127th STATISTICAL MECHANICS CONFERENCE

Abstracts of Invited Talks

Nathan Andrei, Rutgers University
Quantum Zeno Effect in Noisy Integrable Quantum Circuits for Impurity Models
We theoretically study the open quantum system dynamics (in the Trotterized limit) of integrable quantum circuits in the presence of onsite dephasing noise with a spin-1/2 "impurity" interacting at the edge. Using a combination of Bethe Ansatz (BA) and exact diagonalization (ED), we study the dynamics of both the bulk and the impurity for the XXX (Heisenberg) and the XX qubit chains in the presence and absence of bulk noise. In the absence of noise, we show that the impurity exhibits two distinct phases, the bound mode phase where the impurity keeps oscillating in time, and the Kondo phase where it decays with Kondo time t_K . Turning on the bulk dephasing noise, we find for the two models that in the long-time limit in both regimes the quantum Zeno effect takes place where the dynamics of the impurity magnetization slows down as the noise strength γ increases. The impurity magnetization in the bound mode regime shows the opposite effect, decaying faster as the noise strength increases for short times ($t \ll 1/\gamma$). We show that the Zeno effect slowing down the impurity dynamics in the long-time limit is driven by the change in bulk dynamics from ballistic (KPZ) universality class in the XX (XXX) chain to diffusive dynamics in the presence of the noise.

Baruch Barzel – Bar-Ilan University
Navigating network dynamics
Universal network characteristics, such as the scale-free degree distribution and the small world phenomena, are the bread and butter of network science. But how do we translate such topological features into an understanding of the system's dynamic behavior: for instance, how does the small world structure impact the patterns of flow in the system? Or how does the presence of hubs affect the distribution of influence? These questions touch on the interplay between the network structure and its intrinsic nonlinear dynamics - a challenging combination that rarely succumbs to analytical treatment. It is, therefore, no surprise that, upon observation, network dynamics seem diverse and unpredictable - a *zoo* of diverging timescales, propagation patterns, spreading dynamics and critical transitions. Hence, it seems that the concept of *universality*, which ignited the field of network science at the turn of the century - this concept breaks down when it comes to dynamics, as diversity wins over universality. How, then, can we understand, predict and influence the network's actual behavior? Our research over the past decade offers an optimistic view on this question, by exposing the deep universality that characterizes network dynamics. This universality allows a systematic translation of structure into dynamics, from state transitions, to propagation timescales, localization, and spectral analysis. It allows us to expose the relevant parameters that actually control the system's behavior, and - ultimately - steer the system towards desired states with minimal intervention.

Giulio Biroli, Ecole Normale Supérieure
Statistical Physics and Generative AI
Generative AI represents a groundbreaking development within the broader "Machine Learning Revolution," significantly influencing technology, science, and society. In this seminar, I will first present "diffusion models," which are currently the state-of-the-art machine learning methods 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 initiate from a simple white noise input and evolve it 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 characterize 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.

Roberto Car, Princeton University
Thermal and quenched disorder in ferroelectrics
Developments in machine learning and deep neural network representations make possible to study the ferroelectric phase transition, beyond mean field and reduced models, with molecular dynamics (MD) simulations of ab-initio quality. I will illustrate the approach with recent studies of two perovskite materials at ambient pressure: lead titanate (PTO), a prototypical ferroelectric crystal, and lead magnesium niobate (PMN), a chemically disordered perovskite that exhibits glassy behavior, called relaxor, and bears similarities with spin and fragile structural glasses. In both cases, simulations predict thermodynamic and dielectric properties in good agreement with experiment and provide fresh insight into the microscopic mechanisms of the transition. In PTO, a unified picture emerges that reconciles diffraction and optical experiments. In PMN, the simulations reveal quasi-localized vibrational modes that underlie universal glassy features.

