Soliton Molecules and Optical Rogue Waves

Benasque, October 2014

INSTITUT FÜR PHYSIK

Fedor Mitschke
Universität Rostock, Institut für Physik

fedor.mitschke@uni-rostock.de

Part V a

Optical Supercontinuum

Why generate broadband light from lasers?

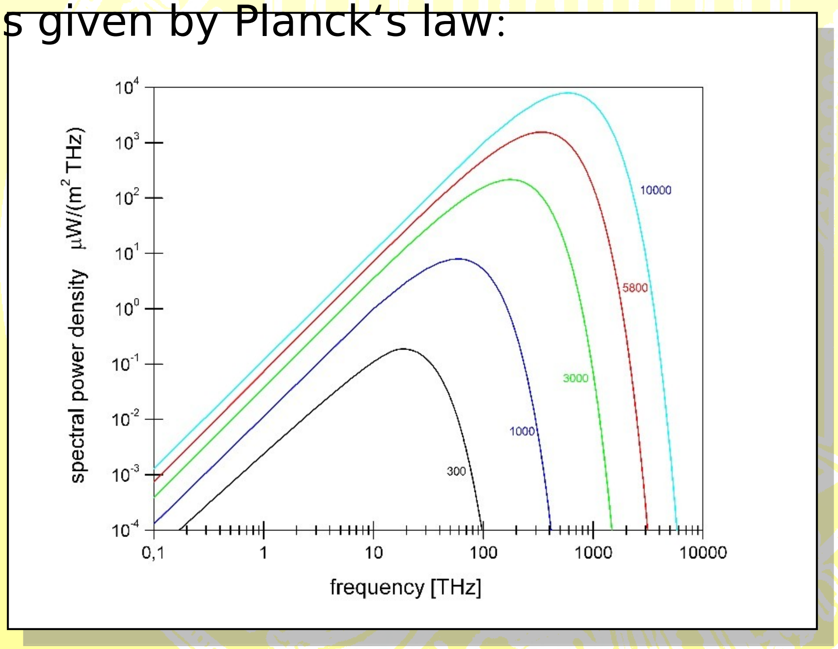
Lasers are the ultimate narrowband (long temporal coherence) sources,
but broadband (temporally incoherent) light also has many uses, e.g.:

- coherence tomography
- metrology

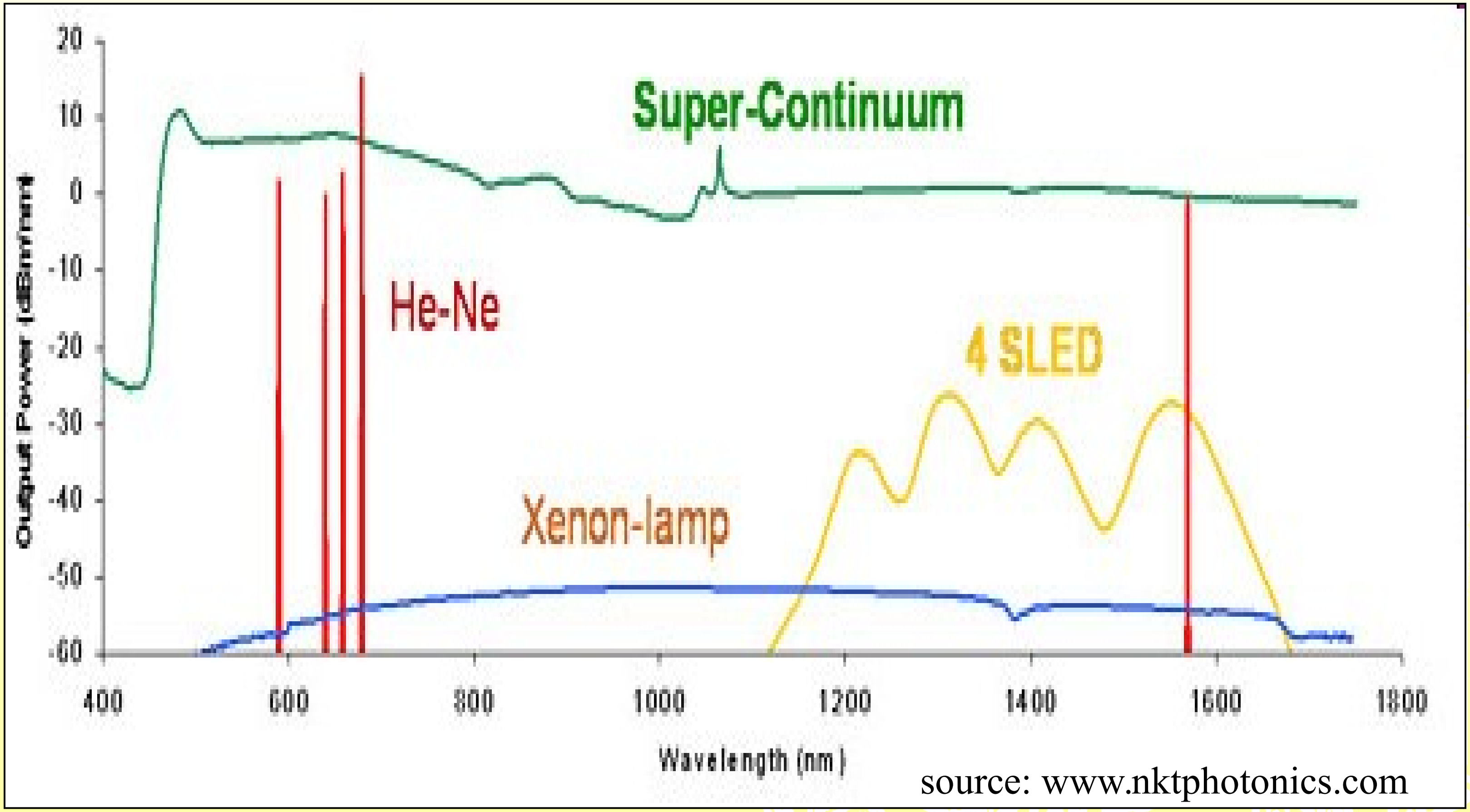
Spectral power density of thermal light is given by Planck‘s law:

$$I_\nu d\nu = \frac{2\pi h\nu^3}{c^2}\,\frac{1}{e^{\frac{h\nu}{kT}}-1}\,d\nu$$

at any frequency ν,
there is a single parameter T



Why generate broadband light from lasers?

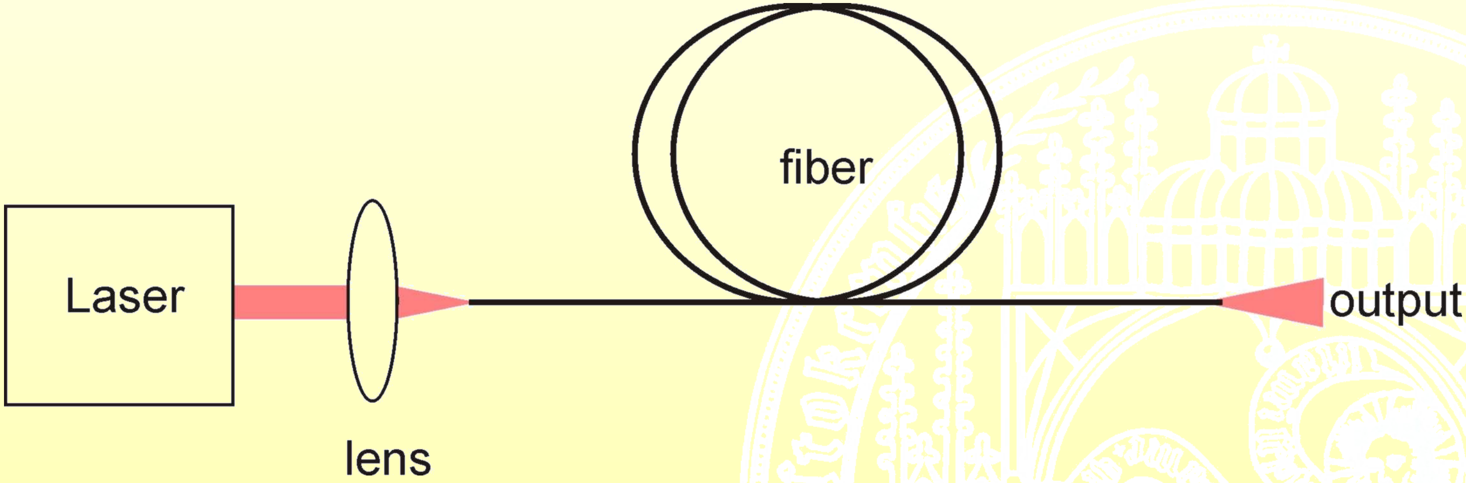


source: www.nktphotonics.com

... to overcome the Planck barrier!

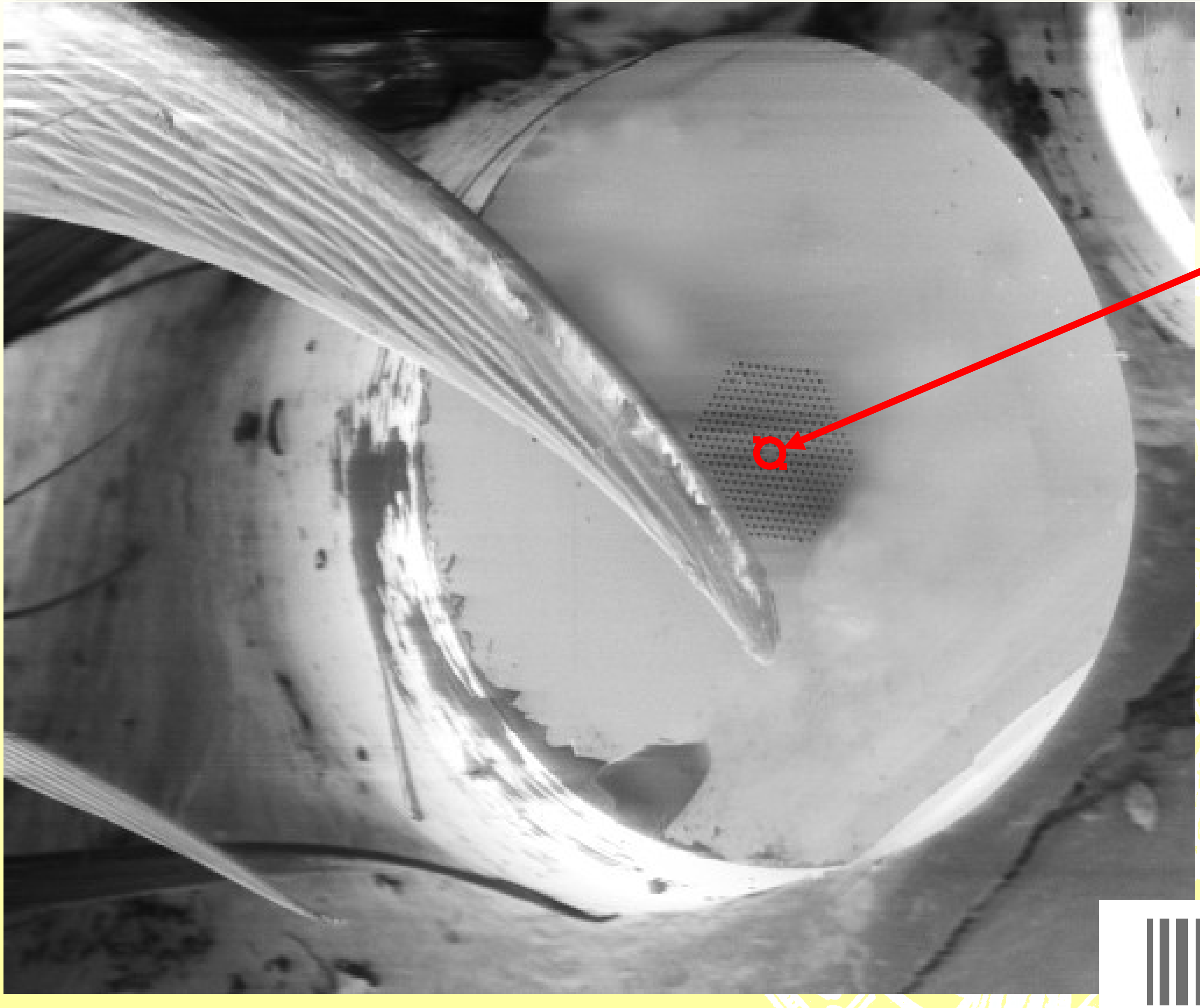
How to generate broadband light from lasers

