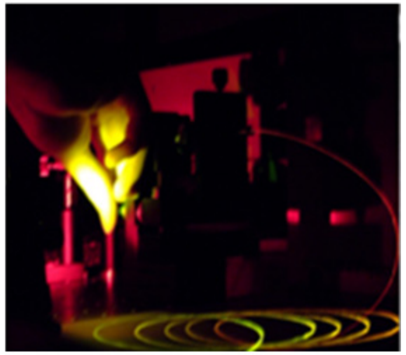
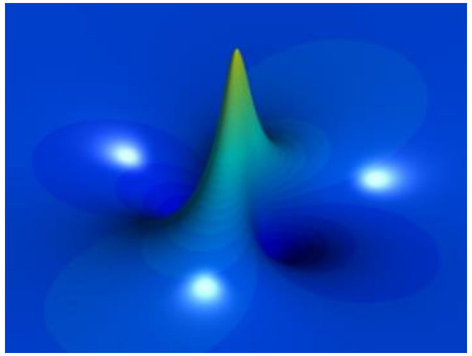
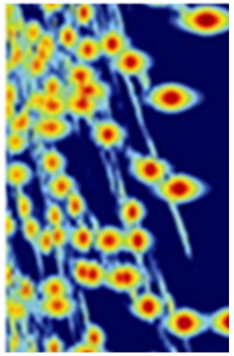
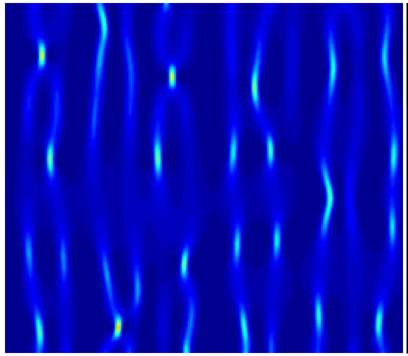
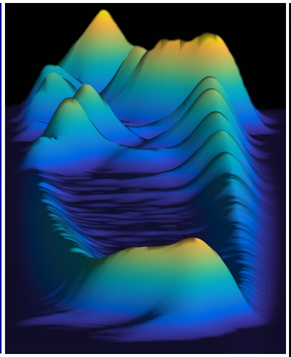
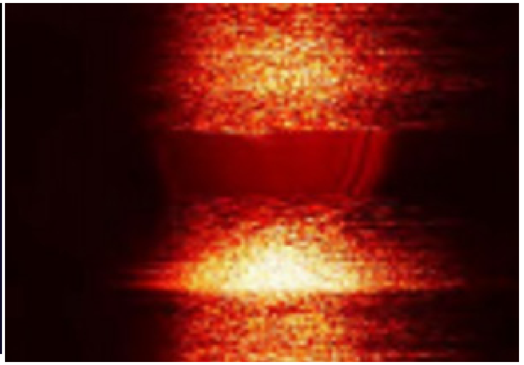
Ultrafast Measurements and Extreme Events in Nonlinear Fibre Optics

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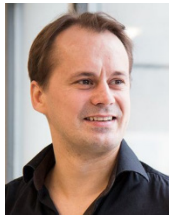
Ultrafast Measurements and Extreme Events in Nonlinear Fibre Optics

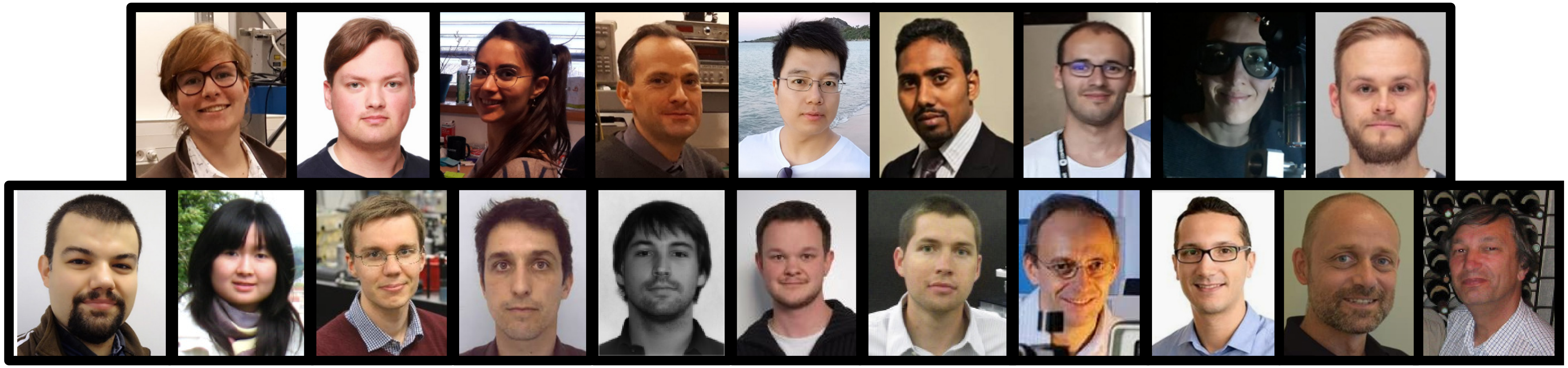


Goery Genty

Tampere University
Tampere University of Applied Sciences

Frederic Dias

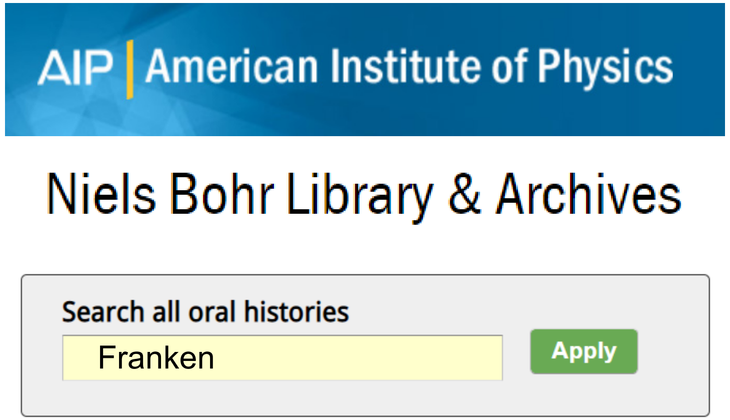
University College Dublin
Ireland's Global University



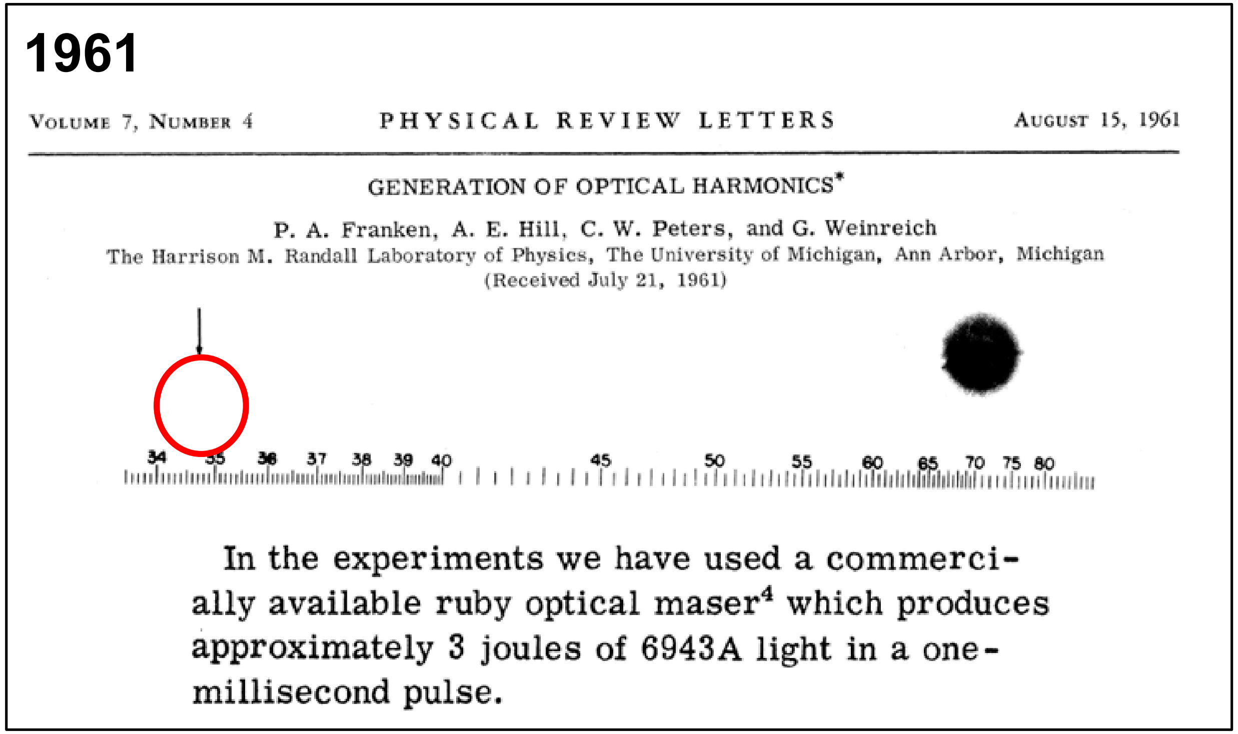
Coraline Lapre, Lauri Salmela, Solveig Perret, Cyril Billet, Fanchao Meng, Amar Ghosh, Etienne Genier, Caroline Amiot, Mikko Narhi, Piotr Ryczkowski, Shanti Toenger, Miro Erkintalo, Thibaut Sylvestre, Christophe Finot, Benjamin Wetzel, Bertrand Kibler, Guy Millot, Amin Chabchoub, Ole Bang, Nail Akhmediev and many others!

2021 – Sixty years of nonlinear optics !

The high power and spatial coherence of laser light enabled the study of the nonlinear response of light to optical fields



Alan Hill was an undergraduate!



1961

VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

GENERATION OF OPTICAL HARMONICS*

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan
(Received July 21, 1961)

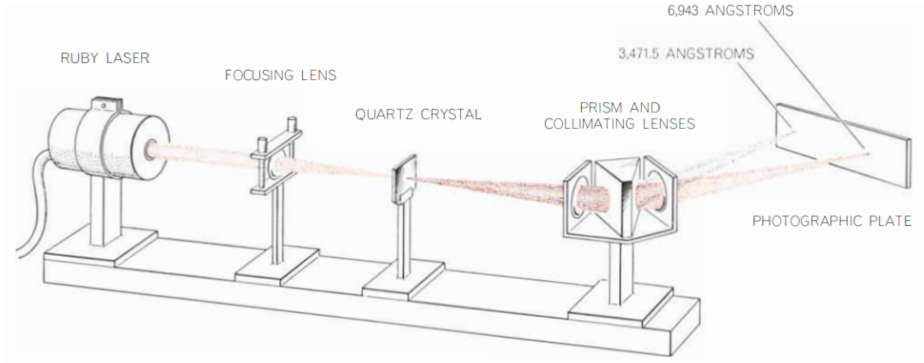
In the experiments we have used a commercially available ruby optical maser[4] which produces approximately 3 joules of 6943A light in a one-millisecond pulse.

(the experimental evidence was removed as a speck of dirt on the photographic plate)

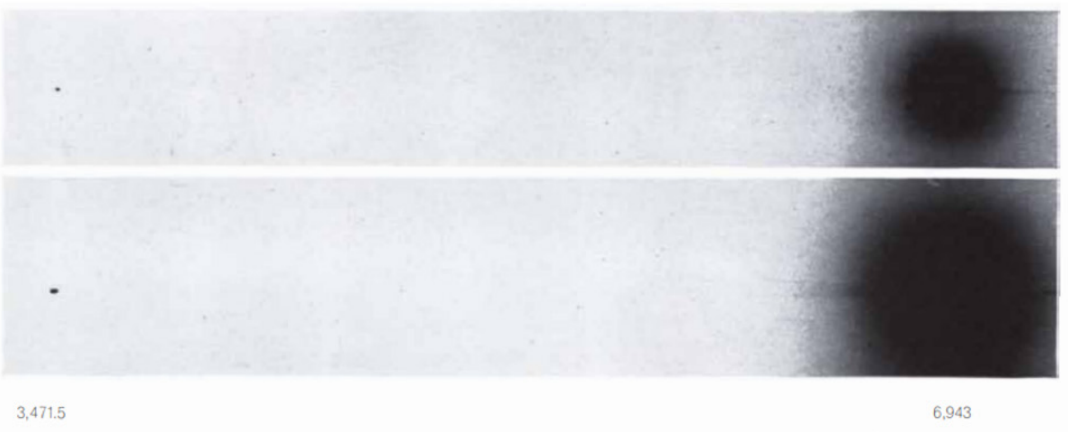
Luckily they were republished elsewhere !

The Interaction of Light with Light

by J. A. Giordmaine



FIRST DEMONSTRATION that ultraviolet light could be generated by the intense flash of a ruby laser was made with this experimental arrangement in 1961 at the University of Michigan. The investigators were Peter A. Franken, Allen E. Hill, C. W. Peters and Gabriel Weinreich. The quartz crystal converted only a hundred-millionth of the incident light to ultraviolet light. On being passed through a prism the ultraviolet is bent more than the red laser light and the two can be photographed separately (*see below*).



FIRST PHOTOGRAPHS of second-harmonic ultraviolet light were made by Franken and his associates. In each case the amount of ultraviolet (*small spots at 3,471.5 angstroms*) is roughly proportional to the square of the amount of red light at 6,943 angstroms.

Nonlinear optics was actually considered earlier: 1926, 1930, 1950

120 SEPTEMBER 1996 PHYSICS TODAY

More on Vavilov's Contributions to 20th-century Physics

What Yuri Nikolaievitch and his colleague omitted to say, but may be of interest to your readers, is that Sergei Vavilov was probably the first scientist to observe a nonlinear optic effect. In 1926, with Vadim L. Levshin, he found a reduction in the absorption of light by uranium glass with an increase of intensity of 454 nm light from a high-intensity spark source.[1] And it was Vavilov who introduced the term "nonlinear optics" into the literature, in a passage in his 1950 book *Mikrostruktura sveta* ("The Microstructure of Light").

References

1. S. I. Vavilov, V. L. Levshin, Z. Phys. **35**, 920 (1926).
2. R. G. W. Brown, E. R. Pike, in *Twentieth Century Physics*, B. Pippard, A. Pais, L. Brown, eds., Bristol (England)/Boston, Institute of Physics/American Institute of Physics (1995), p. 1385.
3. S. I. Vavilov, Dok. Akad. Nauk SSR **11**, 457 (1934).
4. P. A. Čerenkov, Dok. Akad. Nauk SSR **11**, 451 (1934).
5. Usp. fiz. nauk **111**, 702 (1973); **114**, 533 (1974).
6. Sov. Phys. Usp. **16**, 702 (1974); **17**, 950 (1975).

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Über Elementarakte mit zwei Quantensprüngen

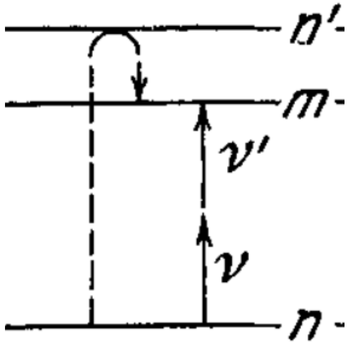
Von Maria Göppert-Mayer

(Göttinger Dissertation)

(Mit 5 Figuren)

Einleitung

Der erste Teil dieser Arbeit beschäftigt sich mit dem Zusammenwirken zweier Lichtquanten in einem Elementarakt. Mit Hilfe der Diracschen Dispersionstheorie[1]) wird die Wahrscheinlichkeit eines dem Ramaneffekt analogen Prozesses, nämlich der Simultanemission zweier Lichtquanten, berechnet.



(Eingegangen 7. Dezember 1930)

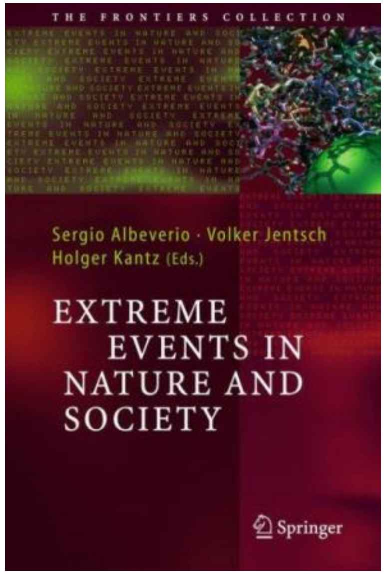
Motivation and Overview – Extreme Events

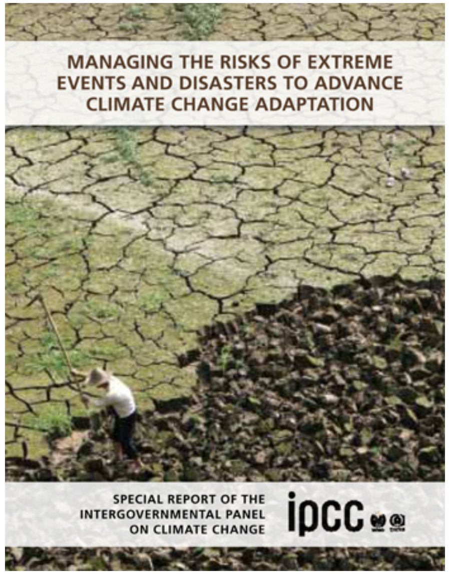
Extreme events are defined by rarity, unpredictability, and often highly destructive impact

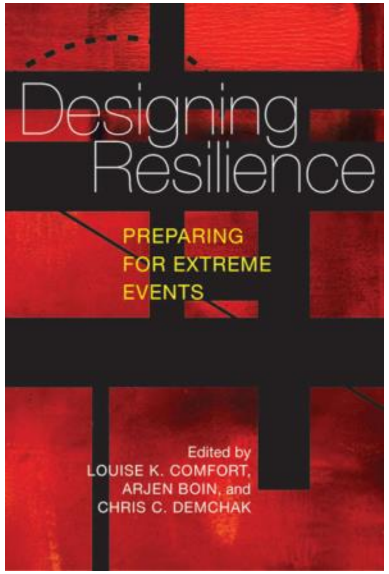
Natural disasters

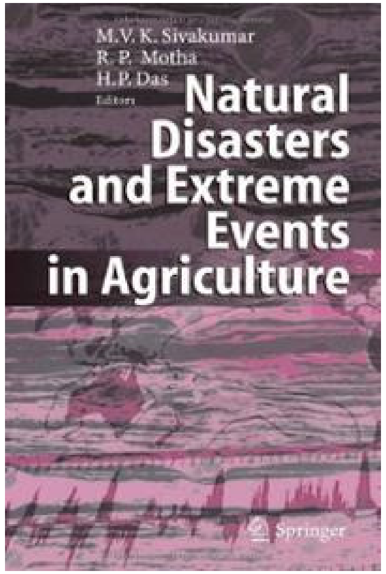
Motivation and Overview – Extreme Events

Extreme events are defined by rarity, unpredictability, and often highly destructive impact









This has created a new interdisciplinary field of science combining areas of specific expertise (geology, climate, hydrodynamics) with statistics, physics, simulations etc.

Rogue waves are a particular type of extreme event

Rogue waves are large and destructive waves that appear on the ocean's surface, outside the range of amplitudes expected from standard linear wave theory

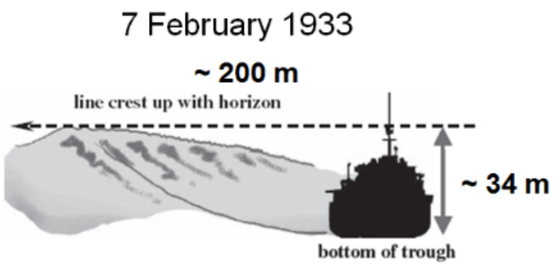
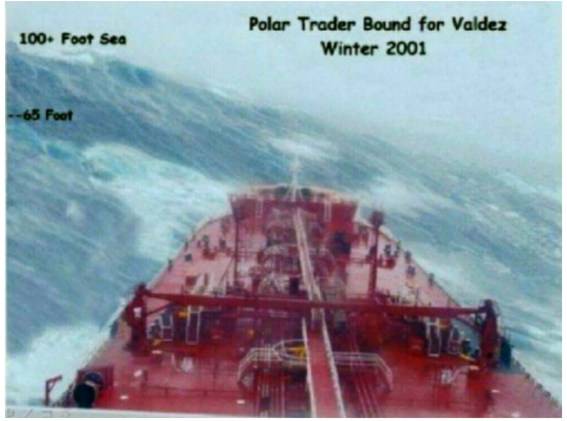
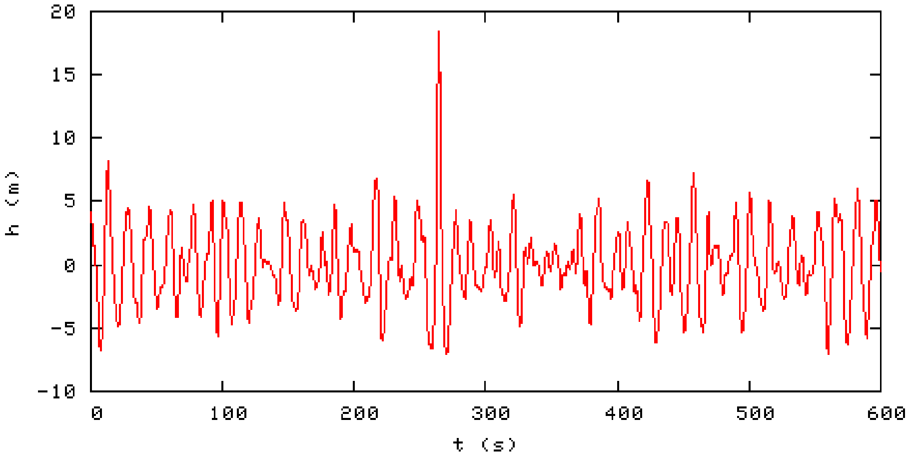


Fig. I.2 Observation of the highest reported wave by the crew members of "Ramapo" (Dennis and Wolff 1996)

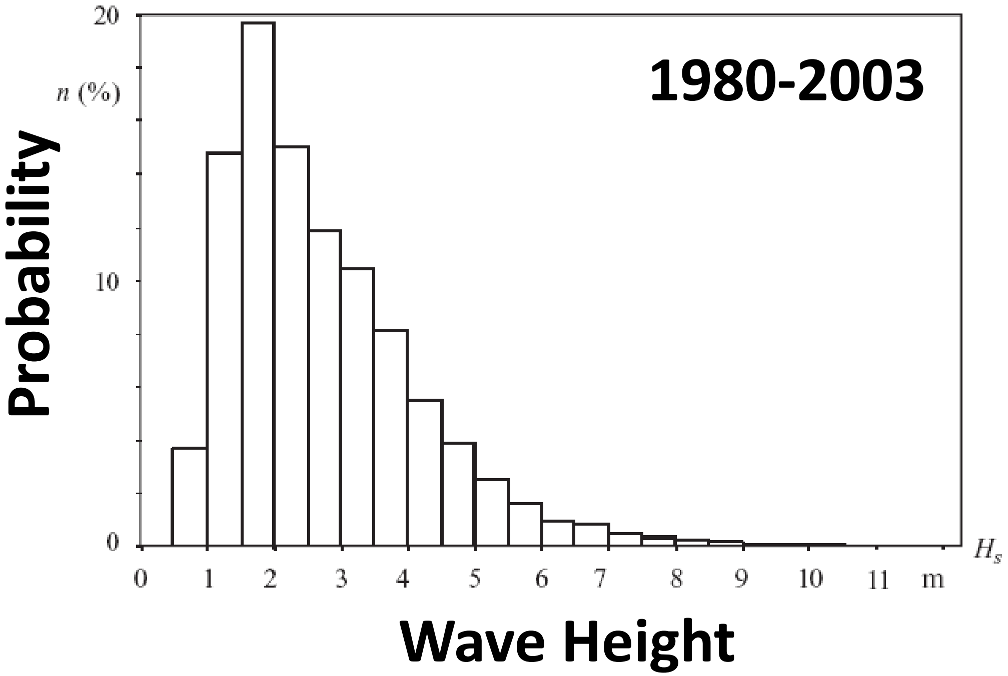


Rogue waves appear in the long tail of wave height distributions

The Draupner Wave of 1995 went beyond anecdote & provided **quantitative data**



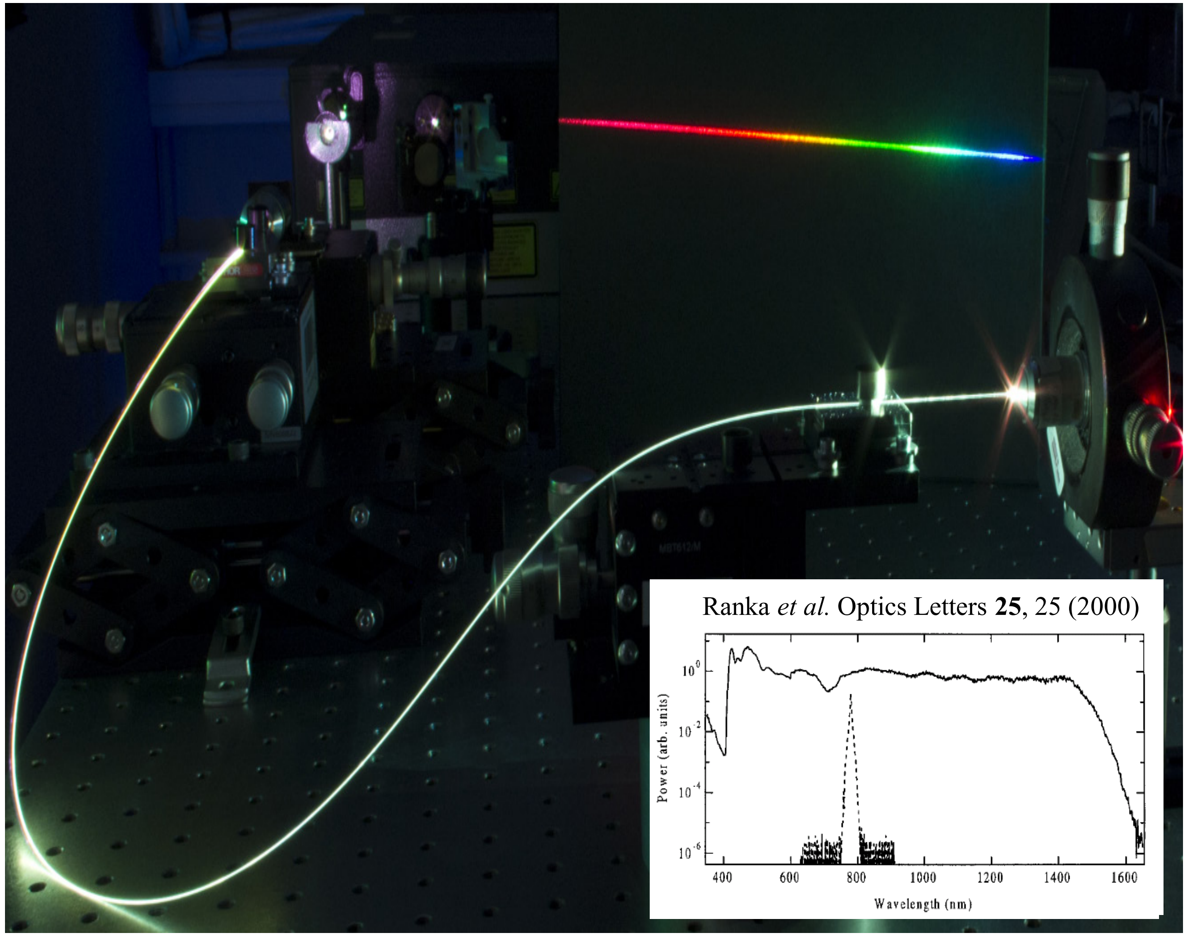
Long term wave height measurements show asymmetric distributions. Rogue waves are “extreme events” in the tails, beyond the predicted Rayleigh distribution



