Ben-Gurion University of the Negev

BELARUSIAN STATE UNIVERSITY

ROGUE WAVES IN PHOTONICS: TRIGGERING EXTREME EVENTS AT THE NANOSCALE IN PHOTONIC SEAS

Presenter:

Roza Navitskaya

PhD student

at Ben-Gurion University of the Negev

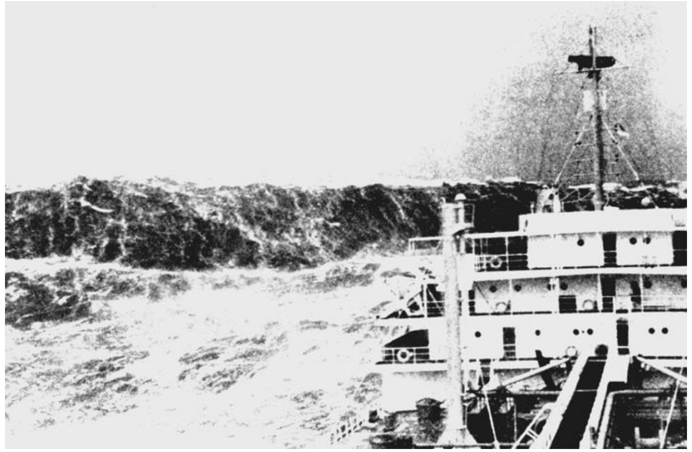
and Belarusian State University

Outline

1. Rogue waves in nature
    - definition and properties
2. Rogue waves in optics and photonics
    - first report of optical rogue waves
    - rogue waves in waveguide arrays
    - spatial rogue waves in multimode waveguides
    - dissipative rogue waves in mode-locked lasers
    - dissipative rogue waves in PT-symmetric waveguides
3. Triggering extreme events at the nanoscale in photonic seas
    - generation of rogue waves in a linear system
    - control of rogue wave formation on a chip

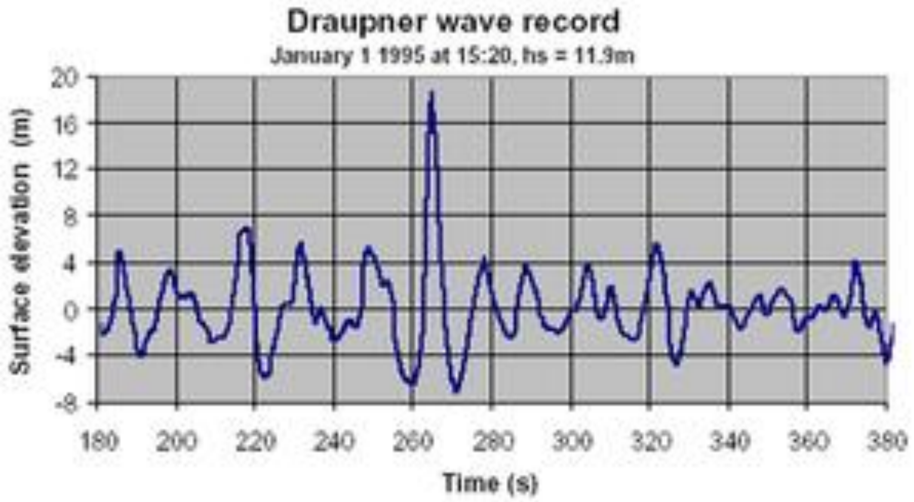
Rogue Waves in Nature

- The extreme localization of waves, either in space or in time, has always been a subject of great interest in science.
- Extreme localization of energy naturally arises in rare phenomena such as hurricanes, tsunamis, rogue waves and tornadoes, which appear at once and disappear in a probabilistic fashion.
- Among various types of rare dynamics, rogue waves are particularly interesting.
- **Rogue waves** (RWs) are isolated events with exceptional amplitude, that form spontaneously and disappear without a trace in different complex systems.



Rogue Waves in Nature

- First reports of rogue waves correspond to oceanography.
- The first documented rogue wave (Draupner wave) was recorded in 1995 in the North sea. It was 25.6 m in height.
- The oceanic RWs are difficult to predict and monitor because of their fleeting existences. However, satellite surveillance has confirmed that rogue waves roam the open oceans, occasionally encountering a ship or seaplatform, sometimes with devastating results.

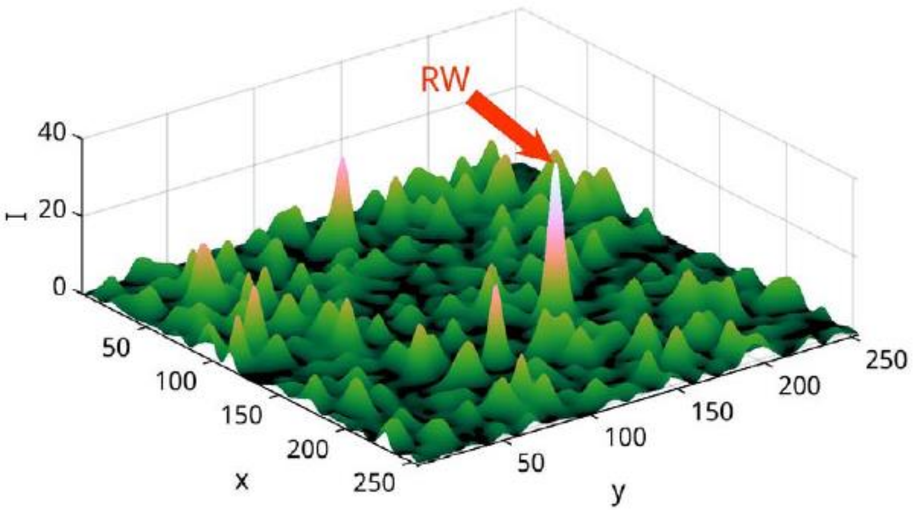


Measured profile of the Draupner rogue wave.

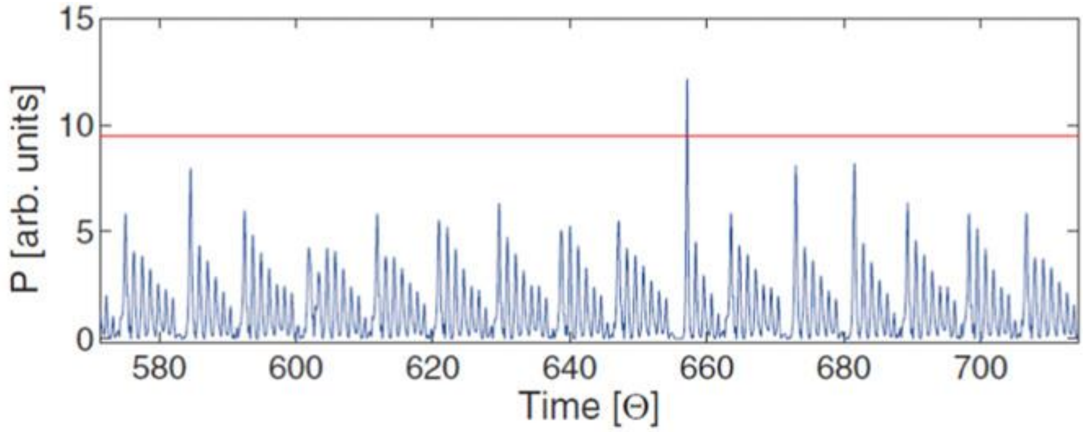
Recreation of the Draupner wave in a circular wave tank [2].

Rogue Waves in Nature

- Rogue waves are characterized by a maximum peak amplitude that is at least twice as large as the significant wave height (SWH).
- The significant wave height is defined as the average of the highest one-third of the waves nearby and represents a widely accepted parameter for the identification of rogue waves.
- This threshold criterion has been initially introduced in hydrodynamics, and is therefore formulated with reference to the wave amplitude.



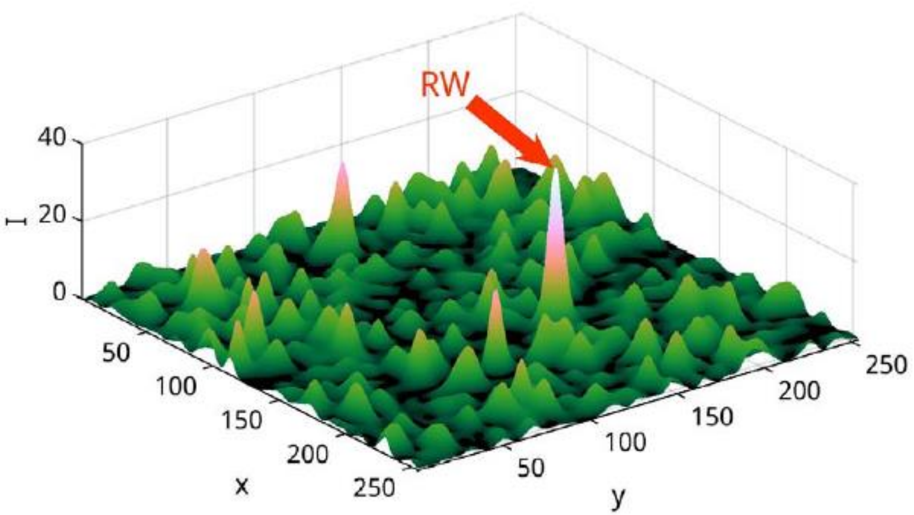
Example of a spatial rogue wave [5].



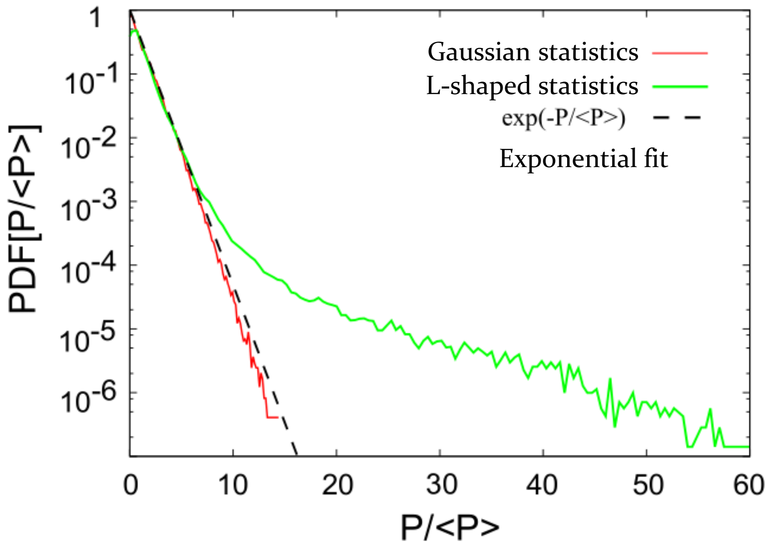
Example of a temporal rogue wave [4].

Rogue Waves in Nature

- The unusual statistics of rogue waves represent one of their defining characteristics.
- Conventional models of ocean waves indicate that the probability of observing large waves should diminish extremely rapidly with wave height, suggesting that the likelihood of observing even a single freak wave in hundreds of years should be essentially non-existent.
- In reality, however, ocean waves appear to follow 'L-shaped' statistics: most waves have small amplitudes, but extreme outliers also occur much more frequently than expected in ordinary (Gaussian) wave statistics.



Example of a spatial rogue wave [5].

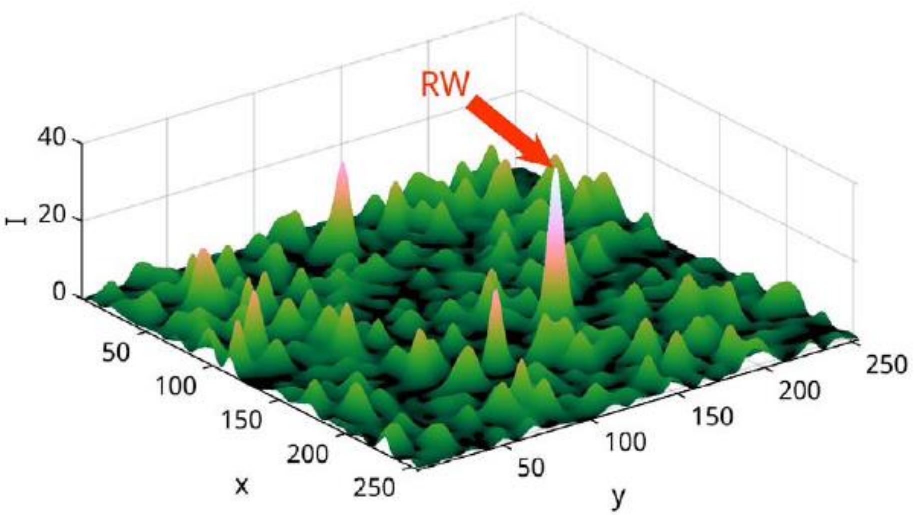


Example of rogue wave statistics [6].

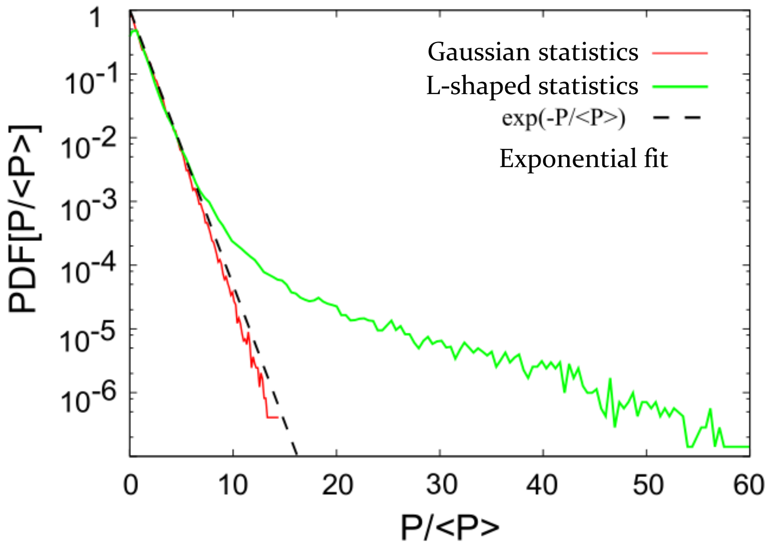
Rogue Waves in Nature

Rogue wave characteristics:

- Form and disappear spontaneously with unpredictable lifetime.
- Maximum amplitude at least twice as large as the significant wave height (SWH).
- 'L-shaped' statistics: most waves have small amplitudes, but extreme outliers also occur much more frequently than expected in ordinary (Gaussian) wave statistics.



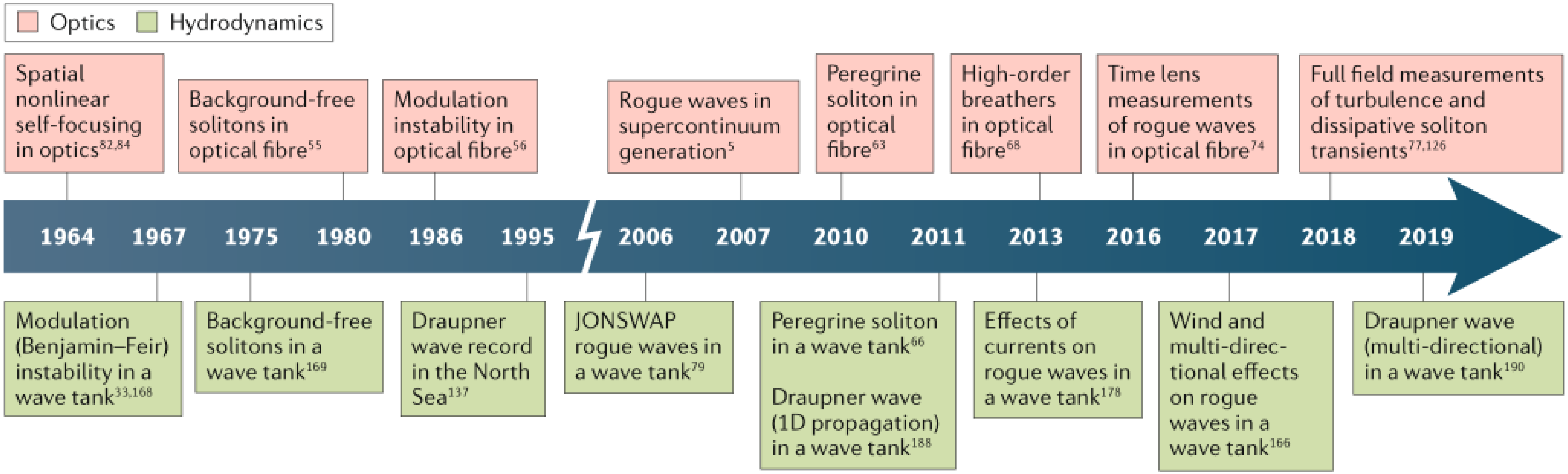
Example of a spatial rogue wave [5].



