Kardar–Parisi–Zhang equation: new trends in theories and experiments

15-26 April 2024 Les Houches School of Physics (France)

AIMS

Mehran Kardar, Giorgio Parisi and Yi-Cheng Zhang proposed in 1986 an equation describing the scale invariance of various phenomena. This field has experienced a second life in recent years with the identification of universal distributions highlighted in very different models, both at the theoretical (spin chains, lattice gases) and experimental (cold atoms, exciton-polaritons) levels. Our goal is to provide a broad and accessible overview of these advances, together with the most recent results on these topics.

TOPICS

- Theory of out-of-equilibrium interfaces in random media
- KPZ scalings in open quantum systems
- Fluctuations in excitons-polaritons gases
- Experimental realization of KPZ fronts
- Driven spin chains
- Mathematical aspects of the KPZ universality class

ORGANISATION

Léonie Canet (LPMMC, Université Grenoble Alpes)
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SCHEDULE

KPZ : new trends in theories and experiments

Program of first week April 15-19, 2024

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
9:00-10:30		T. Prosen	I. Corwin	I. Corwin	T. Prosen	K. Takeuchi
10:30-10:55		coffee break				
10:55-12:25		T. Prosen	I. Corwin	I. Corwin	T. Prosen	K. Takeuchi
12:30-14:00		lunch				
15:00-16:00		G. Barraquand	M. Szymanska	D. Wei	J. Bloch	
16:00-16:30	arrivals	coffee break				excursion
16:30-17:30		G. Parisi	A. Berti A. Orjan		J. Bloch	walk
17:30-19:00	**18h** Welcome	Poster 1 Flash Presentations	Discussion	Poster Session 1	Discussion	
19:30-20:30	dinner					

Program of second week April 22-26, 2024

	Monday	Tuesday	Wednesday	Thursday	Friday
9:00-10:30	S. Diehl	K. Takeuchi	S. Diehl	E. Agoritsas	G. Apolinario B. Maximilien M. Sen
10:30-10:55	coffee break				
10:55-12:25	S. Diehl	S. Diehl	K. Takeuchi	E. Agoritsas	T. Jin G. Pisegna M. Tierz
12:30-14:00	lunch				
15:00-16:00	H. Spohn	I. Carusotto	E. Agoritsas	V. Terras	departures
16:00-16:30	coffee break			coffee break	
16:30-17:00			coffee break		
17:00-17:30	L. Canet			Q. Fontaine F. Vercesi	
17:30-18:00		E. Agoritsas			
18:00-19:00	Poster 2 Flash Presentations	Discussion	Poster Session 2	Discussion	
19:30-20:30	dinner				

SPEAKERS

LECTURES

- **Elisabeth Agoritsas** (DQMP, Université de Genève, Switzerland)
  Interfaces in disordered systems and directed polymer
- **Ivan Corwin** (Columbia University, USA)
  Mathematical aspects of the KPZ universality class
- **Sebastian Diehl** (Universität zu Köln, Germany)
  Keldysh formalism, open quantum systems and gazes of exciton-polaritons
- **Tomaž Prosen** (Univerza v Ljubljani, Slovenia)
  Non-equilibrium lattice quantum systems, emergence of KPZ in spin chains
- **Kazumasa A. Takeuchi** (Tōkyō University, Japan)
  Introduction to the KPZ equation and its experimental aspects

INVITED TALKS

- **Guillaume Barraquand** (ENS Paris, France)
  Non-equilibrium steady-state of the open KPZ equation
- **Jacqueline Bloch** (C2N, Paris-Saclay, France)
  Kardar Parisi Zhang scaling in the coherence of polariton condensates
- **Léonie Canet** (LPMMC, Université Grenoble Alpes, France)
  The non-perturbative side of the KPZ equation
- **Iacopo Carusotto** (INO-CNR BEC Center, Trento, Italy)
  Quantum fluids of light as a platform for non-equilibrium statistical mechanics
- **Giorgio Parisi** (Sapienza Università di Roma, Italy)
  Random considerations on the KPZ equation, the "P" of KPZ
- **Gregory Schehr** (LPTHE, Paris, France)
  Large deviations for the KPZ equation in 1+1 dimension
- **Herbert Spohn** (Technical University of Munich, Germany)
  KPZ equation with two components
- **Marzena Szymanska** (University College London, UK)
  Driven-dissipative superfluids: a compact Kardar-Parisi-Zhang dynamics of the phase
- **Véronique Terras** (LPTMS, Paris-Saclay, France)
  The open XXZ spin chain
- **David Wei** (Max Planck Institute of Quantum Optics, Garching, Germany)
  Quantum gas microscopy of spin superdiffusion in Heisenberg chains

CONTRIBUTED TALKS

- **Ameye Orjan**
  Exploring Floquet Engineering and Parametric Instability in N-Coupled Kerr Oscillators: A Pump Photon Approach
- **Apolinario Gabriel**
  Statistical modeling of bifractal statistics with a superposition of characteristic functionals
- **Bernard Maximilien**
  Anomalous scaling of heterogeneous interfaces: a new picture from sample to sample fluctuations (In collaboration with P. Le Doussal, A. Rosso and C. Texier)
- **Berti Anna**
  The physics of ferromagnetic Bose-Einstein condensate mixtures.
- **Fontaine Quentin**
  Exploring Universal Scaling Laws In Two-Dimensional Polariton Condensates
- **Jin Tony**
  KPZ physics in single-particle, classical or quantum system under monitoring or dephasing.
- **Mu Sen**
  Kardar-Parisi-Zhang Physics in the Density Fluctuations of Localized Two-Dimensional Wave Packets
- **Pisegna Giulia**
  Emergent polar order in non-reciprocally coupled conserved densities
- **Tierz Miguel**
  Random matrix description of the Loschmidt echo of spin chains and dynamical quantum phase transitions.
- **Vercesi Francesco**
  KPZ scaling regimes and phase turbulence from the Kuramoto-Sivashinsky model in one dimension

ABSTRACTS

SYNOPSIS OF LECTURES

Elisabeth Agoritsas

Interfaces in disordered systems and directed polymer

1. Introduction

- Generic theoretical frameworks: disordered elastic systems.
- Threefold motivation: experimental/fundamental/methodological.
- Basic phenomenology and regimes of interest.