M. S. Longuet-Higgins *Journal of Marine Research* 11, 245-266 (1952)

In 2007, “optical rogue waves” were reported in the supercontinuum

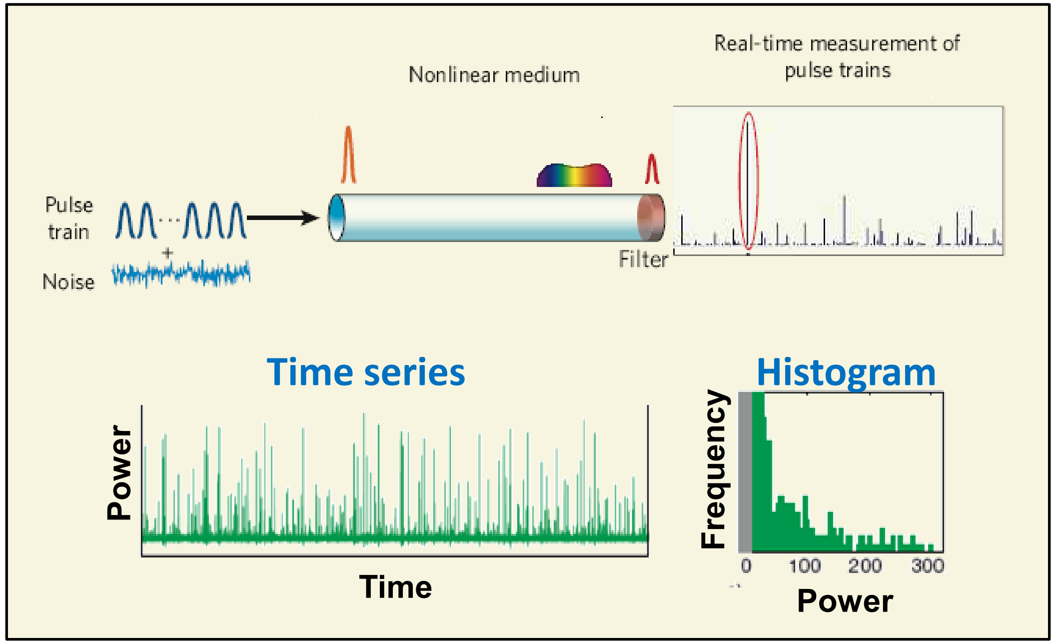
Optical rogue waves appeared in noisy **fibre supercontinuum generation** that showed a long-tailed distribution in intensity fluctuations at particular wavelengths



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

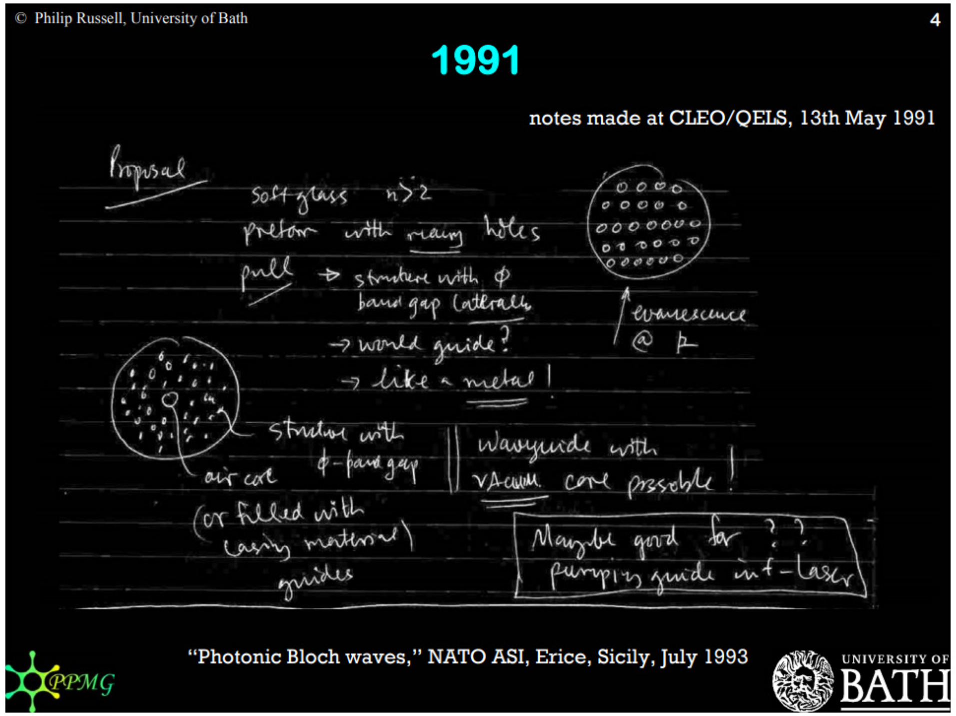
Optical rogue waves

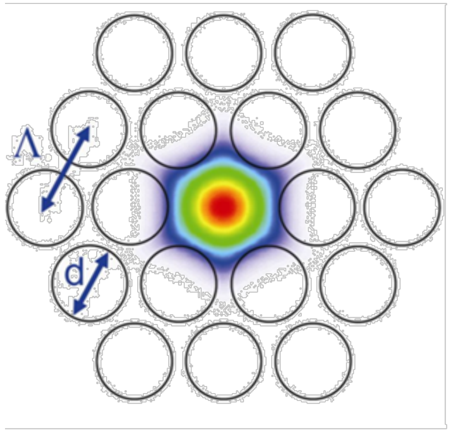
D. R. Solli[1], C. Ropers[1,2], P. Koonath[1] & B. Jalali[1]



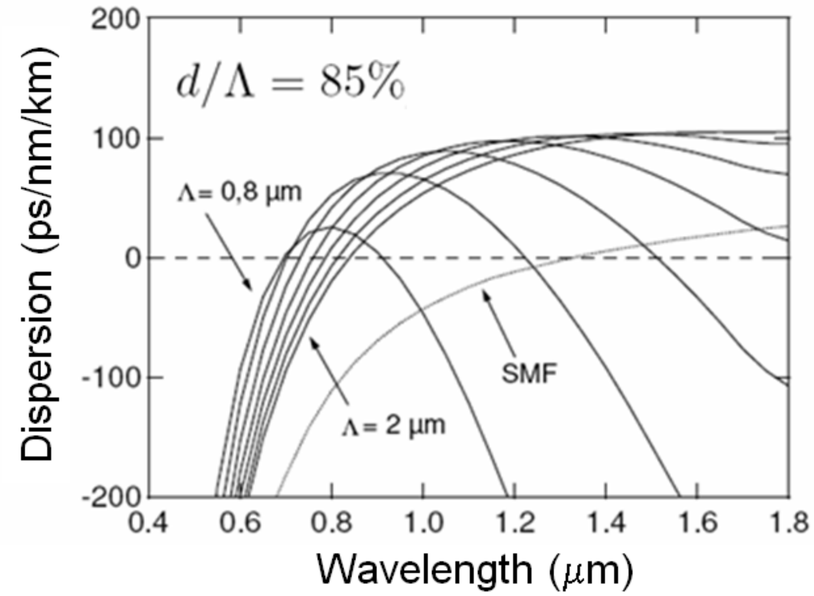
It is important to appreciate the context here

Supercontinuum generation was only possible because of the photonic crystal fiber





Single material (silica)
high air-fill fraction
photonic crystal fibre (PCF)



Dispersion engineering allows fibre zero dispersion wavelength to be matched to readily-available fs sources

The photonic crystal fiber concept celebrated its 30th birthday in 2021 !!

Google now appreciates fibre optics!

Reliable techniques for fabricating small-core waveguides yielded the birth of fibre optics

PROC. IEE, Vol. 113, No. 7, JULY 1966

Dielectric-fibre surface waveguides for optical frequencies

The Nobel Prize in Physics 2009

Details: (i) total internal reflection

(ii) the binary sequences converted to ASCII spell K A O

The femtosecond Ti:Sapphire laser also celebrates its 30th birthday

It was the injection of femtosecond pulses from a Ti:Sapphire into the PCF that led to the supercontinuum

42 OPTICS LETTERS / Vol. 16, No. 1 / January 1, 1991

60-fsec pulse generation from a self-mode-locked Ti:sapphire laser

D. E. Spence, P. N. Kean, and W. Sibbett

J. F. Allen Physics Research Laboratories, Department of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife, KY16 9SS, Scotland

Received July 20, 1990; accepted November 2, 1990

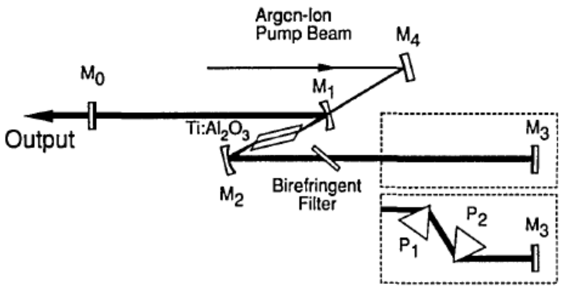


Fig. 1. Schematic of the cavity configuration for self-mode-locked $Ti:Al_2O_3$ laser. The inset shows the intracavity prism sequence for dispersion compensation.

J. Opt. Soc. Am. B/Vol. 8, No. 10/October 1991

Structures for additive pulse mode locking

H. A. Haus, J. G. Fujimoto, and E. P. Ippen

Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received February 1, 1991; revised manuscript received April 29, 1991

We assume that all effects per pass are small and, therefore, additive. In the steady state all changes must add to zero. This fact leads to the master equation:

$$\left[-j\psi - (l + jx) + g\left(1 + \frac{1}{\Omega_g^{2}}\frac{d^2}{dt^2}\right) + jD\frac{d^2}{dt^2} + (\gamma - j\delta)|a|^2\right]a = 0. \quad (2.7)$$

December 15, 1991 / Vol. 16, No. 24 / OPTICS LETTERS

Mode locking in solitary lasers

T. Brabec, Ch. Spielmann, and F. Krausz

Technische Universität Wien, Abteilung für Quantenelektronik und Lasertechnik, Gusshausstrasse 27, A-1040 Wien, Austria

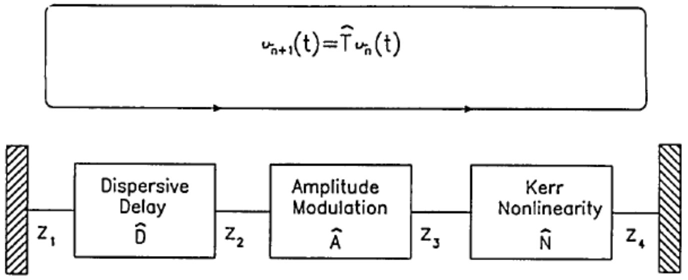
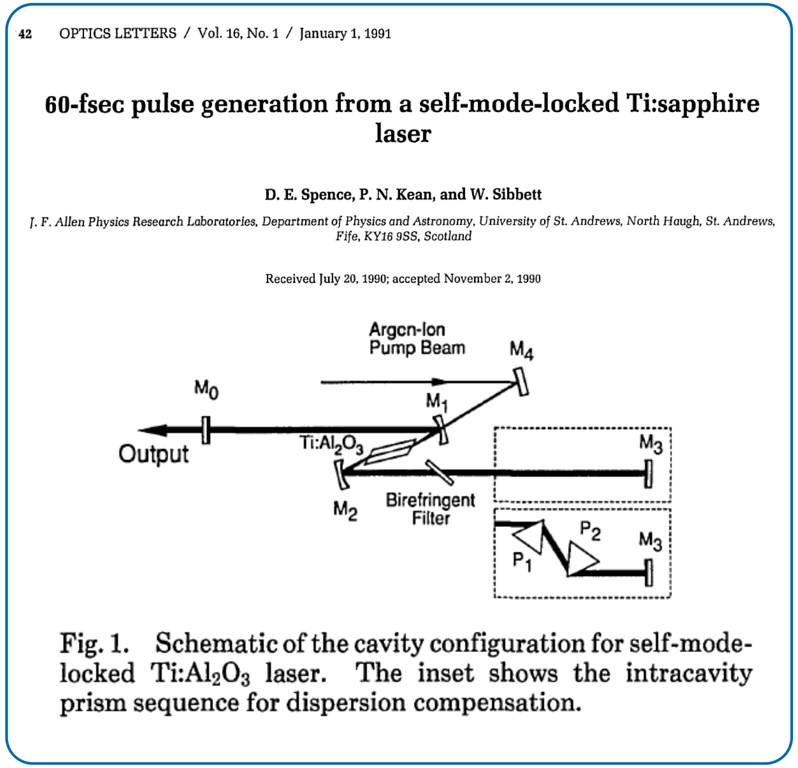


Fig. 1. Schematic of the solitary laser.

The discovery of self-modelocking led to the transfer of soliton concepts into ultrafast laser design, and the concept of the “dissipative soliton” laser

The femtosecond Ti:Sapphire laser also celebrates its 30th birthday

The Kerr lens modelocked Ti:Sapphire oscillates with a spatio-temporal balance between dispersion-managed temporal solitons and diffraction-managed spatial solitons


42 OPTICS LETTERS / Vol. 16, No. 1 / January 1, 1991

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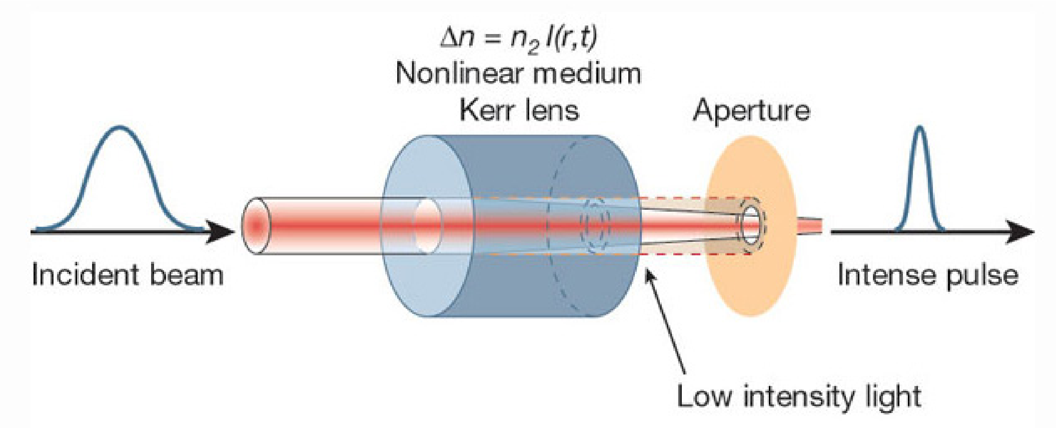


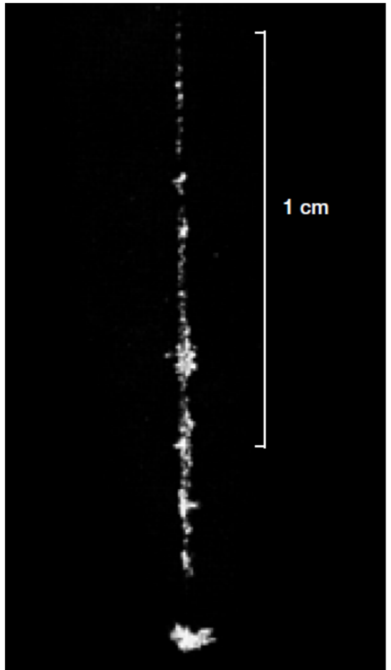
W Sibbett *et al.* The development and application of femtosecond laser systems Optics Express **20** 6989-7001 (2012)

1964 – nonlinear self-focusing and solitons in optics

OPN Optics & Photonics News   November 2010

How the Laser Launched Nonlinear Optics

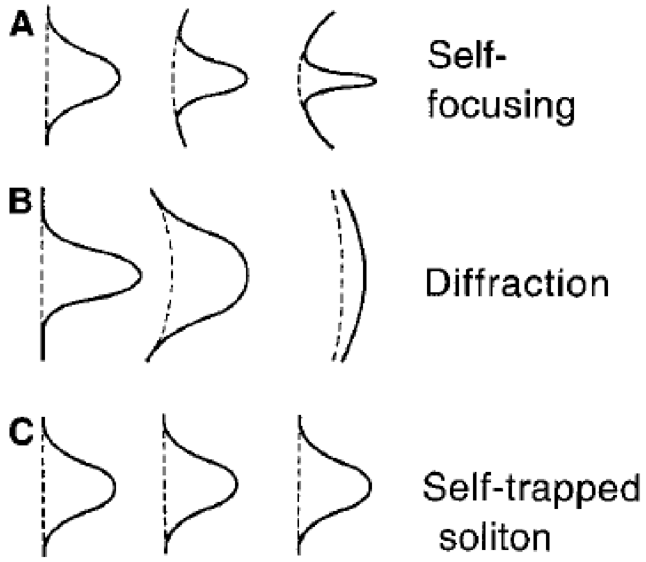
Jeff Hecht



Firing a Q-switched ruby pulse through an f/20 lens produced a long, thin damage zone that revealed self-trapping.

Courtesy of Michael Hercher

The fact that the damaged zone was smaller than the focal spot—and that it did not increase as the beam passed through the glass—led Townes to suggest that optical nonlinearities were offsetting beam diffraction to cause self-trapping.



1964 – Townes theory & the nonlinear Schrödinger equation (NLSE)

VOLUME 13, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1964

SELF-TRAPPING OF OPTICAL BEAMS*

R. Y. Chiao, E. Garmire, and C. H. Townes
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 1 September 1964)

We shall discuss here conditions under which an electromagnetic beam can produce its own dielectric waveguide and propagate without spreading. This may occur in materials whose dielectric constant increases with field intensity, but which are quite homogeneous in the absence of the electromagnetic wave. Such self-trapping in dielectric waveguide modes appears to be possible in intense laser beams, and to produce marked optical and physical effects.

In the case where E_t depends only on y, and under the assumption of linear polarization,

$$\frac{d^2}{dy^2}E_t(y)-\Gamma^2E_t(y)+\frac{\epsilon_2}{2}k_0{}^2E_t{}^3(y)=0. \qquad (5)$$

If E_t represents a slab-shaped beam, confined in the y direction, the boundary conditions are $E(y)\to 0$ as $y\to\infty$ and $dE/dy=0$ at $y=0$. This excludes periodic solutions, so that $\Gamma^2>0$. A mechanical analog of (5) is a particle in a double-well quartic potential-energy function. It is immediate from consideration of this analog that there is a unique solution which is not oscillatory, namely $E_t(y)=E_t(0)/\cosh\Gamma y$, where Γ must equal $\frac{1}{2}\epsilon_2{}^{1/2}k_0E_t(0)$. Note that, given a certain size of the beam ($\sim 1/\Gamma$), the field inside the beam must attain a value $E_t(0)$ for trapping.

First statement of the cubic NLSE in optics & sech-soliton solution

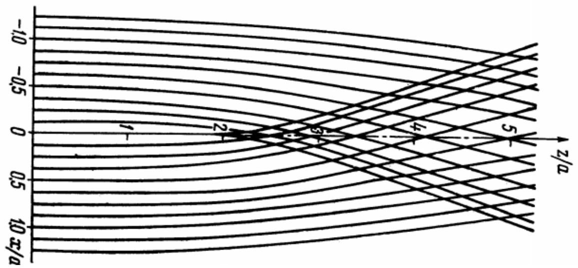
Actually not the first statement of the NLSE

SOVIET PHYSICS JETP VOLUME 23, NUMBER 6 DECEMBER 1966

SELF-FOCUSING AND SELF-TRAPPING OF INTENSE LIGHT BEAMS IN A NONLINEAR MEDIUM

S. A. AKHMANOV, A. P. SUKHORUKOV, and R. V. KHOKHLOV
Moscow State University

$$2ik\frac{\partial A}{\partial z} = \Delta_{\perp}A + \frac{n_2|A|^2}{n_0}k^2A + \frac{n_4|A|^4}{n_0}k^2A. \qquad (8)$$

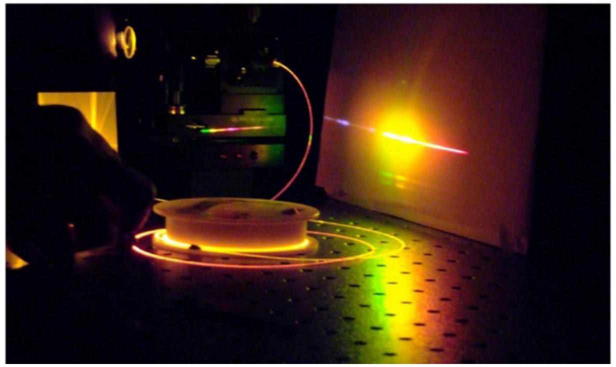


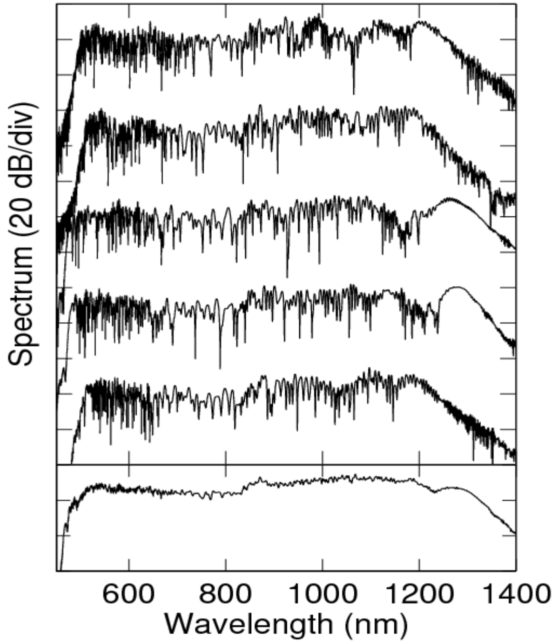
[1] G. A. Askar'yan, JETP **42**, 1567 (1962), Soviet Phys. JETP **15**, 1088 (1962).
[2] V. I. Talanov, Izv. Vuzov, Radiofizika **7**, 564 (1934).
[3] R. Y. Chiao, E. Garmire, and C. Townes, Phys. Rev. Lett. **13**, 479 (1964) (erratum, Phys. Rev. Lett. **14**, 1056 (1965)).
[4] L. V. Keldysh, Report to the Session of the Department of General and Applied Physics of the U.S.S.R. Academy of Sciences, 1964.

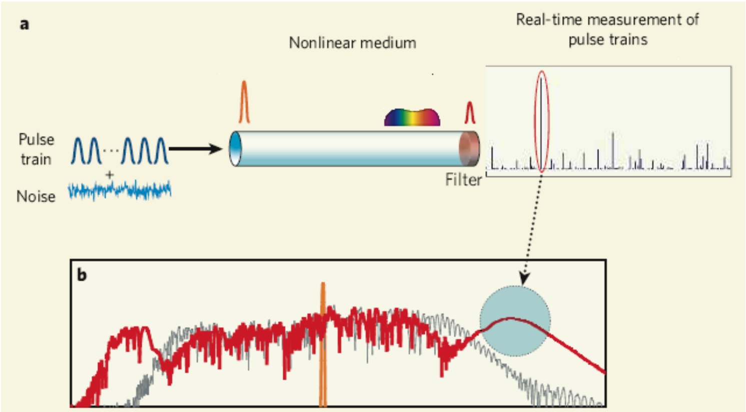
In 1967, Khokhlov & Akhmanov received the Lenin Prize, celebrated with a mural of them both riding a horse upon an SHG crystal converting red to green. It was on the wall for many years at Moscow State University. This photo is from @jeffhecht 's article. Where is the mural now?

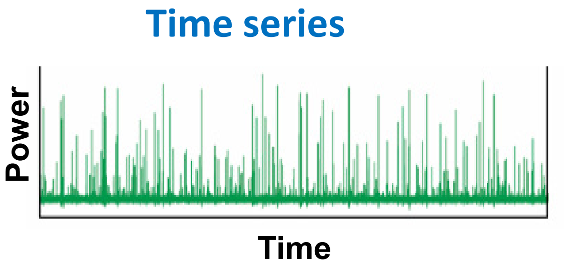
Now we return to “rogue waves” in the supercontinuum

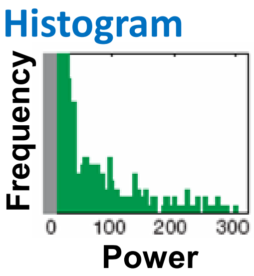
Optical extreme events appeared in the statistics of noisy **supercontinuum generation**

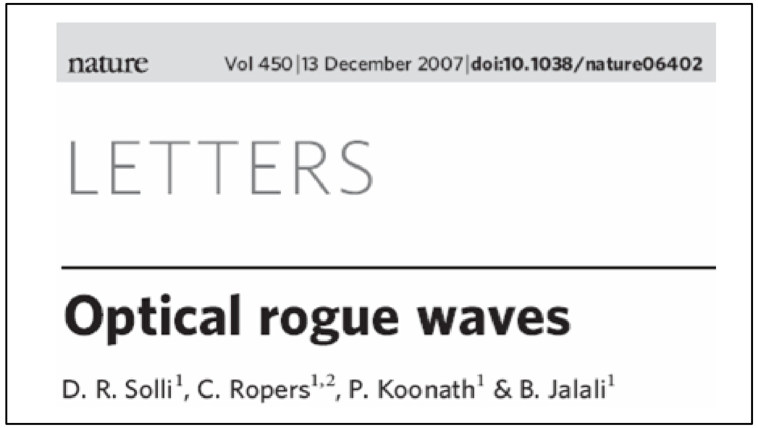






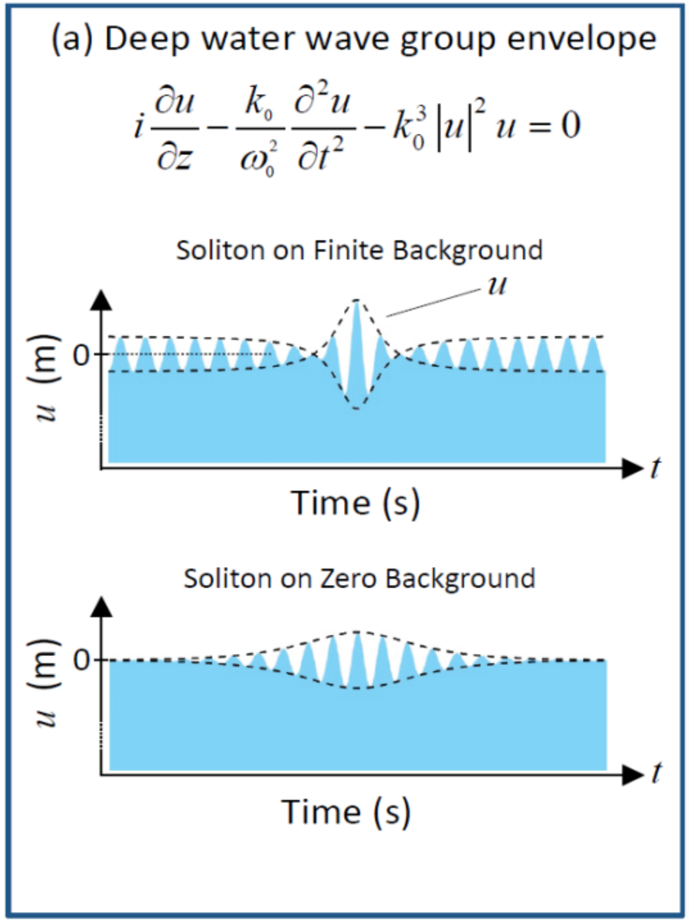




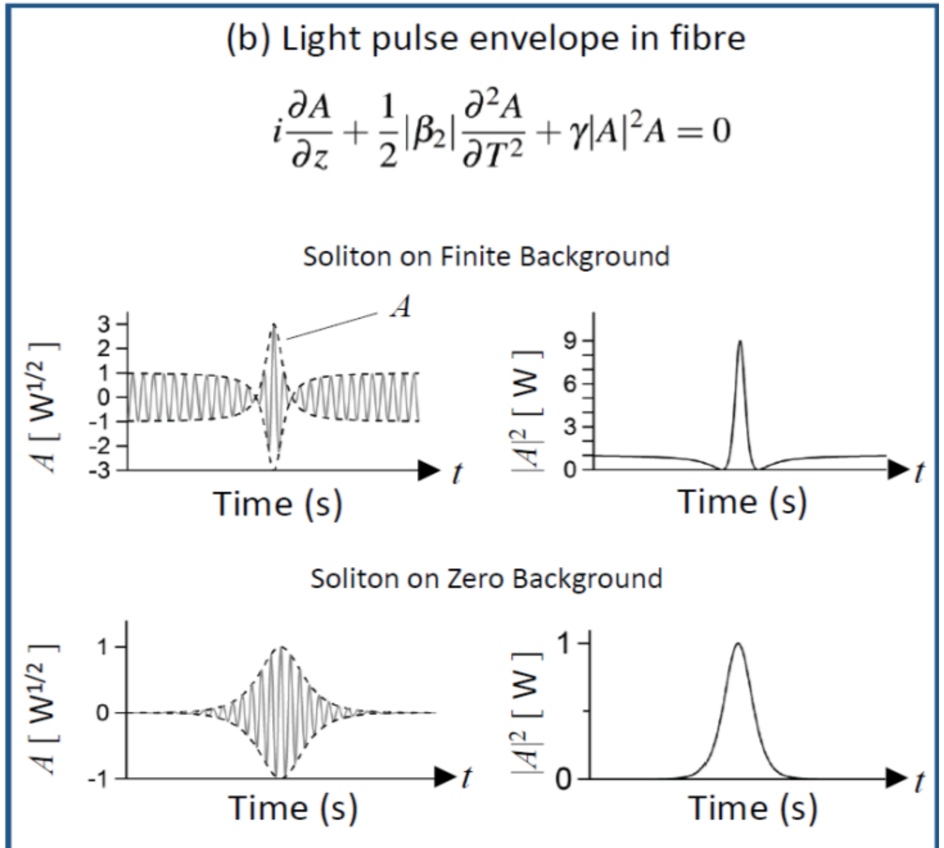


An analogy is suggested by the same governing equation

Light pulse propagation in optical fibre and wave group propagation on deep water are both described by the nonlinear Schrödinger equation (NLSE)



$$i\frac{\partial u}{\partial z} - \frac{k_0}{\omega_0^2}\frac{\partial^2 u}{\partial t^2} - k_0^3 |u|^2 u = 0$$



$$i\frac{\partial A}{\partial z} + \frac{1}{2}|\beta_2|\frac{\partial^2 A}{\partial T^2} + \gamma |A|^2 A = 0$$

Zakharov & Shabat JETP 34, 62-69 (1972)

Why are nonlinear Schrödinger equation-like systems so interesting?