Paul Chaikin, NYU
2D Crystallization and Melting far from equilibrium
Random Organization is a simple dynamical model where overlapping particles are considered active and active particles are given a random kick, a displacement of maximum size epsilon, each cycle. The system evolves until there are no overlaps, an absorbing state. There is a dynamical transition as a function of epsilon – above a critical epsilon the system is active and evolves forever. When repulsion is added to a fraction of the kicks, we have the BRO model, and we observe a variety of ordering phenomena both at the critical epsilon and in the active state. In 2D disks crystalize at criticality. But the crystalline state persists in the active phase to arbitrary density. Melting occurs when the kick size increases and there is a first order transition to an active disordered liquid. A similar reentrant transition occurs when BRO is generalized to a set of needles that pivot about their centers fixed on a square lattice. On increasing the rotational kick size the needles go from an absorbing disordered phase to an active ordered checkerboard phase to a disordered active phase. We are discovering new forms of order and dynamic phase transitions that result from random organization.

Claudio Chamon, Boston University
Circuit complexity and functionality: a thermodynamic perspective
We explore a link between complexity and physics for circuits of given functionality. Taking advantage of the connection between circuit counting problems and the derivation of ensembles in statistical mechanics, we tie the entropy of circuits of a given functionality and fixed number of gates to circuit complexity. We use thermodynamic relations to connect the quantity analogous to the equilibrium temperature to the exponent describing the exponential growth of the number of distinct functionalities as a function of complexity. This connection is intimately related to the finite compressibility of typical circuits. Finally, we use the thermodynamic approach to formulate a framework for the obfuscation of programs of arbitrary length -- an important problem in cryptography -- as thermalization through recursive mixing of neighboring sections of a circuit, which can viewed as the mixing of two containers with ``gases of gates". This recursive process equilibrates the average complexity and leads to the saturation of the circuit entropy, while preserving functionality of the overall circuit. The thermodynamic arguments hinge on ergodicity in the space of circuits which we conjecture is limited to disconnected ergodic sectors due to fragmentation. The notion of fragmentation has important implications for the problem of circuit obfuscation as it implies that there are circuits with same size and functionality that cannot be connected via local moves. Furthermore, we argue that fragmentation is unavoidable unless the complexity classes NP and coNP coincide.

Patrick Charbonneau, Duke University
Jamming the Random Lorentz Gas
Deterministic optimization algorithms unequivocally partition a complex energy landscape in inherent structures (ISs) and their respective basins of attraction. But can one define these basins in a purely geometric model? This is the precise question that arises when jamming hard spheres. In this talk, I introduce a geometric class of gradient descent-like algorithms, which is used to study a system in the hard-sphere universality class, the random Lorentz gas. The resulting IS statistics is found to be strictly inherited from Poisson-Voronoi tessellations. The landscape roughness is further found to give rise to a hierarchical organization of ISs which various algorithms distinctly explore. For instance, greedy and reluctant schemes tend to favor ISs of markedly

different densities. The resulting ISs nevertheless robustly exhibit a universal force distribution, thus confirming the geometric nature of the jamming universality class.

Sean P. Cornelius, Toronto Metropolitan University
Catch-22s of Reservoir Computing
Reservoir Computing (RC) is a simple and popular machine learning framework for learning and forecasting the behavior of unknown dynamical systems. Despite RC's remarkable successes—for example, reconstructing the geometry of chaotic attractors —much remains unknown about its ability to learn the behavior of large nonlinear systems from finite ensembles of training data. Here, I will show how there exist commonly-studied systems for which leading RC frameworks fail to learn unless key information about the dynamics in question is already known. First, I will show how traditional RC models (echo state networks) can suffer from a "learnability transition"—failing to reproduce the correct dynamics from a given initial condition unless initialized with nearly the entire transient trajectory of the real system. I next turn to Next-Generation Reservoir Computing (NGRC), a more recent variant. Though NGRC mitigates some of this reliance on "warm-up" data, I show that it suffers from its own proverbial Catch-22. When NGRC models incorporate the exact nonlinearities appearing in the underlying dynamical laws, they can reliably reconstruct intricate and high-dimensional phase space geometry, even with very sparse training data (e.g., a single example trajectory). Yet, any features short of these exact nonlinearities result in predictions no better than chance. These findings highlight the challenges faced by RC and other statistical forecasting methods in serving as "digital twins" of physical systems.