2. Disordered elastic systems: Recipe

- Description: Hamiltonian, Langevin dynamics, dynamical action.
- Observables: geometrical fluctuations and center-of-mass dynamics.

3. Disordered elastic systems: Statics

- Static interface without disorder (thermal roughness).
- With disorder: roughness regimes and crossover scales. Larkin model.
- Example of model reduction: effective 1D interface starting from a 2D Ginzburg-Laudau description.
- Focus on the 1D interface: mapping to the 1+1 Directed Polymer. Connections to the 1D Kardar-Parisi-Zhang equation and universality class.
- Scaling analysis: power counting versus physical scalings

3. Disordered elastic systems: Dynamics

- Velocity-force characteristics.
- Fast-flow regime.
- Creep regime: how to recover 1/4 creep exponent from 2/3 KPZ exponent.

Ivan Corwin

Mathematical aspects of the KPZ universality class

Lecture 1. Extreme Diffusion or Was Einstein Wrong About Diffusion

In a system of many particles diffusing in a common environment, the first few particles are often quite important. How do they behave and what does that behavior tell us about the environment in which they have evolved? We will approach these problems by studying random walks in random environments and utilizing a connection with the KPZ equation and universality class. In particular, this first lecture will highlight some of the types of tools (stochastic analysis, replicas, Bethe ansatz) and results one can show mathematically about models in the KPZ universality class.

Lecture 2. Pot Of Gold At The End Of The KPZ Rainbow

When people say "KPZ universality class" they presumably mean that many systems converge to a single universal limit. What is that limit and what does it tell us? We will address this question from the perspective of stochastically growing interface models over one spatial dimension. In particular, we will focus on results about the scaling limit of the height function for the multispecies (i.e. multicolor) Asymmetric Simple Exclusion Process (ASEP). The final two lectures will build up the tools to understand and prove these results.

Lecture 3. Colorblind Analysis

We will focus on the single species (colorblind) ASEP and its discrete time relative, the stochastic six vertex (S6V) model. We will show how the Yang-Baxter equation relates the ASEP/S6V height functions to measures written in terms of q-Boson weights and discuss some ideas (determinantal methods, replica Bethe ansatz, and Gibbsian line ensembles) behind extract limits of these measures.

Lecture 4. Back To The Rainbow

Returning to the setting of colors we will show how a colored version of the Yang-Baxter equation allows us to analyze this more general model by leveraging the colored blind analysis in Lecture 3. We will also touch on how, by fusion, it is possible to extend our analysis to a more general class of stochastic vertex models that includes many examples including some touched on in Lecture 1.

Sebastian Diehl

Keldysh formalism, open quantum systems and gazes of exciton-polaritons

Tomaž Prosen

Non-equilibrium lattice quantum systems, emergence of KPZ in spin chains

In the series of four lectures I will introduce and discuss several exactly solvable or integrable non-equilibrium or time-dependent paradigms of quantum and also classical lattice systems (spin chains) with a focus on lattice models in discrete time.

Lecture 1 - Integrable spin chains and quantum circuits
I will introduce Yang-Baxter quantum circuits with a specific focus on unitary six-vertex model (XXZ circuit and XXZ spin chain). With respect to the problem of transport, I will discuss two fruitful aspects: (quaslocal conservation laws and matrix product non-equilibrium steady states of boundary driven chains.

Lecture 2 - XXX circuit and Heisenberg spin chain
I will focus SU(2) symmetric circuit/spin chain and discuss emergent KPZ scaling of dynamical 2-point functions. This lecture will be phenomenology oriented, I will present and discuss state-of-the-art t-DMRG computations and quantum simulations.

Lecture 3 - The classical limit and super-universality of super-diffusion
I will discuss simple symplectic coupled map lattices, or classical circuits,which are integrable and which exhibit the same phenomenology as integrable quantum circuits. A family of these models can be defined w.r.t. almost arbitrary compact Lie Group symmetry and exhibit the same (KPZ) scaling of 2-point functions.

Lecture 4 - Full counting statistics

I will discuss the problem of full counting statistics in integrable spin chains/circuits with a conserved quantity and introduce the concepts of cumulant generating function,dynamical free energy and large deviation. I will present an exactly solvable model of full counting statistics in a classical interacting cellular automaton. Finally, I will return to quantum simulation of full counting statistics in XXX circuit.

Kazumasa A. Takeuchi

Theoretical and experimental physics aspects of the KPZ class for growing interfaces

The KPZ equation and the associated universality class were originally proposed in the context of growing interfaces. The lecture will include a pedagogical introduction to basic properties of the KPZ equation, an illustrative outline of characteristic distribution and correlation properties revealed by exact solutions, and a survey of experimental studies on growing interfaces.

1. Introduction: why should we care this?

2. Scaling exponents and universality classes

3. Basic properties of the KPZ equation

4. Distribution and correlation properties: stationary & non-stationary cases

5. Experimental test of predictions from integrable models

6. Distribution properties for general cases and variational formula

Main reference: K. A. Takeuchi, "An appetizer to modern developments on the Kardar-Parisi-Zhang universality class", Physica A 504, 77-105 (2018). https://doi.org/10.1016/j.physa.2018.03.009

INVITED TALKS

- **Guillaume Barraquand** (ENS Paris, France)
  Non-equilibrium steady-state of the open KPZ equation

  Abstract: It is well-known that the Brownian motion is a stationary measure for the one dimensional KPZ equation on R. This means that if we start from a Brownian motion at time 0, the solution of the KPZ equation at time t remains a Brownian motion, up to a global height shift. For the KPZ equation on a bounded domain like [0,L], however, the stationary process is no longer Brownian in general. Its precise description was obtained only recently. In this talk, I will review recent progress on this question, and discuss connections with Liouville quantum mechanics and Gibbsian line ensembles. This is based on several works with Ivan Corwin, Pierre Le Doussal and Zongrui Yang.

