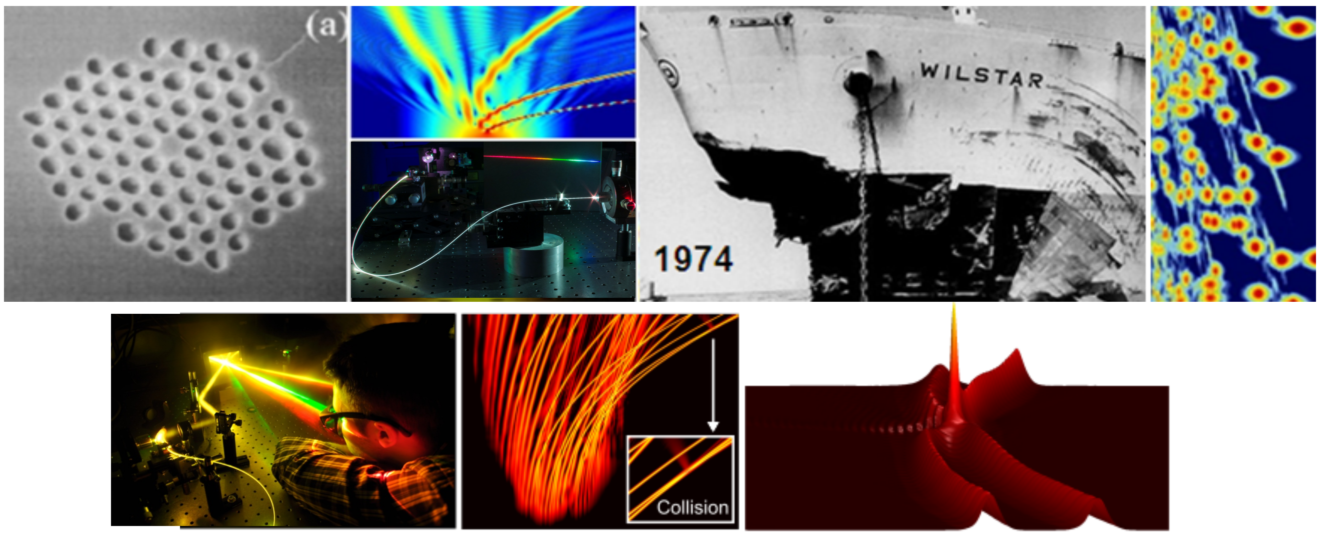
Supercontinuum



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Institute of Physics

Special thanks

John Dudley
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New Zealand

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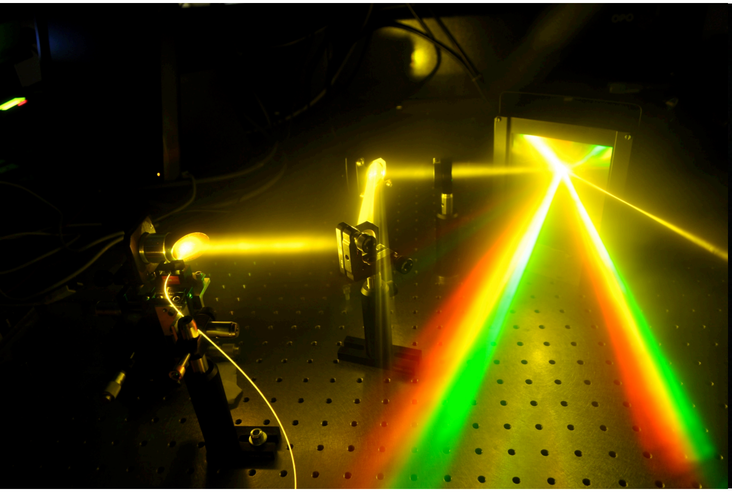
University of eastern Finland, Finland

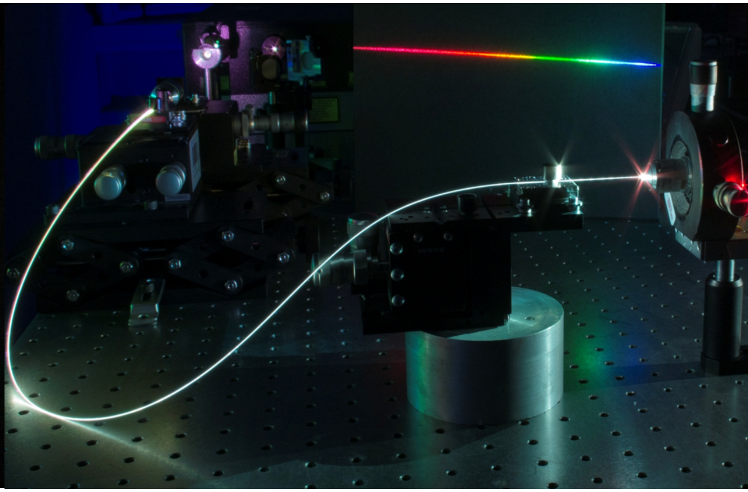
Bertrand Kibler, Christophe Finot,
Julien Fatome. Guy Millot
Université de Bourgogne,
France

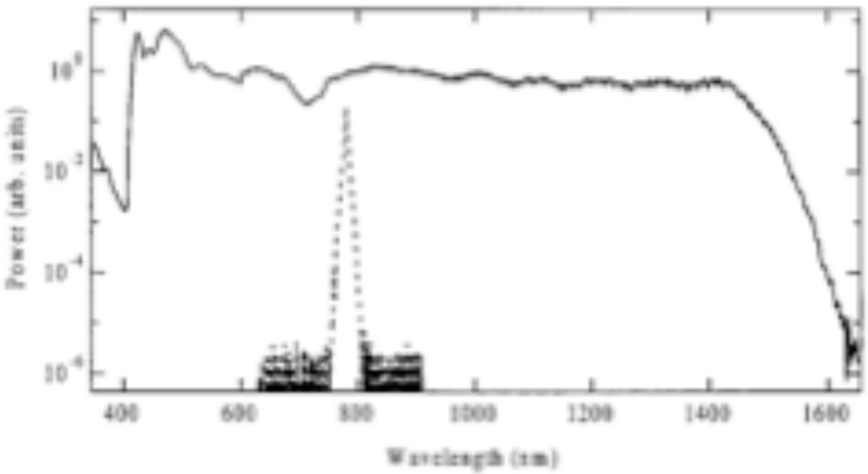
Nail Akhmediev
Research School of Physics
& Engineering
ANU ,Canberra, Australia

What is a supercontinuum?

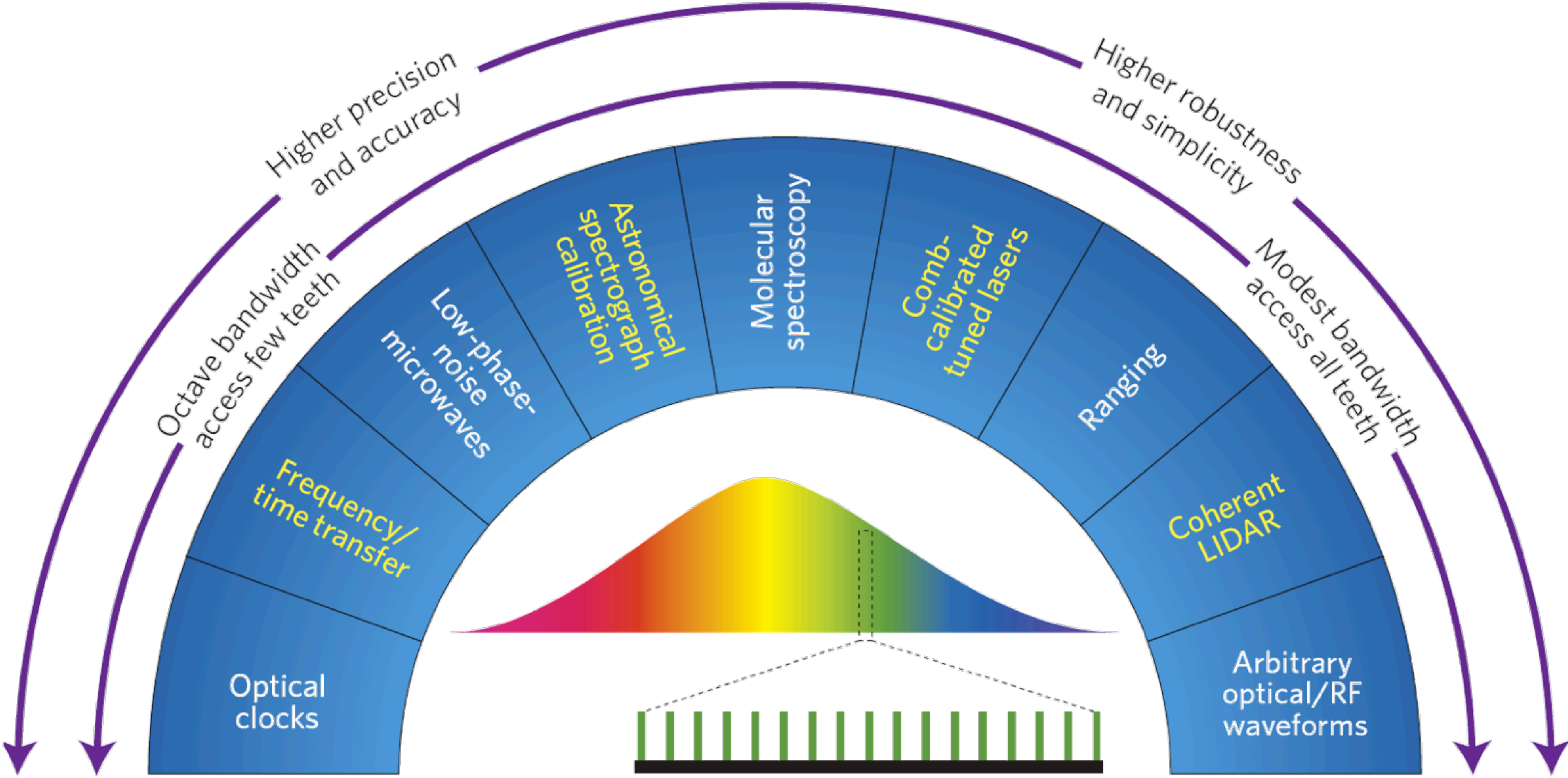
Narrowband field experiences massive continuous spectral broadening in a nonlinear medium







Supercontinuum sources are actually useful!



NATURE PHOTONICS | VOL 5 | APRIL 2011 | www.nature.com/naturephotonics

Outline

- Basics of pulses propagation in nonlinear fibers
  - nonlinear phenomena, numerical modelling
- Regimes of supercontinuum generation
  - Deconstructing the dynamics
- Latest developments
  - Emerging structures
- Noise amplification dynamics
  - Modulation instability and extreme events

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Supercontinuum is 45 years old

Special anniversary at SPIE Photonics West 2014, celebrating the discovery of supercontinuum 45 years ago

- Bob Alfano
- Alex Gaeta
- Roy Taylor
- Steve Cundiff
- Govind Agrawal
- …

Supercontinuum is 45 years old

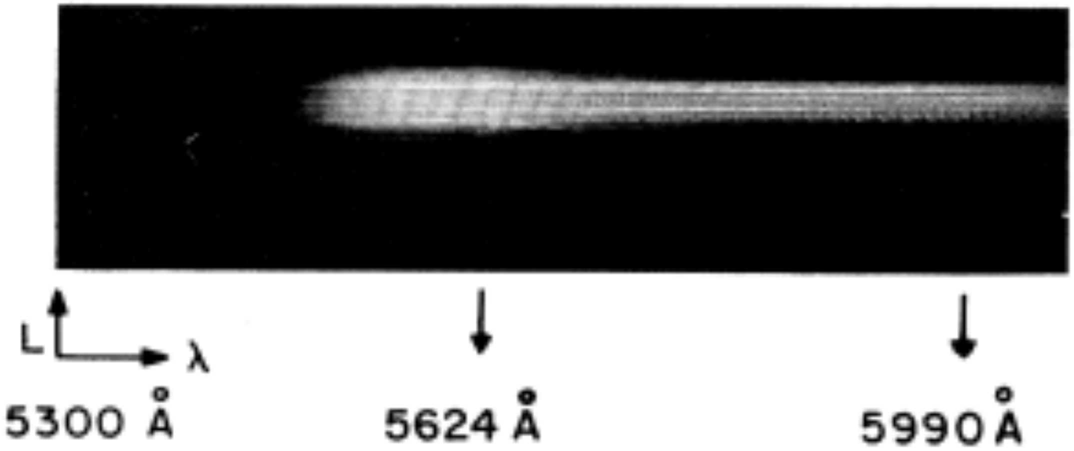
VOLUME 24, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1970

OBSERVATION OF SELF-PHASE MODULATION AND SMALL-SCALE FILAMENTS IN CRYSTALS AND GLASSES

R. R. Alfano* and S. L. Shapiro
Bayside Research Center of General Telephone & Electronics Laboratories Incorporated,
Bayside, New York 11360
(Received 10 December 1969)

EMISSION IN THE REGION 4000 TO 7000 Å VIA FOUR-PHOTON COUPLING IN GLASS

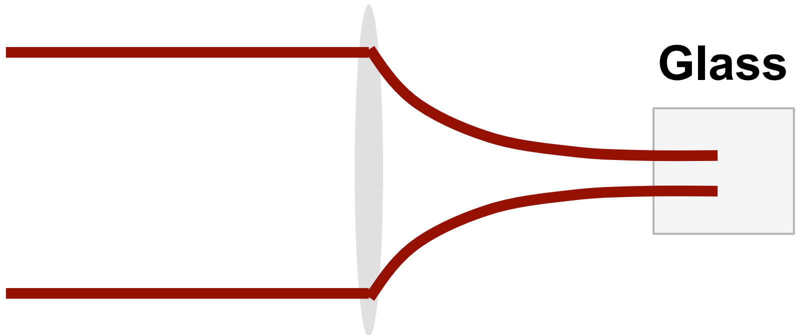
R. R. Alfano and S. L. Shapiro
Bayside Research Center of General Telephone & Electronics Laboratories Incorporated,
Bayside, New York 11360
(Received 9 January 1970)

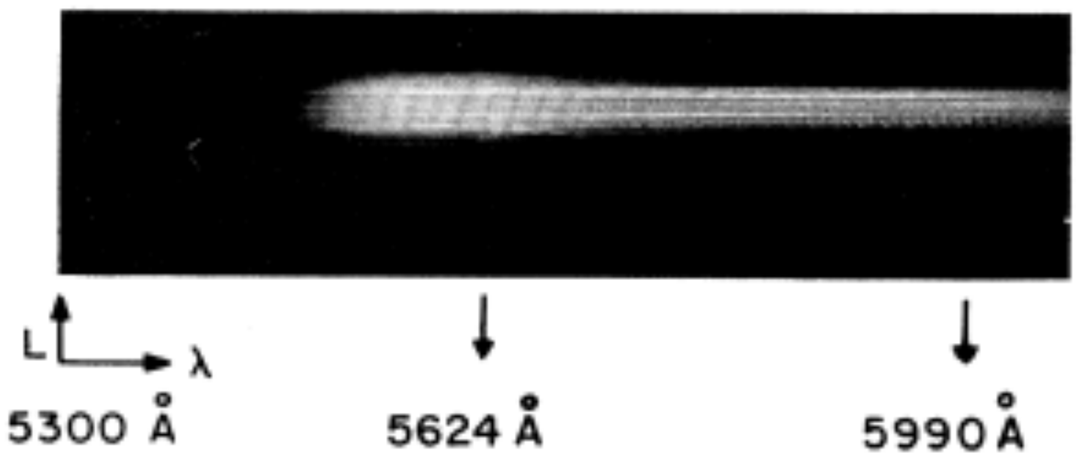


In bulk

Supercontinuum is 45 years old

6 ps pulses
5 mJ
λ = 532 nm





In bulk

There are some issues though

- Limitations
  - Walk off
  - Diffraction
  - Strong dispersion, limited broadening

- Need very high energy
  - Damage

- Fiber is the way to go!

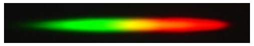
Supercontinuum timeline

Supercontinuum generation in bulk silica (R. Alfano)

Experimental Fiber solitons (L. Mollenauer)

Femtosecond Ti:Sapphire (Sibbett)

Supercontinuum generation in photonic crystal fiber (J. Ranka et al.)

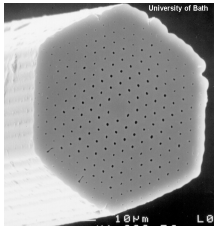


Varenna

1970 | 1980 | 1990 | 2000 | 2005 | Today

Nonlinearity in silica fiber (R. Stolen & Lin

Supercontinuum generation in silica fiber (R. Stolen & Lin)

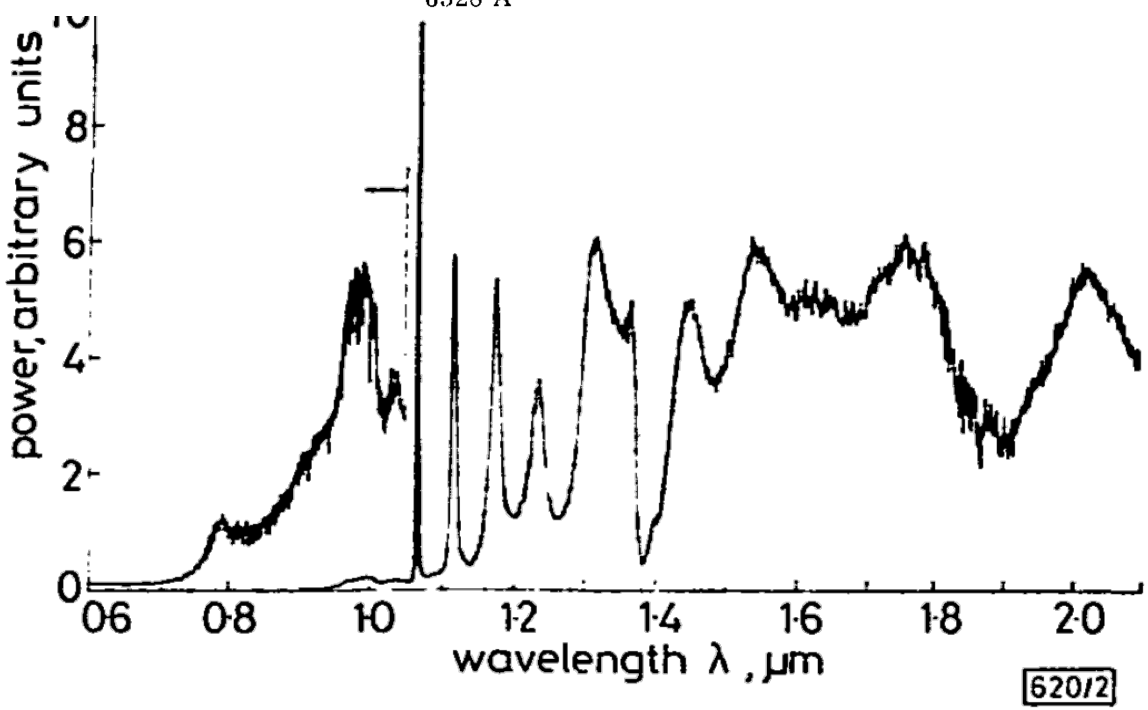


Solid core photonic crystal fiber (P. Russell)

Nobel prize Hall & Hänsch

But “only” 36 years old in fiber

Lin *et al*., Electron. Lett. 14, 822 (1978)

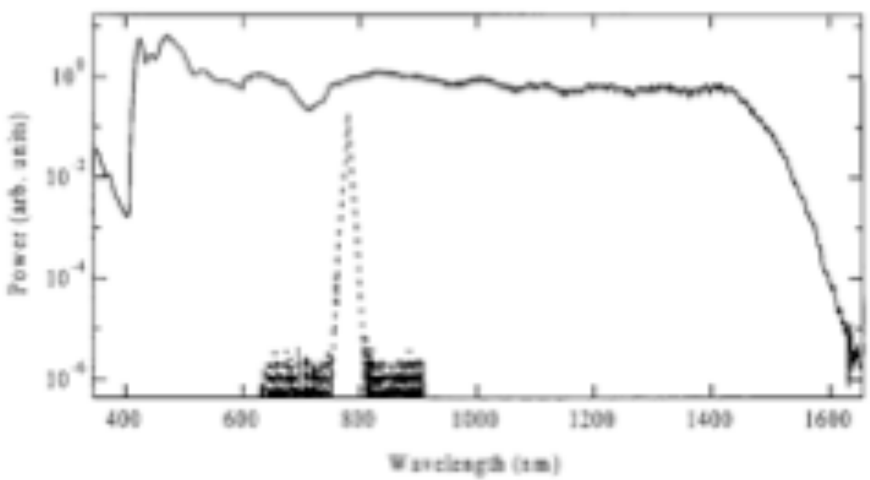


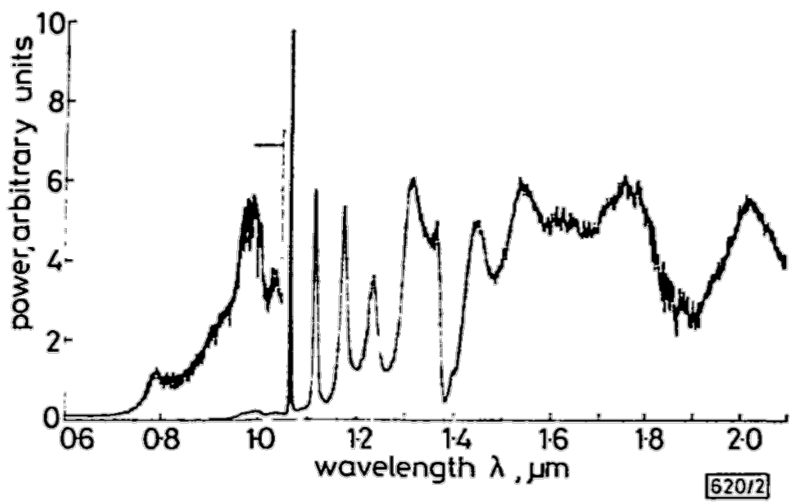
Truth be told: this is an amazing result!

But “only” 36 years old in fiber

Visible continuum generation in air–silica microstructure optical fibers with anomalous dispersion at 800 nm

Jinendra K. Ranka, Robert S. Windeler, and Andrew J. Stentz
Bell Laboratories, Lucent Technologies, 700 Mountain Avenue, Murray Hill, New Jersey 07974





Truth be told: this is an amazing result!

A historical note

PHYSICAL REVIEW A VOLUME 21, NUMBER 4 APRIL 1980

Combined stimulated Raman scattering and continuum self-phase modulations

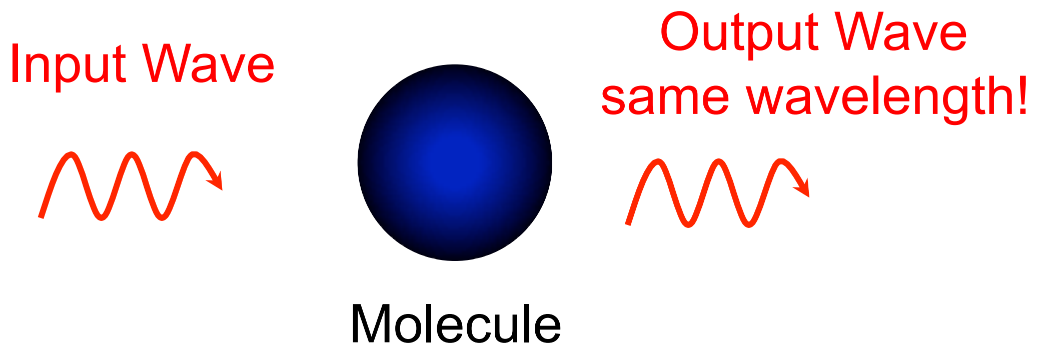
Joel I. Gersten*
Institute for Advanced Studies, Hebrew University, Mount Scopus Campus, Jerusalem, Israel

R. R. Alfano and Milivoj Belic
Department of Physics, The City College of New York, New York, N. Y. 10031
(Received 8 January 1979)

A theory describing the combined effects of stimulated Raman scattering and continuum self-phase modulation is developed. As may be expected, the effects are not simply additive. Calculations are presented which determine the interaction of these effects in various limits.

In the case of self-phase modulation (SPM), however, the repopulation of the spectral intensity takes place in a more gradual manner. Owing to the nonlinearity of the medium, the pulse heterodynes against itself and gradually increases its spectral width. There is a continuum of frequencies produced in this process. Supercontinuum generation spanning the visible and infrared region was first observed by Alfano and Shapiro when intense picosecond laser pulses were passed through liquids and solids.[3]

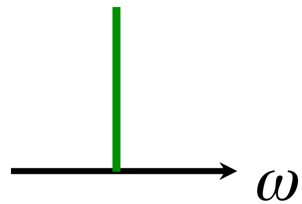
Linear Optics

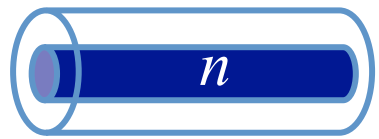


- Linear optics (attenuation and dispersion)
  - Optics of weak light (low intensity)
- Light is deflected or delayed
  - **FREQUENCY** unaffected

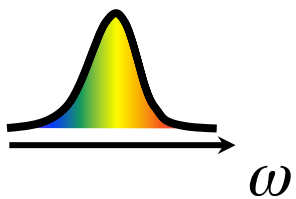
Dispersion

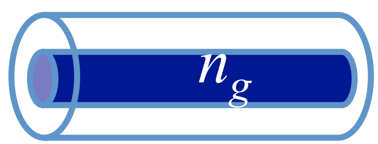
- Monochromatic light propagates with phase velocity c/n





- Light pulse composed of multiple frequency components
  - travels at the group velocity

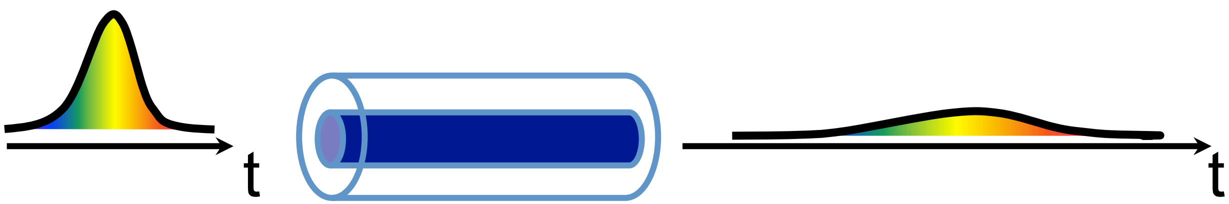




$$v_g = \frac{c}{n_g} \qquad n_g = n + \omega \frac{dn}{d\omega}$$

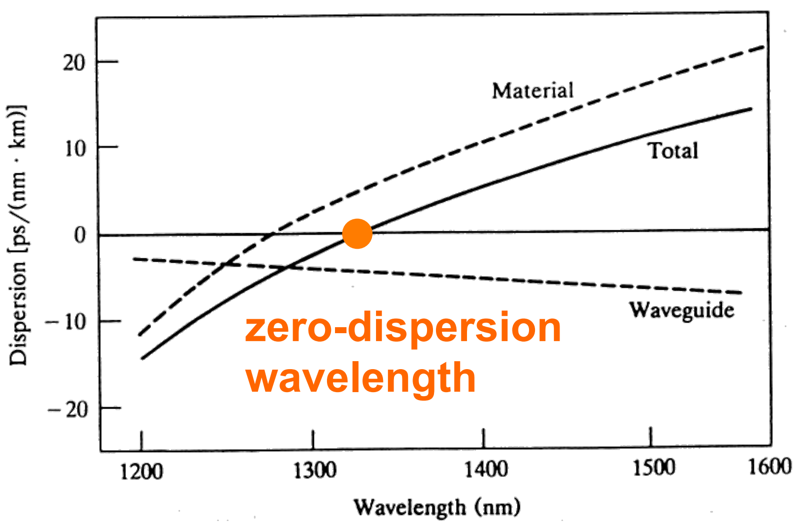
- Dispersion = frequency-dependence of v_g
  - frequency-dependence of refractive index of silica n (material dispersion)
  - frequency-dependence of the size of the mode (waveguide dispersion)

Dispersion



- Different spectral components of the pulse travel at different speeds
- Intensity of a pulse travelling though a fiber is dispersed in time ⇒ pulse spreads in time
- Spectrum unchanged

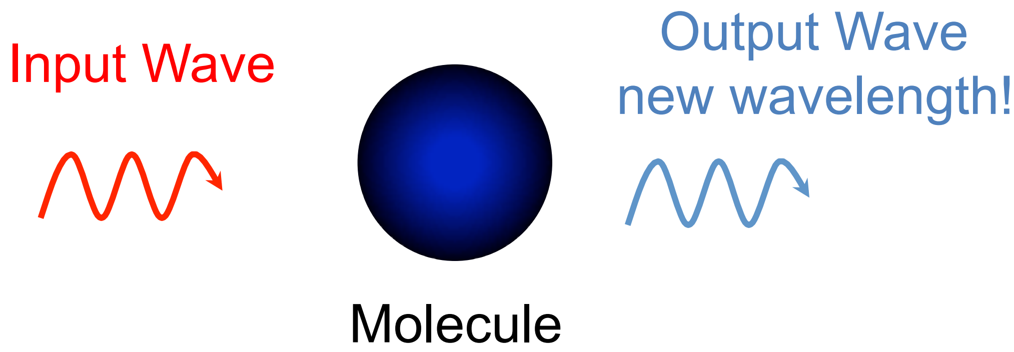
Dispersion



- D<0: normal dispersion
  - Higher frequencies (shorter wavelengths) travel faster than lower frequencies (longer wavelengths)
- D>0: anomalous dispersion
  - Higher frequencies (shorter wavelengths) travel slower than lower freq. (longer wavelengths)
- D=0: zero-dispersion wavelength

- Dispersion leads to walk-off between spectral components of pulses
  - limits the efficiency of nonlinear effects

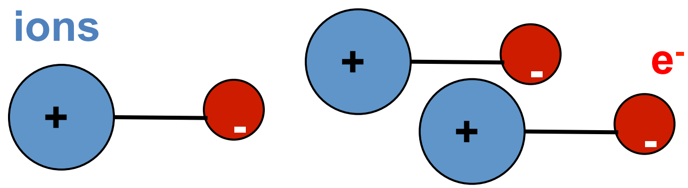
Nonlinear Optics



- Nonlinear optics (scattering and nonlinear refractive index)
  - Optics of intense light
- Light induces effects on its own **AMPLITUDE/PHASE**
  - Affects its **FREQUENCY**

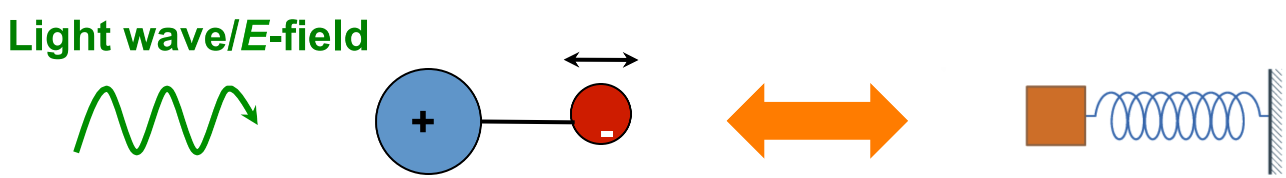
Origin of nonlinear effects

- Medium: collection of charged particles



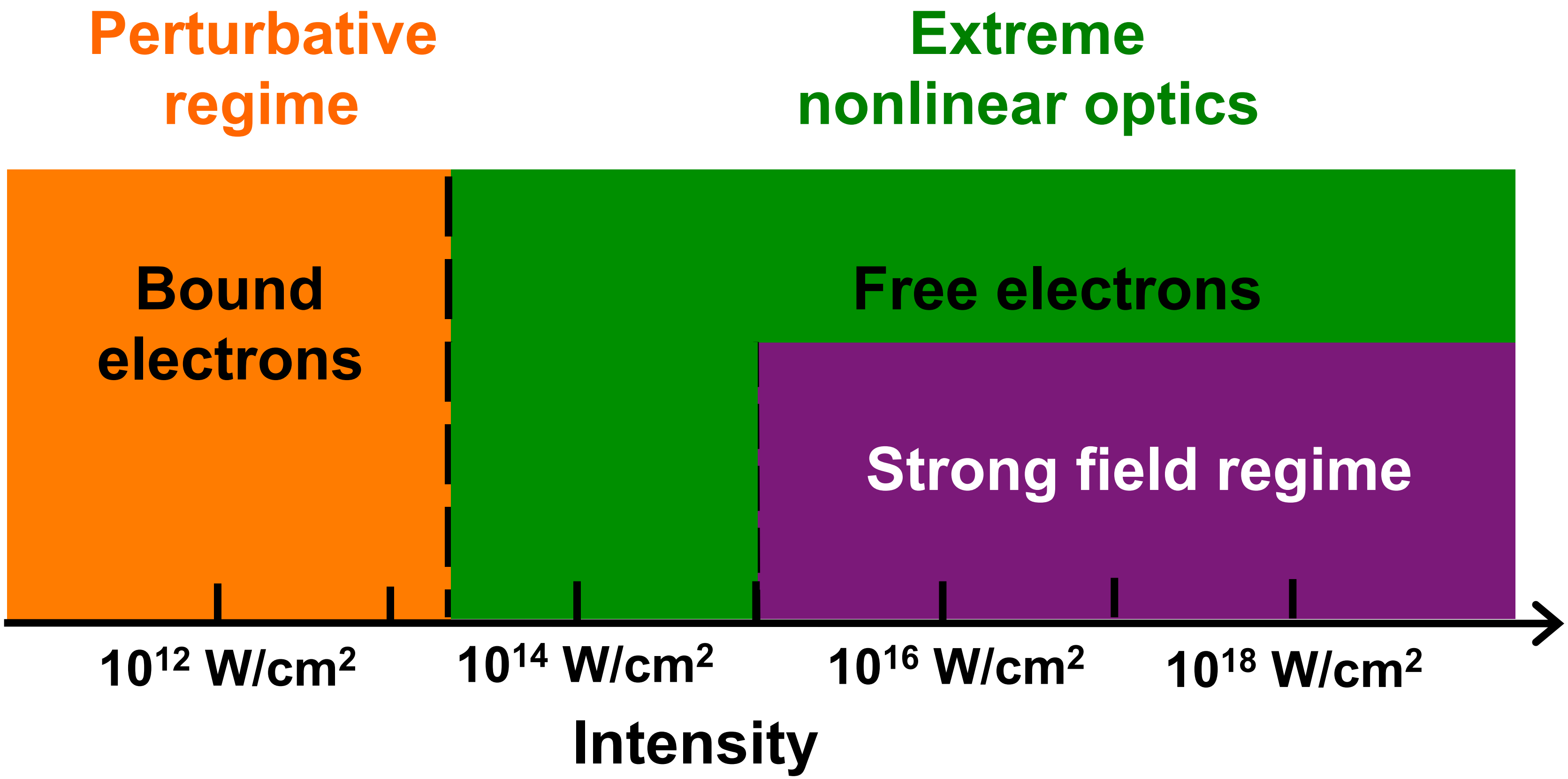
- Light wave travels in the material=oscillating electric field applied → charges moves, electric dipole

- Induced electric dipole moment (i.e. induced polarization)
  - Light radiated at same frequency

