tion in the upper mantle and the overlying crust and its transport and storage in Earth's crust beneath the Yellowstone volcanic field. This type of modeling can find the best fit from input data that span a broad range of spatial scales and physical parameters. Thus, the approach allows for a more robust interpretation of past events and offers a better model of future events. The results show that intruding material from the upper mantle produced primary melts (molten material that has the same composition as the source material that it melted from) from the combination of excess heat and decompression (a process in which reduced pressure can lead to melting) induced by tectonic forces. The proposed mechanism required little to no hot materials sourced from a mantle plume. In addition, the nearby Wyoming Craton, which is a dense ancient rock that extends under Earth's crust on the hot upper mantle (asthenosphere), promotes delamination of the oldest part of the lithosphere and enhances local melting of rocks.

The study of Cao *et al* predicts bifurcation (melt traveling in two split directions as it rises to Earth's surface) of the upwelling melts in the crust, which is consistent with previous magnetotelluric imaging (*5*). This implies that a volcano-free segment of the Eastern Snake River Plain, which stretches southwest from the Yellowstone volcanic field, could force upwelling melt to migrate in different paths—toward the southwest of the Snake River Plain and northeast toward Yellowstone. The basaltic melt that migrates toward Yellowstone stops its vertical movement when the density of the basaltic melt becomes greater than that of the surrounding crustal silicic rocks, which it is intruding in the lower crust. This creates bodies of basaltic partial melt in the lower crust (*1*) above which ongoing extension of the crust allows for incremental injection of basaltic material into the middle-to-upper crust. The resulting injected basaltic melt eventually differentiates and forms the body of silicic partial melt in the upper crust (*1*–*4*) that feeds the surficial eruptions that have occurred in the Yellowstone region.

The findings of Cao *et al.* suggest the existence of a translithospheric magma plumbing system—a vertical network of magma channels and reservoirs that transports magma from the asthenosphere to the surface—beneath the Yellowstone volcanic field. This implies that lithospheric tectonics plays an essential role in producing asthenosphere-sourced melts in the Yellowstone volcanic region with little to no contribution from a mantle plume, supporting the nonplume hypothesis. Cao *et al.* provide important new constraints for melt formation in Yellowstone that could help to better understand the physics of the magmatic system at depth. Beyond the Yellowstone volcanic system, geodynamic modeling can be applied to other volcanic systems around the world to reveal subsurface processes that give rise to melt generation, mobility, and eruptions on the surface. This information is essential for assessing hazards and associated risks of large and active volcanic systems. ☐

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PHYSICS

A universal law for random fluctuations

A two-dimensional array of quasiparticles confirms a universal scaling theory for nonequilibrium systems