Eduardo Fradkin, University of Illinois
An exactly solvable model of pinned incommensurate charge density waves in two dimensions
The problem of randomly pinned incommensurate charge-density waves (ICDW) in two dimensions is a long poorly understood problem. A well-known argument by Imry and Ma (and a similar more specific argument by Larkin) implies that there is no long range ICDW order below four dimensions. In this talk I will present results obtained with Matthew O'Brien for a large N limit which has a phase transition (of the Berezhinskii-Kosterlitz-Thouless type) in the absence of disorder and with a random field that coupes to the CDW order parameter. A peculiarity of the model is that in order to have a BKT transition in the clean limit the order parameter is actually a composite of two fluctuating fields. I will discuss the clean and "dirty" cases both in the large N limit and to order 1/N. In the disordered cat we obtain expressions for teh correctors in teh string and weak disorder regimes. I will also comment briefly on the effects of quantum fluctuations. This theory is of interest for other problems involving composite order parameters with and without random fields.

Andrea Gambassi, SISSA - International School for Advanced Studies
Casimir-like forces in flocking active matter
Confining in space the correlated fluctuations of statistical systems in thermal equilibrium is known to result into long-range effective forces on the spatial boundaries, which are the classical analogue of the celebrated Casimir effect of QED. In this talk I show that Casimir-like forces emerge also in the non-equilibrium context provided by flocking active matter.
In particular, in two spatial dimensions, I consider a system of interacting and aligning self-propelled particles in the bulk phase — known as flocking phase — in which they exhibit a collective motion. In the presence of a transverse confinement by parallel walls, a Casimir-like force emerges on the boundaries. This force decays algebraically and slowly upon increasing the separation between the walls, displaying a certain degree of universality. The numerical evidence can be rationalized via a linearized hydrodynamic approach which, however, leaves some open questions.

Subhro Ghosh, National University of Singapore
Fractal Gaussian Networks: A sparse random graph model based on Gaussian Multiplicative Chaos
We propose a novel stochastic network model, called Fractal Gaussian Network (FGN), that embodies well-defined and analytically tractable fractal structures. Such fractal structures have been empirically observed in diverse applications. FGNs interpolate between the popular purely random geometric graphs (a.k.a. the Poisson Boolean network), and random graphs with

increasingly fractal behavior, forming a parametric family of sparse random geometric graphs that are parametrized by a fractality parameter which governs the strength of the fractal structure. FGNs are driven by the latent spatial geometry of Gaussian Multiplicative Chaos (GMC), a canonical model of fractality in mathematical physics.
We investigate the asymptotics of various small motif counts in the FGN, the natural question of detecting fractality, the problem of parameter estimation and the fundamental properties of the FGN as a random graph model. We substantiate our model with phenomenological analysis of the FGN in the context of available scientific literature for fractality in networks, including applications to real-world massive network data.

Gourab Ghoshal, University of Rochester
Meaning from Matter: Towards a theory of semantic information
Living systems continuously interact with their environments by gathering, processing, and acting upon external stimuli. This dynamic exchange generates new correlations while diminishing others. As observers, we can quantify these correlations using tools from information theory. However, these tools leave an essential question unanswered: what do these correlations mean to the system that manipulates them? We propose that the meaning of a correlation is found in its utility, specifically in relation to the system's viability. Viability, we argue, is the fundamental intrinsic measure of utility for biotic systems. Thus, the semantic content of information is defined by its necessity in maintaining the system's viability. We trace the evolution of this concept, from early efforts to formalize a Semantic Information Theory (SIT) to more recent operationalizations. We present key results from studies on resource-gathering populations, and planetary biosphere models, offering insights into how semantic information contributes to the viability of living systems.