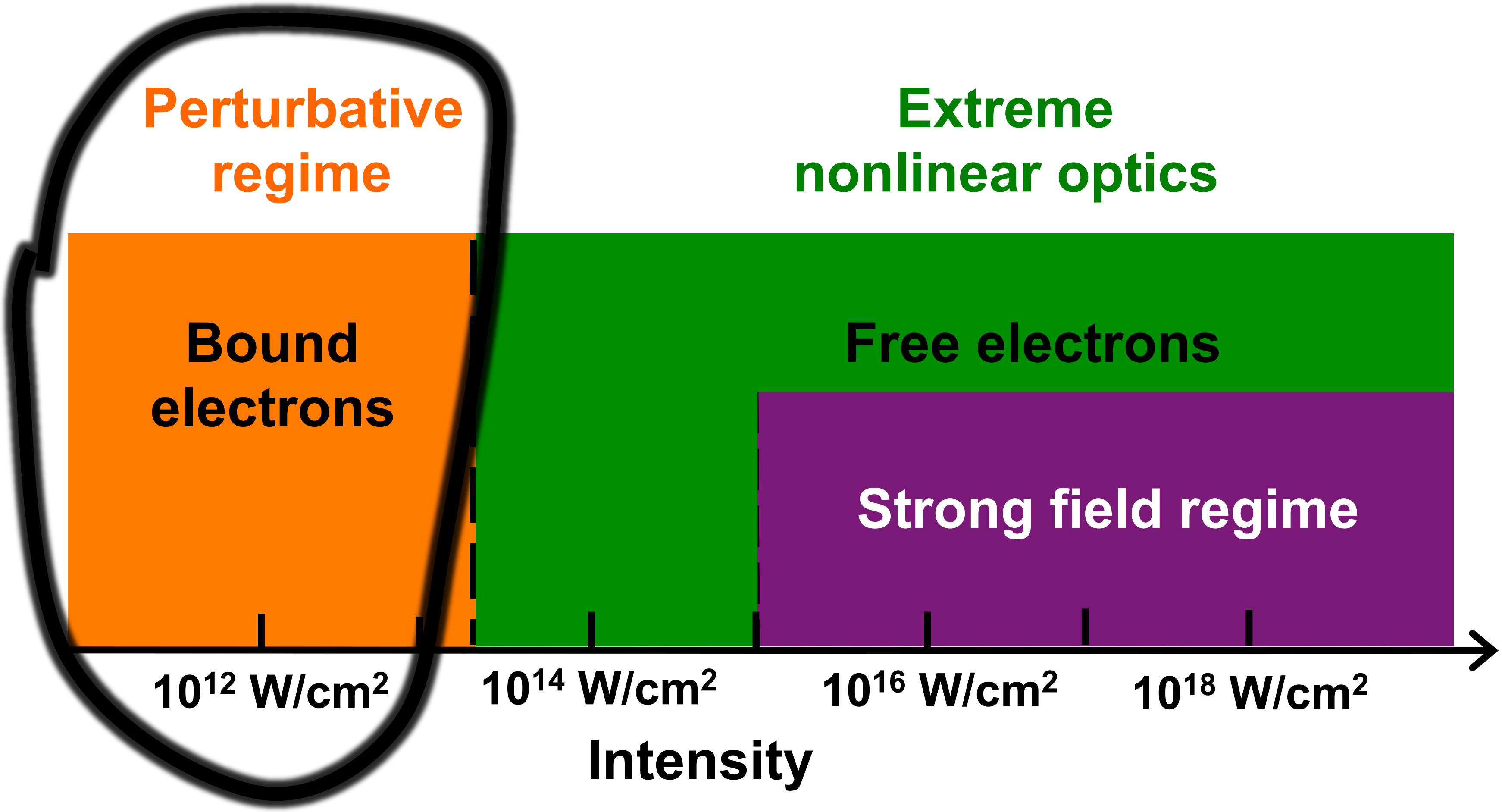


- If electric field large, motion of bound electrons is anharmonic = nonlinear (~spring distorted)
  - Light radiated at harmonic frequencies

Regimes of nonlinear optics



Regimes of nonlinear optics



Nonlinear pulse propagation in optical fibers

- Pulse propagation in optical fiber obeys :

$$\nabla \times \nabla \times E(r,t) + \frac{1}{c^2}\frac{\partial^2 E(r,t)}{\partial t^2} = -\mu_0 \frac{\partial^2 P(r,t)}{\partial t^2}$$

with $P(r,t) = P_L(r,t) + P_{NL}(r,t)$

$$P(r,t) = \underbrace{\varepsilon_0 \chi^{(0)} + \varepsilon_0 \chi^{(1)} E(r,t)}_{\text{Dispersion}} + \underbrace{\varepsilon_0 \chi^{(2)} E^2(r,t) + \varepsilon_0 \chi^{(3)} E^3(r,t) + \ldots}_{\text{Nonlinearity}}$$

Dispersion **Nonlinearity**

Nonlinear pulse propagation in optical fibers

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- In silica: $\chi^{(2)}$=0 (centro-symmetric material)

- Only **THIRD-ORDER** nonlinear effects

Representation of optical pulses

E-field associated with short laser pulses:

$$E(r,z,t) = F(r)A(z,t)e^{i\omega_0 t} \begin{cases} F(r) \text{ modal distribution} \\ A(z,t) \text{ temporal envelope} \\ \omega_0 = \dfrac{2\pi c}{\lambda_0} \text{ carrier frequency} \end{cases}$$

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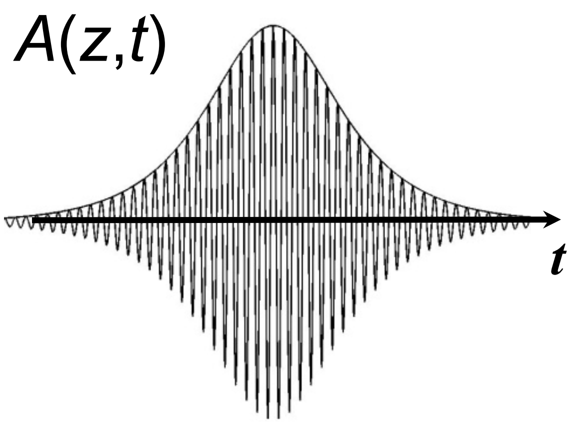

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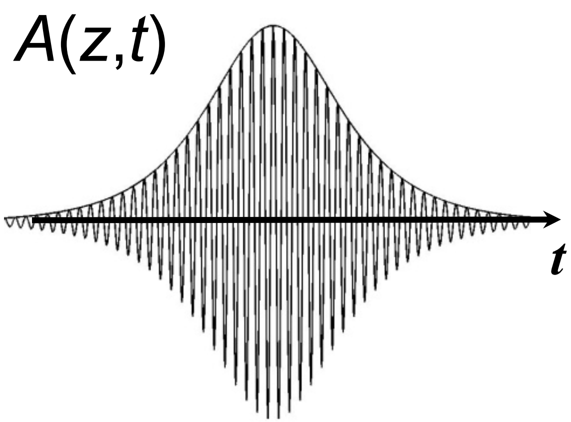
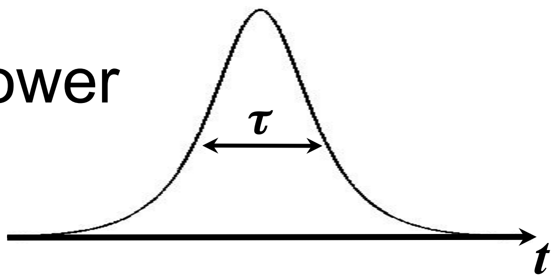


What you measure in practice

$P(z,t)=|A(z,t)|^2$: power



P_p: peak intensity (from 100 W to 10^5 W)

τ: pulse duration (from 10^{-9} s to 10^{-15} s)

Representation of optical pulses

E-field associated with short laser pulses:

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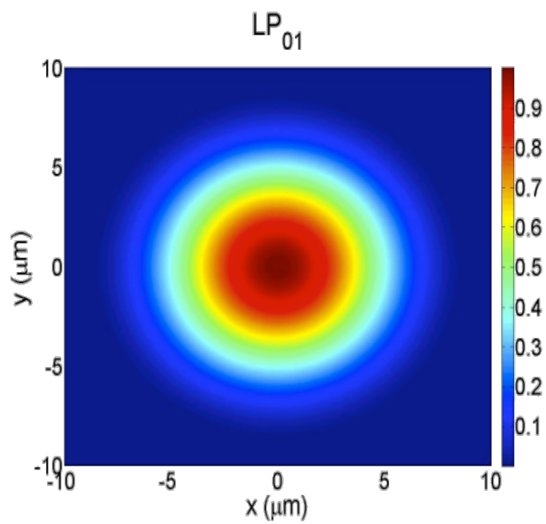
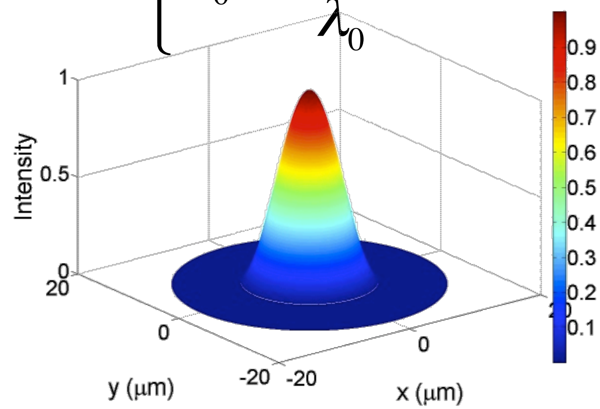




- Consider only fundamental mode (Gaussian)
- Does not vary with propagation
- Only temporal effects matters, no diffraction

Pulse propagation equation

- Generalized nonlinear Schrödinger Equation (GNLSE)

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

Loss ***Dispersion*** ***Self-Steepening term*** ***SPM, FWM, Raman***

Intensity-dependent ref. index $\gamma = n_2\omega_0/cA_{eff}$

Raman response $R(T) = (1-f_R)\delta(T) + f_R h_R(T)$

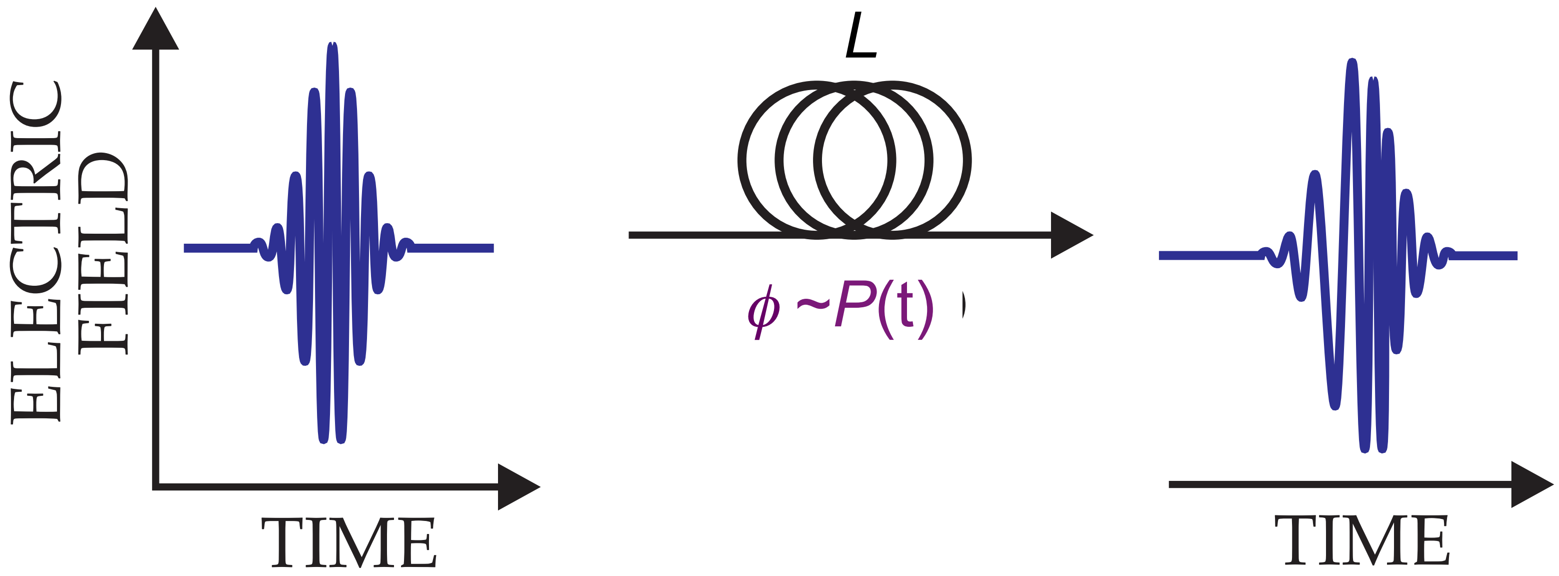
- Can include noise, frequency-dependent mode area, polarization…etc

- Validity: down to single cycle regime

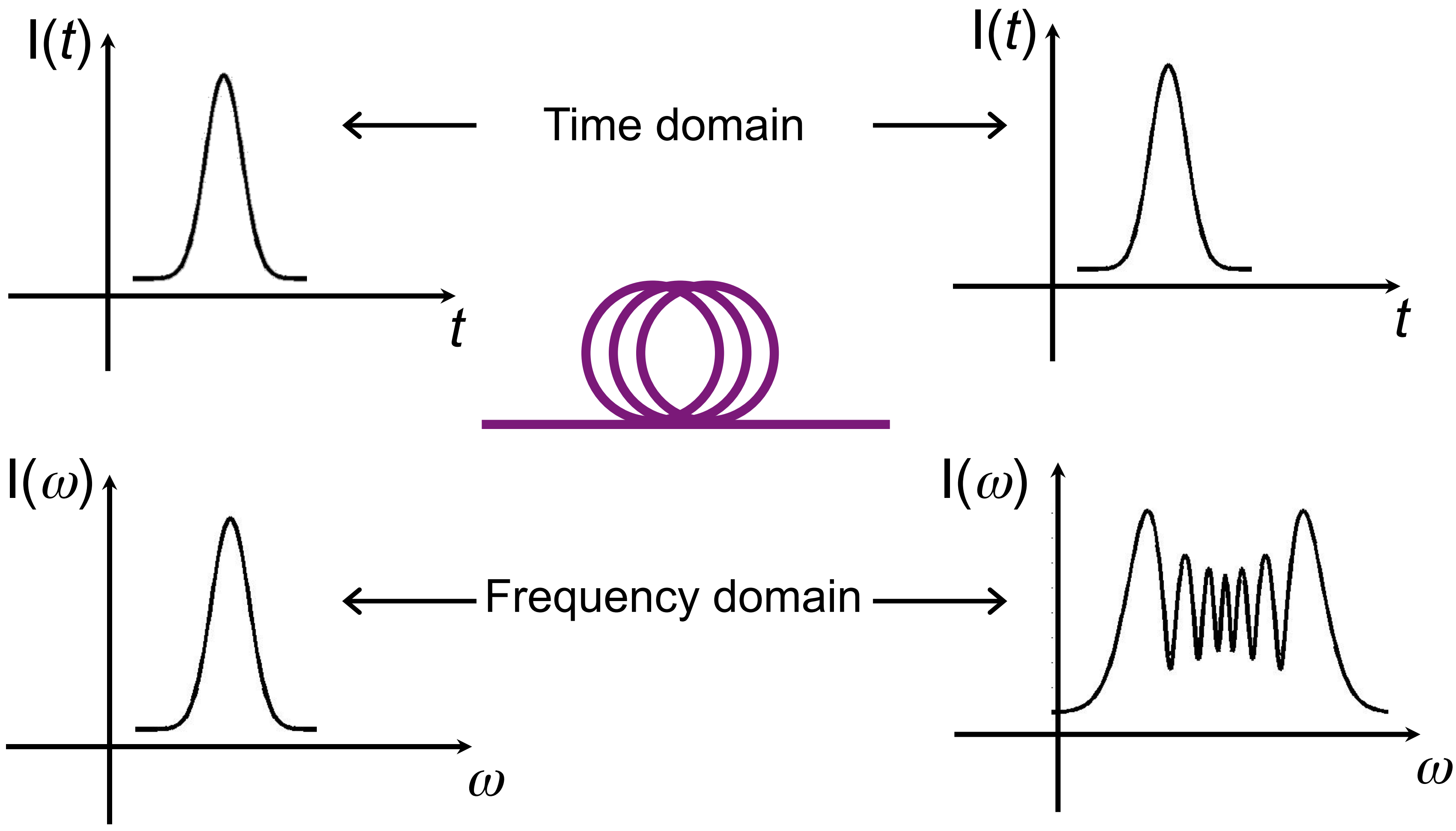
Self-Phase Modulation

- Light modulates its own phase: $\phi_{NL}(t,L) = \gamma\, P(t)\, L$

- The frequency of the pulse is time-dependent: chirp



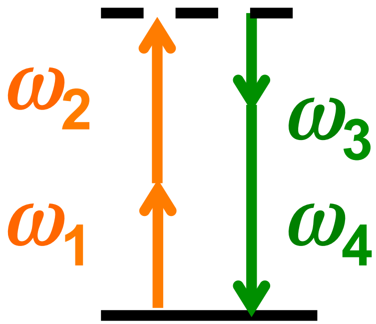
Self-Phase Modulation

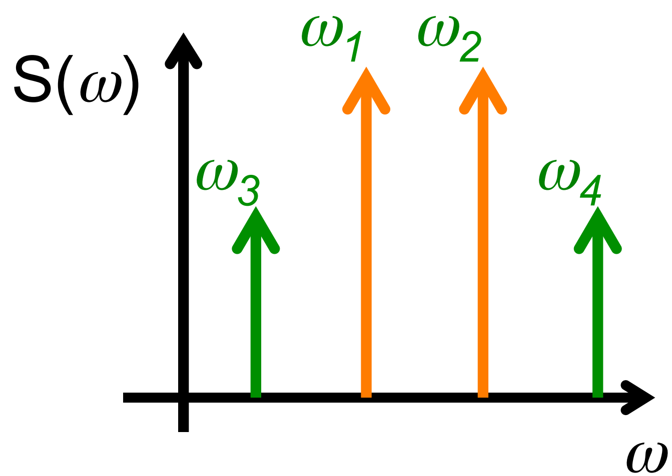


- Spectrum broadens but temporal profile unchanged

Four-Wave Mixing

- Nonlinear mixing between two optical signals at different frequencies generates signals at the frequency difference





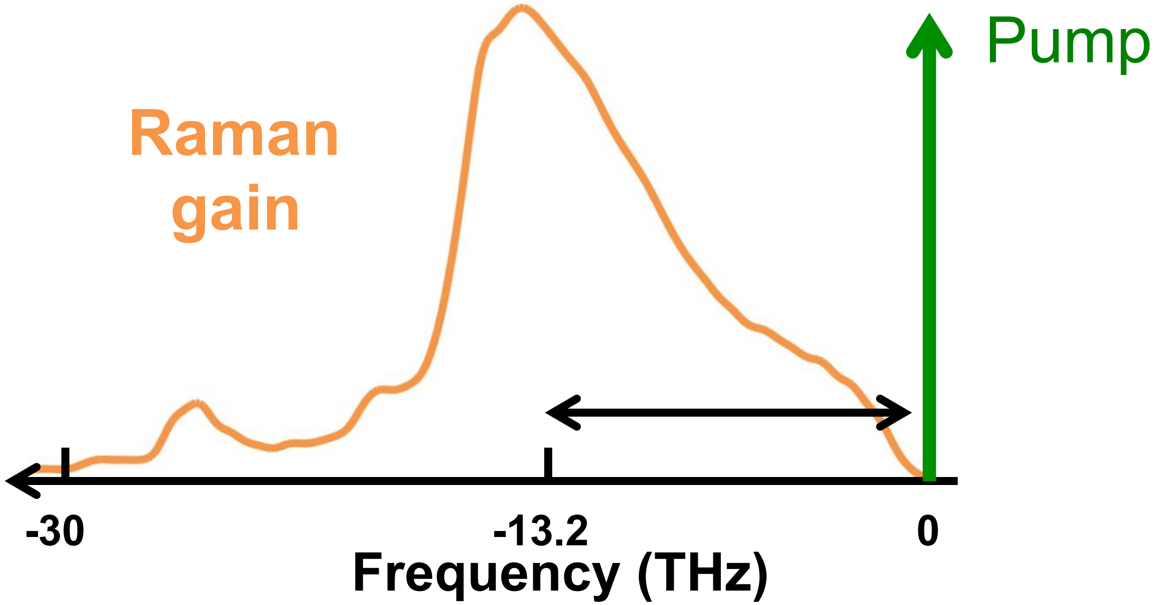
- Energy conservation + phase-matching condition

$$\omega_1 + \omega_2 \rightarrow \omega_3 + \omega_4$$

$$\beta(\omega_1) + \beta(\omega_2) \rightarrow \beta(\omega_3) + \beta(\omega_4)$$

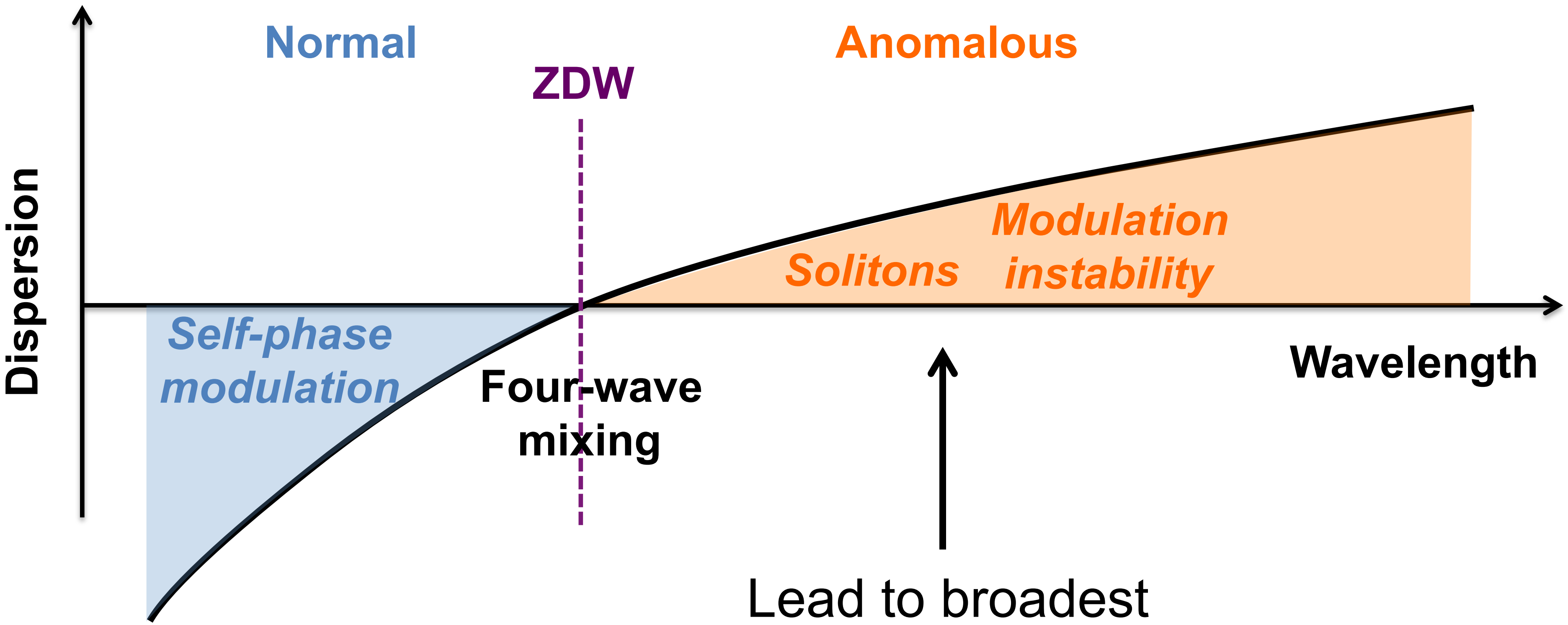
Stimulated Raman Scattering

- Interaction between light and vibrational modes of molecules
- High intensity pump induces gain for a wave with shorter frequency (longer wavelengths)



- Raman gain is broadband and depends on material

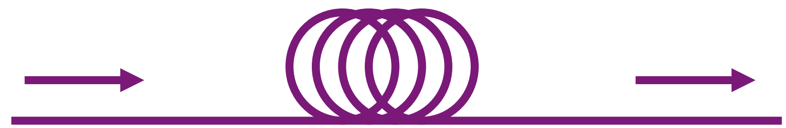
Pump wavelength is crucial



Lead to broadest supercontinuum spectra

Fibers for nonlinear optics

- Pulse propagation in optical fibers
  - No diffraction, long interaction length



- Dispersion/nonlinearity can be controlled: crucial!
  - propagation dynamics depend on pump wavelength relative to fiber zero dispersion wavelength (ZDW)

"NEW" FIBERS

Small core, high doping
Photonic crystal fibers
Tapered fibers
Non-silica materials

PARAMETER CONTROL

Dispersion
nonlinearity
Confinement

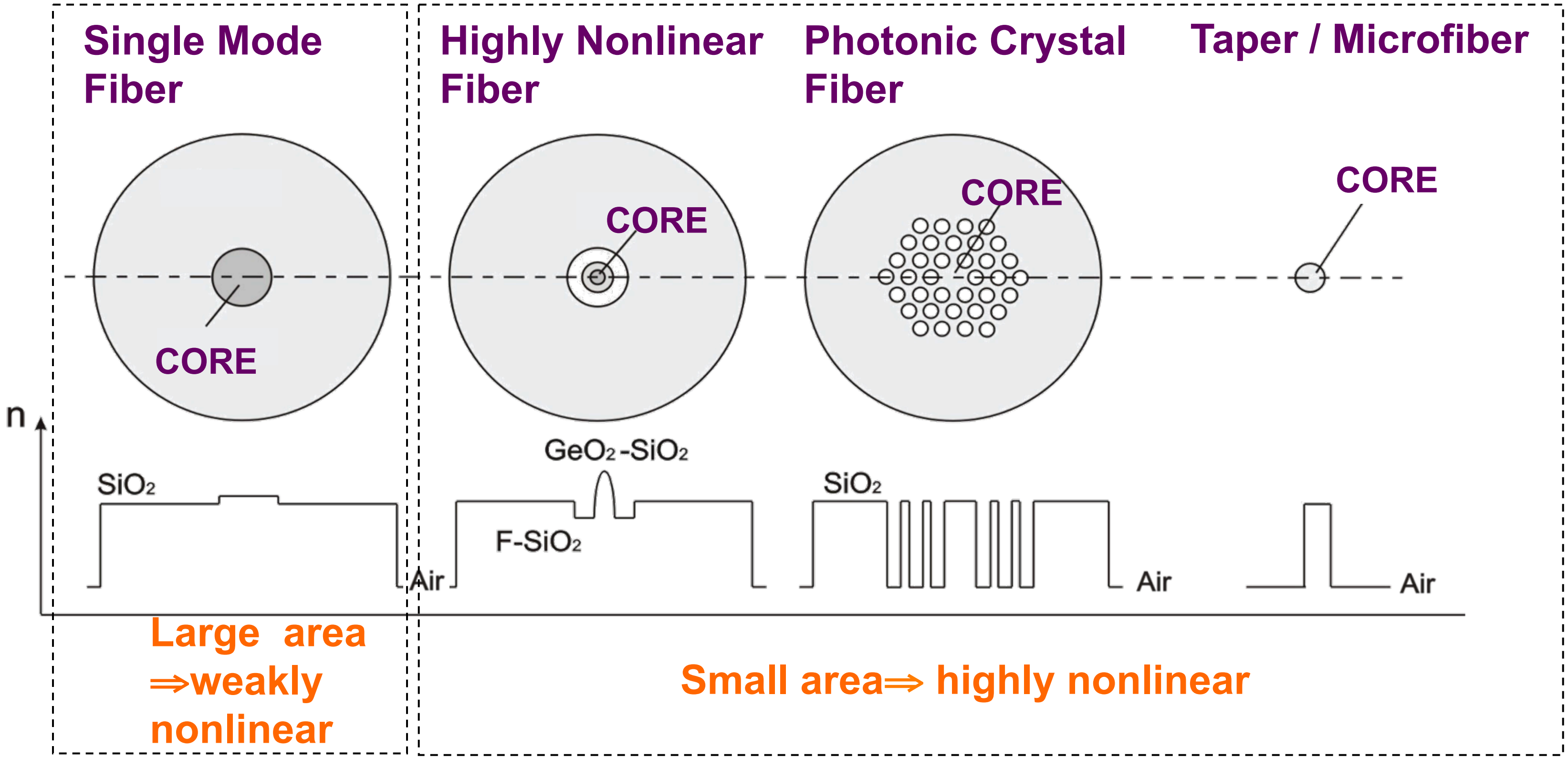
→

APPLICATIONS

Supercontinuum
Frequency conversion
Pulse compression
Amplification

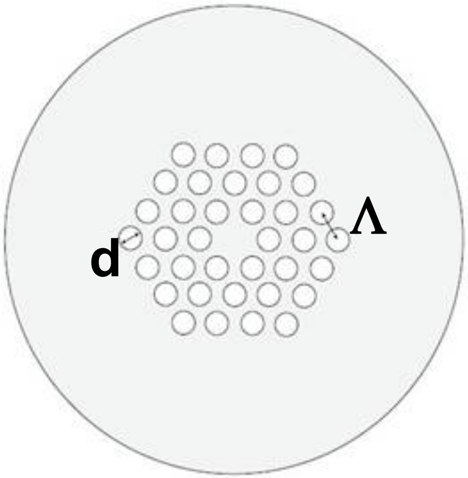
Fibers for nonlinear optics

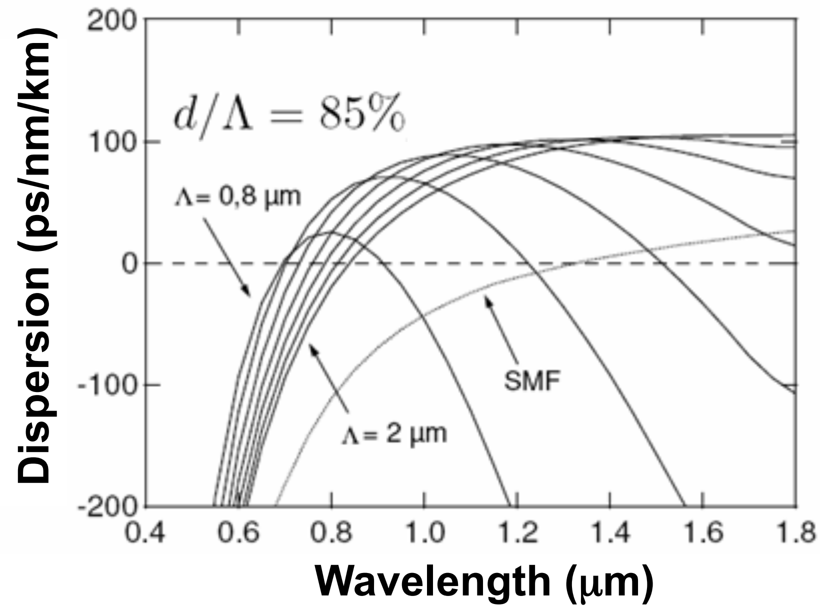
- Both chemistry and geometry affects the refractive index profile
  - Determine modal confinement (nonlinearity) and dispersion characteristics
  - Wide range of possibilities



Photonic crystal fibers

- Generally single material with a high air-fill fraction



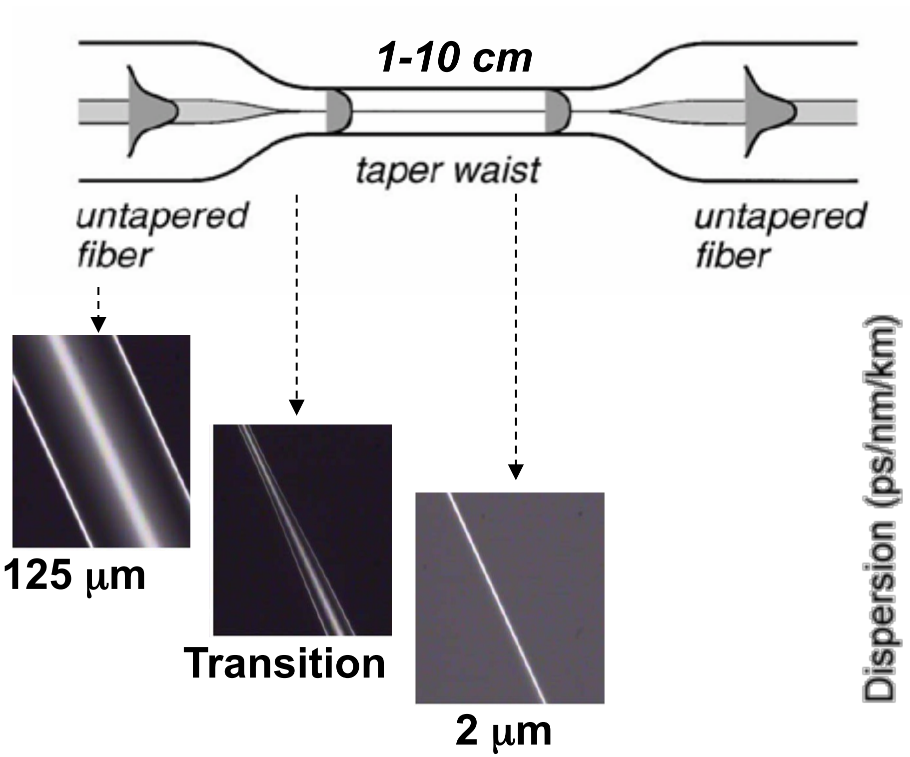


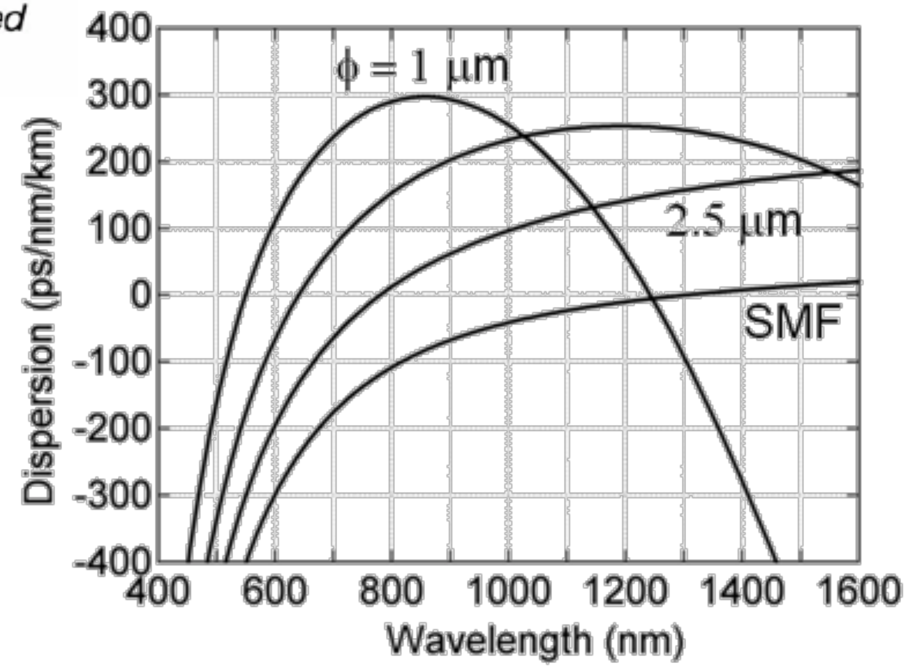
- ZDW displaced to shorter wavelengths (match high-power short pulse sources)
- Large nonlinearity (x100 compared to standard fibers)

$\Rightarrow$ nonlinear effects dramatically enhanced

Taper/microfibers

- Tapering standard fibers: similar properties to photonic crystal fibers





Dispersion engineering

Micro/nano- structured waveguides: engineered nonlinearity and dispersion

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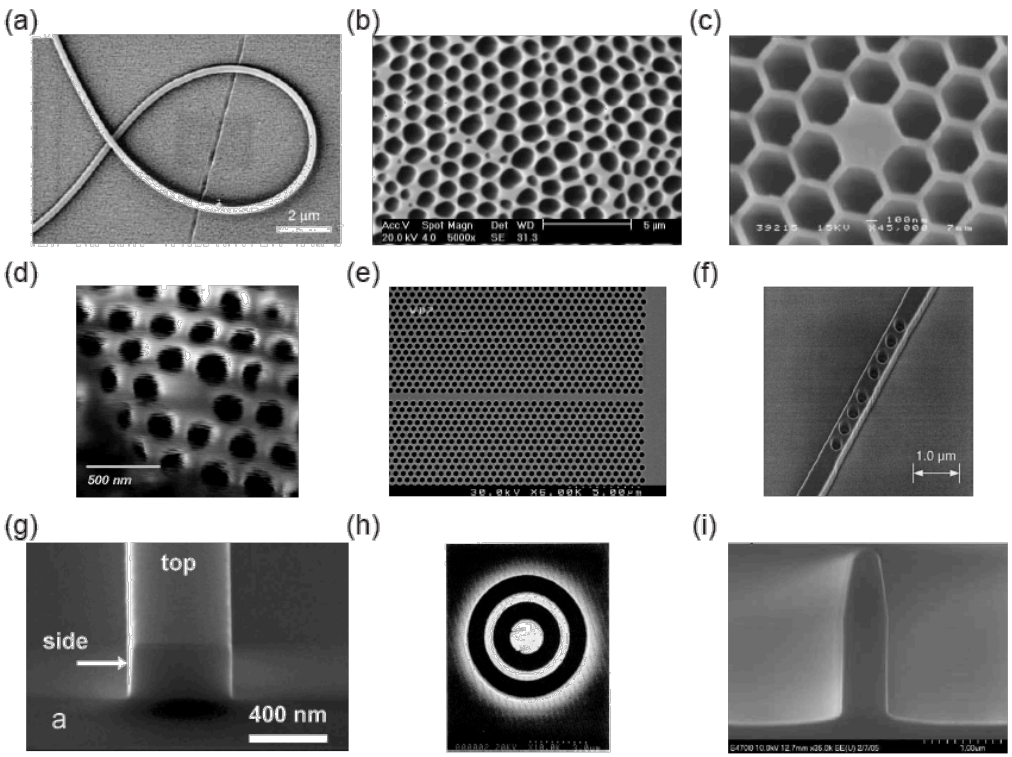
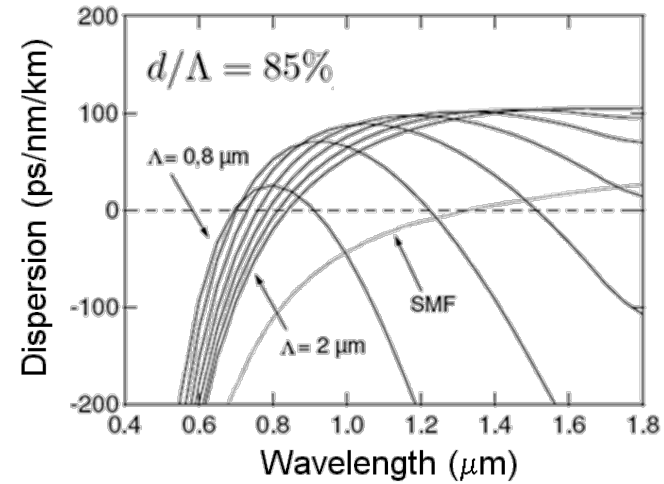
Nonlinear optics in photonic nanowires

Mark A. Foster[1], Amy C. Turner[2], Michal Lipson[2], and Alexander L. Gaeta[1]

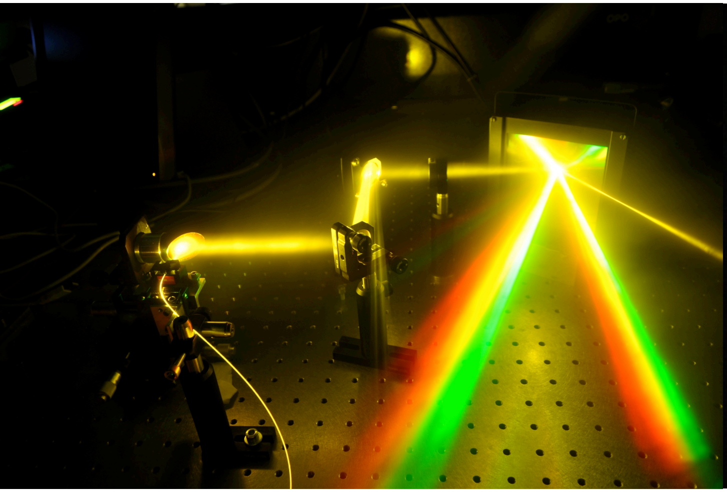


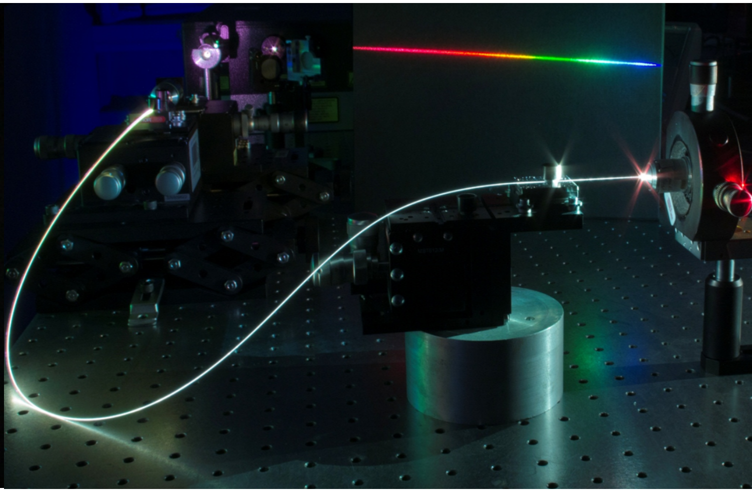


- Tune dispersion vs. pump wavelength
- Light tightly confined → very large intensities!