The standard setup:



- high laser power
- highly nonlinear fiber

microstructured fiber

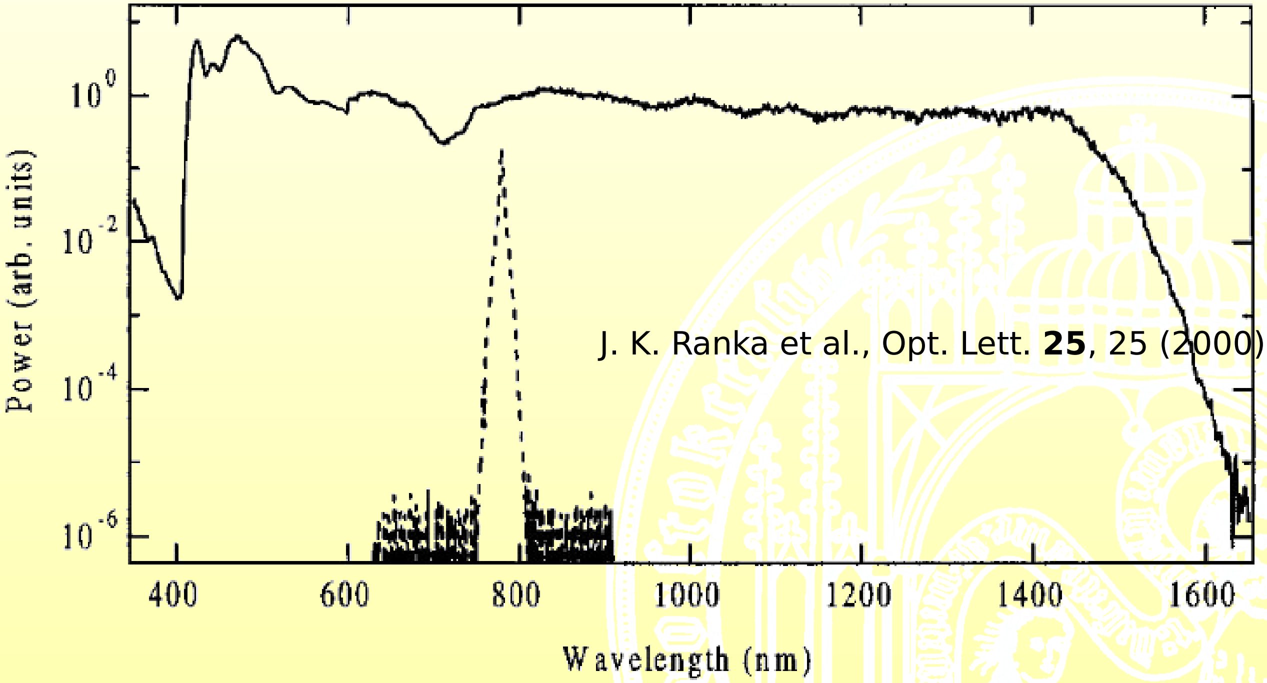


light-guiding core

holey fiber and the tarsal claw of an ant

No universal definition of supercontinuum.

» Spectral width close to one octave or beyond «



J. K. Ranka et al., Opt. Lett. **25**, 25 (2000)

Supercontinuum generated in 75 cm of microstructured fiber, covering ca. two octaves. Inset: initial 100-fs pulse

How does the structure arise?

- For fs pump pulses: soliton fission, subsequent soliton frequency shift

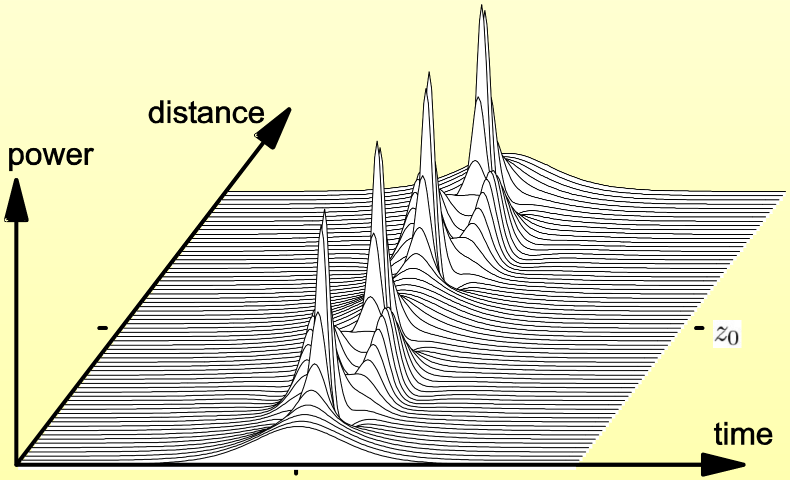
  For ps and longer pump: length scale for fission to arise may be longer than fiber. Dominant process is modulation instability sideband generation.

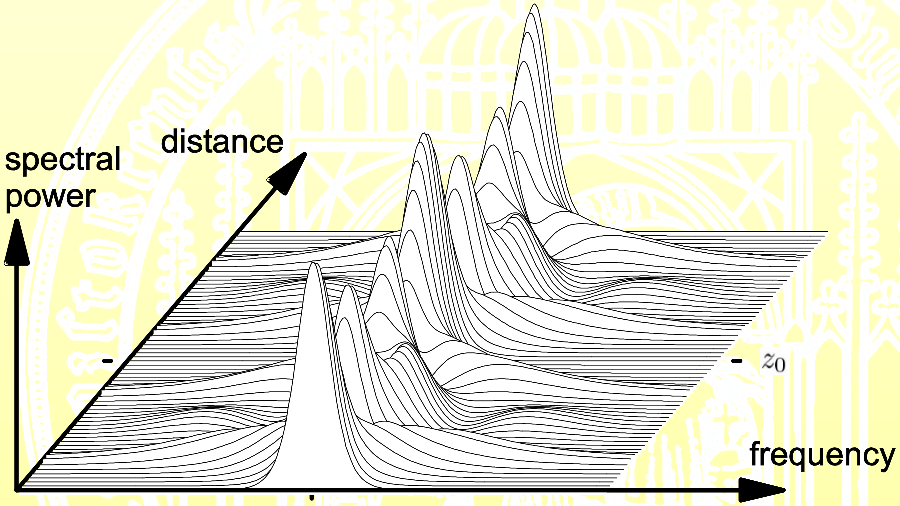
higher-order solitons

$$\boxed{P_1 T_0^2 = N^2 \frac{|\beta_2|}{\gamma}}$$

Length scale $z_0 = \frac{\pi}{2} L_{\mathrm{D}} = \frac{\pi}{2} \frac{T_0^2}{|\beta_2|}$

$N = 3$





How does the structure arise?

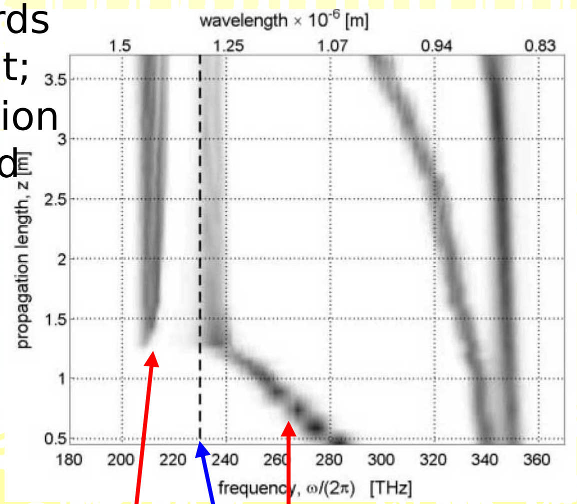
- For fs pump pulses: soliton fission, subsequent soliton frequency shift

  For ps and longer pump: length scale for fission to arise may be longer than fiber. Dominant process is modulation instability sideband generation.

- Then, all kinds of interactions:
  Raman shifting, four-wave mixing, coupling between solitons and radiation, etc.