Nonlinear optical waveguides provide a platform to study a wide range of other systems

www.sciencemag.org SCIENCE VOL 319 7 MARCH 2008

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 also showed by theoretical calculations that such a system is capable of probing the quantum effects of horizons, in particular Hawking radiation.

NATURE REVIEWS | PHYSICS VOLUME 1 | NOVEMBER 2019 | 675

REVIEWS

Rogue waves and analogies in optics and oceanography

John M. Dudley[1]*, Goëry Genty[2], Arnaud Mussot[3], Amin Chabchoub[4] and Frédéric Dias[5]

nature COMMUNICATIONS

Received: 30 April 2019; Accepted: 20 January 2020;
Published online: 10 February 2020

ARTICLE

https://doi.org/10.1038/s41467-020-14634-0 OPEN

Supersymmetry in the time domain and its applications in optics

Carlos García-Meca[1,2]*, Andrés Macho Ortiz[1,2]* & Roberto Llorente Sáez[1]

nature physics ARTICLES

PUBLISHED ONLINE: 31 AUGUST 2015 | DOI: 10.1038/NPHYS3451

Optical simulations of gravitational effects in the Newton–Schrödinger system

Rivka Bekenstein*, Ran Schley, Maor Mutzafi, Carmel Rotschild and Mordechai Segev

Some predictions of Einstein's theory of general relativity (GR) still elude observation, hence analogous systems, such as optical set-ups, have been suggested as platforms for emulating GR phenomena. GR is inherently nonlinear: for example, the curvature of space is induced by masses whose dynamics is also affected by the curved space they themselves induce. But, thus far all GR emulation experiments with optical systems have reproduced only linear dynamics. Here, we study gravitational effects with optical wavepackets under a long-range nonlocal thermal nonlinearity. This system is mathematically equivalent to the Newton–Schrödinger model proposed to describe the gravitational self-interaction of quantum wavepackets. We emulate gravitational phenomena by creating interactions between a wavepacket and the gravitational potential of a massive star, observing gravitational lensing, tidal forces and gravitational redshift and blueshift. These wavepackets interact in the curved space they themselves induce, exhibiting complex nonlinear dynamics arising from the interplay between diffraction, interference and the emulated gravitational effects.

nature COMMUNICATIONS

ARTICLE

Received 14 Mar 2014 | Accepted 12 Aug 2014 | Published 17 Sep 2014 DOI: 10.1038/ncomms5969

Nonlinear optics of fibre event horizons

Karen E. Webb[1], Miro Erkintalo[1], Yiqing Xu[1,2], Neil G.R. Broderick[1], John M. Dudley[3], Goëry Genty[4] & Stuart G. Murdoch[1]

PHYSICAL REVIEW LETTERS 122, 010404 (2019)

Editors' Suggestion

Observation of Stimulated Hawking Radiation in an Optical Analogue

Jonathan Drori,[1] Yuval Rosenberg,[1] David Bermudez,[2] Yaron Silberberg,[1] and Ulf Leonhardt[1]
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(Received 28 August 2018; revised manuscript received 12 November 2018; published 9 January 2019)

The theory of Hawking radiation can be tested in laboratory analogues of black holes. We use light pulses in nonlinear fiber optics to establish artificial event horizons. Each pulse generates a moving perturbation of the refractive index via the Kerr effect. Probe light perceives this as an event horizon when its group velocity, slowed down by the perturbation, matches the speed of the pulse. We have observed in our experiment that the probe stimulates Hawking radiation, which occurs in a regime of extreme nonlinear fiber optics where positive and negative frequencies mix.

The validity or otherwise of some of these analogies is still an open question

What we set out to explain in 2007 …

1. Is the study of ocean rogue waves **using an analogy with optics** really valid? In any case, are optical rogue waves perhaps interesting in their own right?

2. Are ocean rogue waves generated from **linear or nonlinear effects** or both?

Linear Waves

Speed and other properties do not depend on amplitude

Nonlinear Waves

Speed and other properties depend on amplitude

Linear → **Nonlinear**

First we examine rogue waves in supercontinuum generation

The NLSE describes the evolution of an ultrashort pulse envelope in space and time

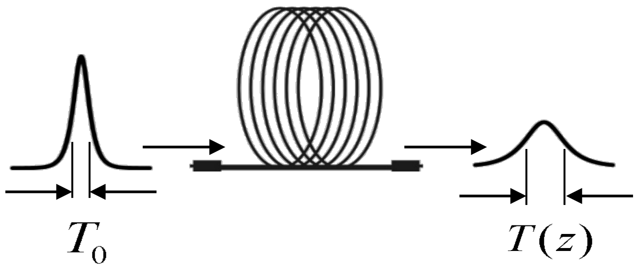
$$\mathrm{i}\frac{\partial A(z,T)}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A(z,T)}{\partial T^2} - \gamma\,|A(z,T)|^2 A(z,T)$$

co-moving time $T = t - z/v_g = t - \beta_1 z$

Kerr nonlinearity $\gamma = n_2\omega_0/cA_{eff}$

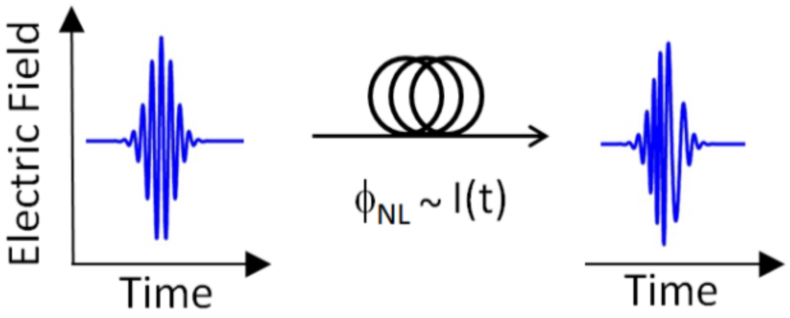
instantaneous power (W) $|A(z,T)|^2$

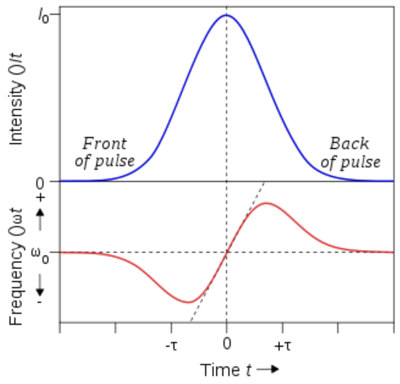
Linear dispersion (GVD) changes temporal pulse shape but does not alter the spectrum



$$T(z) = T_0\left(1 + \frac{|\beta_2|\,z}{T_0^2}\right)^{1/2}$$

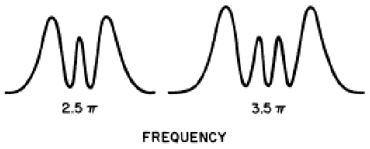
Nonlinear self phase modulation (SPM) broadens the spectrum but does not alter the temporal intensity





$$A(z,T) = A(0,T)\exp(i\phi_{NL}(z,T))$$

$$\phi_{NL}(z,T) = \gamma z\,|A(0,T)|^2 \qquad \delta\omega(T) = -\frac{\partial \phi_{NL}}{\partial T}$$



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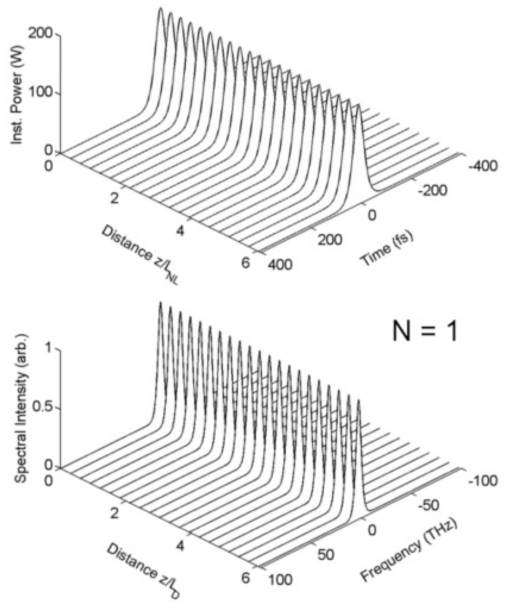
Kerr nonlinearity $\gamma = n_2\omega_0/cA_{eff}$

instantaneous power (W) $|A(z,T)|^2$

Fundamental solitons



Initial condition – fundamental soliton

$$A(z=0,T) = \sqrt{P_0}\,\mathrm{sech}(T/T_0)$$

$$\frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} = 1$$

$$\Longrightarrow \quad P_0 = \frac{|\beta_2|}{\gamma T_0^2}$$

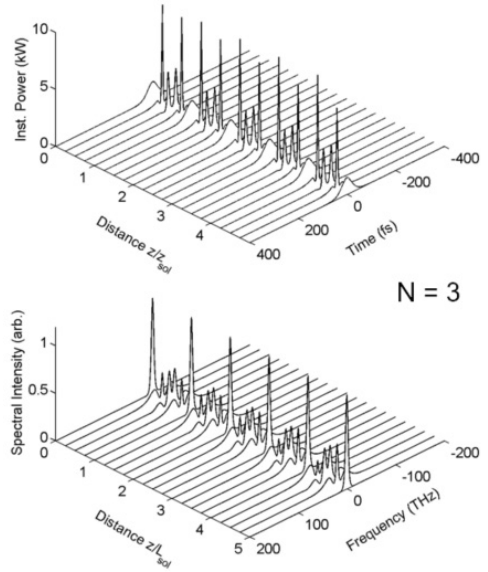
Invariant evolution

$$A(z,T) = \sqrt{P_0}\,\mathrm{sech}(T/T_0)\exp(\mathrm{i}k_{\mathrm{sol}}z)$$

$$k_{sol} = \gamma P_0/2$$

soliton wavenumber

Higher order solitons



Initial condition – high order soliton

$$A(z=0,T) = \sqrt{P_0}\,\mathrm{sech}(T/T_0)$$

$$\frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} = N^2$$

$$N = 2, 3, 4, 5, \ldots$$

$$\Longrightarrow \quad P_0 = N^2\frac{|\beta_2|}{\gamma T_0^2}$$

Periodic evolution

$$z_{\mathrm{sol}} = \frac{\pi}{2}L_D$$

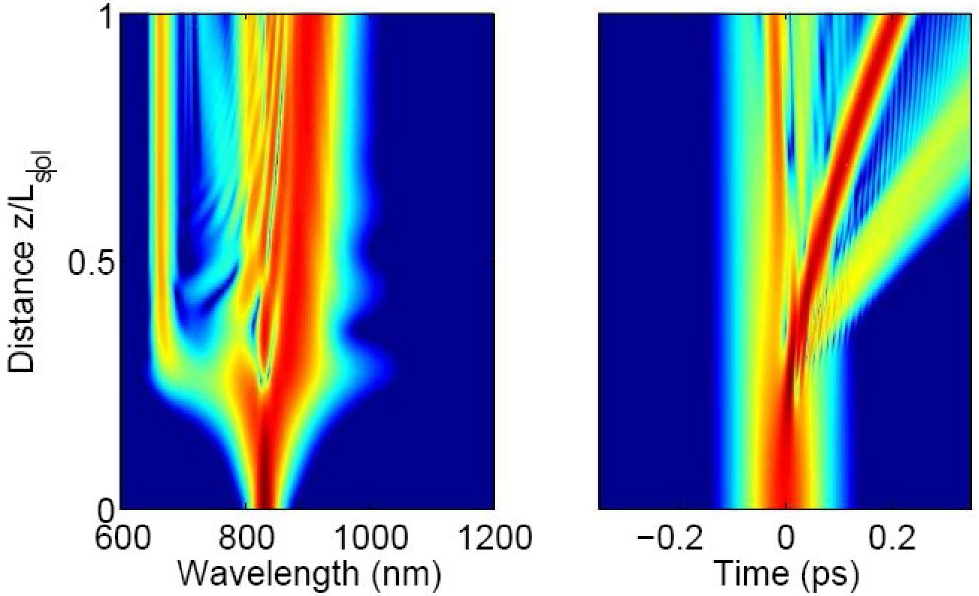
Supercontinuum physics and soliton dynamics

With fs pulses injected in the anomalous dispersion regime the supercontinuum develops from perturbed higher-order soliton propagation (soliton fission)

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A - \sum_{k>2} \frac{\mathrm{i}^{k+1}}{k!}\beta_k \frac{\partial^k A}{\partial T^k} = i\gamma\left(1 + \mathrm{i}\tau_{\text{shock}}\frac{\partial}{\partial T}\right)\left(A(z,t)\int_{-\infty}^{+\infty} R(T')|A(z,T-T')|^2 dT'\right)$$

Linear dispersion *Self-steepening* *SPM, FWM, Raman*

Spectral Evolution **Temporal Evolution**



1. SPM & GVD on their own yield ideal periodic evolution
2. Perturbations (Raman, high-order dispersion…) induce <u>**fission**</u> into fundamental solitons
3. Solitons generate blue-shifted <u>**dispersive waves**</u>
4. **<u>Raman soliton self-frequency shift</u> to longer wavelengths**

Golovchenko, Dianov, Karasik, Prokhorov, Serkin., JETP Lett. **42** 87-91 (1985)

Blow & Wood, IEEE J. Quant. Electron. **25** 2665-2673 (1989)

Dudley, Genty, Coen, Rev. Mod. Phys. **78** 1135-1184 (2006)

Agrawal, Nonlinear Fibre Optics 6th Ed (2019)

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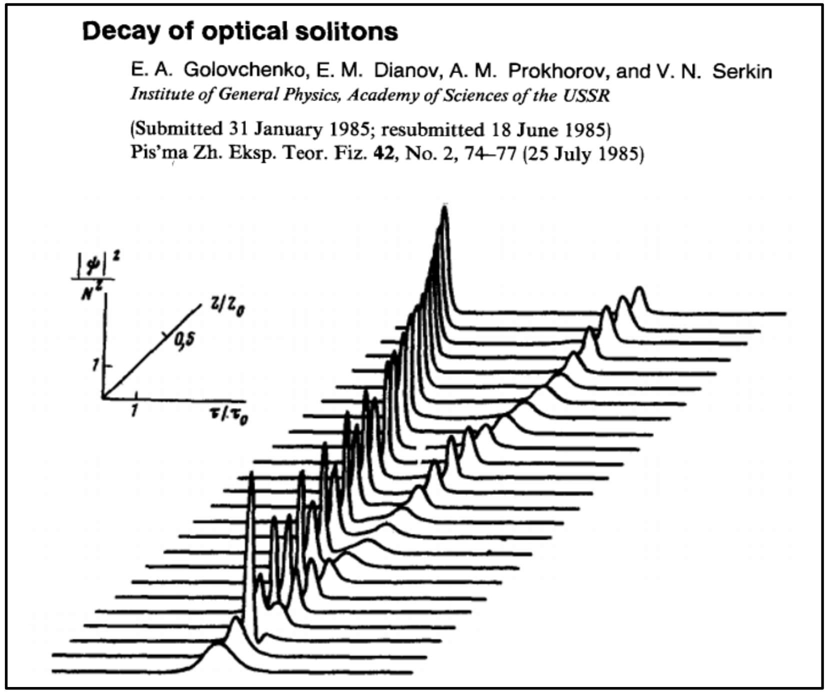
Linear dispersion — *Self-steepening* — *SPM, FWM, Raman*


Decay of optical solitons

E. A. Golovchenko, E. M. Dianov, A. M. Prokhorov, and V. N. Serkin
Institute of General Physics, Academy of Sciences of the USSR

(Submitted 31 January 1985; resubmitted 18 June 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **42**, No. 2, 74–77 (25 July 1985)

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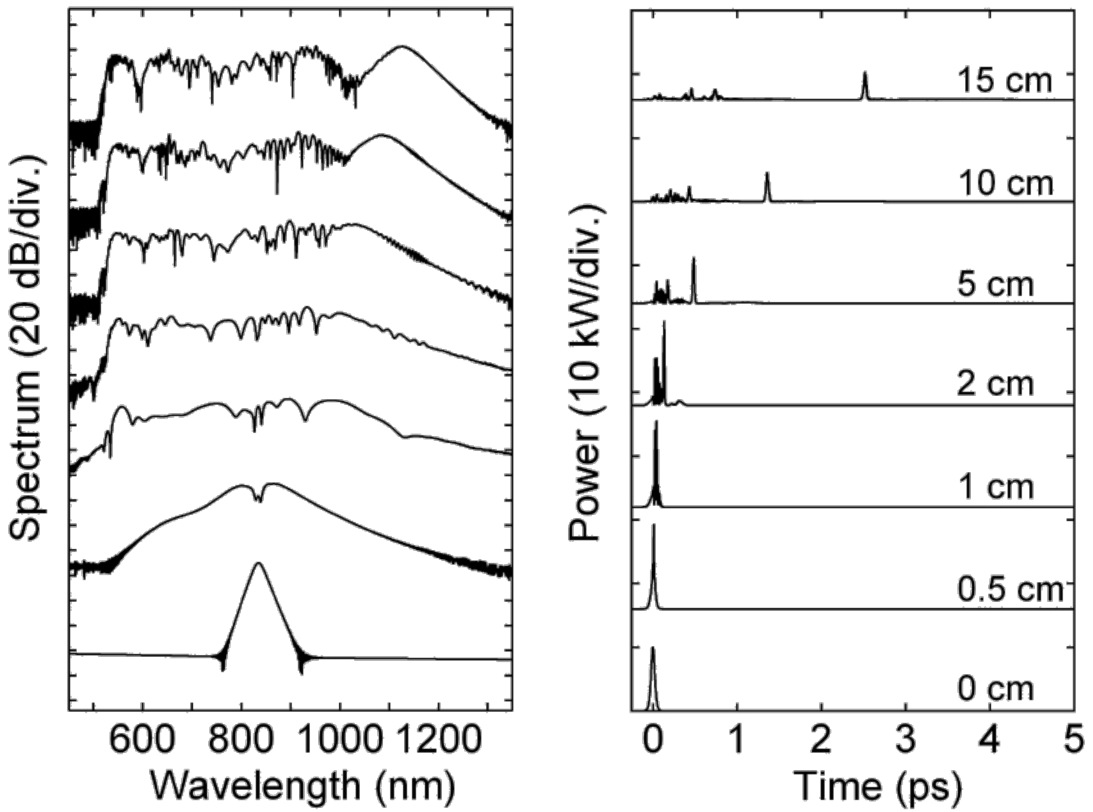
More complex supercontinuum dynamics

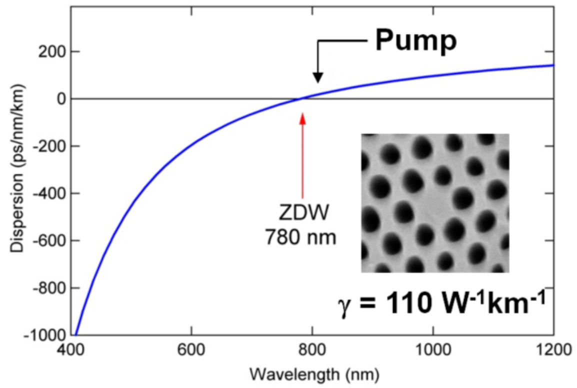
Spectral Evolution

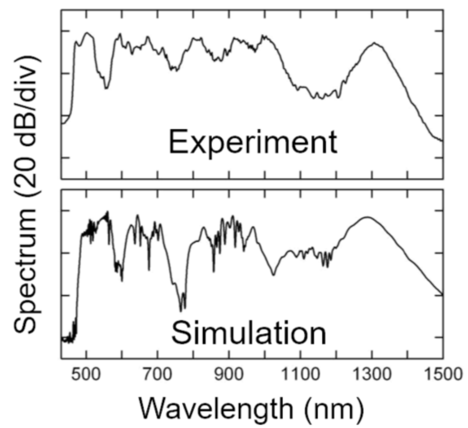
Temporal Evolution



FWHM 50 fs, 835 nm, 0.5 nJ, 15 cm PCF, N ~ 9

Input pulses: FWHM 22 fs, 810 nm, 0.9 nJ, 15 cm PCF





Corwin et al. PRL 90 113904 (2003)

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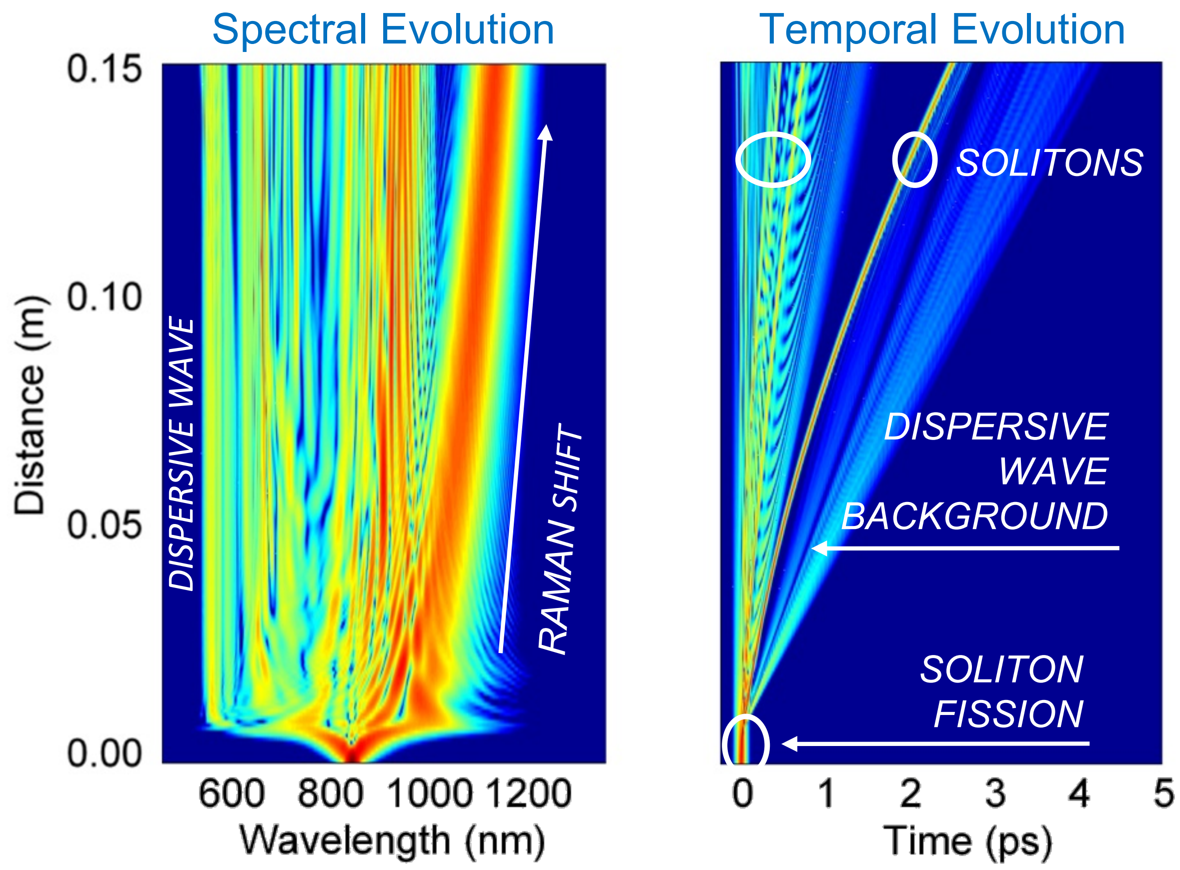
More complex supercontinuum dynamics



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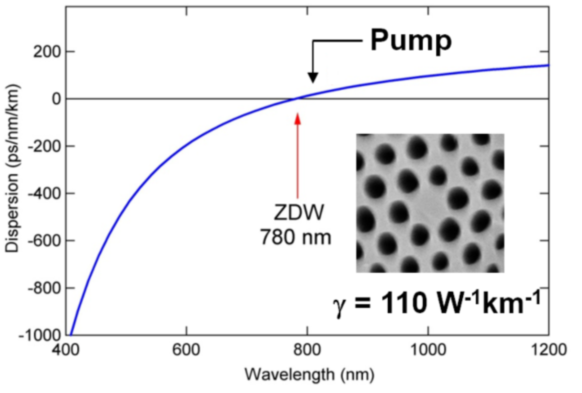

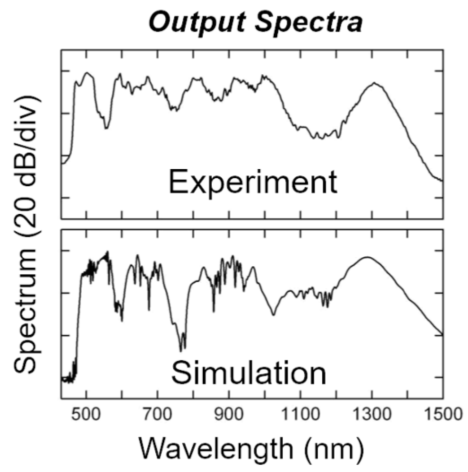

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But supercontinuum instabilities were seen in experiments

After the 1999 results, octave-spanning supercontinuum spectra were readily generated but why did some experiments show **highly-structured**, and others **smooth** spectra?