Supercontinuum generation is easy

Pretty much anything works…



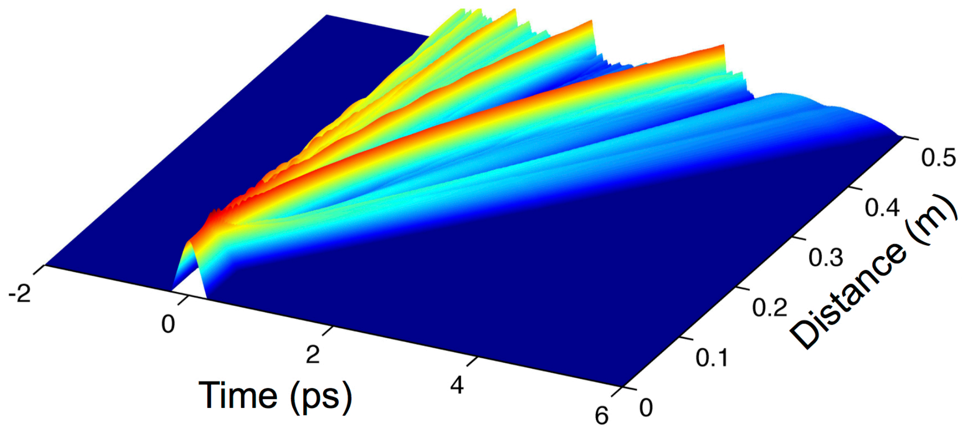


Source: fs, ps, ns pulses, CW lasers

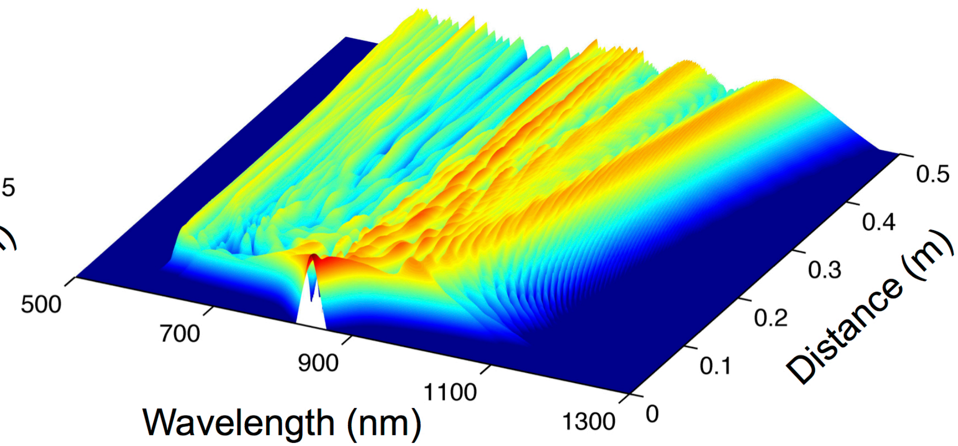
Fibers: PCFs, HNLF, DSF, SMF 28

Dynamics are rather complex…

Time evolution



Spectral evolution



	Short pulses	Long pulses
Anomalous	• Soliton • Dispersive waves	• Modulation instability • Solitons dynamics
Normal	• Self-phase modulation • Four-wave mixing	• Raman scattering • Four-wave mixing

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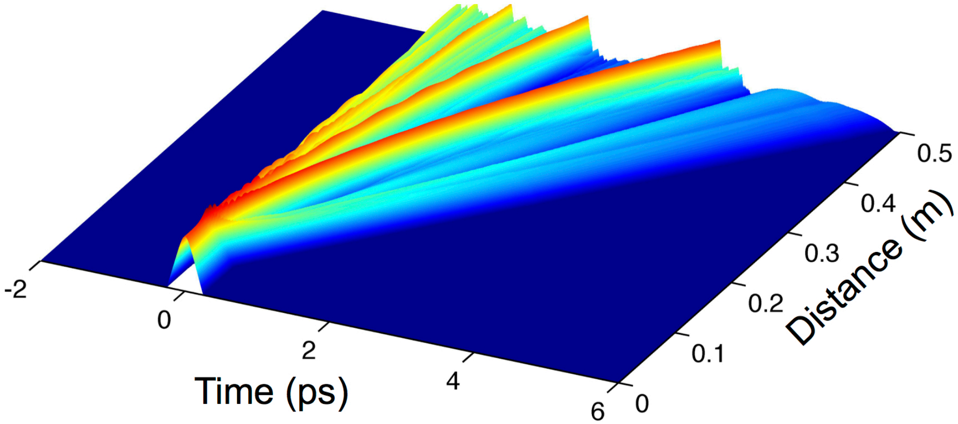
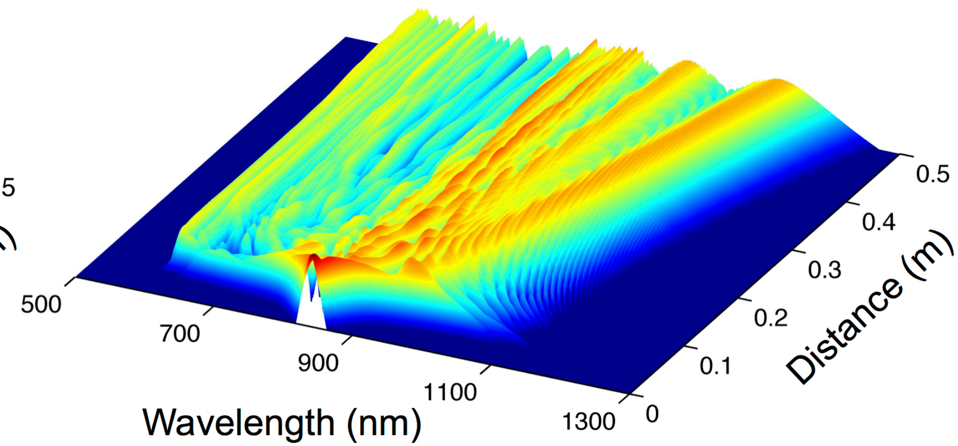
Time evolution



Spectral evolution



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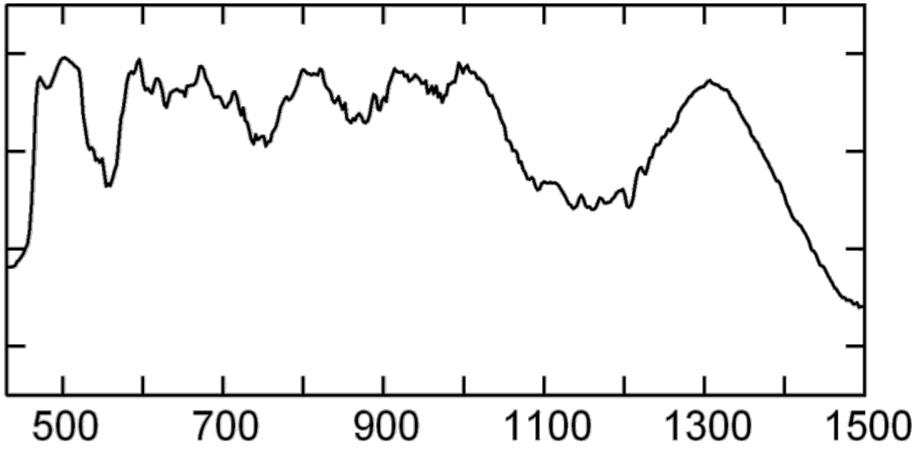
Coherent

Incoherent

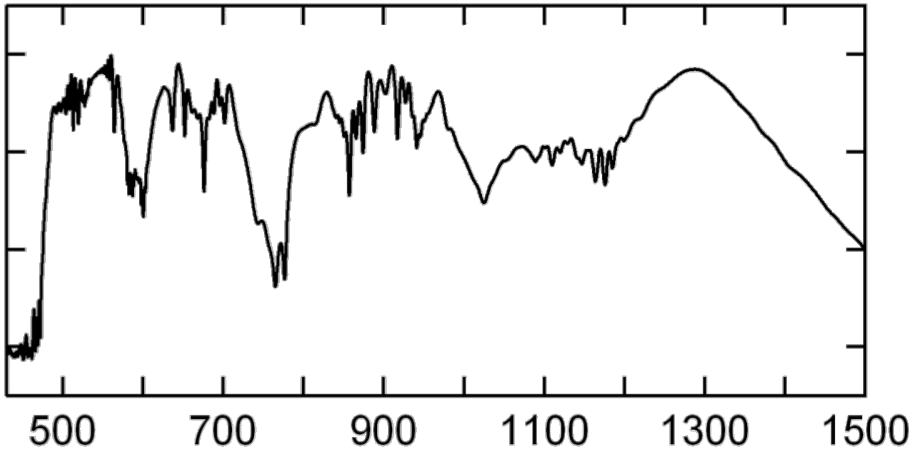
Modelling supercontinuum

- Good agreement with experimental results

Experiment



Simulation



- Success in modeling: physics well-understood

Understanding pulse propagation dynamics

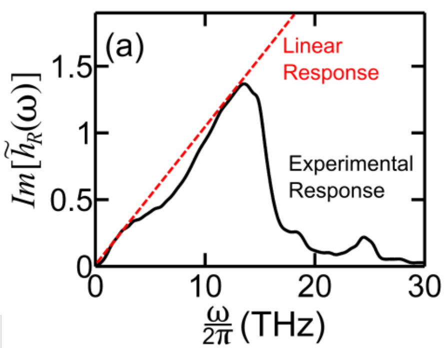
- Numerical (analytical) modelling
- Visualization
- Need to be done properly!

Modeling supercontinuum

- Generalized nonlinear Schrödinger Equation (GNLSE)

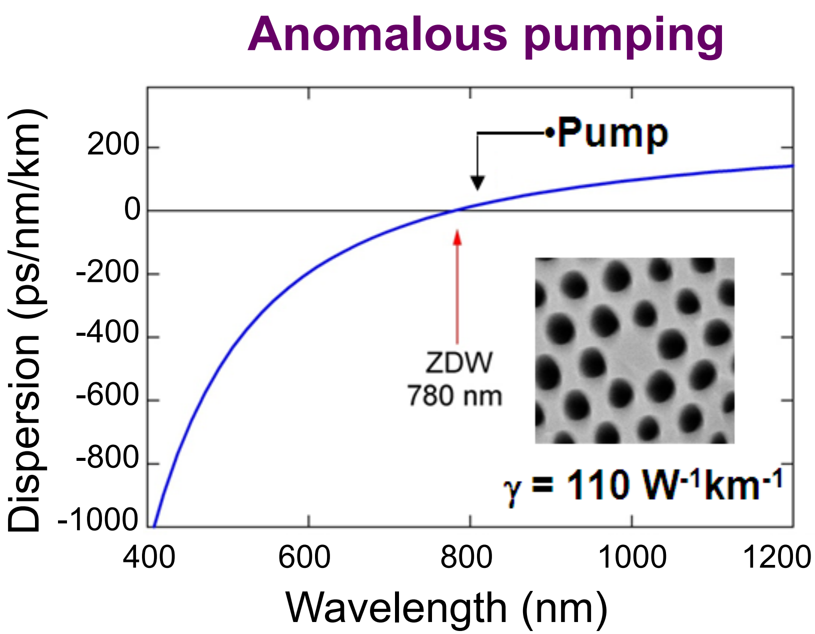
$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A - \sum_{k\geq 2} \frac{\mathrm{i}^{k+1}}{k!}\beta_k \frac{\partial^k A}{\partial T^k} = i\gamma\left(1 + \mathrm{i}\tau_{\mathrm{shock}}\frac{\partial}{\partial T}\right)\left(A(z,t)\int_{-\infty}^{+\infty} R(T')|A(z,T-T')|^2 dT'\right)$$

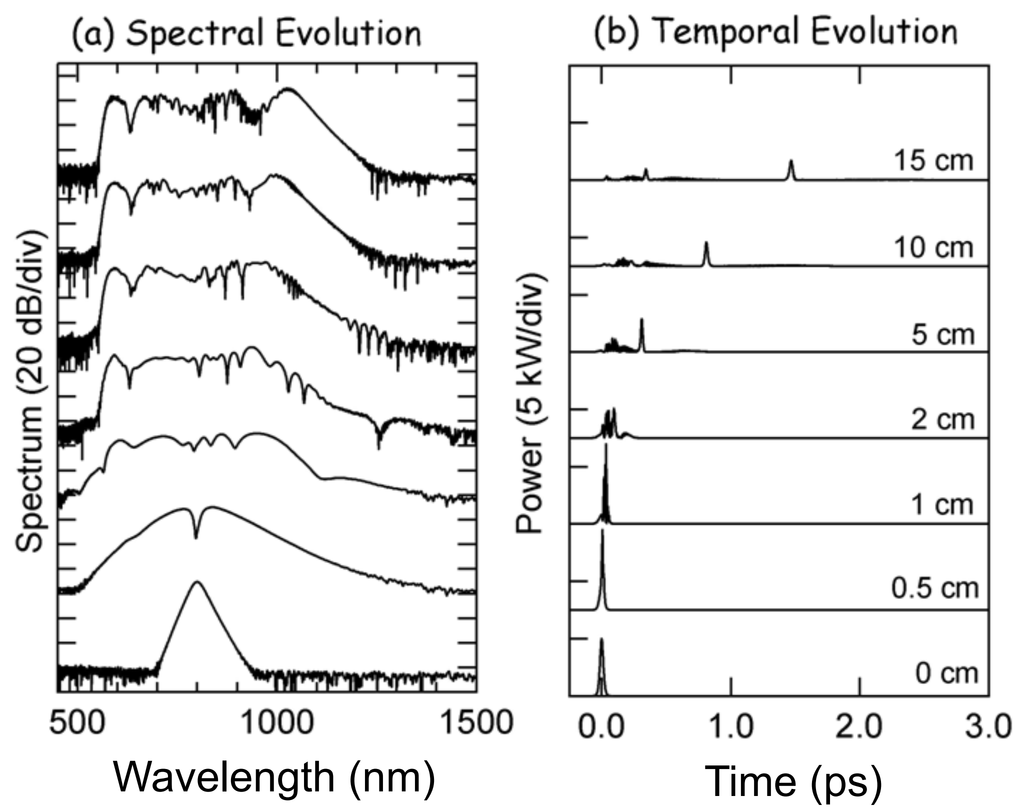
- Important considerations
  - window size (avoid wrapping around)
  - temporal/spectral resolution
  - step size (FWM artefacts)
  - DO NOT use linear Raman model
  - Disp. coeff. must be changed if you change the pump wavelength
  - Better to use full β (and not 25th order…)



Short pulse regime and anomalous dispersion

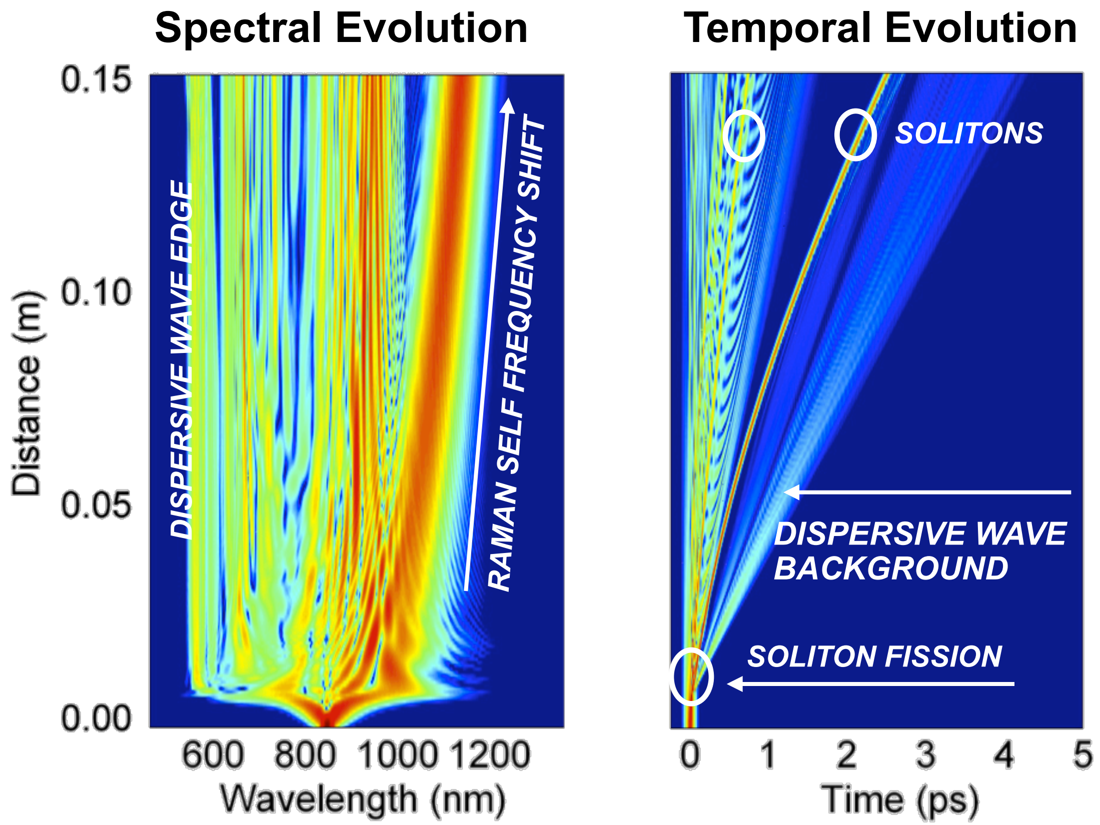
- 30 fs, 10 kW input pulses





- Evolution can be divided in 3 stages
  - Initial higher-order soliton compression (spectral broadening),
  - soliton fission and dispersive wave generation
  - Raman self-frequency shift

Better in color



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Deconstructing supercontinuum dynamics

- Understanding the complex dynamics: study separately the different stages

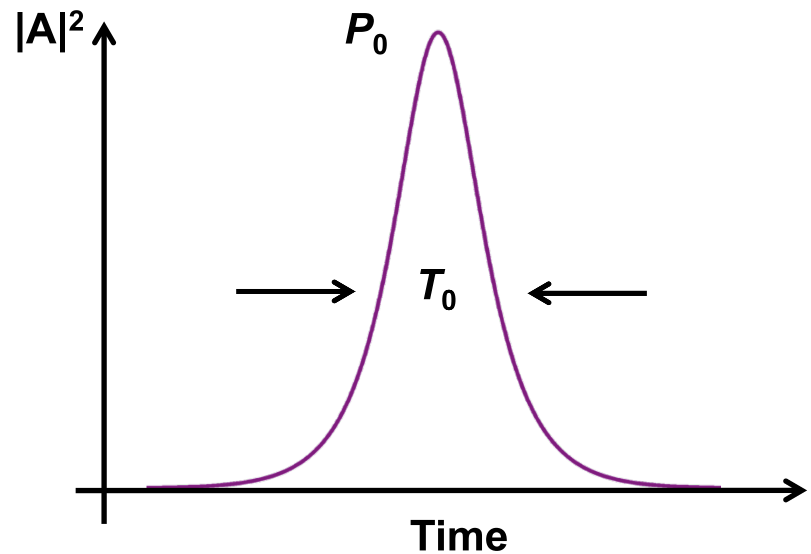
- Soliton propagation dynamics
  - Fundamental solitons
  - Higher-order solitons
  - Effect of perturbation: higher-order dispersion and Raman scattering

Fundamental soliton

- Fundamental soliton are invariant solution of the nonlinear Schrödinger equation (chirp from self-phase modulation balances chirp from ANOMALOUS dispersion)

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

GVD   Kerr effect



Requirements

$$\begin{cases} A(z=0,T)=\sqrt{P_0}\,\mathrm{sech}(T/T_0) \qquad A(z,T)=\sqrt{P_0}\,\mathrm{sech}(T/T_0)e^{jk_{sol}z} \\ N=\sqrt{L_d/L_{nl}}=\sqrt{\gamma P_0T_0^2/|\beta_2|}=1 \end{cases}$$

Soliton number

$\gamma P_0/2$

Fundamental soliton

- Fundamental soliton is invariant upon propagation (except for a constant nonlinear phase-shift)

Requirements $\begin{cases} A(z=0,T)=\sqrt{P_0}\,\mathrm{sech}(T/T_0) \\ N=\sqrt{L_d/L_{nl}}=\sqrt{\gamma P_0 T_0^2/|\beta_2|}=1 \end{cases}$ **Soliton number**

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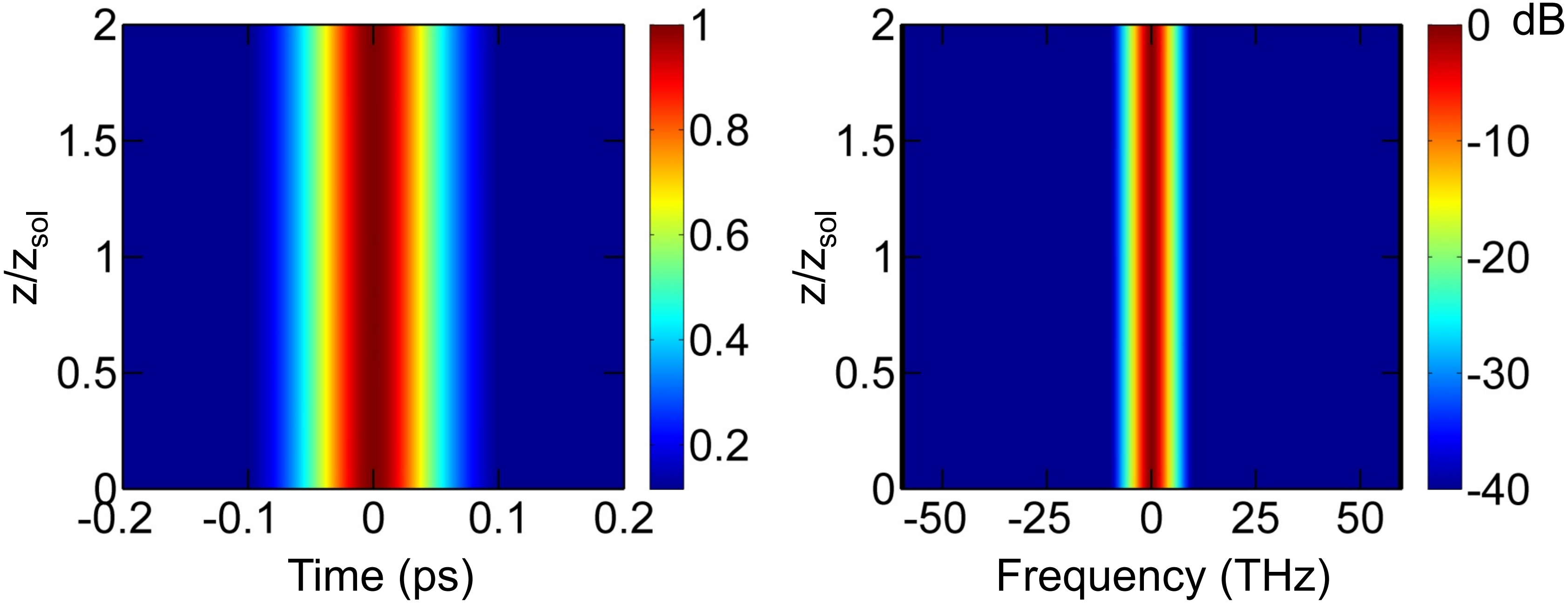
$\gamma P_0/2$

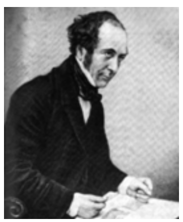
Time evolution

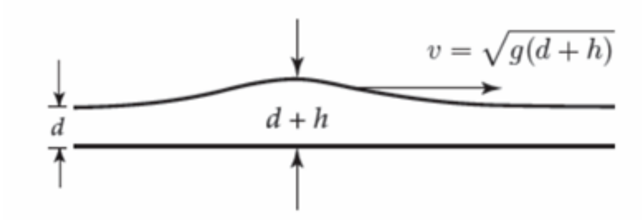
Spectrum evolution

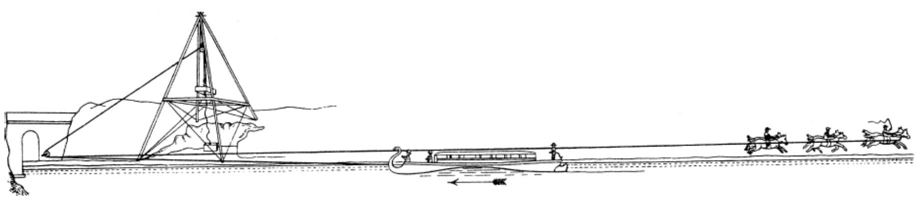


Solitons

- First soliton was observed as the “wave of translation” by Russell (1834)







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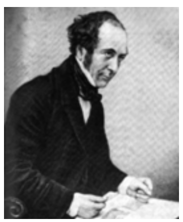
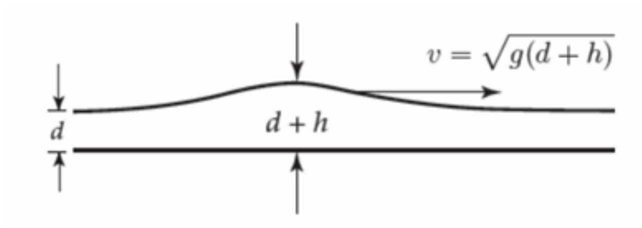
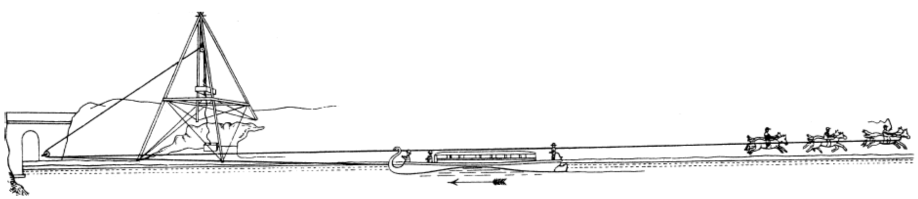






- Soliton experience elastic scattering

Higher-order solitons

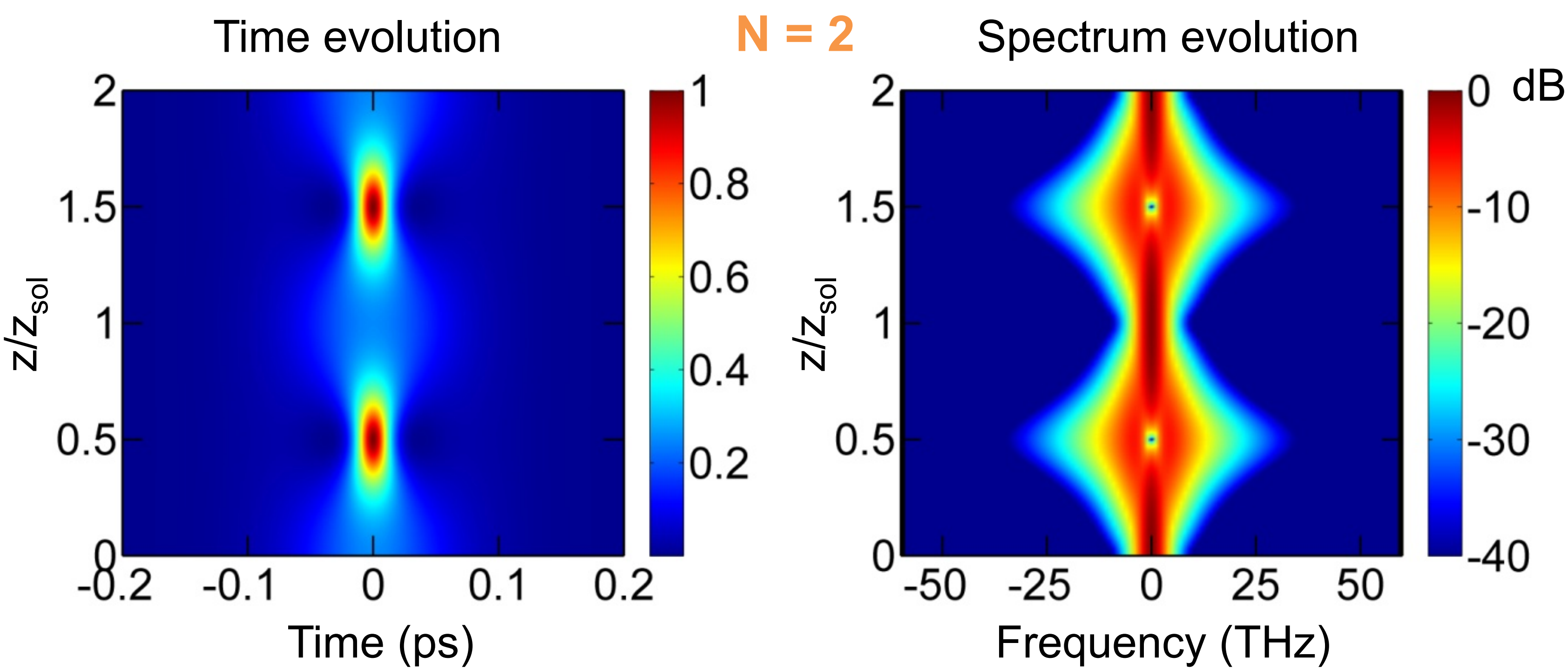
- Higher-order soliton is periodic upon propagation $A(z+z_{sol},T) = A(z,T)$

Requirements
$$\begin{cases} A(z=0,T) = \sqrt{P_0}\,\mathrm{sech}(T/T_0) \\ N = \sqrt{L_d/L_{nl}} = \sqrt{\gamma P_0 T_0^2/|\beta_2|} = 2,3,4\ldots \end{cases}$$

Quantized!

$$z_{sol} = \frac{\pi}{2}L_d = \frac{\pi}{2}T_0^2/|\beta_2|$$

Soliton period



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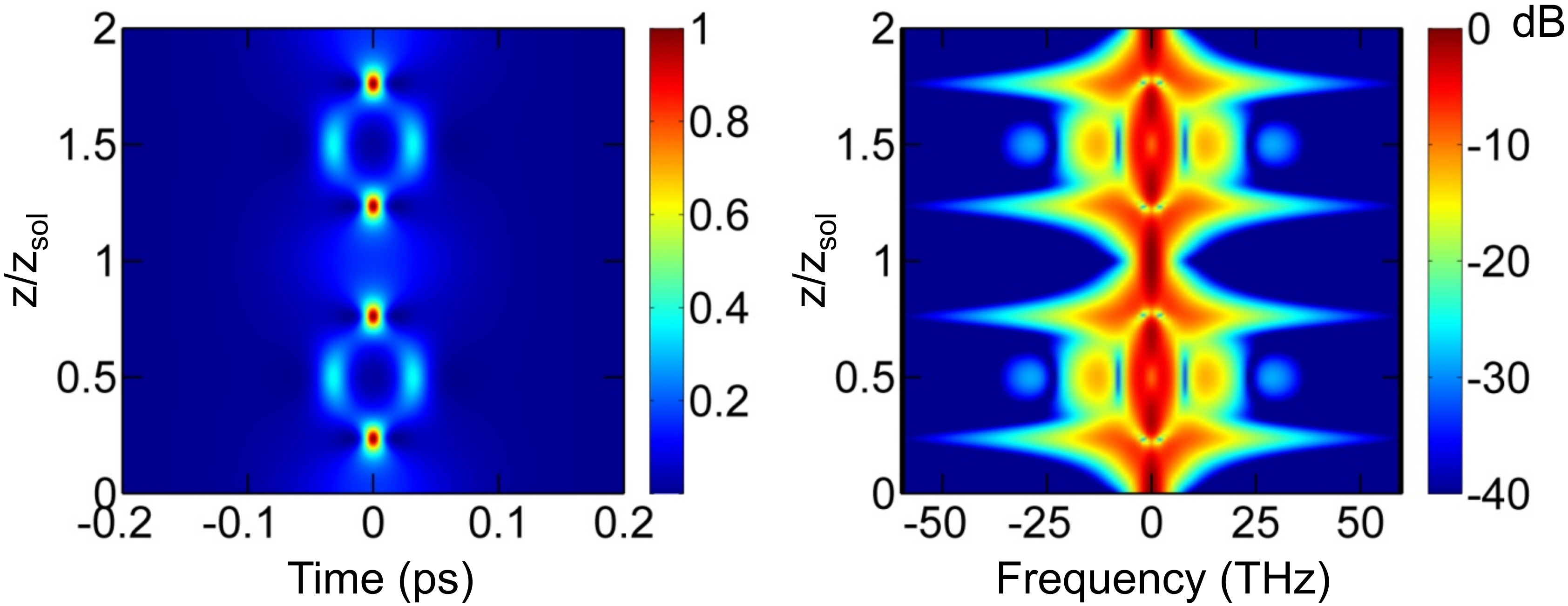
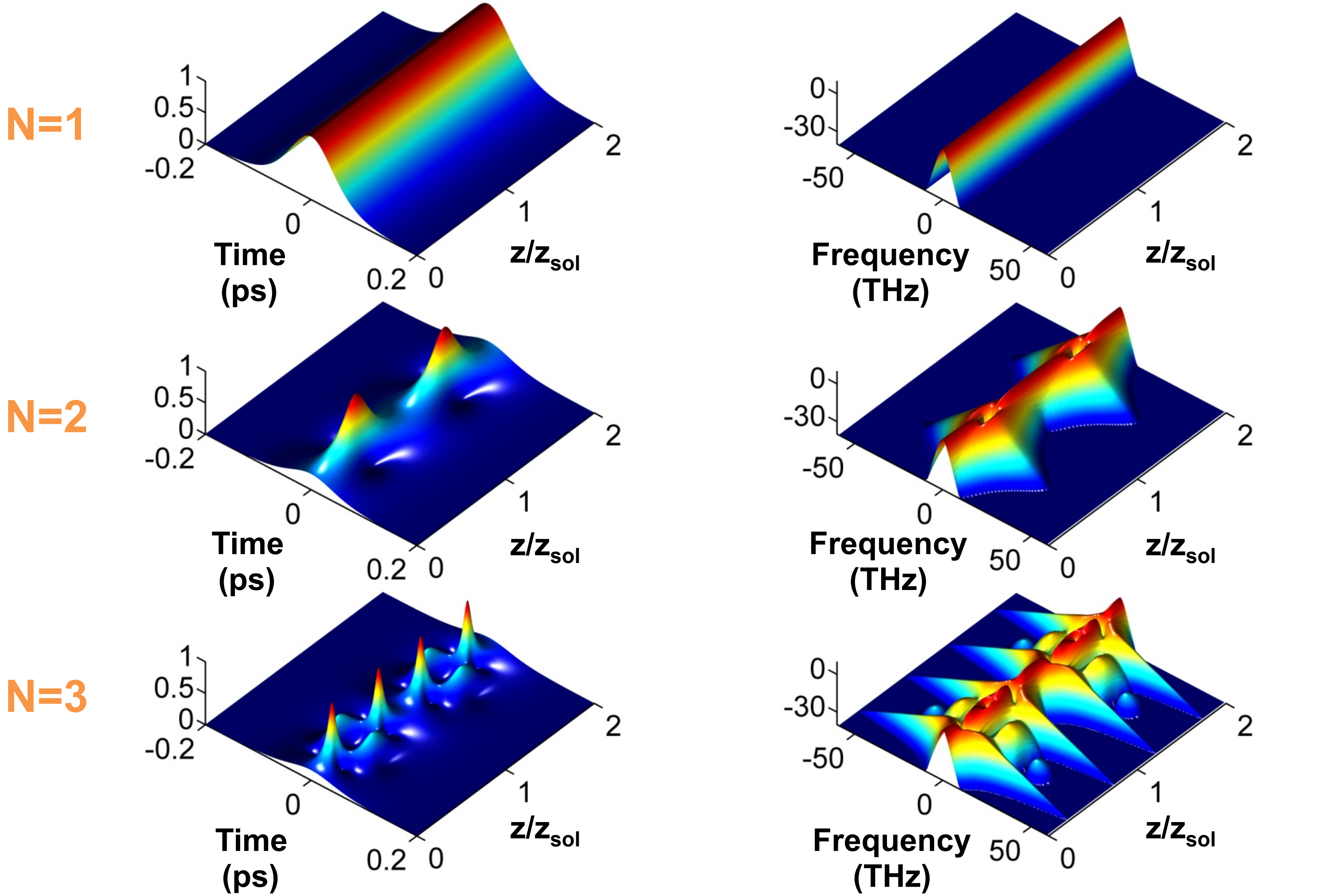
Soliton period