- The dispersion curve determines frequency pairs for phase-matching between two waves

- Example: A soliton which gets Raman-shifted towards a zero-dispersion wavelength (β_3<0) will not cross it; some of its energy will leak into the normal dispersion regime as a dispersive wave which remains coupled to the soliton



radiation

soliton

zero dispersion wavelength

Skryabin *et al.*, Science **301**, 1705 (2003

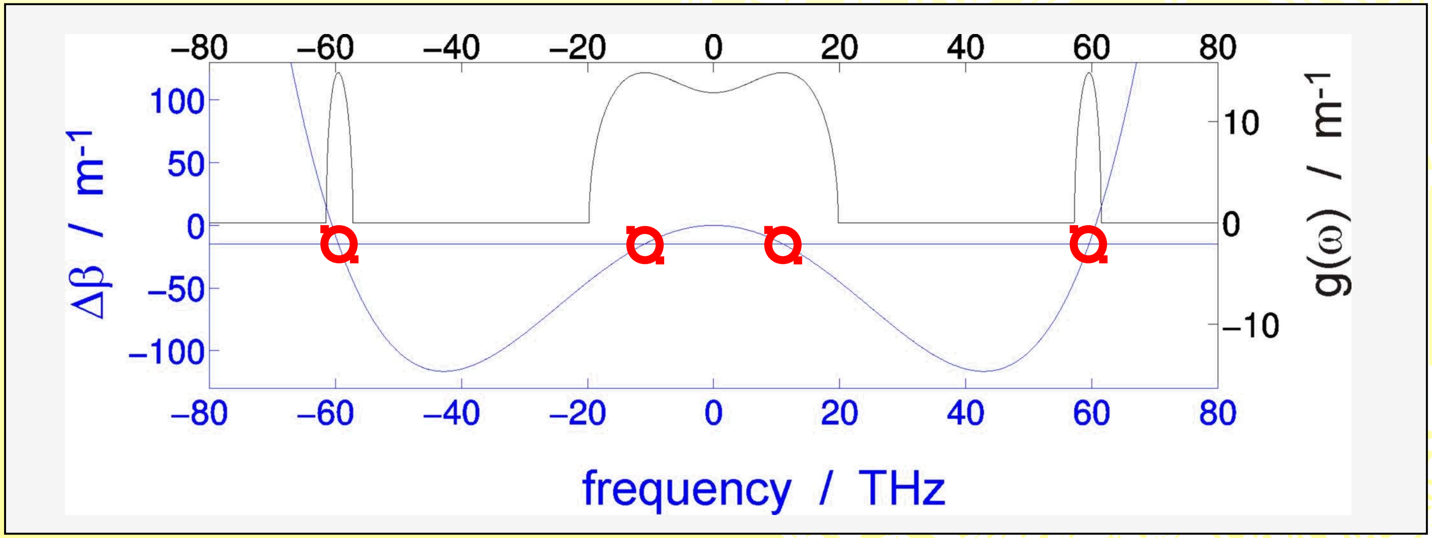
Spectrum may exhibit peaks placed symmetrically to carrier: four wave mixing

phase matching yields possible FWM frequencies:

$$\Delta\beta = \beta(\omega_\mathrm{p} + \Delta\omega) + \beta(\omega_\mathrm{p} - \Delta\omega) - 2\beta(\omega_\mathrm{p}) + 2\gamma\hat{P} = 0$$

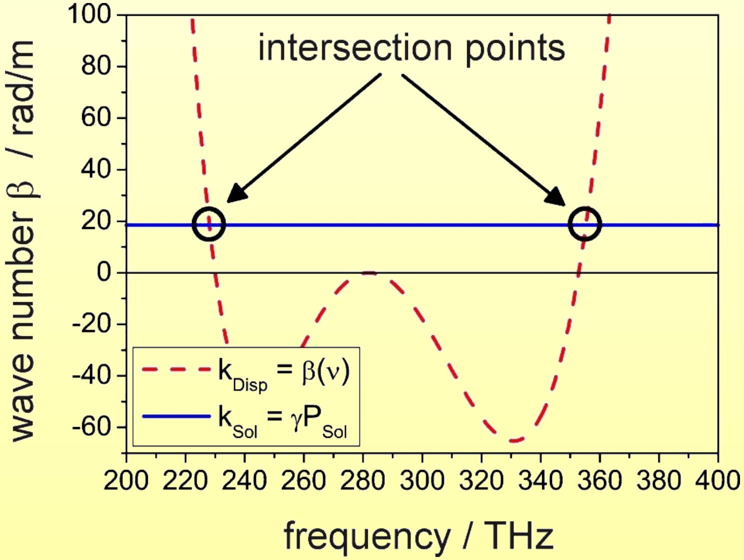
inserting the series expansion of β, odd terms cancel:

$$\frac{\beta_2}{2!}(\Delta\omega)^2 + \frac{\beta_4}{4!}(\Delta\omega)^4 + \ldots + \gamma\hat{P} = 0$$

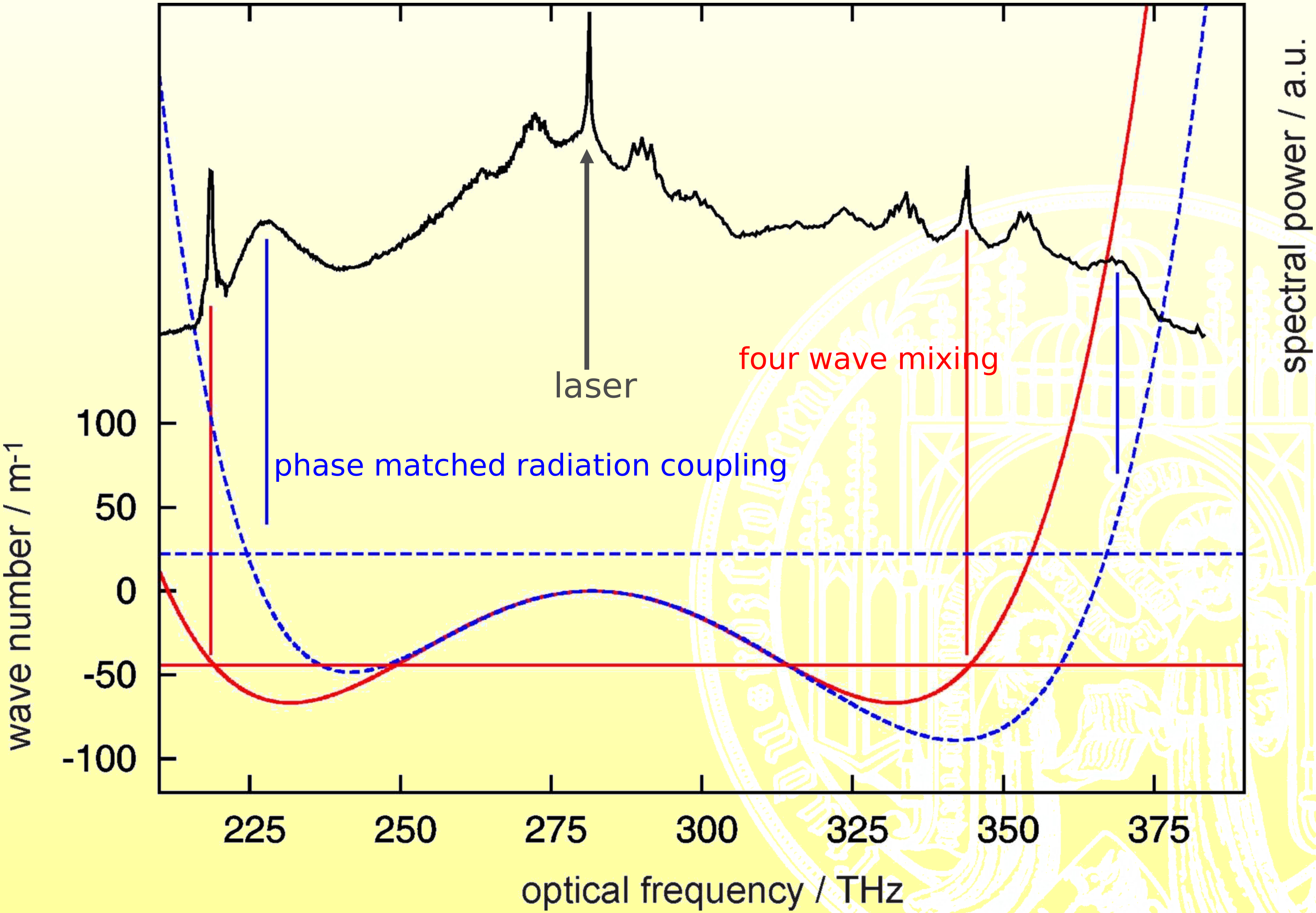


Spectrum may exhibit peaks placed asymmetrically to carrier: Coupling to radiation

$$\frac{\beta_2}{2!}(\Delta\omega)^2 + \frac{\beta_3}{3!}(\Delta\omega)^3 + \ldots = \gamma\hat{P}$$



Interpretation of such a spectrum



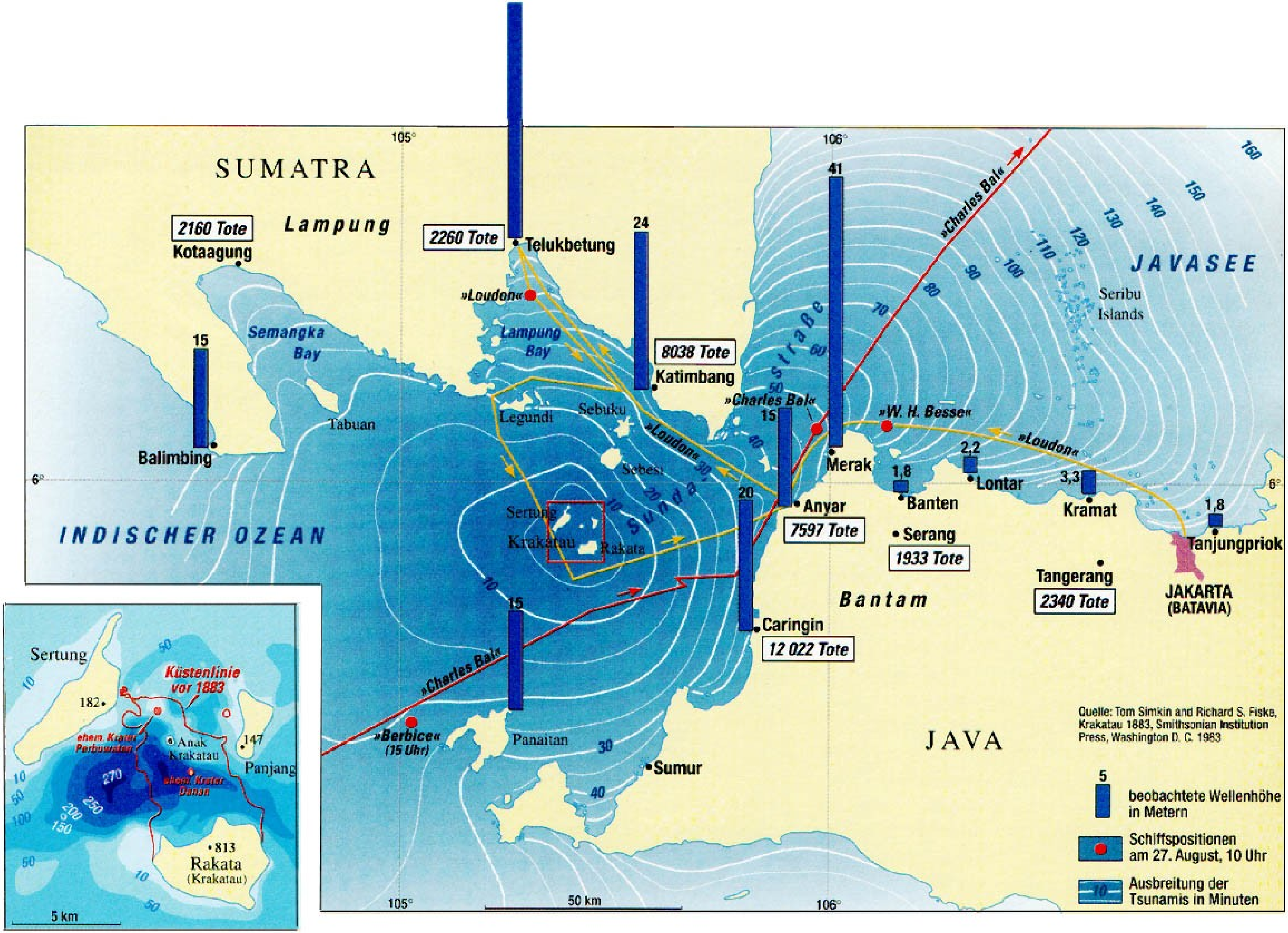
review article

J. M. Dudley, G. Genty, S. Coen,
"Supercontinuum Generation in Photonic Crystal Fiber,"
Reviews of Modern Physics **78,** 1135-1184 (2006)

