OPTICAL PHYSICS

Photonics and the Nobel Prize in Physics

Giorgio Parisi recently shared a Nobel Prize in Physics for his contribution to the theory of complex systems. What is not well known is that photonics was crucial to validating Parisi's predictions.

Claudio Conti and Eugenio DelRe

The Nobel Prize in Physics 2021 has been awarded to Syukuro Manabe and Klauss Hasselmann for "quantifying and reliably predicting global warming" and to Giorgio Parisi "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales".

Light plays a central role in the present understanding of climate change. Our planet's energy balance is thought to be driven principally by two opposing mechanisms, energy absorption in the form of visible light from the Sun, and energy release as lower-frequency infrared radiation. In this tug of war — which involves albedo, scattering and thermal reemission — photonics, especially through the development of innovative materials and effects, can play a prominent role in limiting global warming.

What is perhaps less expected and intuitive is that photonics is also instrumental in providing a direct testbed and experimental demonstration of the intricate interplay between the disorder and fluctuations predicted by Parisi. This role of photonics was explicitly underlined by the Nobel Committee in detailing the scientific background to this year's prize[1]. It is the unveiling of this interplay that may hold the key to taming the apparent unpredictability of complex systems.

In his work on spin glass theory[2], Parisi investigated the interaction between disorder and fluctuations and introduced the idea of replica symmetry breaking. The mechanism involves a conceptual expansion of statistical mechanics to systems that manifest disorder and frustration.