Time evolution **N = 3** Spectrum evolution



Nicer in 3D



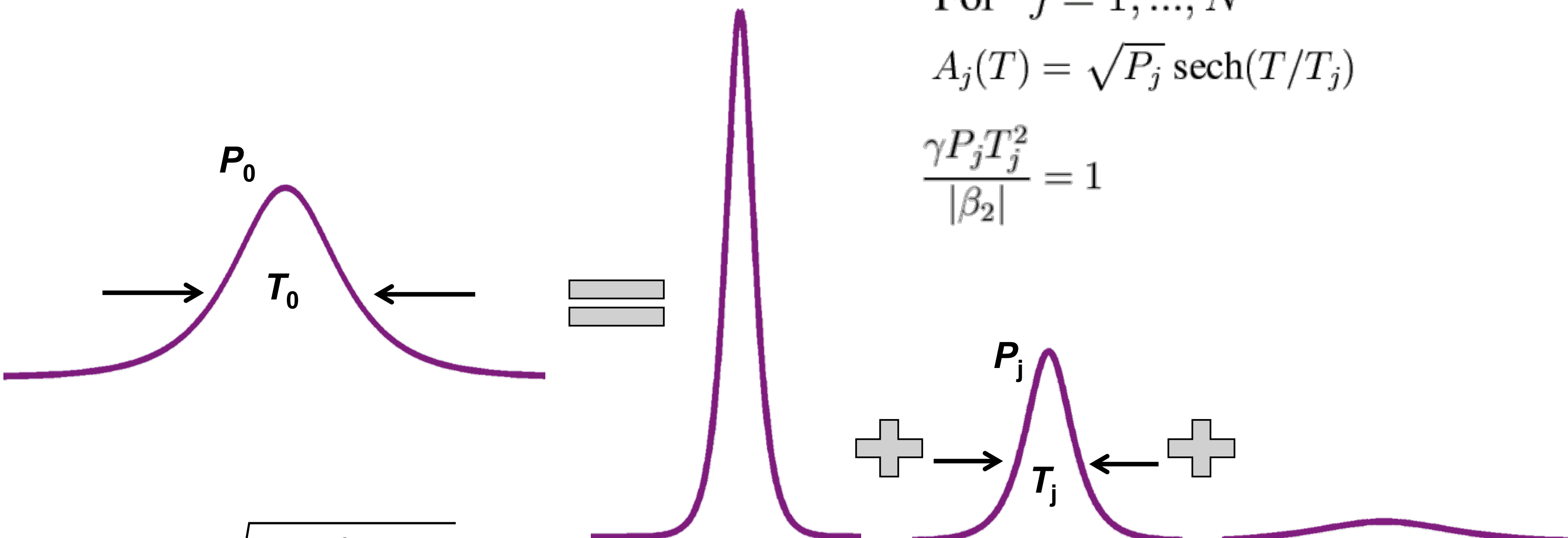
Higher-order solitons

- Higher-order soliton corresponds to the interference of fundamental solitons with different amplitudes (and phase)

For $j = 1, ..., N$

$$A_j(T) = \sqrt{P_j}\,\mathrm{sech}(T/T_j)$$

$$\frac{\gamma P_j T_j^2}{|\beta_2|} = 1$$



$$N = \sqrt{\gamma P_0 T_0^2 / |\beta_2|} = 3$$

$$P_j = \frac{(2N - 2j + 1)^2}{N^2} P_0 \qquad T_j = \frac{T_0}{2N - 2j + 1}$$

Perturbations of solitons

- Solitons (fundamental/higher-order)
  - Solutions of pure NLS (only GVD and Kerr nonlinearity)

$$\frac{\partial A}{\partial z} + \underbrace{i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2}}_{\textbf{GVD}} = \underbrace{i\gamma |A|^2 A}_{\textbf{Kerr}}$$

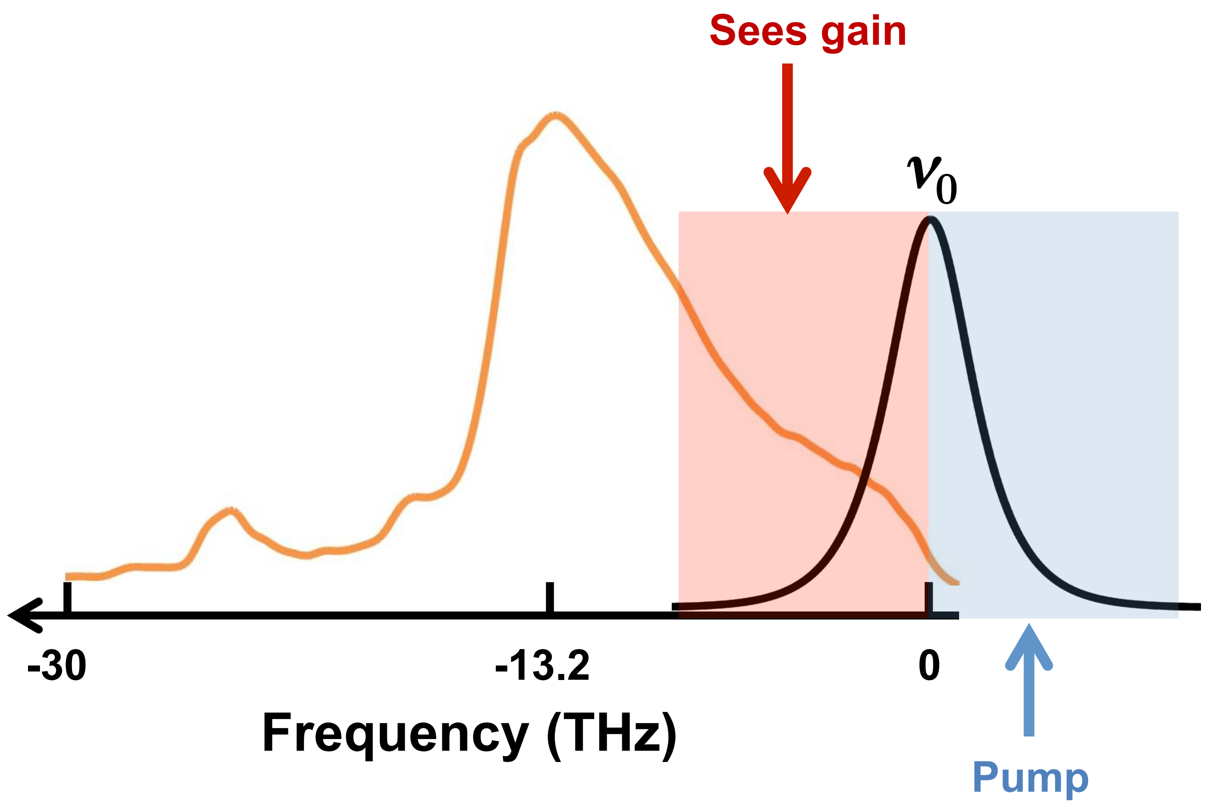
- Higher-order dispersion and Raman scattering perturb the evolution of solitons
  - Soliton self-frequency shift
  - Dispersive wave generation
  - Soliton fission

$$\frac{\partial A}{\partial z} + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} \underbrace{\boxed{- \frac{\beta_3}{6}\frac{\partial^3 A}{\partial T^3} + \ldots}}_{\textbf{HOD}} = i\gamma(1 - f_R)|A|^2 A + \underbrace{\boxed{f_R A\left(h_R * |A|^2\right)}}_{\textbf{Raman}}$$

Raman perturbation of soliton

Mitschke and Mollenauer OL 11, 659 (1986)

Gordon OL 11, 662 (1986)



- Frequency of soliton shifts towards lower frequencies (longer wavelengths) with propagation

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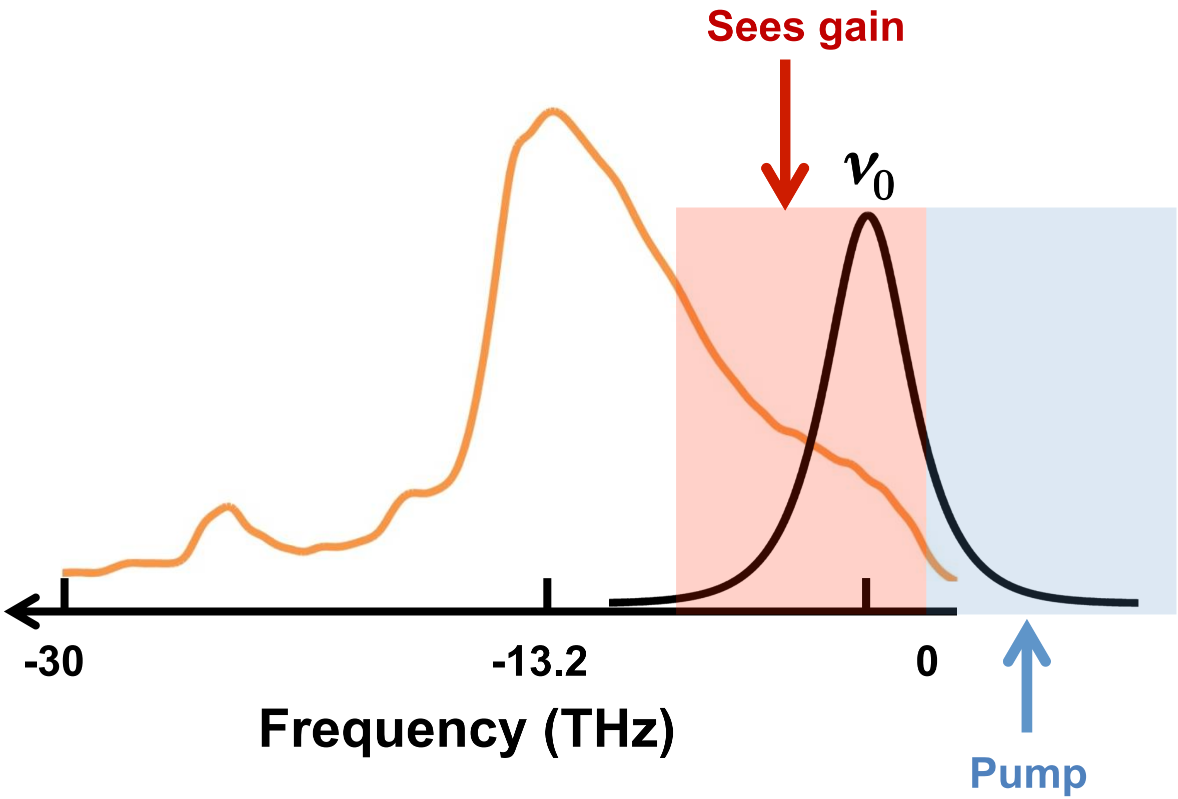

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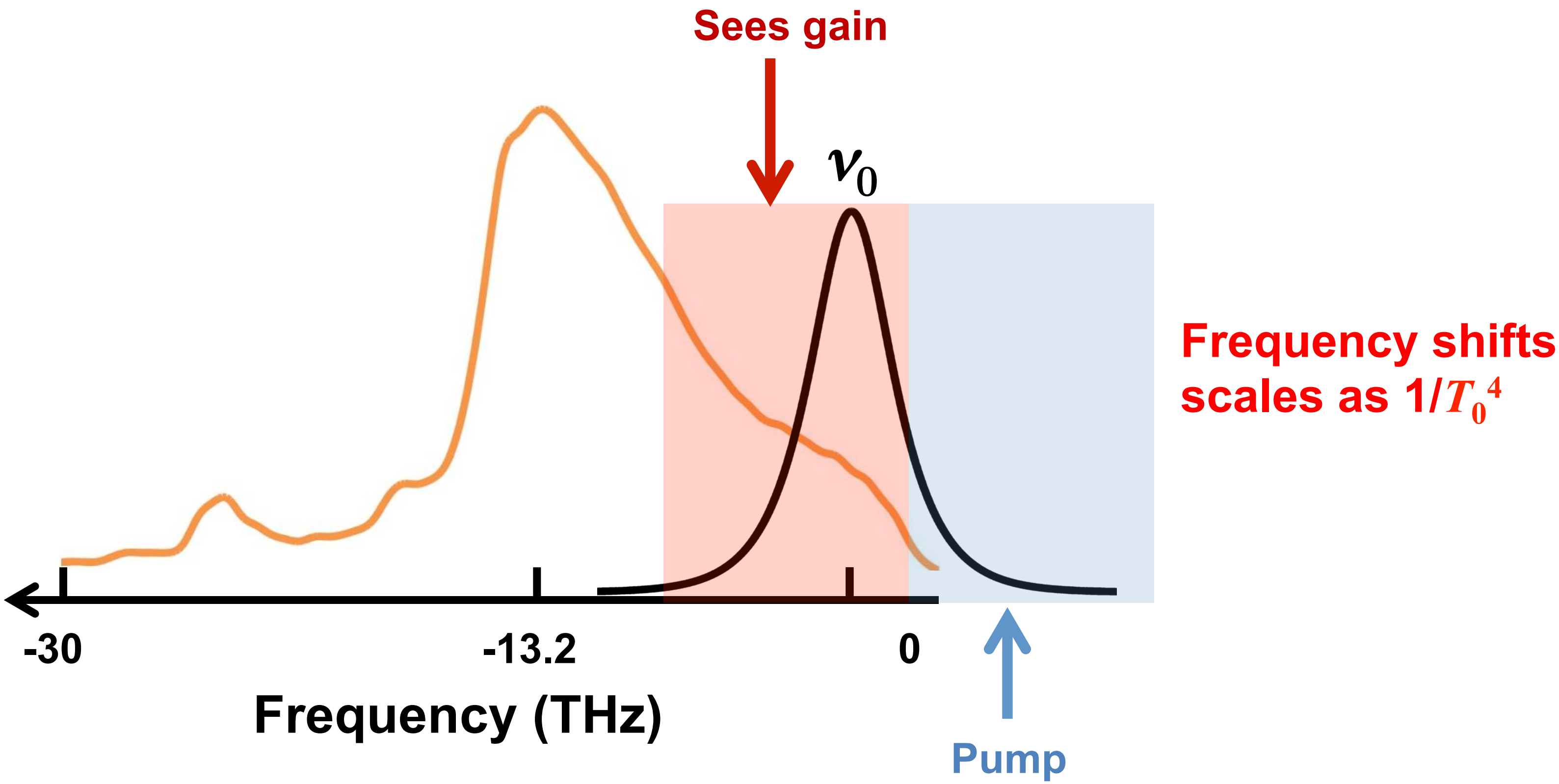
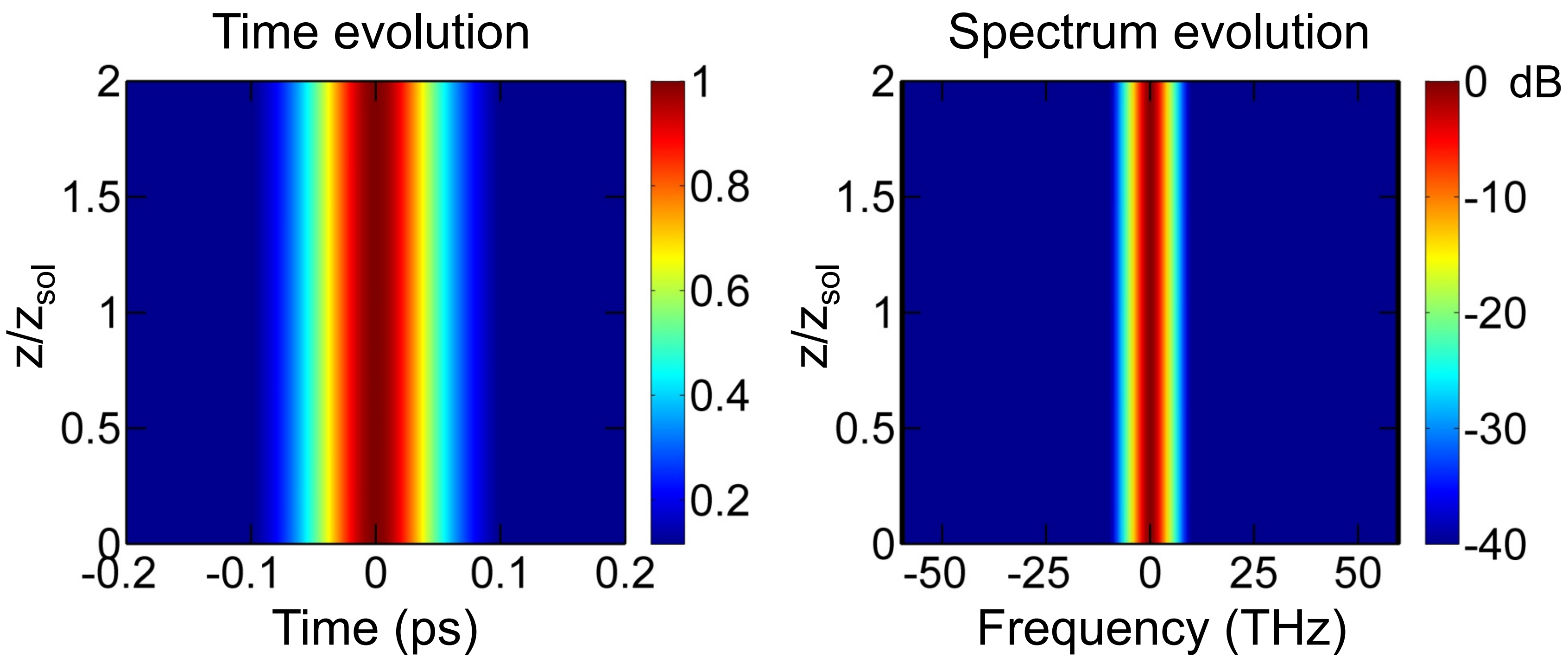


- Frequency of soliton shifts towards lower frequencies (longer wavelengths) with propagation = soliton SELF-frequency shift

N=1 soliton

- Fundamental solitons are propagation-invariant



Soliton self-frequency shift

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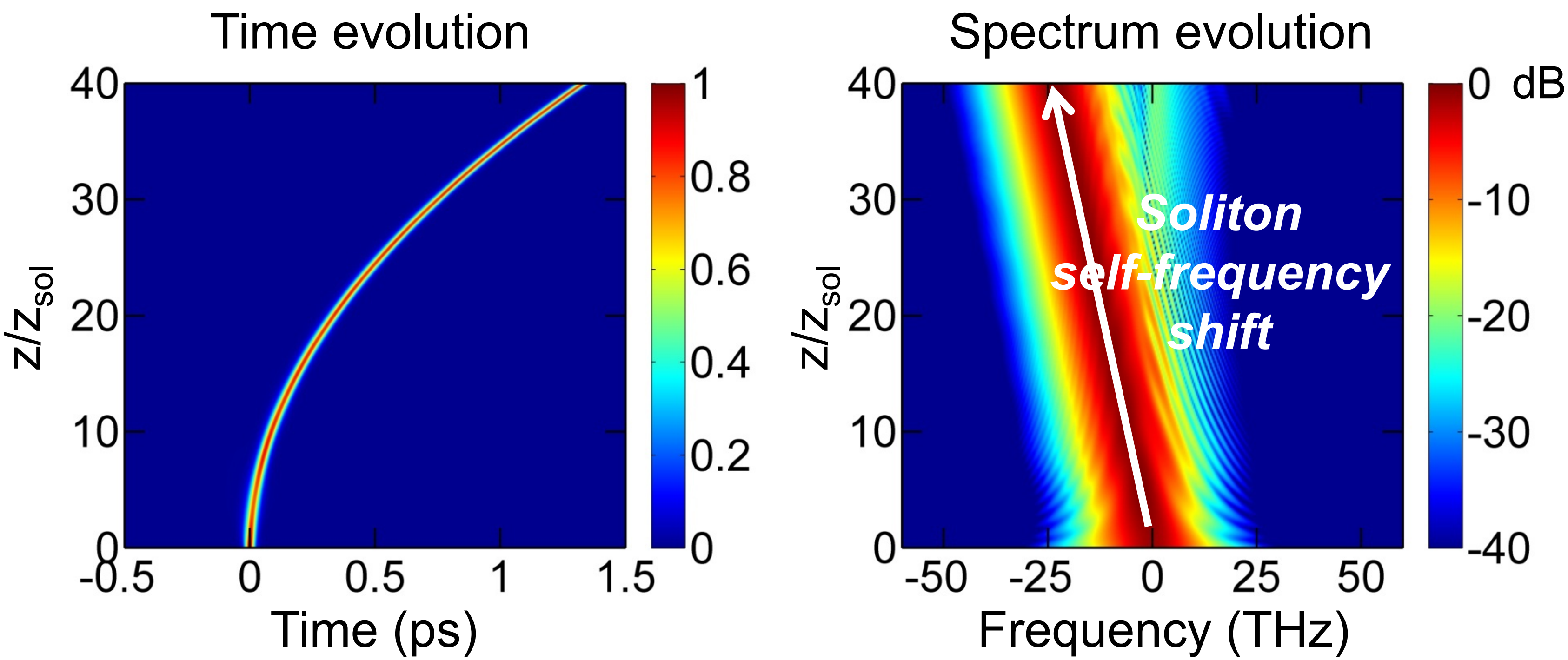
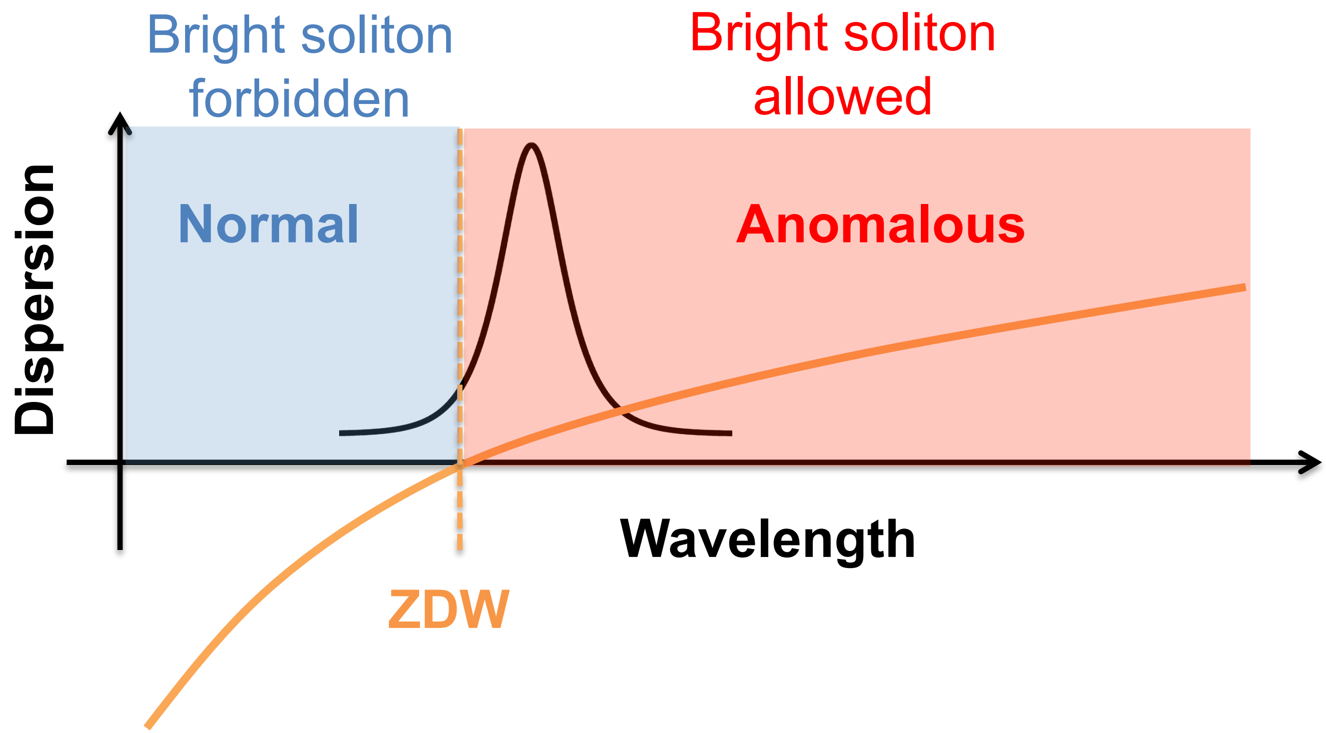


- Parabolic/linear trajectory in the time/frequency domain

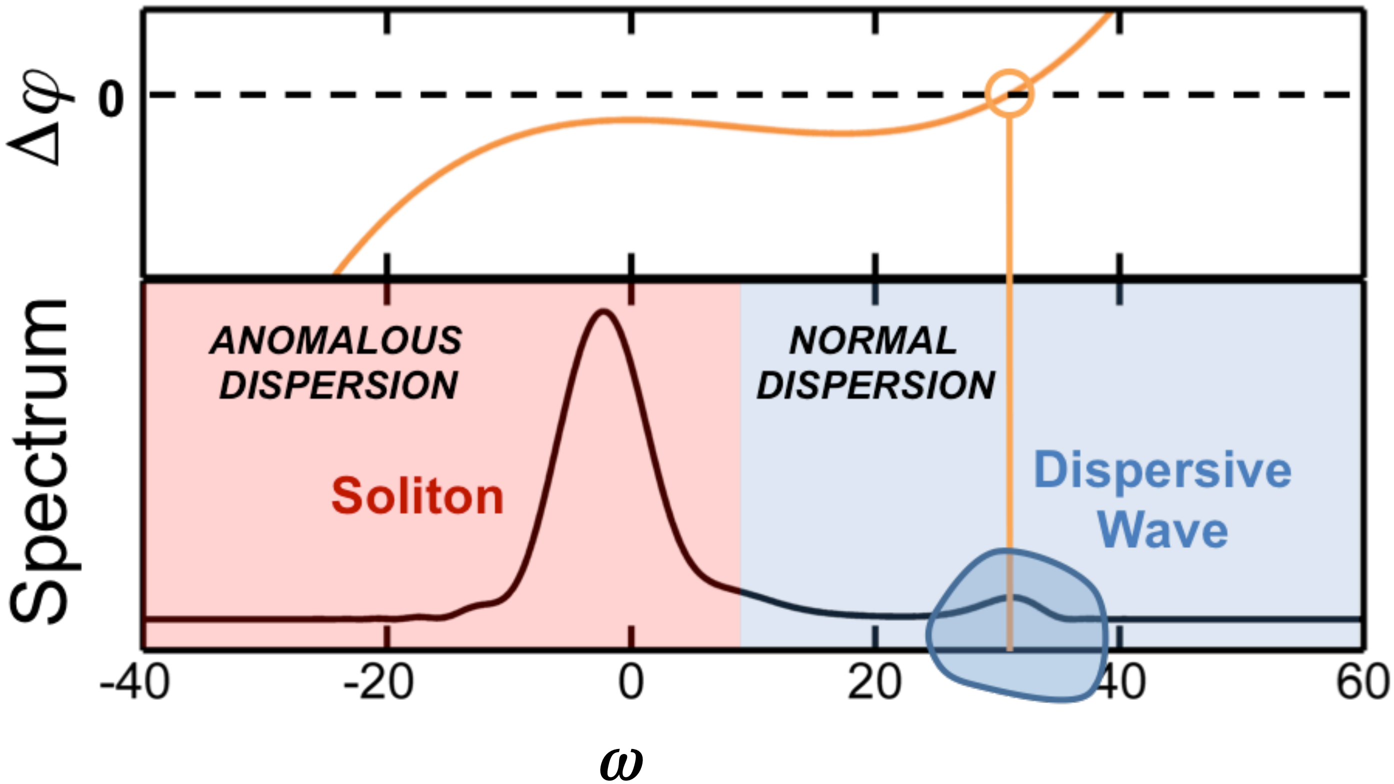
Higher-order dispersion perturbation



- Dispersion depends on wavelength/frequency
- Soliton near ZDW strongly perturbed: part of its spectrum extends in the normal dispersion regime!

Dispersive wave generation

- Dispersive wave located in the normal dispersion regime
  - phase-matching condition: $\phi_{soliton} = \phi_{disp.\ wave}$



Wai, Menyuk et al. OL 11, 464 (1986)

Akhmediev et al., Phys. Rev. A 51, 2602 (1995)

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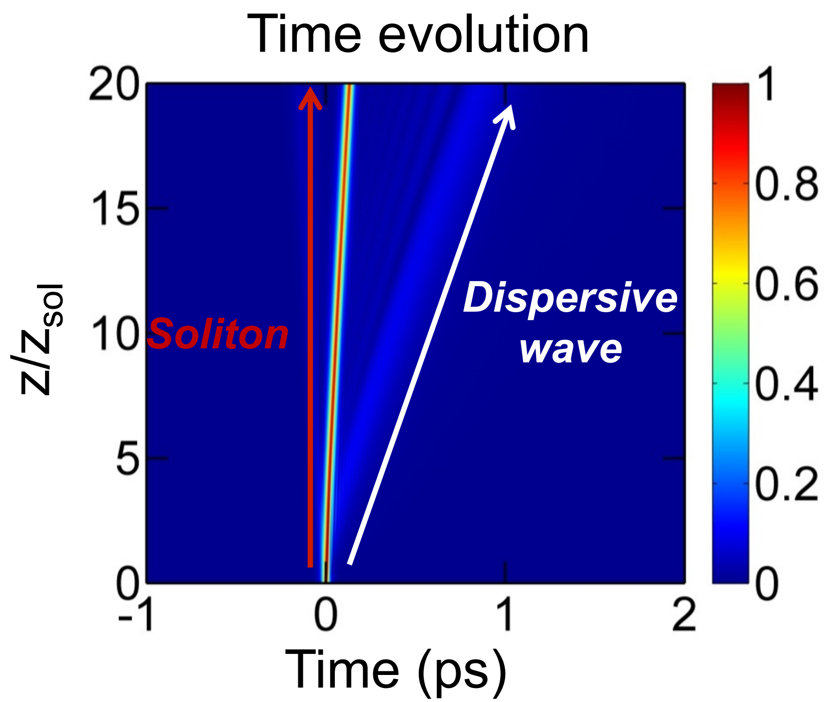

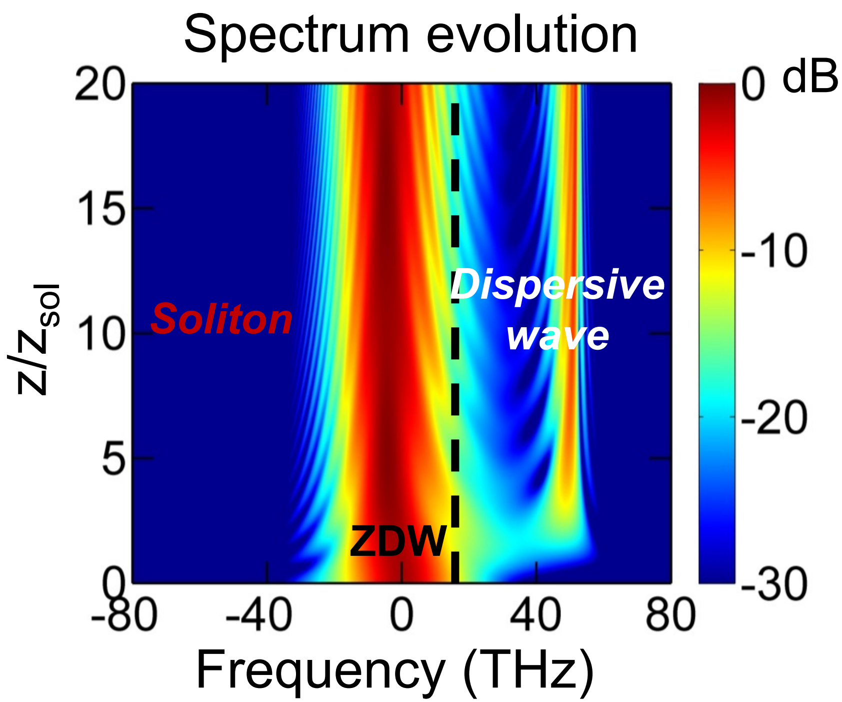

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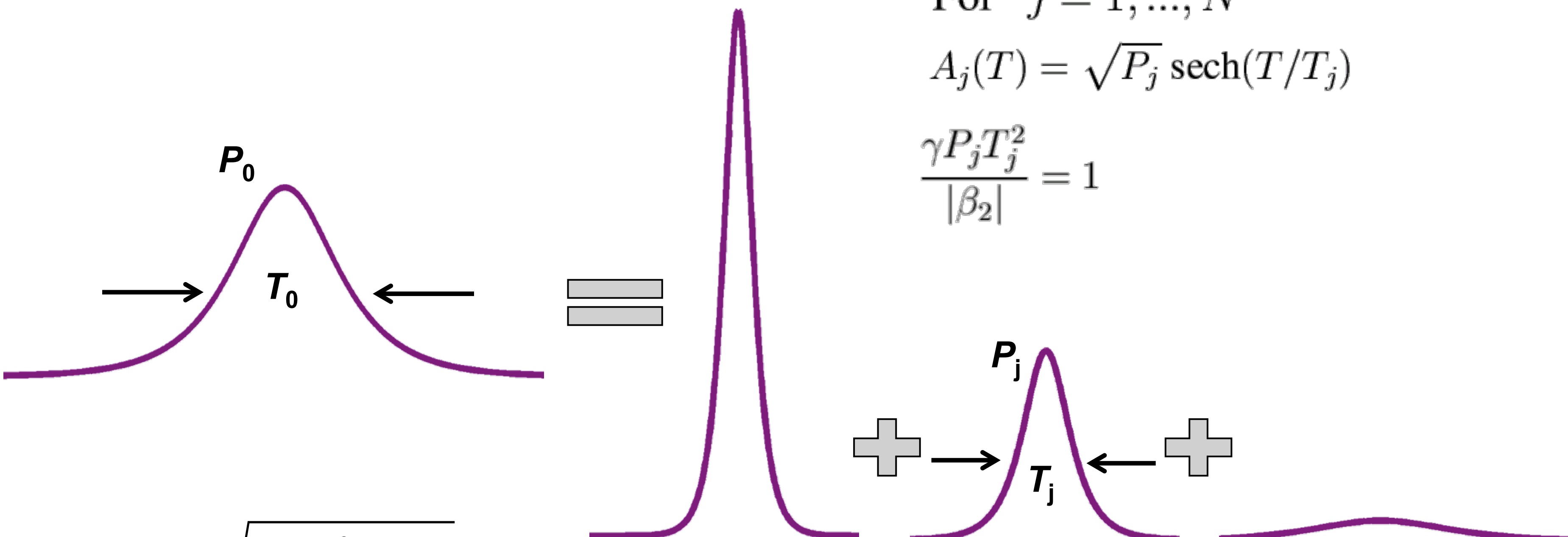