Part V b

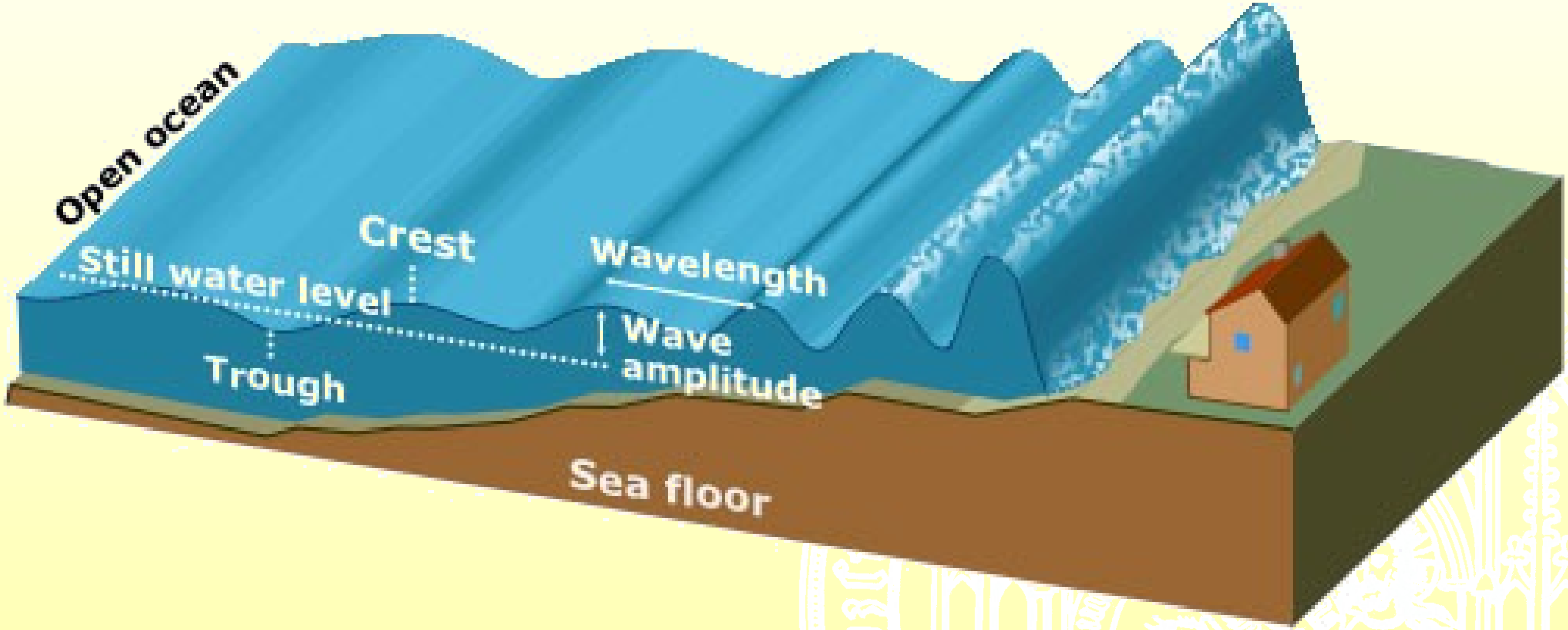
Some analogies to water waves: Tsunamis and Rogue Waves

The Krakatoa Tsunami, 20.5.1883



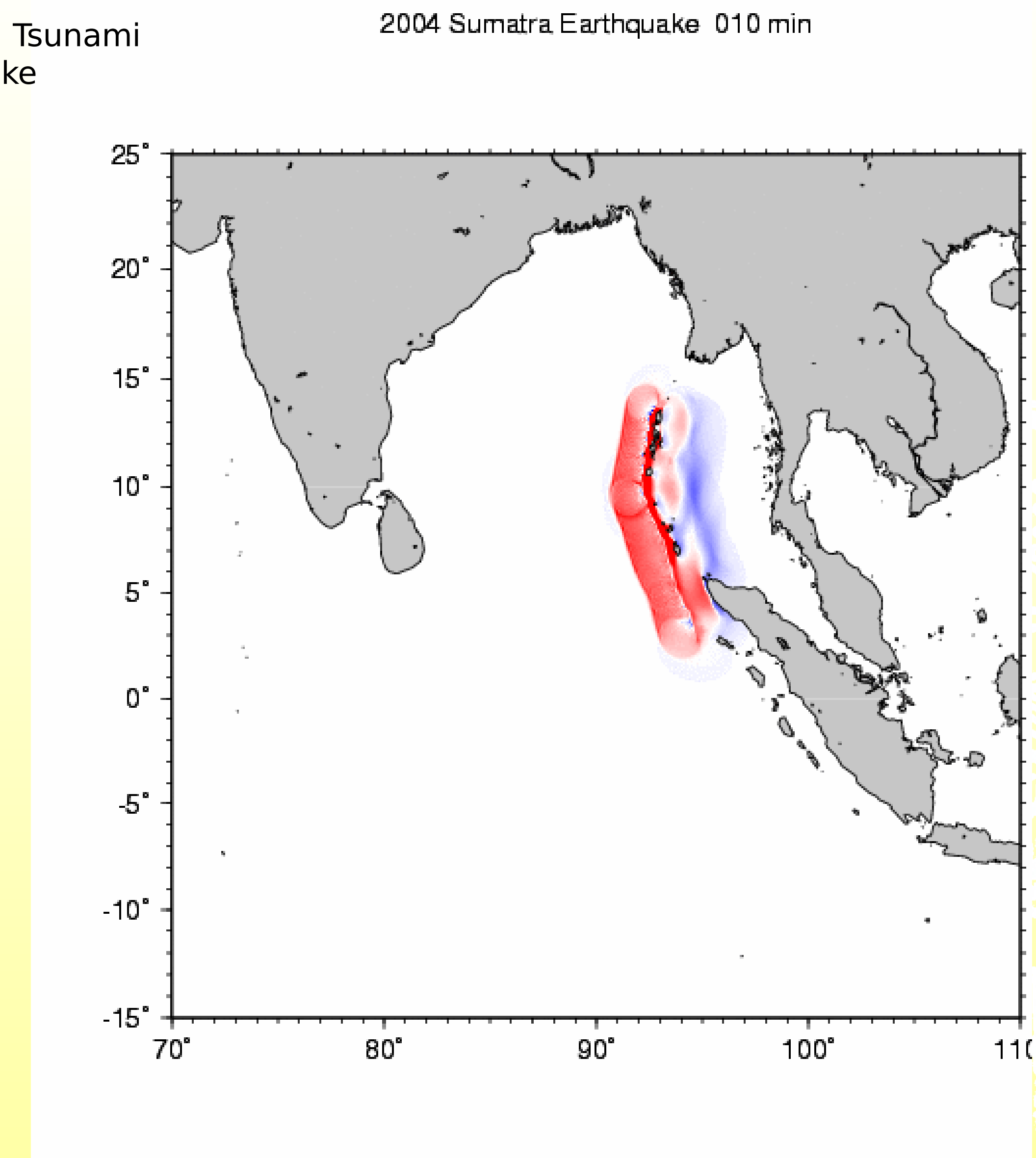
crest heigh

after GEO Special INDONESIEN (April 1995)



A tsunami slows down in shallower water; therefore the crest go

Courtesy Unesco International Tsunami Information Center, Kenji Satake



The devastating tsunami of 2004

Rogue Waves

Donald Sinclair Swan: The Great Wa

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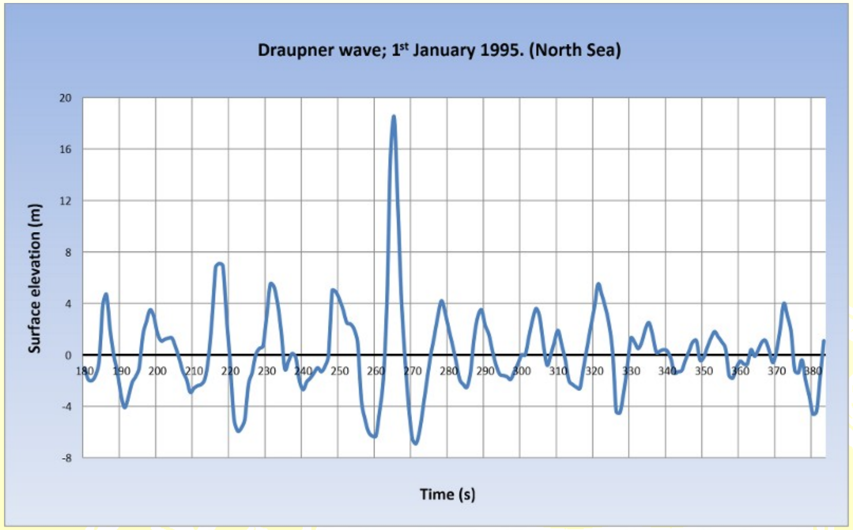
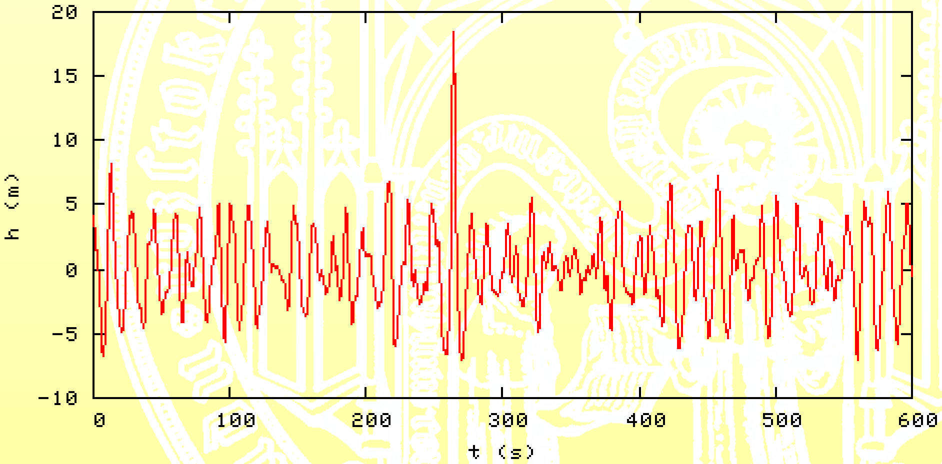
Draupner platform

Location: North Sea, 160 km offshore Norway.
Seven risers, two riser platforms
standing in 70 metres water depth.