- **Jacqueline Bloch** (C2N, Paris-Saclay, France)
  Kardar Parisi Zhang scaling in the coherence of polariton condensates

  Abstract: Cavity polaritons are hybrid light-matter quasiparticles emerging from the strong coupling between photons confined in cavities and electronic excitations named excitons confined in quantum wells. Cavity polaritons present rich physical properties emerging from this mixed nature. From their photonic component, they exhibit a light effective mass and large coherence areas (micron scale) together with a coupling to the bath of electromagnetic modes outside the cavity (driven dissipative nature). From their excitonic component, polaritons interact with each other and thus present a significant Kerr non-linearity. Semiconductor microcavities, in which cavity polaritons can be generated, appear as a powerful platform to explore the physics of quantum fluids in a driven dissipative context [1]. For instance, Bose Einstein condensation can be triggered with the characteristic onset of macroscopic coherence but with distinct physical properties related to their out of equilibrium regime. Indeed in 2015, it was discovered the phase dynamics of driven dissipative polariton condensates obeys the celebrated Kardar Parisi Zhang (KPA) equation [2]. This means that the spatio-temporal coherence decay should reveal universal KPZ scalings. Interestingly, since the phase is a compact variable, periodically defined between 0 and 2 the physics is enriched with the possible emergence of vortices. Actually even in 1D, where usually vortices are excluded,

spatio-temporel vortices have been predicted to play a role [6] so that a rich phase diagram is predicted [2-5]. In the present talk, after a general introduction to cavity polaritons, I will explain how we could generate extended 1D polariton condensates and probe their first order coherence. We demonstrate that the spatio-temporal decay of the first order coherence presents universal scaling laws characteristic for the KPZ universality class in 1D [8]. The influence of vortices in these experiments will be discussed as well as the extension of this work to 2D [9]. This work highlights the profound difference between driven-dissipative out of equilibrium condensates and their equilibrium counterparts. We anticipate that this physics should also be relevant in extended vertical cavity lasers.
[1] I. Carusotto and C Ciuti, Rev. Mod. Phys. 85, 299 (2013) [2] M. Kardar, G. Parisi, and Y. C. Zhang, Phys. Rev. Lett. 56, 889 (1986) [3] E. Altman, et al., Phys. Rev. X 5, 011017 (2015). [4] K. Ji, et al., Phys. Rev. B 91, 045301 (2015). [5] L. He, et al., Phys. Rev. B 92, 155307 (2015) [6] L. He et al, Phys. Rev. Lett. 118, 085301 (2017). [7] F. Vercesi et al., Phys. Rev. Research 5, 043062 (2023) [8] Q. Fontaine et al, Nature 608, 687 (2022) [9] K. Deligiannis et al., Phys. Rev. Research 4, 043207 (2022).

- **Léonie Canet** (LPMMC, Université Grenoble Alpes, France)
  The non-perturbative side of the KPZ equation

Abstract: In this talk, I will discuss the non-perturbative aspect of the KPZ equation, and show how it can be described using functional and non-perturbative renormalisation group (FRG) [1]. First, in all dimensions d>1, the KPZ rough phase is controlled by a genuinely strong-coupling fixed point, ie it cannot be accessed at any order of the perturbation theory performed around vanishing non-linearity. One needs a non-perturbative method, such as the FRG, to capture it and compute the associated universal statistical properties [2]. I will explain the general setting of the FRG and the results which can be obtained for the KPZ equation in d>1. Second, even in d=1, the non-perturbative nature of the KPZ equation arises. Although the KPZ equation is exactly solvable in this dimension, and its statistical properties are known to an exquisite degree, recent numerical simulations [3] unveiled a new scaling, with a dynamical exponent z=1 different from the KPZ one z=3/2. I will show that this scaling is controlled by a fixed point which had been missed so far and which corresponds to an infinite effective coupling. This fixed point can be accessed using the FRG, and it yields z=1 [4]. The FRG also allows for the calculation of the correlation function at this fixed point. I will discuss the associated scaling function, providing both an analytical

asymptotic form and the complete numerical solution, which accurately matches the result from the numerical simulations.

[1] N. Dupuis et al, Phys. Rep. 910, 1 (2021). [2] L. Canet, H. Chaté, B. Delamotte, N. Wschebor, PRL 104, 150601 (2010). [3] Cartes, Tirapegui, Pandit, Brachet, Phil. Trans. Roy. Soc. A 380, 20120090 (2022). [4] Vercesi, Fontaine, Brachet, Canet, PRL 131, 247101 (2023).

- **Iacopo Carusotto** (INO-CNR BEC Center, Trento, Italy)
  Quantum fluids of light as a platform for non-equilibrium statistical mechanics

  Abstract: In this talk I will give a short introduction to the field of quantum fluids of light as a promising platform to investigate non-equilibrium statistical mechanics effects. Milestones experiments will be reviewed and open challenges will be sketched. A brief summary of the different experimental realizations will also be given.

- **Giorgio Parisi** (Sapienza Università di Roma, Italy)
  Random considerations on the KPZ equation, the "P" of KPZ

- **Grégory Schehr** (LPTHE, Paris, France)
  Large deviations for the KPZ equation in 1+1 dimension

  Abstract: It is now well known that the typical fluctuations of the KPZ height field in 1+1 dimension (say in the droplet geometry) are described, at short time, by a Gaussian and, at large time, by the Tracy-Widom distribution corresponding to the Gaussian Unitary Ensemble of Random Matrix Theory. In this talk, I will instead discuss the atypical fluctuations for the KPZ equation, which are described by large deviation forms. These questions have attracted a growing interest during the last decade, both in the physics and in the maths literature. If time permits, I will then present the implications of these results for one-dimensional trapped fermions at finite temperature.

- **Herbert Spohn** (Technical University of Munich, Germany)
  KPZ equation with two components

  Abstract: Discussed are older results on models when the flux Jacobian is non-degenerate, which are based on nonlinear fluctuating hydrodynamics. Current research elucidates the intriguing scaling behavior when the flux Jacobian is degenerate.