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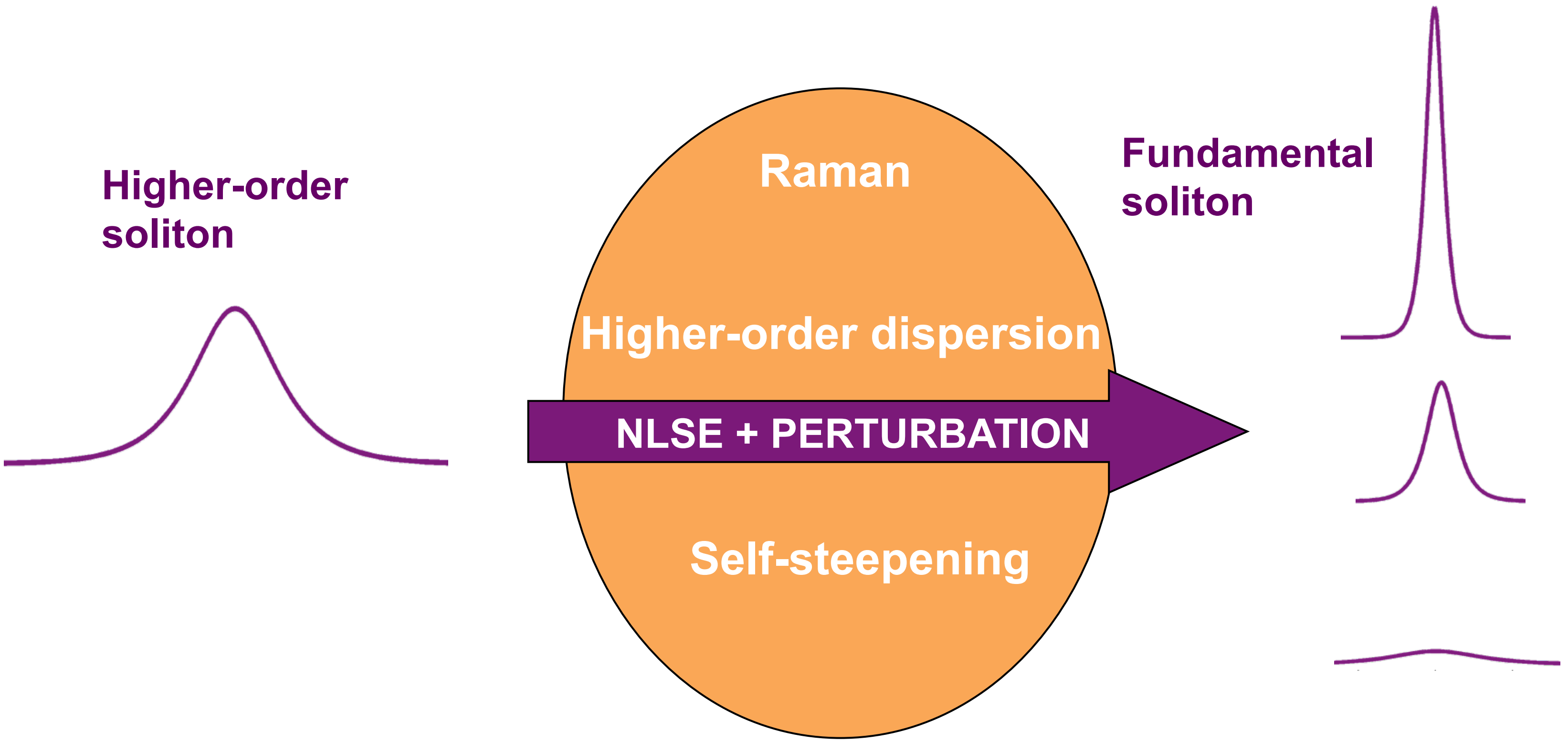
Soliton fission

- Higher-order *N*-soliton is unstable, sensitive to perturbations

➡ *N*-soliton breaks up into *N* fundamental solitons



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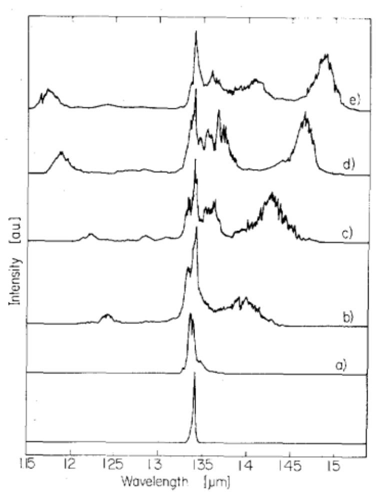
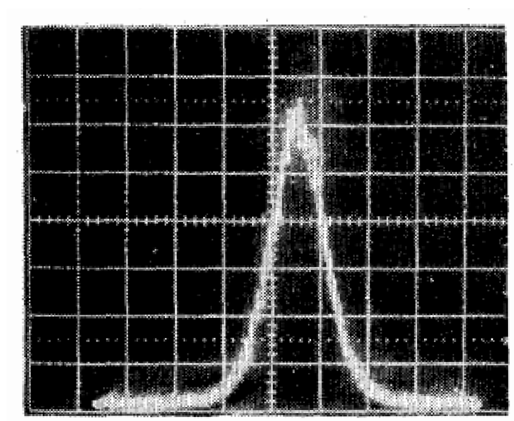
1938 IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-23, NO. 11, NOVEMBER 1987

Ultrashort Pulse Propagation, Pulse Breakup, and Fundamental Soliton Formation in a Single-Mode Optical Fiber

P. BEAUD, W. HODEL, B. ZYSSET, AND H. P. WEBER, SENIOR MEMBER, IEEE





Raman perturbation of *N*-Soliton

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Fission of optical solitons induced by stimulated Raman effect

Kuochou Tai and Akira Hasegawa

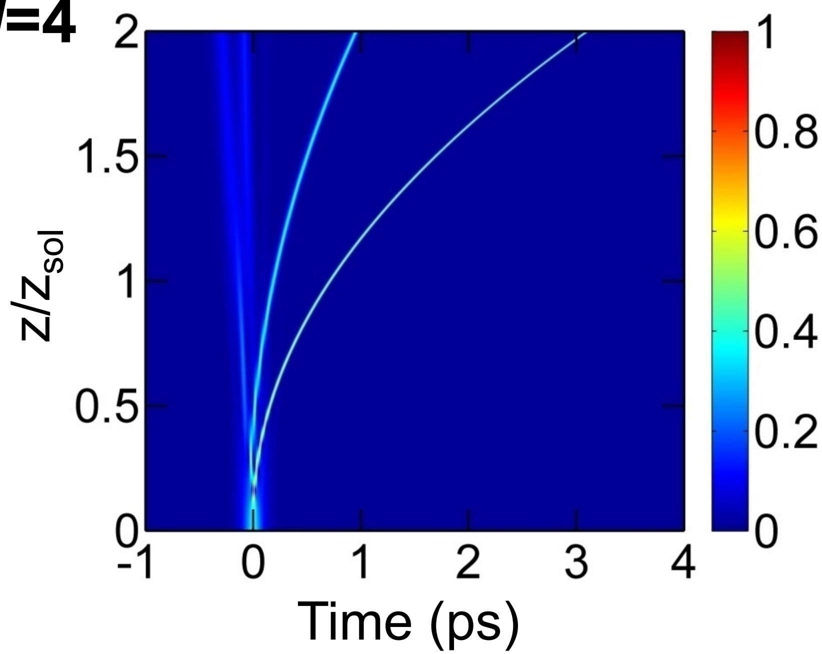
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

Naoaki Bekki

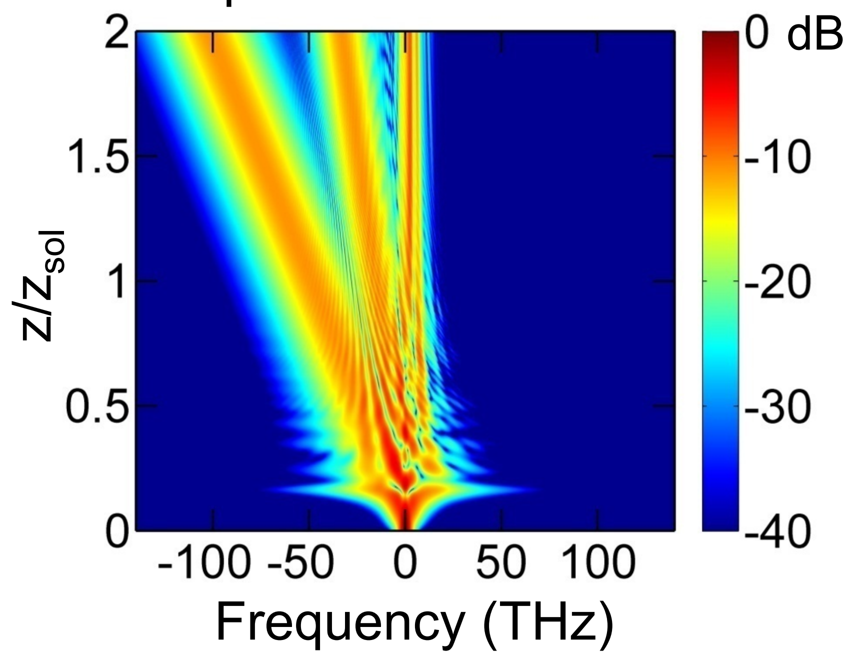
Institute for Fusion Studies, University of Texas, Austin, Texas 78712

***N*=4**

Time evolution



Spectrum evolution



Fission of *N*-soliton

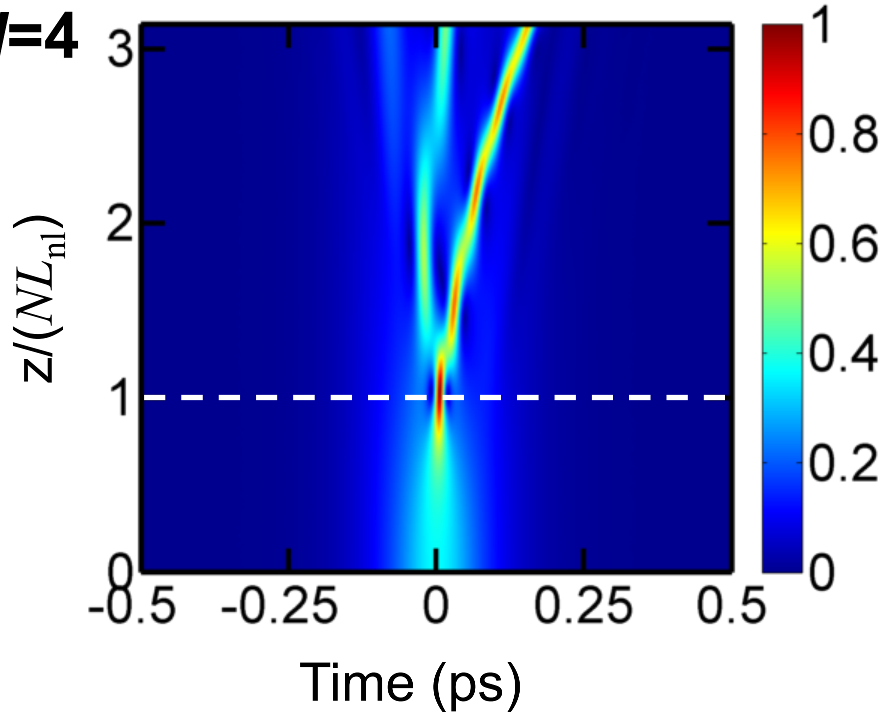
- Fission length: $L_{fiss} \approx L_d/N = N\, L_{nl}$

Raman perturbation

Higher-order dispersion perturbation

***N*=4**

Time evolution



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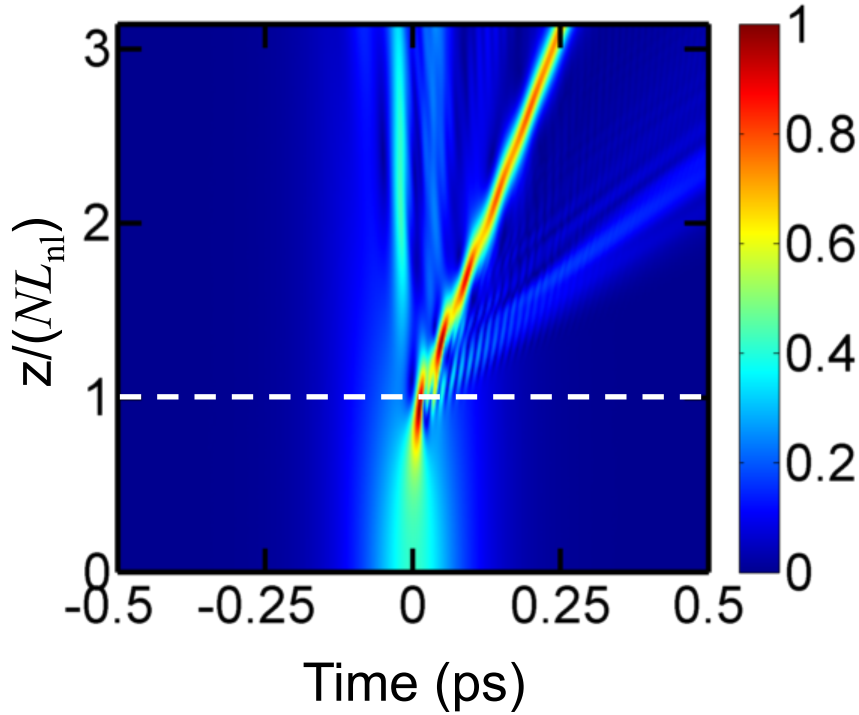
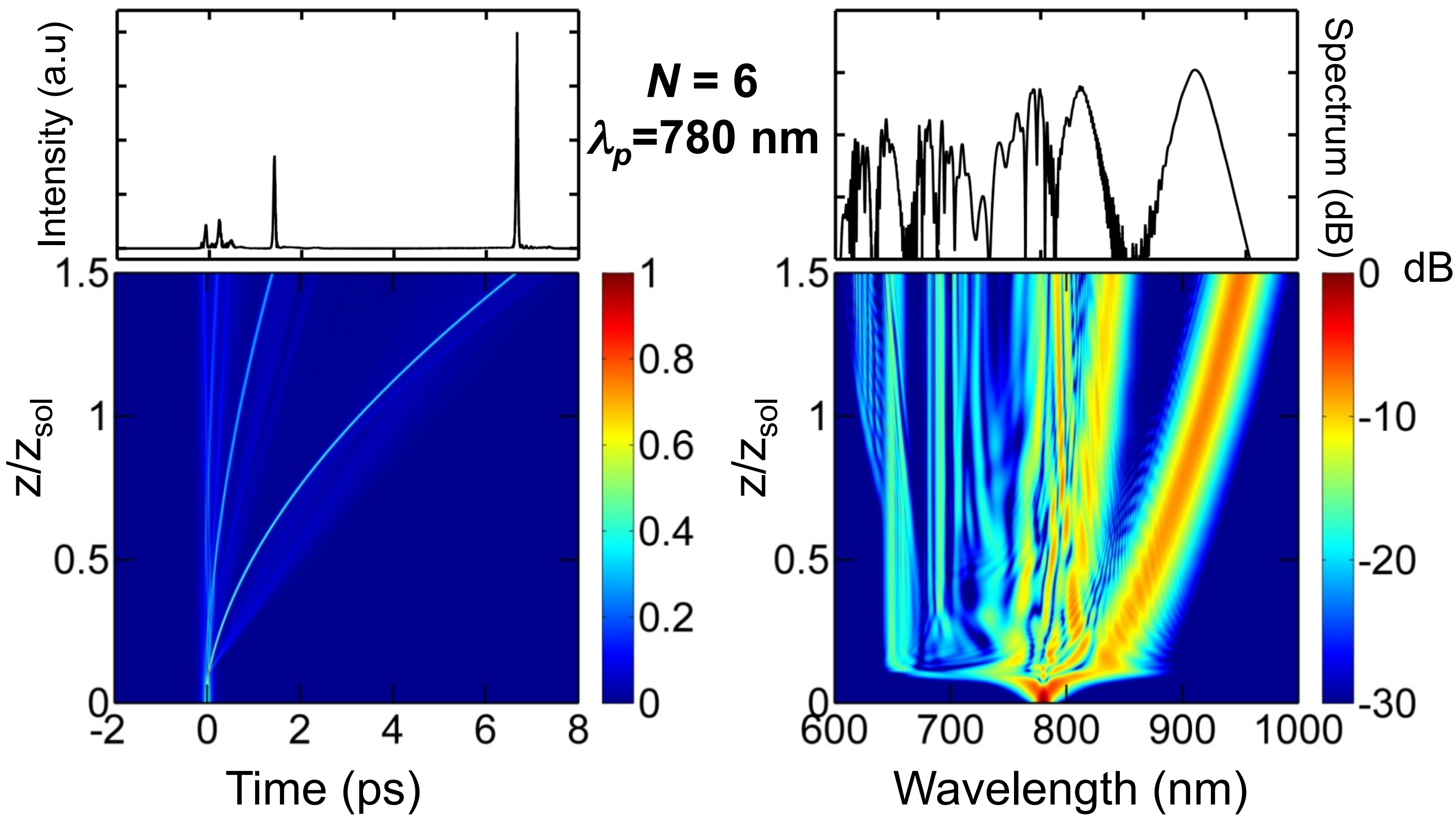


Let's put everything together

- Soliton fission + dispersive wave radiation + soliton self-frequency shift = supercontinuum generation



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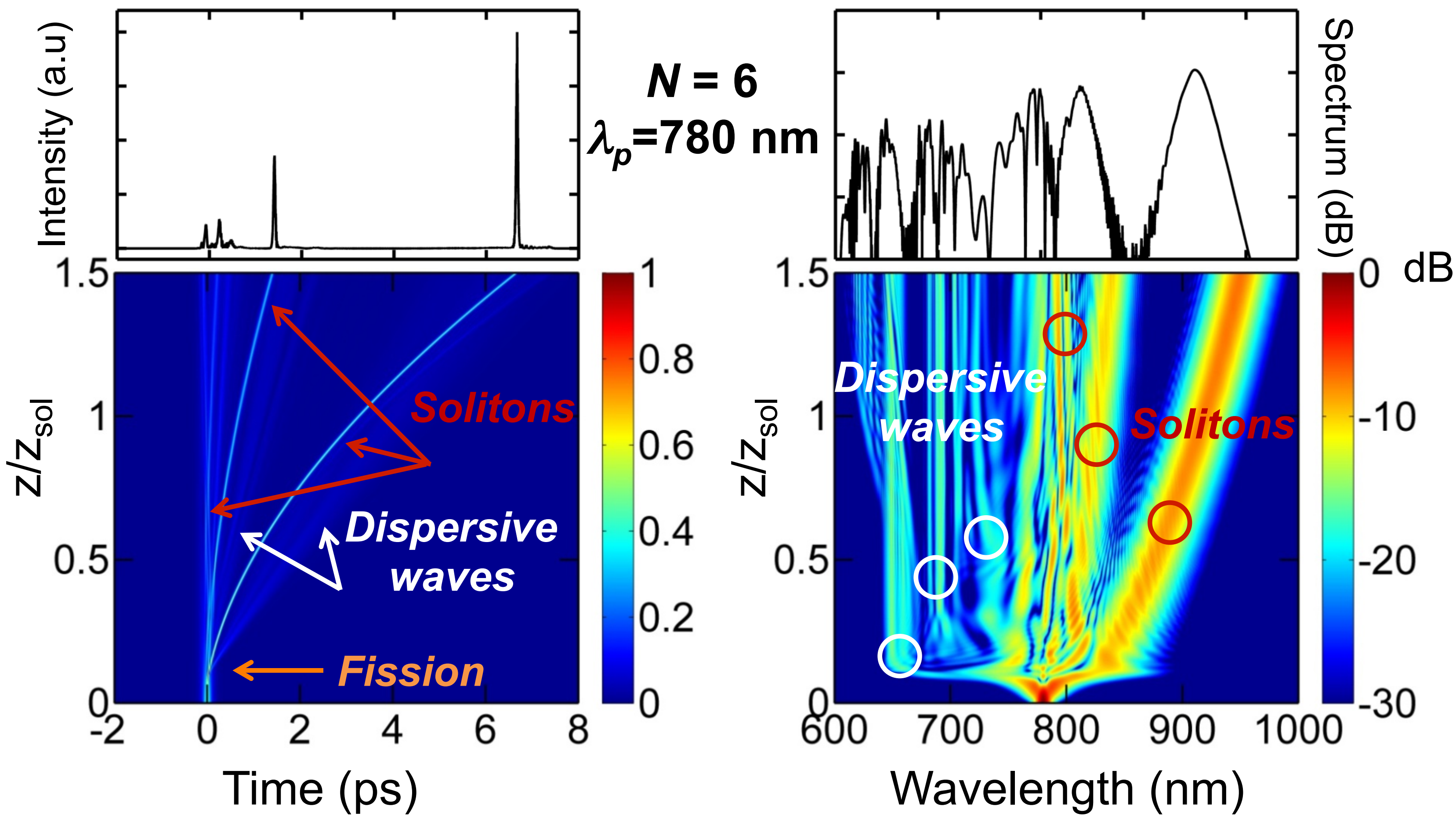
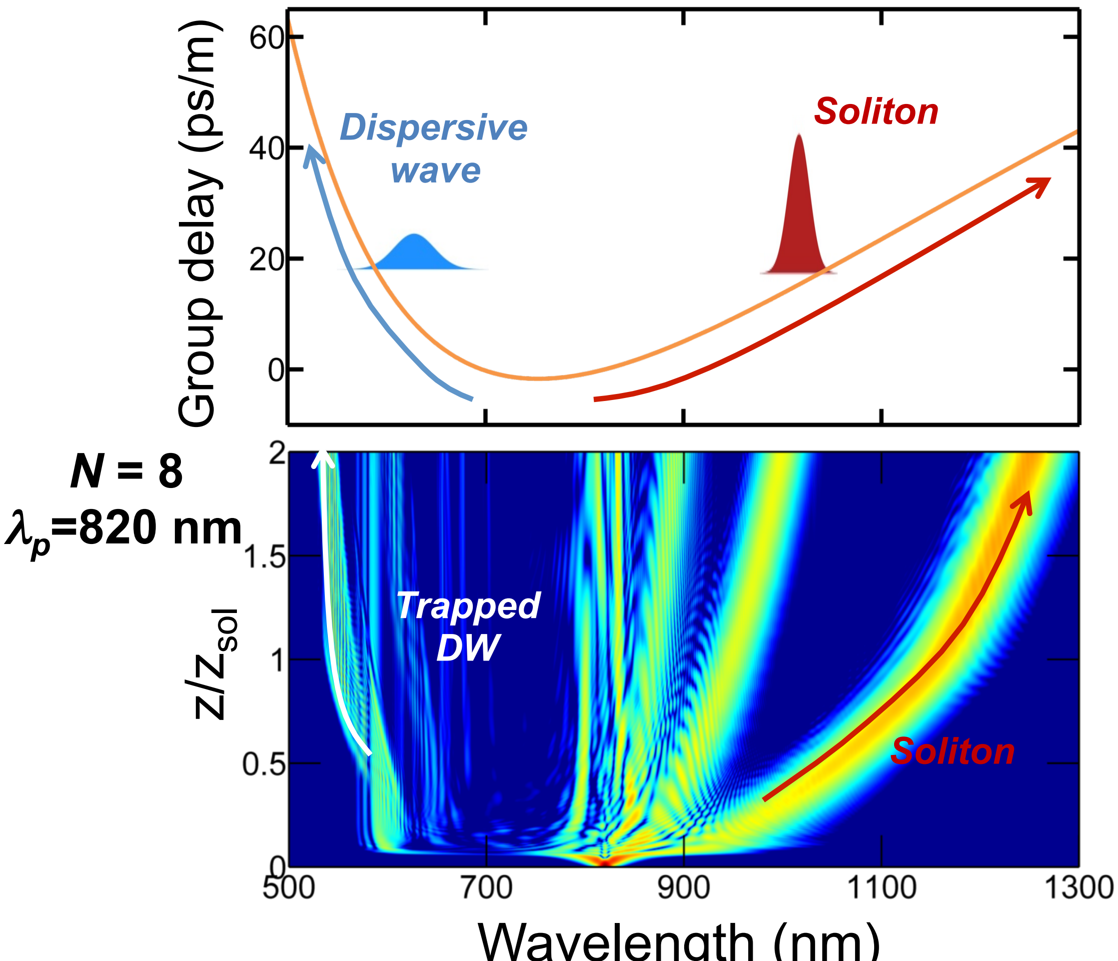
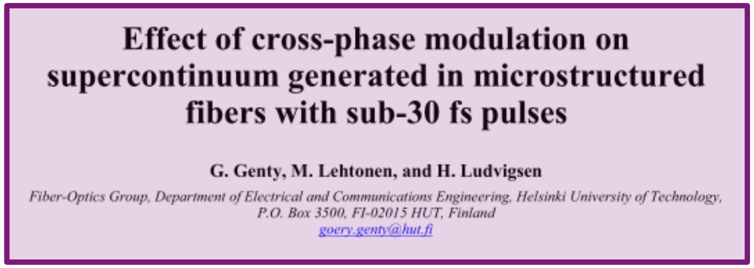


Dispersive wave trapping

- Continuously redshifting soliton induces a continuous blueshift of the dispersive wave



Soliton acts as a nonlinear potential barrier for the weaker dispersive wave



Effect of cross-phase modulation on supercontinuum generated in microstructured fibers with sub-30 fs pulses

G. Genty, M. Lehtonen, and H. Ludvigsen

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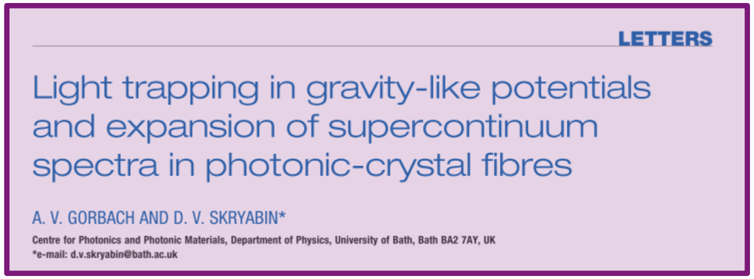
goery.genty@hut.fi



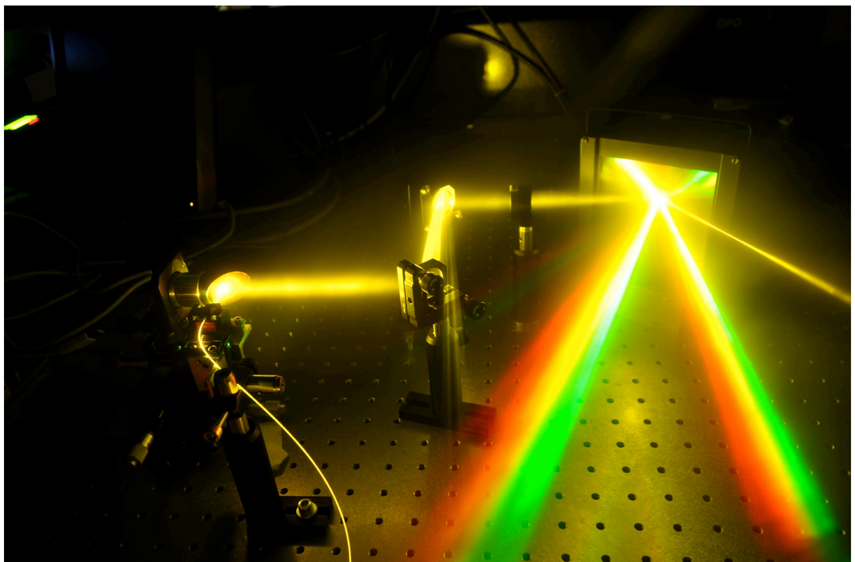
LETTERS

Light trapping in gravity-like potentials and expansion of supercontinuum spectra in photonic-crystal fibres

A. V. GORBACH AND D. V. SKRYABIN*

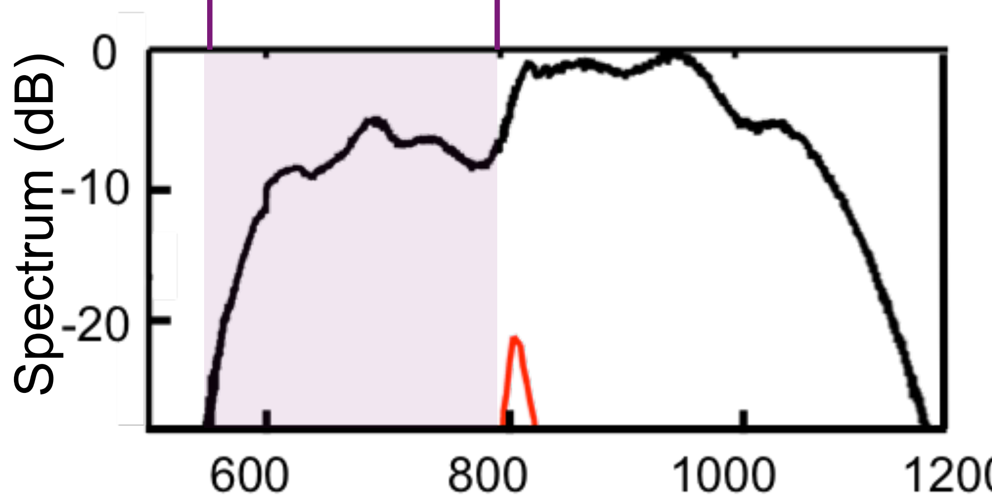
Centre for Photonics and Photonic Materials, Department of Physics, University of Bath, Bath BA2 7AY, UK
*e-mail: d.v.skryabin@bath.ac.uk

Dispersive waves corresponds to visible light

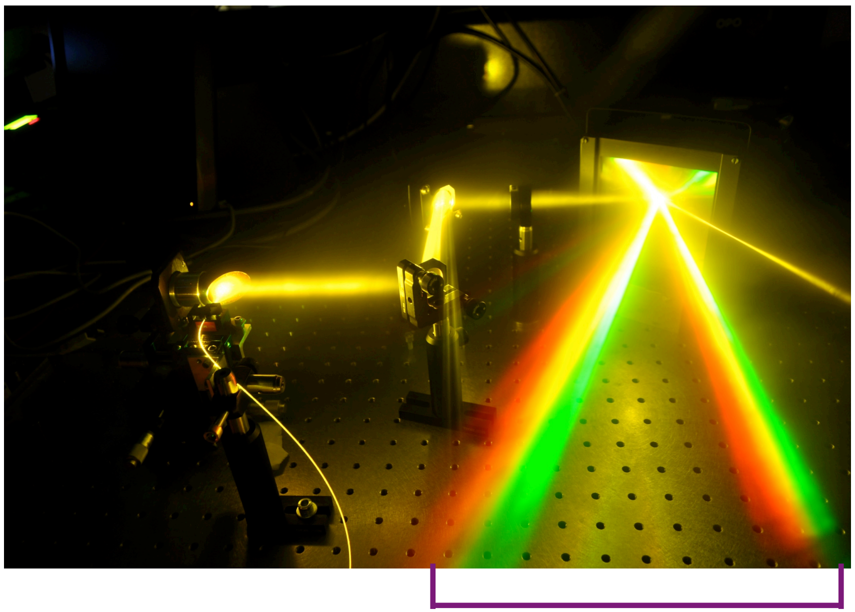


Dispersive waves

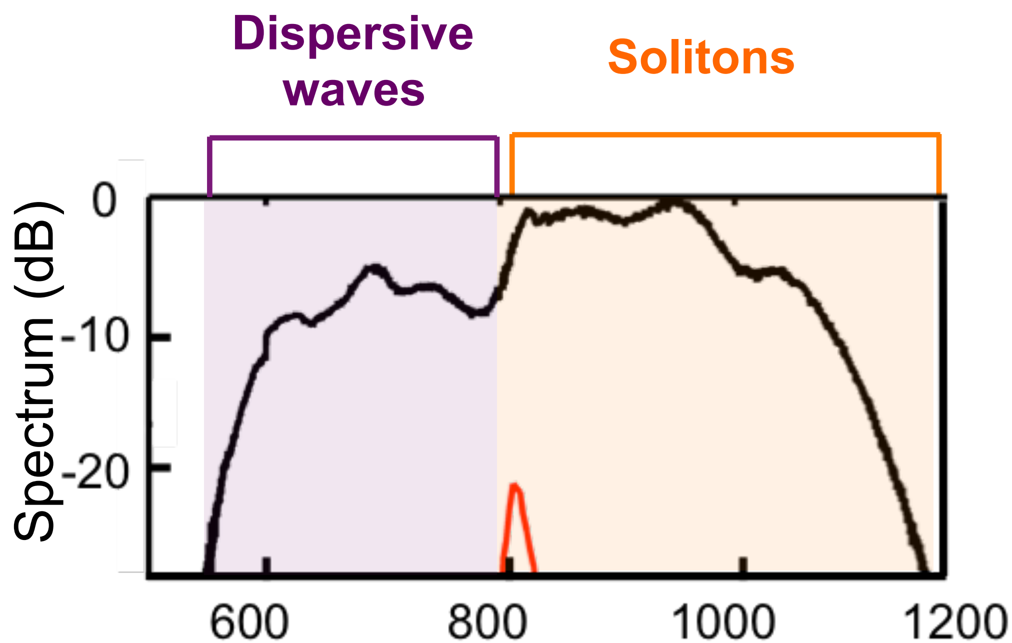
Dispersive waves



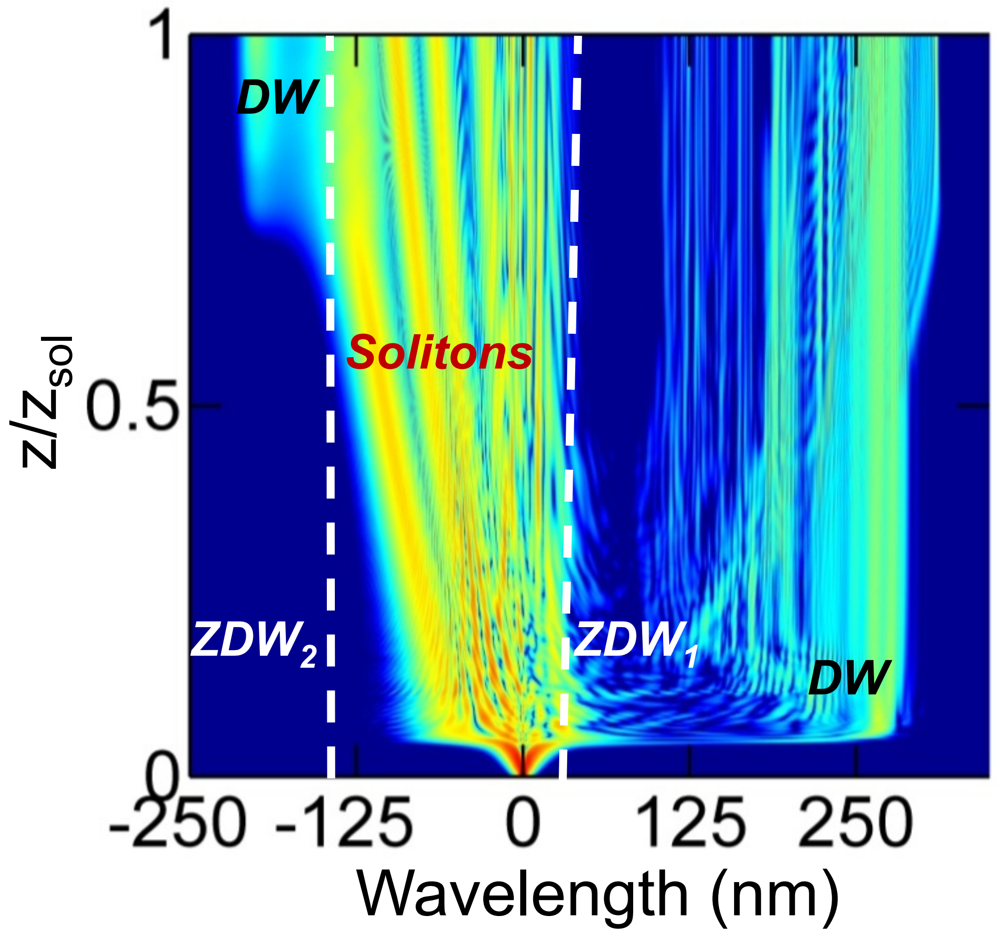
And solitons to infrared light

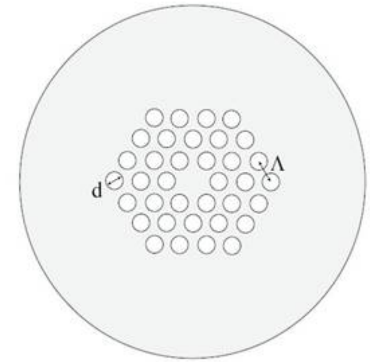


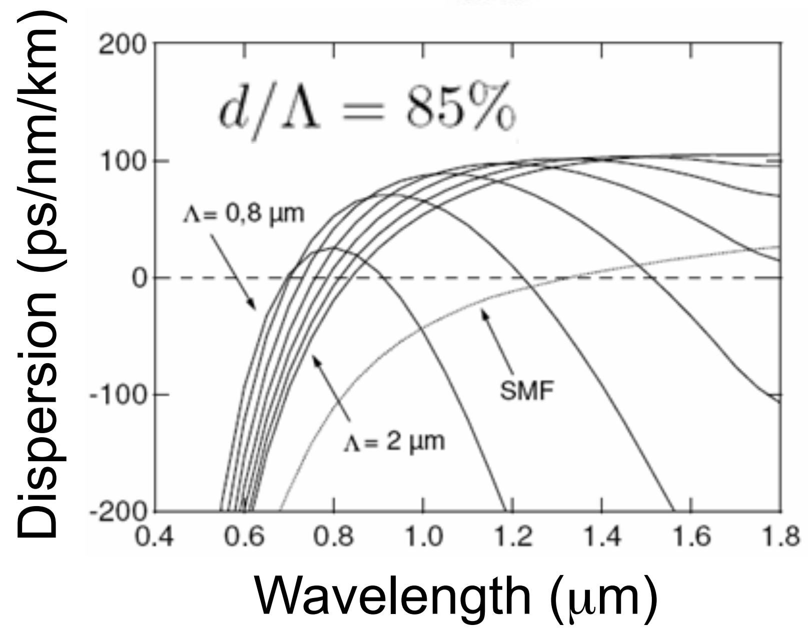
Dispersive waves



Fiber with two zero-dispersion wavelengths



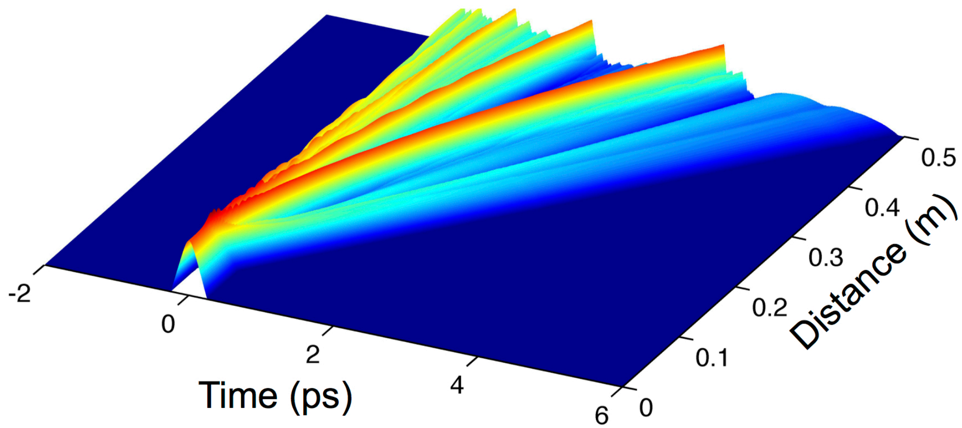




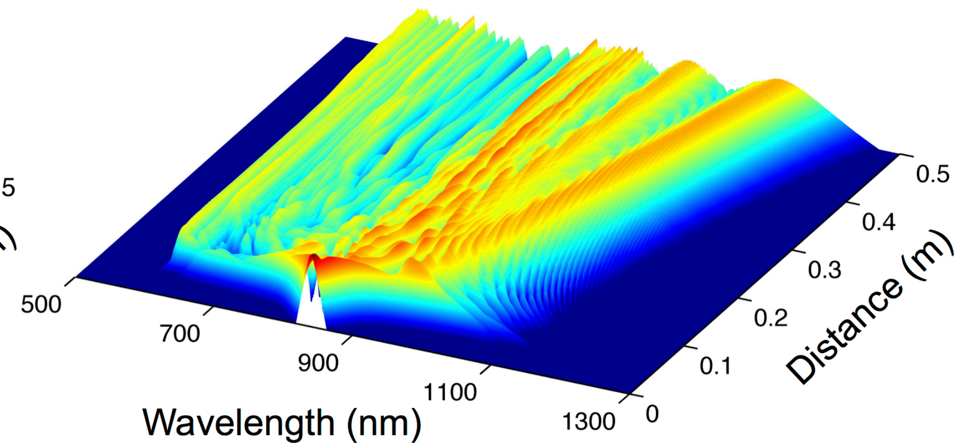
G. Genty *et al*. Opt. Express **12**, 3471-3480 (2004)