Example of rogue wave statistics [6].

Rogue Waves in Optics and Photonics

- Optical RWs are analogous to the oceanic RWs – rare anomalous events with large amplitude.
- Deep research into the optical rogue waves has developed considerably since 2007, following the introduction of an analogy between the generation of large ocean waves and the propagation of light in optical fibers.



Timeline illustrating the parallel developments in fibre optics (top) and hydrodynamics (bottom) [2].

Rogue Waves in Optics and Photonics

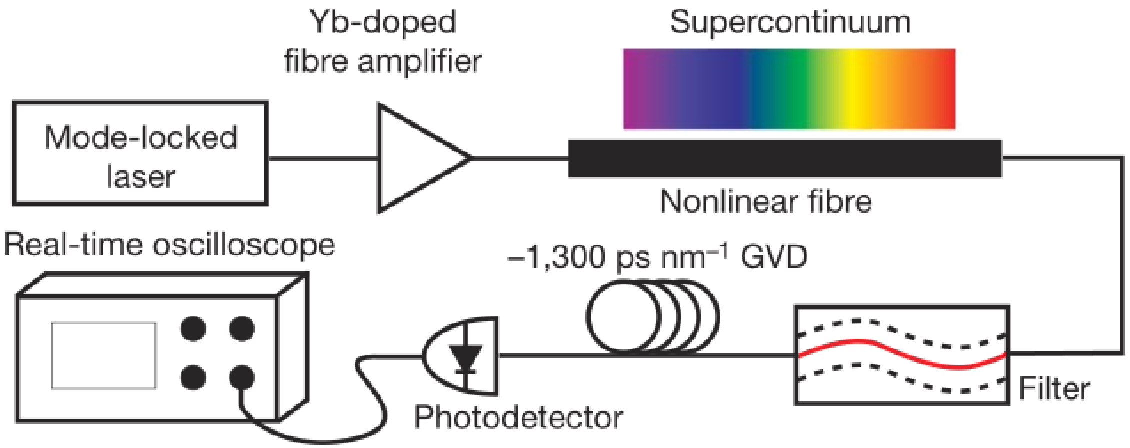
- Rogue waves have been observed in a large number of systems sharing diverse degrees of randomness, noise, unpredictability, linear and nonlinear responses.
- Key triggering mechanisms of rogue waves formation are randomness and nonlinearity.

Rogue Waves in Optics and Photonics

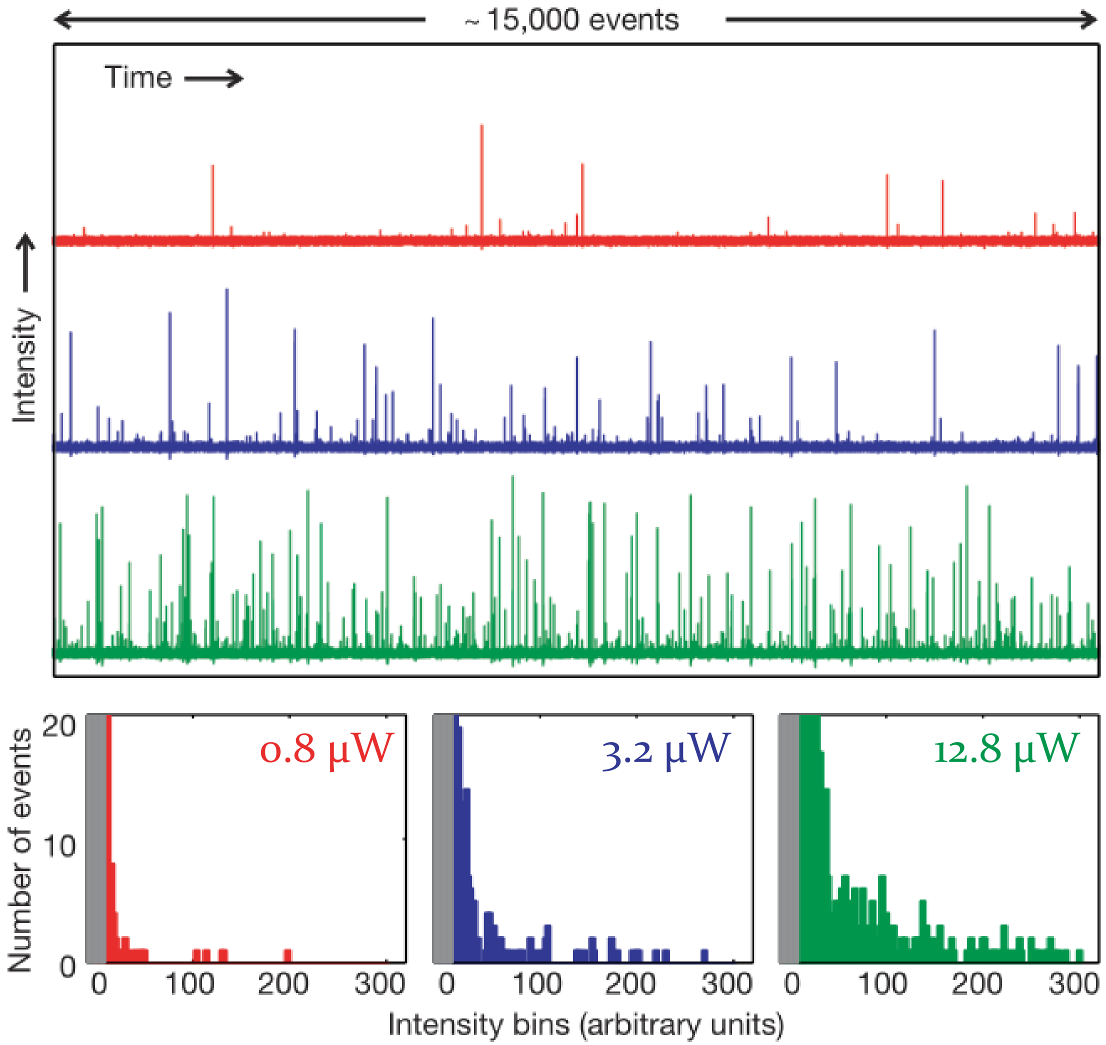
First report of optical rogue waves [3]:

- The observation of rogue waves in a highly nonlinear microstructured optical fibre, near the threshold of soliton-fission supercontinuum generation

- Supercontinuum generation - a noise-sensitive nonlinear process in which extremely broadband radiation is generated from a narrowband input.



Schematic of experimental apparatus.



Time traces and associated histograms for different average power levels.

Rogue Waves in Optics and Photonics

First report of optical rogue waves [3]:

- **Kerr nonlinearity:**
  $\tilde{n} = n + \overline{n_2}|E|^2$, $\overline{n_2}$ is the Kerr coefficient.

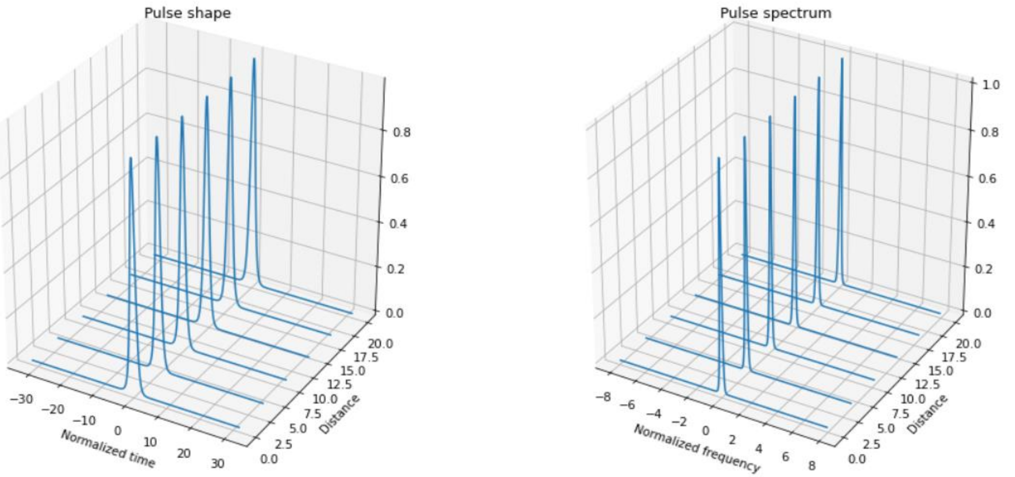
  Kerr nonlinearity can produce spectral broadening or narrowing depending on the input pulse parameters.

- **Solitons** – pulses which temporal form and spectrum either do not change or follow a periodic evolution during propagation in the waveguide.

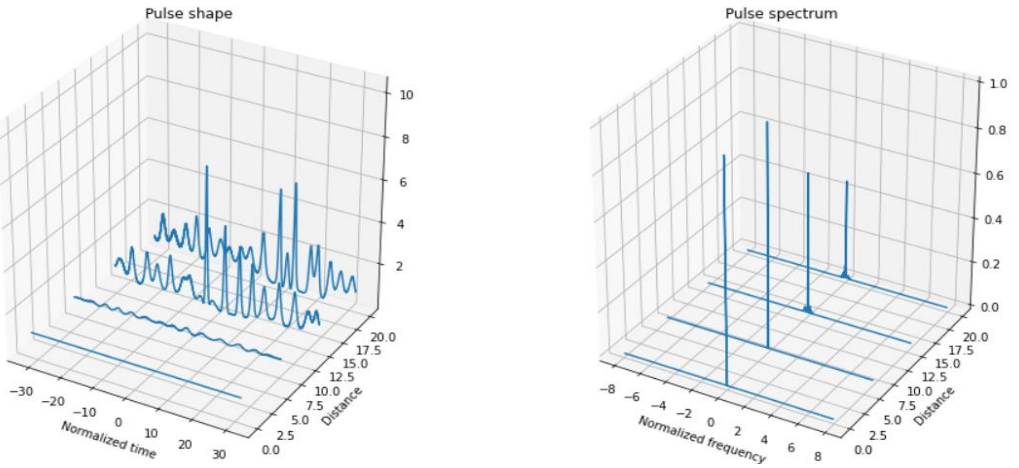
  Solitons can be formed when dispersive and nonlinear effects compensate each other.

- **Modulation instability** effect corresponds to a spontaneous temporal modulation of the input CW beam and its transformation into a pulse train.

  Small noise-like perturbations grow exponentially while the input beam propagates in the waveguide.



Example of solitonic pulse propagation.



Example of modulation instability effect.

Rogue Waves in Optics and Photonics

First report of optical rogue waves [3]:

- The generation of rogue waves was simulated using the generalized nonlinear Schrödinger equation (NLSE):

$$\frac{\partial A}{\partial z} - i \sum_{m=2} \frac{i^m \beta_m}{m!} \frac{\partial^m A}{\partial t^m} = i\gamma \left(|A|^2 A + \frac{i}{\omega_0} \frac{\partial}{\partial t} (|A|^2 A) - T_R A \frac{\partial |A|^2}{\partial t} \right)$$

- β_m are values that characterize the fibre dispersion, γ is the nonlinear coefficient of the fibre, ω_o is the central carrier frequency of the field, and T_R is a parameter that characterizes the delayed nonlinear response of silica fibre.

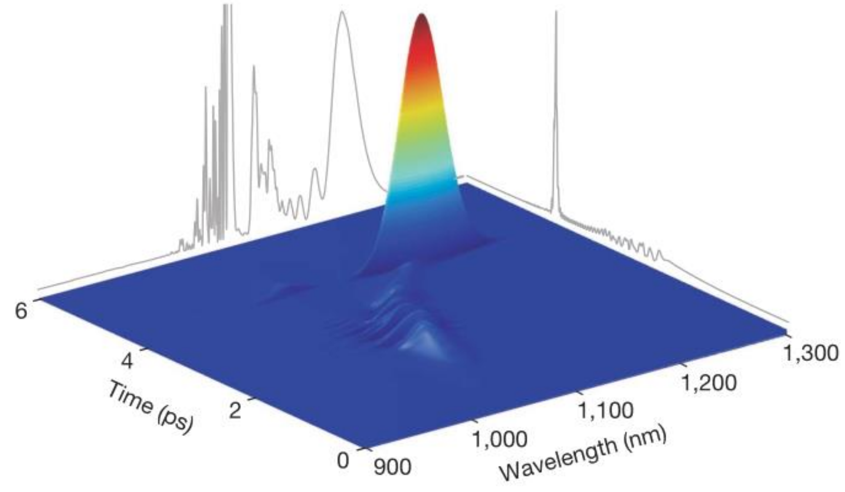
- The bracketed terms on the right-hand side of the equation describe the Kerr nonlinearity, self-steepening and the vibrational Raman response of the medium, respectively.

- This equation has been successfully used to model supercontinuum generation in the presence of noise and can be used to predict optical rogue waves.

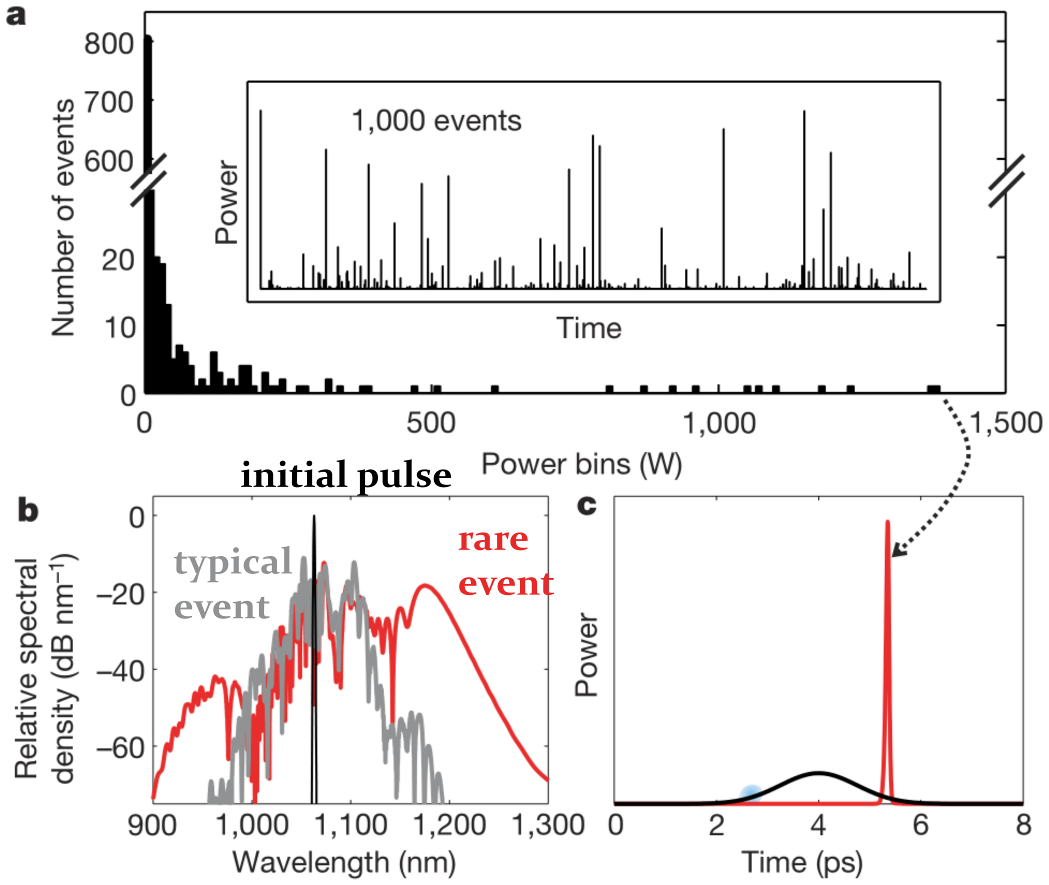
Rogue Waves in Optics and Photonics

First report of optical rogue waves [3]:

- RWs arise from initially smooth pulses owing to power transfer seeded by a small noise perturbation (modulation instability effect).
- Rogue waves represent extreme soliton-like pulses that have unpredictable lifetime, follow unusual L-shaped statistics, occur in a nonlinear medium, are broadband and temporally steep compared with typical events.