- **Marzena Szymanska** (University College London, UK)
  Driven-dissipative superfluids: a compact Kardar-Parisi-Zhang dynamics of the phase

  Abstract: Driven-dissipative quantum fluids can differ substantially from their equilibrium counterparts. The long-wavelength phase dynamics of a polariton/photon condensate has been shown to obey Kardar-Parisi-Zhang (KPZ) equation. Since the phase is a compact variable, vortices in 2D and phase slips in 1D can proliferate destroying the KPZ scaling. The interplay between KPZ physics and topological defects is currently subject of great interest, especially in polariton context. In this talk, I will review our work on the topic [1,2,3].
  In particular, we demonstrate [1,3] that in the optical parametric oscillator regime of a polariton condensate, simply changing the strength of the pumping mechanism can substantially alter the level of effective spatial anisotropy and move the system into distinct scaling regimes. These include (i) the classic algebraically ordered superfluid below the Berezinskii-Kosterlitz-Thouless (BKT) transition, as in equilibrium; (ii) the nonequilibrium, long-wavelength-fluctuation-dominated Kardar-Parisi-Zhang (KPZ) phase; and the two associated topological-defect-dominated disordered phases caused by proliferation of (iii) entropic BKT vortex-antivortex pairs or (iv) repelling vortices in the KPZ phase. We then study the dynamics of vortices in the compact Kardar-Parisi-Zhang equation [2], after a sudden quench across the critical region. Our exact numerical solution of the phase-ordering kinetics shows that the unique interplay between nonequilibrium and the variable degree of spatial anisotropy leads to different critical regimes. We provide an analytical expression for the vortex evolution, based on scaling arguments, which agrees with the numerical results, and confirms the form of the interaction potential between vortices in this system. Finally, we consider multicomponent system relevant to polariton condensate with different polarisations. The effective theory for Z2 degenerate coupled condensates with U(1)xU(1) symmetries maps onto coupled multicomponent KPZ equations. We perform dynamical

renormalisation group analysis as well as exact numerical simulations to place polariton condensates in the subspace of a generally rich flow diagram.

[1] A. Ferrier, A. Zamora, G. Dagvadorj, and M.H. Szymańska Phys. Rev. B 105, 205301 (2022); [2] A. Zamora, N. Lad, and M. H. Szymanska Phys. Rev. Lett. 125, 265701 (2020); [3] A. Zamora, L. M. Sieberer, K. Dunnett, S. Diehl, and M. H. Szymańska Phys. Rev. X 7, 041006 (2017)

- **Véronique Terras** (LPTMS, Paris-Saclay, France)
  The open XXZ spin chain

  Abstract: The open XXZ spin chain is an integrable model. It can be mapped on an open ASEP model. The model can be exactly solved by Algebraic Bethe Ansatz when the boundary fields are longitudinal, i.e. oriented along the direction of anisotropy, and by Separation of Variables for more general boundary fields. We review here the solution of this model by these different integrability techniques. If time permits, the problem of the computation of the correlation functions will also be briefly discussed.

- **David Wei** (Max Planck Institute of Quantum Optics, Garching, Germany)
  Quantum gas microscopy of spin superdiffusion in Heisenberg chains

CONTRIBUTED TALKS

- **Ameye Orjan**

  Exploring Floquet Engineering and Parametric Instability in N-Coupled Kerr Oscillators: A Pump Photon Approach

  Abstract: Non-equilibrium many-body systems manifest across multiple physics disciplines. Typically, the problem touches on describing the stationary behavior of complex models of coupled nonlinear oscillators. In my talk, I will discuss our recently developed framework for describing many-body out-of-equilibrium stationary states, in both the quantum and classical limits. In our approach, we address the shortcomings of the rotating-wave approximation (RWA) for periodically driven oscillators. Specifically, combining the canonical quantum description with the RWA yields incorrect results for finite detuning. Consequently, the standard RWA description breaks the quantum-to-classical limit [1]. To address this, we introduce an alternative operator basis that reconciles the RWA with off-resonant driving. We demonstrate our approach for single nonlinear oscillators and extend it to more complex many-body networks. More specifically, we explore the steady-state topologies and phase diagrams of so-called Kerr Parametric Oscillator (KPO) networks. It has been shown that systems of coupled KPOs can be used as Ising machines holding potential for neuromorphic computations. I will present a novel approach that complements existing methodologies, enabling a comprehensive understanding of the emergence of phase transitions within systems involving many-coupled KPOs [2]. Our findings give insight into how to operate KPO networks as Ising chains and networks.

  [1] K. Seibold, O. Ameye, and O. Zilberberg, Floquet engineering counting pump photons, (in preparation). [2] O. Ameye, A. Eichler, and O. Zilberberg, Mapping the parametric instability of N-coupled Kerr Parametric Oscillators, (in preparation).

- **Apolinario Gabriel**
  Statistical modeling of bifractal statistics with a superposition of characteristic functionals

Abstract: We study an ensemble of random fields, each with statistics described by a general characteristic functional. Intermittency is produced by letting the typical length scale of these fields be a random variable. This ensemble decomposition approach [Wilczek, New J. Phys. 18, 125009 (2016)] allows for an analytically tractable approximation to turbulent statistics. We build bifractal statistics by choosing an appropriate distribution for the random length scale. As a result, the velocity statistics are Gaussian, but increment and velocity gradient moments are bifractal. Skewness, a hallmark of turbulent fields, is obtained by truncating a Taylor-expanded cumulant generating functional, a useful approximation to non-Gaussian fields.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 101001081).

- **Bernard Maximilien**
  Title: Anomalous scaling of heterogeneous interfaces: a new picture from sample to sample fluctuations (In collaboration with P. Le Doussal, A. Rosso and C. Texier)

Abstract: We study a discrete model of an heterogeneous elastic line with internal disorder, submitted to thermal fluctuations. The monomers are connected through random springs with independent and identically distributed elastic constants drawn from $p(k)\sim k^{\mu-1}$ for $k\to0$. When $\mu>1$, the scaling of the standard Edwards-Wilkinson model is recovered. When $\mu<1$, the elastic line exhibits an anomalous scaling of the type observed in many growth models and experiments. Here we derive and use the exact expression for the exact probability distribution of the line shape at equilibrium, as well as the spectral properties of the matrix containing the random couplings,to fully characterize the sample to sample fluctuations. Our results lead to novel scaling predictions that partially disagree with previous works, but which are corroborated by numerical simulations. We also provide a novel interpretation of the anomalous scaling in terms of the abrupt jumps in the line's shape that dominate the average value of the observable.

- **Berti Anna**
  The physics of ferromagnetic Bose-Einstein condensate mixtures.

  Abstract: Bose-Einstein condensates (BEC) of ultracold atoms have proven to be a promising platform for the realization of analog models. While the analogy is typically exploited in the gravitational context, coherently coupled two-component BEC mixtures behave analogously to a spin chain, showing a para-to-ferromagnetic quantum phase transition (QPT) driven by interactions. The unique combination of superfluidity and ferromagnetic character, the absence of decoherence and dissipation and the impressive experimental control on these systems, make them an ideal platform to study the nature of magnetic elementary excitations, out-of-equilibrium spin dynamics, QPT in lower dimensionality, metastability and more.