Dynamics are rather complex…

Time evolution



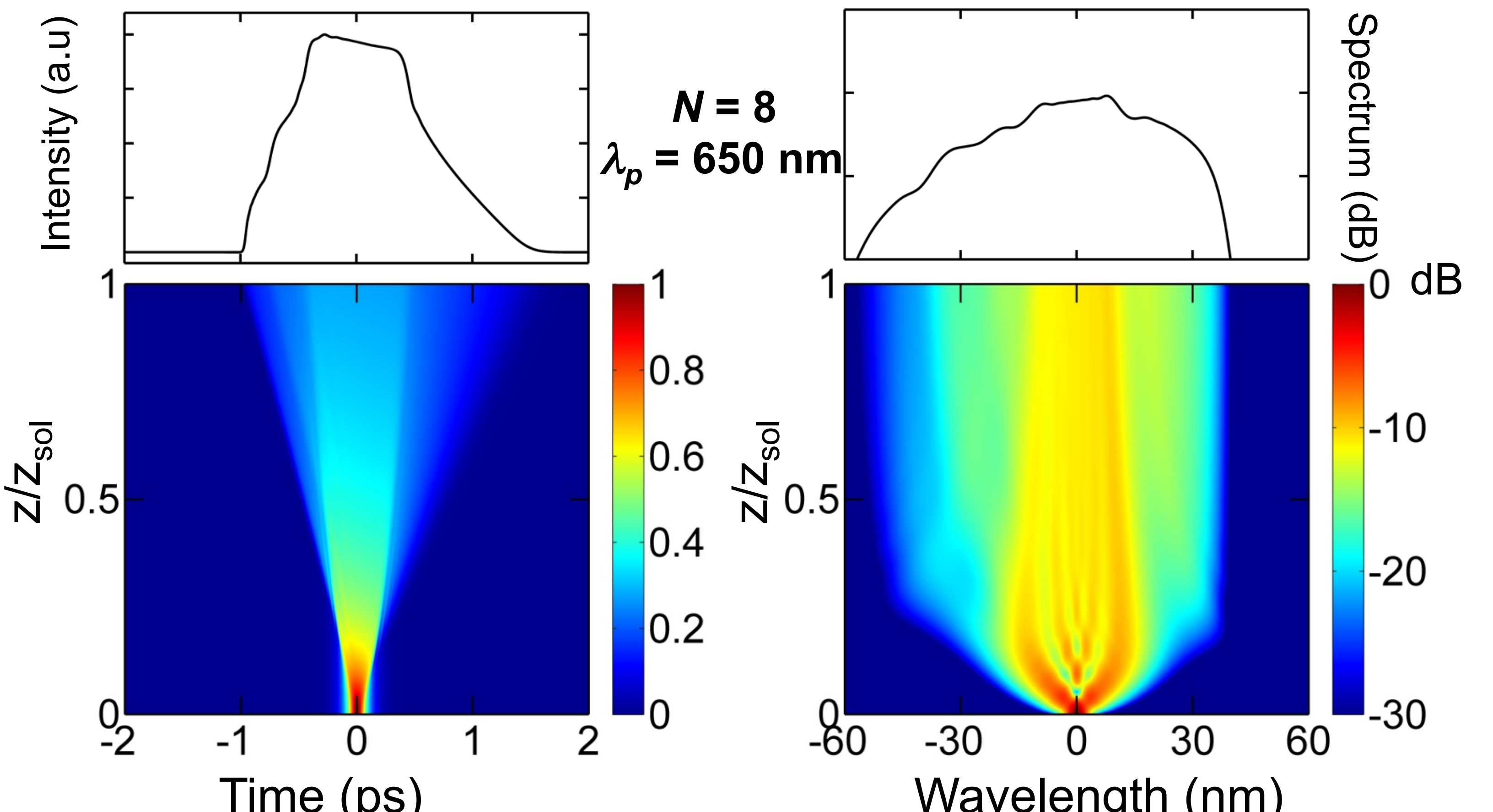
Spectral evolution



	Short pulses	Long pulses
Anomalous	• Soliton • Dispersive waves	• Modulation instability • Solitons dynamics
Normal	• Self-phase modulation • Four-wave mixing	• Raman scattering • Four-wave mixing

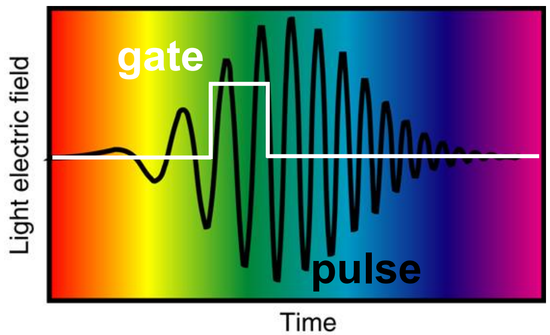
Short pulses and normal dispersion regime

- No bright solitons in normal dispersion regime: different dynamics
- Self-phase modulation, four-wave mixing



Time-frequency analysis

- Ultrafast dynamics can be conveniently visualized in the time-frequency domain

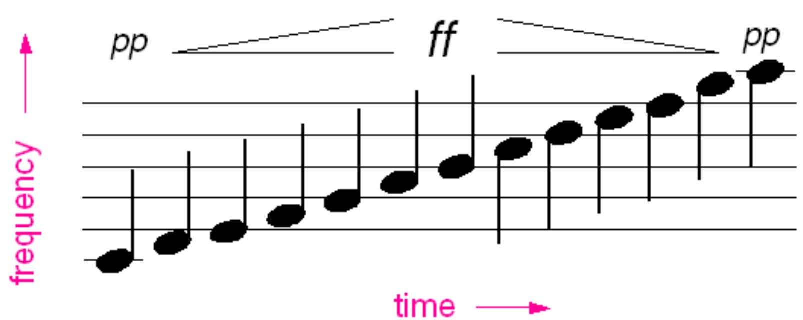


Courtesy of R. Trebino

Spectrogram / short-time Fourier Transform

$$\Sigma_g^E(\omega,\tau) = \left| \int_{-\infty}^{\infty} E(t) g(t-\tau) \exp(i\omega t) dt \right|^2$$

Field to be measured   *Gate*



Foing, Likforman, Joffre, Migus IEEE J Quant. Electron 28 , 2285 (1992) ; Linden, Giessen, Kuhl Phys Stat. Sol. B 206, 119 (1998)

Time-frequency analysis

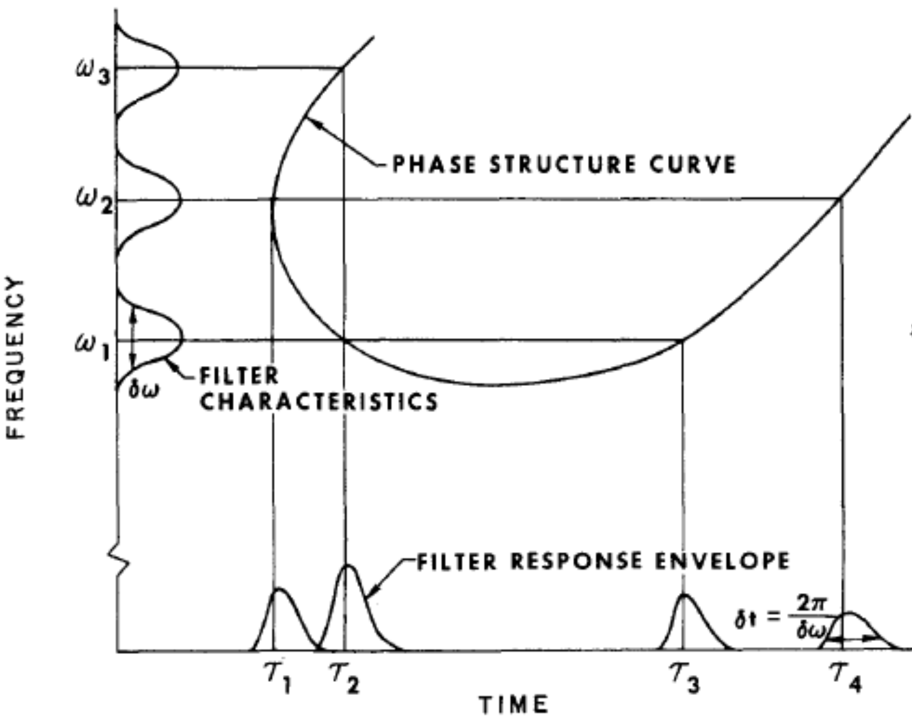
JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 10 SEPTEMBER 1971

Measurement and Interpretation of Dynamic Spectrograms of Picosecond Light Pulses*

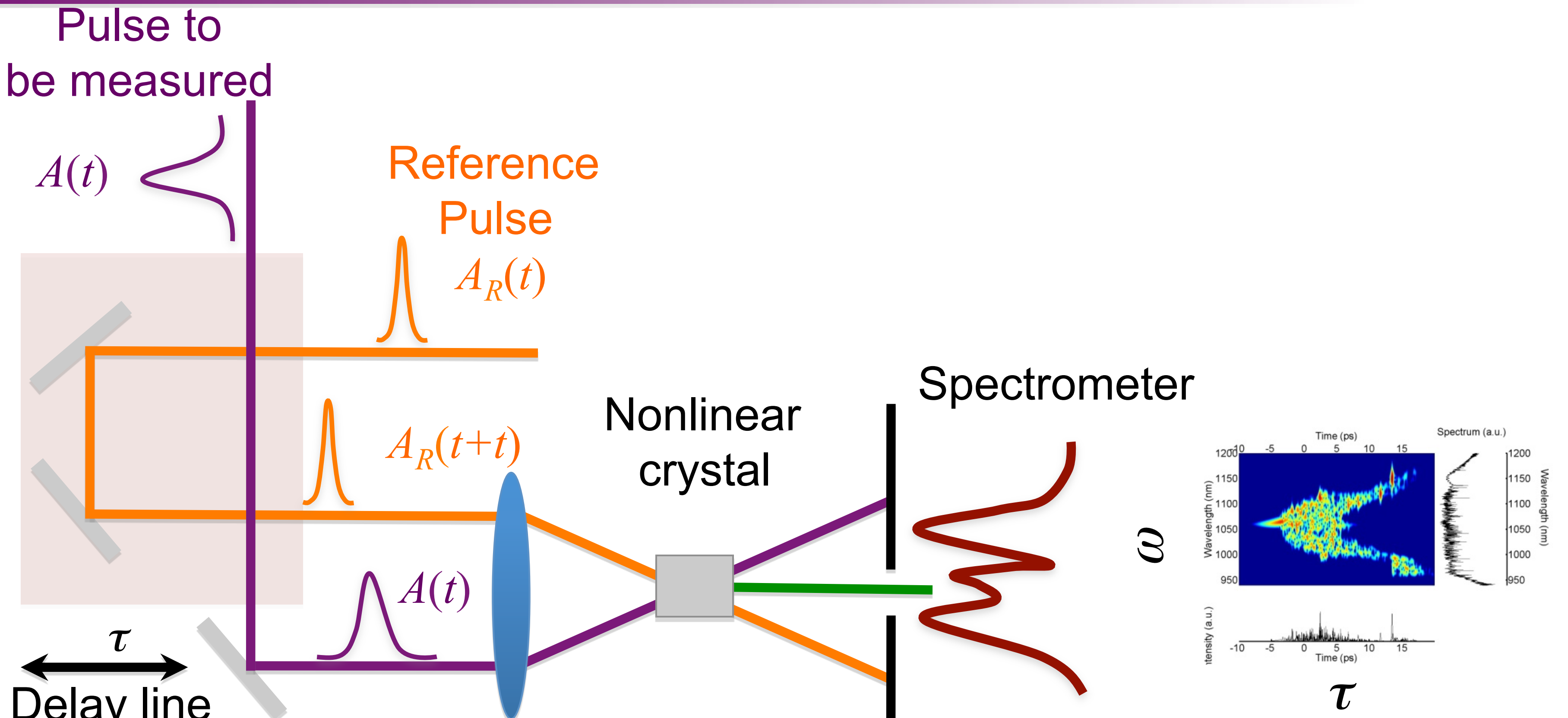
E.B. Treacy

United Aircraft Research Laboratories, East Hartford, Connecticut 06108

(Received 25 November 1970)



Experimental implementation



$$I(\omega,\tau) \propto \int_{-\infty}^{+\infty} E(t)E_R(t+\tau)e^{j\omega t}dt$$

$$E(t,\tau) \propto E(t)E_R(t+\tau)$$

Cross-correlation Frequency Resolved Optical Gating

Short ref. pulse → $A(\omega,\tau)$

One more thing

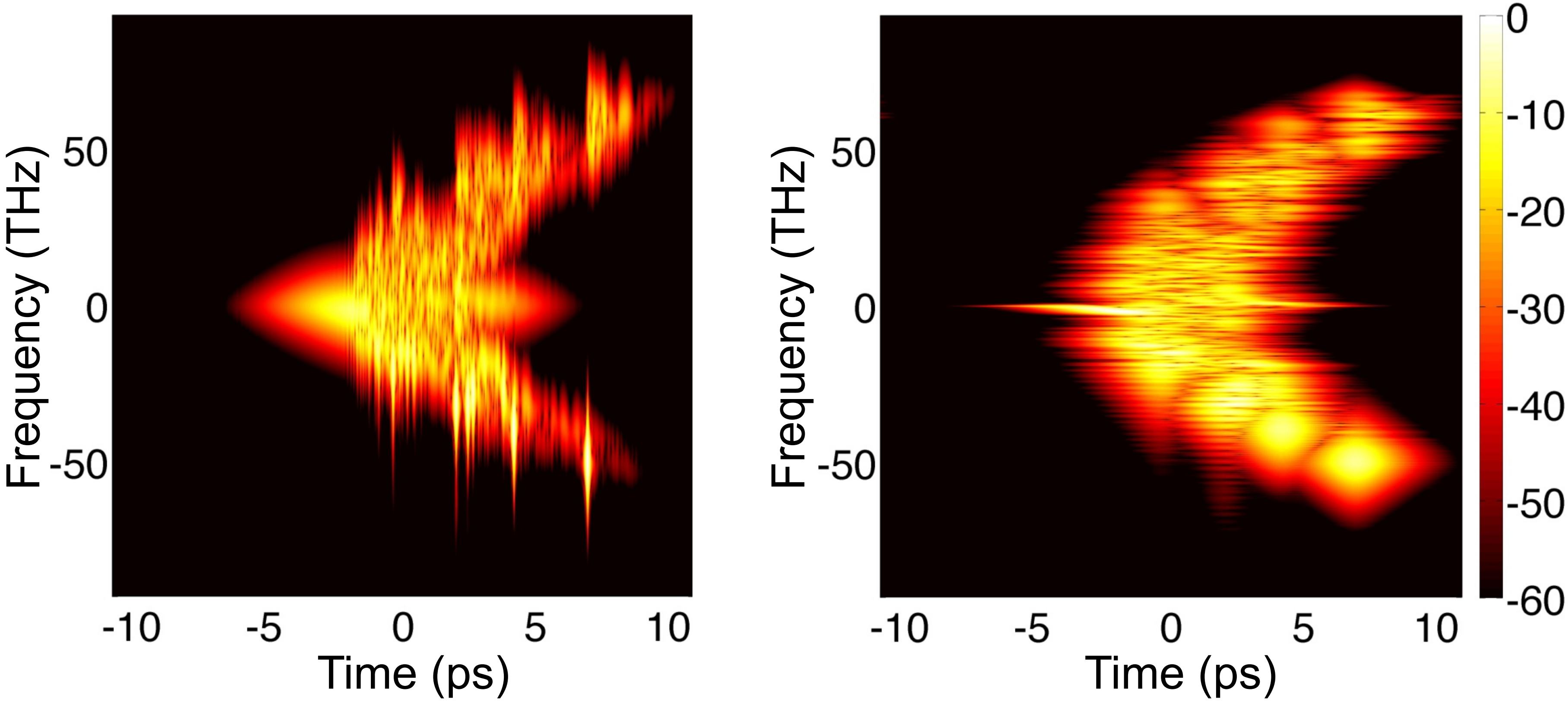
THEORY OF COMMUNICATION*

By D. GABOR, Dr. Ing., Associate Member.†

(The paper was first received 25th November, 1944, and in revised form 24th September, 1945.)

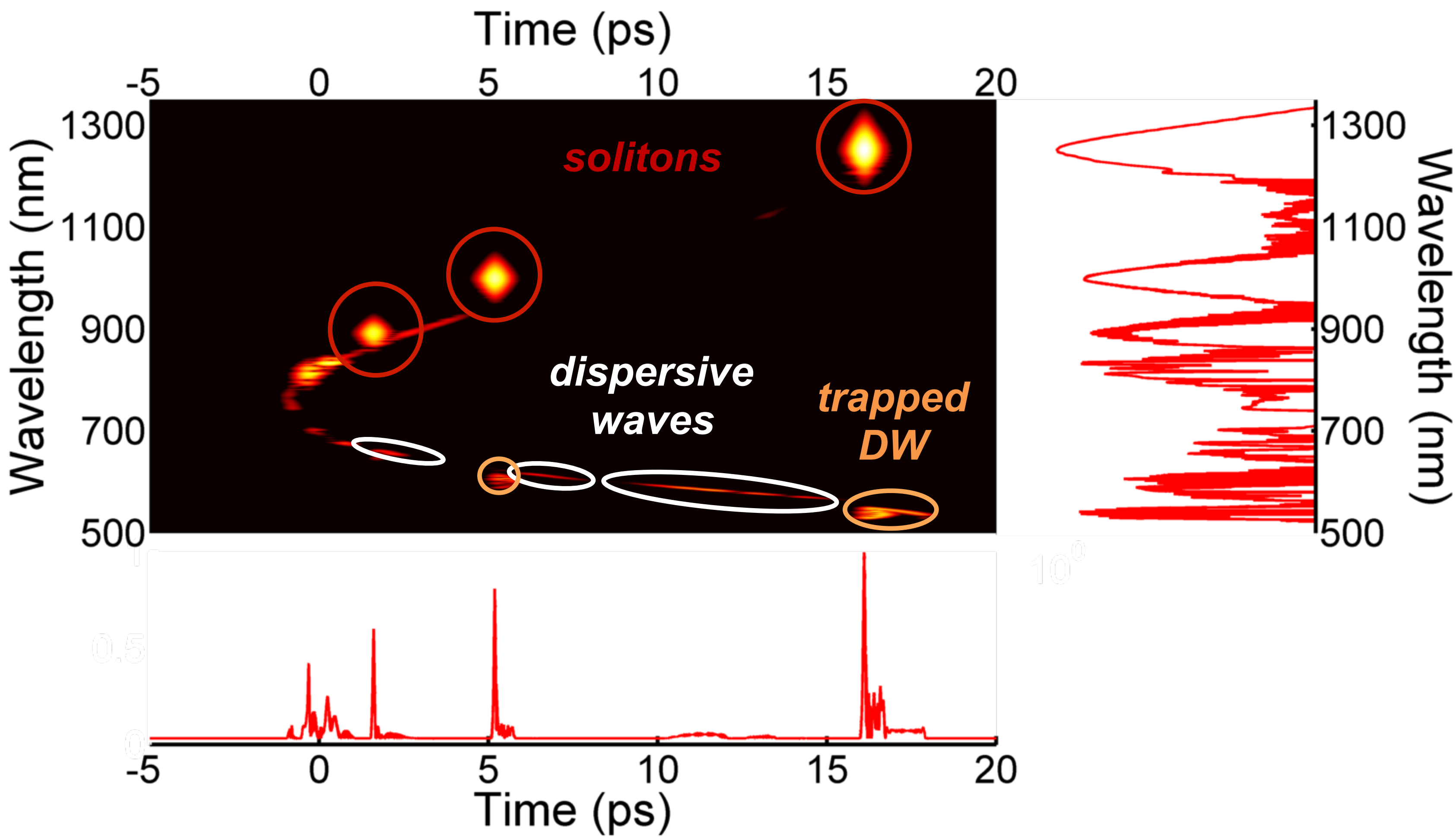
Reference pulse duration determines the resolution!

$$\boxed{\Delta t \Delta f \geq 1/2}$$



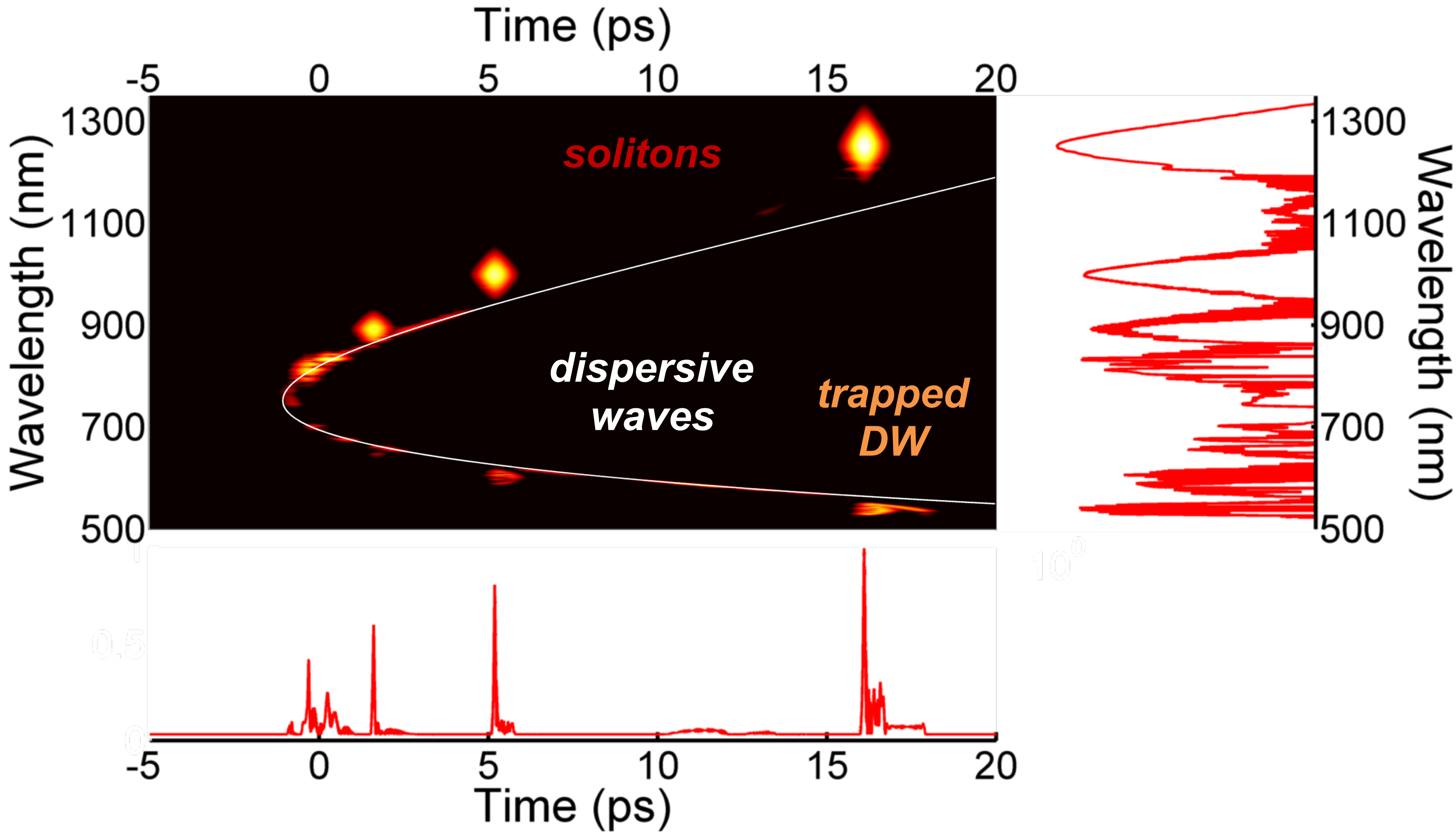
Spectrogram of supercontinuum

- Time-spectrum representation allows to conveniently identify dynamics



Spectrogram of supercontinuum

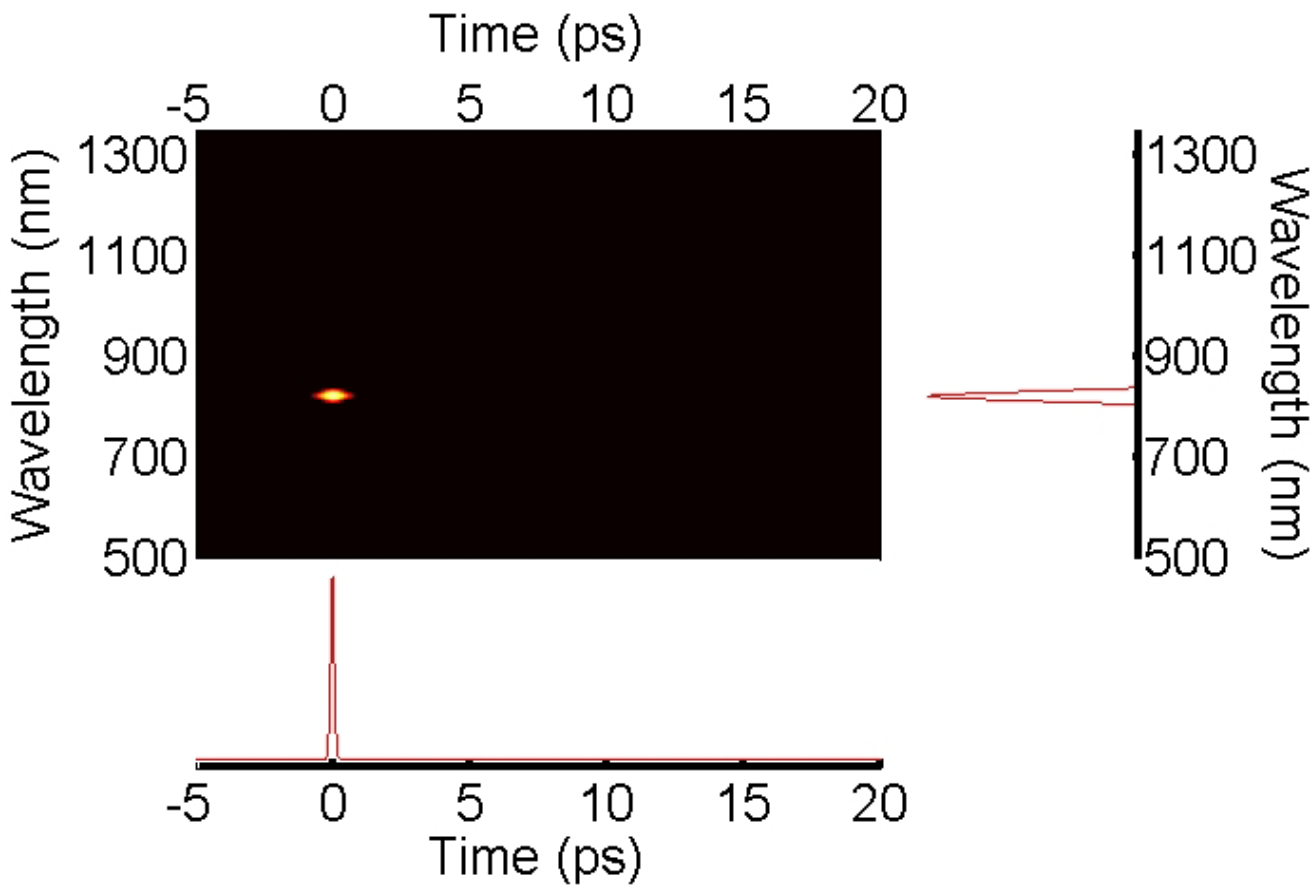
- Time-spectrum representation allows to conveniently identify dynamics



Visualizing dynamics

- Even better: spectrogram movies….

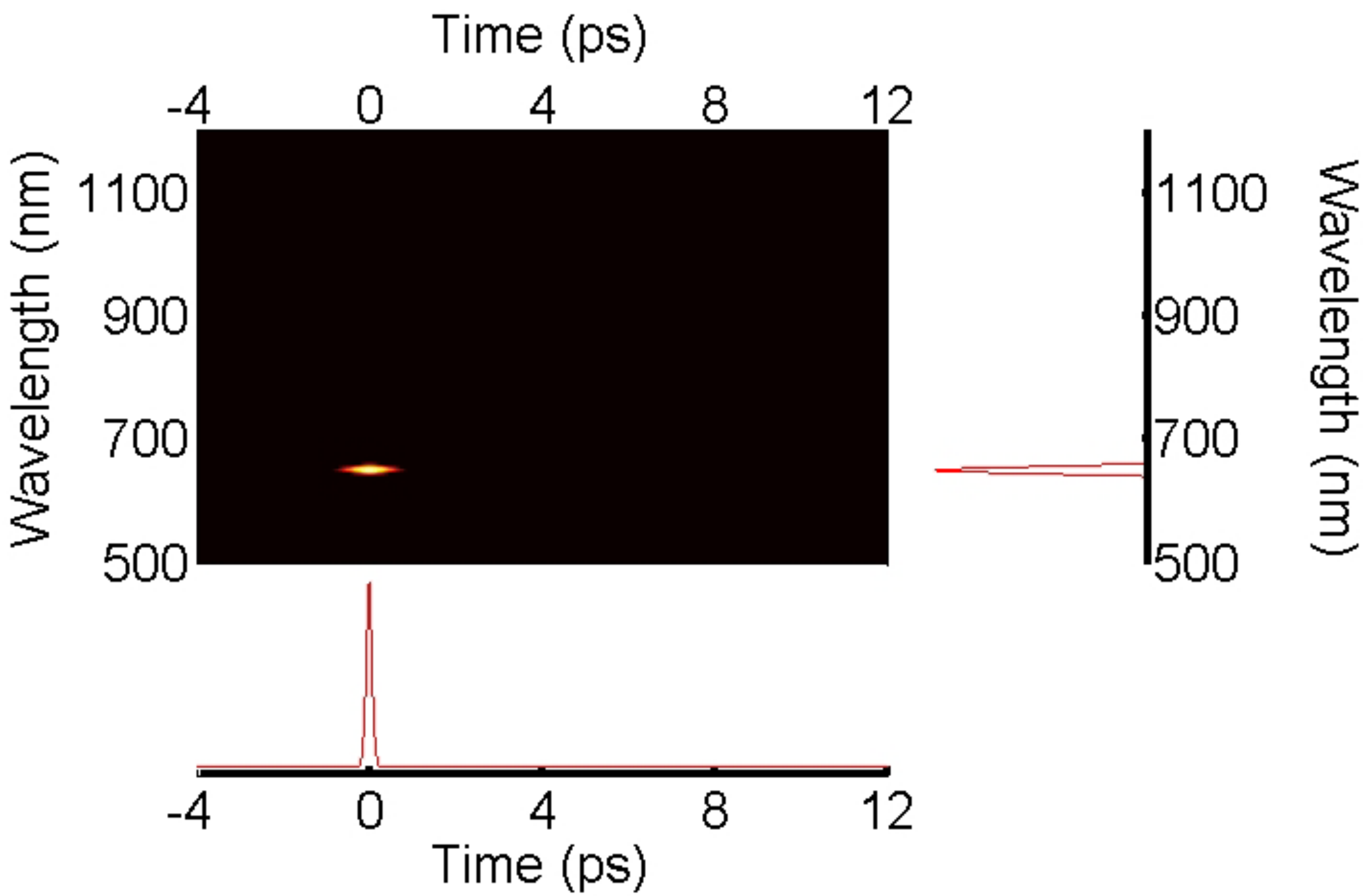
λ_p = 820 nm (anomalous)
N = 8



Visualizing dynamics

- Even better: spectrogram movies….