Time–wavelength profile of an optical rogue wave.

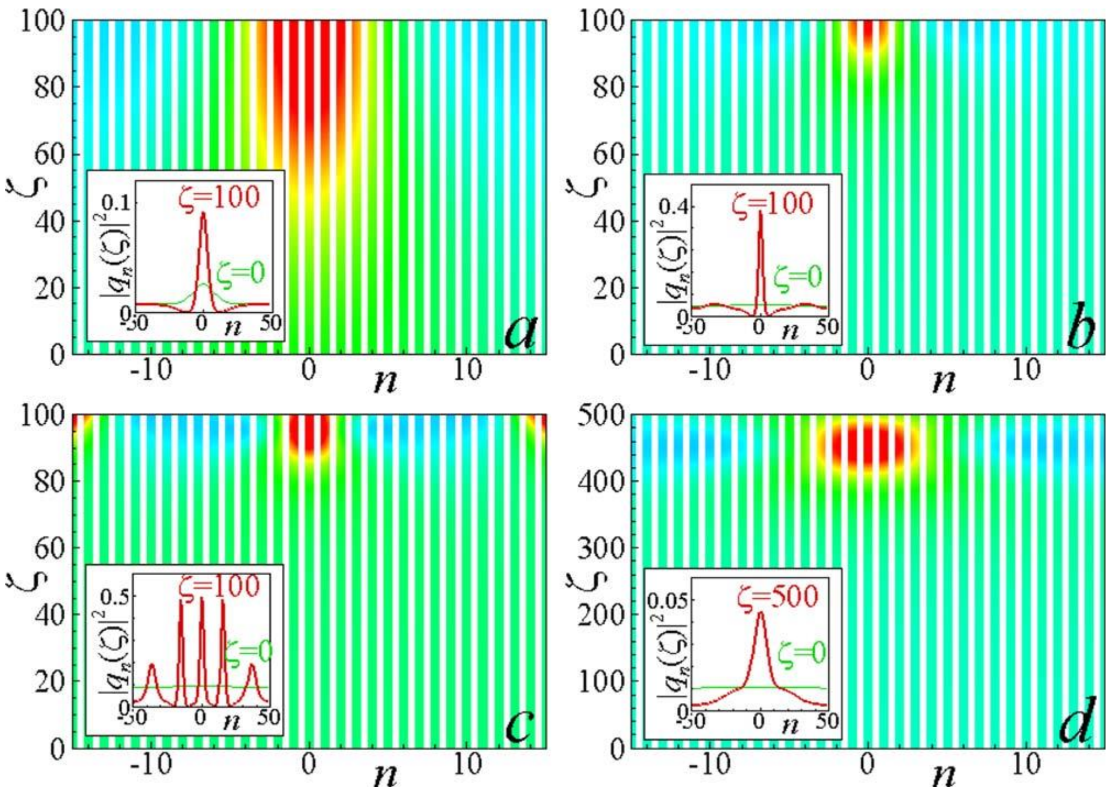


Simulation of optical rogue waves: the time trace, histogram, relative spectral densities and temporal profiles of the seed pulse, typical event and rare event.

Rogue Waves in Optics and Photonics

Rogue waves in an array of waveguides [7]:

- In an array of nonlinear waveguides, a giant compression of the input beam can be achieved by exciting a rogue wave.
- Input field almost homogeneously distributed over hundreds of waveguides concentrates practically all the energy into a single waveguide at the output plane of the structure.
- The process of rogue-wave formation is the inverse of diffraction of the total energy in a single waveguide into neighboring ones.
- Such rogue waves can be used to construct optical energy concentrators. Concentration occurs despite the fact that the input energy has nearly homogeneous distribution.



Contour plot of intensity on the (n, ζ) plane. Parameters are a, ε=0.1, L=100; b, ε=0.2, L=100; c, ε=0.3, L=100; d, ε=0.1, L=500 (ε is the background intensity, L is the waveguides length, n is the waveguide number). The insets show input and output field profiles.

Rogue Waves in Optics and Photonics

Rogue waves in an array of waveguides [8]:

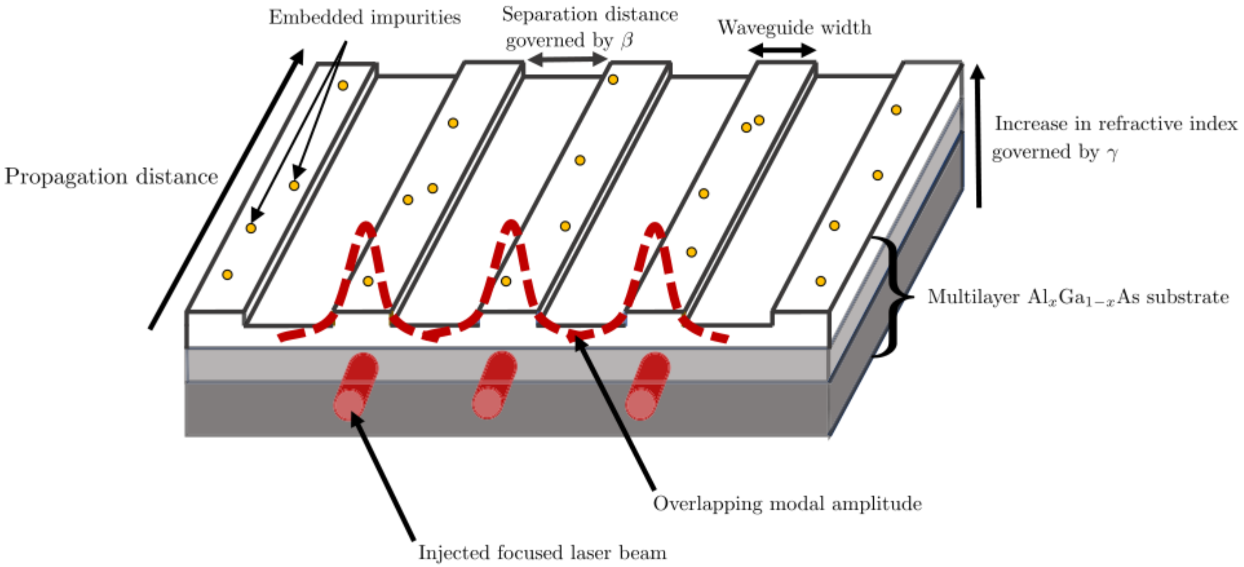
- The propagation of waves in the nonlinear waveguide array is simulated using unstable NLSE (UNLSE):

$$i\frac{\partial A_m}{\partial z} + \beta(A_{m+1} - 2A_m + A_{m-1}) + \gamma|A_m|^2 A_m + \Gamma_m A_m = 0,$$

- $A_m(z)$ is a complex valued function, β is a coupling parameter, γ is a nonlinear coefficient, m represents a waveguide in a chain of N waveguides, and Γ_m represents a waveguide-dependent fluctuating parameter (describes defects in the waveguides, which result in disorder and additional instability in the system).

- The separation between lattice waveguides is set to unity, and the lattice includes a coupled, nearest neighbors interaction, a nonlinear term, and the unstable term.

- UNLSE describes a system that balances the effects of nonlinearity and dispersion, and includes the instability of the medium.

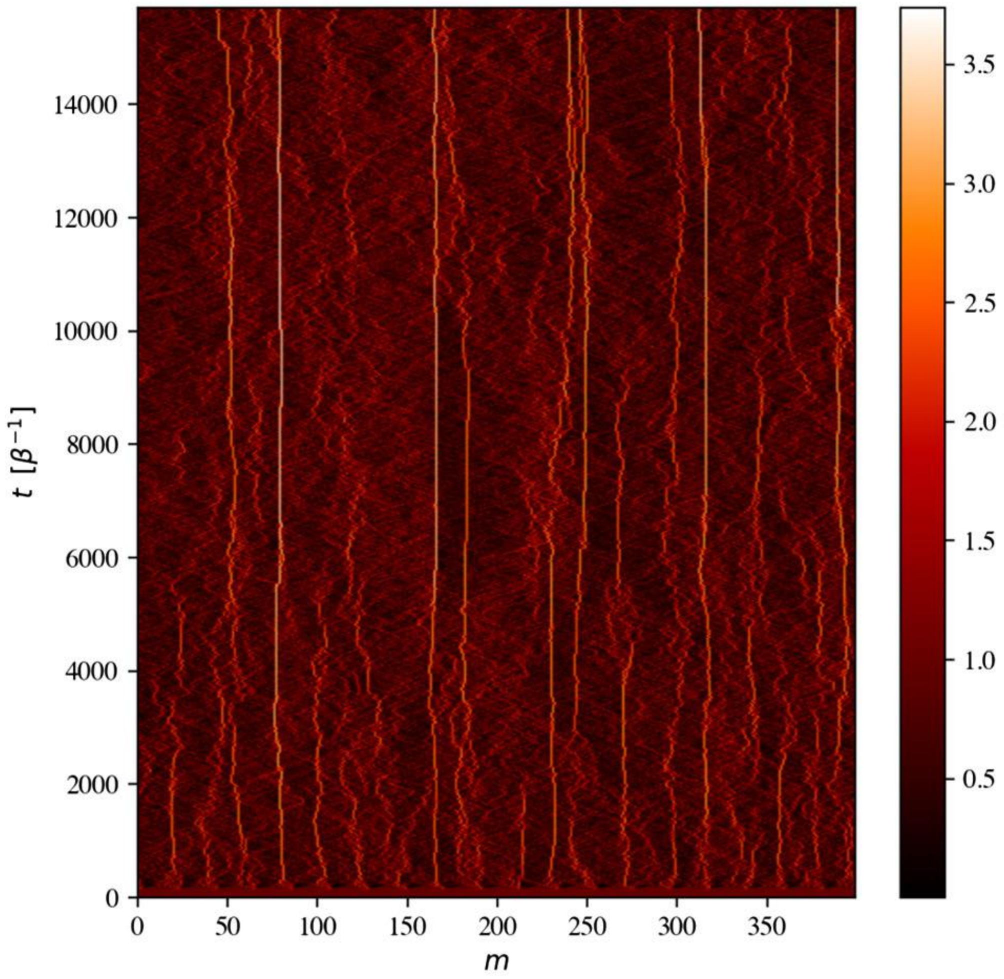


Schematic illustration of a possible experimental setup. A focused light beam is injected and allowed to propagate along the waveguide. The waveguides usually have a defined separation distance. Yellow circles represent embedded defects.

Rogue Waves in Optics and Photonics

Rogue waves in an array of waveguides [8]:

- Long-lived rogue waves in discrete optical systems have been observed as a result of modulation instability effect.
- Modulation instability leads to an exponential increase in amplitude, and it occurs in UNLSE due to a small perturbation on a finite amplitude plane wave.
- The interplay between self-focusing and modulation instability leads to formation of large amplitude waves. These waves can be classified as solitons that emerge from the finite background amplitude.
- The onset times of long-lived rogue waves are smaller for larger modulation instability or disorder.

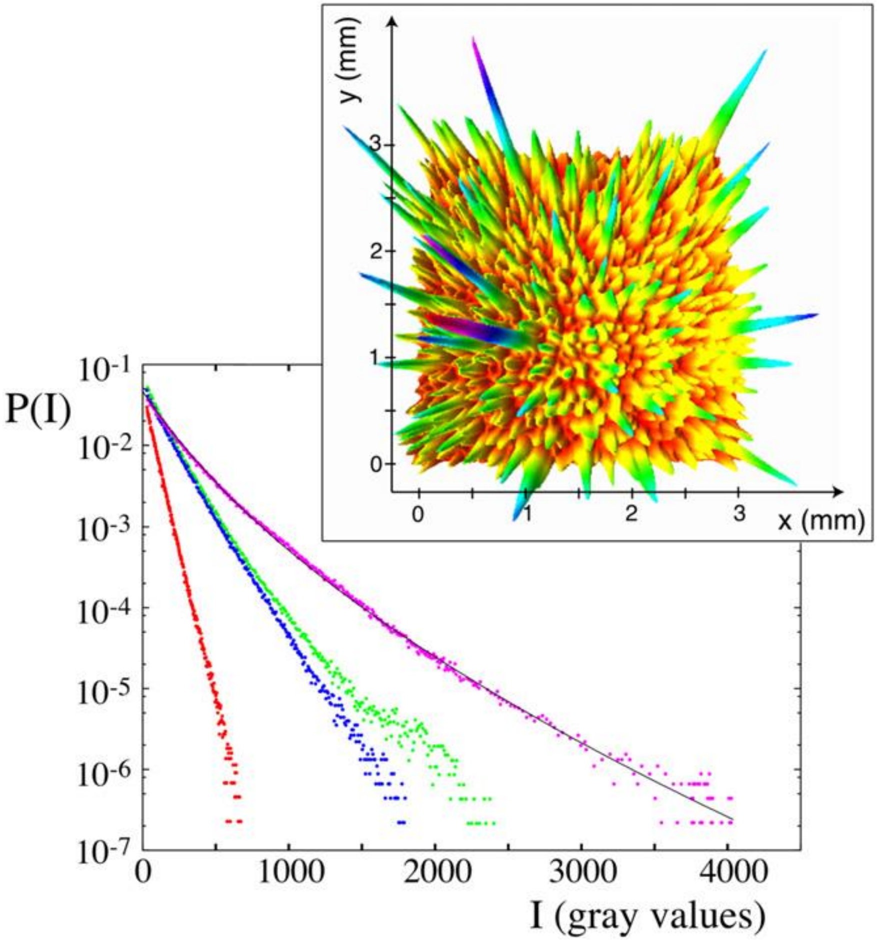


Time evolution of field intensity showing multiple long-lived rogue waves (initial condition - a plain wave with a periodically modulated perturbation).

Rogue Waves in Optics and Photonics

Spatial rogue waves in multimode waveguides [4]:

- Rogue waves can be observed not only in time, but in space too – for example, in multimode fibers with different degrees of nonlinearity.
- Spatial RWs are formed as a result of spontaneous synchronization of waveguide transverse modes.
- For low pump intensity, the amplitude of the cavity field follows a Gaussian statistics. For high pump, the emergence of spatiotemporal pulses with much higher amplitude with respect to the background is observed.
- The rogue pulses develop spontaneously in time and in space.