Ranka *et al.* Optics Letters 25 25 (2000)

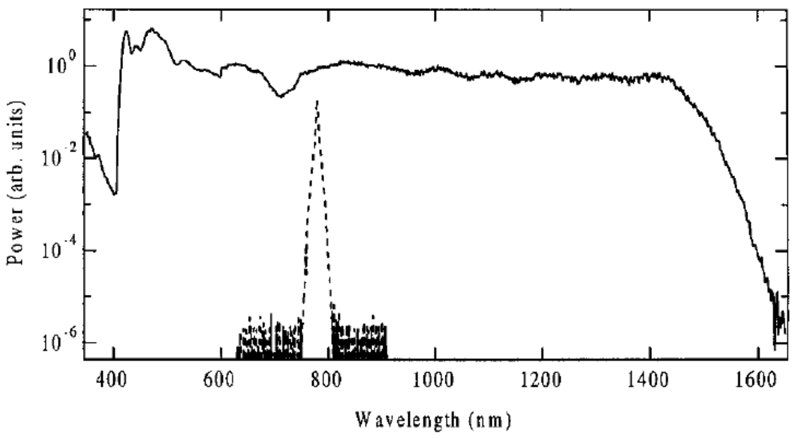
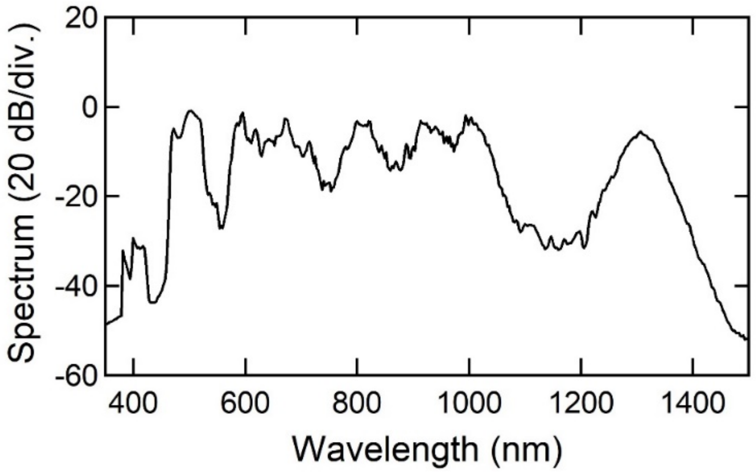


Fig. 4. Optical spectrum of the continuum generated in a 75-cm section of microstructure fiber. The dashed curve shows the spectrum of the initial 100-fs pulse.

Corwin *et al.* Phys Rev Lett 90 113904 (2003)



duration of 22 fs FWHM and a spectral bandwidth of 45 nm into a 15 cm long microstructure fiber

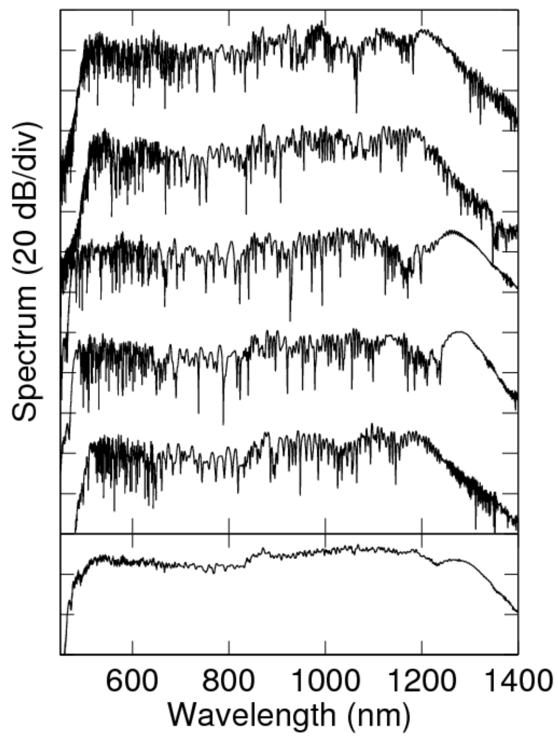
The smooth spectra were unsuitable for frequency combs - an underlying instability?

Modelling gave the answer, reproducing the instabilities

With long pulses, soliton-driven supercontinuum generation can be highly unstable.

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A - \sum_{k\geq 2}\frac{\mathrm{i}^{k+1}}{k!}\beta_k\frac{\partial^k A}{\partial T^k} = i\gamma\left(1 + \mathrm{i}\tau_{\mathrm{shock}}\frac{\partial}{\partial T}\right)\left(A(z,t)\int_{-\infty}^{+\infty}R(T')|A(z,T-T')|^2 dT'\right)$$

Stochastic simulations

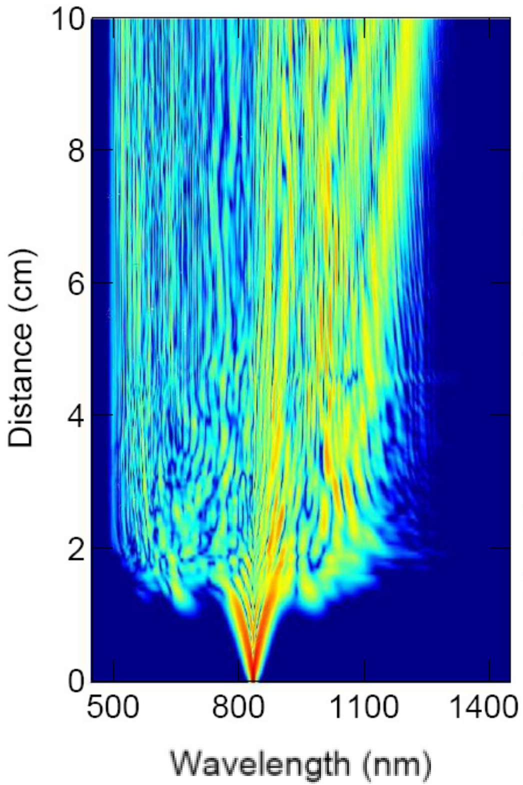


Simulation results

5 individual realizations identical apart from quantum noise

Successive pulses from a pulse train generate different spectra

The smooth spectrum is an artifact



The physics

- sensitivity of soliton fission to noise
- incoherent growth of spectral components outside the initial pulse bandwidth

J. M. Dudley, G. Genty, S. Coen, Rev. Mod. Phys. 78 1135 (2006)

The source of supercontinuum noise – modulation instability

Modulation instability (MI) is a fundamental property of nonlinear systems where modulation on a continuous wave grows exponentially

T. B. Benjamin and J. E. Feir, *J. Fluid Mech.* **27**, 417 (1967)

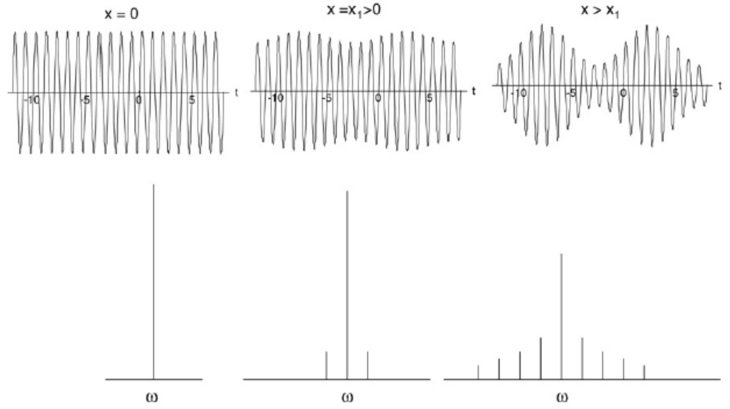


Fig. 1. Top: evolution of a nonlinear wave train in the course of MI. Bottom: the corresponding evolution of wave spectrum.

Lake, Yuen et. al. *J. Fluid Mech.* **83**, 49 (1977)

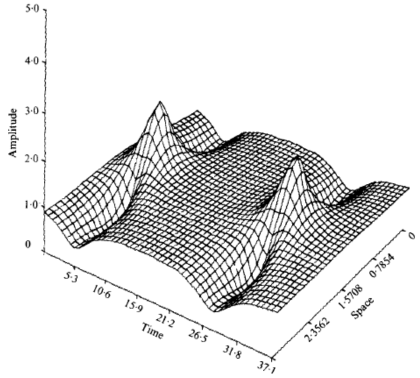


FIGURE 8. Fermi–Pasta–Ulam recurrence in nonlinear Schrödinger equation.

Physica D 238 (2009) 540–548

Modulation instability: The beginning

V.E. Zakharov [a,b], L.A. Ostrovsky [c,d,*]

[a] Department of Mathematics, University of Arizona, Tucson, AZ, USA
[b] Lebedev Institute of Physics, Russian Acad. Sci., Russia
[c] Zel Technologies/NOAA Earth Science Research Laboratory, USA
[d] Institute of Applied Physics, Russian Acad. Sci., Russia

When stimulated by a coherent modulation, MI leads to **coherent solitons & breathers**

When stimulated by noise, MI leads to chaos & **“rogue wave” statistics**

An extensive area of earlier work in mathematical physics

fore, $E(f)$ receives complex values. As a consequence, b_f, b_f^+ will involve a real exponential increasing with time, whence it follows that the states with small $N_f = b_f^+ b_f$ are unstable.

In order to be sure in the stability of the excited states, let us restrict the class of possible types of interaction forces, supposing inequality (7) to be satisfied for all types we shall consider. It is interesting to note

Bogolubov recognized the unstable branch but seems not to have studied it further!

N. Bogolubov
On the Theory of Superfluidity
Journal of Physics 11 23–32 (1947)

V. I. Bespalov and V. I. Talanov
Filamentary structure of light beams
in nonlinear liquids
JETP Lett. 3, 307-310, (1966)

J. Lighthill
Contributions to the theory of waves
in nonlinear dispersive system
J. Inst. Math. Appl. 1 269 (1965)

G.B. Whitham
A general approach to linear and
nonlinear dispersive waves using
a Lagrangian
J. Fluid Mech. 22 273 (1965)

T. B. Benjamin, J. E. Feir
The disintegration of wave trains
on deep water. Part I. Theory
J. Fluid Mech. 27 417 (1967)

Zakharov, Ostrovsky, Litvat, Akhmanov, Brewer, Levi-Civita, Karpman, Ham, Krasovskii, Hasegawa *et al.*

Coherent solitons and breathers

Before studying random nonlinear structures from modulation instability, we first see if we can excite the expected mathematical breather structures from a coherent modulation

$$i\psi_\xi + \frac{1}{2}\psi_{\tau\tau} + |\psi|^2\psi = 0$$

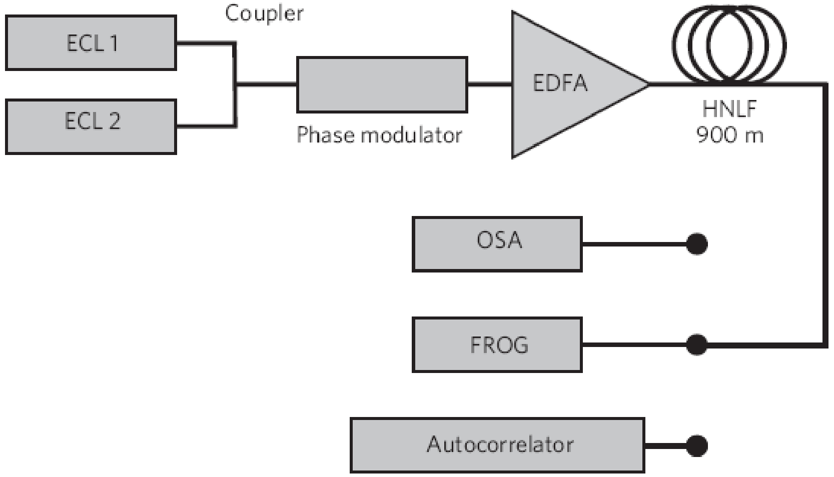
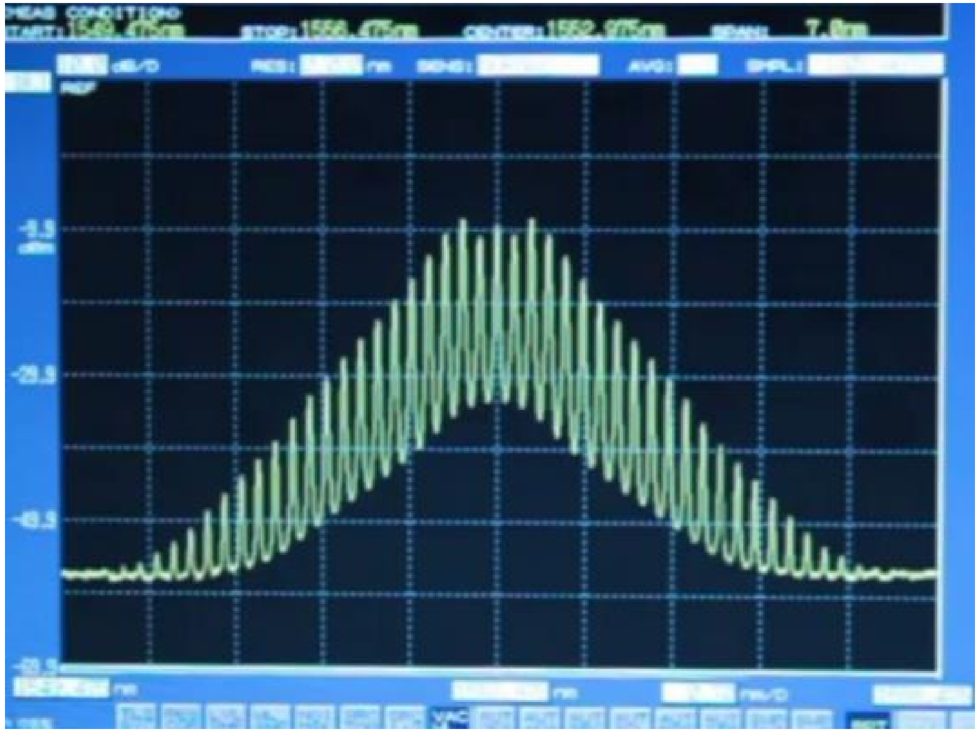


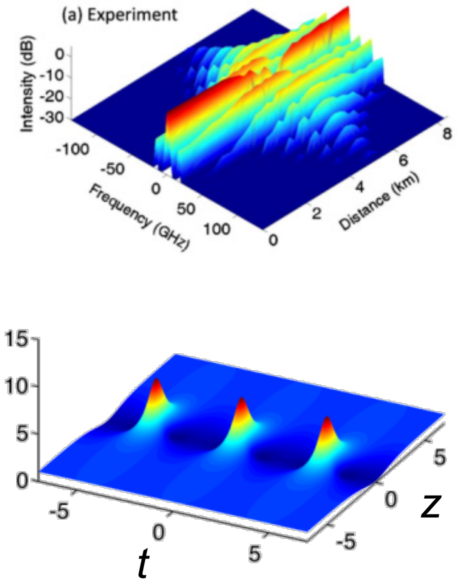
Figure 3 | Experimental set-up. ECL: external-cavity laser; OSA: optical spectrum analyser; FROG: frequency-resolved optical gating. HNLF: highly nonlinear fibre. EDFA: erbium-doped fibre amplifier.

We create frequency-domain initial conditions based on the analytic mathematical form for a particular soliton structure



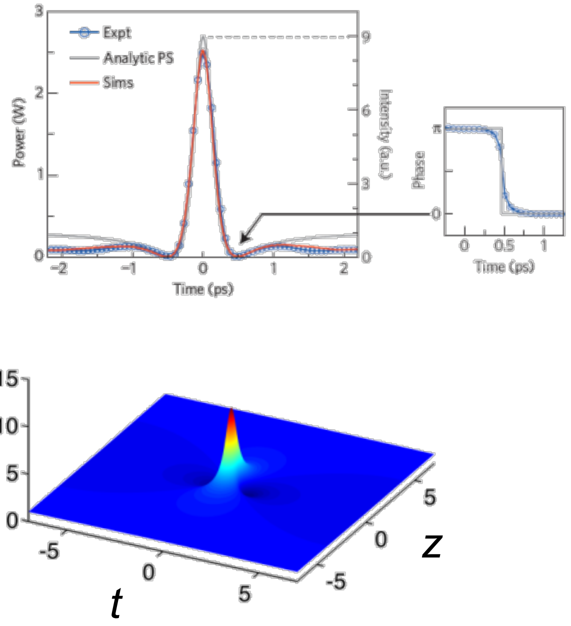
Solitons and breathers in modulation instability

With coherent initial modulation, modulation instability evolves towards stable breather or soliton structures. This has been confirmed in experiments.



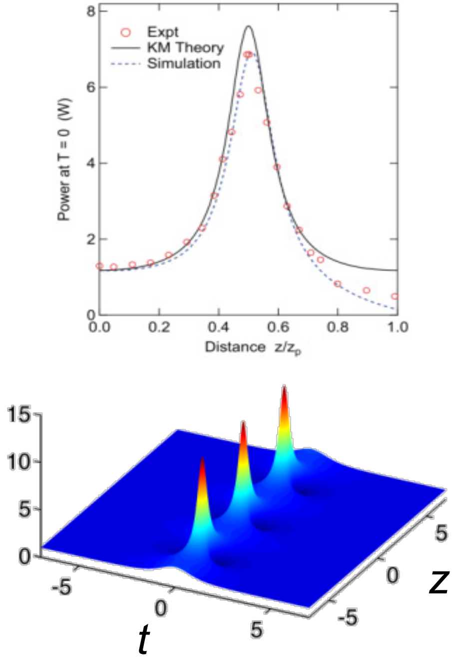
Akhmediev breather (AB)

Hammani *et al.*,
OL (2011)



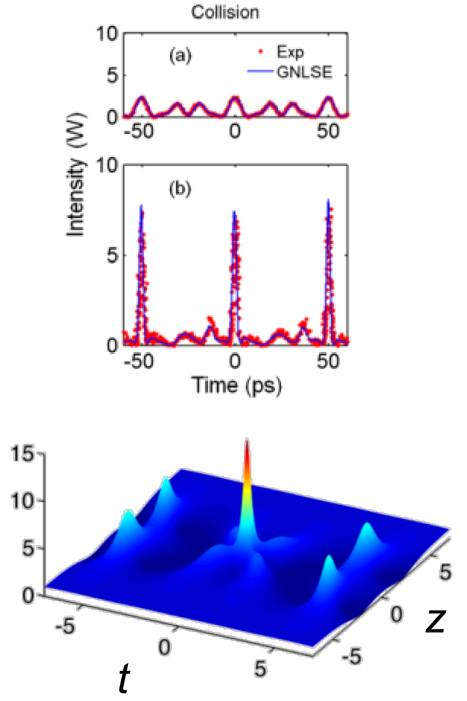
Peregrine soliton

Kibler *et al.*,
Nat. Phys. (2010)



Kuznetsov-Ma soliton

Kibler *et al.*,
Sci. Rep. (2012)



Higher-order AB

Frisquet *et al.*,
PRX (2013)

Transferring results into hydrodynamics

The generation of coherent structures from induced modulation instability has also been performed in hydrodynamic wave tanks, confirming the NLSE analogy between the systems

PRL **106,** 204502 (2011) PHYSICAL REVIEW LETTERS week ending 20 MAY 2011

Rogue Wave Observation in a Water Wave Tank

A. Chabchoub,[1,*] N. P. Hoffmann,[1] and N. Akhmediev[2]
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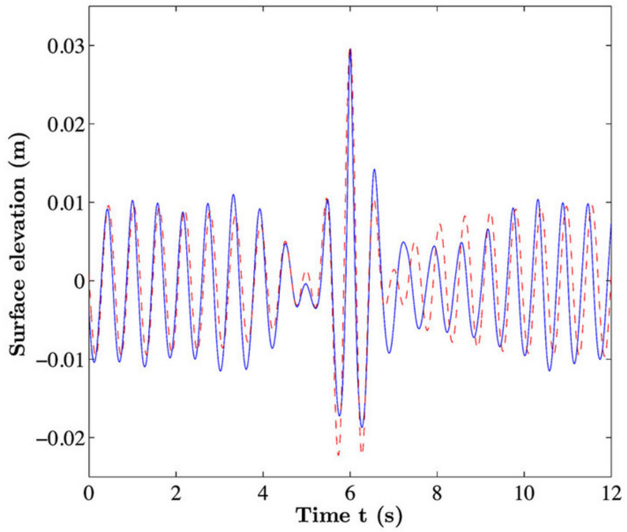
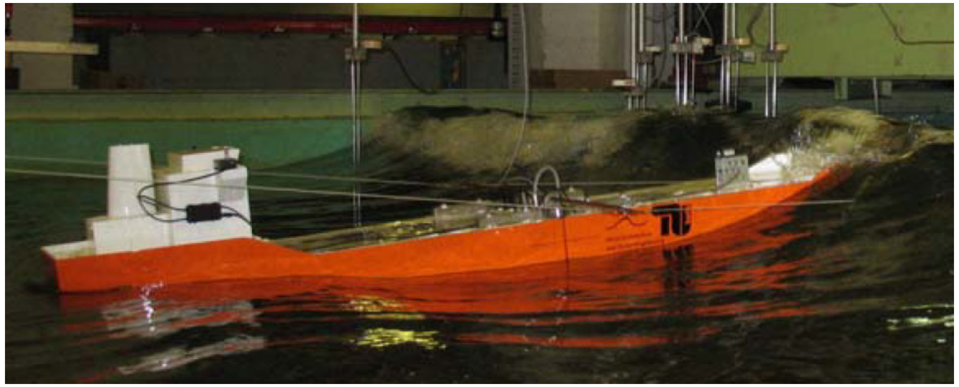
[2]*Optical Sciences Group, Research School of Physics and Engineering, The Australian National University, Canberra ACT 0200, Australia*
(Received 28 February 2011; published 16 May 2011)



OPEN ACCESS Freely available online PLOS ONE

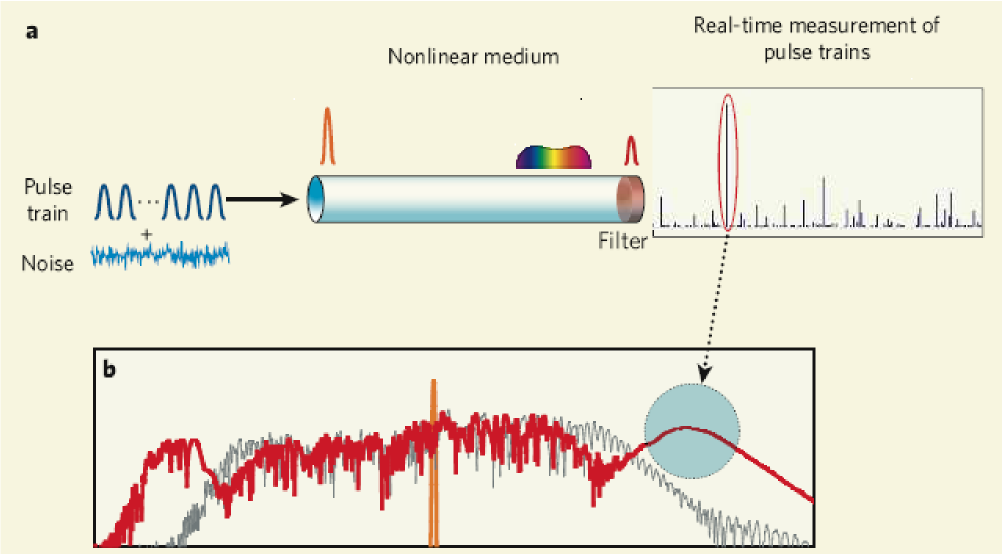
Rogue Waves: From Nonlinear Schrödinger Breather Solutions to Sea-Keeping Test

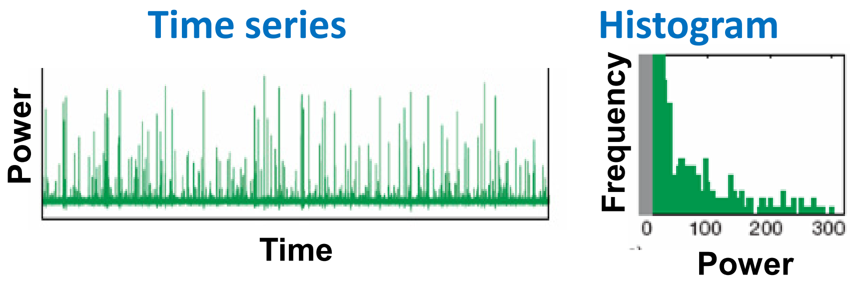
Miguel Onorato[1,2], Davide Proment[3]*, Günther Clauss[4], Marco Klein[4]
1 Dipartimento di Fisica, Università degli Studi di Torino, Torino, Italy, **2** INFN, Sezione di Torino, Torino, Italy, **3** School of Mathematics, University of East Anglia, Norwich, United Kingdom, **4** Ocean Engineering Division, Technical University of Berlin, Berlin, Germany

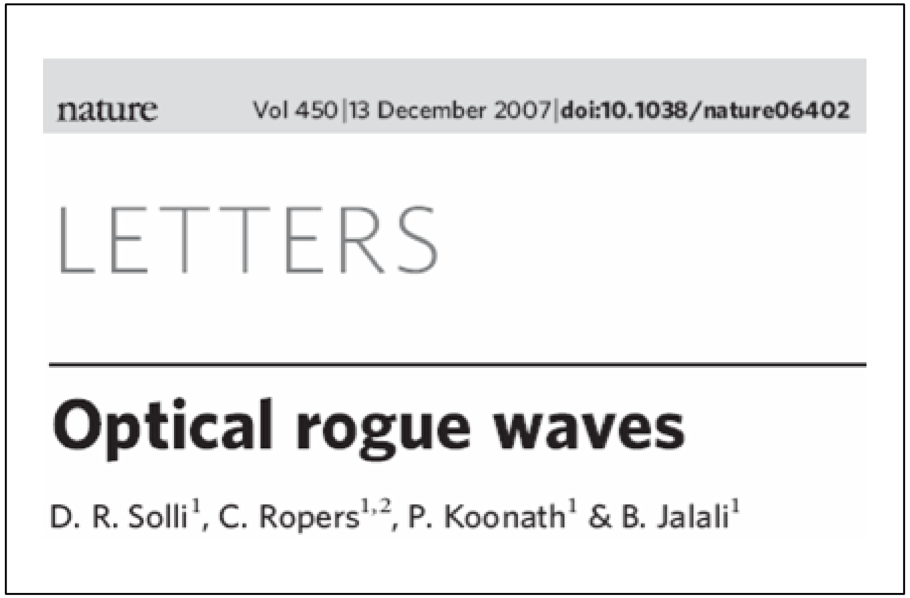


Measuring spectral instabilities in real-time

What was significant about the 2007 measurements in supercontinuum generation was the ability to measure the spectral instabilities in real time