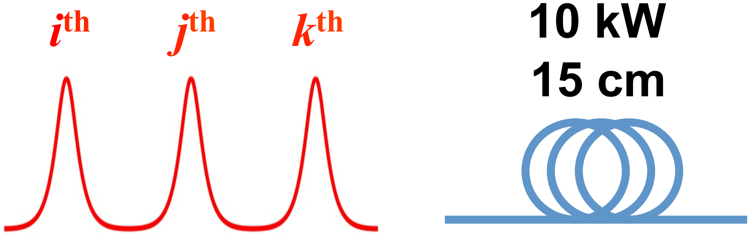
λ_p = 650 nm (normal)
N = 6

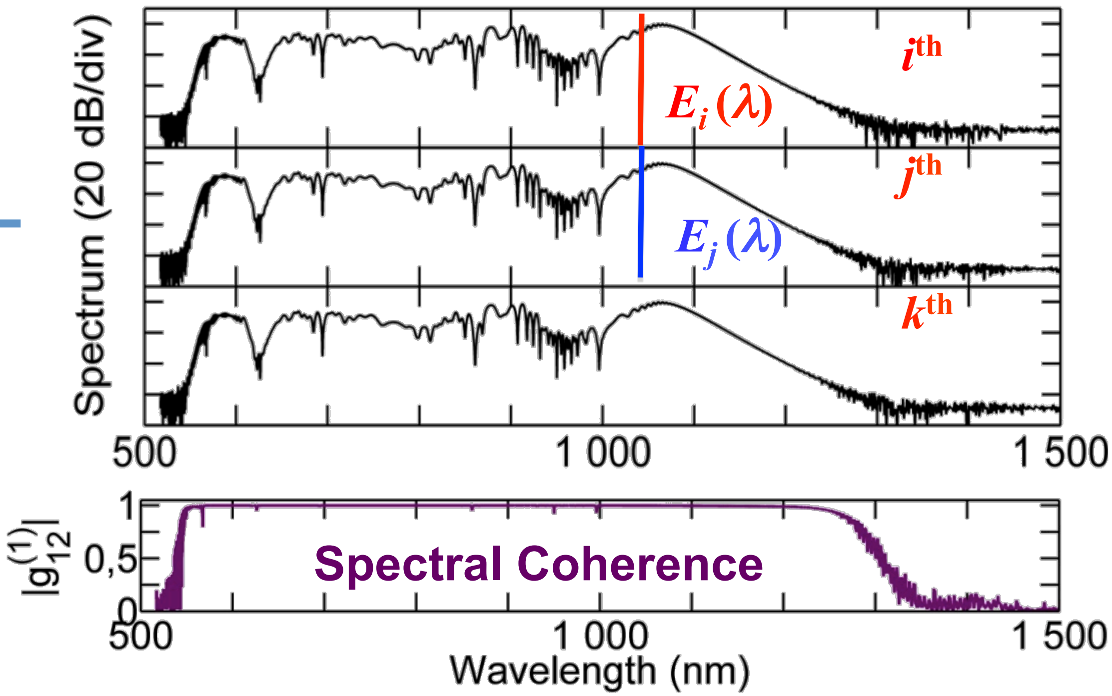


Coherence of supercontinuum

- Spectral coherence: "How spectra differs from shot to shot?"

30 fs pulse @ 800 nm
10 kW
15 cm



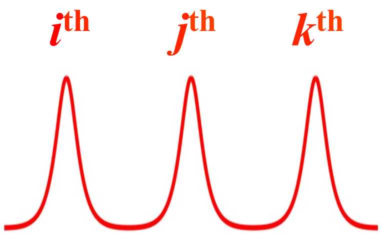


$$g_{12}^{(1)}(\lambda) = \frac{\left\langle E_i(\lambda) E_j^*(\lambda) \right\rangle_{i \neq j}}{S(\lambda)}$$

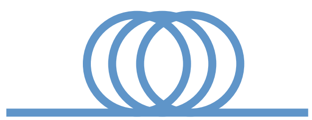
Dudley et al., OL 27, 1180 (2002)

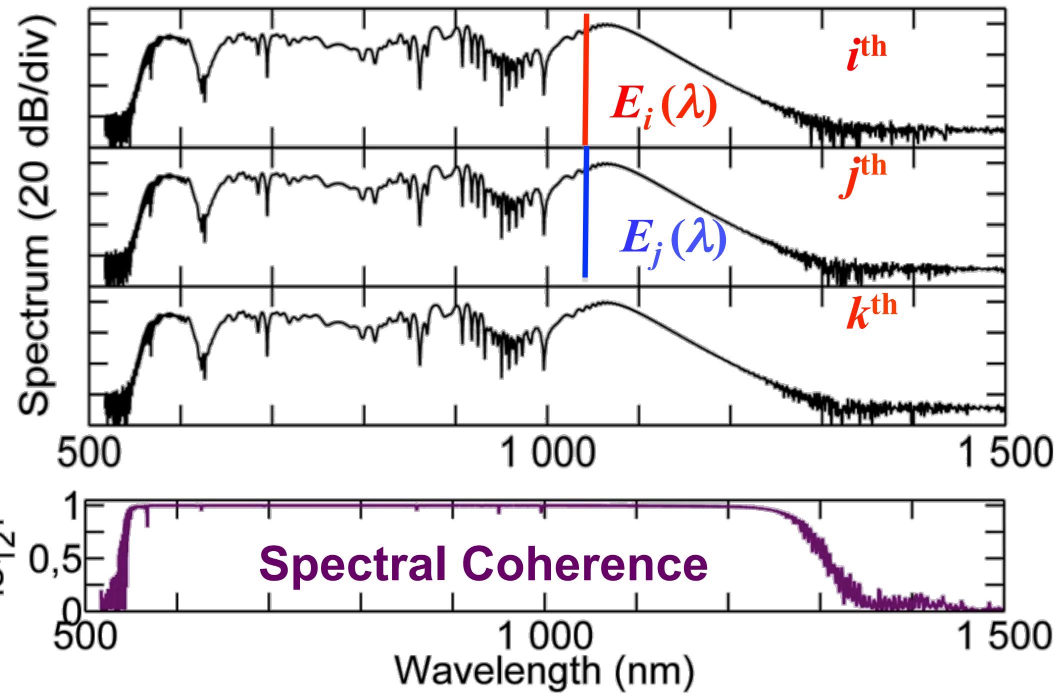
Coherence of supercontinuum

- Spectral coherence: “How spectra differs from shot to shot?”



30 fs pulse @ 800 nm
10 kW
15 cm





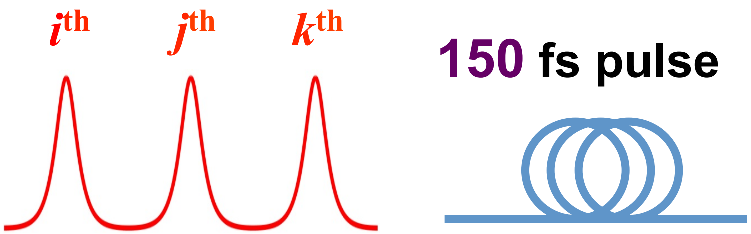
$$g_{12}^{(1)}(\lambda) = \frac{\left\langle E_i(\lambda) E_j^*(\lambda) \right\rangle_{i \neq j}}{S(\lambda)}$$

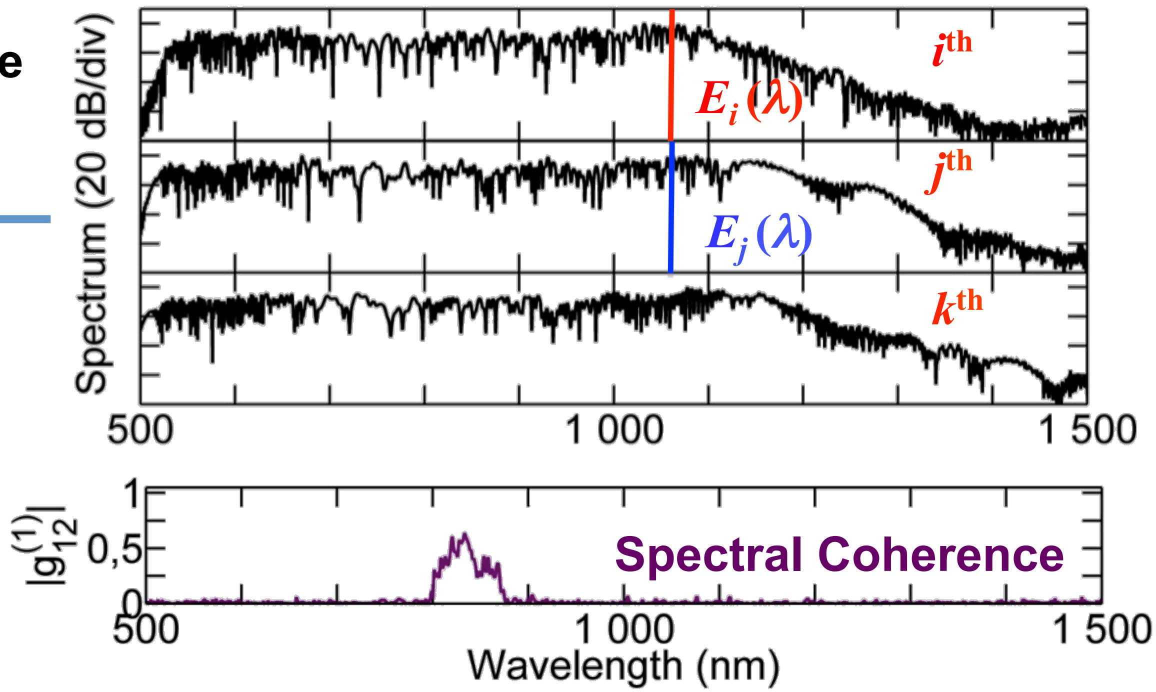
Dudley et al., OL 27, 1180 (2002)

Frequency combs

Coherence of supercontinuum

- BUT supercontinuum is not necessarily coherent!





$$g_{12}^{(1)}(\lambda) = \frac{\left\langle E_i(\lambda) E_j^*(\lambda) \right\rangle_{i \neq j}}{S(\lambda)}$$

Dudley et al., OL 27, 1180 (2002)

Coherence of supercontinuum

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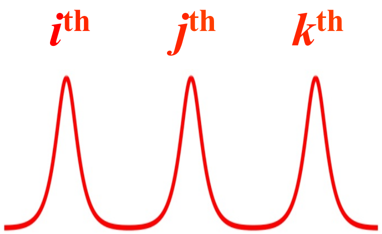
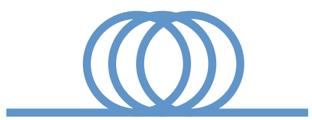
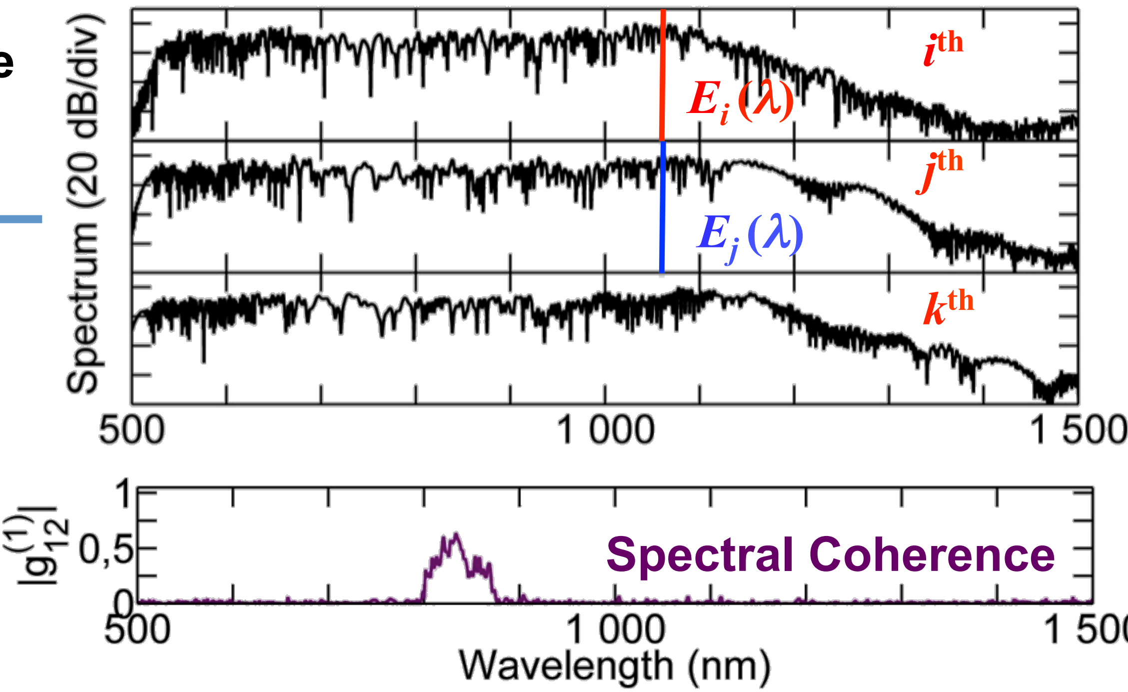


150 fs pulse





$$g_{12}^{(1)}(\lambda) = \frac{\left\langle E_i(\lambda) E_j^*(\lambda) \right\rangle_{i \neq j}}{S(\lambda)}$$

Dudley et al., OL 27, 1180 (2002)

Imaging, sensing

Supercontinuum coherence

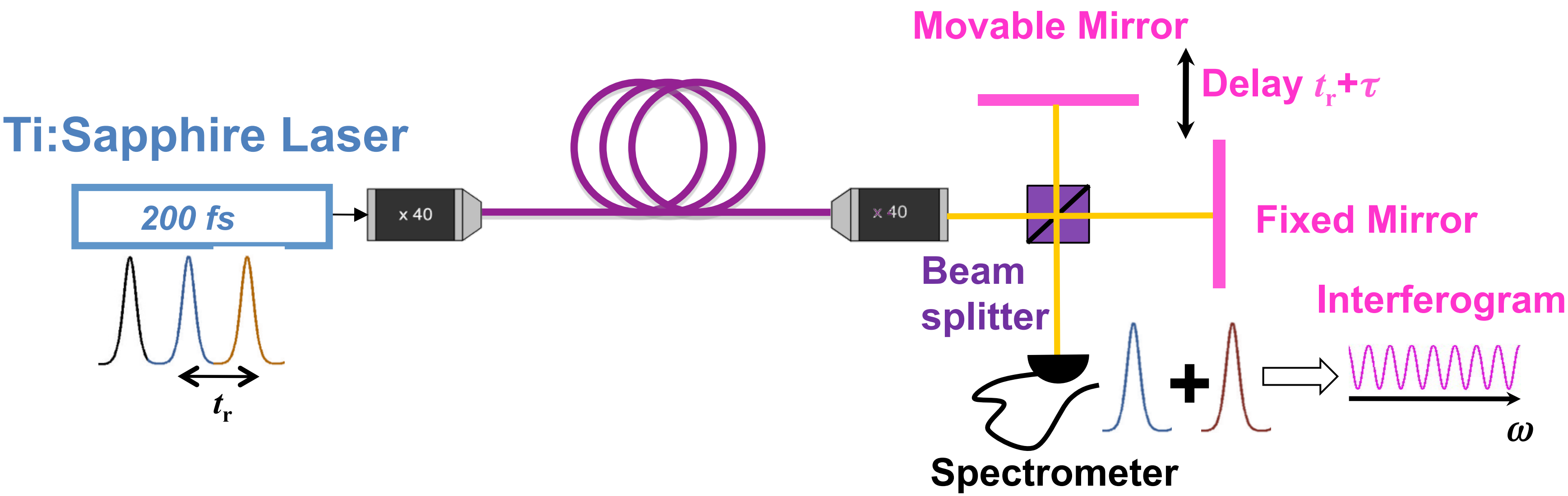
$$N = \sqrt{\frac{\gamma P_p \tau^2}{|\beta_2|}} = \tau \sqrt{\frac{\gamma P_p}{|\beta_2|}} \approx 16$$

	Short pulses	Long pulses
Anomalous	• Soliton • Dispersive waves	• Modulation instability • Solitons dynamics
Normal	• Self-phase modulation • Four-wave mixing	• Raman scattering • Four-wave mixing

Coherent

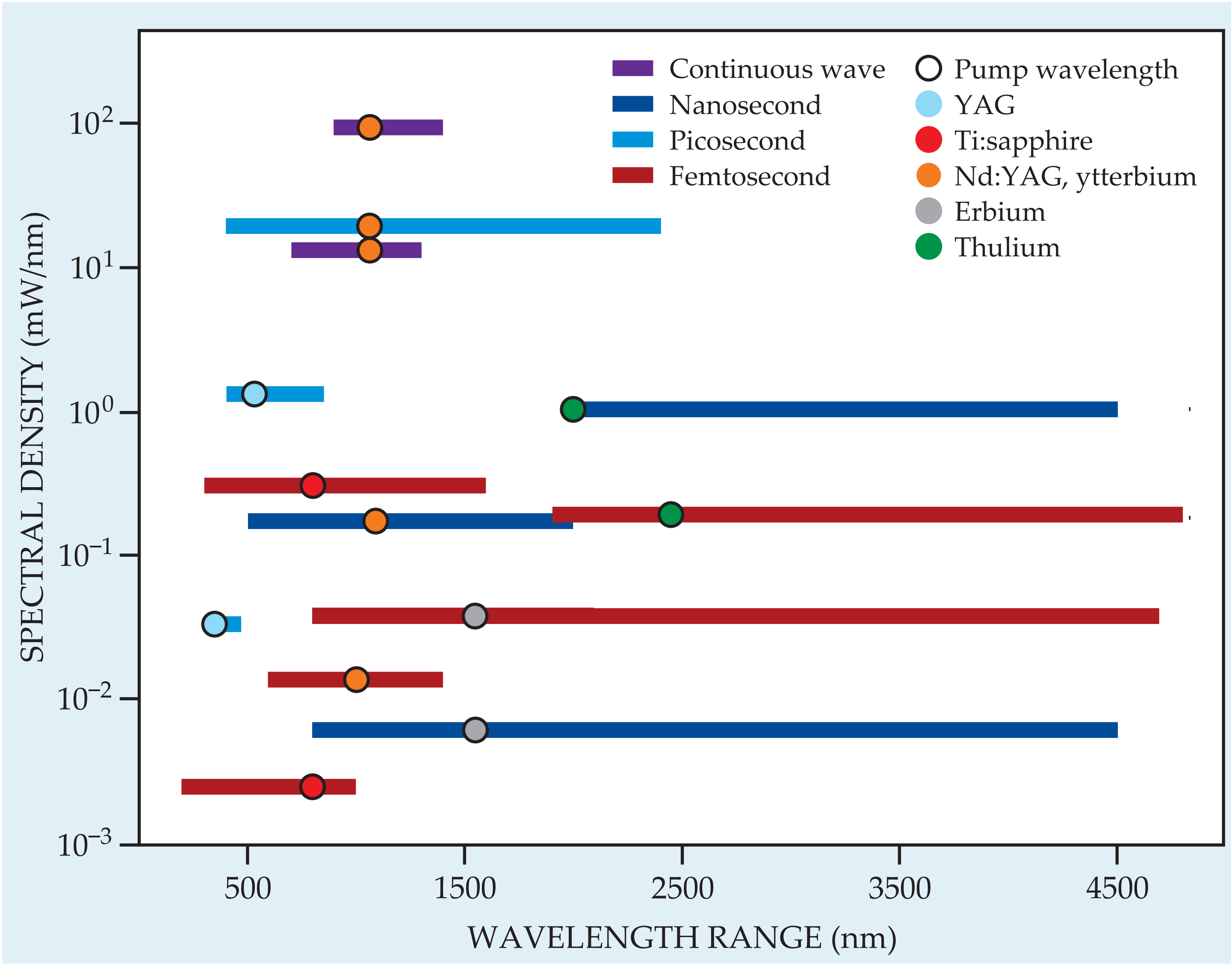
Incoherent

Measuring supercontinuum coherence

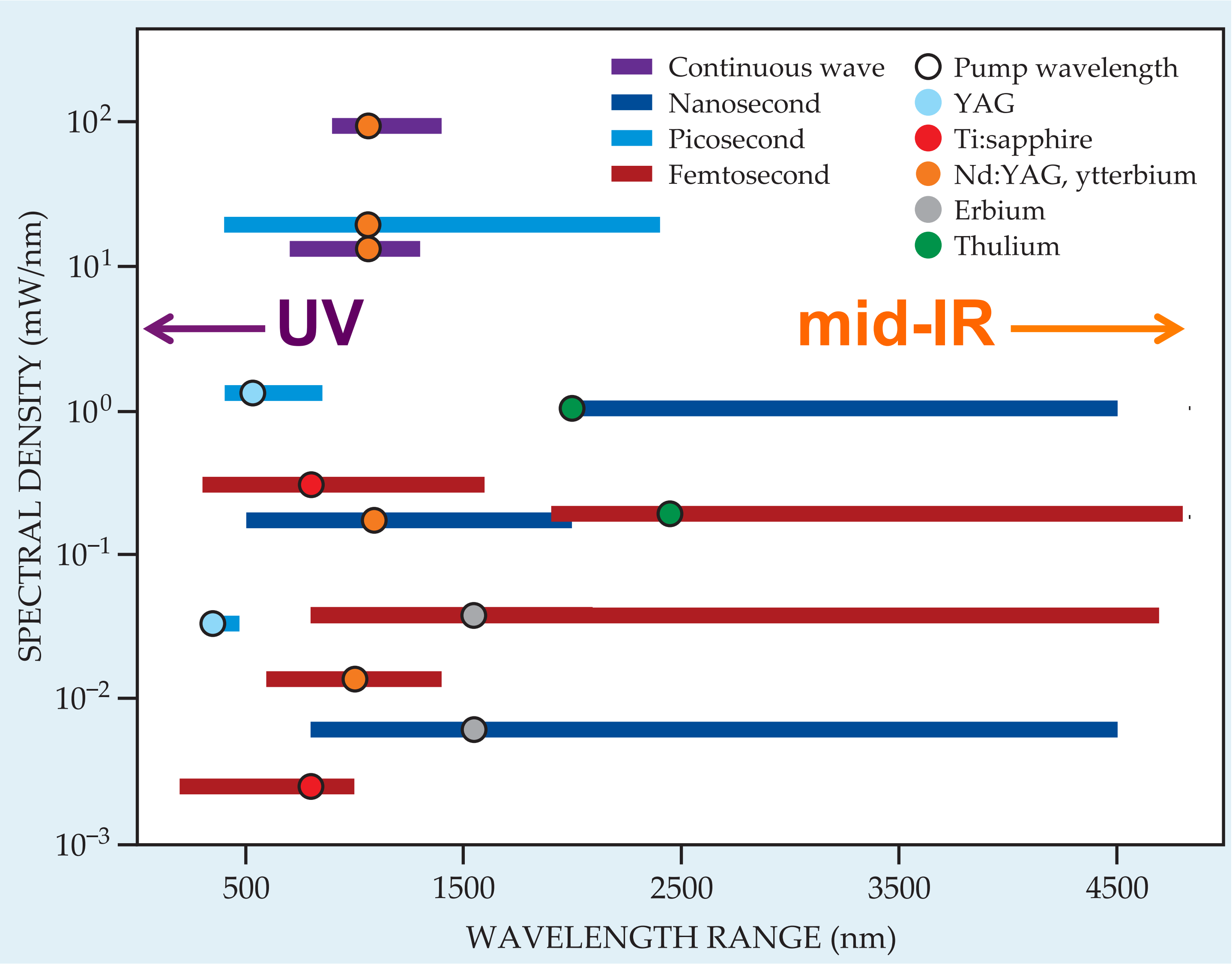


- Michelson interferometer
- Spectral interference
- Fringes visibility gives the coherence function

State-of-the-art



State-of-the-art



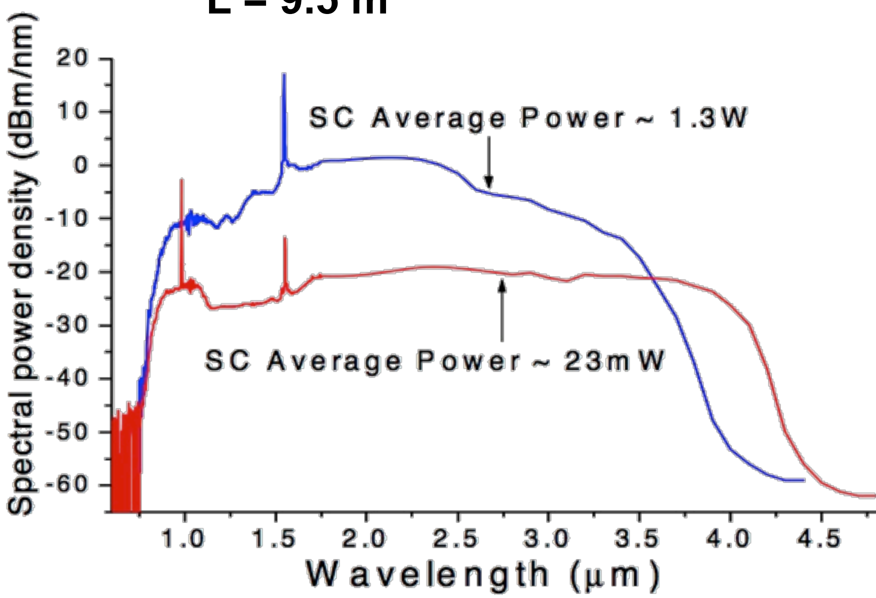
Extension to the mid-IR

- Use of materials with low losses in the mid-IR

Fluoride (ZBLAN) fibers

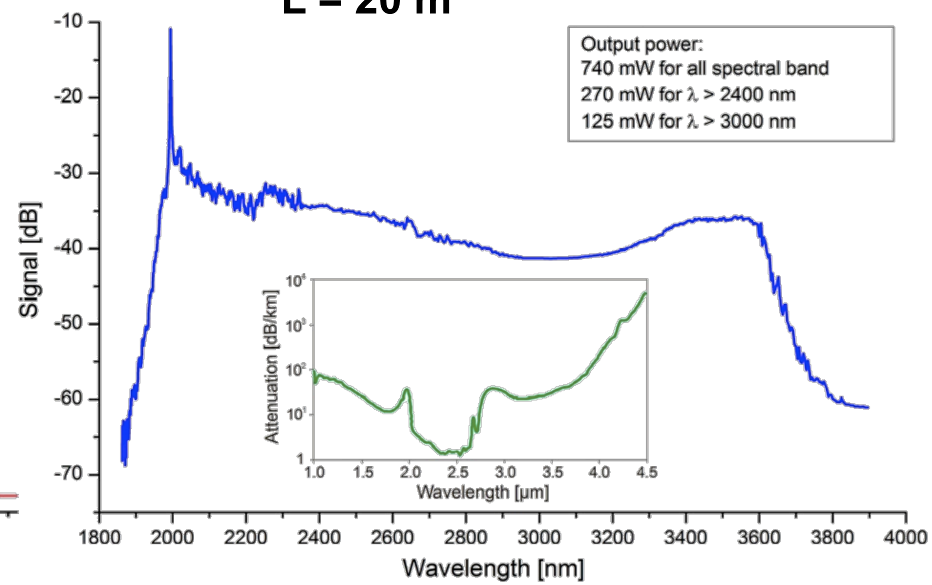
Material ZDW 1.6 microns
$n_2 = n_2^{silica}$

Pp = 3 kW, Pav = 1.3 W
L = 9.5 m



Xia et al. Opt. Express 15, 865 (2007)

Pp = 29 kW, Pav = 0.4 W
L = 20 m

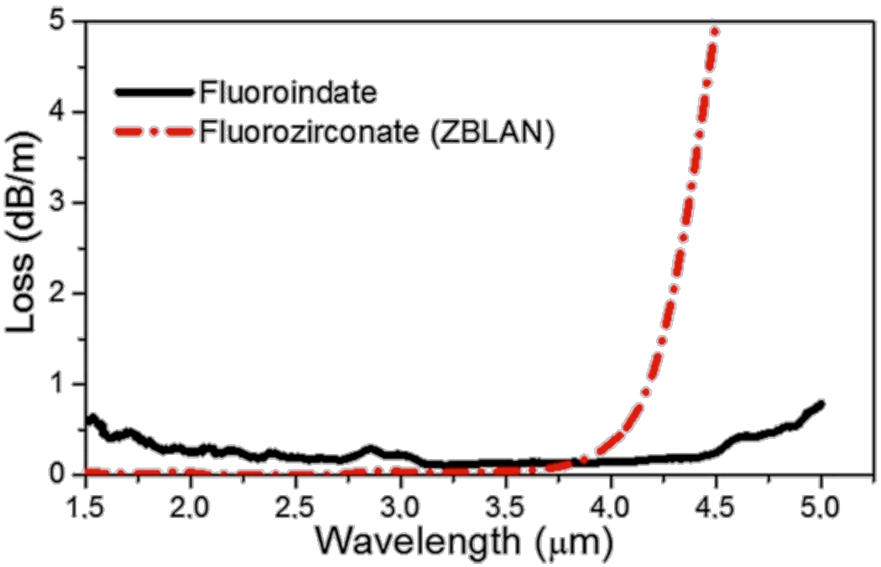


Swiderski et al. Opt. Express 21, 7851 (2013)

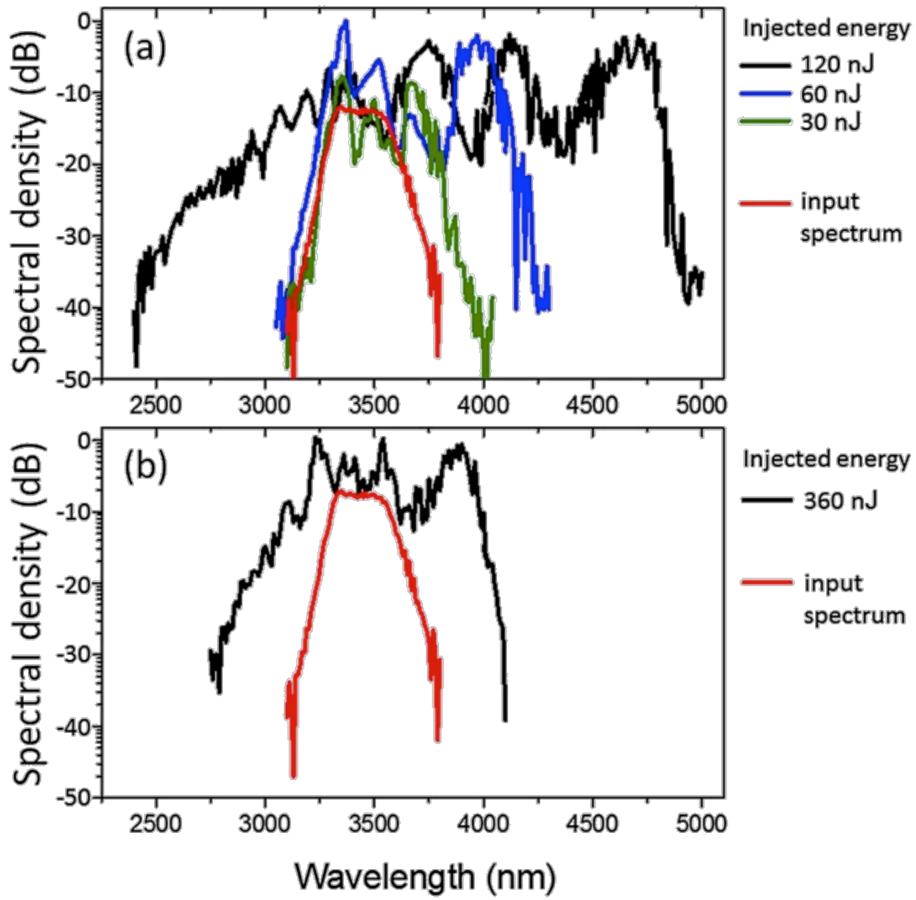
Extension to the mid-IR

Fluoroindate fibers

Theberge et al., OL 38, 4683 (2013)



Pp = 1.7 MW
L = 9.5 m

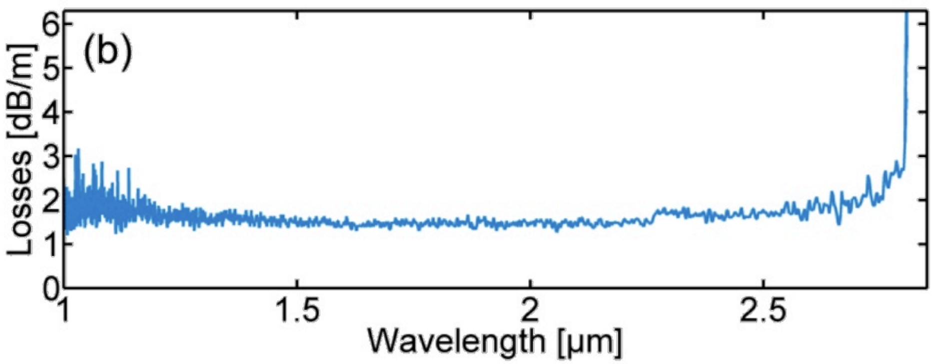


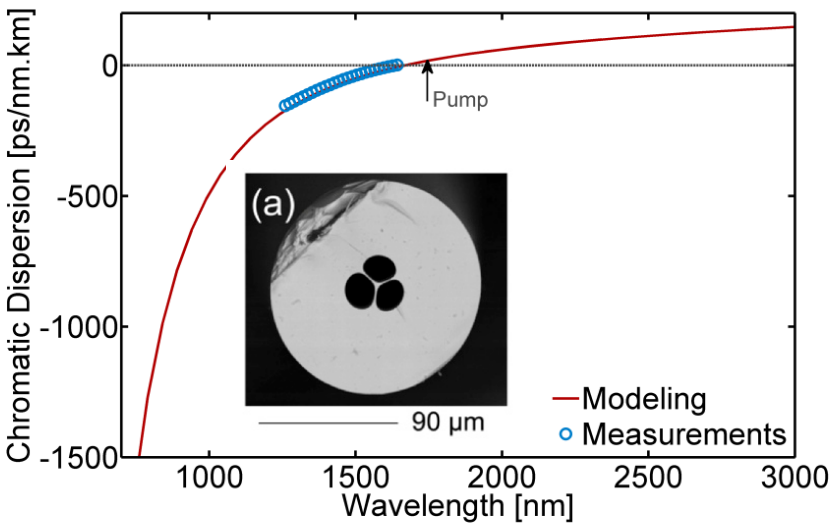
Extension to the mid-IR

- Enhanced nonlinearity

Tellurite fibers (PCFs)

Material ZDW 2.2 microns
$n_2 = n_2^{silica} \times 10\text{-}20$





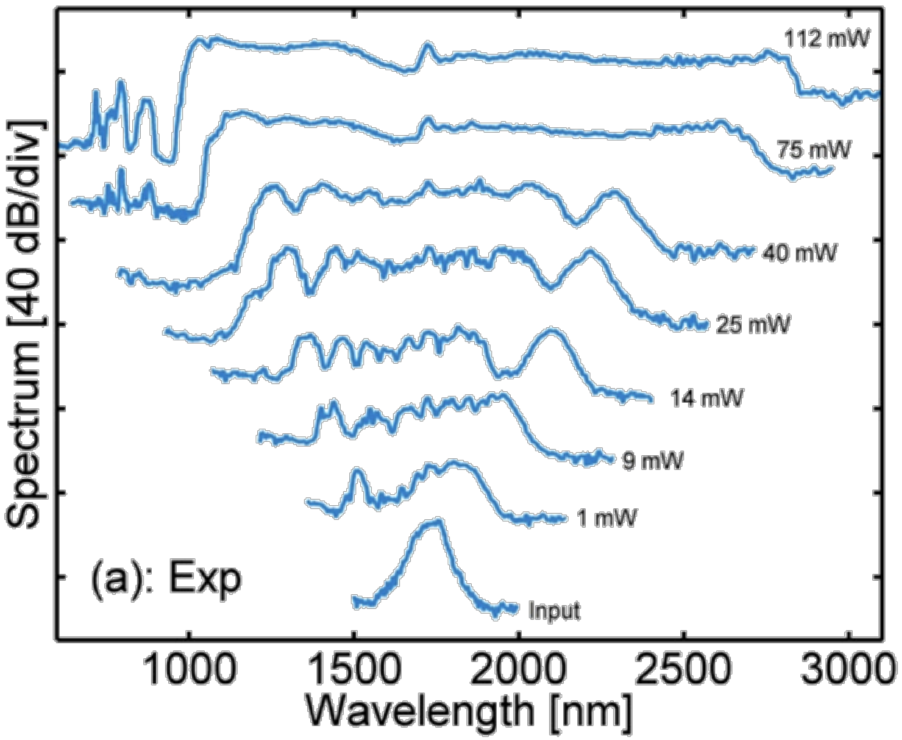
Savelii et al. Opt. Express 20, 27083 (2012)

Extension to the mid-IR

- Enhanced nonlinearity

Tellurite fibers (PCFs)

Material ZDW 2.2 microns
$n_2 = n_2^{silica} x10\text{-}20$



Pp = 7 kW, Pav = 112 mW
L = 2 cm

Savelii et al. Opt. Express 20, 27083 (2012)