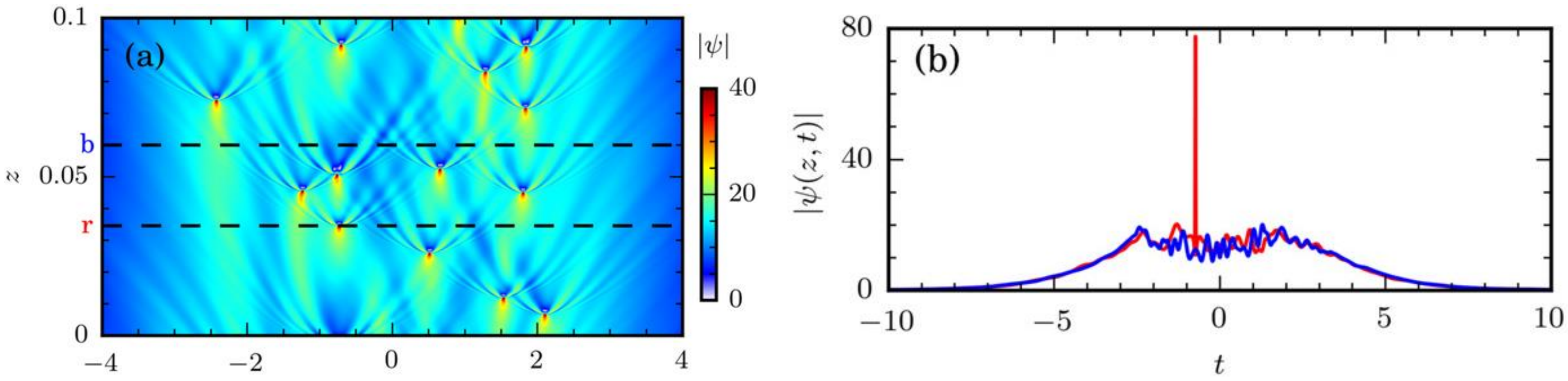


Probability distribution function (PDF) of the cavity field intensity; the nonlinearity is increased from the steepest to the shallowest distribution; inset: instantaneous profile of the cavity field intensity.

Rogue Waves in Optics and Photonics

Rogue waves in mode-locked lasers [4]:

- RWs can be generated in systems with loss and gain, such as lasers working in highly nonlinear, non-stationary regime.
- Rogue waves represent chaotic dissipative solitons with noise-like features (shown in figure).
- Any localized initial condition that is sufficiently close to the solution converges to it after the transient has decayed.



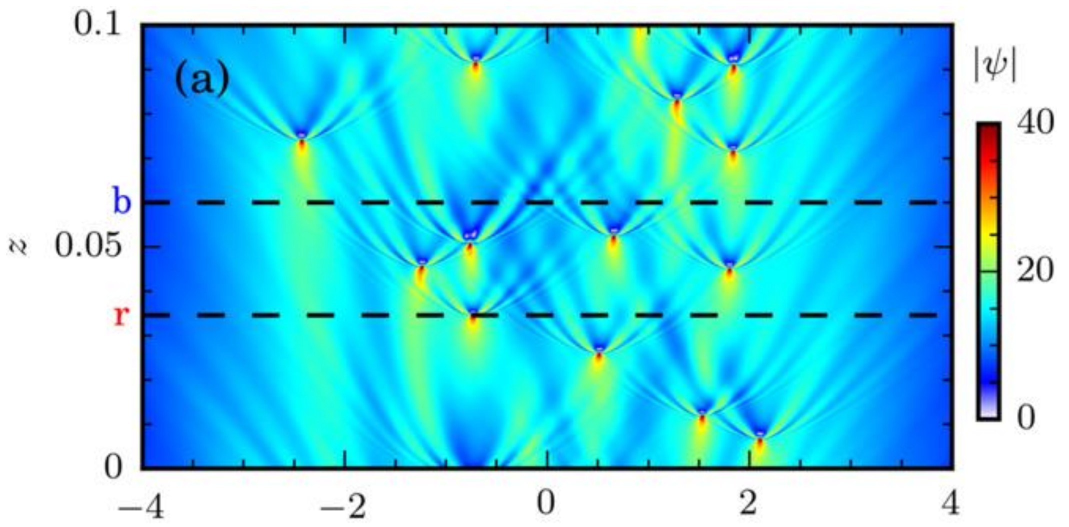
(a) Pulse amplitude evolution along z. (b) Pulse profiles at two different z (labeled 'b' and 'r' in (a) for blue and red profiles).

Rogue Waves in Optics and Photonics

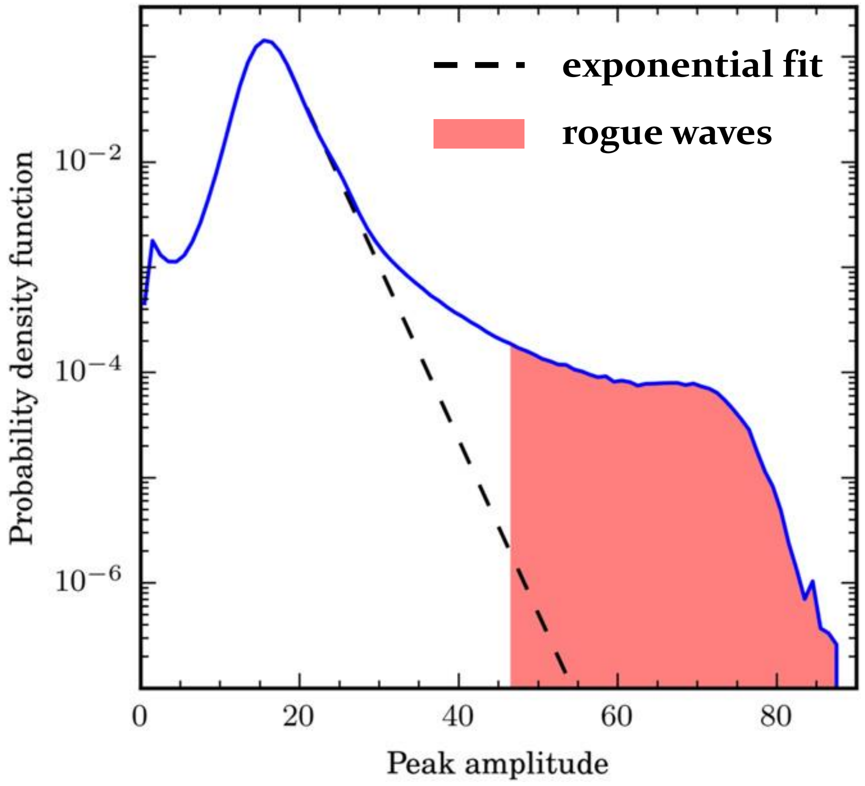
Rogue waves in mode-locked lasers [4]:

- These chaotic solitonic spikes have the main features of dissipative rogue waves: amplitudes more than 2.2 times higher than SWH value, L-shaped probability density function (PDF) of the peak amplitudes, and spontaneous nature.

- The significant wave-height (SWH) amplitude is 20.8. The dissipative RWs have amplitudes exceeding 45.8 (2.2 times the SWH).



(a) Pulse amplitude evolution along z.



Probability density function (PDF) of the peak amplitudes in logarithmic scale.

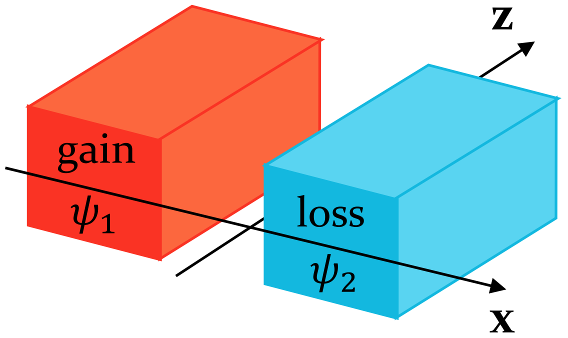
Rogue Waves in Optics and Photonics

Rogue waves in PT-symmetric waveguides [9]:

- Rogue waves can be generated due to the modulation instability effect in a parity-time (PT)-symmetric system, which represents a Kerr-nonlinear optical coupler with balanced gain and loss in its cores.

- This system is described by coupled NLSEs for field variables ψ_1 and ψ_2:

$$i\frac{\partial\psi_1}{\partial z} = -\frac{\partial^2\psi_1}{\partial x^2} + (\chi_1|\psi_1|^2 + \chi|\psi_2|^2)\psi_1 + i\gamma\psi_1 - \psi_2,$$
$$i\frac{\partial\psi_2}{\partial z} = -\frac{\partial^2\psi_2}{\partial x^2} + (\chi_1|\psi_2|^2 + \chi|\psi_1|^2)\psi_2 - i\gamma\psi_2 - \psi_1.$$



- These equations are coupled nonlinearly by the cross-phase modulation (XPM) ~ χ, and linearly by the last terms with respective coupling constant scaled to be 1. A constant γ > 0 describes the PT –balanced gain and dissipation, χ_1 describes the self-phase modulation (SPM) effect.

- The case when $\gamma \leq 1$ is considered, corresponding to the gain/loss term small enough compared to the linear coupling.

Rogue Waves in Optics and Photonics

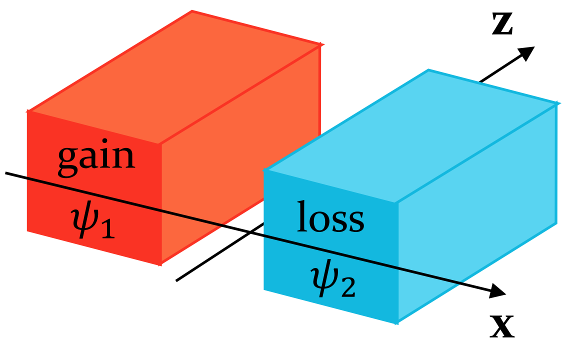
Rogue waves in PT-symmetric waveguides [9]:

- The PT-symmetric (+) and antisymmetric (–) solutions are given by

$$\psi_2(x,z) = \pm e^{\pm i\delta}\psi_1(x,z),$$

where $\gamma = \sin(\delta)$, $0 < \delta < \pi/2$, and the function $\psi_1$obeys the single equation:

$$i\frac{\partial\psi_1}{\partial z} = -\frac{\partial^2\psi_1}{\partial x^2} + (\chi_1 + \chi)|\psi_1|^2\psi_1 \mp \cos(\delta)\,\psi_1.$$



Rogue Waves in Optics and Photonics

Rogue waves in PT-symmetric waveguides [9]:

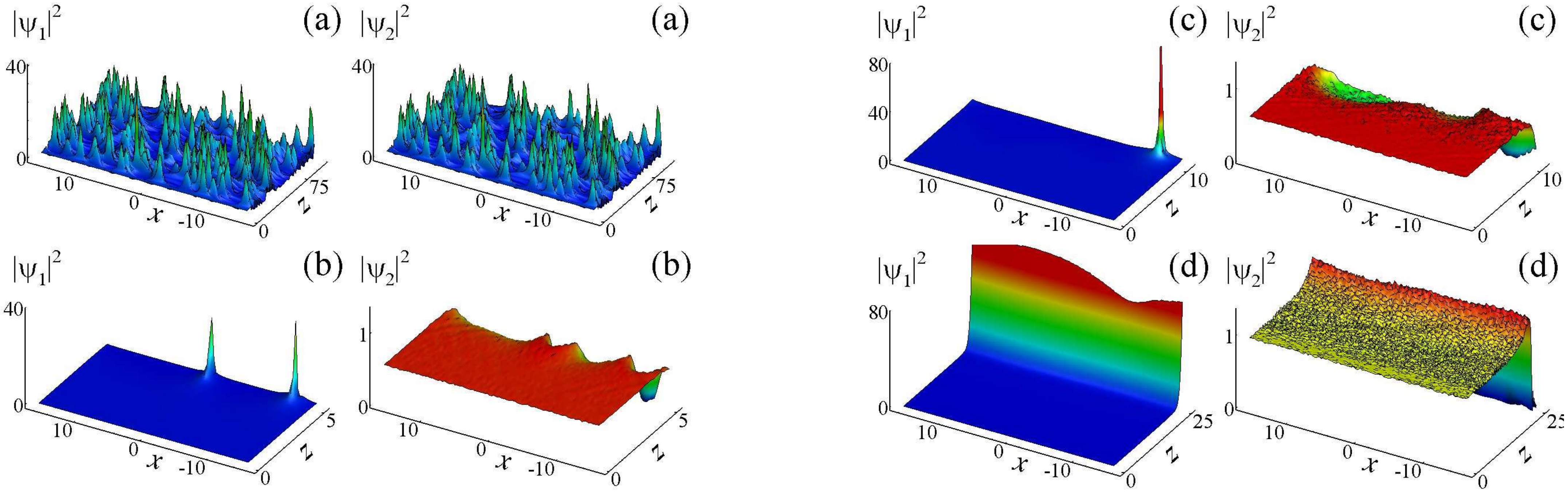
- The modulation instability effect depends on the values and signs of χ_1 (SPM) and χ (XPM):

(a) $\chi_1 + \chi < 0, \chi < 0$ (focusing XPM)

(b) $\chi_1 + \chi < 0, \chi > 0$ (defocusing XPM)

(c) $\chi_1 + \chi > 0, \chi_1 < -\chi$, $\chi > 0$, (defocusing XPM)

(d) $\chi_1 + \chi > 0, \chi_1 > 0, \chi > 0$, (defocusing XPM and SPM)

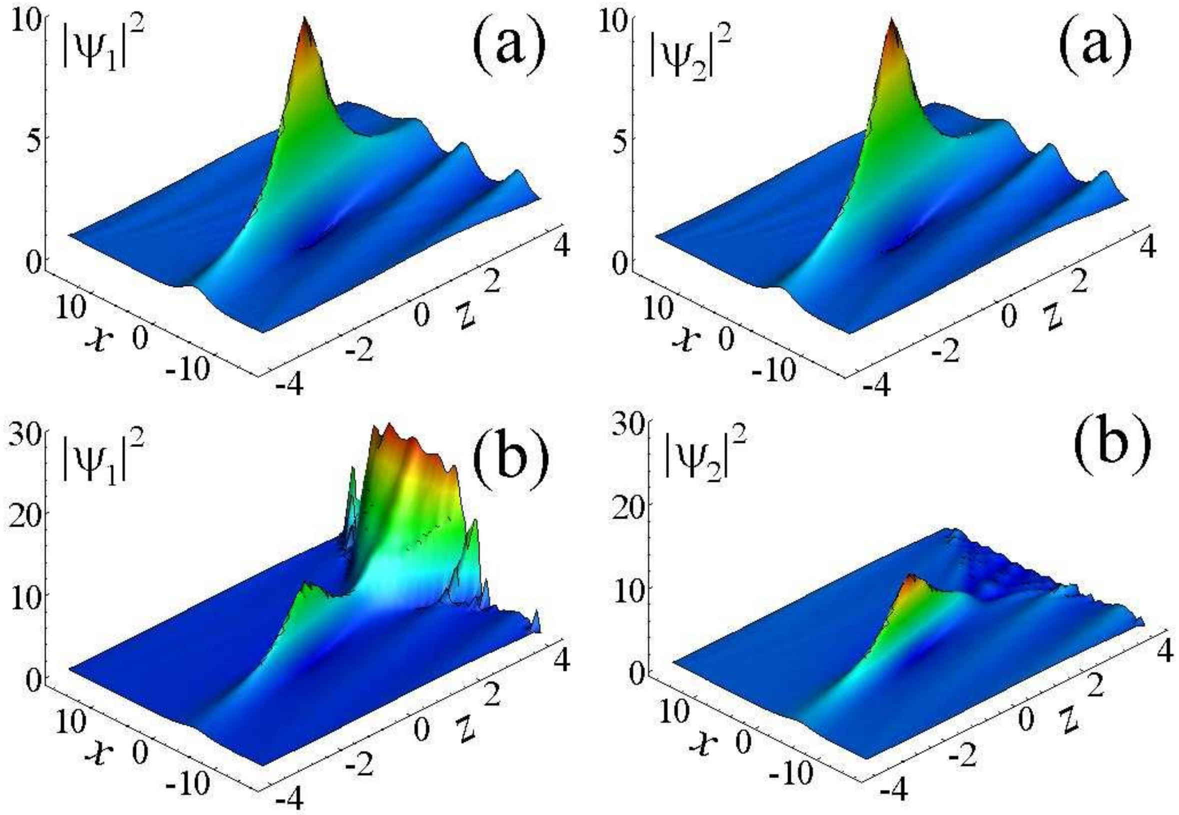


The evolution of field components $|\psi_1(x,z)|^2$ and $|\psi_2(x,z)|^2$ (left and right columns) of the plane-wave solution with parameters $k = 0$, $\delta = \pi/4$, $\rho = 1.604$, $\chi_1 = 0.5$, $\chi = -1$ (a), $\rho = 0.76$, $\chi_1 = -1.5$, $\chi = 1$ (b), $\rho = 0.79$, $\chi_1 = -0.5$, $\chi = 1$ (c) and $\rho = 0.98$, $\chi_1 = 0.25$, $\chi = 1$ (d).