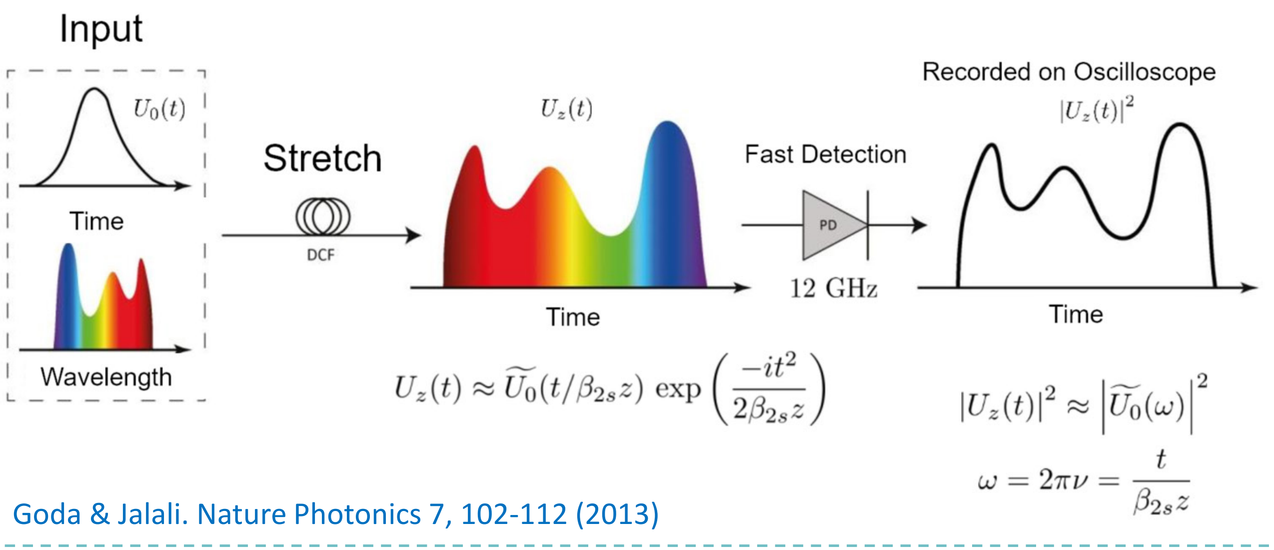


Measuring spectral instabilities in real-time

Dispersive Fourier Transform

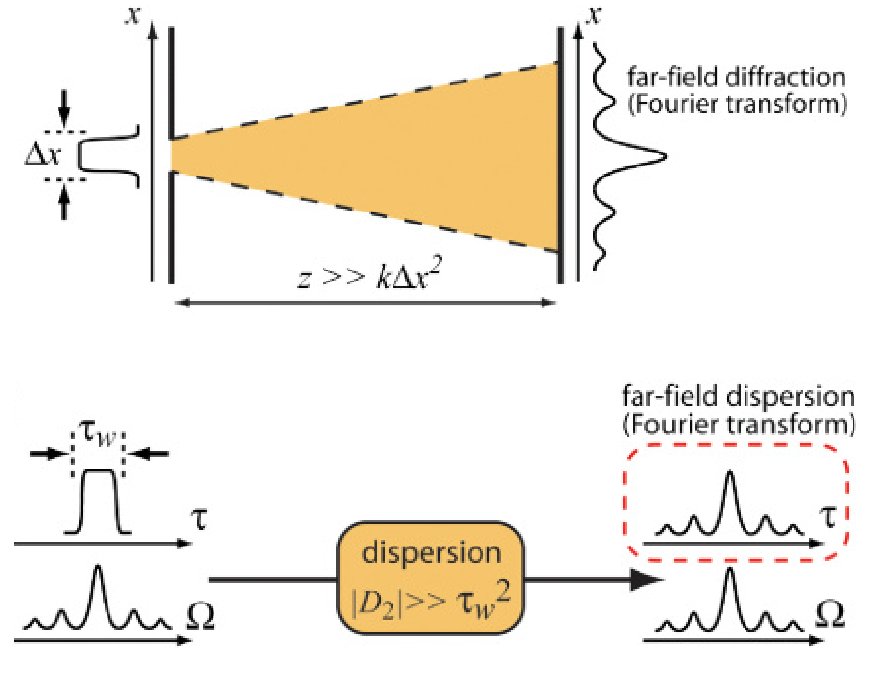
(measures spectral intensity, sub-nm resolution)

Principle: The temporal intensity of a pulse stretched by large linear dispersion is proportional to its spectral intensity



Goda & Jalali. Nature Photonics 7, 102-112 (2013)

Analogous to spatial far-field diffraction



R. Salem *et al.* Advances in Optics and Photonics **5**, 274-317 (2013)

Shot-to-shot spectra are stretched to 5-10 nanoseconds and measured using a fast oscilloscope

This was in fact a much earlier idea – the "spectron"

Self-action of wave packets in a nonlinear medium and femtosecond laser pulse generation

S. A. Akhmanov, V. A. Vysloukh, and A. S. Chirkin

M. V. Lomonosov Moscow State University
Usp. Fiz. Nauk **149**, 449–509 (July 1986)

1.4.1. "Spectron"; pulse shape in the far-zone

Let us analyze the propagation of PM pulses in a dispersive medium for arbitrary initial shape of the profile $\rho_0(t)$. At the output of a frequency-modulating device a pulse has the form

$$A_0(t) = \rho_0(t)\, e^{-i\alpha_0 t^2/2}. \qquad (1.37)$$

Evolution of this pulse in a dispersive medium in the second-order approximation of dispersion theory is described by the expression (1.12). In this case, at a distance $z = F = (\alpha_0 k_2)^{-1}$ we obtain

$$A(\eta, z) = (i \cdot 2\pi k_2 z)^{-1/2} \tilde{\rho}_0(\alpha_0 \tau_0 \eta)\, e^{i\alpha_0 \eta^2/2}, \qquad (1.38)$$

$$\tilde{\rho}_0(\alpha_0 \tau_0 \eta) = \int_{-\infty}^{+\infty} \rho_0\left(\frac{t}{\tau_0}\right) e^{-i\alpha_0 \eta t}\, dt. \qquad (1.39)$$

From the obtained result it is possible to draw the following conclusions about the pulse in the "focal" plane of the "time" lens. The pulse shape is exactly the same as the Fourier-spectrum of the initial pulse.[34,39] Such pulses are called "spectrons."[20,40] The profile of pulses turns out to be sym-

232 OPTICS LETTERS / Vol. 8, No. 4 / April 1983

Real-time Fourier transformation in dispersive optical fibers

Tomasz Jannson

Research Division, National Technical Systems, Inc., Los Angeles, California, 90066

Received November 22, 1982

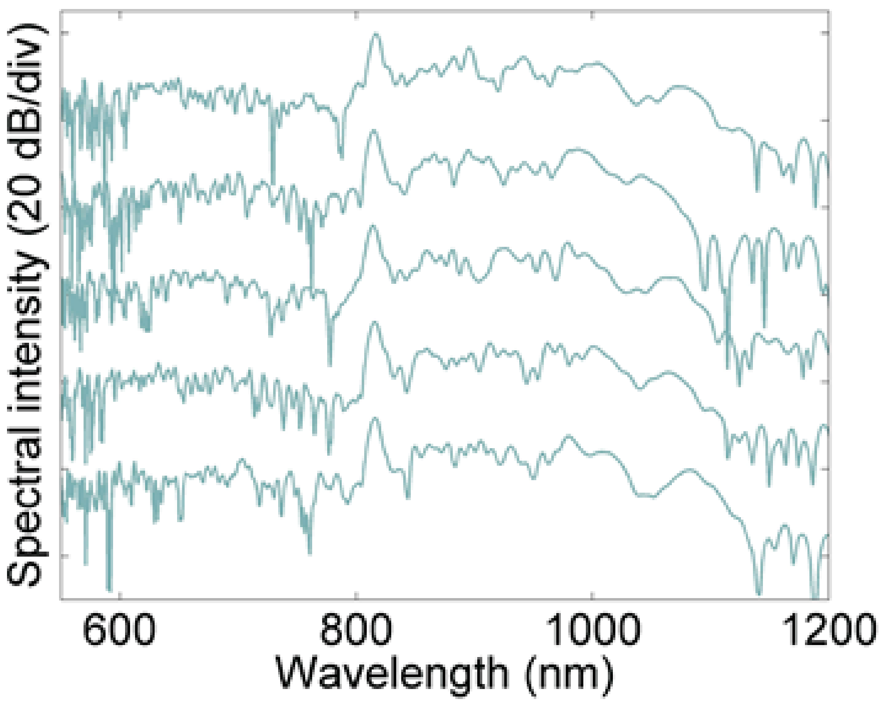
The general concept of temporal Fourier transformation in dispersive media is analyzed. The real-time optical Fourier transformer is shown to be realizable by using dispersive single-mode fibers and chirping lasers.

[20] Yu. E. D'yakov and S. Yu. Nikitin, Zadachi po statisticheskoĭ radiofizike i optike, Moscow State University Press, M., 1985 (Problems on statistical radiophysics and optics).

Measuring spectral instabilities in real-time

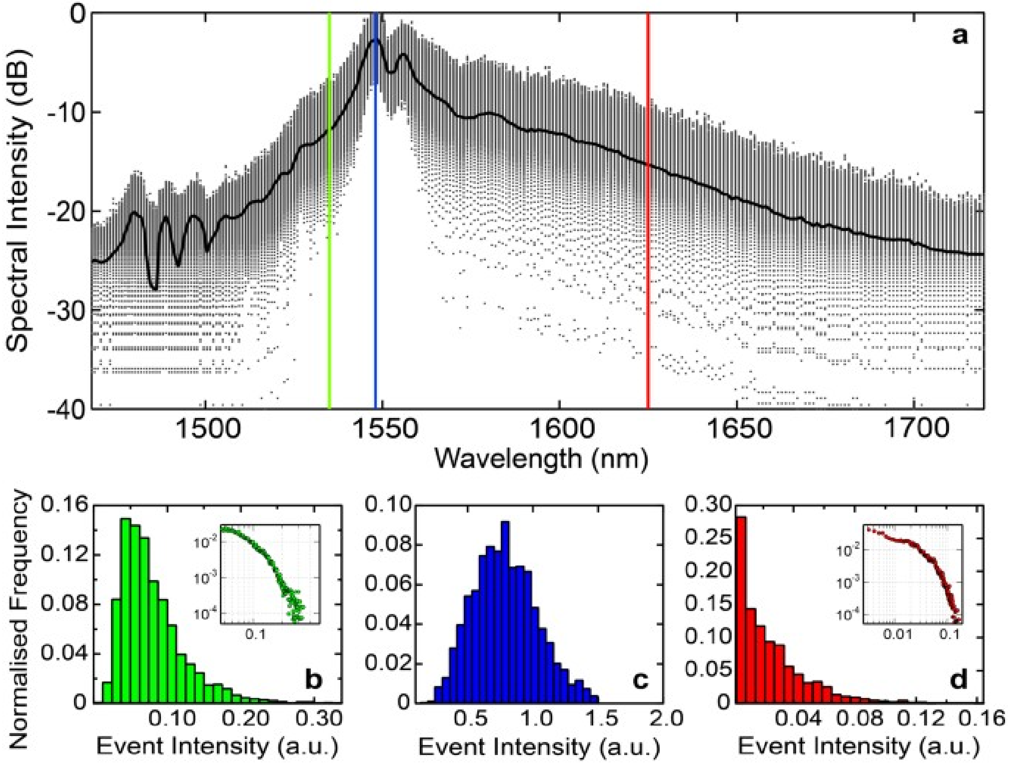
When applied to supercontinuum generation we can directly measure noise-induced shot-to-shot fluctuations in spectral structure, and the associated statistics

Godin et al. Opt. Exp. **21** 18452 (2013)



Around 830 nm

Wetzel *et al.* Sci. Rep. **2** 882 (2012)

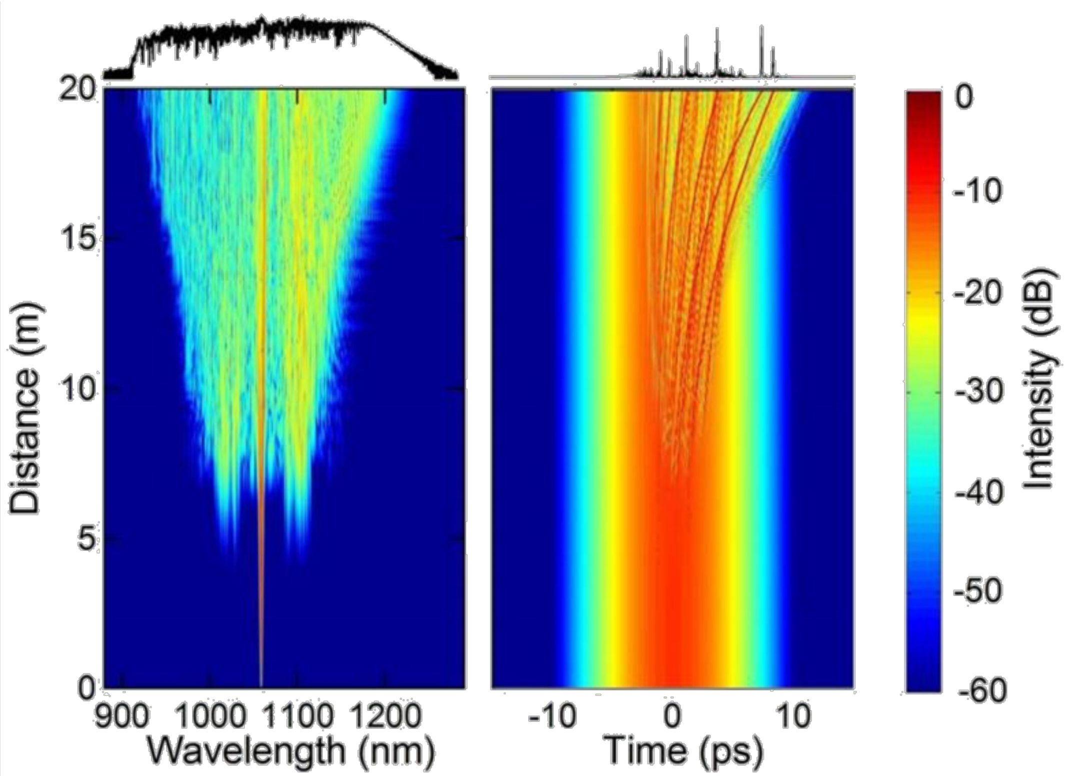


Around 1550 nm

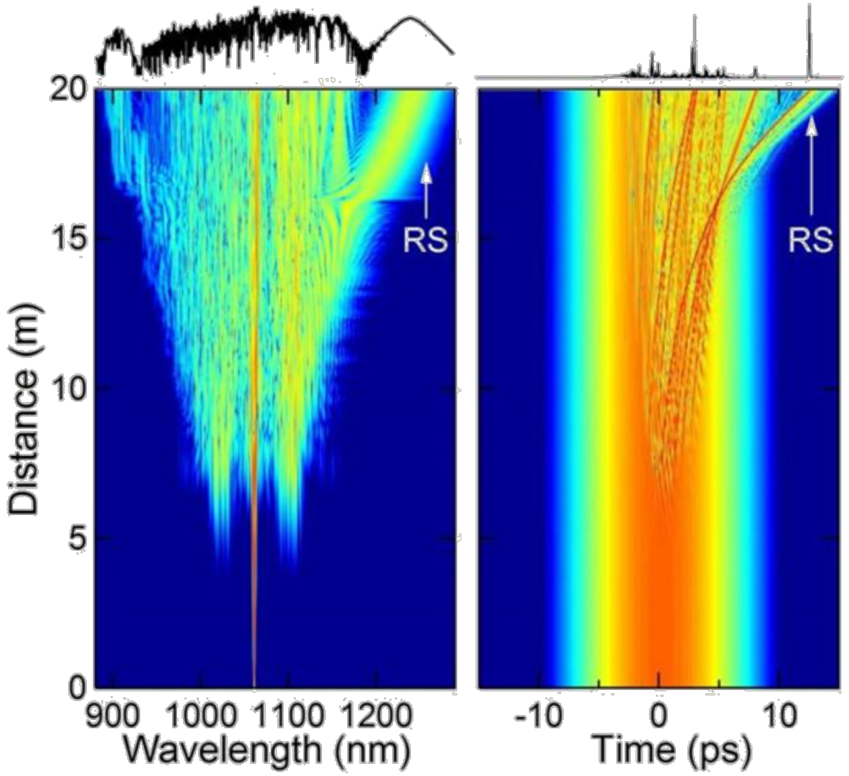
What makes an optical rogue wave different?

To understand the physics of optical rogue waves in the supercontinuum, we use simulations to see the effect of random noise on the input pulse

Most simulations yield dynamics like this



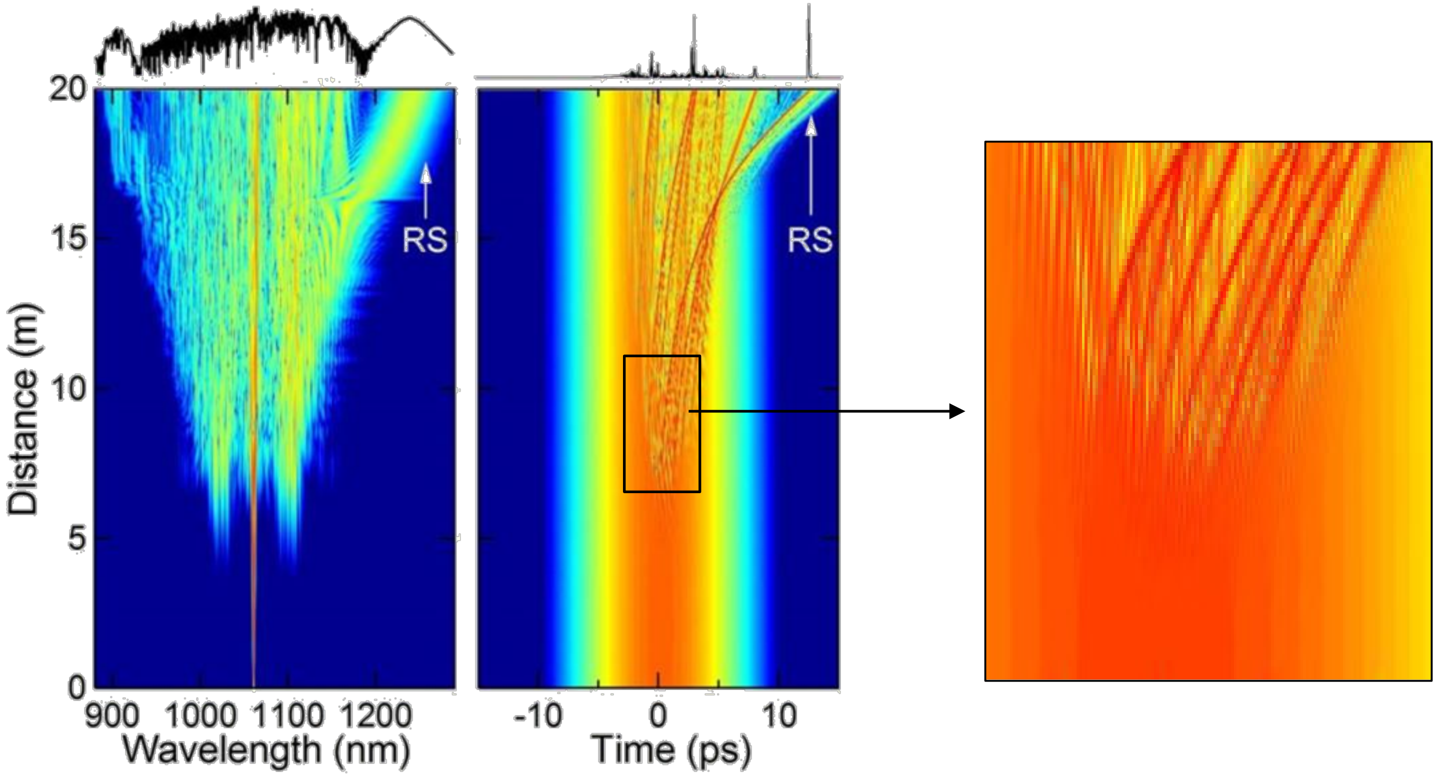
A small number of simulations yield dynamics like this (RS = rogue soliton)



What makes an optical rogue wave different?

Random noise can lead to very different dynamics, and in a small number of cases, the emergence of extreme rogue solitons that undergo dramatic shifts to longer wavelengths

A small number of simulations yield dynamics like this (RS = rogue soliton)



The physics

Random noise
Chaotic modulation instability
Chaotic soliton dynamics
Inelastic (Raman) energy transfer

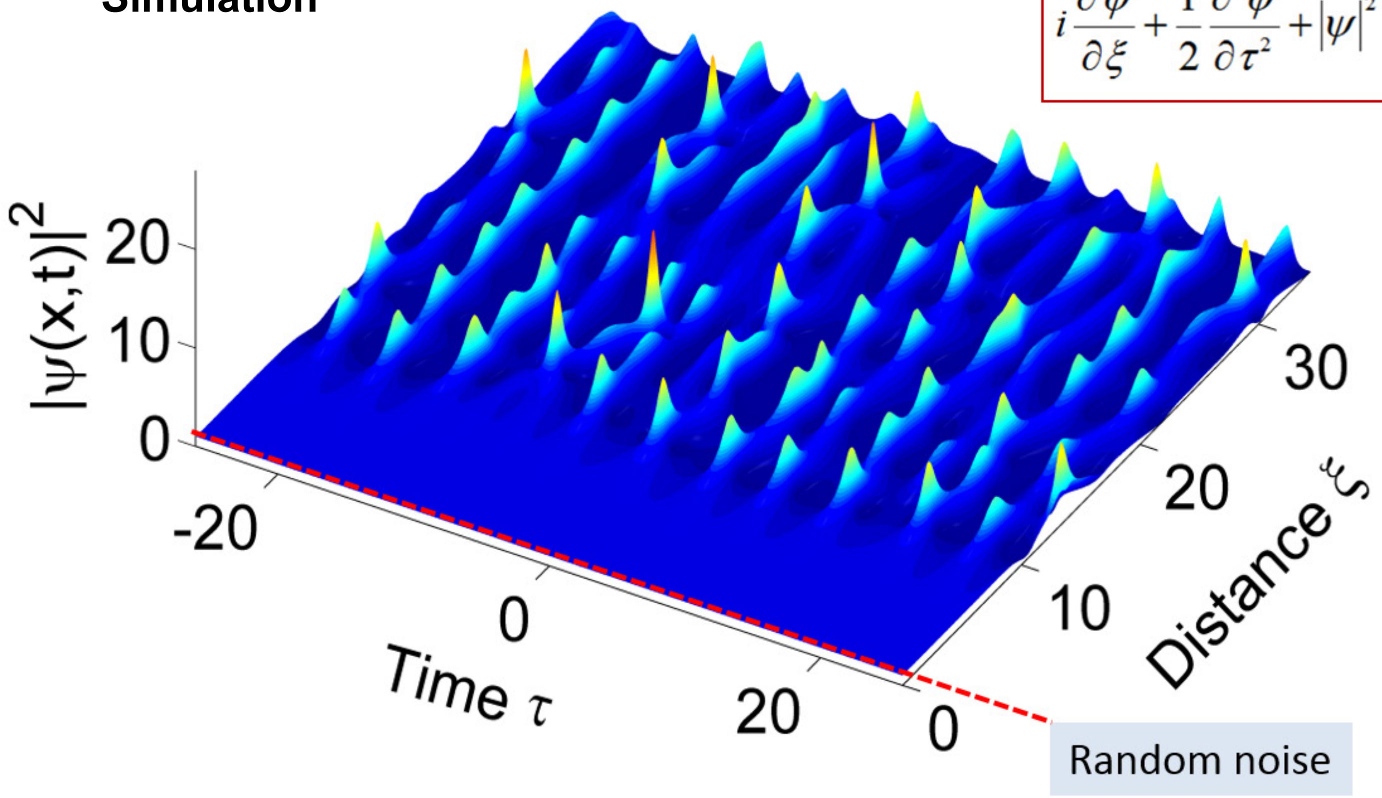
One soliton can become
larger than the others

The next step: looking at incoherent modulation instability

Can we measure noise-seeded random modulation instability dynamics in more detail?

Numerical Simulation

$$i\frac{\partial\psi}{\partial\xi}+\frac{1}{2}\frac{\partial^2\psi}{\partial\tau^2}+|\psi|^2\psi=0$$



In particular

Can we also measure statistics of the temporal fluctuations?

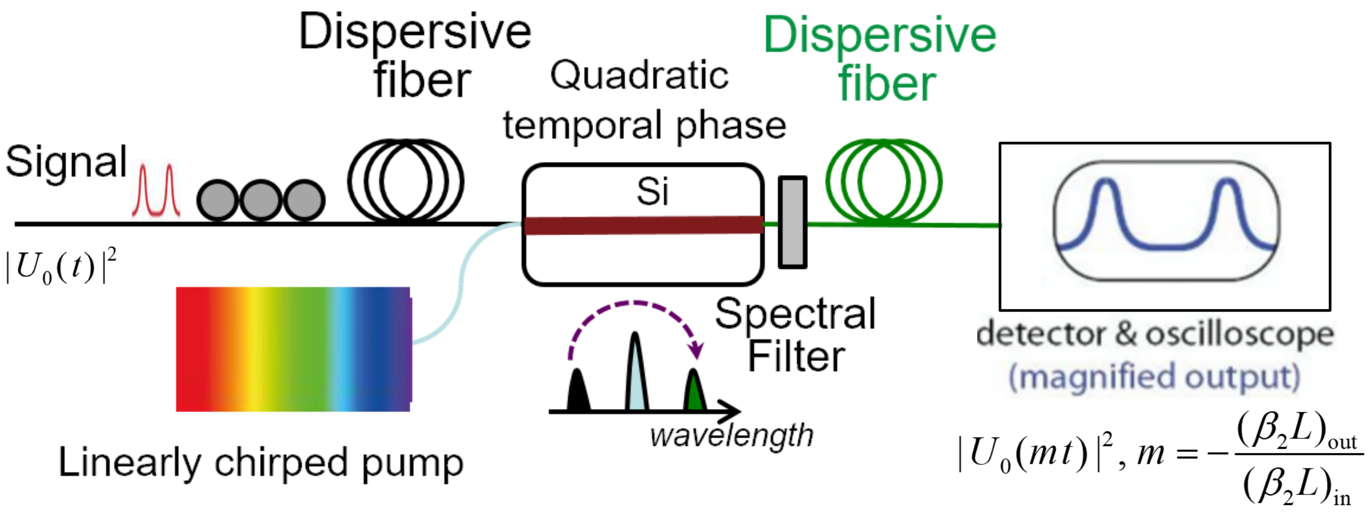
Can we measure the intensity profiles of the chaotic temporal peaks and compare with analytic soliton / breather structures?