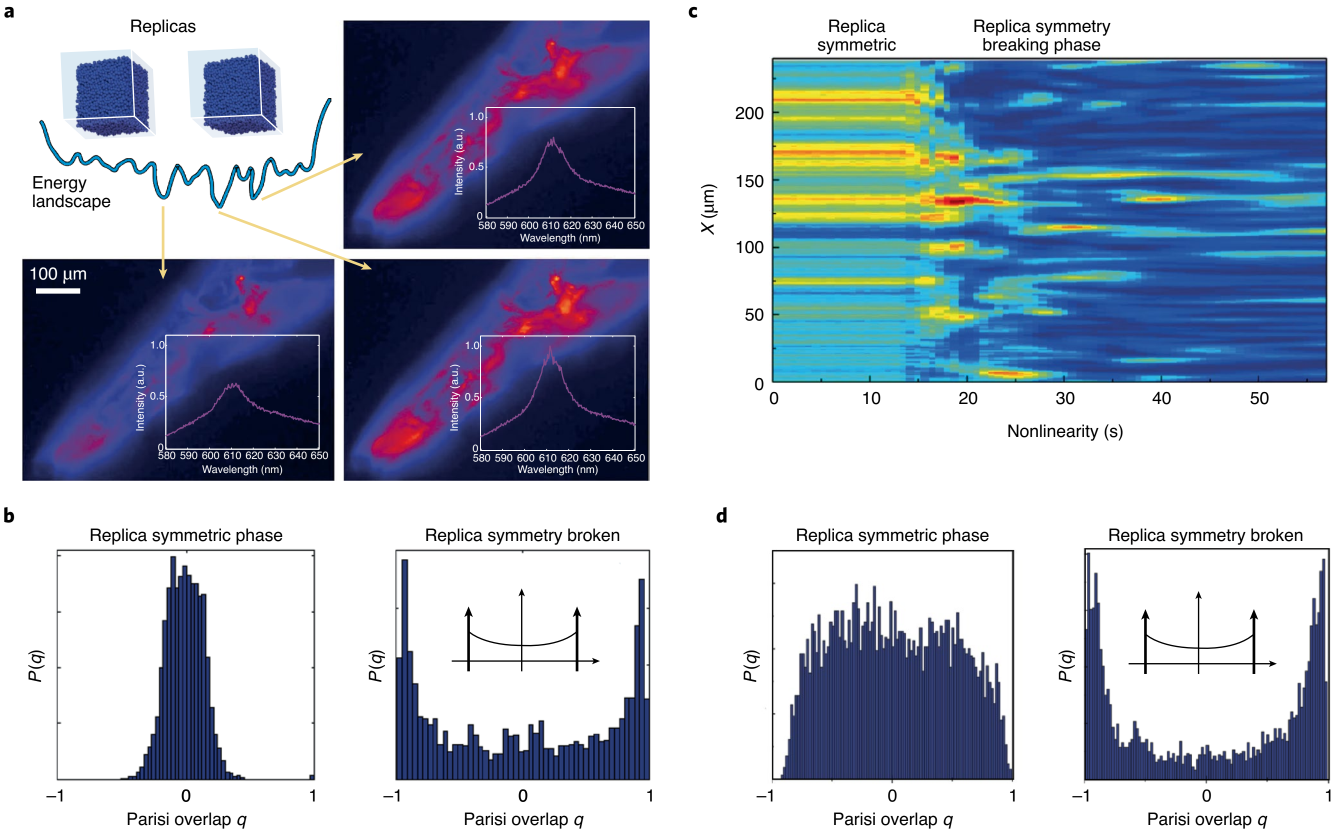

Fig. 1 | Photonics and replica symmetry breaking. a, Intensity distribution and spectrum of identical random laser experiments. Fluctuations erratically drive the systems through numerous competing states in the 'energy landscape'. **b**, The observed statistical distribution $P(q)$ of the Parisi overlap shows a signature transition to a double-peaked shape[9]. The inset show the model case of spin glasses[2,3]. **c**, In nonlinear optical beam propagation, above a threshold nonlinearity the output intensity distribution undergoes a transition to a strongly fluctuating regime. **d**, Also in this case, the replica symmetry breaking is demonstrated by measuring the distribution of the Parisi overlap[10]. Panels adapted with permission under a Creative Commons licence CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/) from: **a**,**b**, ref. [9]; **c**,**d**, ref. [10].

Elegant and powerful, the idea has found its theoretical and numerical realization in spin glasses, a modelling landmark developed over four decades in complex systems science[3]. What has always been elusive is a full experimental validation of the effect, including the underlying machinery of replica symmetry breaking. This is where photonics steps in.

Experimentally accessible multimodal nonlinear optical systems form a physical realization of a spin glass. Fluctuations have a central role in photonics. For example, they determine the linewidth of a laser and the ultimate resolution of an imaging system. However, it is in nonlinear multimodal optical systems that the interplay between built-in disorder and noise comes to dominate behaviour. This has been observed across different frameworks, including highly nonlinear optical fibres, spatial and temporal solitons, supercontinuum generation and beam filamentation.

The central trait of a system with a random material distribution and a strongly nonlinear optical regime is a large variability in observable quantities, such as spectra or speckle patterns. This variability can cause two identical realizations of one complex optical system (that is, 'two replicas') to lead to two macroscopically different responses, even when the two experiments are performed in exactly the same conditions. For example, two random lasers, each characterized by many modes (spatial and temporal) and strong nonlinear interaction, can display wholly different emission spectra even if they are driven by one and the same disorder (Fig. 1). It turns out that as the energy grows above a certain threshold, several states become available to the wave dynamics, the result being an intricate form of mode competition with an associated so-called energy landscape. A complexity-driven laser will lock onto different states each time it is turned on. Much like noise can couple different local equilibrium configurations for spins, so here it can cause the random laser to jump from one lasing state to another, enhancing fluctuations and leading to strongly varying output features.

In Parisi's conceptual framework, the energy landscape holds the key to the true nature of complex behaviour. To demonstrate this, he introduced the so-called Parisi overlap, an observable quantity that provides direct evidence of broken replica symmetry. Although the mechanism of replica symmetry breaking can be analysed in detail in numerical experiments, it is the direct observation of the role played by the Parisi overlap that has been achieved in photonics.

The idea that multimodal nonlinear optical systems have an underlying energy landscape was introduced in a series of theoretical papers starting in 2005[4–7], a prediction that was corroborated by early experimental observations[8]. The signature splitting of the Parisi overlap (Fig. 1) was directly demonstrated in 2015[9] in a random laser, and, in 2017, also in nonlinear optical propagation in disordered photorefractive waveguides[10]. As outlined by the Nobel Committee[1], the results in random lasers, reproduced by other groups, have opened many new questions and directions in 'photonic spin glasses'.

The core idea that underpins photonic spin glasses is the identification of mode amplitudes as complex-valued 'spins'. In these terms, the spectral emission from a laser and the spatial distribution of an optical beam are observable quantities determined by the spins. Measuring the outcome of different replicas of the same system allows us to compute the statistical distribution of the Parisi overlap, that is, the shot-to-shot correlation of the fluctuations. The characteristic transition from a Gaussian-like shape to a doubled-peaked shape at the replica symmetry breaking, predicted by Parisi, is strikingly clear in photonic experiments (Fig. 1).

Photonic spin glasses offer at once a class of new physical systems for testing the fundamentals of the science of complex systems and the basis for unexpected applications. They may form the backbone for innovative, efficient and environmentally friendly classical and quantum computing hardware, as large-scale Ising machines for solving combinatorial optimization and photonic neural networks.

But even with all of this said, the experimental confirmation of Parisi's idea in itself adds an important tassel in our understanding and, hopefully, taming of the effects of complexity-driven dynamics, such as the ever-changing climate of our planet. ❐

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Competing interests

The authors declare no competing interests.

ATTOSECOND OPTICS

Probing attosecond phenomena in solids

A sub-cycle modulation in reflectivity is observed in bulk crystals subjected to intense laser fields. The effect provides a new way to probe attosecond dynamics in materials.

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Attosecond science — studies involving timescales of 10^{-18} seconds —has progressed from the investigation of electron dynamics in atoms and molecules in gaseous media to the exploration of quantum phenomena in condensed matter systems. Landmark experiments in strongly driven dielectric media include the observation of carrier-envelope phase-dependent current[1], high-harmonic generation[2] and attosecond transient absorption[3]. Now, writing in