  [1] Cominotti, Berti, et al, PRX 13 (2), 021037 (2023) [2] Zenesini et al, Nature Phys., 1-6 (2024).

- **Fontaine Quentin**
  Exploring Universal Scaling Laws In Two-Dimensional Polariton Condensates

  Abstract: Revealing universal behaviors in different systems is a hallmark of statistical physics. In this context, the Kardar-Parisi-Zhang (KPZ) [1] equation is a paradigmatic example of universality out of equilibrium. This equation describes the critical roughening of stochastically growing interfaces in classical systems. The spatial and temporal correlation functions of the height profile exhibit scalings, with critical exponents specific to the KPZ universality class and depending only on dimensionality. While KPZ physics has been thoroughly studied in one-dimensional (1D) systems, an experimental platform is still missing for its exploration in two dimensions (2D). Interestingly, theoretical predictions show that the phase of polariton condensates behaves as an interface, whose spatio-temporal evolution is described by the KPZ equation [2]. Since the phase is a compact variable, the physics is enriched by the possible emergence of spatial and spatio-temporal vortices. Recent experiments have demonstrated that the coherence of 1D polariton condensates show spatiotemporal

decay characteristic of the KPZ universality class. [3]. In this talk, we report optical interferometry experiments on extended 2D polariton condensates generated in lattices of coupled microcavities. We retrieve the spatio-temporal decay of the first order coherence |g(1)|. Close to condensation threshold, the |g(1)| temporal decay can be nicely fitted by a stretched exponential using the characteristic KPZ growth exponent $2\beta \simeq 0.48$. At higher powers, the coherence dynamics evolves into an exponential decay. We will discuss the overall measured spatio-temporal coherence behavior in the KPZ phase as well as the role of vortices in the departure from this phase at higher powers, in accordance with theoretical predictions [4, 5].

[1] M. Kardar, G. Parisi, Y.-C. Zhang. Phys. Rev. Lett., 56:889–892, 1986. [2] L. He, L. M. Sieberer, E. Altman, S. Diehl. Phys. Rev. B, 92:155307, 2015. [3] Q. Fontaine, et al, Nature, 608(7924):687–691, 2022. [4] Q. Mei, K. Ji, M. Wouters. Phys. Rev. B, 103(4):045302, 202. [5] K. Deligiannis, Q. Fontaine, D. Squizzato, M. Richard, S. Ravets, J. Bloch, A. Minguzzi, L. Canet, Phys. Rev. Res., 4:043207, 2022.

- **Jin Tony**

  KPZ physics in single-particle, classical or quantum system under monitoring or dephasing.

  ***Abstract**:* I will present some of the recent results concerning the dynamical fluctuations of single, classical or quantum, particle subject to external monitoring or dephasing. Exploiting analogies with KPZ physics, I will show that these systems have non trivial scaling of their fluctuations and can exhibit phase transition in dimensions higher than 1.

- **Mu Sen**

  Kardar-Parisi-Zhang Physics in the Density Fluctuations of Localized Two-Dimensional Wave Packets

  ***Abstract**:* We identify the key features of Kardar-Parisi-Zhang universality class in the fluctuations of the wave density logarithm, in a two-dimensional Anderson localized wave packet. In our numerical analysis, the fluctuations are found to exhibit an algebraic

scaling with distance characterized by an exponent of 1/3, and a Tracy-Widom probability distribution of the fluctuations. Additionally, within a directed polymer picture of KPZ physics, we identify the dominant contribution of a directed path to the wave packet density and find that its transverse fluctuations are characterized by a roughness exponent 2/3. Leveraging on this connection with KPZ physics, we verify that an Anderson localized wave packet in 2D exhibits a stretched-exponential correction to its well-known exponential localization.

- **Pisegna Giulia**

  Emergent polar order in non-reciprocally coupled conserved densities

  Abstract*:* In a stochastic field theory for two species of particle densities with non-reciprocal interactions, polar order emerges spontaneously in the form of traveling waves. We build the equation of motion for a suitable polar order parameter to show that its dynamics differs strikingly from existing field theories for flocking. Stability analysis of the ordered state shows that the theory developed up to linear terms in deviations from perfect order is robust under spontaneous fluctuations at every d. When non-linearities are included, the fluctuations remarkably follow a noisy Burgers equation driven by non-reciprocity. Using a Renormalization Group approach, we confirm that our theory falls in the Burgers/KPZ universality class, hence validating robust long-range order properties.

- **Tierz Miguel**

  Random matrix description of the Loschmidt echo of spin chains and dynamical quantum phase transitions.

  Abstract*:* We will explain the random matrix formulation of the Loschmidt echo for several spin chain and fermionic models. This will help us discover new dynamical quantum phase transitions. The XX spin chain case produces three primary outcomes. Firstly, a third-order phase transition occurs at a rescaled critical time, which we determine. Secondly, this third-order phase transition persists away from the thermodynamic limit. For values below the critical point, the difference between the thermodynamic limit and a finite chain decreases exponentially as the system size increases. This is based on the joint work David Pérez-García, Leonardo Santilli, and Miguel Tierz, Quantum 8, 1271 (2024), other works involving D. Pérez-García and/or L. Santilli, and work in progress.

- **Vercesi Francesco**

  Scaling regimes of the phase turbulence in the complex Ginzburg-Landau equation

  Abstract: We study the phase turbulence of the one-dimensional complex Ginzburg-Landau equation, in which the defect-free chaotic dynamics of the order parameter maps to a phase equation well approximated by the Kuramoto-Sivashinsky model. In this regime, the behaviour of the large wavelength modes belongs to the Kardar-Parisi-Zhang universality class [1]. We present numerical evidence of the existence of an additional scale-invariant regime, with dynamical scaling exponent z=1, emerging at scales which are intermediate between the microscopic, intrinsic to the modulational instability, and the macroscopic ones. We argue that this new regime is a signature of the universality class corresponding to the inviscid limit of the Kardar-Parisi-Zhang equation [2].

  [1] D. Roy and R. Pandit, Phys. Rev. E 101, (2020). [2] C. Fontaine, F. Vercesi, M. Brachet, and L. Canet, Phys. Rev. Lett. 131, (2023).