Rogue Waves in Optics and Photonics

Rogue waves in PT-symmetric waveguides [9]:

- The rogue wave form is close to the Peregrine soliton:



Peregrine solutions in the PT -symmetric system for k = 0.6, ρ = 1.0, χ_1 = 0.5, χ = –1, and $\delta = \pi/4$ (a), or $\delta = 3\pi/4$ (b).

Rogue Waves in Optics and Photonics

- The emergence, dynamics and prediction of rogue waves has been in the focus of interest in diverse fields of science (oceanography, physics of fluids, optics, matter waves physics, sociology, bio-sciences) over the last fifteen years.

- Optical RWs were observed both in time (1D) and space (2D).

- RWs were investigated in different nonlinear systems: optical fibers with dispersion and nonlinearity, mode-locked fiber and Ti:Sapphire lasers, semiconductor lasers, etc.

- The open questions in understanding the physics of rogue waves are:
  the conditions of their emergence; the role of linear and nonlinear effects in this process; influence of higher-order nonlinear effects; formation of RWs in linear systems; possibility of prediction, control and artificial generation of RWs.

- Prediction and control of optical RWs involves the use of machine learning techniques to detect patterns and build models based on analysis of large data sets.

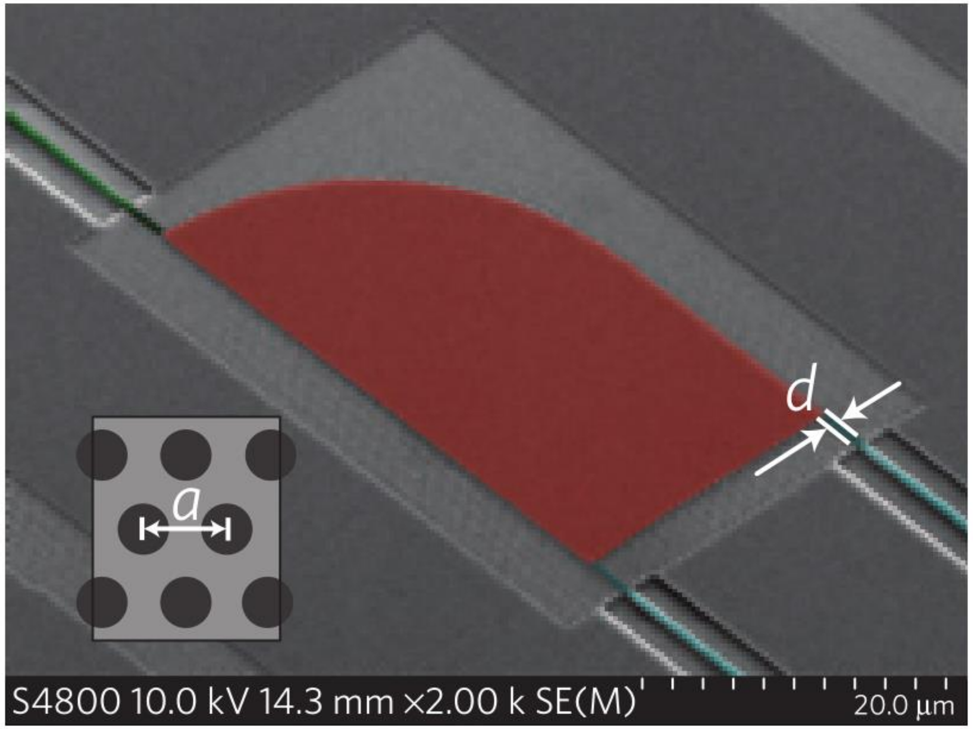
Triggering extreme events at the nanoscale in photonic seas

- The onset of rogue waves can be triggered controllably.
- Rogue waves are formed in a deterministic dielectric structure that does not require nonlinear properties - an integrated optical resonator, realized on a photonic crystal chip.
- The generation of RWs is systematically used to break the diffraction limit of light propagation.
- The combined ultrafast (163 fs long) and subwavelength (206 nm wide) localization of photons at a wavelength λ=1.55 μm is reported by exploiting a new mechanism for the generation of rogue waves.

[1] C. Liu, R. E. C. van der Wel, N. Rotenberg, L. Kuipers, T. F. Krauss, A. Di Falco and A. Fratalocchi, Triggering extreme events at the nanoscale in photonic seas, NATURE PHYSICS, 11, 358–363, 2015

Triggering extreme events at the nanoscale in photonic seas

- The system is a two-dimensional photonic crystal (PhC) resonator, integrated onto a chip, whose shape has been suitably engineered in a quarter-stadium form.
- This particular shape has been chosen to allow the generation of an incoherent wave ensemble through the mechanism of wave chaos.
- Even though the material exhibits no nonlinearity, the stadium shape supports chaotic motion for light rays, and fully randomizes any input wavefront into an ensemble of strongly incoherent waves.
- In this system, suitably engineered losses trigger a mechanism of spontaneous synchronization, which builds up energy into giant nanostructures of light.



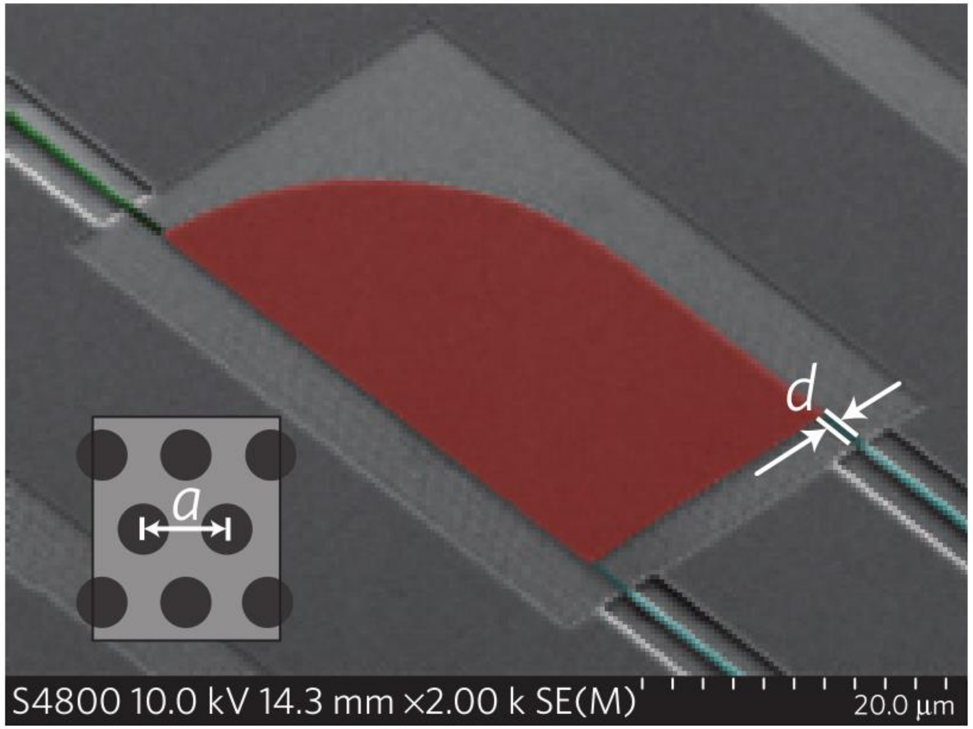
SEM image of the resonator structure.

Triggering extreme events at the nanoscale in photonic seas

- Investigating the generation of localized rare events from an incoherent sea of random waves $\psi(\boldsymbol{r},t)$:

$$\psi(\boldsymbol{r},t) = \int a(\boldsymbol{k},\omega)e^{i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r}+\varphi(\boldsymbol{k},\omega))}\,d\omega d\boldsymbol{k},$$

with $a(\boldsymbol{k},\omega)$ and $\varphi(\boldsymbol{k},\omega)$ random amplitudes and phases, respectively, depending on the wavevector k and frequency ω.

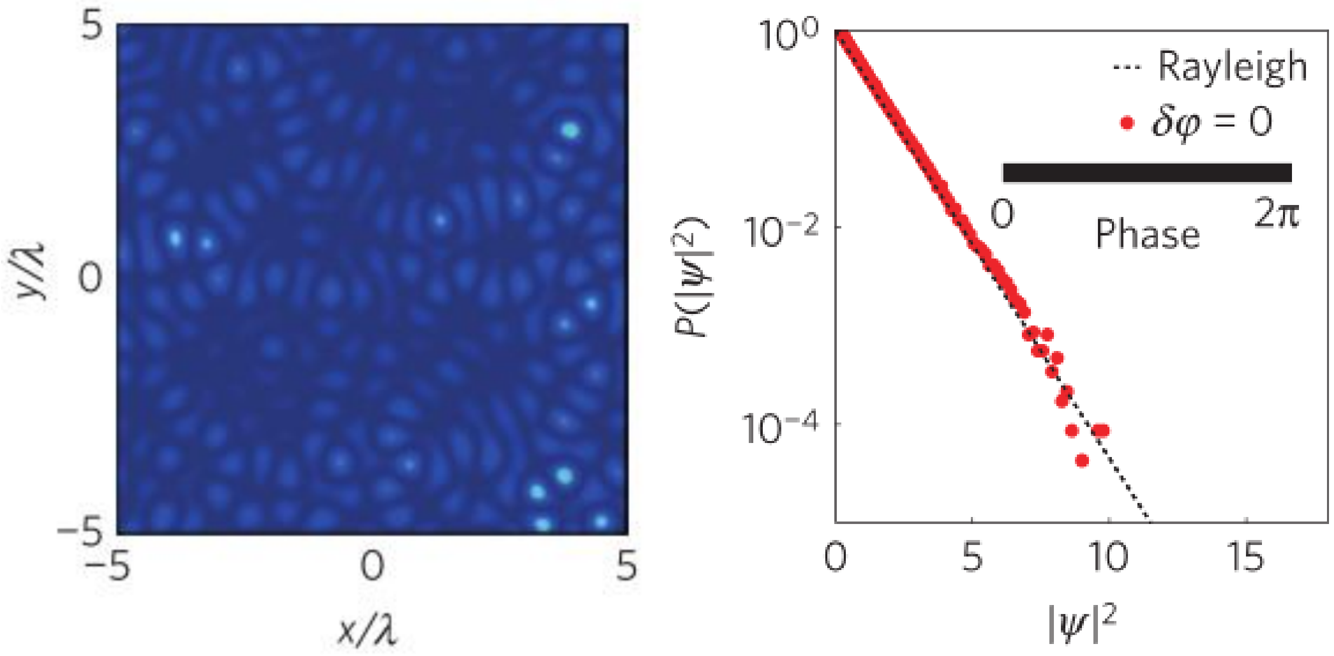


SEM image of the resonator structure.

Triggering extreme events at the nanoscale in photonic seas

$$\psi(\mathbf{r},t) = \int a(\mathbf{k},\omega)e^{i(\omega t-\mathbf{k}\cdot\mathbf{r}+\varphi(\mathbf{k},\omega))}\,d\omega d\mathbf{k},$$

- If *a* and ϕ are distributed uniformly, this equation describes a classical random walk whose intensity probability density $P(I) = P(|\psi|^2) = e^{-I}$.
- Simulation: an ensemble of 2,000 random waves with amplitudes *a(**k**)* uniformly distributed in [0, 1], with randomly displaced wavevectors |**k**| < 2π/λ and uniformly distributed frequencies ω ∈ [1, 2].
- For these conditions, no rare event of large intensity is generated.

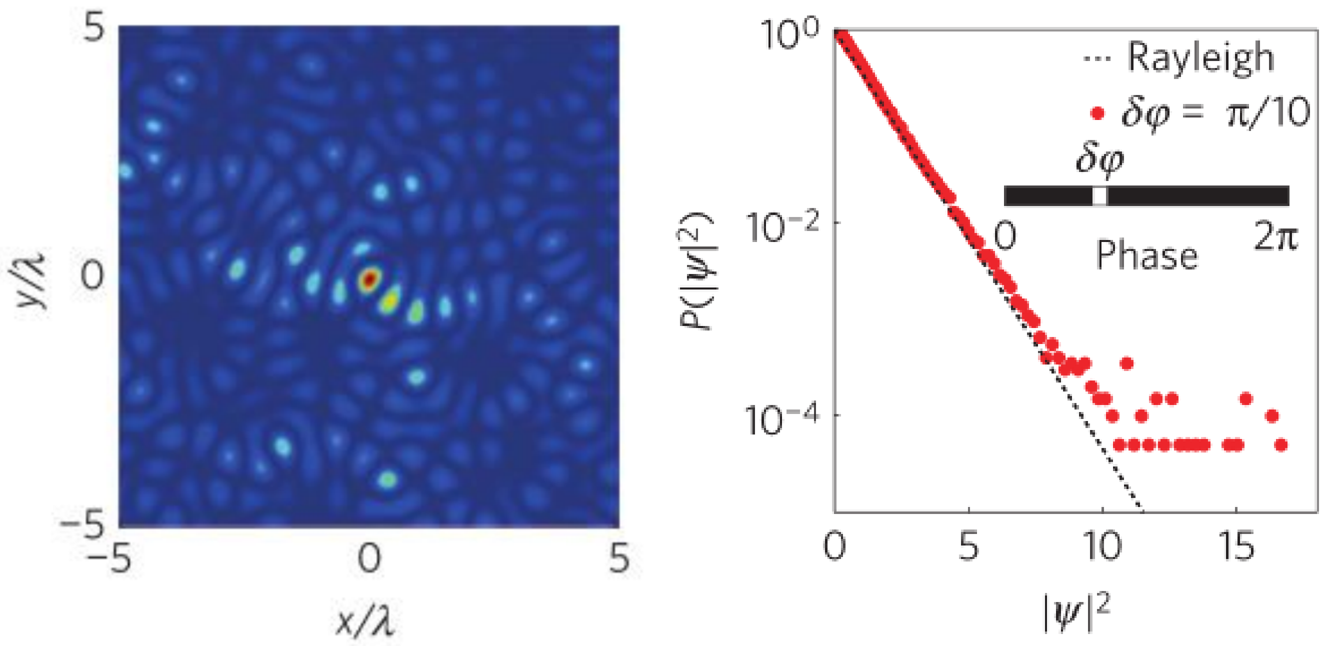


Spatial wave pattern and intensity probability density generated by an ensemble of 2,000 random waves with uniform phase distribution.