Measuring temporal instabilities in real-time

Time lens magnifier

(temporal intensity, sub-ps resolution)

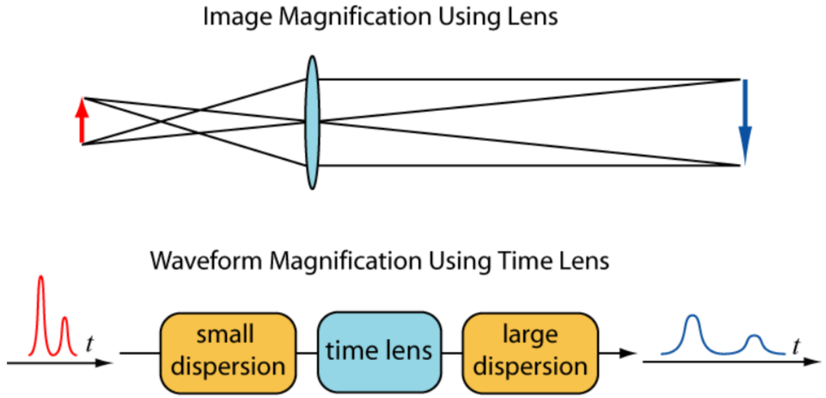
Principle: A signal experiencing dispersion before and after quadratic temporal phase is temporally magnified



R. Salem et al., Adv. Opt Photonics 5, 274-317 (2013)

Analogous to temporal imaging

Dispersion & quadratic phase yield a time-domain analogue of a thin lens imaging system



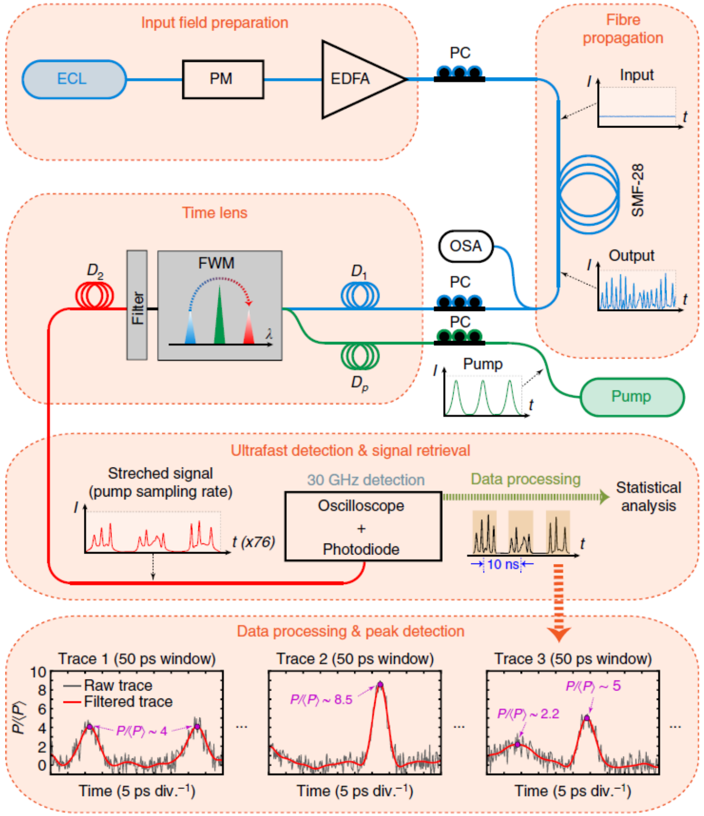
Picosecond structures are stretched to the nanosecond scale and measured using a fast oscilloscope

Time-lens measurements of modulation instability

NATURE COMMUNICATIONS | 7:13675 | DOI: 10.1038/ncomms13675 | www.nature.com/naturecommunications

Real-time measurements of spontaneous breathers and rogue wave events in optical fibre modulation instability

Mikko Närhi[1], Benjamin Wetzel[2,3], Cyril Billet[4], Shanti Toenger[1,4], Thibaut Sylvestre[4], Jean-Marc Merolla[4], Roberto Morandotti[2,5,6], Frederic Dias[7], Goëry Genty[1] & John M. Dudley[4]

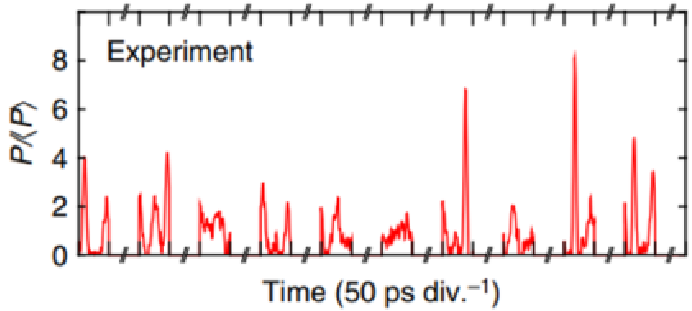


Direct measurement of instability time series and histogram

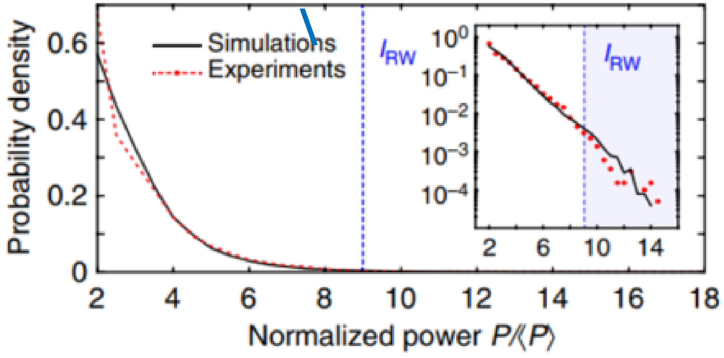
Comparison with stochastic NLSE simulations

Comparing intensity peaks with analytic soliton profiles

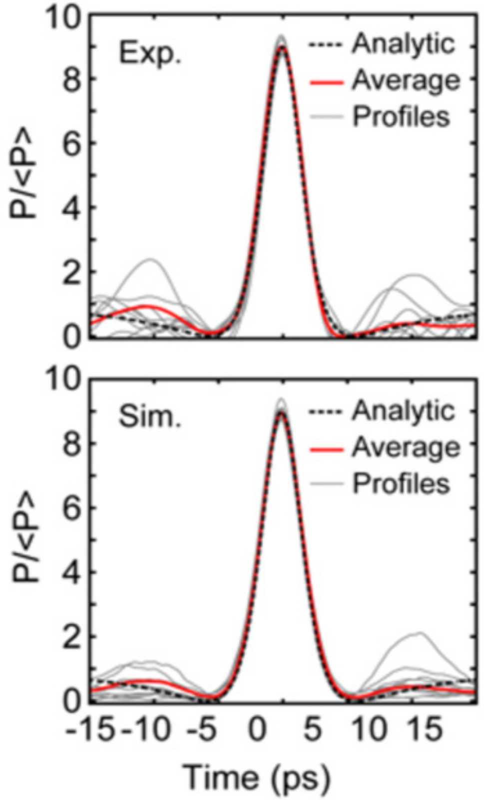
Time series



Histogram

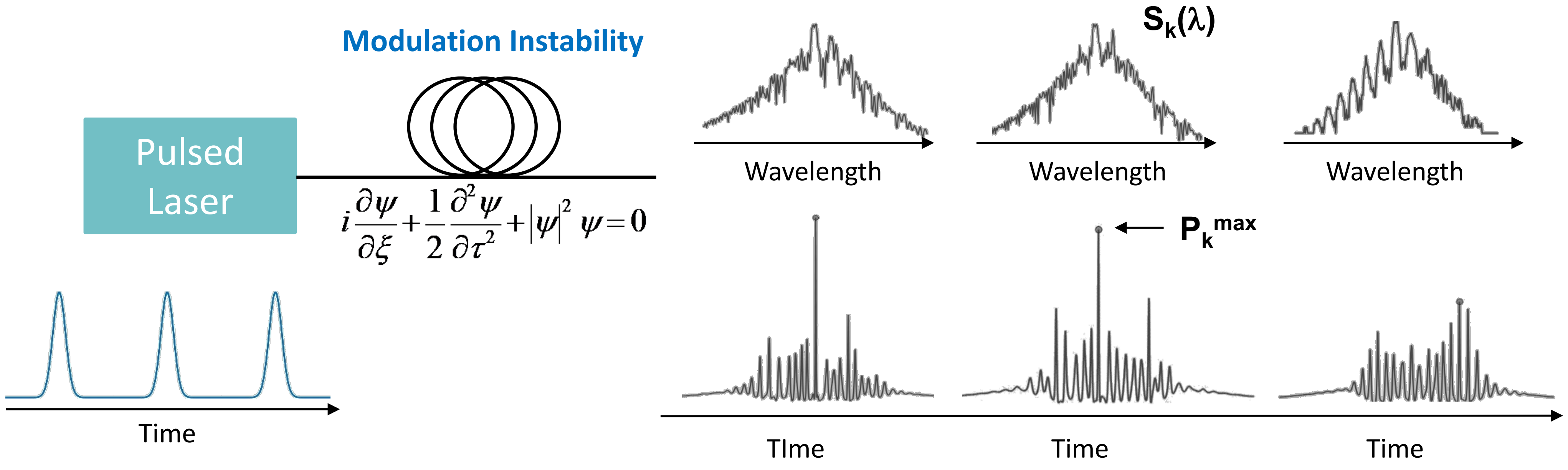


Peregrine solitons



What if you do not have a time lens?

Even when time lens measurements are not possible, a **neural network** algorithm can be trained to determine key temporal characteristics based only on measurements of spectral intensity (i.e. no spectral phase information).



$$i\frac{\partial\psi}{\partial\xi}+\frac{1}{2}\frac{\partial^2\psi}{\partial\tau^2}+|\psi|^2\,\psi=0$$

$$E_k(t)\leftrightarrow\tilde{E}_k(\omega)$$

$$S_k(\omega)=\left|\tilde{E}_k(\omega)\right|^2$$

$$I_k(t)=\left|E_k(t)\right|^2$$

Can we configure a neural network to map complex shot to shot spectra to the peak intensity of the corresponding modulated temporal intensity profile (rogue waves)? Can $S_k(\lambda)$ predict P_k^{max} ?

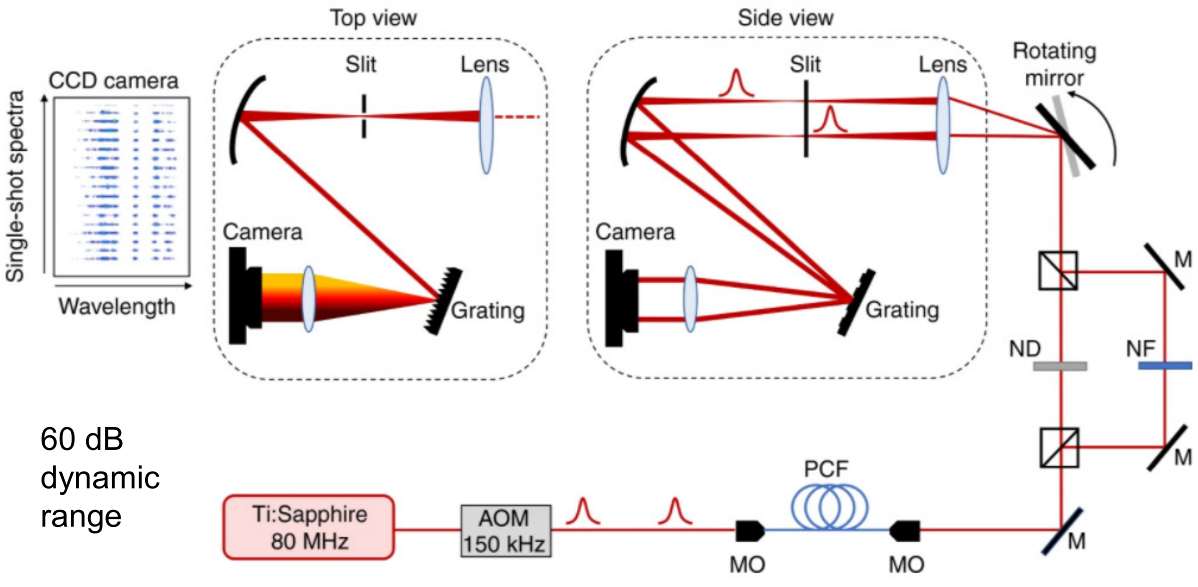
Experimental setup

Modelling suggests that this requires a very high dynamic range real-time spectrometer, so experiments are performed using a reduced repetition rate laser and scanning bulk monochromator

NATURE COMMUNICATIONS | DOI: 10.1038/s41467-018-07355-y

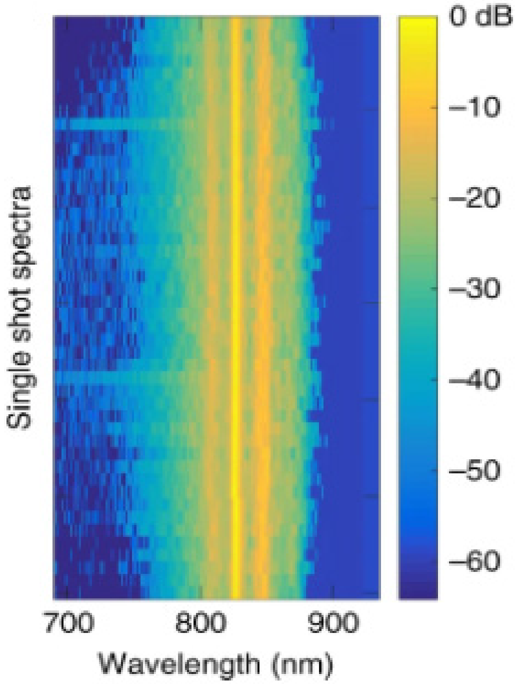
Machine learning analysis of extreme events in optical fibre modulation instability

Mikko Närhi[1], Lauri Salmela[1], Juha Toivonen[1], Cyril Billet[2], John M. Dudley[2] & Goëry Genty[1]

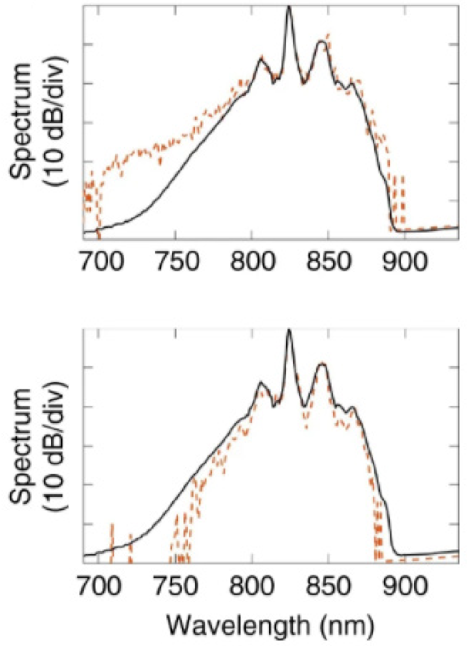


60 dB dynamic range

60 measurements show large shot-to-shot fluctuations

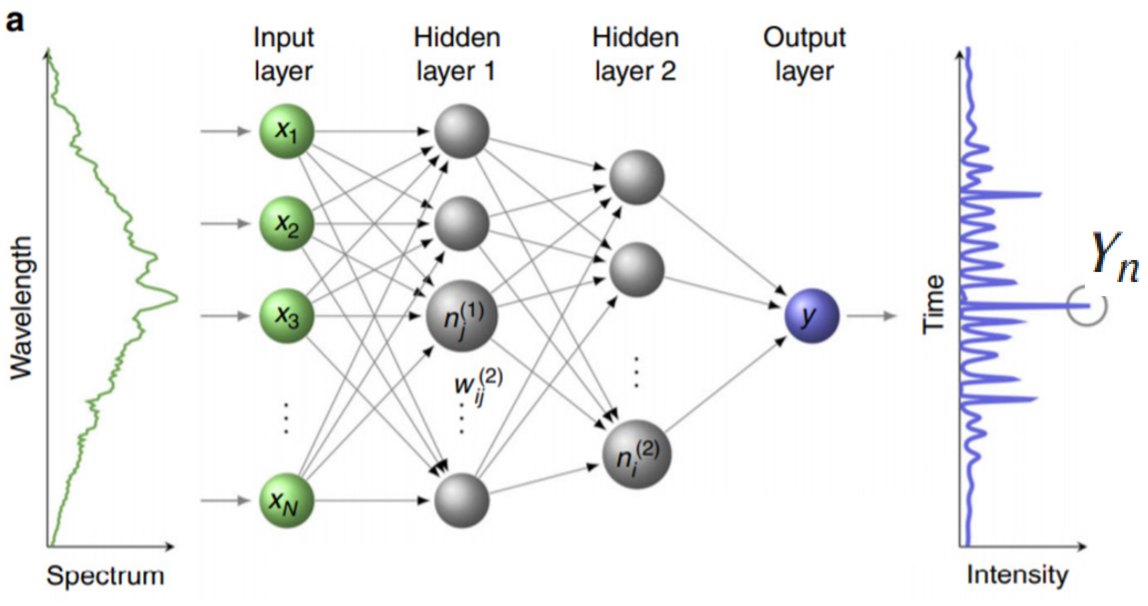


Single shot spectra (red) compared to mean (black)



Training a neural network to analyse modulation instability

We use a standard neural network architecture and use simulations to train a network to correlate the full MI spectrum with the corresponding peak of the associated temporal intensity profile.



$\mathbf{X}_n = [x_1, x_2 ... x_N]$

Architecture

Feedforward

2 hidden layers (30, 10 nodes)

Training using NLSE simulations

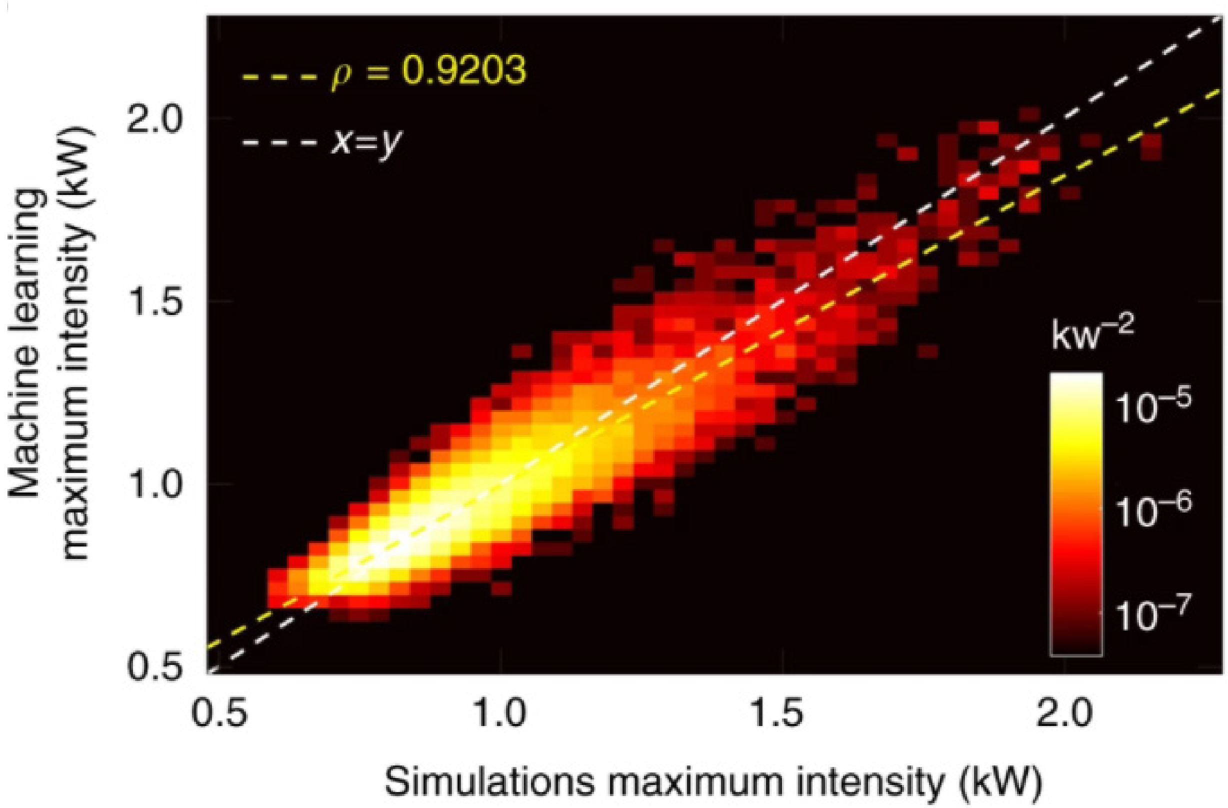
$(\mathbf{X}_n, Y_n)$, $n = 1 \ldots 30{,}000$

$\mathbf{X}_n = [x_1, x_2 ... x_N]$, $N = 121$

300 epochs of 30,000 simulations

Testing the trained neural network

We use a standard neural network architecture and use simulations to train a network to correlate the full MI spectrum with the corresponding peak of the associated temporal intensity profile.



Testing the trained network

Use 20,000 simulations not in the training set.

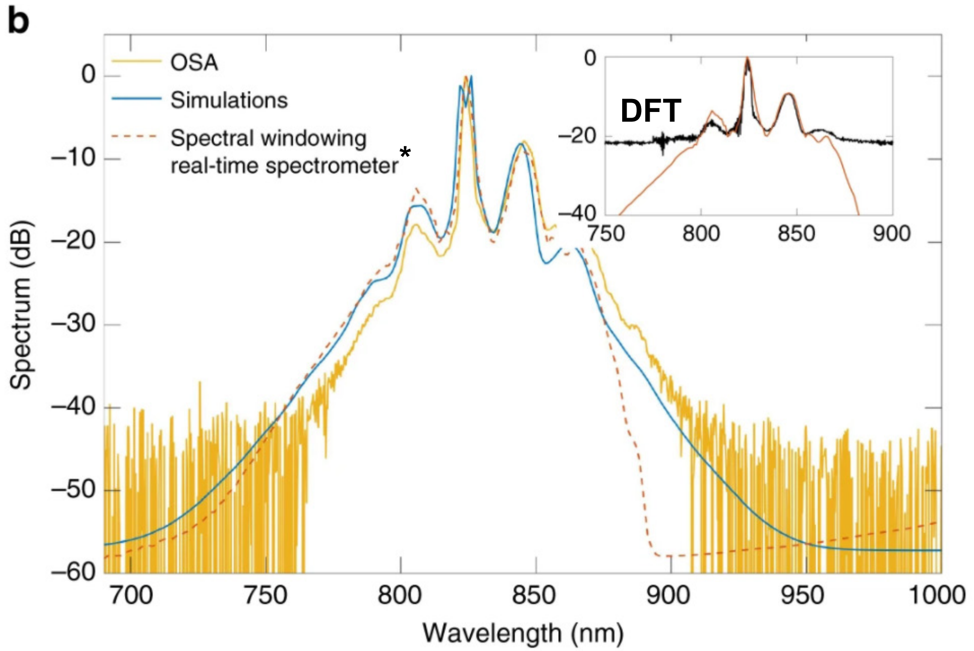
For each spectrum we predict the peak intensity.

We plot the predicted intensity against the known ground truth intensity from the corresponding simulation.

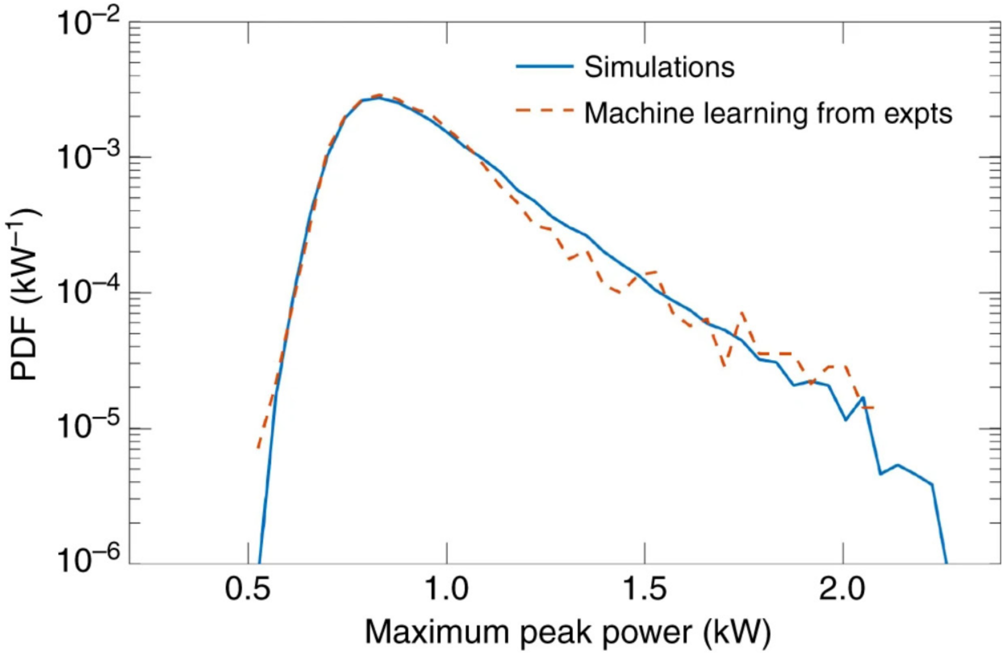
We obtain very high correlation.

Analysing experimental spectra to predict time-domain peaks

Based on 3000 **measured** real-time **spectra,** we determine the corresponding temporal peaks and compute the associated **temporal** probability density function.



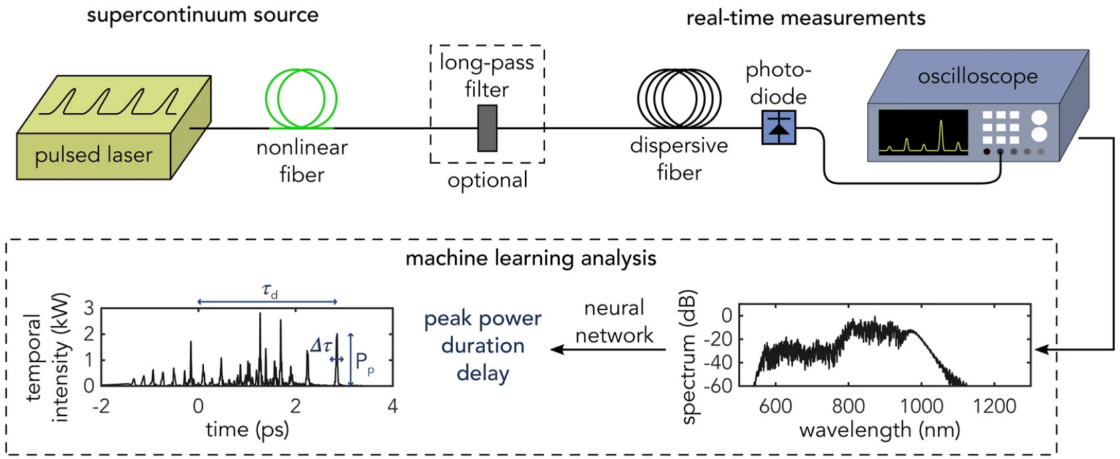
* Training for experimental data also includes the wavelength response of the spectrometer



We compare the machine learning predictions with fully realistic simulations of our experiments.

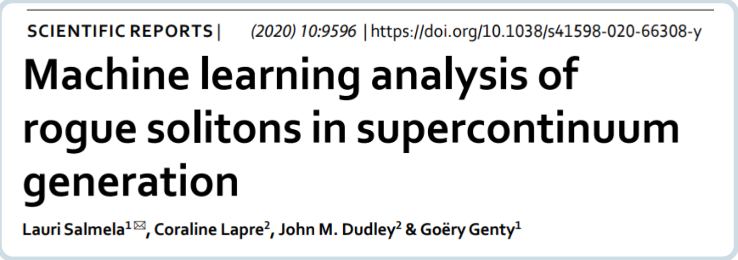
Can we do the same in supercontinuum generation?

In other words, based on spectral data only, can we determine the properties of the most red-shifted solitons ("rogue solitons") in a temporal supercontinuum field?