POSTER CONTRIBUTIONS

POSTER SESSION 1

(flash presentations Tuesday 16 at 5:30pm
poster session Thursday 18 at 4:30pm)

Bestler Markus

Towards out-of-equilibrium topological quasi magnonics

We study an ensemble of random fields, each with statistics described by a general characteristic functional. Intermittency is produced by letting the typical length scale of these fields be a random variable. This ensemble decomposition approach [Wilczek, New J. Phys. 18, 125009 (2016)] allows for an analytically tractable approximation to turbulent statistics. We build bifractal statistics by choosing an appropriate distribution for the random length scale. As a result, the velocity statistics are Gaussian, but increment and velocity gradient moments are bifractal. Skewness, a hallmark of turbulent fields, is obtained by truncating a Taylor-expanded cumulant generating functional, a useful approximation to non-Gaussian fields. This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 101001081).

Coquand Olivier

The effect of disorder on the roughness of crystalline surfaces

Crystalline surfaces, or membranes, are well known for their exotic mechanical properties, such as an anomalous Hooke's law, due to their bidimensional character. This work presents a renormalization group calculation of the effect of frozen disorder (atom vacancies, impurities, ...) on the roughness exponent of crystalline surfaces, and its comparison to the experimental results.

Domenech Iván Álvarez

Shape effects in the fluctuations of random isochrones on a square lattice

We consider the isochrone curves in first-passage percolation on a 2D square lattice, i.e. the boundary of the set of points which can be reached in less than a given time from a certain origin. The occurrence of an instantaneous average shape is described in terms of its Fourier components, highlighting a crossover between a diamond and a circular geometry as the noise level is increased. Generally, these isochrones can be understood as fluctuating interfaces with an inhomogeneous local width which reveals the underlying lattice structure. We show that once these inhomogeneities have been taken into account, the fluctuations fall into the Kardar-Parisi-Zhang (KPZ) universality class with very good accuracy, where they reproduce the Family-Vicsek Ansatz with the expected exponents and the Tracy-Widom histogram for the local radial fluctuations.

Enns Sven

Polarization of Photon Bose-Einstein Condensates (PBEC) and preparation of PBEC in lattices

We experimentally investigate properties of harmonically trapped photon gases and Bose-Einstein Condensates in a dye-filled microcavity. Here we analyze the polarization of thermal and condensed light and their dependence on the pump beam's polarization. We show that, in agreement with previous theoretical work by Moodie et al. [1], there is a remarkable increase of the polarization strength above the condensation threshold. While the polarization of the condensate follows the polarization of the pump beam, the thermal light stays unpolarized. Using the technique of Direct Laser Writing (DLW) we can fabricate polymer structures on the surface of the cavity mirrors which act as potential landscapes for the photon gas due to the change of the effective refractive index. With this, a dimensional crossover from 2D to 1D has already been demonstrated. To experimentally realize theoretically predicted phenomena as incoherent, asymmetric transport [2], we fabricate lattice potentials and perform preliminary measurements.

[1] R. I. Moodie, P. Kirton, and J. Keeling, Polarization dynamics in a photon bose-einstein condensate, Phys. Rev. A 96 (2017). [2] L. Garbe, Y. Minoguchi, J. Huber, P. Rabl, The bosonic skin effect: Boundary condensation in asymmetric transport, SciPost Phys. 16, 029 (2024)

Gosteva Liubov

Functional RG to unveil the z=1 scaling in the multidimensional KPZ and Burgers equations

Recent numerical simulations of the 1D KPZ equation uncovered a new scaling regime with the dynamical exponent z=1 in the tensionless limit. The same scaling is observed in the inviscid limit for the Burgers equation, which maps to the KPZ equation [1]. This new scaling regime was confirmed by the functional renormalization group (FRG) analysis, which showed the existence of a corresponding UV-stable fixed point [2]. We expect that a similar fixed point exists in the multidimensional case as well. The aim of the current ongoing work is to prove it within FRG both for the KPZ and Burgers equations. This poster is devoted to the preliminary steps undertaken in this direction: establishing the appropriate action in the Martin-Siggia-Rose-Janssen-de Dominicis formalism for the Burgers equation, which takes into account the mapping to the KPZ equation in the multidimensional case, and identifying the extended symmetries of the model.

[1] C. Cartes, E. Tirapegui, R. Pandit, M. Brachet, The Galerkin-truncated Burgers equation: crossover from inviscid-thermalized to Kardar–Parisi–Zhang scaling, Phil. Trans. R. Soc. A 380, 20210090 (2022). [2] C. Fontaine, F. Vercesi, M. Brachet, L. Canet, The unpredicted scaling of the one-dimensional Kardar-Parisi-Zhang equation, Phys. Rev. Lett. 131, 247101 (2023).

Helluin Félix

Exploring universal scaling regimes of interacting 2D EP BEC

Two-dimensional exciton-polariton condensates offer a promising platform for realizing the (2+1)-dimensional Kardar-Parisi-Zhang (KPZ) universality class within a driven-open quantum system. By conducting extensive numerical simulations of an incoherently pumped and interacting condensate coupled to an exciton reservoir, we demonstrate the accessibility of signatures of the KPZ universality class under realistic experimental conditions. Furthermore, we show that the effective nonlinearity of the phase dynamics can be finely adjusted across a broad range by varying the exciton-polariton interaction strength. This flexibility enables us to explore other regimes, such as the Edwards-Wilkinson regime where the phase dynamics decouples from the condensate density and is weakly nonlinear. For strong interactions, both density and phase dynamics play significant roles in the condensate dynamics, leading to the emergence of a vortex phase.

Izem Noam

Kardar-Parisi-Zhang universality in quantum Anderson localization

Kardar-Parisi-Zhang (KPZ) universality, traditionally associated with the growth of interfaces, manifests itself in many systems including quantum ones. In particular, this physics can be related to quantum localization (Anderson localization) in two dimensions. In this study, we use extended numerical simulations to show that fluctuations of localized eigenstates are well-described by KPZ characteristic exponents.

Jangip Sandeep

Large Deviation in active matter

I shall present our recent result about large deviation of current in a one-dimensional system of active particles. Due to the active nature of particles, the current fluctuations have different scaling regimes. Moreover, the fluctuations have long-term memory of the initial state. Our results easily extend for two-time large deviation functional of the current, enabling us to compute two-time correlations. More generally, our theoretical method easily extends for multi-time large deviations. Much of our results are validated with extensive numerical simulations.