A ship after being damaged by a rogue wave.

Photo credit: H. Gunther and W. Rosenthal, source- http://en.es-static.us/upl/2011/04/wave_destruction.jpeg

nature Vol 450|13 December 2007|doi:10.1038/nature06402

LETTERS

Optical rogue waves

D. R. Solli[1], C. Ropers[1,2], P. Koonath[1] & B. Jalali[1]

Recent observations show that the probability of encountering an extremely large rogue wave in the open ocean is much larger than expected from ordinary wave-amplitude statistics[1–3]. Although considerable effort has been directed towards understanding the physics behind these mysterious and potentially destructive events, the complete picture remains uncertain. Furthermore, rogue waves have not yet been observed in other physical systems. Here, we introduce the concept of optical rogue waves, a counterpart of the infamous rare water waves. Using a new real-time detection technique, we study a system that exposes extremely steep, large waves as rare outcomes from an almost identically prepared initial population of waves. Specifically, we report the observation of rogue waves in an optical system, based on a microstructured optical fibre, near the threshold of soliton-fission supercontinuum generation[4,5]—a noise-sensitive[5–7] nonlinear process in which extremely broadband radiation is generated from a narrowband input[8]. We model the generation of these rogue waves using the generalized nonlinear Schrödinger equation[9] and demonstrate that they arise infrequently from initially smooth pulses owing to power transfer seeded by a small noise perturbation.

For centuries, seafarers have told tales of giant waves that can appear without warning on the high seas. These mountainous waves were said to be capable of destroying a vessel or swallowing it beneath the surface, and then disappearing without the slightest trace. Until

Although the physics behind rogue waves is still under investigation, observations indicate that they have unusually steep, solitary or tightly grouped profiles, which appear like "walls of water"[10]. These features imply that rogue waves have relatively broadband frequency content compared with normal waves, and also suggest a possible connection with solitons—solitary waves, first observed by J. S. Russell in the nineteenth century, that propagate without spreading in water because of a balance between dispersion and nonlinearity. As rogue waves are exceedingly difficult to study directly, the relationship between rogue waves and solitons has not yet been definitively established, but it is believed that they are connected.

So far, the study of rogue waves in the scientific literature has focused on hydrodynamic studies and experiments. Intriguingly, there are other physical systems that possess similar nonlinear characteristics and may also support rogue waves. Here we report the observation and numerical modelling of optical rogue waves in a system based on probabilistic supercontinuum generation in a highly nonlinear microstructured optical fibre. We coin the term 'optical rogue waves' based on striking phenomenological and physical similarities between the extreme events of this optical system and oceanic rogue waves.

Supercontinuum generation has received a great deal of attention in recent years for its complex physics and wealth of potential applications[5,8]. An extremely broadband supercontinuum source can be cre-

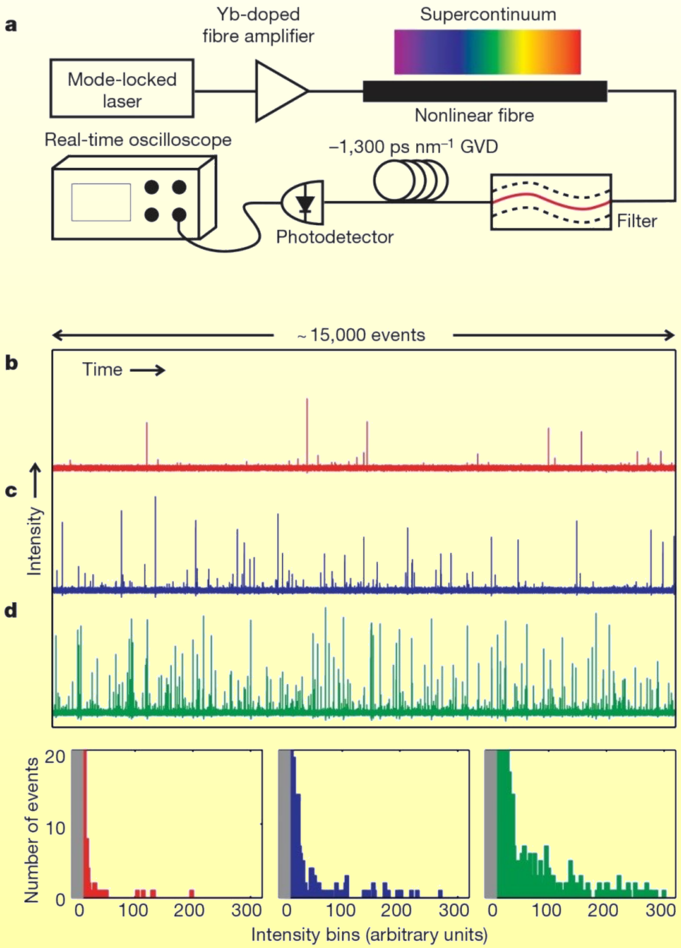
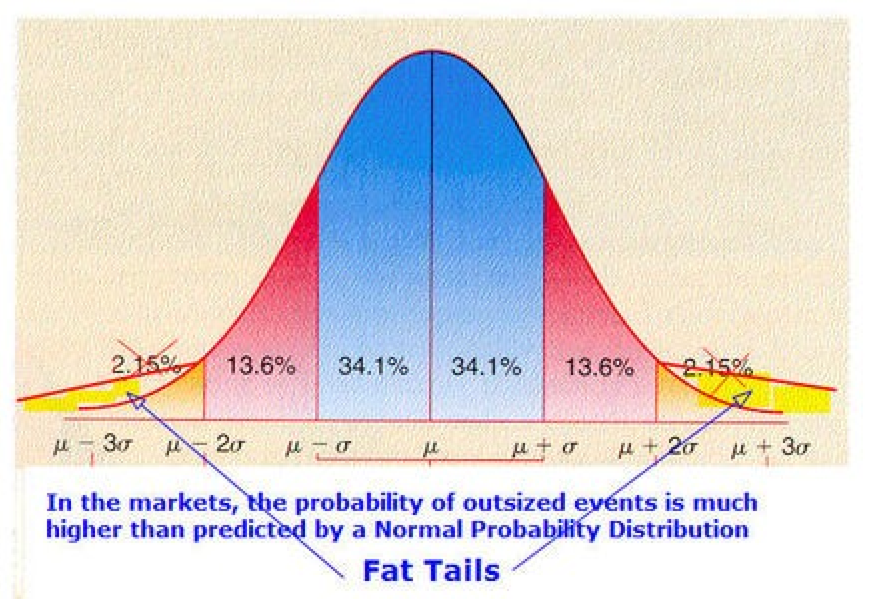


Figure 1 | Experimental observation of optical rogue waves. a, Schematic of experimental apparatus. **b–d**, Single-shot time traces containing roughly 15,000 pulses each and associated histograms (bottom of figure: left, **b**; middle, **c**; right, **d**) for average power levels 0.8 μW (red), 3.2 μW (blue) and 12.8 μW (green), respectively. The grey shaded area in each histogram demarcates the noise floor of the measurement process. In each measurement, the vast majority of events (>99.5% for the lowest power) are buried in this low intensity range, and the rogue events reach intensities of at least 30–40 times the average value. These distributions are very different from those encountered in most stochastic processes.

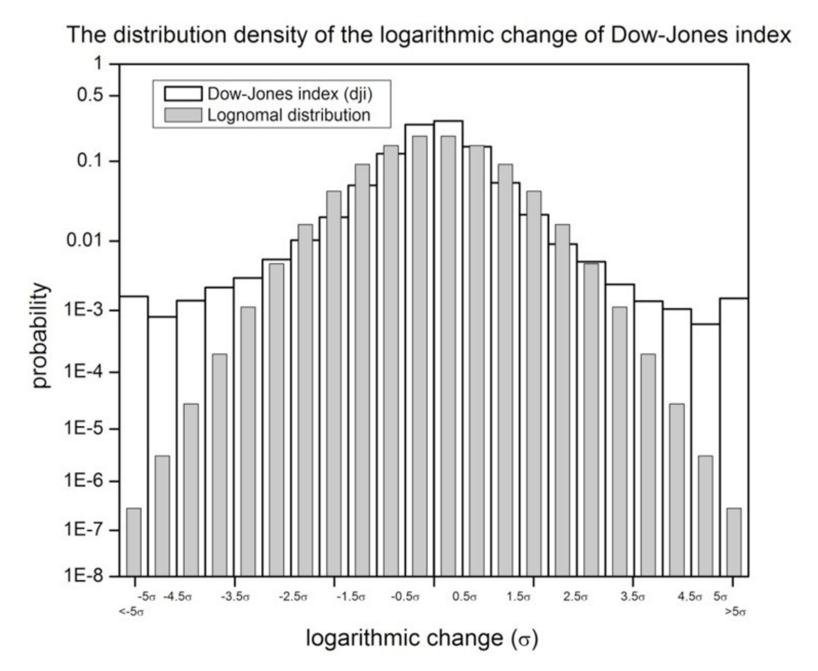
Fat-tail statistics actually occurs in many contexts



In the markets, the probability of outsized events is much higher than predicted by a Normal Probability Distribution

Fat Tails

www.stock-options-made-easy.com

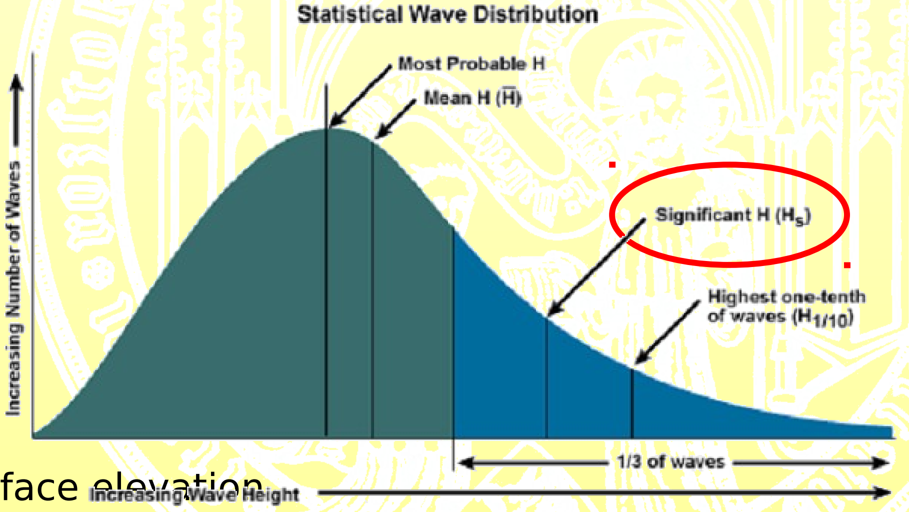

The distribution density of the logarithmic change of Dow-Jones index

.worldeconomicsassociation.org

What is the definition of an optical rogue wave?