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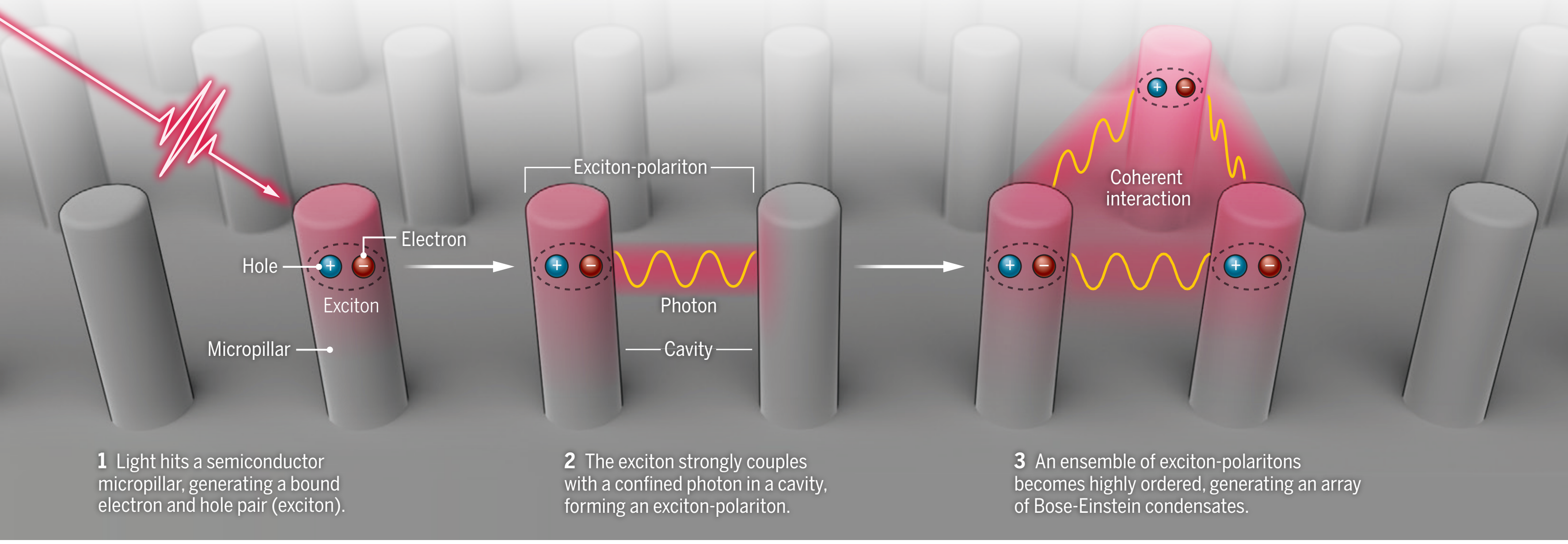
Nonequilibrium random behaviors, such as the growth of bacterial colonies and propagation of wildfire fronts, are difficult to predict because of the inherent uncertainty of complex systems in which many entities interact with each other. The Kardar-Parisi-Zhang (KPZ) differential equation (*1*) models the random growth of interfaces in two-dimensional (2D) crystal surfaces, describing how the roughness of an interface changes with respect to time and spatial size. The theory is presumed to provide a universal framework for describing the fluctuation dynamics of a wide range of nonequilibrium systems in different dimensions (*2*–*4*). However, experimental validation of the theory is scarce and often demonstrated in 1D systems. On page XXX of this issue, Widmann *et al.* (*5*) report an observation of the KPZ theory in a 2D platform that is different from a crystal surface, proving that diverse physical systems can share fundamentally similar predictable behavior.

When atoms with an even total number of protons, neutrons, and electrons (bosonic atoms) are cooled to near absolute zero (0 K), they merge into a highly organized state that exhibits wavelike behavior—a Bose-Einstein condensate. These condensates provide experimental platforms for studying quantum mechanical behaviors, which deviate from a classical system, by amplifying microscopic quantum phenomena to an observable signal on a macroscopic level. They also exhibit quantum fluctuations, which manifest themselves in stochastic variations of their macroscopic properties, such as phase and wavelength. This provides a suitable environment for experimentally simulating KPZ theory. However, Bose-Einstein condensates of bosonic atoms may only exist at extremely low temperature, which is challenging to experimentally implement. Exciton-polaritons, which are part-light–part-matter quasiparticles that arise in an array of semiconductor micropillars (*6*), have properties that are similar to those of bosonic atoms and can undergo Bose-Einstein condensation. They offer room-temperature operation and are highly scalable. KPZ theory has been confirmed in a 1D chain of exciton-polariton condensates (*7*). However, evidence of the theory in a 2D exciton-polariton system has been elusive.

Widmann *et al.* now demonstrate KPZ scaling in a 2D array of exciton-polariton condensates that emerge in an array of semiconductor micropillars. Upon light irradiation, confined photons (light particles) in each microcavity between pillars coupled strongly with excitons (electrically neutral pairs of positively and negatively charged quasiparticles) that are also generated in each pillar. Spontaneous synchronization of the phases and frequencies of excitons and photons formed coherent flows of exciton-polariton condensates that could be visualized experimentally through optical spectra.