Johnsrud Martin

Phase diagram of the Non-Reciprocal Cahn-Hilliard model and the effects of symmetry

The interactions of active particles may be non-reciprocal, breaking action-reaction symmetry and leading to novel physics not seen in equilibrium systems. In this work, we study the phase diagram for restricted versions of the Non-Reciprocal Cahn-Hilliard (NRCH) model. This model serves as a test kitchen for the effects of non-reciprocity on the phase separation. We draw the full linear phase diagram, illustrating the onset of phase separation. By contrasting a model with continuous symmetry to one without, we illustrate how this affects phase separation. We further show, using analytical and numerical methods, how non-reciprocity gives rise to out-of-equilibrium steady states with non-zero currents. These observations are shown to be robust to noise and to be valid in a large part of parameter space. Finally, we discuss how to quantify the departure from equilibrium using time-reversal symmetry and the rate of entropy production, and where further analysis is needed to fully capture the rich physics of non-reciprocal interactions.

Krauß Joshua

Hydrodynamic description of vortices in Photon Bose-Einstein Condensates

Open dissipative systems of quantum fluids, especially in presence of vortices, are well studied numerically. Motivated by that we strive for finding a corresponding approximate analytical description of photon Bose-Einstein condensates in the presence of vortices. To this end we consider a complex Gross-Pitaevski equation and extend the variational approximation to open dissipative systems in such a way that it is not only working for specific functions. To this end we develop a variational projection method and combine it with known methods from hydrodynamics. With this we approximately obtain a vortex solution and its corresponding velocity field, which depend on the respective open system parameters and have the same properties as obtained numerically.

POSTER SESSION 2

(flash presentations Monday 22 at 5:30pm
poster session Wednesday 24 at 5pm)

Olsen Hazel

Phase transition between dynamical localization and delocalization in the kicked Lieb-Liniger gas at strong coupling

The quantum kicked rotor is a Floquet system with a very rich phenomenology including dynamical localisation, which is analogous to Anderson localisation but in momentum space. We study the effect of strong interaction by considering the Lieb-Liniger model subjected to kicks in the large but finite coupling limit. For infinite coupling (Tonks-Girardeau limit), dynamical localization is the rule. For large but finite coupling, a transition towards delocalization may occur. Using Bethe ansatz, we show that below a certain value of the coupling, for sufficiently large amplitudes of the kicks, the energy no longer saturates at large times. A tentative phase diagram is given.

Pinto Dias Daniela

Exploring universal scaling laws in the coherence of out-of equilibrium polariton condensates

Abstract: Revealing universal behaviors in different systems is a hallmark of statistical physics. At equilibrium, simple models, like the Ising model, have been essential in understanding the critical properties of a whole class of systems. Reversely, a clear description of the universal properties of several non-equilibrium systems remains elusive. In this context, the Kardar-Parisi-Zhang (KPZ) equation [1] has emerged as a quintessential model to investigate non-equilibrium phenomena and phase transitions. This equation was originally derived to describe the critical roughening of growing interfaces in classical systems.
Current theoretical and experimental results show that the wavefront of an extended one-dimensional polariton condensate behaves as an interface, whose spatio-temporal evolution is described by the KPZ equation and falls into the one-dimensional KPZ universality class [2]. Recent theoretical works suggest that in a two-dimensional (2D) polariton system, universal KPZ properties can emerge [3, 4], but the experimental evidence is still missing. Those results are also relevant for out-of-equilibrium Bose-Einstein condensates and lasers. Determining if KPZ physics governs the phase correlations in all those systems is of critical importance. For instance, it would set an intrinsic limitation on the achievable coherence of extended solid-state lasers.
In this poster, I will explain how to generate an extended polariton condensate in a 2D polariton lattice

made of optical microcavities in semiconductor materials. Then, I will explain how we explore KPZ physics by probing the spatio-temporal coherence of our condensate using standard Michelson measurements. Finally, I will show the first preliminary results we obtained on the signature of this universal feature in the 2D polariton condensate.

[1] M. Kardar, G. Parisi, and Y. C. Zhang, Phys. Rev. Lett. 56, 889 (1986). [2] Q. Fontaine, D. Squizzato et al., Nature 608, 687-691 (2022). [3] Q. Mei, K. Ji, and M. Wouters, Phys. Rev. B 103, 045302 (2021). [4] K. Deligiannis, Q. Fontaine, D. Squizzato, et al., Phys. Rev. Res. 4, 043207 (2022).

Rozas Garcia Enrique

Asymptotic universal tails in the electronic density of states disordered systems

A hallmark of quenched disorder in condensed matter systems is the formation of exponential tails at the band edges of the electronic density of states. These tails take a universal Lifshitz form for a Gaussian white noise disorder potential. In my talk, I will discuss how to determine the Lifshitz tail using path-integral methods for a simple system with a single parabolic conduction band. I will focus on the computation of the exact fluctuation prefactor, which in the field-theory description is determined by fluctuations around the most likely potential configuration at a given energy. This prefactor contains the determinant of a fluctuation operator, and I will show how a full computation of the fluctuation spectrum can be avoided by using a Gel'fand-Yaglom formalism, which provides a concise general derivation of fluctuation corrections in disorder problems. The methods used here may be extended to the calculation of the right and left tails of the height distribution in surface growth problems such as KPZ. The talk is based on my recent paper arXiv:2311.14785, accepted for publication in Phys. Rev. E as a Letter.

Villarrubia Moreno Daniel

Mapping of First-Passage Percolation into bond percolation under extreme disorder