Thierry Giamarchi, Université de Genève
One-dimensional disordered bosons, Bose glass and quantum transport
Disorder has a profound effect on the properties of quantum particles and in the case of on dimensional interacting bosons leads to the existence of a localized phase, known as the Bose glass phase. Understanding the properties of such a phase, in particular at finite temperature remains a considerable challenge. I will discuss in this talk the various methods, ranging from renormalization group, replica variational methods and numerical approaches that allow to investigate such physics, in particular to obtain the transport properties of such systems, at finite frequency and temperature. I will also discuss the connection with recent experiments done for disordered or quasi-periodic potentials in cold atomic gases.

Michelle Girvan, University of Maryland
Self-organization of excitatory-inhibitory balance facilitates robust performance in reservoir computers
Hyperparameter tuning is crucial for optimizing machine learning architectures, including Reservoir Computing (RC), known for its low computational cost and versatility across a range of practical applications. While randomly generated reservoirs are computationally efficient, they pose challenges in task-specific parameter optimization. This study proposes a novel approach inspired by the balanced excitatory-inhibitory (E-I) state observed in biological neural networks to address this issue. By emphasizing the stabilizing effect of inhibition, we demonstrate the robustness of RC systems within balanced to slightly over-inhibited states. We introduce an unsupervised local adaptation rule aimed at tuning the network to a specific firing rate setpoint, leveraging feedback from its prior state to mitigate local imbalances resulting from global hyperparameter optimization. Additionally, we present a one-step adaptation rule applicable when explicit network connectivity knowledge is available. To simplify this method, we emulate natural heterogeneity in neuronal firing rates, eliminating the need for meticulous firing rate setpoint fine-tuning. Empirical validation showcases the efficacy of our approach in driving the system to a locally balanced state, thereby enhancing RC performance across various practical scenarios. This study advances the understanding and application of RC, bridging insights from biological neural networks to achieve superior machine learning performance.

Giuseppe Gonnella, University of Bari and INFN, sez. di Bari
Dynamics of Active Brownian Particles in two dimensions: macro and microphase separation, cluster diffusion, particle geometry effects.
Active matter systems are non-equilibrium systems in which individual particles, biological or artificial, continually consume internal energy to self-propel, breaking time-reversal symmetry at a local scale and in a sustained way. Their non-equilibrium nature allows a variety of intriguing phenomena to appear, for example, the phase separation in a dense and dilute phase in the complete absence of attractive interactions, called motility induced phase separation (MIPS). We would like to illustrate peculiar features of MIPS in a paradigmatic model of active matter, the Active Brownian Particles (ABPs) in two spatial dimensions. Even though MIPS preserves many aspects of an equilibrium phase separation, the physics at play is more complex, leading to new phenomena. We explain the growth exponent z =1/3 in terms of an aggregation-condensation mechanism, also taking into account the fractal geometry of aggregates and the diffusion properties of single clusters. We found anomalous dependence of the cluster diffusion coefficient on the cluster mass, since it decreases as the inverse of the square root of mass but still increasing with the square of the Peclet number as in the case of single particles. Moreover, on top of this ordinary equilibrium-like coarsening, we found evidence of another ordering mechanism, i.e., the micro-phase separation of the dense phase into hexatic domains and vapour bubbles. Finally, we show that changing the geometry of active particles from disks to dumbbells has enormous effects on the dynamics of MIPS, both affecting the value of the growth exponent and the motion of single clusters that acquire evident ballistic behavior.

Mehran Kardar, MIT
Glass of directed polymers
Eigenvalues of a class of (product of tridiagonal) random matrices are relevant to computing free energies of a collection of non-intersecting directed paths in a random medium. Numerical and analytical methods are employed to characterizes statistics of these eigenvalues**.**

Avraham Klein, Ariel University
How viscous bubbles collapse: non-inertial hydrodynamics in curved geometries
A traditional and powerful method for studying the behavior of thin liquid sheets is to harness the analogy to elastic media. However, in rapidly evolving viscous films this analogy is broken. I will show that for this case, the film evolves through a geometrically nonlinear dynamics, where the driving mechanism is the flow of curvature, whose behavior has remained almost unexplored. I will demonstrate the dynamics by studying a decades old puzzle: the collapse of a rapidly depressurized bubble. I will show that the collapse is driven by a dynamically triggered topological instability, which is forbidden in the elastic analog and creates a moving "front" in the liquid film. In turn, the propagating front triggers a symmetry-breaking instability to wrinkle formation. I will discuss why these dynamics should appear in additional systems as well, such as viscous electron flows in graphene.