Triggering extreme events at the nanoscale in photonic seas

$$\psi(\boldsymbol{r}, t) = \int a(\boldsymbol{k}, \omega) e^{i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r} + \varphi(\boldsymbol{k},\omega))}\, d\omega d\boldsymbol{k},$$

- When the phase probability distribution is diluted by, for example, a range of inaccessible values for ϕ (δϕ=π/10), the statistics deviates from Gaussian, and and rare events appear.
- The probability distribution has characteristic 'L' shape with a long tail, which is the hallmark for the appearance of rogue waves.
- The generation of rare events can be intuitively explained by using the idea of path cancellation.



Spatial wave pattern and intensity probability density generated by an ensemble of 2,000 random waves with diluted phase distribution.

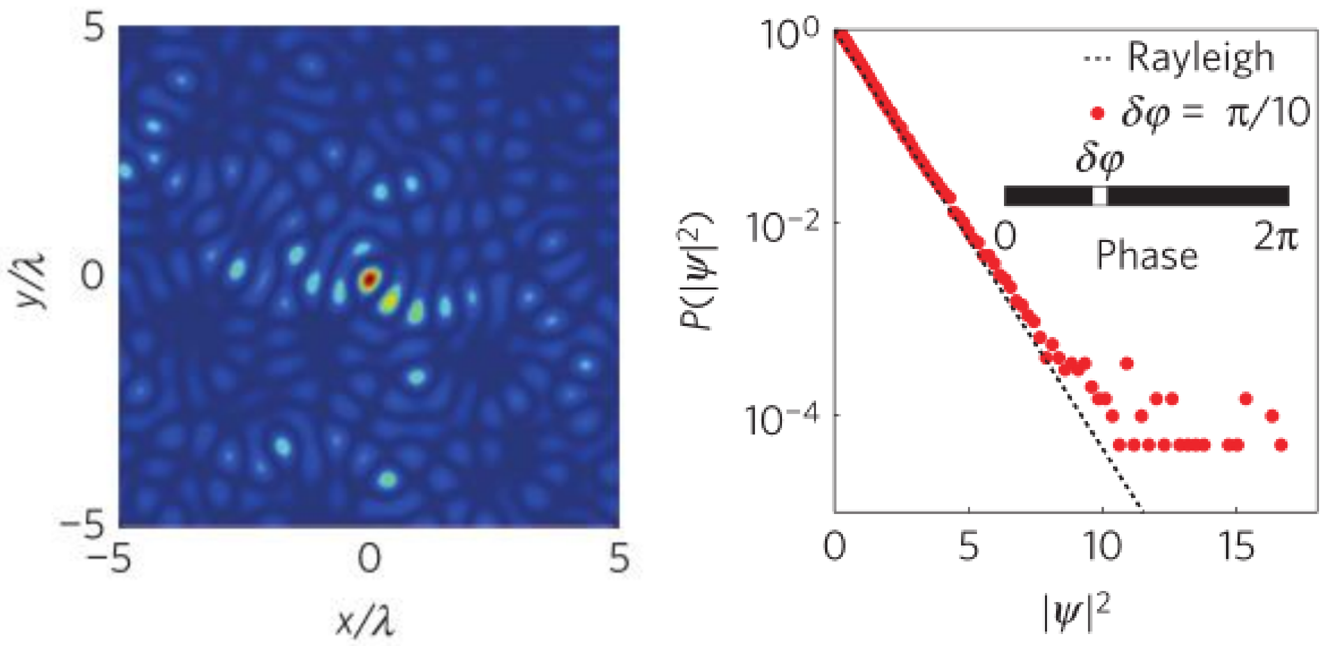
Triggering extreme events at the nanoscale in photonic seas

- A rare event can be expressed as follows:

$$\psi(\boldsymbol{r}, t) = \int a_0 e^{i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r} + \varphi_0)}\, d\omega d\boldsymbol{k}$$

- When such a synchronization involves all the frequency bandwidth Δω of the field, the spectral energy contained at each frequency ω ∈ Δω is constructively summed up and the resulting intensity reaches the largest possible value for that particular field.

- This equation can be regarded as a spontaneous synchronization of statistical origin.



Spatial wave pattern and intensity probability density generated by an ensemble of 2,000 random waves with diluted phase distribution.

Triggering extreme events at the nanoscale in photonic seas

$$\psi(\boldsymbol{r}, t) = \int a_0 e^{i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r} + \varphi_0)}\, d\omega d\boldsymbol{k},$$

- Notably, this equation embeds a super-oscillatory nature that beats the diffraction limit even when only diffraction-limited components are allowed to interfere.

- In particular, if a build up process is considered where all the possible components $k = |k| < 2\pi/\lambda$ are summed up, by integrating one can obtain:

$$\psi(\boldsymbol{r}, t) \sim J_0(k|\boldsymbol{r}|)\frac{sin\left(\frac{\delta\omega}{2}t\right)}{t},$$

where δω is the frequency bandwidth.

- This equation exhibits a subwavelength spatial full-width at half-maximum (FWHM) that is 25% smaller than the diffraction limit $\lambda/2$, and a time FWHM of $\tau = 2\pi/\delta\omega$.

Triggering extreme events at the nanoscale in photonic seas

$$\psi(\boldsymbol{r}, t) = \int a_0 e^{i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r} + \varphi_0)}\, d\omega d\boldsymbol{k},$$

- Notably, this equation embeds a super-oscillatory nature that beats the diffraction limit even when only diffraction-limited components are allowed to interfere.
- In particular, if a build up process is considered where all the possible components $k = |k| < 2\pi/\lambda$ are summed up, by integrating one can obtain:

$$\psi(\boldsymbol{r}, t) \sim J_0(k|\boldsymbol{r}|)\frac{sin\left(\frac{\delta\omega}{2}t\right)}{t},$$

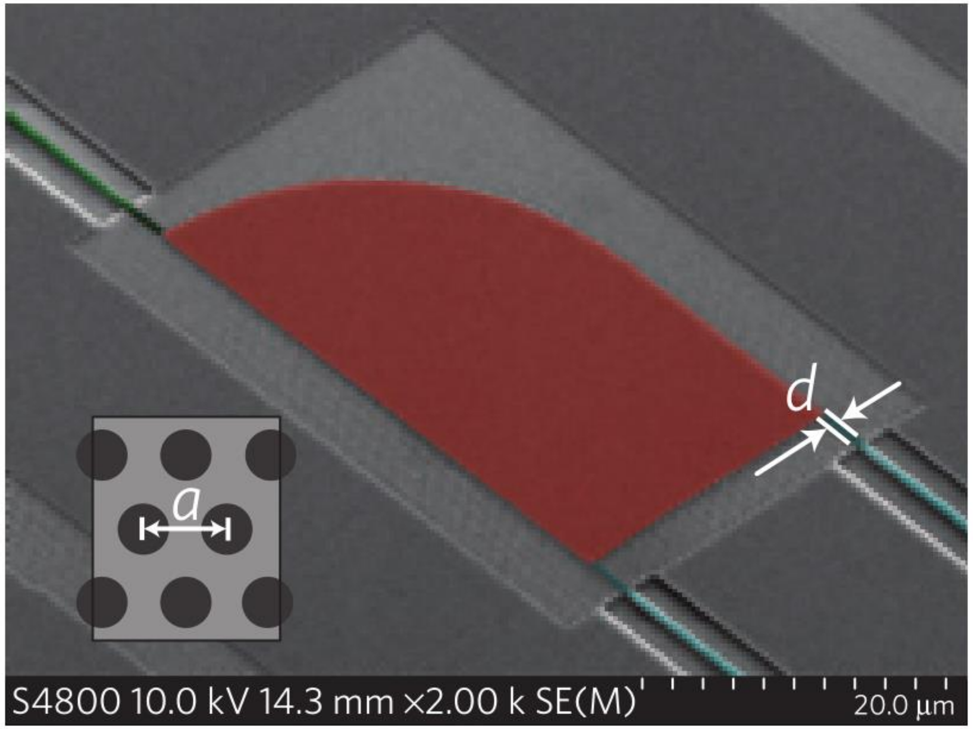
where δω is the frequency bandwidth.

- Subwavelength confinement originates from the Bessel wave $J_0(k|\boldsymbol{r}|)$, which is able to oscillate faster than its band limited Fourier components owing to super-oscillations.
- The brightness of the energy spot depends on the spectral bandwidth δω of the waves that get synchronized: the larger the bandwidth, the larger the energy peak of the rogue wave.

Triggering extreme events at the nanoscale in photonic seas

- To illustrate the generation of ultrafast, sub-λ rogue waves in an integrated structure, two-dimensional PhC optical cavities with losses controlled by the width of the output channels were designed.

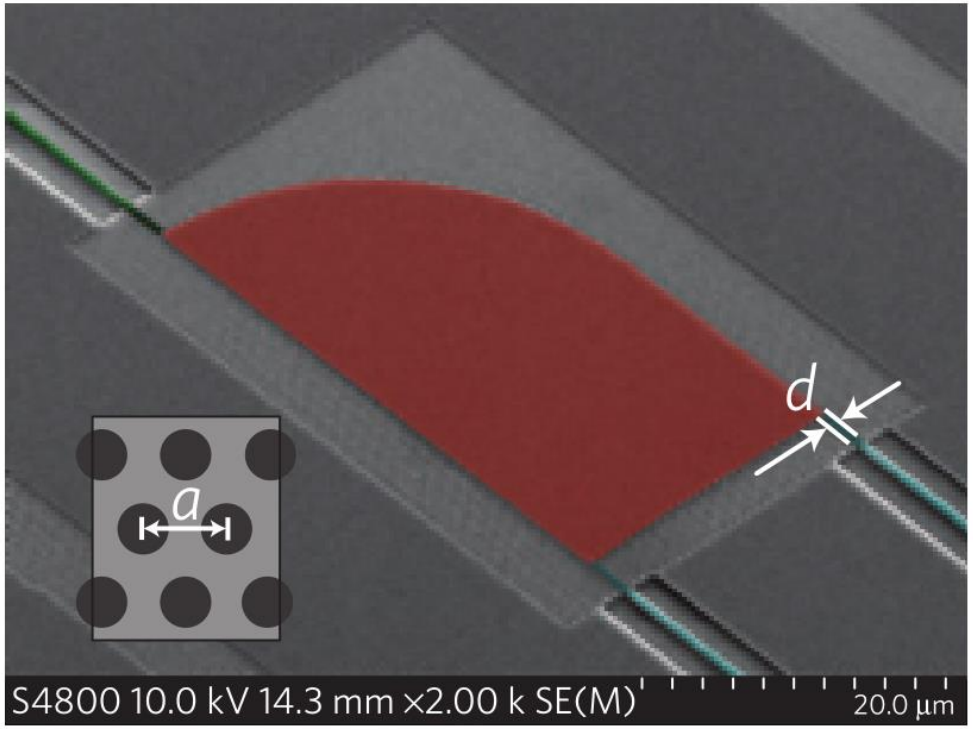
- Light of a frequency within the bandgap of the photonic crystal can escape from the system only via the input/output channels, otherwise being reflected at the resonator boundaries.



SEM image of the resonator structure.

Triggering extreme events at the nanoscale in photonic seas

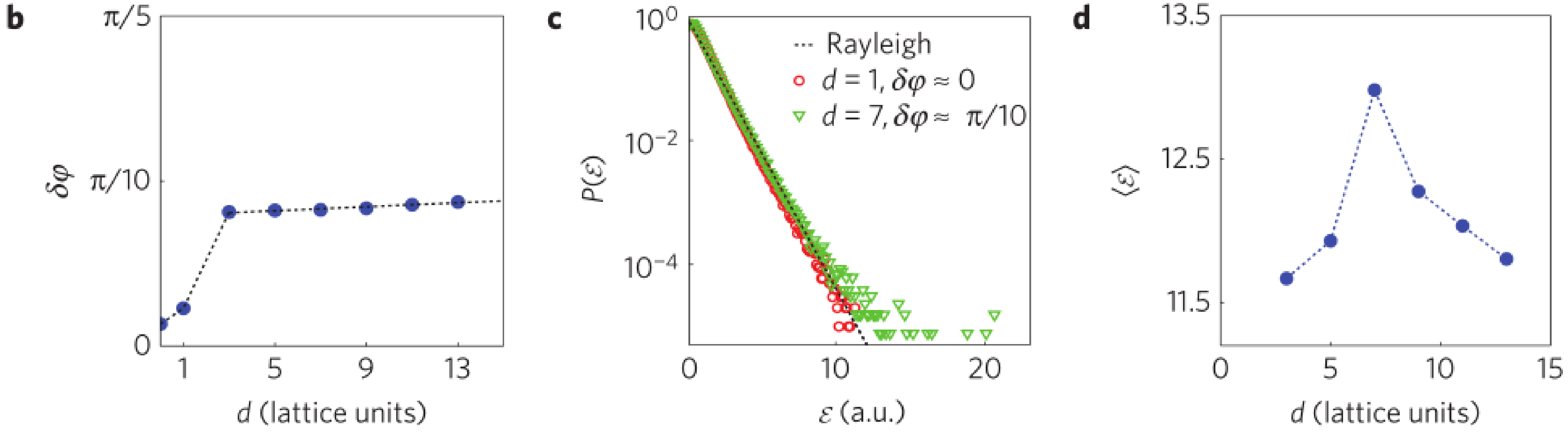
- Light of a frequency within the bandgap of the photonic crystal can escape from the system only via the input/output channels, otherwise being reflected at the resonator boundaries.
- The cancellation of some paths inhibits the random walk from exploring the full set of phases, creating a gap δϕ in the phase distribution.
- The waveguide spacing is varied by removing an integer number of rows from the photonic crystal lattice.



SEM image of the resonator structure.

Triggering extreme events at the nanoscale in photonic seas

- The relationship between the phase gap δϕ and the output waveguide width *d* is far from trivial, and is assessed via parallel finite-difference time-domain (FDTD) simulations.
- For *d*≥3, a small gap of ~π/10 opens up, which slowly increases in size for larger *d*.

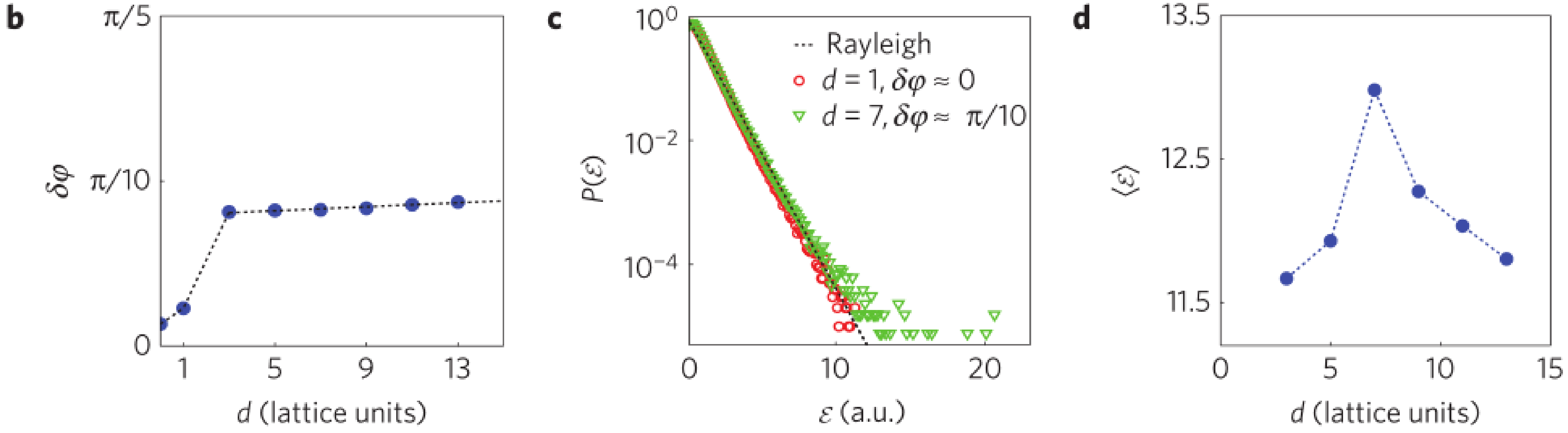


b: Largest gap, δφ, in the phase probability density versus waveguide spacing d. c: Probability distribution of the electromagnetic energy density, E, for d=1 (circle markers), d=7 (triangle markers) and a classical random walk process (dashed line). d: Order parameter, η=<ε>, versus d.