A test bed for random behaviors

A macroscopic array of exciton-polariton condensates emits spatially ordered, coherent light. Random fluctuations arise because exciton-polaritons condensates are short-lived, perturbing the coherent phase pattern that can be experimentally observed. This offers a two-dimensional platform for proving the Kardar-Parisi-Zhang theory, which describes a universal scaling of non-equilibrium, random behaviors with time and spatial size.

1 Light hits a semiconductor micropillar, generating a bound electron and hole pair (exciton).

2 The exciton strongly couples with a confined photon in a cavity, forming an exciton-polariton.

3 An ensemble of exciton-polaritons becomes highly ordered, generating an array of Bose-Einstein condensates.

GRAPHIC: N. BURGESS/SCIENCE

A periodic array of exciton-polariton condensates may be considered as a resonant 2D photonic crystal that emits light characterized by spatially extended periodic phase patterns. Fluctuations of polariton phase and density may perturb and modify these phase patterns. The fluctuations are inevitable because exciton-polaritons are short-lived and readily lost by photon emission. When incoherent excitons (that lost their phase coherence with the incident light) are injected into the pillar array using an external laser, they produce an external reservoir that continuously replenishes new excitons to sustain exciton-polariton condensates. This creates a continuous gain and loss of polaritons within the array, which causes the condensates to flow from one location to another across the array of pillars. The spatial fluctuation of the condensates is similar to the classical Huygens clock effect—the phenomenon where two pendulum clocks moving in opposite directions on the same support synchronize over time to minimize the energy loss (*8*). The phases and frequencies of hundreds of exciton-polariton condensates become coherent to optimize the gain-to-loss ratio of polaritons but still cause deviation of the symmetry of the phase pattern of light emitted by the structure from the lattice symmetry of the micropillar array. This introduces nonlinear disorders in the 2D system that are suitable for testing the KPZ theory.

The time- and space-resolved phase correlations of exciton-polaritons in a lattice of semiconductor micropillars provide valuable information on the fluctuation dynamics of the system. In particular, the phase correlation function indicates the spatial or temporal degree of ordering within a system. Widmann *et al.* measured the laser power–dependent phase correlation function of exciton-polariton condensates in two different lattice configurations: triangular and quadratic. In both cases, the correlation function aligned with KPZ scaling in a narrow range of laser power that is slightly above the threshold of Bose-Einstein condensation of exciton-polaritons. Under this condition, the balance between gain and loss of polaritons can be fulfilled by a variety of phase patterns, which implies that the system is truly unpredictable. This observation can be considered as a manifestation of KPZ universality in a 2D platform.

Widmann *et al.* also show substantial deviation of the exciton-polariton condensates' behavior from the equilibrium scaling law, which is described by the Berezinskii-Kosterlitz-Thouless theory (*9*, *10*). The KPZ scaling appeared to prevail over the equilibrium model, implying that the nonequilibrium dynamics of the exciton-polariton condensates could be governed by the Nambu-Goldstone modes (*11*), which are excited energy states populated by quantum fluctuations that exhibit phase patterns different from the ground state. This is observed at low pump power close to the threshold of Bose-Einstein condensation. By contrast, at high pump power, the phase pattern that corresponds to the lowest energy state is densely populated within exciton-polaritons and dominates over other scarce phase patterns. In this regime, the system is expected to return to the equilibrium scaling at the laser power that is beyond the Bose-Einstein condensation threshold.

The observations of Widmann *et al.* may imply that material and optical systems of very different natures can be described by the same mathematical model. For example, propagation of the forest fire line (*2*), growth of bacterial colonies (*3*), and the turbulent flow of liquid crystals (*4*) may exhibit the same scaling dynamics. From a philosophical point of view, this may be seen as a manifestation of harmony in nature that persists despite diversity in its constituents. Beyond validation of 2D KPZ scaling, demonstrating the KPZ theory in higher-dimension systems could further confirm its remarkable universality. Theoretically, it is plausible that nonequilibrium dynamics of 3D physical systems would also fall within the scaling rule (*12*). A 3D array of exciton-polariton condensates made of a resonant photonic crystal could expand the observation into higher dimensions. □

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