István A. Kovács, Northwestern University
How can we learn from noisy, incomplete or even biased network data?
Network theory is a powerful tool to describe and study complex systems, and there has been tremendous progress in mapping large networks in all areas of science, leading to a growing library of complex network datasets. Yet, inherent limitations of the measurements lead to errors, biases and missing data and the situation likely gets worse as datasets get larger. Therefore, as in any other quantitative field, it would be of paramount importance to characterize the uncertainty of our maps. Yet, unlike a simple error bar for a single valued quantity, the uncertainty of a network structure itself is expected to have a complex, network structure, requiring novel methodologies. Focusing on biological networks, we show how such detailed information can help us to solve key problems, such as link prediction, noise reduction or functional annotation. I will close by discussing our recent results on assessing and reducing biases in network data. To conclude, putting error bars on our network maps is not a nuisance but an essential ingredient in addressing long standing problems in the field.

Jorge Kurchan, Laboratoire de Physique, Ecole Normale Superieure, Paris
Time reparametrization softness resolves the dilemma of glass dynamics
Time reparametrization softness is the property that a system's dynamics may change dramatically their pace under a weak appropriate perturbation. It has long been recognized as central to the glass phenomenology (although seldom with that name), and more recently as a mechanism whereby a `gravity'-like low energy limit arises in some quantum systems, such as the SYK (Sachdev Ye Kitaev) model.
It has now been recognized as resolving the dilemma of whether glasses are purely dynamic, or the consequence of static thermodynamic features. The answer is `both'.

Demian Levis, University of Barcelona
Out-of-equilibrium phenomena in self-driven spin models: synchronisation, flocking and all that
Out-of-equilibrium systems can self-organise in a variety of states lifting the constraints imposed by thermal equilibrium. Among these out-of-equilibrium systems, is active matter, made of 'biomimetic' units that break equilibrium at the level of each single constituent. In this talk I'll consider spins in the plane, driven out-of-equilibrium at the level of each spin and address the question of how different type of drives, affect the collective behaviour of well-known models. I'll start by considering rotors (XY spins) in a square lattice and thus the fate of the Kosterlitz-Thouless phase transition scenario in the presence of (i) self-spinning at a given intrinsic frequency and (ii) non-reciprocal couplings. The first case corresponds to the problem of synchronisation of locally coupled Kuramoto oscillators, while the second is related to the problem of flocking (or the emergence of collective motion). If time allows, I'll also discuss how non-reciprocity affects the dynamics of mean-field spin-glasses and under which conditions one can find a non-reciprocal glassy state.

Andrea Liu, University of Pennsylvania
Many more is different
In 1972 Phil Andersen articulated the motto of condensed matter physics as "More is different." However, for most condensed matter systems many more is quite similar to more. Here I argue for a class of condensed matter, "adaptive matter," in which many more is different. The ultimate example of adaptive matter is the brain, whose cognitive capabilities increase as size increases from 302 neurons (C. Elegans) to a million neurons (honeybees) to 100 billion neurons (humans). I propose that adaptive matter provides a unifying conceptual framework for understanding not only a wide range of living systems responsible for function, but also physical systems capable of being trained to develop special collective behaviors.