Rogue (freak, monster, killer, extreme, abnormal) waves
are usually understood to be defined by three properties:

- They appear ‚out of nowhere‘ and disappear ‚without a trace‘ just as sud
- Their crest height exceeds that of other waves considerably
  In hydrodynamics, at least twice the significant wave height
- The amplitude statistics displays a fat tail



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Significant wave height in hydrodynamics:
1) mean wave height (trough to crest)
   of the highest third of the waves
2) four times the standard deviation of the surface elevation

Optical rogue waves:
typically discussed in context of supercontinuum genera

Different explanations for their generation have been a
including

- ➢ Largest soliton systematically shifted to long-wavelength side

  Solli *et al.* Nature (2007)

- ➢ Collision of solitons

  Mussot *et al.* Opt. Express (2009); Erkintalo *et al.* Opt. Lett. (2010)

- ➢ Collision of Akhmediev Breathers

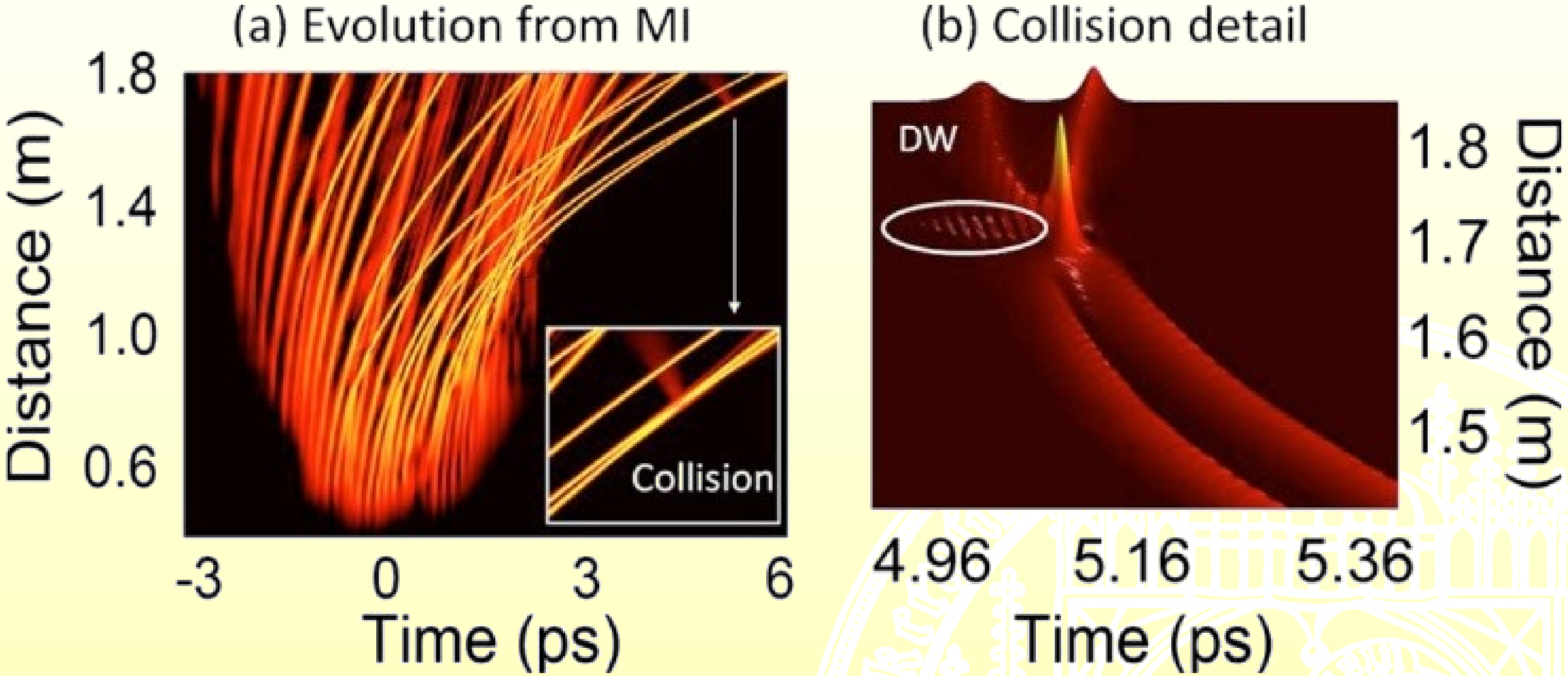
  Akhmediev *et al.* Phys. Lett. A (2009)

- ➢ A Peregrine soliton

  Kibler *et al.* Nature Physics (2010)

- ➢ Collision of soliton with dispersive wave; energy transfer to soliton

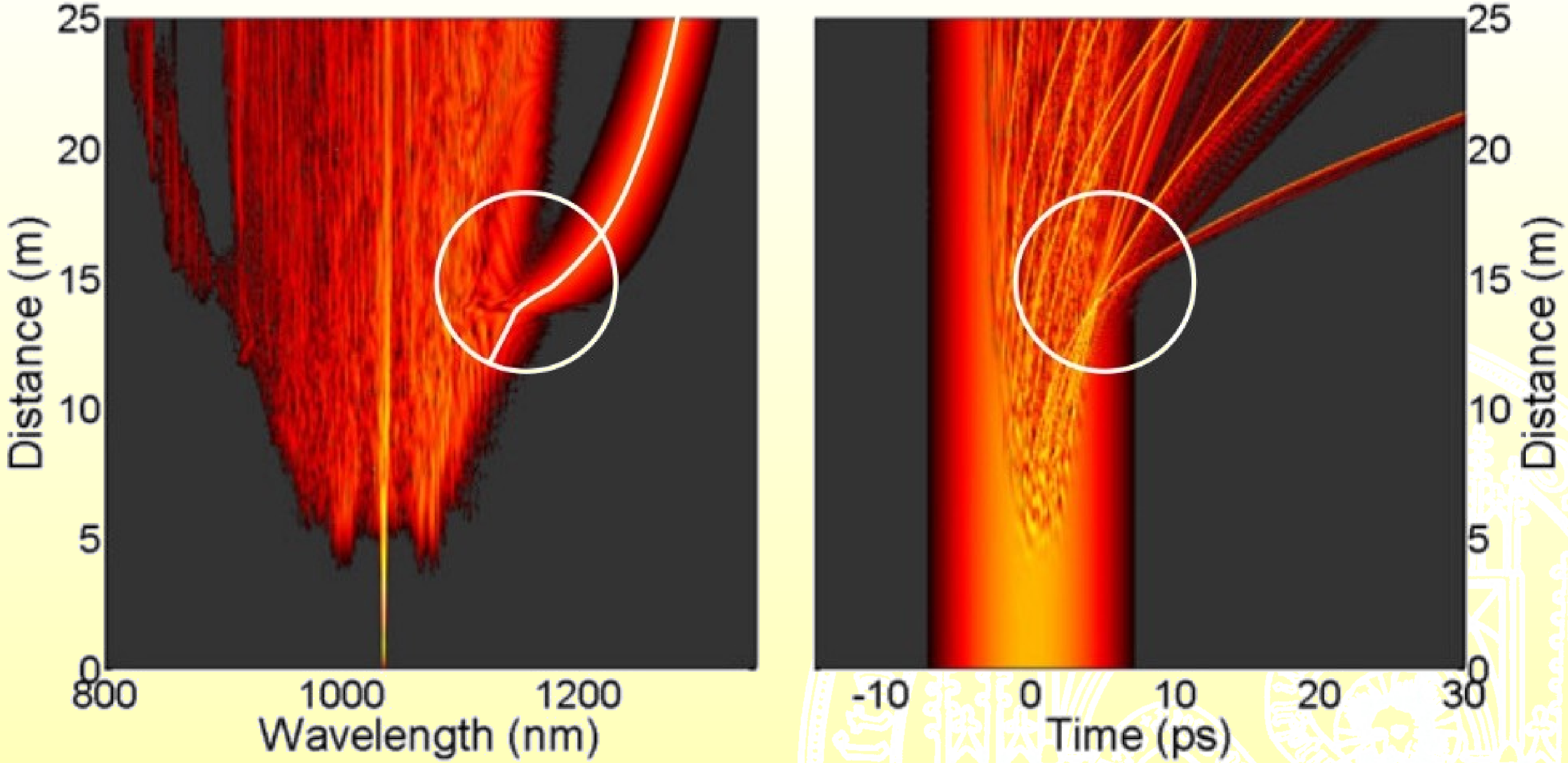
  Driben *et al.* Opt. Express (2010); Demircan *et al.*



M. Erkintalo, G. Genty, J. M. Dudley, Opt. Lett. **35**, 658

Left:
From modulational instability / Akhmediev breather arises a number of solitons, subject to Raman shifting and cross phase modulation. Occasionally collisions occ

Right:
3-D rendering of inset shows a large peak arising. It sheds dispersive waves



M. Erkintalo, G. Genty, J. M. Dudley, Eur. Phys. J. Special Topics **185**, 135 (20

Optical rogue wave formation by soliton collision (density plot; simulation)
The point of collision and following transient behavior in the spectrum is emphasized by w