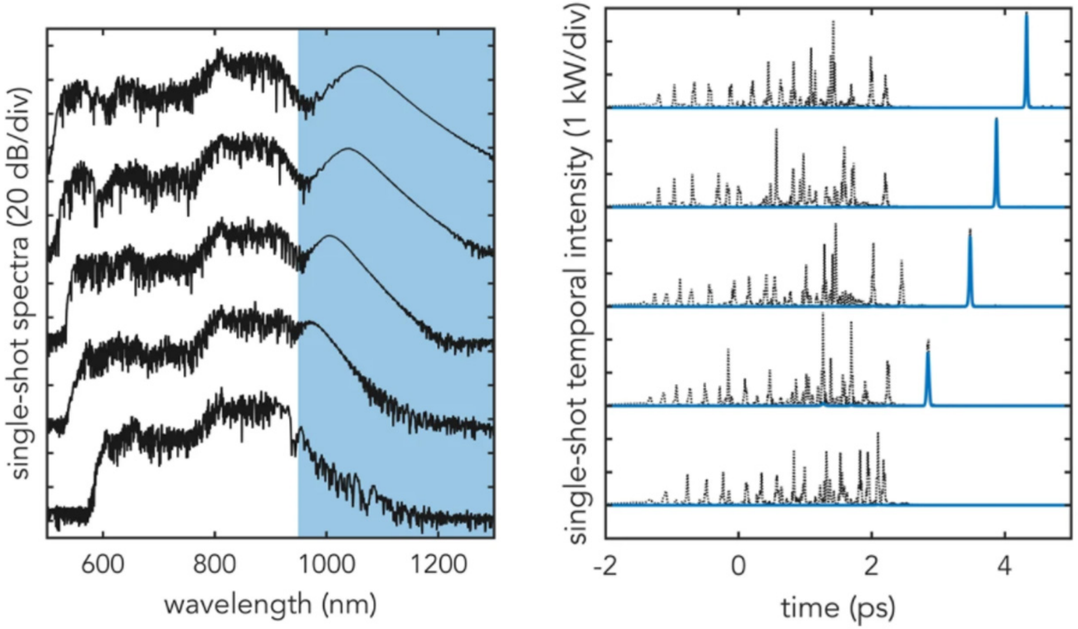
Temporal peak power
Temporal duration
Temporal walk-off

Spectrum


SCIENTIFIC REPORTS | (2020) 10:9596 | https://doi.org/10.1038/s41598-020-66308-y

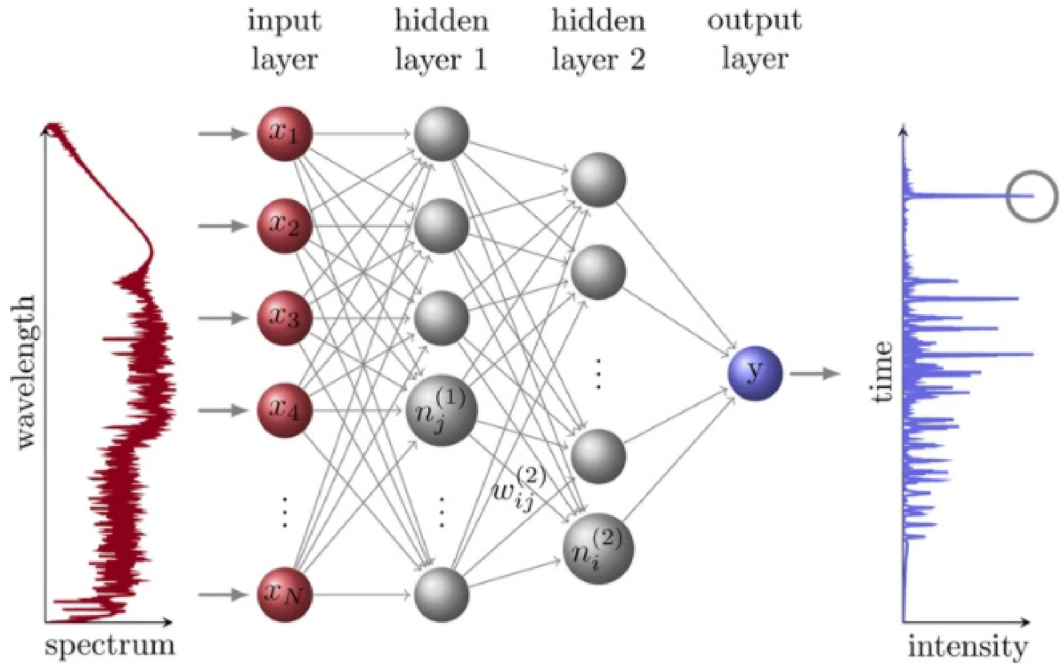
Machine learning analysis of rogue solitons in supercontinuum generation

Lauri Salmela[1], Coraline Lapre[2], John M. Dudley[2] & Goëry Genty[1]



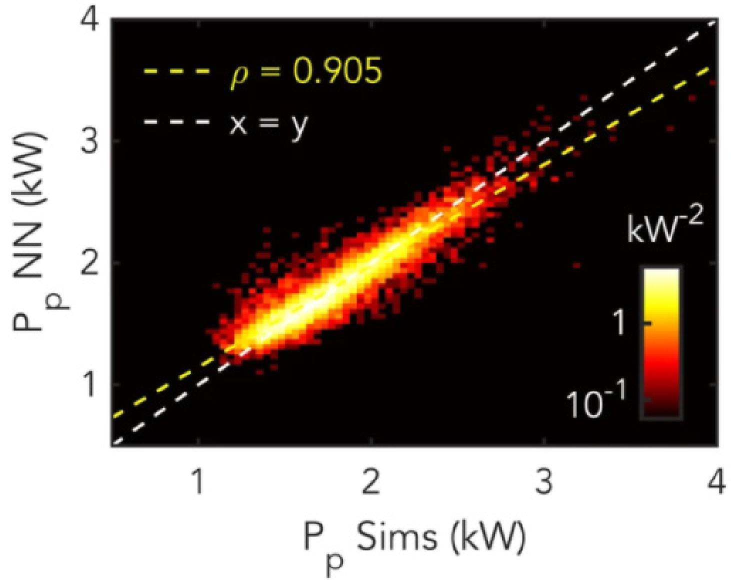
Machine learning and rogue solitons

We train a neural network to correlate the full supercontinuum spectrum with the peak intensity of the the red-shifted "rogue" soliton



The Approach

1. Train using 20000 simulations
2. Test using 10000 independent simulations
3. Compare predicted peak intensity with simulation "ground truth"



Conclusion: a neural network can use only supercontinuum spectral data to infer maximum temporal peak power of red-shifted Raman solitons

Model free modelling of nonlinear fibre propagation

Numerical integration of generalized nonlinear propagation equations can be time-consuming. Can we train a neural network to model nonlinear propagation directly?

Optics in 2021

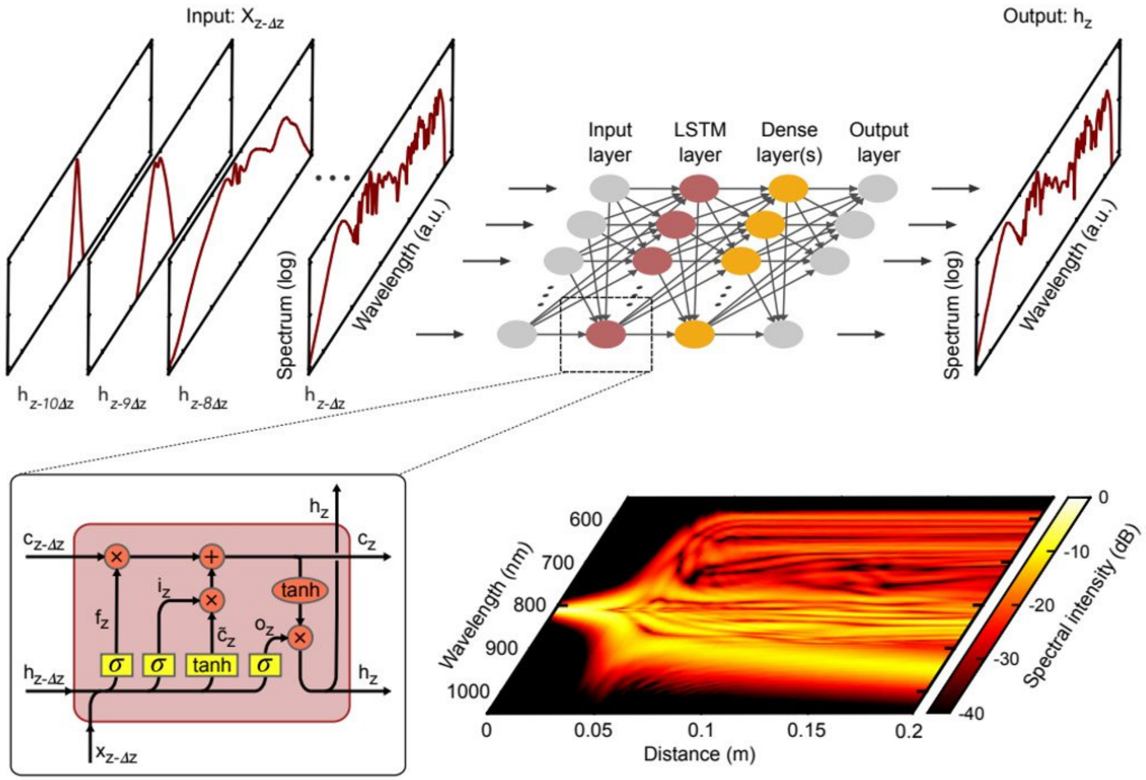
RESEARCHERS

L. Salmela and **G. Genty** (goery.genty@tuni.fi), Tampere University of Technology, Tampere, Finland

J. M. Dudley, CNRS-Université Bourgogne Franche-Comté, Besançon, France

REFERENCES

1. L. Salmela et al. Nat. Mach. Intell. **3**, 344 (2021)
2. L. Salmela et al. Paper EJ-1.2 MON, 2021 CLEO Europe & European Quantum Electronics Conference (2021)
3. G. P. Agrawal. *Nonlinear Fiber Optics* (Academic Press, 2019)
4. G. Genty et al. Nat. Photon. **15**, 91 (2021)
5. U. Teğin et al. Nat. Mach. Intell. **3**, 387 (2021)

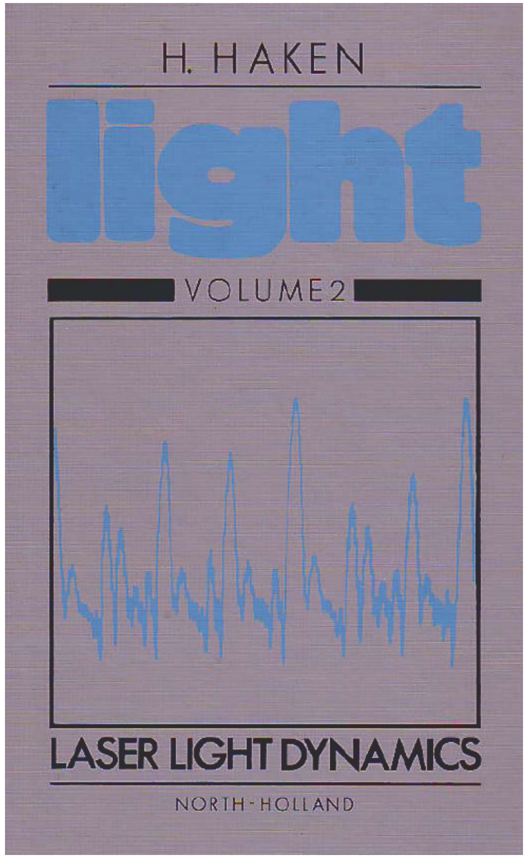


Top: Ten consecutive numerically simulated spectral-intensity profiles are input into a recurrent neural network, the output of which is the predicted spectrum at the next step.
Bottom left: Operation of a cell in the long short-term memory (LSTM) recurrent layer.
Bottom right: The network's predicted spectral-intensity evolution along the fiber.

From waveguides to lasers …

Instabilities have been observed since the first development of lasers in the 1960s but we can now use ultrafast real-time characterization tools to uncover new details

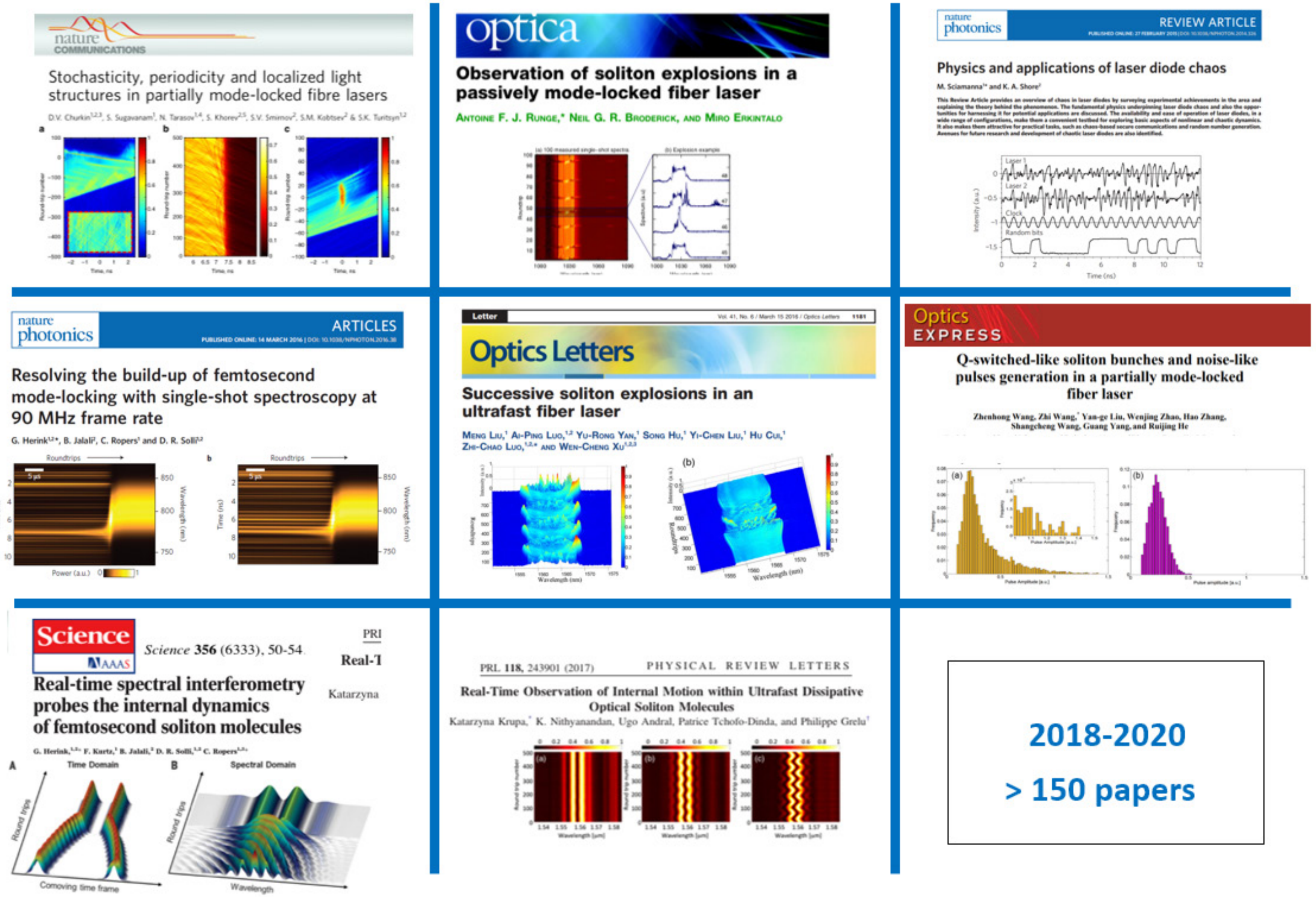
1985



2015

2016

2017



Understanding instabilities in lasers

In addition to new measurement techniques, we now have the general framework of the **dissipative soliton** to describe lasers where nonlinear dynamics coexist with gain & loss


nature photonics

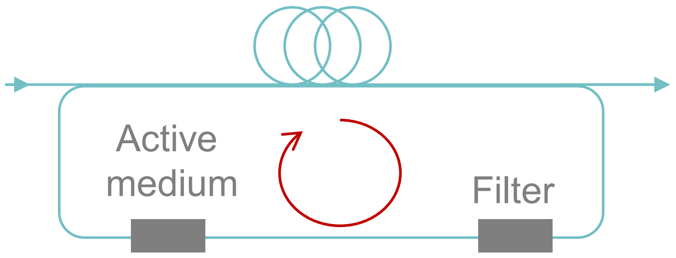
REVIEW ARTICLE

PUBLISHED ONLINE: XX FEBRUARY 2012 | DOI: 10.1038/NPHOTON.2012.345

Dissipative solitons for mode-locked lasers

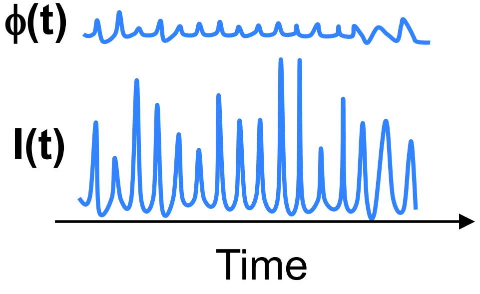
Philippe Grelu[1]* and Nail Akhmediev[2]

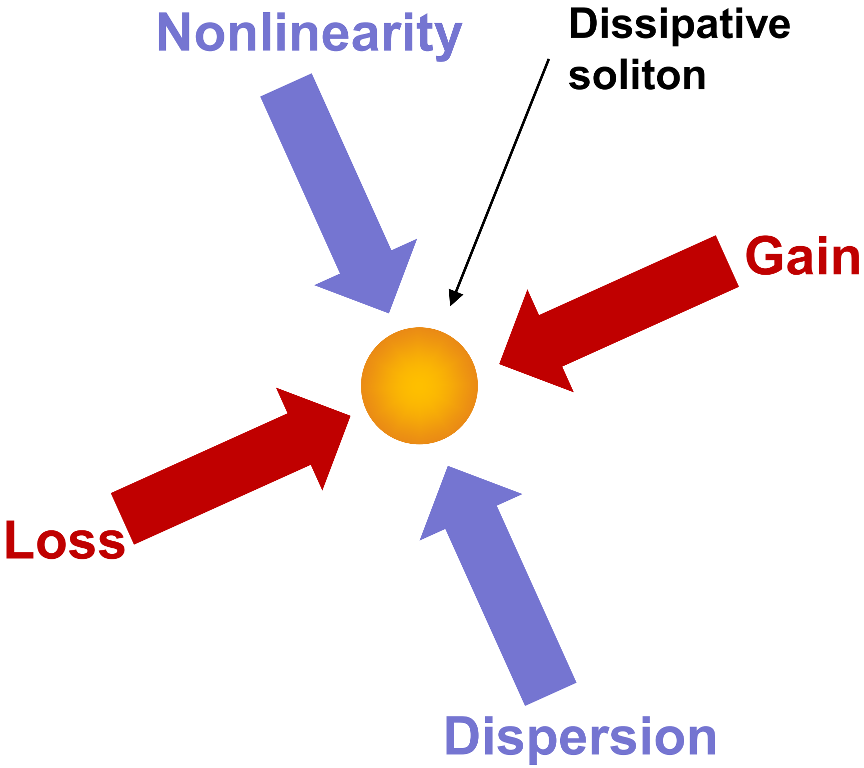
Nonlinearity, Dispersion



Dissipation ≡ Energy exchange

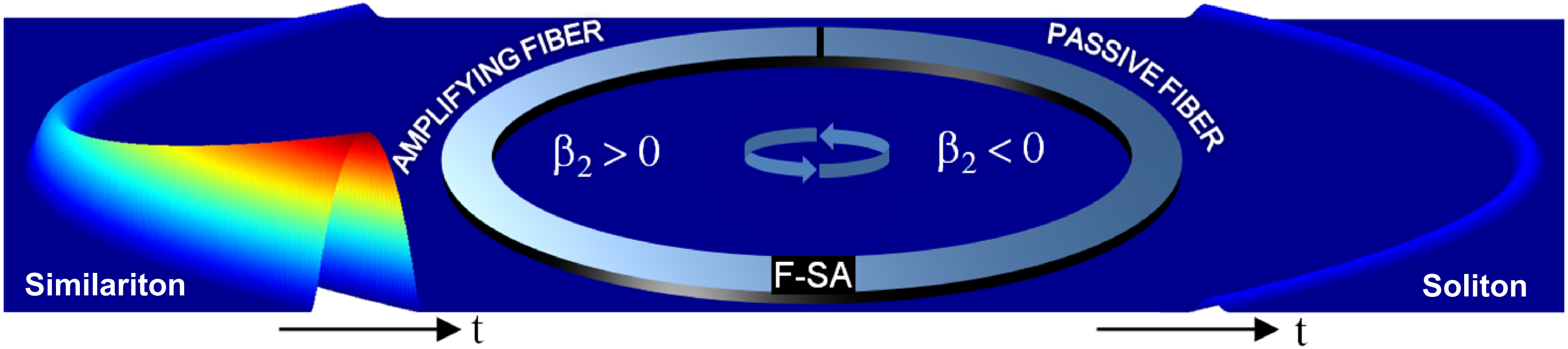
Instabilities & Nonlinear dynamics





Spectral Instabilities in a Soliton-Similariton Laser

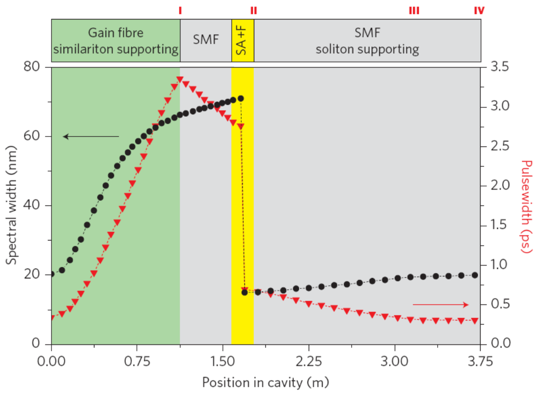
The soliton similariton laser is a novel fibre oscillator where two conceptually different nonlinear structures co-exist within a highly dissipative fibre laser cavity



NATURE PHOTONICS | VOL 4 | MAY 2010 |

Soliton–similariton fibre laser

Bulent Oktem[1], Coşkun Ülgüdür[2] and F. Ömer Ilday[2]*



news & views

ULTRAFAST OPTICS

Nonlinear attraction

A new femtosecond fibre laser design combines two distinct regimes of nonlinear dynamic attraction within a single cavity to yield robust and low-noise performance.

John M. Dudley

Spectral Instabilities in a Soliton-Similariton Laser

A similariton or self-similar amplifier is one where all input pulses evolve asymptotically to the same output pulse (a nonlinear attractor)

nature physics | VOL 3 | SEPTEMBER 2007

Self-similarity in ultrafast nonlinear optics

JOHN M. DUDLEY[1]*, CHRISTOPHE FINOT[2,3], DAVID J. RICHARDSON[2] AND GUY MILLOT[3]

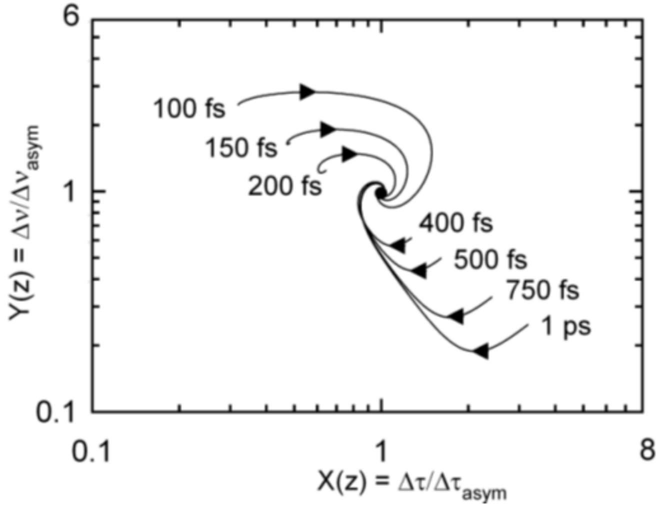
$$\Psi(z,T) = A(z,T)\exp(i\Phi(z,T))$$

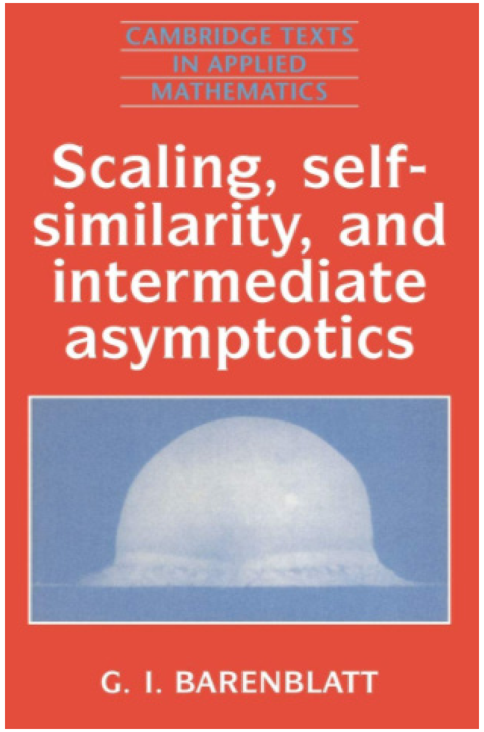
$$A(z,T) = A_0 \exp\left(\frac{g}{3}z\right)\sqrt{1-\frac{T^2}{T_p^2(z)}}$$

$$\Phi(z,T) = \varphi_0 + \frac{3\gamma A_0^2}{2g}\exp\left(\frac{2}{3}gz\right) - \frac{g}{6\beta_2}T^2$$

$$A_0 = \frac{1}{2}\left(\frac{gU_{in}}{\sqrt{\gamma\beta_2/2}}\right)^{\frac{1}{3}} \quad T_p(z) = \frac{6\sqrt{\gamma\beta_2/2}}{g}A_0\exp\left(\frac{g}{3}z\right)$$

Similariton Attraction





G. I. Taylor: Proc. Royal Soc. London A 201 175-196 (1950)

Q. Can similariton evolution make fibre lasers more robust against nonlinear instability?

Characterizing more extreme intracavity laser dynamics

Experiments using real-time dispersive Fourier transform measurements reveal comparable rich dynamics as suggested by the modelling


SCIENTIFIC REPORTS

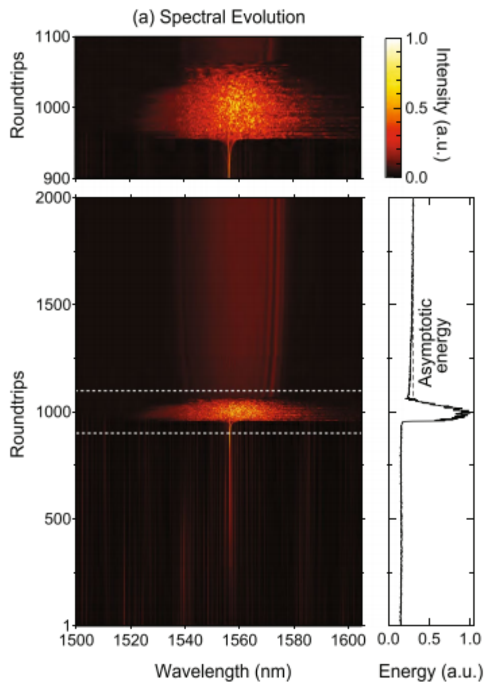
natureresearch

Real-time characterization of spectral instabilities in a mode-locked fibre laser exhibiting soliton-similariton dynamics

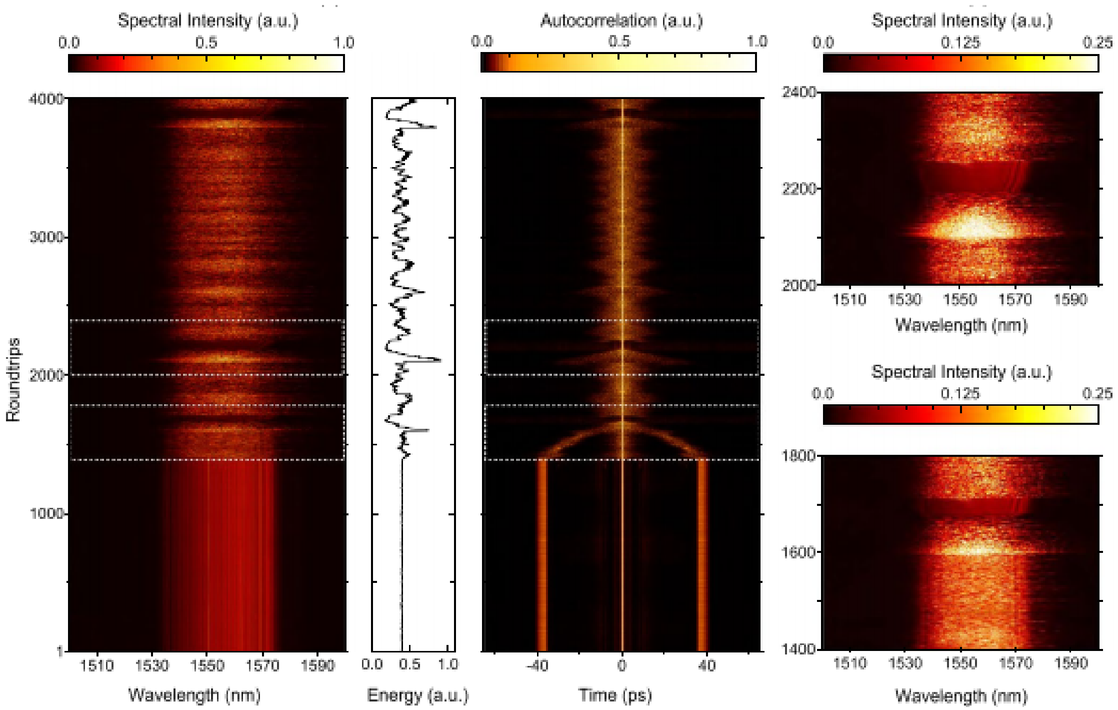
Coraline Lapre[1], Cyril Billet[1], Fanchao Meng[1], Piotr Ryczkowski[2], Thibaut Sylvestre[1], Christophe Finot[3], Göery Genty[2] & John M. Dudley[1]

The study of dissipative solitons in mode-locked lasers reveals a rich landscape of interaction dynamics resulting from the interplay of nonlinearity, dispersion and dissipation. Here, we characterize a range of instabilities in a dissipative soliton fibre laser in a regime where both conventional soliton and similariton propagation play significant roles in the intracavity pulse shaping. Specifically, we use the Dispersive Fourier Transform technique to perform real-time spectral measurements of buildup dynamics from noise to the generation of stable single pulses, phase evolution dynamics of bound state "similariton molecules", and several examples of intermittent instability and explosion dynamics. These results show that the instabilities previously seen in other classes of passively mode-locked fibre lasers are also observed in the presence of strong nonlinear attraction of similariton evolution in an optical fibre amplifier.