Geometry on random manifolds presents both applied and fundamental interest, with applications ranging from the physics of polymers and membranes to quantum gravity. It was recently shown that, in the case of random surfaces which are flat in average and with short-range correlations in the curvature, geodesics present fractal structure, governed by exponents corresponding to the Kardar-Parisi-Zhang universality class (KPZ). When the manifold is discretized the problem is called First-Passage Percolation (FPP). The FPP model consists of an undirected lattice where a link-time t is assigned randomly to each edge between neighboring nodes. Link-times are independent and identically distributed positive random numbers with common cumulative distribution function F(t). The principal object of study in FPP are geodesics, i.e. the minimal-time paths joining pairs of nodes, and balls B(T) given by the set of nodes which can be reached from the origin in a time less than the passage time T. When the lattice structure is smooth, the ball B(T) grows linearly with T and has a non random asymptotic shape. However when the probability function is properly tuned to introduce a high level of noise in the link-time distribution, the shape of the ball becomes completely irregular. In a previous work we analyzed the statistical properties of arrival times to FPP in weak-disorder regime and we showed a crossover between Gaussian and KPZ universality, with the crossover length decreasing as the disorder grows. In this work we have gone one step further by considering the strong-disorder regime, where a new characteristic length appears below which the model displays bond-percolation universality class. In our work we provide a thorough characterization of the bond-percolation phase reproducing its critical exponents through a scaling analysis of the balls, for three different distributions: Weibull, Pareto and Log-Normal. The behavior of the new characteristic length can be explained from the properties of the link-time distribution. Moreover, the interplay between the correlation length intrinsic to percolation and this new characteristic length determines the crossover between initial percolation-like growth and asymptotic KPZ scaling. We also provide a first study of the behavior of this interplay. As long as the new characteristic length stays above the correlation length intrinsic to percolation, we were allowedto observe percolation-like growth in FPP models. But when the correlation length of percolation overtakes the FPP characteristic length, the model starts to develop KPZ scaling.

Weinberger Harvey

Effective Theories for Coupled Non-Equilibrium Condensates

Exciton-polaritons (EP) in microcavities present an exciting platform for studying novel out-of-equilibrium phenomena. Specifically, Bose-Einstein Condensates observed in EP systems are a promising arena for investigating the universal properties of the Kardar-Parisi-Zhang (KPZ) class. We consider a two-component spinor condensate that preserves the $U(1) \times U(1)$ symmetry. Through analytical methods, we demonstrate that the effective theory at low energy maps onto a set of coupled KPZ equations. Dynamical renormalization group analysis reveals an exotic phase diagram, offering additional tunability due to corrections in the KPZ non-linear intermode couplings. Alongside the analytical solutions from the RG flows, we conduct a numerical study of the parameter space. Specifically, we examine the distributions of the fluctuation fields and evaluate the corresponding dynamical exponents. This study can be further used to explain the behaviour of topological excitations in the condensate.

Yzewyn Michiel

Kardar-Parisi-Zhang scaling in Photon Bose-Einstein-condensates

Photon Bose-Einstein-condensates could provide a novel platform for the study of out-of-equilibrium systems exhibiting Kardar-Parisi-Zhang dynamics. Condensation is achieved in coupled optical cavities filled with dye molecules which ensure thermalization of the photons through repeated absorptions and reemissions. The unavoidable photon losses that are a consequence of the finite reflectivity of the cavity mirrors require continous laser pumping to achieve a driven-dissipative steady state. This system is described by a classical field model. We use both numerical and analytical approaches to investigate KPZ scaling. In particular, the most favorable system parameters are indentified for its experimental observation in 1D and 2D setups. For 2D systems an interplay between KPZ and BKT physics is expected.

Zündel Martina

Model A O(2) and beyond equilibrium

We study the theory of driven open bosonic systems in the semi-classical limit using the functional renormalization group. First, we investigate what is the most general action for this model being in equilibrium and which symmetry relations hold. We consider the flow of the effective action in equilibrium, and characterize the purely dissipative Model A O(2) Wilson Fisher (WF) fixed point in 3d. We give a quantitative result for the dynamical critical exponent z. It has been shown in 3d that the out-of-equilibrium action flows to the equilibrium Model A WF fixed point, in one spatial dimension, the KPZ fixed point will change this picture.

Świerczewski Stanislaw

The Gross-Pitaevskii equation vs the compact KPZ equation – mapping procedure and comparison of vortex number dynamics in a 2D exciton-polariton condensate

Bosonic quasiparticles - exciton-polaritons, which arise from the strong coupling of excitons and cavity photons, have emerged as a promising platform for the study of a wide range of quantum phenomena. Due to their hybrid nature, exciton-polaritons have an extremely low effective mass, allowing condensation even at relatively high temperatures. Interestingly, the fluctuations observed in the condensate phase obey the dynamics predicted by the KPZ (Kardar-Parisi-Zhang) equation [1,2]. Here we present the systematic procedure for mapping the governing equations of condensate dynamics onto the KPZ equation and the phase-supporting compact KPZ equation [3]. We first present a step-by-step description of the transformation from the generalized open-dissipative nonlinear Schrödinger equation to the compact KPZ equation in the one- and two-dimensional case. We then show the same procedure for the Open Dissipative Gross-Pitaevskii Equation (ODGPE) coupled to the excitonic reservoir rate equation. Finally, we attempt to compare the dynamics predicted by the compact KPZ equation [4] and the ODGPE by studying the evolution of the number of spatial vortices in a 2D exciton-polariton condensate.

[1] K. Deligiannis et al. Kardar-Parisi-Zhang universality in discrete two-dimensional driven-dissipative exciton-polariton condensates, Phys. Rev. Res. 4, 043207 (2002). [2] Ferrier, A., Zamora, A., Dagvadorj, G. & Szymańska, M. Searching for the Kardar–Parisi–Zhang phase in microcavity polaritons. Phys. Rev. B

105, 205301 (2022) [3] L. M. Sieberer, G. Wachtel, E. Altman, and S. Diehl Lattice duality for the compact Kardar-Parisi-Zhang equation Phys. Rev. B 94, 104521 (2016) [4] A. Zamora, N. Lad, and M. H. Szymanska Vortex Dynamics in a Compact Kardar-Parisi-Zhang System Phys. Rev. Lett. 125, 265701 (2020)

Chevalier Carole

Taxol-induced formation of tau islands on microtubules

A widely used method to observe microtubules (MTs) is to stabilize them with taxol molecules. However, a study of tau protein island formation shows that there is competition between tau and Taxol (Siahaan et al. 2022). It is clearly shown that tau islands compact the lattice of MT and tau preferentially attaches to the compacted lattice. In addition, taxol extends the lattice but doesn't prevent the lattice from being compacted by tau. We model the tau-taxol competition by a floor field on a one-dimensional lattice. The main idea is to introduce a floor field depending on the tau and taxol molecules adsorbed on the lattice. In this way, we can model the influence of tau and taxol on the dynamics by compacting and expanding the MT lattice. We show that tau-taxol competition can explain the formation of tau islands in the absence of particle-particle interactions other than steric hindrance.

Ray Tamoghna

Ergodic and chaotic properties in Tavis-Cummings dimer: quantum and classical limit

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