Energy transfer to and velocity change of the lower frequency soliton is appare

Optical rogue waves:
typically discussed in context of supercontinuum genera

Different explanations for their generation have been a
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  Solli *et al.* Nature (2007)
- Collision of solitons
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- Collision of soliton with dispersive wave; energy transfer to soliton
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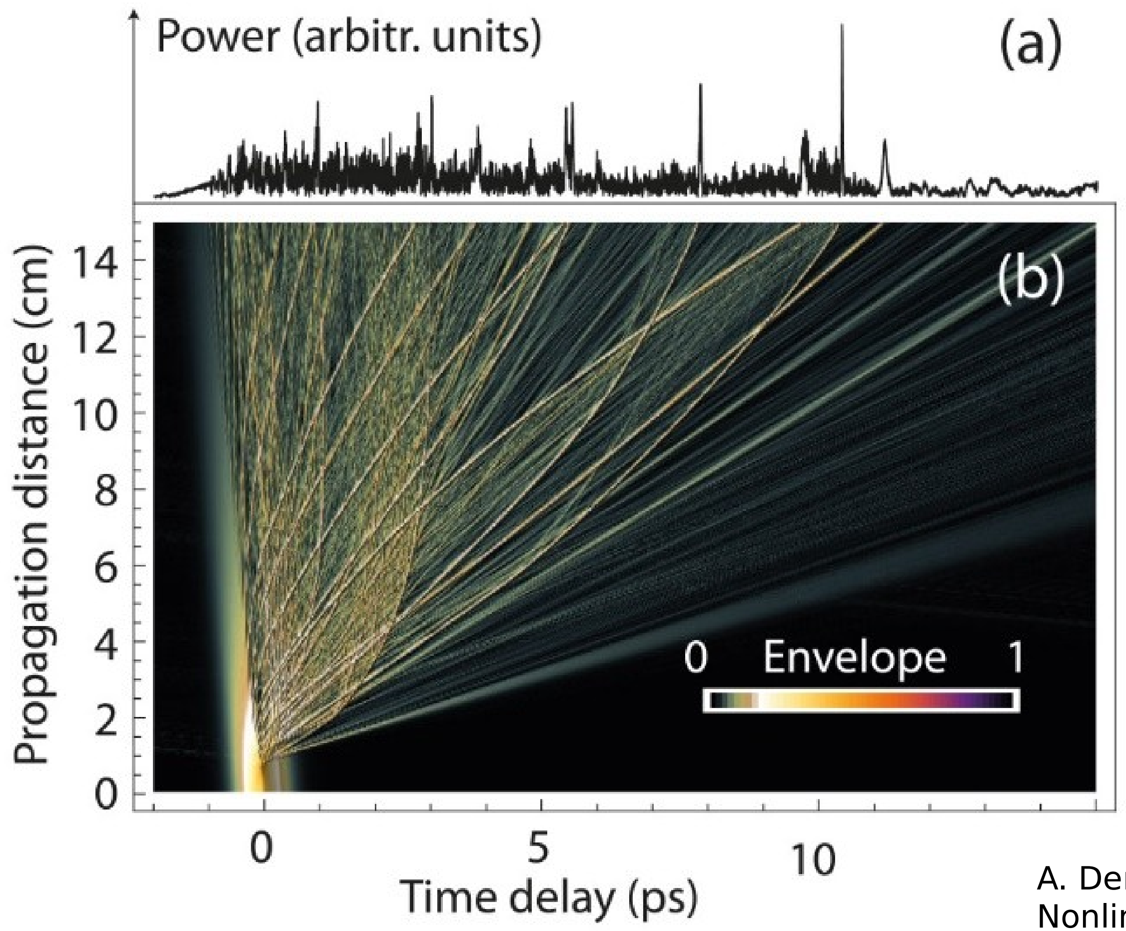
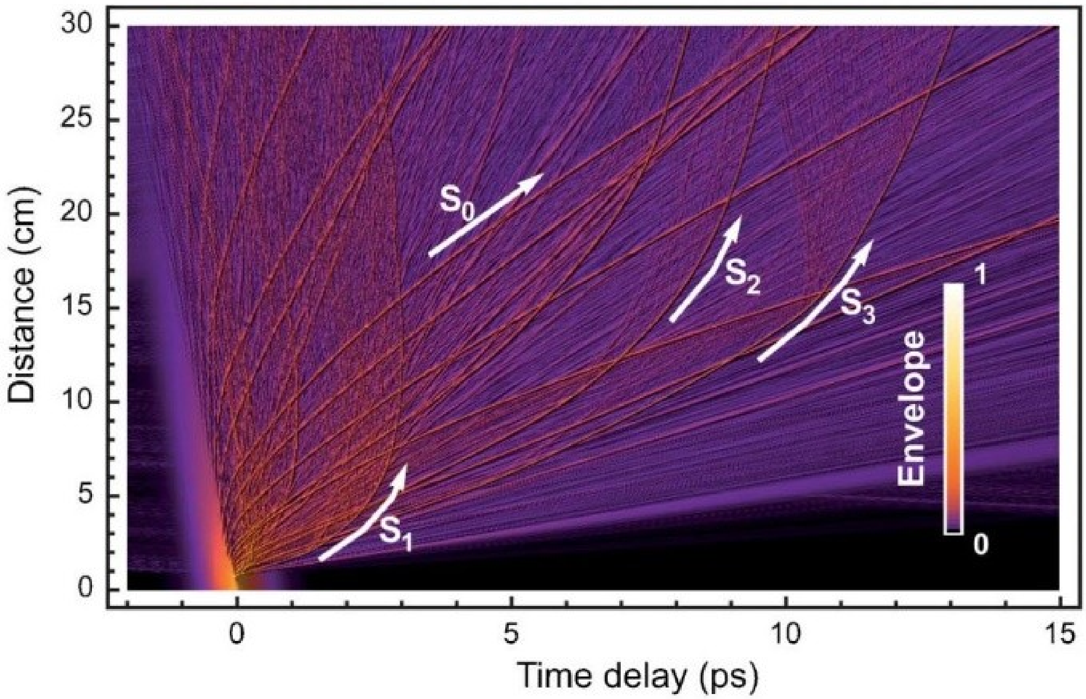


A. Demircan, Sh. Amiranashvili, C. Brée, FM, G. St
Nonlinear Phenomena in Complex Systems **16**, 2

Decay of strong input pulse into sequence of solitons and also radiation.

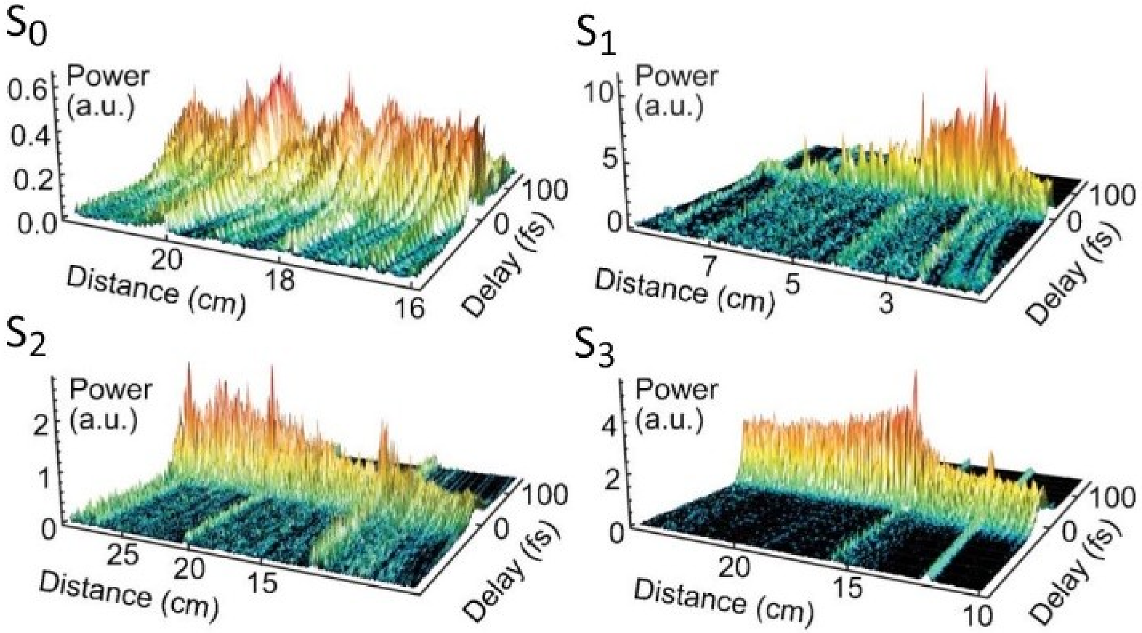
Simulation artificially prepared **without Raman term**.
Soliton trajectories therefore must be straight in the absence of interactions.



A Demircan, S Amiranashvili, C Brée, Ch Mahn
G Steinmeyer, Scient. Reports **2**,850 (2012)

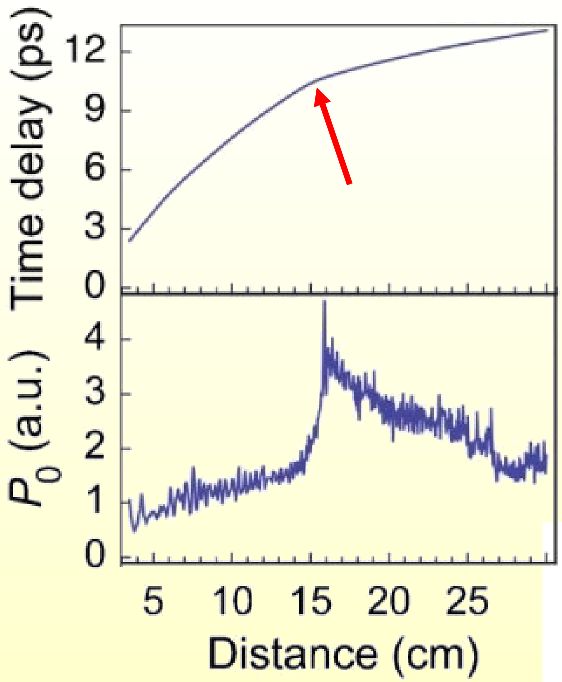
Simulation **without Raman te**
Examples of soliton trajectorie

