder per se without appealing to the presence of a non-magnetic component. Our results demonstrate the emergence of the 3D randomly diluted Ising model universality class in a random mixture of two Ising magnets. While the asymptotic critical exponents coincide with those known for the site-diluted 3D Ising model, the effective critical behavior is triggered by parameters s and c . The impact of their interplay is a subject of detailed analysis [2].

M.D., M.K. and Yu.H were supported by the National Research Foundation of Ukraine Project 2023.03/0099 “Criticality of complex systems: fundamental aspects and applications”.

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Contribution

Poster

Critical properties of random long-range interacting spin systems

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We analyse a challenging issue of an impact of weak structural disorder on the critical behaviour of a spin system with long-range, power-law decaying interactions. Applying field-theoretical renormalization group methods we analyse critical properties of weakly diluted (random) n -vector model with the long-range interaction decaying with distance as $\sim x^{-d-\sigma}$ in a d -dimensional space. It is known that in a certain region in the parametric $n-d-\sigma$ space such model belongs to the new dilution-induced universality class [1]. Stability boundary of this region [2] and the correlation critical exponent ν characterizing new universality class [3] have been already calculated within the $\epsilon' = 2\sigma - d$ -expansion. To get more reliable data we extract values of stability border as well as the critical exponent ν characterizing this universality class from the perturbative renormalization group functions using fixed spatial dimension approach at $d=3$ and applying asymptotic series resummation methods.

M.D. and D.S. acknowledge the support of the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences, Materials Science and Engineering Division, under Award No. DE-SC0013599 (Subaward No. UTAUS-SUB00000795)

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Contribution

Poster

Dynamics of correlations of many colliding particles

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The talk provides an overview of some advances in the mathematical understanding of the nature of the dynamics of the correlations of many colliding particles. The fundamental equations of modern mathematical physics are studied, particularly the hierarchies of the evolution equations of many hard spheres and their asymptotic behavior described by kinetic nonlinear equations.

First, an approach to describing correlations in a system of colliding particles interacting as hard spheres is discussed, based on a hierarchy of equations for the evolution of a sequence of correlation functions that are cumulants of distribution functions, called the Liouville hierarchy [1]. It is proven that the constructed dynamics of correlations underlie the description of the dynamics of both a finite and an infinite number of hard spheres obeying the BBGKY hierarchies for reduced distribution functions or reduced correlation functions. The structure of expansions representing non-perturbative solutions of the Cauchy problem for these hierarchies of evolution equations is formulated. It has been established that the concept of cumulants of the groups of operators of the Liouville equations underlies non-perturbative expansions of solutions to the hierarchies of fundamental equations describing the evolution of observables and of the state of many hard spheres, as well as forms the basis of the kinetic description of their collective behavior.

In the talk, we also consider a new approach to the problem of a rigorous description of kinetic evolution employing reduced (marginal) observables governed by the dual BBGKY hierarchy [2]. One of the advantages of the developed approach to the derivation of kinetic equations from the underlying dynamics of many particles is that it provides an opportunity to construct kinetic equations with initial correlations, in particular, correlations characterizing the condensed states of a system, and describing the processes of the propagation of initial correlations within suitable scaling limits.

[1] Gerasimenko V I and Gapyak I V (2022) Propagation of correlations in a hard-sphere system. J Stat. Phys. 189 (2) doi:10.1007/s10955-022-02958-8

[2] Gerasimenko V I and Gapyak I V (2021) Boltzmann-Grad asymptotic behavior of collisional dynamics. Reviews in Math. Phys. 33, 2130001 32
doi:10.1142/S0129055X21300016

Contribution

Poster

Scaling of the binary intrinsic dimension of correlated growth dynamics data

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Detecting and quantifying correlations in generic datasets is challenging, since the data can be high dimensional and reflect diverse types of interactions. The intrinsic dimension (ID), defined as the minimum number of variables required to describe a dataset, provides a powerful framework for addressing this challenge. In this work, we investigate the ID of binary data as a tool to study nonequilibrium dynamics. Leveraging a recently developed method for estimating the ID of binary datasets, we focus on data generated by stochastic dynamics in prototypical surface growth models. Our results show that even when reducing such stochastic dynamics to binary form, the binary intrinsic dimension (BID) retains essential physical information. Specifically, by performing a scaling analysis of the BID, we show that it effectively captures the scaling exponents of the underlying universality class. These findings highlight the ability of the BID to discern fundamental properties of nonequilibrium systems and offer a novel perspective on the complexity of nonequilibrium binary data.

Contribution

Poster

Smoothly vanishing density in the contact process by an interplay of disorder and long-distance dispersal

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Realistic modeling of ecological population dynamics requires spatially explicit descriptions that can take into account spatial heterogeneity as well as long-distance dispersal. Here, we present Monte Carlo simulations and numerical renormalization group results for the paradigmatic model, the contact process, in the combined presence of these factors in both one and two-dimensional systems. Our results confirm our analytic arguments stating that the density vanishes smoothly at the extinction threshold, in a way characteristic of infinite-order transitions. This extremely smooth vanishing of the global density entails an enhanced exposure of the population to extinction events. At the same time, a reverse order parameter, the local persistence displays a discontinuity characteristic of mixed-order transitions, as it approaches a non-universal critical value algebraically with an exponent $\beta'_p < 1$.

Reference:

R. Juhász, I. A. Kovács, SciPost Phys. Core **7**, 044 (2024)

Contribution

Poster