Yang-Yu Liu, Harvard University
Deep Reinforcement Learning for Combinatorial Optimization
Traditional algorithms for solving combinatorial optimization problems often rely on hand-crafted heuristics that sequentially construct solutions. These heuristics, typically designed by domain experts, can be suboptimal due to the complexity of the problems. Reinforcement learning (RL) offers a promising alternative by automating the search for these heuristics, enabling an agent to learn decision-making through trial and error. Deep reinforcement learning (DRL), a combination of RL and deep learning, allows agents to directly process unstructured input data, eliminating the need for manually defined state spaces. DRL can handle large datasets and determine optimal actions to maximize a specific objective. In this talk, I will introduce two DRL-based methods we recently developed, FINDER [1] and DIRAC [2], to solve two classic combinatorial optimization problems: the network dismantling problem and the spin glass ground state problem. Extensive experiments across various settings show that FINDER significantly outperforms existing methods in terms of solution quality and is several orders of magnitude faster for large networks. FINDER opens new possibilities for using DRL to uncover the organizing principles of complex networks, helping to design more robust networks against attacks and failures. DIRAC, on the other hand, demonstrates superior scalability compared to other methods and can enhance any thermal annealing technique. Extensive calculations on 2D, 3D, and 4D Edwards-Anderson spin glass instances showcase DIRAC's strong performance. Furthermore, DIRAC's use of the gauge transformation technique establishes a deep connection between statistical physics and artificial intelligence. This approach creates a promising path for reinforcement learning models to explore vast

configuration spaces, which could be invaluable for solving many other challenging combinatorial optimization problems.

Gustavo Lozano, Universidad de Buenos Aires, Argentina
Generalised Gibbs ensemble for spherically constrained harmonic models
We build and analytically calculate the Generalised Gibbs Ensemble partition function of the integrable Soft Neumann Model. This is the model of a classical particle which is constrained to move, on average over the initial conditions, on an N dimensional sphere, and feels the effect of anisotropic harmonic potentials. We derive all relevant averaged static observables in the (thermodynamic) $N \to \infty$limit. We compare them to their long term dynamic averages finding excellent agreement in all phases of a non-trivial phase diagram determined by the characteristics of the initial conditions and the amount of energy injected or extracted in an instantaneous quench.

Marcelo Magnasco, Rockefeller University
Dynamic control of traveling waves in recurrent neural networks
Training of artificial recurrent neural networks for tasks requiring long memory times often results in the emergence of traveling waves that implement the actual memory; traveling waves are also associated with the appearance of eigenvalues with unit absolute value. I will present explicit models for encoding and decoding of information into waves, and will demonstrate how the particular dynamical feature of unitary dynamics, marginal stability and emergence of center manifolds, allows broad control over the propagation paths and dynamics of such waves. We show explicitly how to harness such dynamics to solve a classical problem, the detection of connectedness, by implementing a wave-based floodfill algorithm.

Vieri Mastropietro, Universita' di Roma La Sapienza
Fine structure constant, anomalous magnetic factor and transport coefficients
The fine structure constant can be determined by the electron magnetic moment, the Hall conductivity or the optical conductivity of graphene. The precision of the measurements offers a very stringent test for the theory, in particular for the Standard Model. The magnetic factor is determined by the truncation of the (divergent) series expansion at a certain order, and the expectation is that the error introduced is of the order of truncation; in the case of the transport coefficients instead the higher orders contributions are expected to be exactly vanishing. We present some rigorous results based on Renormalization Group proving the validity of such properties in a finite range of parameters. The irrelevant terms generated by the lattice play a crucial role in the cancellations ensuring such results and cannot be neglected.

Stephen Miller, Rutgers University
Sandpile models and the security of post-quantum cryptography.
Perhaps the most fundamental problem in the Geometry of Numbers, dating back to Minkowski in the late 19th century, is to find short vectors in lattices. This problem has only grown in interest, with its connections to sphere packing and algorithmic number theory. In particular, many if not most of the leading Post-Quantum Cryptosystem candidates depend on the algorithmic difficulty of finding short vectors in particular lattices. I'll discuss a statistical approach to understand the most well-known algorithm for this purpose (the LLL algorithm), and some hints as to what Self-Organized Criticality sandpile models have to say about why these systems might be weaker against LLL than previously thought. (Joint work with Nick Genise and Seungki Kim.)