Triggering extreme events at the nanoscale in photonic seas

- The average energy density $\eta =< \varepsilon >$ can be used to measure the largest deviation from the Rayleigh law, and acts as an order parameter for the observation of rogue waves in the system:

$$\eta =< \varepsilon >= \int \varepsilon' P(\varepsilon') d\varepsilon'$$

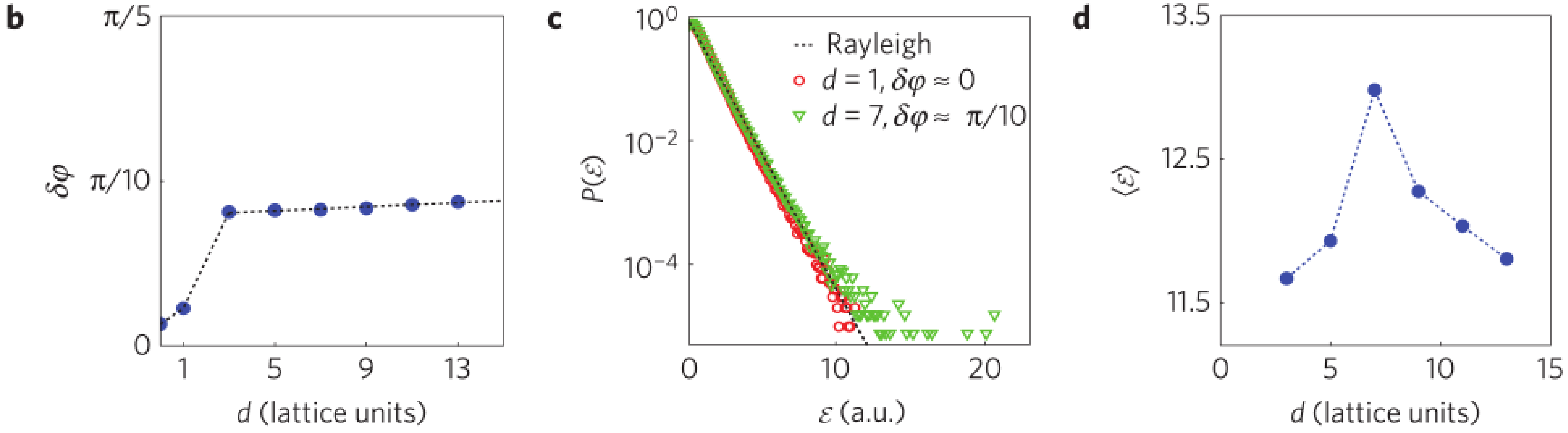


b: Largest gap, δφ, in the phase probability density versus waveguide spacing d. c: Probability distribution of the electromagnetic energy density, E, for d=1 (circle markers), d=7 (triangle markers) and a classical random walk process (dashed line). d: Order parameter, η=<ε>, versus d.

Triggering extreme events at the nanoscale in photonic seas

- For a maximum of $\eta =< \varepsilon >$ around d =7, the rare events of energy twice as high as the Rayleigh limit are observed.

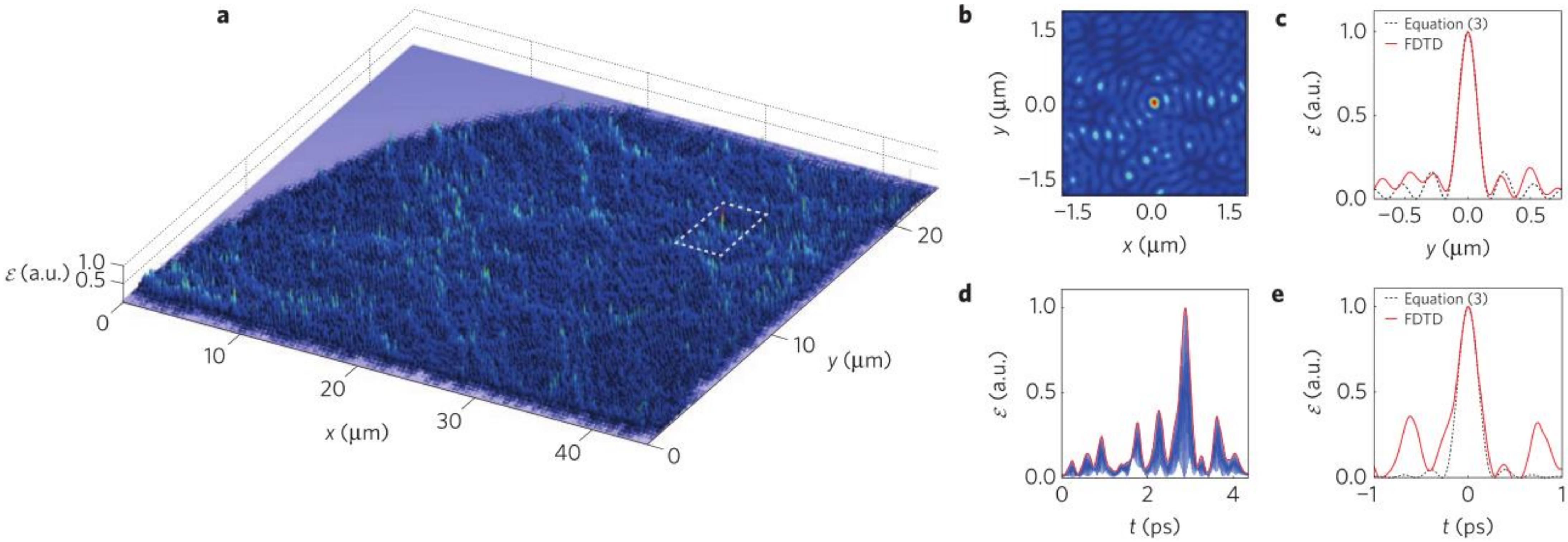
- η vs d plot shows the competition between a larger gap in phase space due to the increase of d and the reduction of the chaotic strength of the cavity due to the larger output waveguides.



b: Largest gap, δφ, in the phase probability density versus waveguide spacing d. c: Probability distribution of the electromagnetic energy density, E, for d=1 (circle markers), d=7 (triangle markers) and a classical random walk process (dashed line). d: Order parameter, η=<ε>, versus d.

Triggering extreme events at the nanoscale in photonic seas

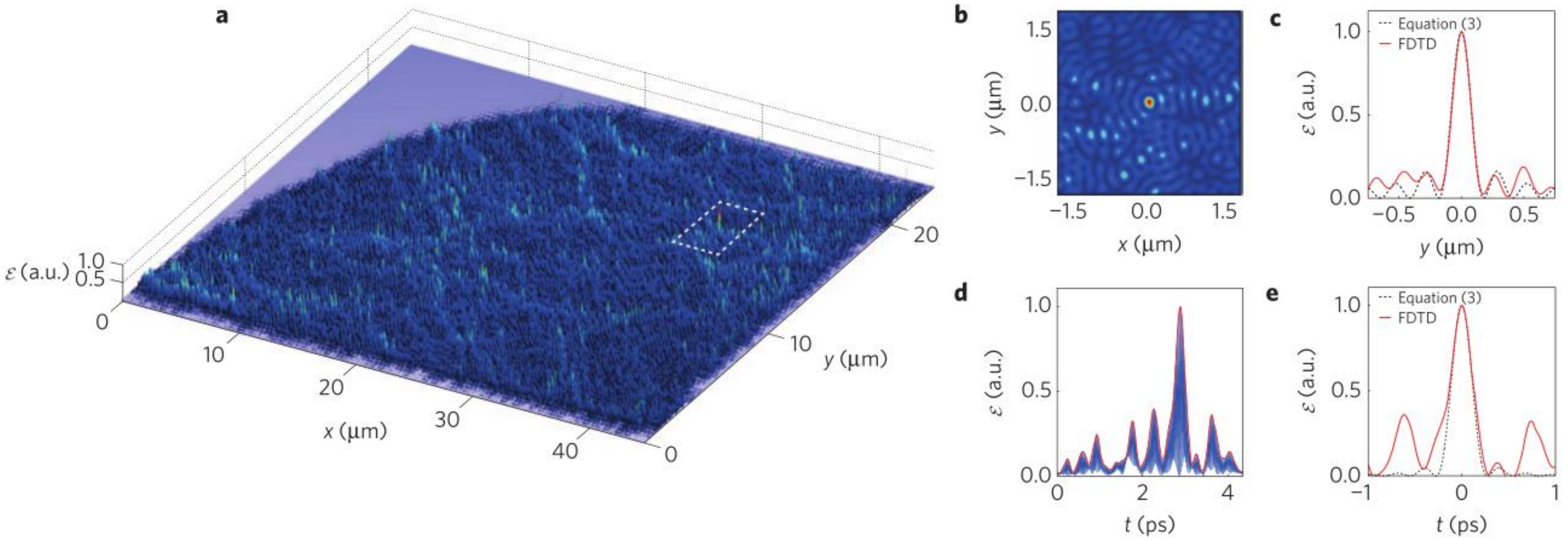
- FDTD results for the optimal case d=7, showing the spatial distribution of the electromagnetic energy density inside the cavity when an isolated rogue wave is formed simultaneously in both space and time:



a: Electromagnetic energy distribution in the cavity in the presence of an extremely localized rogue wave.
b: Zoomed detail on the RW energy peak in the area indicated by the dashed rectangle in a.
c-e: Temporal and spatial dynamics of the RW.

Triggering extreme events at the nanoscale in photonic seas

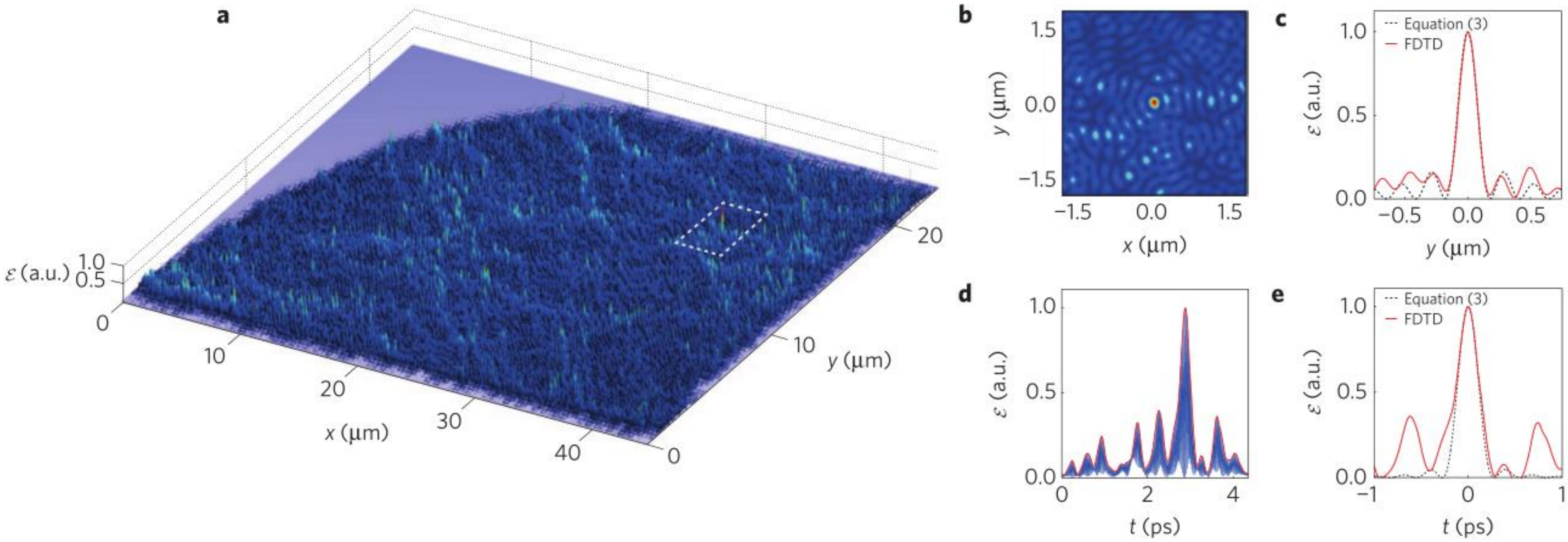
- The spatial hot spot has electromagnetic field 2.51 times higher in space and 2.20 times higher in time than its SWH. The time evolution of the rogue wave exhibits a FWHM of ~250 fs, corresponding to the bandwidth $\delta\lambda = \lambda_0^2\, \delta\omega/2\pi c$ = 30 nm.



a: Electromagnetic energy distribution in the cavity in the presence of an extremely localized rogue wave.
b: Zoomed detail on the RW energy peak in the area indicated by the dashed rectangle in a.
c-e: Temporal and spatial dynamics of the RW.

Triggering extreme events at the nanoscale in photonic seas

- This means that such rogue waves are constructively accessing the spectral energy contained in the whole frequency bandwidth of the field. This also identifies the maximum value of $\eta(d)$ as the maximum energy that can be extracted for the given input bandwidth of 30 nm.



a: Electromagnetic energy distribution in the cavity in the presence of an extremely localized rogue wave.
b: Zoomed detail on the RW energy peak in the area indicated by the dashed rectangle in a.
c-e: Temporal and spatial dynamics of the RW.