Startup



Chaos and Intermittence

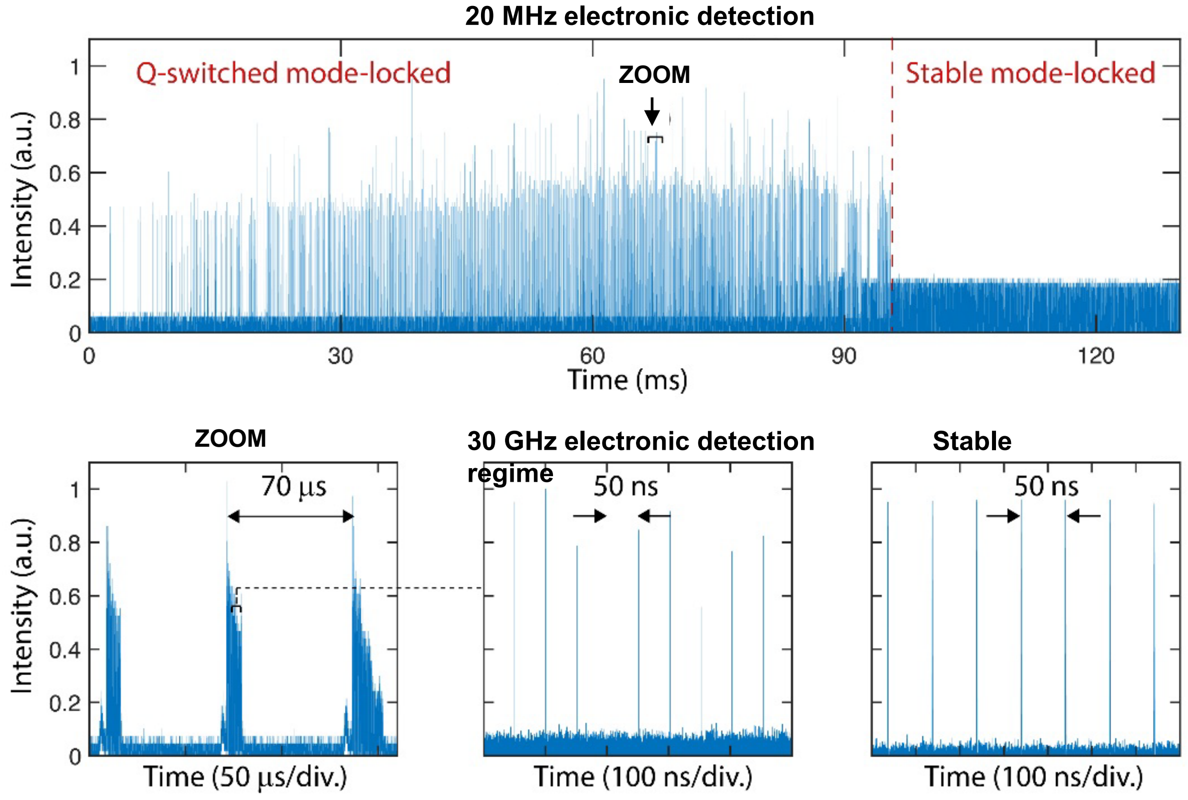


Work by many other groups as well

What actually happens when you turn on a fibre laser?

The build-up of stable mode-locking in a fiber laser typically shows complex dynamics

Slow detection over long time window



Structures with different time scales

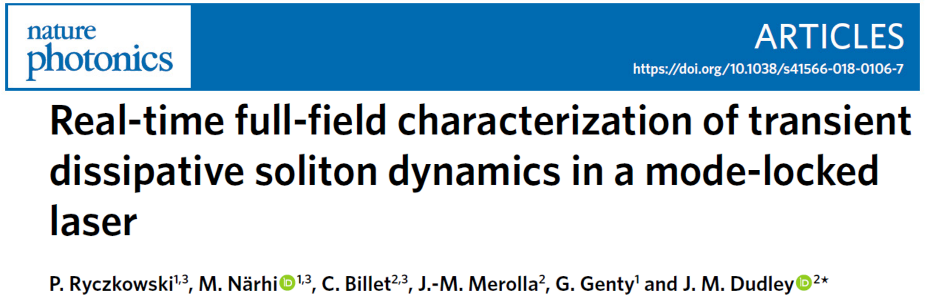
Pseudo-periodic Q-switched bursts with sub-ms period

Periodic quasi mode-locked pulses with roundtrip period (50 ns)

Q: Can we measure the sub-picosecond chaotic build-up dynamics?

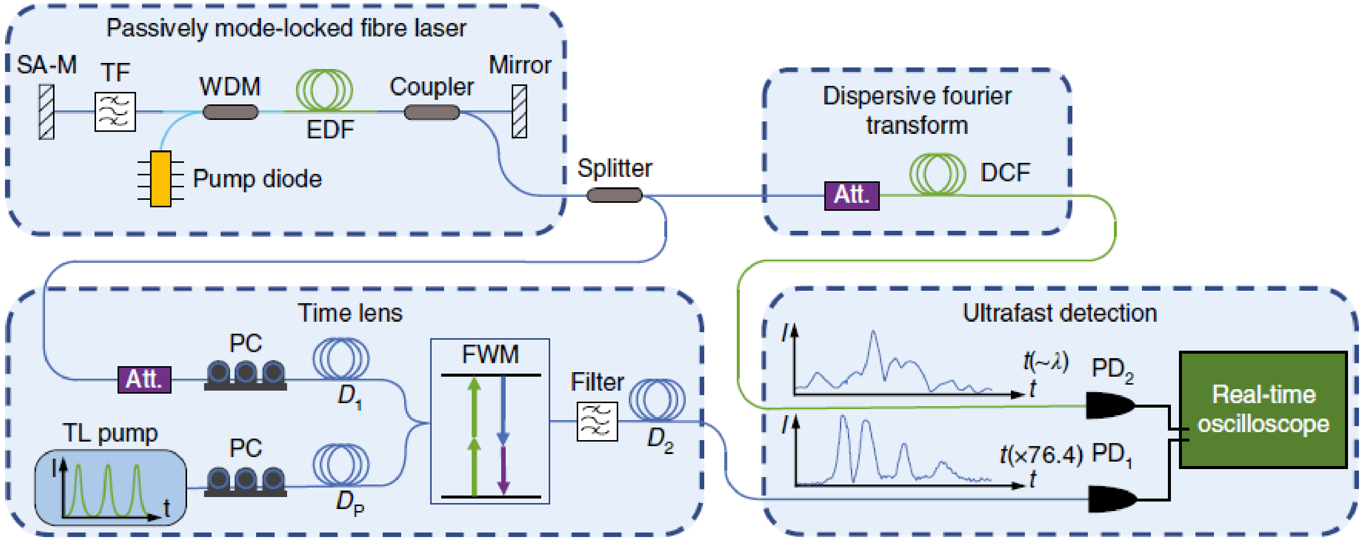
Measuring instabilities in lasers

Simultaneous time lens & dispersive Fourier transform provides complete real time characterization of soliton buildup from noise in a SESAM-modelocked soliton fibre laser

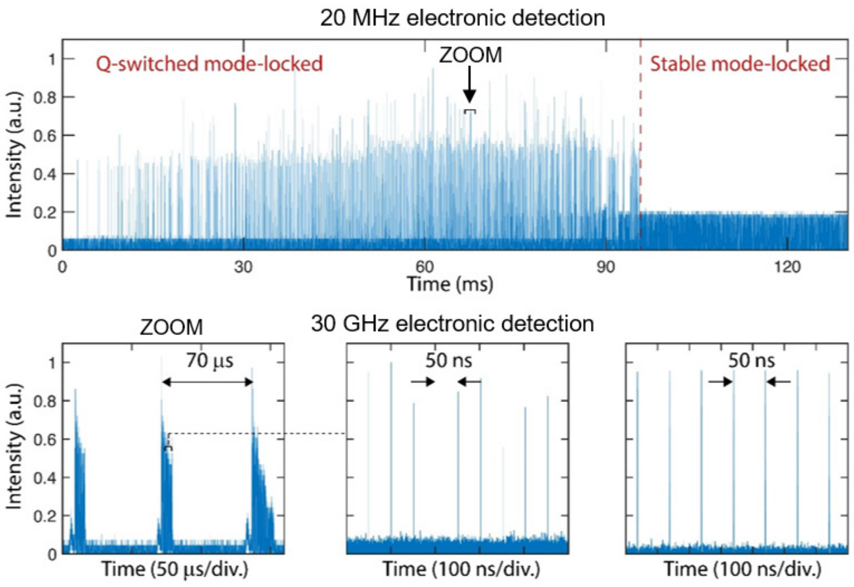

nature photonics ARTICLES
https://doi.org/10.1038/s41566-018-0106-7

Real-time full-field characterization of transient dissipative soliton dynamics in a mode-locked laser

P. Ryczkowski[1,3], M. Närhi[1,3], C. Billet[2,3], J.-M. Merolla[2], G. Genty[1] and J. M. Dudley[2*]

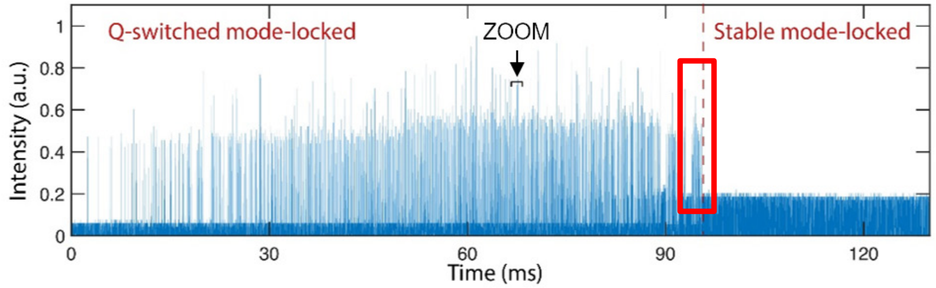


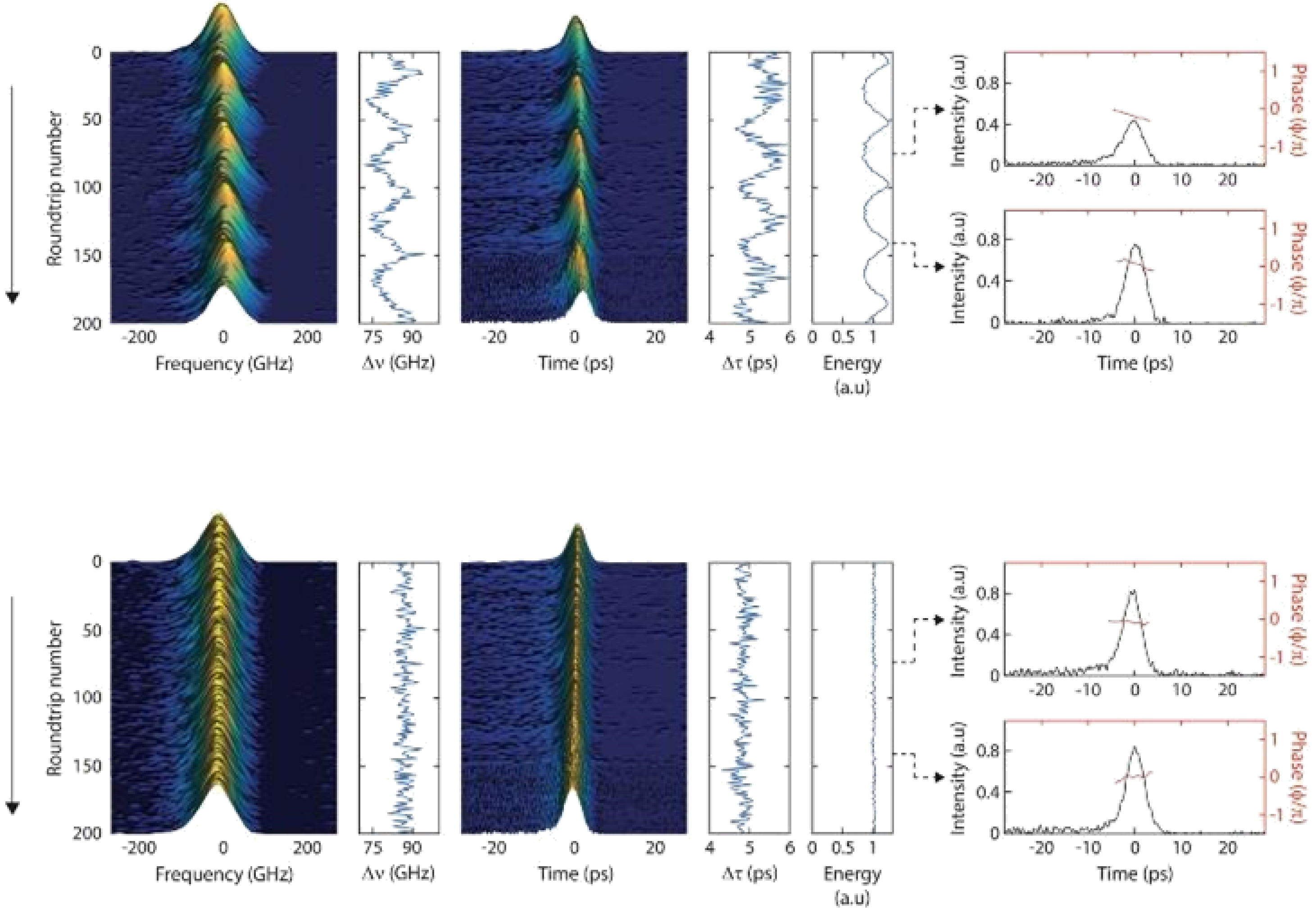
In how much detail can we study startup dynamics in a dissipative soliton laser?



Multiscale dynamics where we need ps resolution over a measurement window of 50 µs

Build up of solitons from noise





The regime just before stability shows periodic soliton breathing

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Real-time full-field characterization of transient dissipative soliton dynamics in a mode-locked laser

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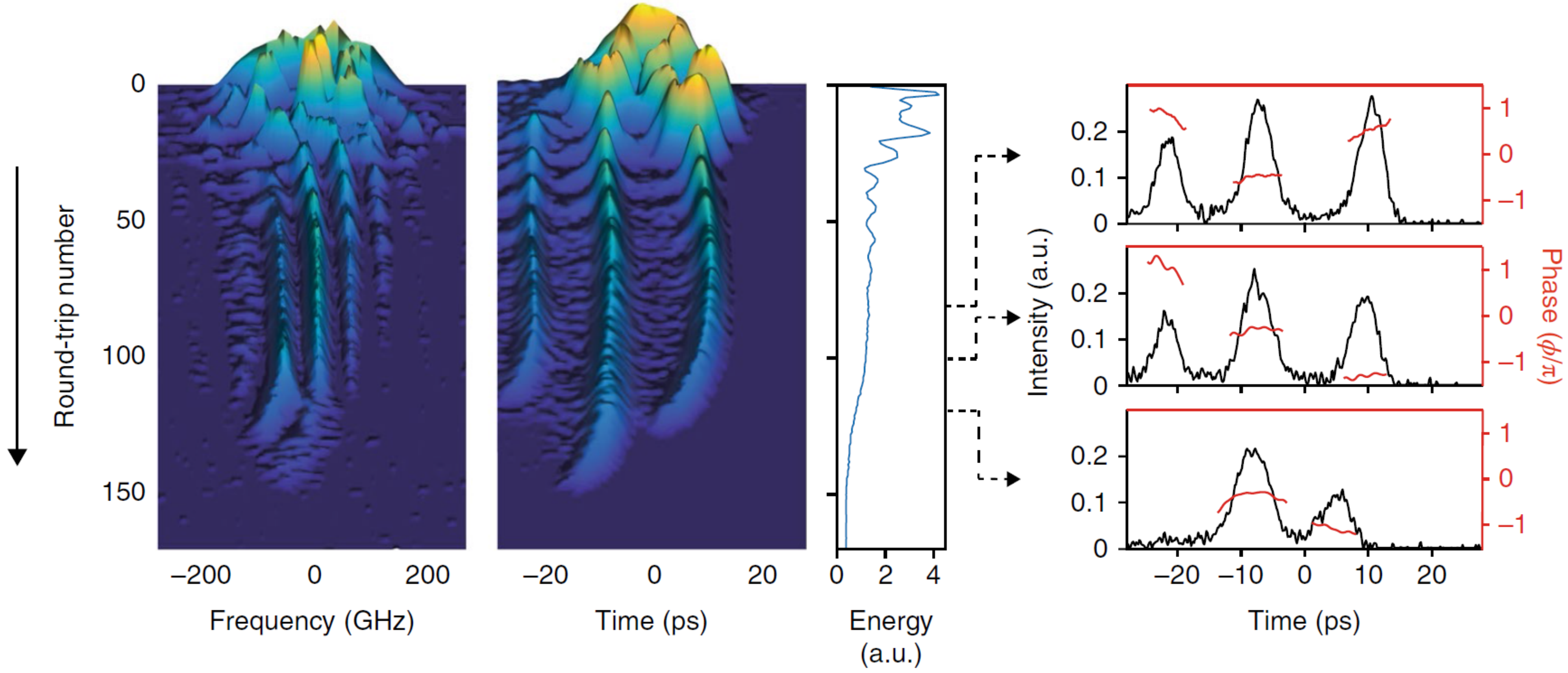
DECEMBER 2018 OSA OPTICS & PHOTONICS NEWS

OPTICS 2018

Ultrafast Laser Solitons Born from Chaos

Build up of solitons from noise

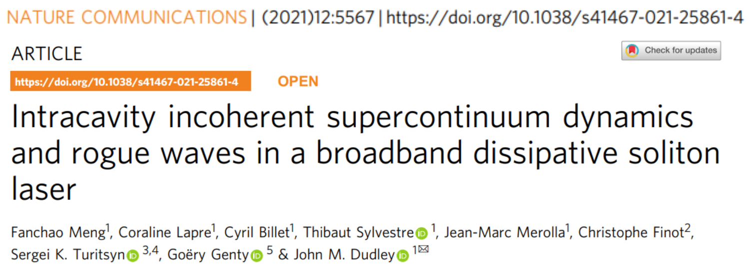
We see complex dynamics and multiple pulses, with phases of growth and collapse



Ryczkowski et al. Nature Photonics **12**, 221-227 (2018)

New results from a broadband noise-like pulse laser

Time lens measurements in a 1000 nm broadband **noise-like pulse laser** reveal soliton instability properties and statistics in excellent quantitative agreement with modelling

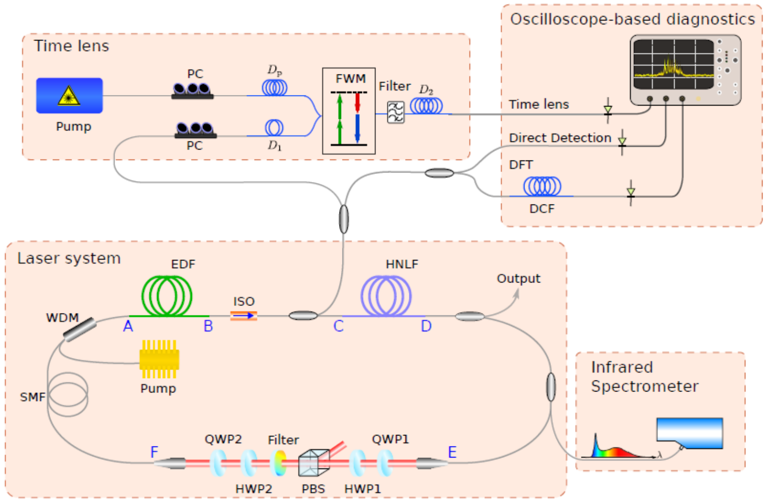

NATURE COMMUNICATIONS | (2021)12:5567 | https://doi.org/10.1038/s41467-021-25861-4

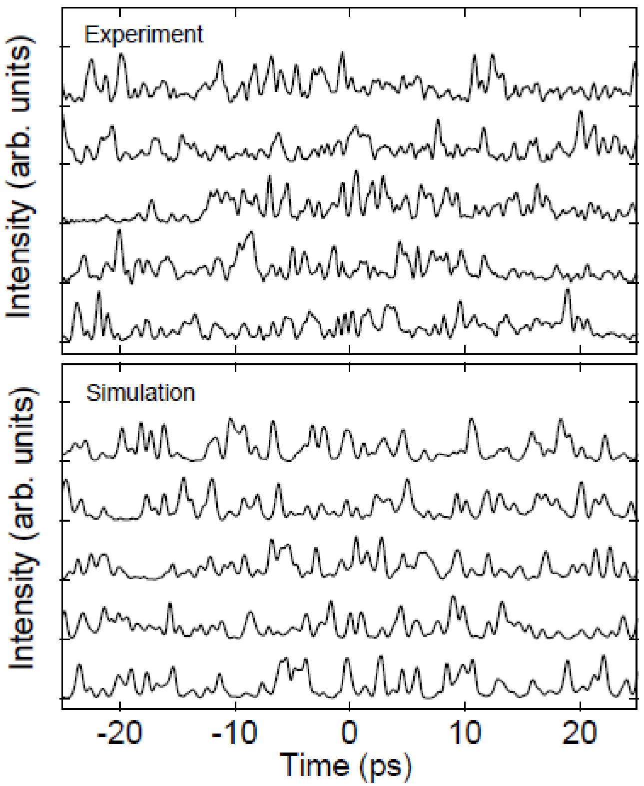
ARTICLE

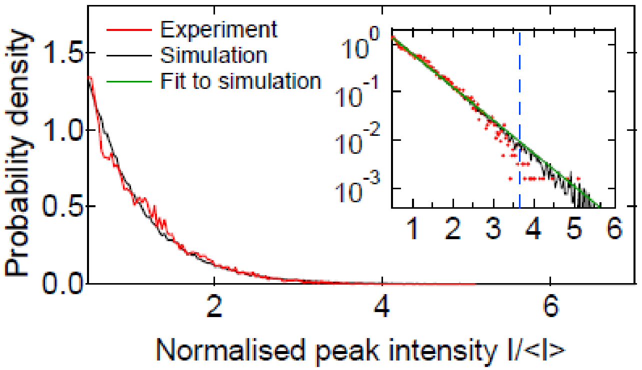
https://doi.org/10.1038/s41467-021-25861-4 OPEN

Intracavity incoherent supercontinuum dynamics and rogue waves in a broadband dissipative soliton laser

Fanchao Meng[1], Coraline Lapre[1], Cyril Billet[1], Thibaut Sylvestre[1], Jean-Marc Merolla[1], Christophe Finot[2], Sergei K. Turitsyn[3,4], Goëry Genty[5] & John M. Dudley[1]



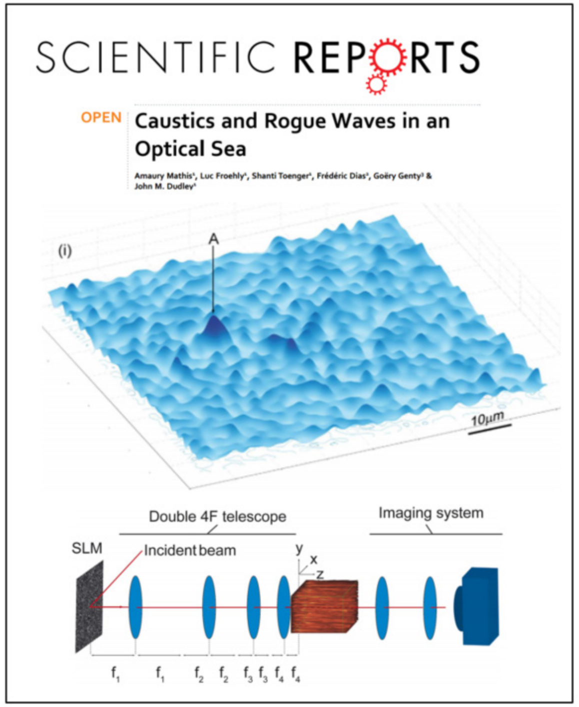


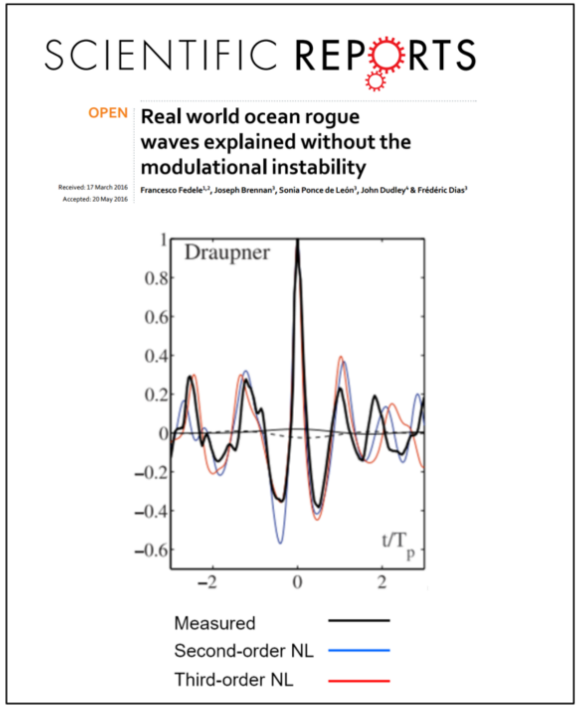


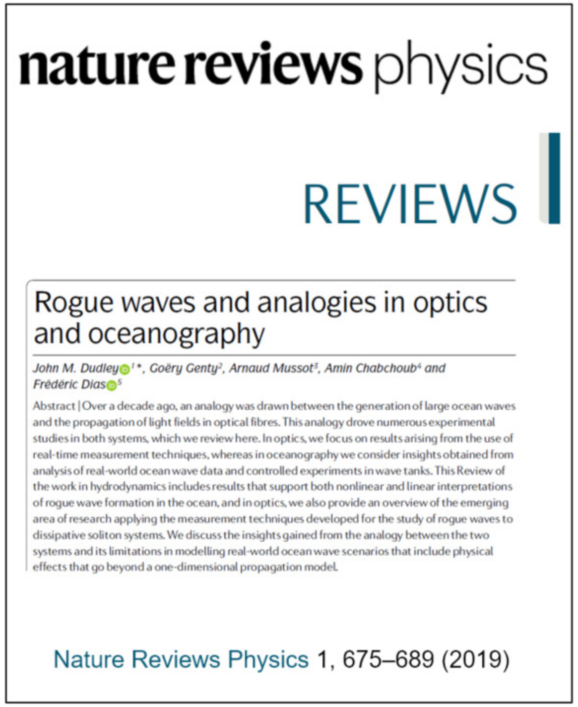
Conclusions

1. Optical rogue waves can emerge out of fibre nonlinear dynamics due to the noise sensitivity of modulation instability and soliton propagation

2. But other experiments & modelling in both optics and hydrodynamics suggest that nonlinearity is not the only way in which extreme wave events can occur







Conclusions

3. Real-time measurement techniques provide new windows into studying instabilities in both fibre propagation and in ultrafast lasers

4. Techniques such as the dispersive Fourier transform and the time lens are now becoming necessary elements in experimental setups

5. Machine learning is an extremely promising addition to both experiment and analysis in nonlinear fibre optics, and maybe the future of ultrafast laser development

nature photonics
FOCUS | REVIEW ARTICLE
https://doi.org/10.1038/s41566-020-00716-4

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Machine learning and applications in ultrafast photonics

Goëry Genty[1]✉, Lauri Salmela[1], John M. Dudley[2], Daniel Brunner[2], Alexey Kokhanovskiy[3], Sergei Kobtsev[3] and Sergei K. Turitsyn[3,4]