Adilson Motter, Northwestern University
Converse Symmetry Breaking
Symmetry breaking, where a system's symmetry is not inherited by its stable states, drives numerous effects in physics. This talk will discuss *converse symmetry breaking*, a striking emergent phenomenon where stable states can be symmetric only when the system itself is not. Through theoretical predictions and experimental demonstrations, I will illustrate its relevance and applications to diverse network problems. Additionally, I will discuss how this phenomenon challenges conventional assumptions, revealing that behavioral homogeneity often necessitates underlying system heterogeneities. Ultimately, I hope to convey that our study of network

systems not only builds on statistical and nonlinear physics but also contributes to foundational discoveries in these fields.

Frank Scheffold, University of Fribourg, Switzerland
The Impact of Hyperuniformity and Bounded Hole Sizes on Bandgap Formation and Light Localisation
The concept of hyperuniformity, introduced by Torquato and Stillinger at the beginning of the century, has opened up a new perspective on disordered yet highly correlated structures, with far-reaching implications for material design, particularly in optics and optical metamaterials. Stealthy hyperuniformity expanded on these ideas in optics, showing that a certain class of amorphous systems could be fully transparent. In this talk, I will present experimental and numerical studies on light transport in hyperuniform networks in two and three dimensions. I will discuss the role of statistical fluctuations in the formation of bandgaps and localized regimes. Zhang, Stillinger, and Torquato argued that another structural property is essential for forming a bandgap: uniformity and the resulting bounded hole sizes (empty regions) which prevent deep penetration of unscattered photons into the bulk of the material. Such structural 'rigidity' confers novel physical properties to disordered systems, including the desired bandgap. Qualitatively, stealthy hyperuniformity can provide both mechanisms. Stealthiness implies bounded hole sizes and suppresses scattering at small angles while enhancing backscattering through short-range order. I will speculate about the role of these statistical signatures in photonics when combined with the local network topology.

Paul Steinhardt, Princeton University
The search for quasicrystals: here, there, and everywhere
The talk will first briefly discuss the subtle relation between quasicrystals and hyperuniformity. Then it will describe current progress in searching for quasicrystals in unexpected places outside the laboratory.

Zoltan Toroczkai, University of Notre Dame
From networks to mechanisms: degree preserving network growth
Modeling real-world networks is a key focus area of Network Science. I will first provide a brief overview into the state-of-the-art of network modeling, then turn to the discussion of network evolution models. In current network-evolution models, the degree of each node varies or grows arbitrarily, yet there are many networks for which a different description is required. In some networks, node degree saturates, such as the number of active contacts of a person, and in some it is fixed, such as the valence of an atom in a molecule. I will introduce a novel family of network growth processes that preserve node degree (DPG), resulting in structures substantially different from those reported previously. We demonstrated that, despite it being an NP (non-deterministic polynomial time)-hard problem in general, the exact structure of most real-world networks can be generated from degree-preserving growth. We also show that this process can create scale-free networks with arbitrary exponents, however, without preferential attachment. If preferential attachment is an effective rich-gets-richer mechanism applied to connectivity formation, then degree-preserving growth is a type of "tinkering" mechanism, a property observed in many real systems, e.g., by the Nobel Laurate F. Jacob in: "Evolution and Tinkering", Science, 196, 1161 (1977)). Finally, I will present applications of DPG to epidemics control via network immunization, viral marketing, knowledge dissemination, the design of molecular isomers with desired properties and to a problem in number theory.

Thomas Truskett, University of Texas
Illuminating Disorder: Optical Properties of Complex Plasmonic Assemblies
The many-body optical response of disordered plasmonic nanoparticle assemblies can be continuously tuned through the structural organization and composition of their colloidal building blocks. However, progress in the design and experimental realization of these materials has been limited by challenges associated with controlling and characterizing disordered assemblies and predicting their optical properties. In this talk, I'll discuss experimental studies of the assembly of disordered optical materials, such as doped metal oxide nanocrystal gel networks, informed by electromagnetic computations on large-scale simulated structures. The simulations illustrate how disordered structure modulates optical properties, and how optical measurements can help characterize nanoscale structure.