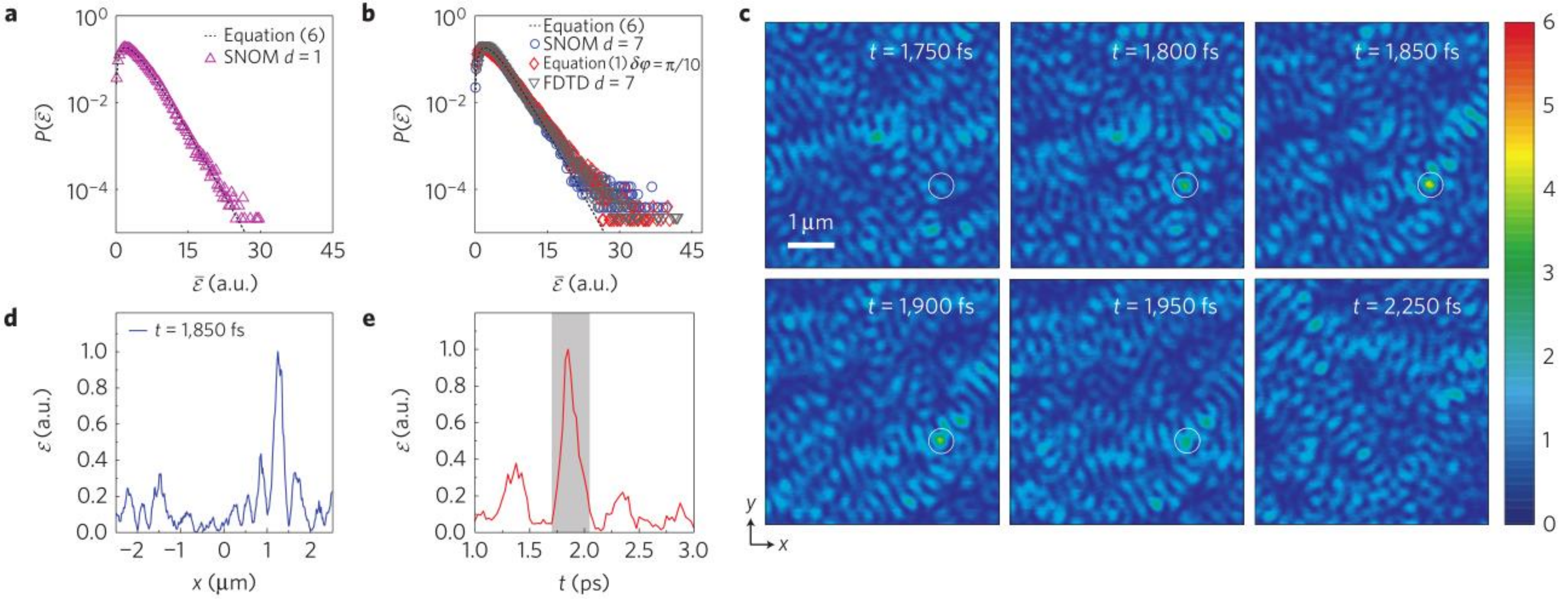
Triggering extreme events at the nanoscale in photonic seas

Experiment:

- A number of silicon-on-insulator planar photonic crystal cavities with output couplers of different widths were fabricated to observe nanoscale RWs on chips.
- The fabrication of optical resonators is realized by a silicon-on-insulator substrate consisting of a 220-nm-thick silicon layer on a 2-μm-thick layer of SiO_2.
- 1,550 nm, 150 fs light pulses were launched into these resonators and the electromagnetic field was imaged with an NSOM (near-field scanning optical microscopy).
- The RW dynamics was recorded only after the light pulse has been inside the cavity for a sufficiently long time to generate a photonic sea.

Triggering extreme events at the nanoscale in photonic seas

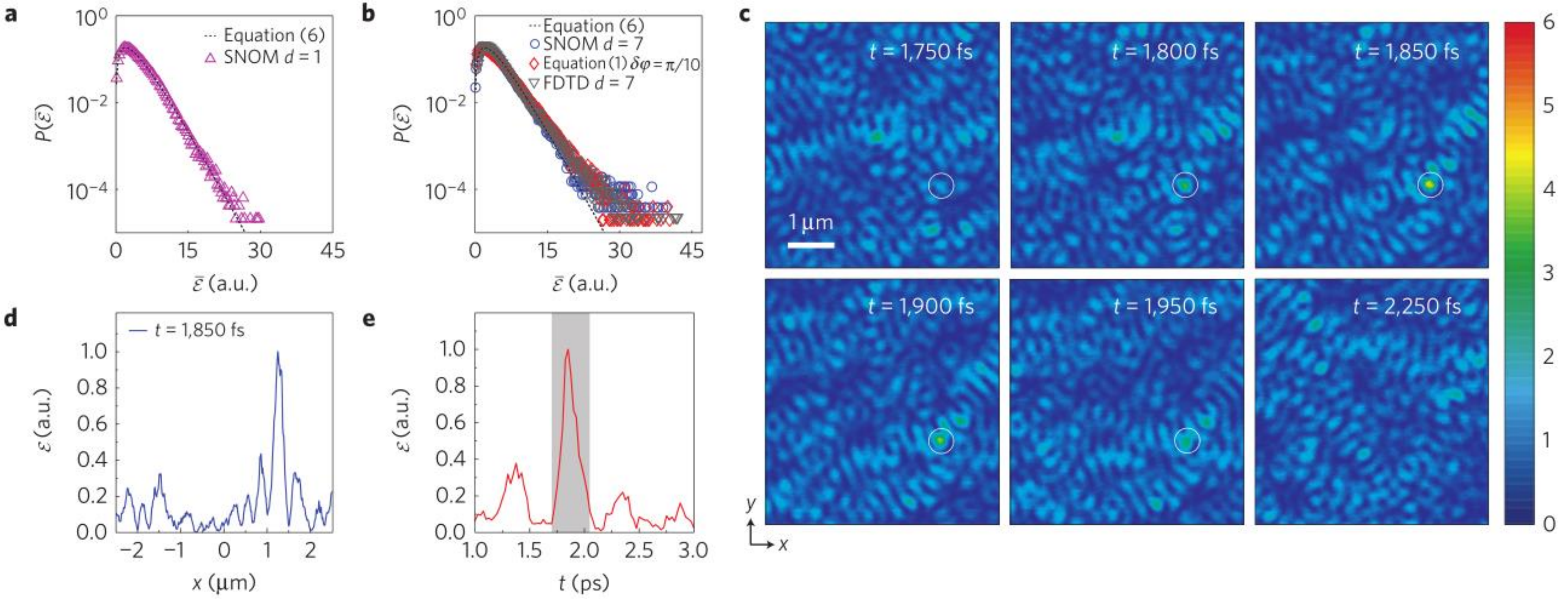
- The statistical analysis of light dynamics inside the optical resonator, providing a quantitative comparison between theory and experimental NSOM results:



a: Time-averaged energy probability density retrieved from NSOM experiments for d=1. b: Comparison of FDTD results and NSOM experiments for the case of d=7. c: Time evolution of the electromagnetic energy density when a nanoscale rogue wave settles in. d,e: Spatial and temporal dynamics of the RW energy peak.

Triggering extreme events at the nanoscale in photonic seas

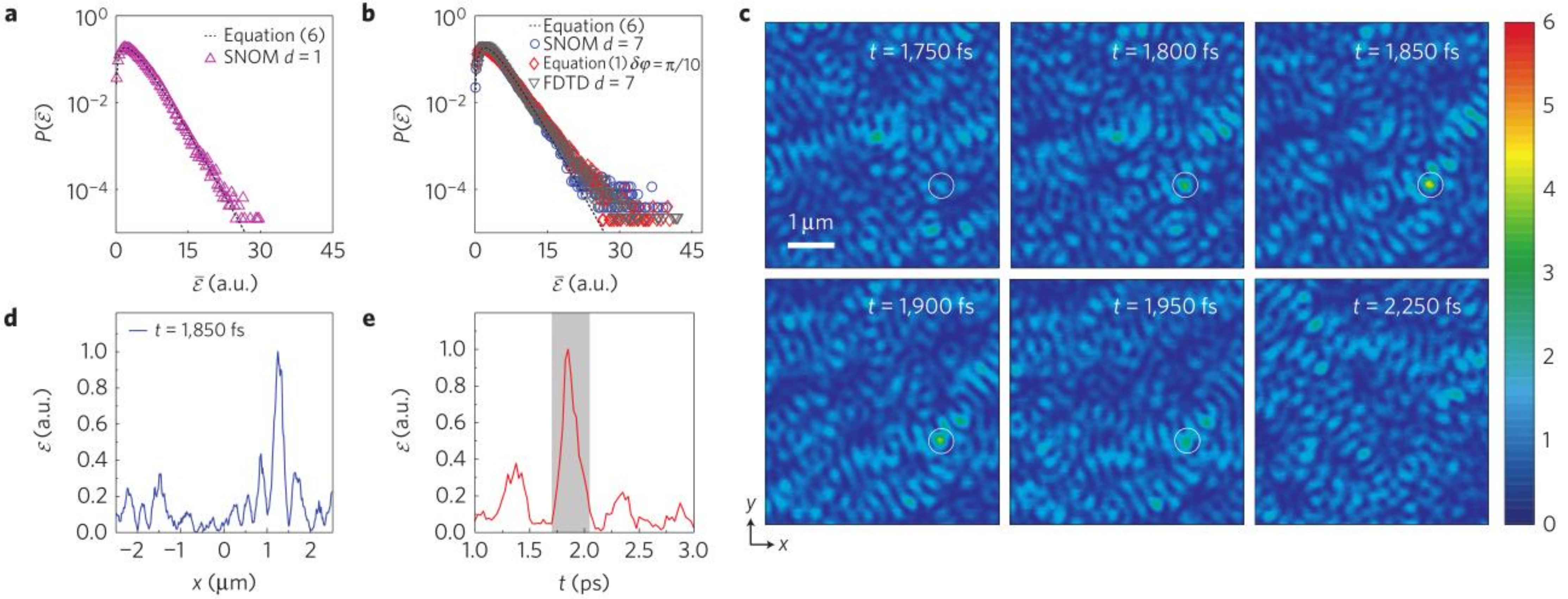
- The experimentally generated rogue waves exhibit a field peak amplitude that is 2.41 times higher than their SWH in space and 2.1 times higher in time.



a: Time-averaged energy probability density retrieved from NSOM experiments for d=1. b: Comparison of FDTD results and NSOM experiments for the case of d=7. c: Time evolution of the electromagnetic energy density when a nanoscale rogue wave settles in. d,e: Spatial and temporal dynamics of the RW energy peak.

Triggering extreme events at the nanoscale in photonic seas

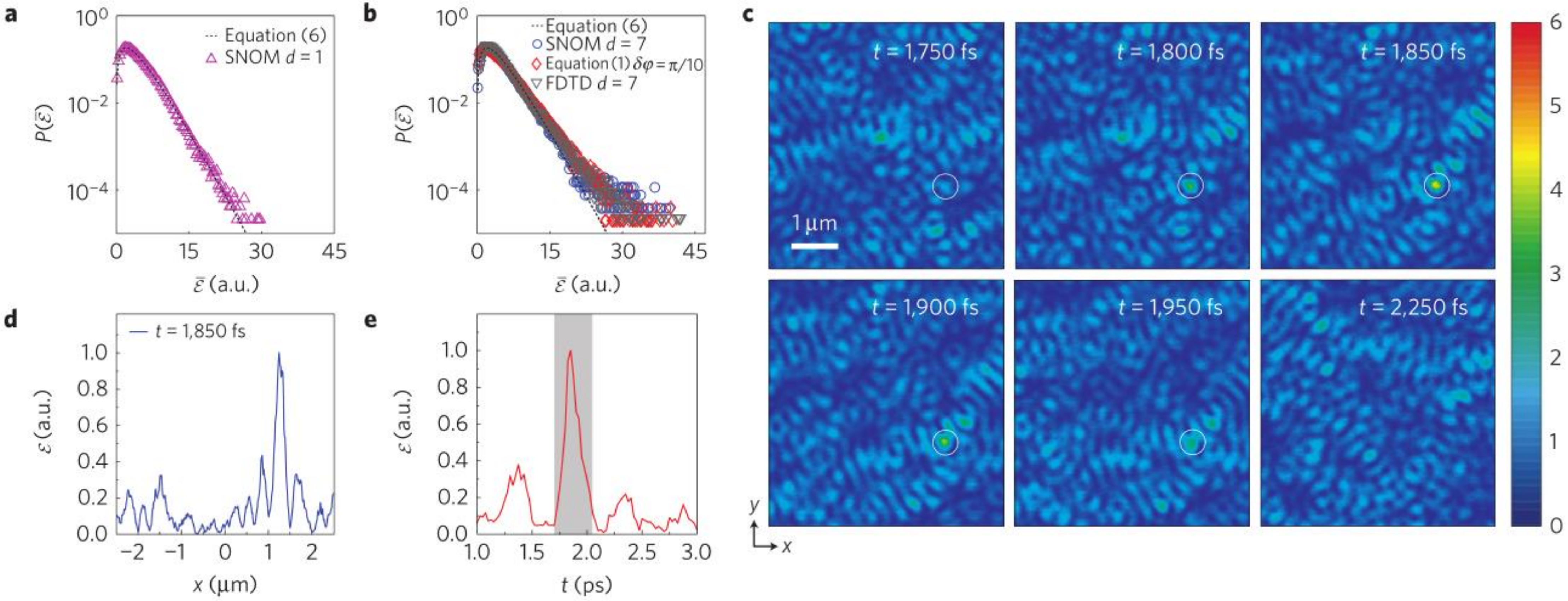
- Experimentally generated RWs exhibit a subwavelength spatial FWHM of 206 nm, which is 25% smaller than λ/2n=287 nm (n=2.7 is the eff. index of the guided modes inside the cavity).



a: Time-averaged energy probability density retrieved from NSOM experiments for d=1. b: Comparison of FDTD results and NSOM experiments for the case of d=7. c: Time evolution of the electromagnetic energy density when a nanoscale rogue wave settles in. d,e: Spatial and temporal dynamics of the RW energy peak.

Triggering extreme events at the nanoscale in photonic seas

- The temporal FWHM extension of the rogue wave is 163 fs and corresponds to a bandwidth of δλ=49 nm, which matches the full electromagnetic field bandwidth (≈50 nm).



a: Time-averaged energy probability density retrieved from NSOM experiments for d=1. b: Comparison of FDTD results and NSOM experiments for the case of d=7. c: Time evolution of the electromagnetic energy density when a nanoscale rogue wave settles in. d,e: Spatial and temporal dynamics of the RW energy peak.

Triggering extreme events at the nanoscale in photonic seas

Conclusions:

- Proposed and demonstrated a simple integrated platform that generates ultrafast rare events, which exploit the spectral energy of the full frequency bandwidth of an incoherent field to build up nanostructures of light with giant intensity.
- The analytical model, FDTD simulations and experimental observations agree extremely well, showing that the statistics of these ultrashort subwavelength structures can be generated on demand, including their spatio-temporal shape.

Triggering extreme events at the nanoscale in photonic seas

Applications:

- The reported chaotic resonators open up new possibilities, both in fundamental and applied science.
- The use of rare events provides an alternative approach for generating subdiffraction-limited light using randomness.
- Many applications may benefit from such an extreme light–matter interaction, where their appearance is not constrained to any specific position but conversely requires a large intensity and a given distribution.
- These range from extremely sensitive spectrometers based on speckle, to new sensing apparatus based on random light patterns randomly displaced in two dimensions, low-threshold lasers sustained by randomly localized electromagnetic modes, and new energy-harvesting devices relying on chaotic light motion.

References

[1] C. Liu, R. E. C. van der Wel, N. Rotenberg, L. Kuipers, T. F. Krauss, A. Di Falco and A. Fratalocchi, Triggering extreme events at the nanoscale in photonic seas, NATURE PHYSICS, 11, 358–363, 2015

[2] John M. Dudley, Goëry Genty, Arnaud Mussot, Amin Chabchoub and Frédéric Dias, Rogue waves and analogies in optics and oceanography, Nature Reviews Physics, vol. 1, p. 675–689, 2019

[3] Solli D.R., Ropers C., Koonath P. and Jalali B., Optical rogue waves, Nature 450 1054, 2007

[4] Akhmediev, N. et al. Roadmap on optical rogue waves and extreme events. J. Opt. 18, 063001, 2016.

[5] Cristina Rimoldi, Franco Prati, Stéphane Barland, Giovanna Tissoni, Optical Rogue Waves in a Laser with Saturable Absorber

[6] Pierre Suret, Pierre Walczak, and Stephane Randoux, Optical Rogue Waves in integrable turbulence, Phys. Rev. Lett. 114, 143903, 2015.

[7] Yuliy V. Bludov, Vladimir V. Konotop, and Nail Akhmediev, Rogue waves as spatial energy concentrators in arrays of nonlinear waveguides, Opt. Lett. 34, 3015-3017, 2009

[8] C. D. Pelwan, A. Quandt, and R. Warmbier, Onset times of long-lived rogue waves in an optical waveguide array, J. Opt. Soc. Am. A 37, C67-C72, 2020

[9] Yu V. Bludov, R. Driben, V. V. Konotop, and B. A. Malomed, Instabilities, solitons and rogue waves in PT-coupled nonlinear waveguides, J. Opt. 15, 064010, 2013.