S_0 moves straight,
S_1, S_2, and S_3 are curved or ben



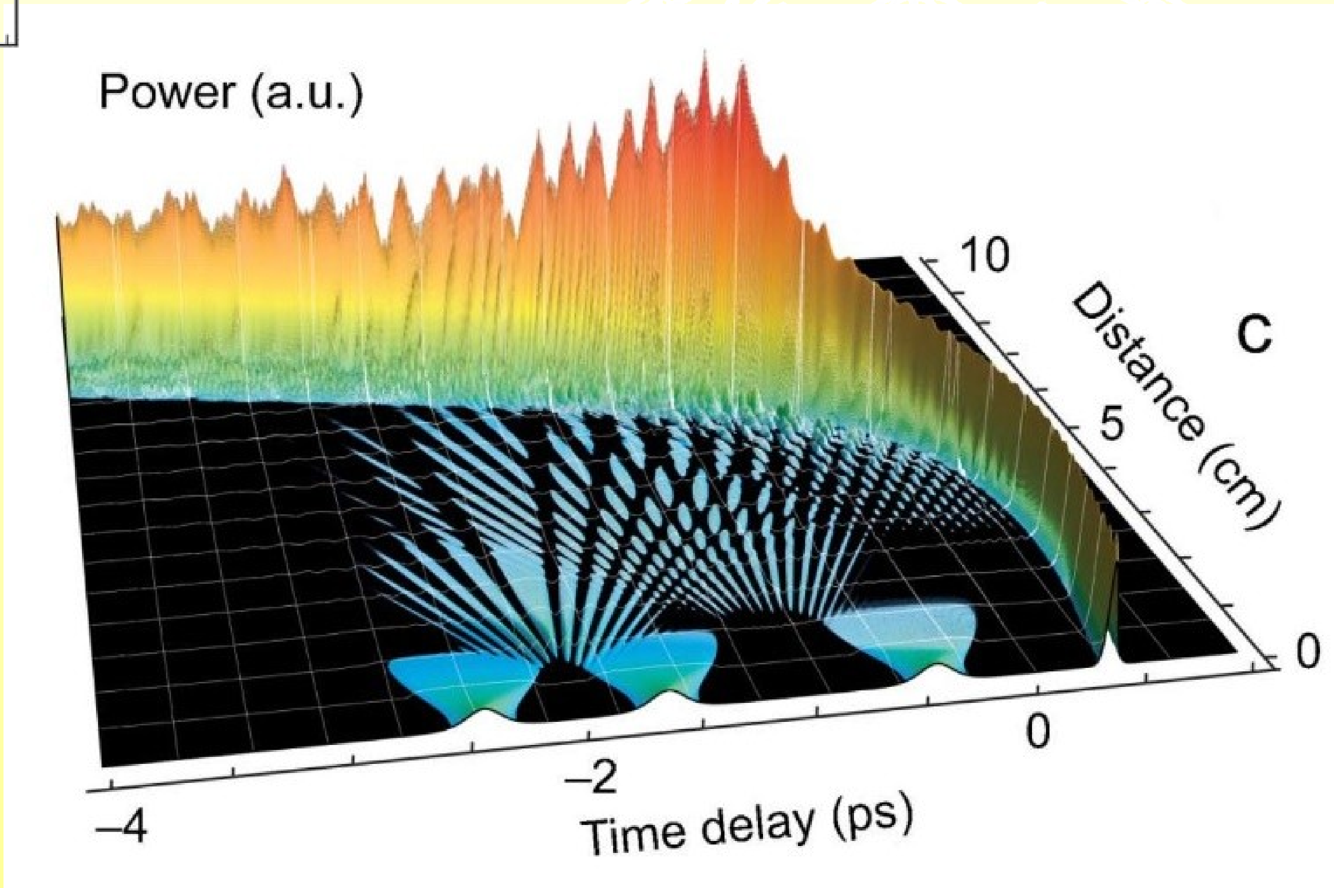
Close-up view of S_0 – S_3

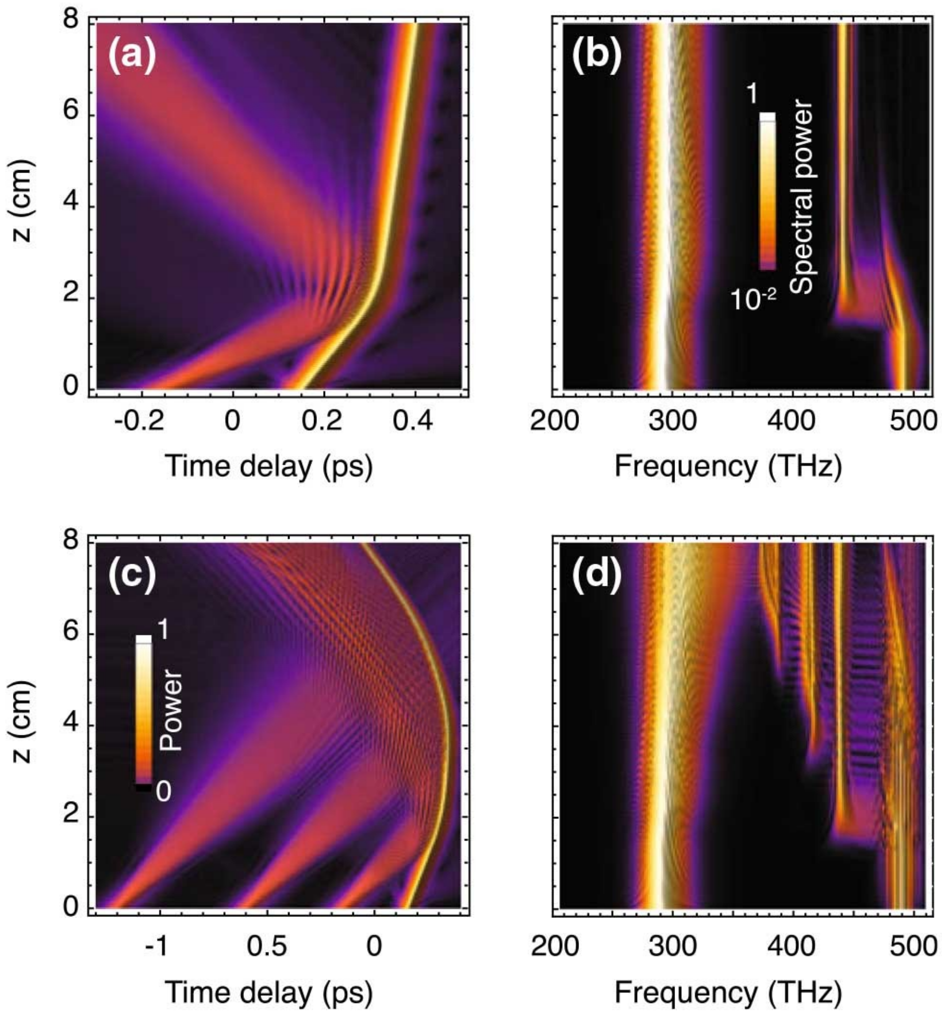
Note how S_3 in particular
suddenly grows



At the position where the trajectory of S_3 ben
it‘s peak power rises sharply

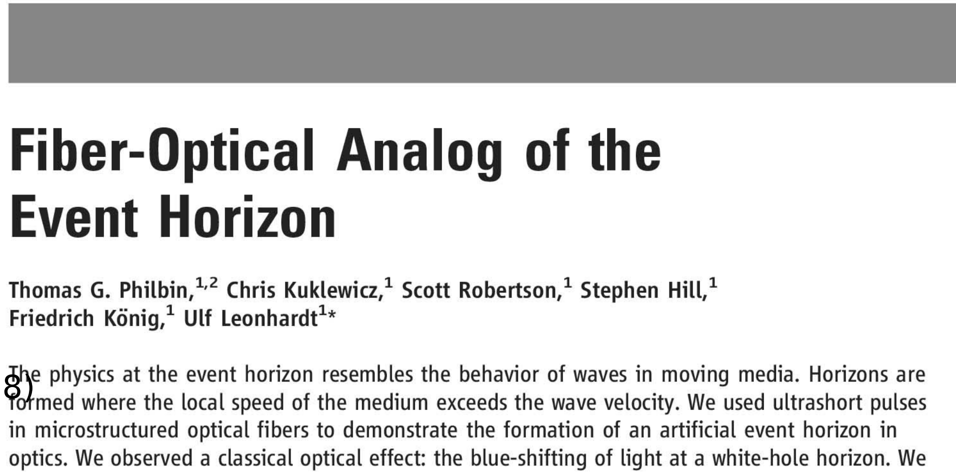
There, interaction with dispersive waves feeds energy into the soliton
(coordinates shifted, rotated for better view)





reflection of one (a,b) and
three (c,d) dispersive waves near 50
off a soliton at ≈300 THz
demonstrates the soliton‘s impenet

A Demircan, S Amiranashvili, C Brée, Ch Mahnke, F
G Steinmeyer, Appl. Phys. B (2013)



Fiber-Optical Analog of the Event Horizon

Thomas G. Philbin,[1,2] Chris Kuklewicz,[1] Scott Robertson,[1] Stephen Hill,[1]
Friedrich König,[1] Ulf Leonhardt[1]*

The physics at the event horizon resembles the behavior of waves in moving media. Horizons are formed where the local speed of the medium exceeds the wave velocity. We used ultrashort pulses in microstructured optical fibers to demonstrate the formation of an artificial event horizon in optics. We observed a classical optical effect: the blue-shifting of light at a white-hole horizon. We

Science **319**, 1367 (2008)

some comments on rogue waves

fiber-optic rogue waves:

- soliton collision limited in peak power, >2 solitons unlikely
- Akhmediev breather: how to excite two? also, fully coherent
- Peregrine soliton: fully coherent

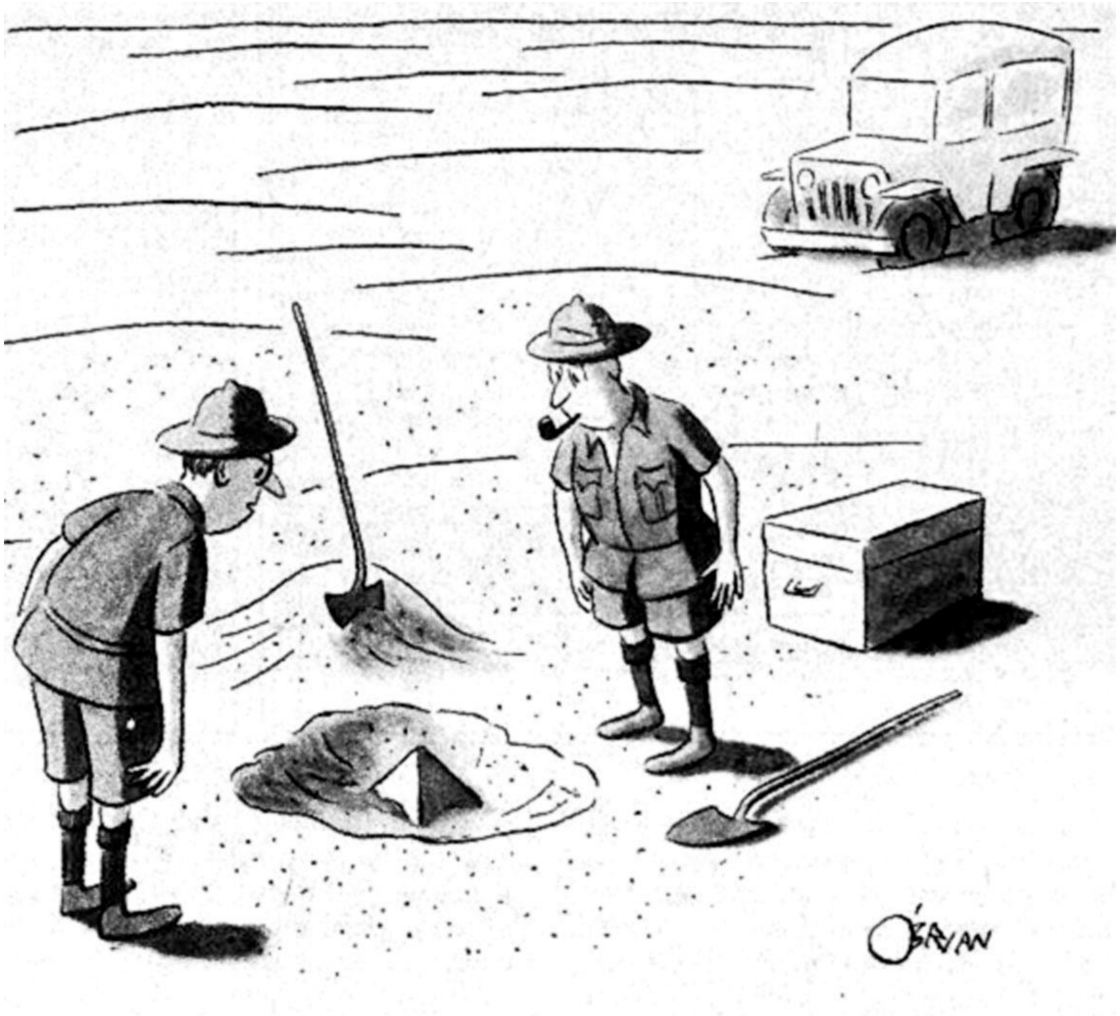
Likely more than a single mechanism

ocean rogue waves:

- two-dimensional
- unlikely to be fully coherent mechanism

Unlikely to be in close correspondence to fiber optics

Katsushika Hokusai (1760-1849) ca. 1830: *Under the Great Wave off*



„This could be the discovery of the century.
Depending, of course, on how far down it goes.“

thank you

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