Alessandro Vespignani, Northeastern University
Modeling the Unseen: From Reaction-Diffusion Systems to Pandemic Propagation
The propagation of infectious diseases is a complex phenomenon shaped by the interplay between biological dynamics and human interactions. Reaction-diffusion (RD) systems serve as a foundational framework for modeling the spatial and temporal spread of epidemics, capturing the local disease dynamics and spatial dispersal processes. A key element for the understanding of epidemic diffusion across scales is the integration of RD models with high-resolution network data. I will present how network-informed models enable high-resolution modeling of global and local epidemic dynamics. Real-world applications from recent pandemics will provide examples of the central role of network-augmented approaches in defining analytic tools for managing and mitigating the impact of epidemics and supporting decision-making during public health crises.

Dashun Wang, Northwestern University
Understanding the punctuated dynamics of scientific and technological frontiers
The frontiers of science and technology are not only essential for advancing knowledge but also for driving human progress and rising standards of living, with implications ranging from improved health outcomes to strengthened workforce competitiveness. The evolution of these frontiers often follows punctuated dynamics, suggesting a high degree of inherent randomness. Despite its critical importance, our understanding of the basic principles governing these punctuated dynamics remains limited. Here we collect novel datasets tracking the evolution of frontiers across six diverse domains, ranging from artificial intelligence algorithms to solving NP-hard problems and from biomedical challenges to physical wheel-building experiments. Analyzing over 6.1 million solutions to 5.8 thousand tasks, we uncover three fundamental patterns: first, the evolution of frontiers is characterized by rapid progression in establishing new frontiers mixed with long periods of stasis; second, bursts of new frontiers show a high degree of temporal clustering, leading to short-term predictability and long-term unpredictability; third, despite the differences in the scale, scope, and definition of the six settings, the empirical patterns are remarkably consistent across the diverse domains we study. We show that these patterns fundamentally challenge existing theoretical frameworks from complex systems, record statistics, economics of innovation, and cultural evolution. Recognizing that existing models do not account for the types of innovations driving progress, we propose a novel one-parameter model that explicitly differentiates between radical and incremental innovations. We analytically solve the model and find that, despite its simplicity, the model is strikingly capable of explaining all empirical observations we observe. Overall, these results not only further our quantitative understanding of the punctuated frontier dynamics but also highlight the importance of integrating radical and incremental approaches to catalyze and sustain progress.

Haina Wang, University of Pennsylvania
Designer pair statistics of disordered many-particle systems with novel properties
The knowledge of exact analytical functional forms for the pair correlation function $g\_2(r)$ and its corresponding structure factor $S(k)$ of disordered many-particle systems is limited. For fundamental and practical reasons, it is highly desirable to add to the existing database of analytical functional forms for such pair statistics. Here, we design a plethora of such pair functions in direct and Fourier spaces across the first three Euclidean space dimensions that are realizable by diverse many-particle systems with varying degrees of correlated disorder across length scales, spanning a wide spectrum of hyperuniform, typical nonhyperuniform, and antihyperuniform ones. This is accomplished by utilizing an efficient inverse algorithm that determines equilibrium states with up to pair interactions at positive temperatures that precisely match targeted forms for both $g\_2(r)$ and $S(k)$. Among other results, we realize an example with the strongest hyperuniform property among known positive-temperature equilibrium states, critical-point systems (implying unusual 1D systems with phase transitions) that are not in the Ising universality class, systems that attain self-similar pair statistics under Fourier transformation, and an experimentally feasible polymer model. We show that our pair functions enable one to achieve many-particle systems with a wide range of translational order and self-diffusion coefficients , which are inversely related to one another. One can design other realizable pair statistics via linear combinations of our functions or by applying our inverse procedure to other desirable functional forms.

Our approach facilitates the inverse design of materials with desirable physical and chemical properties by tuning their pair statistics.