Extension to the mid-IR

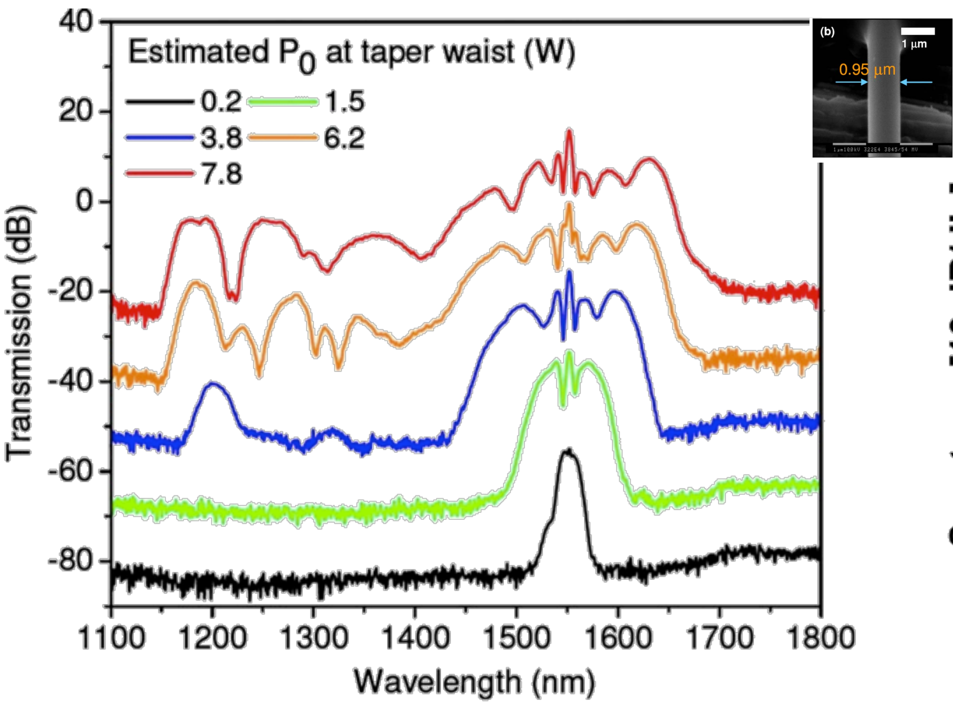
- Enhanced nonlinearity

Sulfide/Chalcogenide fibers

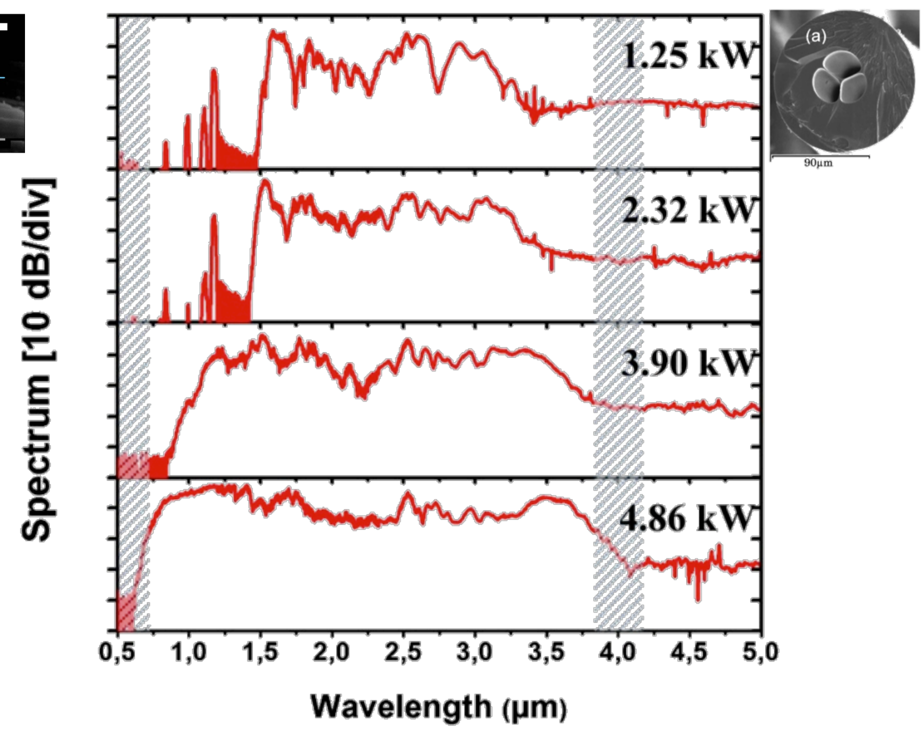
Material ZDW 5 microns

$n_2 = n_2^{silica} \times 100$

Pp = 8 W, Pav = 80 μW
L = 3 cm



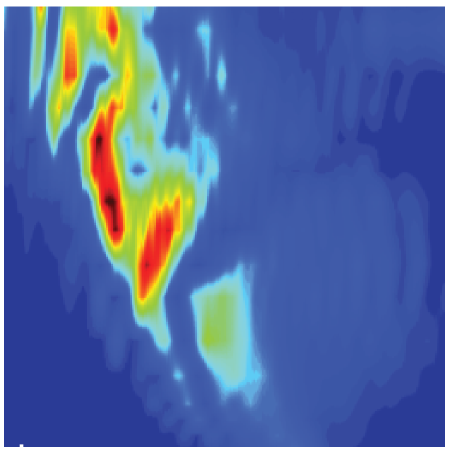
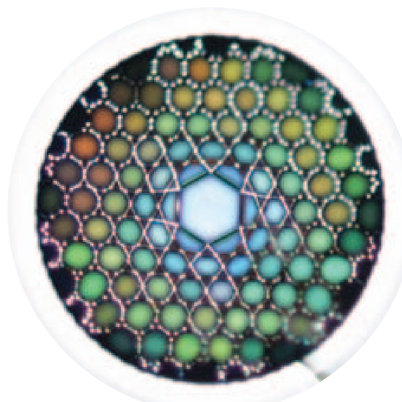
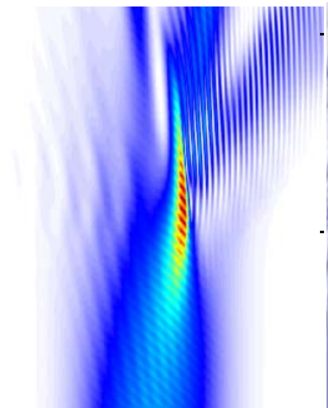
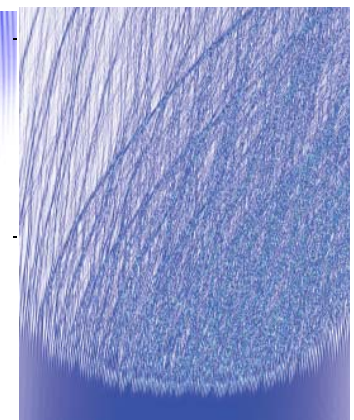
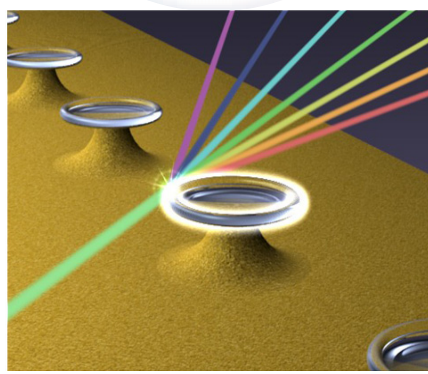
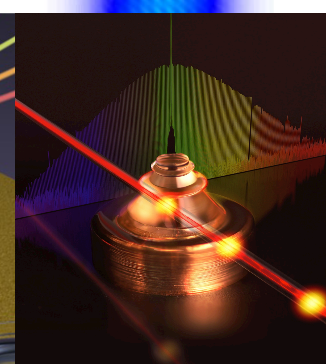
Pp = 5 kW, Pav = 80 mW
L = 2 cm



Yeom et al. OL 33, 660 (2008)

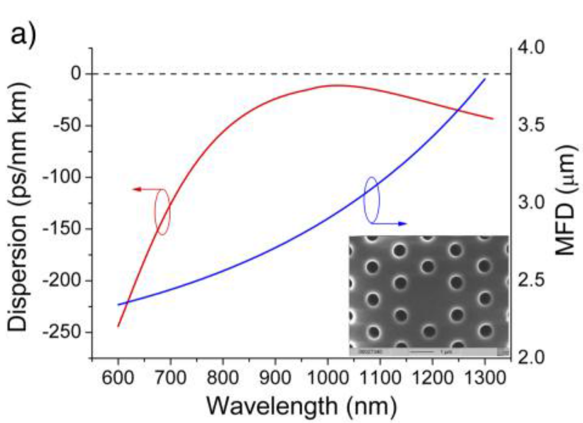
Mouawad et al. OL 39, 2685 (2014)

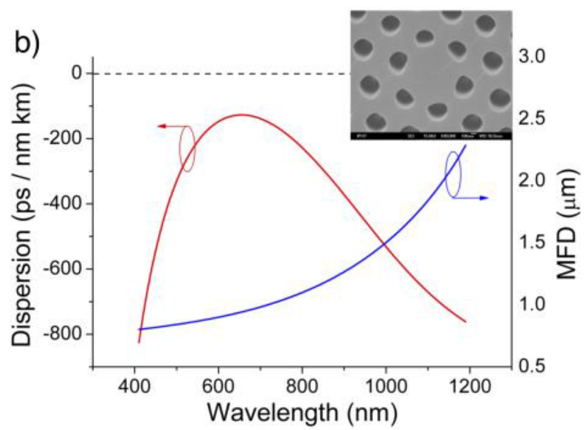
Emerging structures for supercontinuum generation

Fibers with all-normal dispersion

- Fibers with normal dispersion at all wavelengths: ANDI
- Allows for high coherence and stability, flat spectra
- Can reach octave-spanning

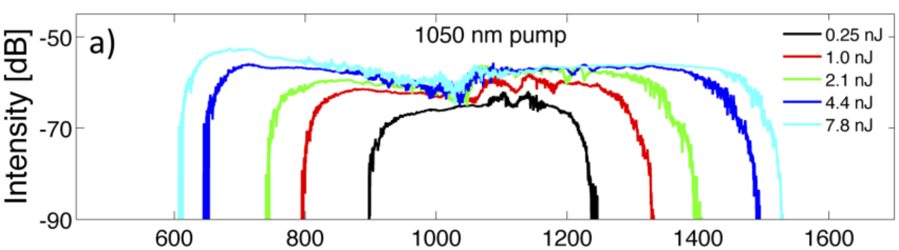


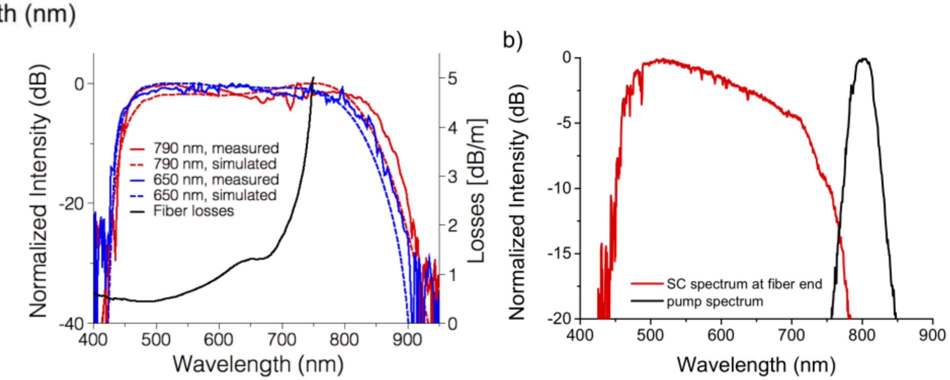


Coherent octave spanning near-infrared and visible supercontinuum generation in all-normal dispersion photonic crystal fibers

Alexander M. Heidt,[1,2*] Alexander Hartung,[2] Gurthwin W. Bosman,[1] Patrizia Krok,[1] Erich G. Rohwer,[1] Heinrich Schwoerer[1], and Hartmut Bartelt[2]

14 February 2011 / Vol. 19, No. 4 / OPTICS EXPRESS 3775

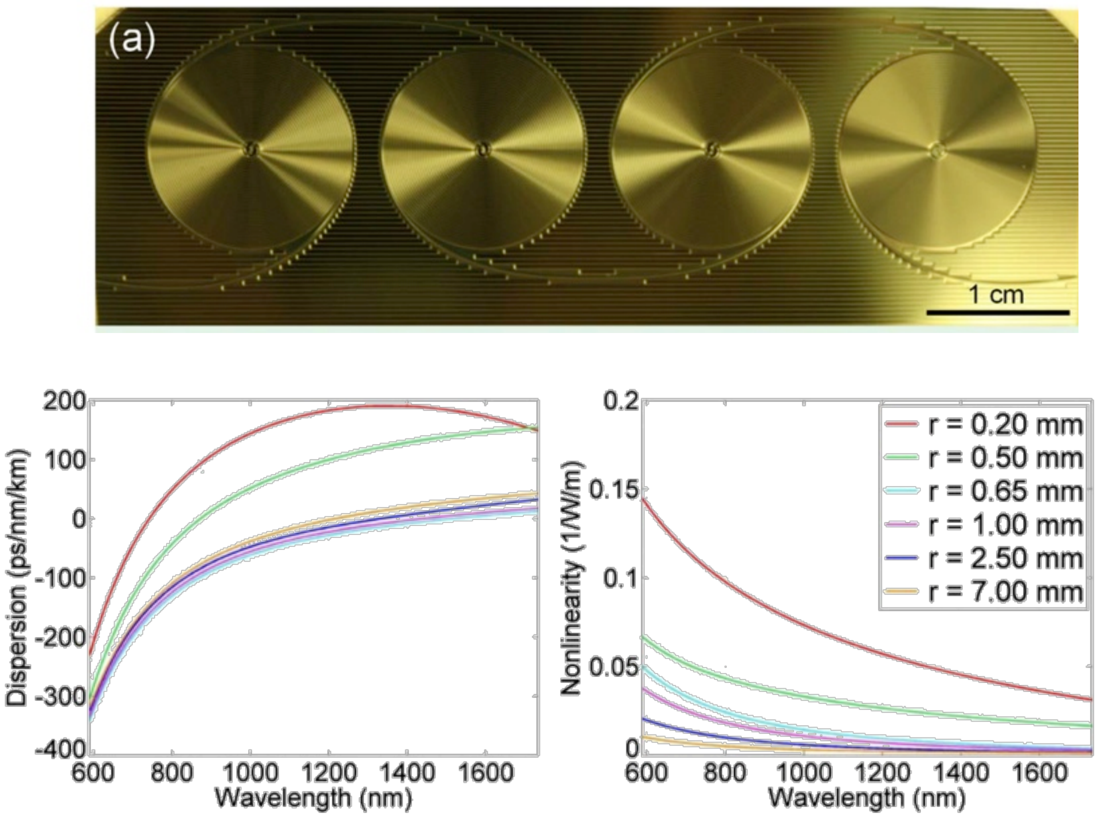




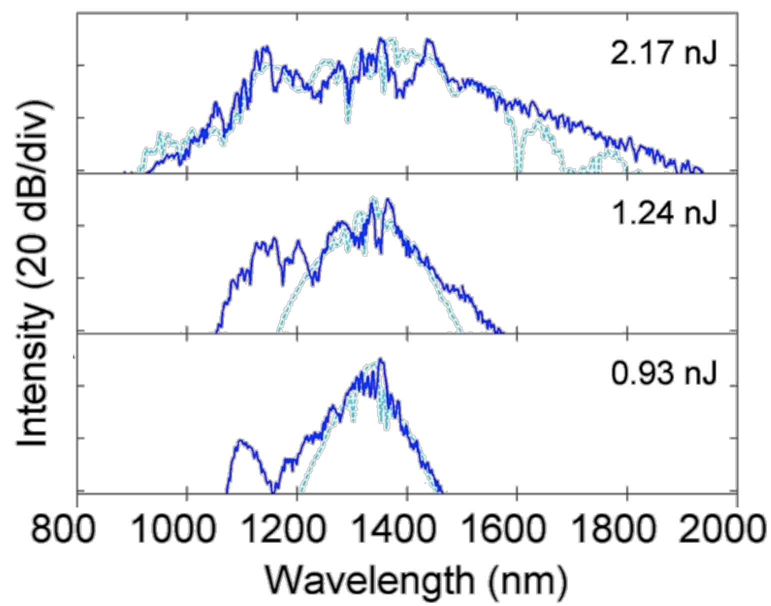
On-chip supercontinuum

Silica

Oh et al., OL 39, 1046 (2014)



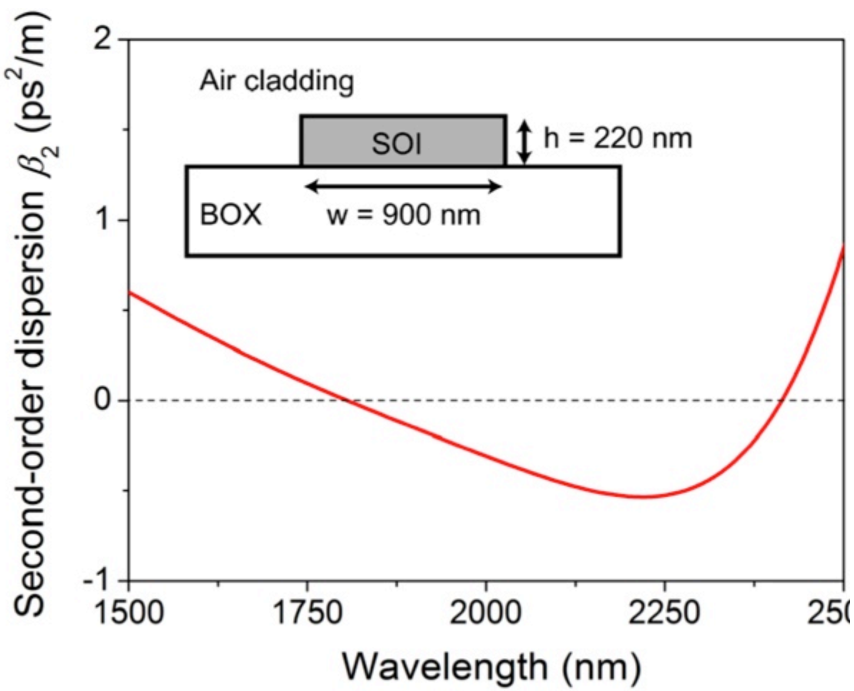
Pp = 12 kW, Pav = 175 mW
L = 3.5 cm



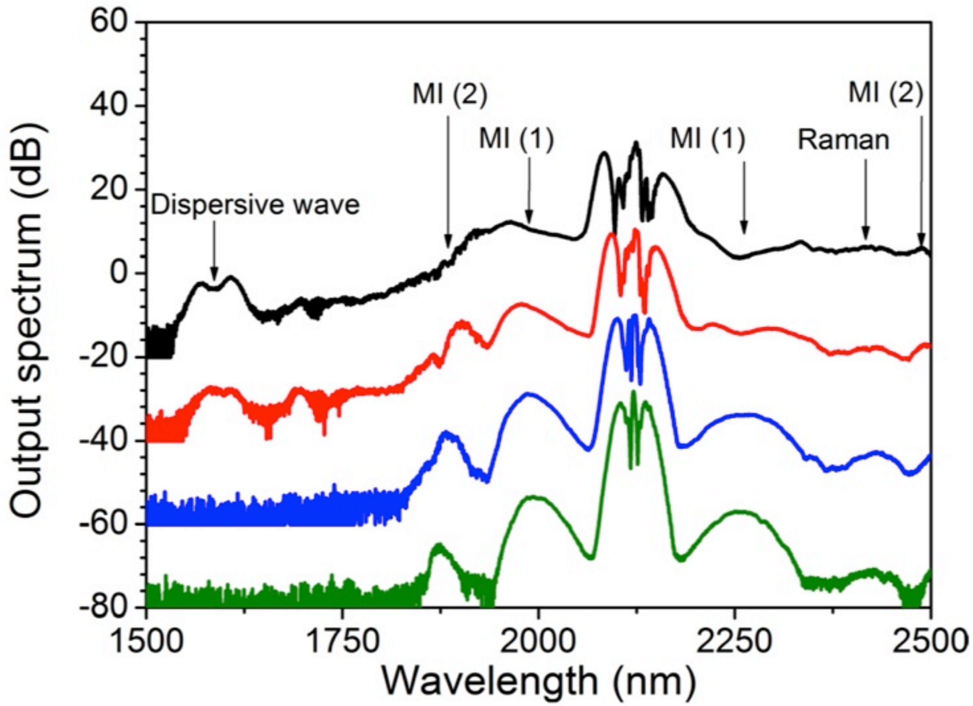
On-chip supercontinuum

Silicon

Kuyken et al., Opt. Express 19, 20172 (2011)



Pp = 12 W
L = 1 cm

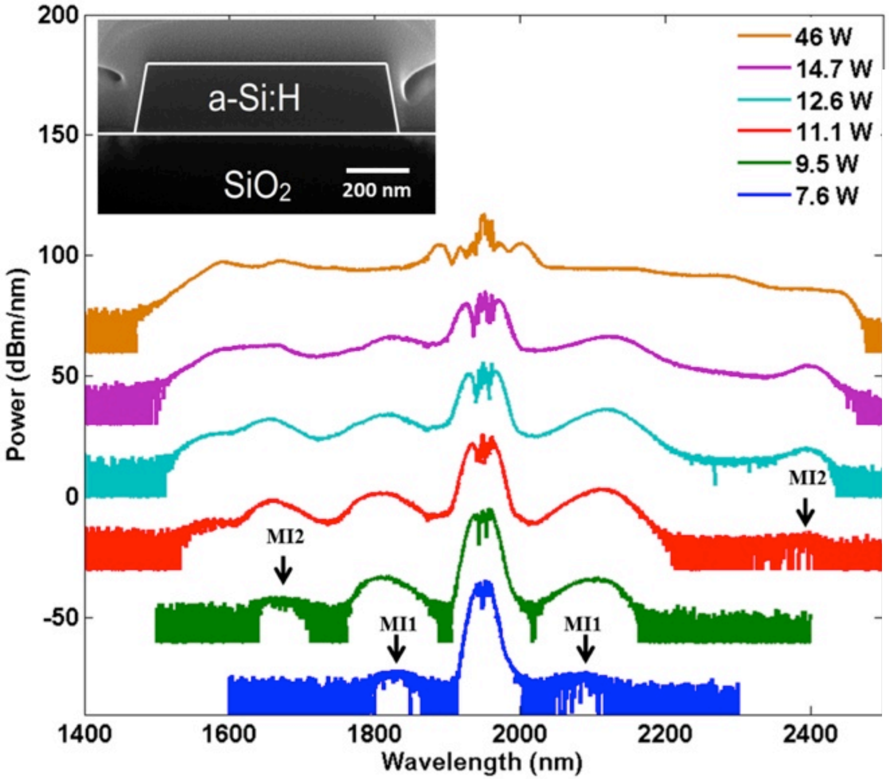


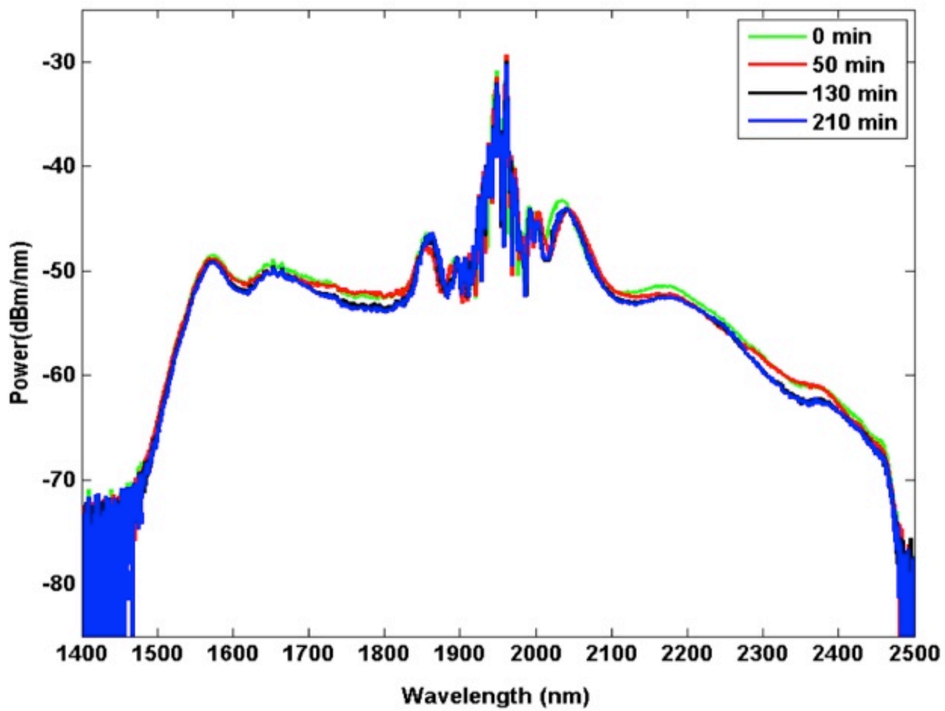
On-chip supercontinuum

Hydrogeneted Silicon

Dave et et al., Opt. Express 21, 32034 (2013)

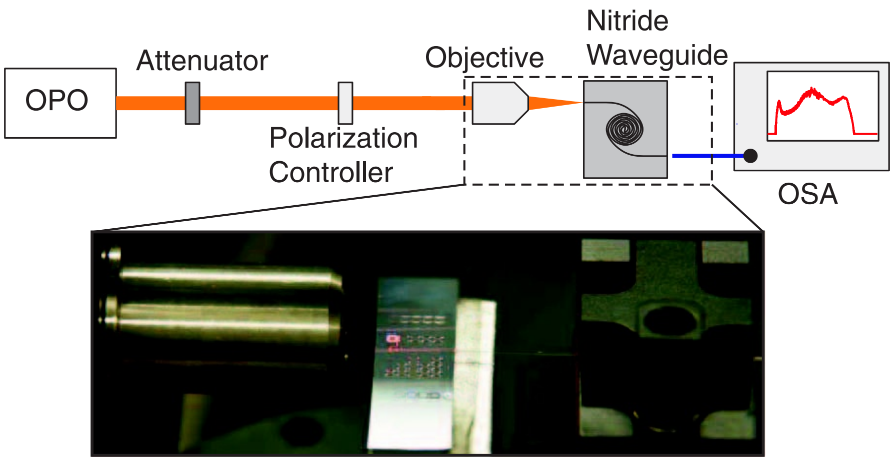
Pp = 16.5 W, Pav = .5 mW
L = 1 cm

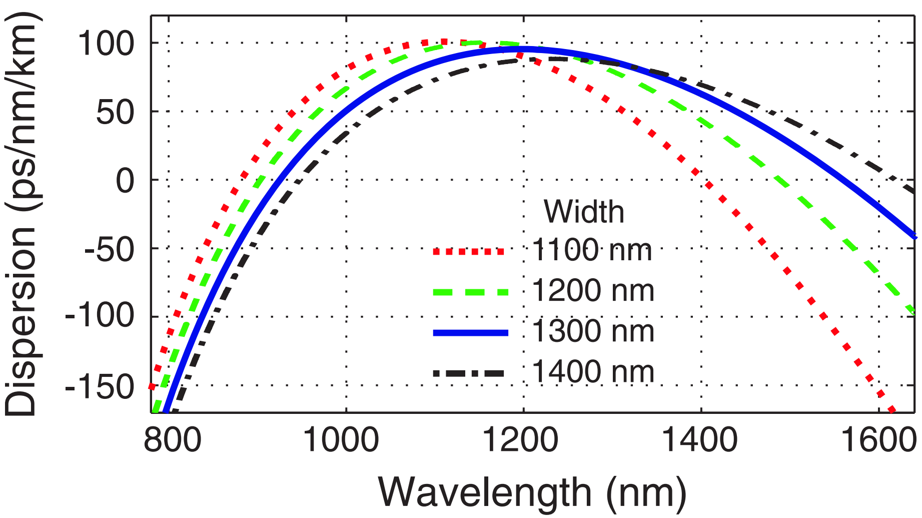




On-chip supercontinuum

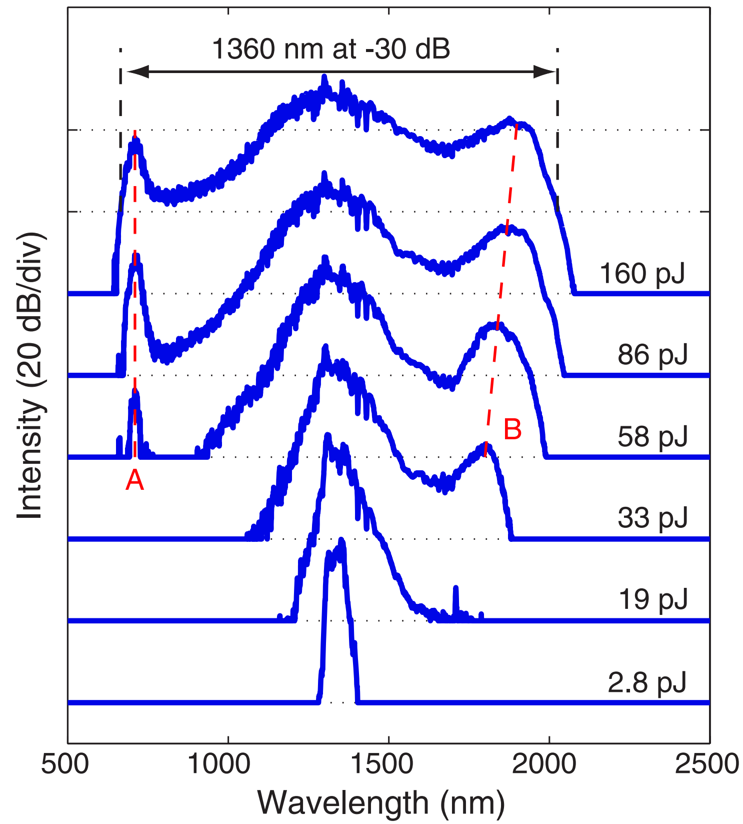
Silicon nitride



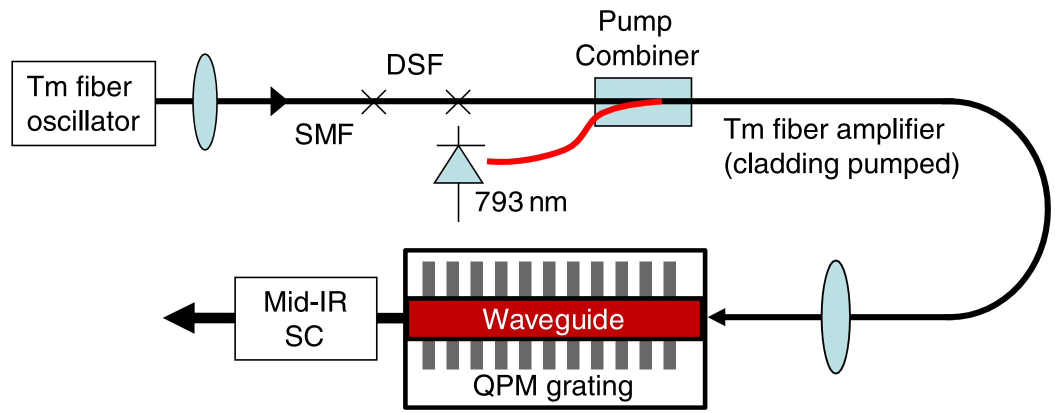


Halir et al. Opt. Lett 37, 1685 (2012)

Pp = 800 W, Pav = 13 mW
L = 4.3 cm

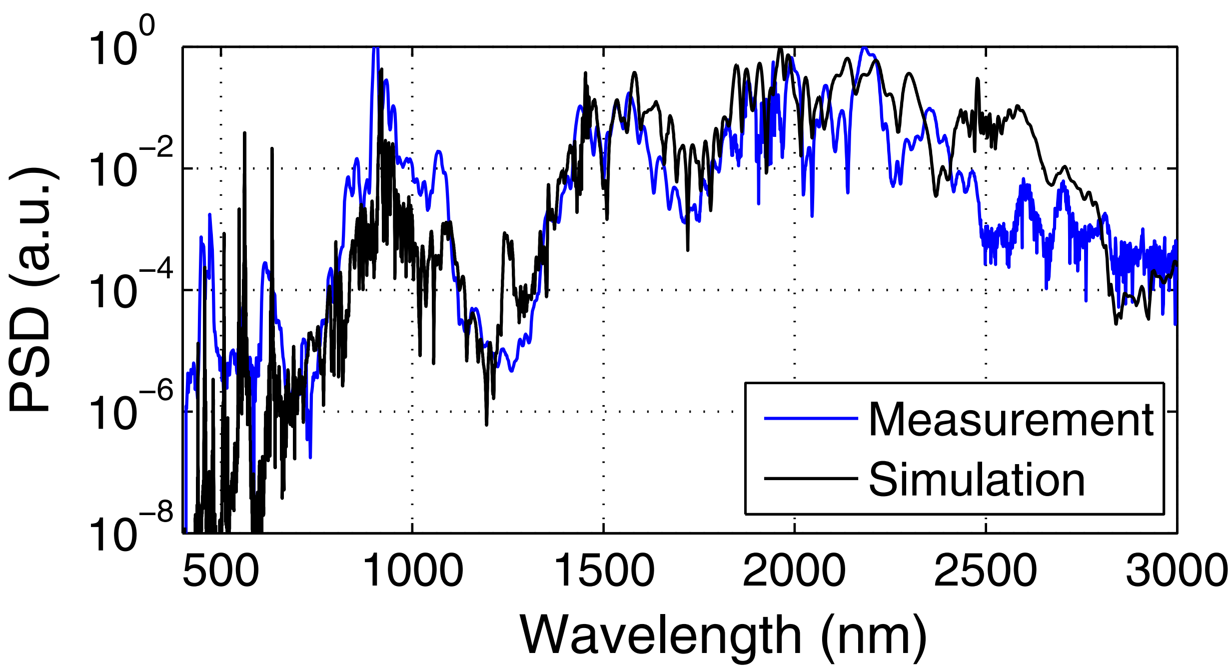


On-chip supercontinuum



Lithium Niobate

Phillips et al. Opt. Lett 36, 3912-3914 (2011)

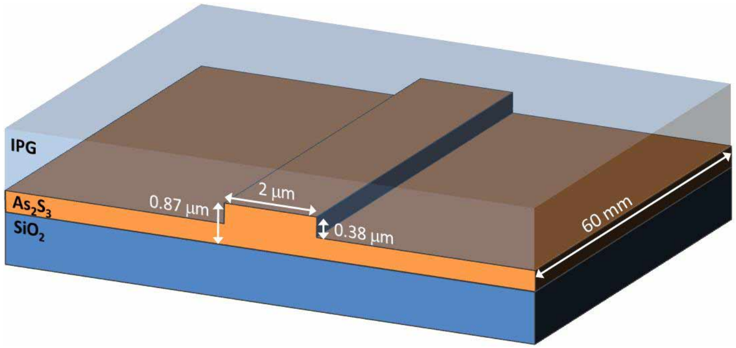


Pp = 72 kW, Pav = 500 mW
L = 1.85 cm

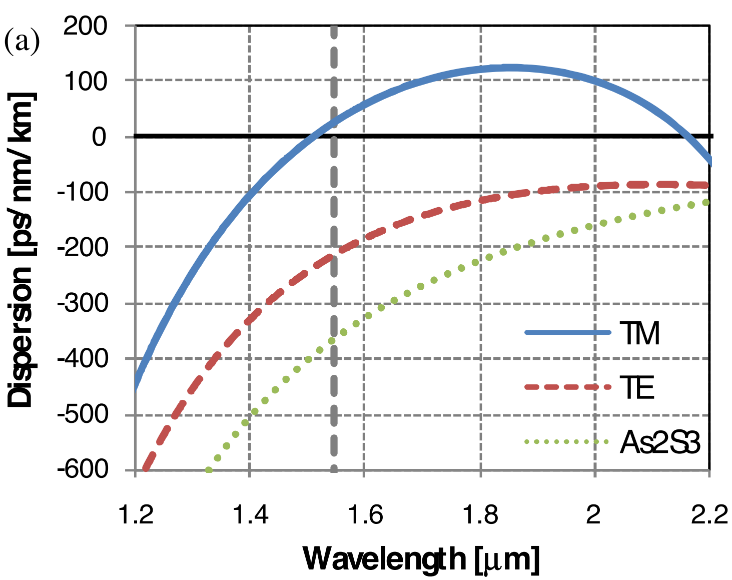
On-chip supercontinuum

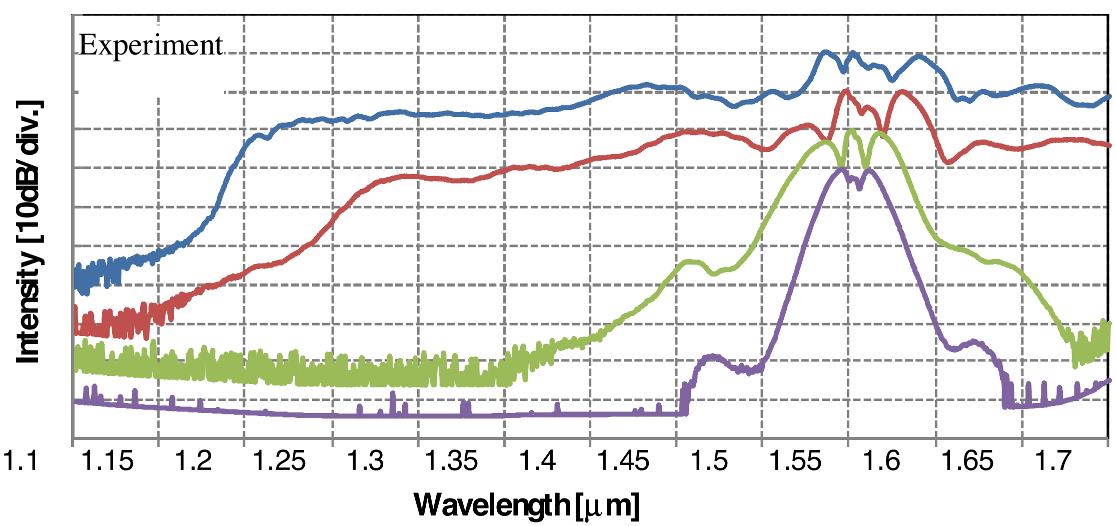
Chalcogenide

Lamont et al. Opt. Express 16, 14938 (2008)



Pp = 68 W, Pav = .5 mW
L = 6 cm

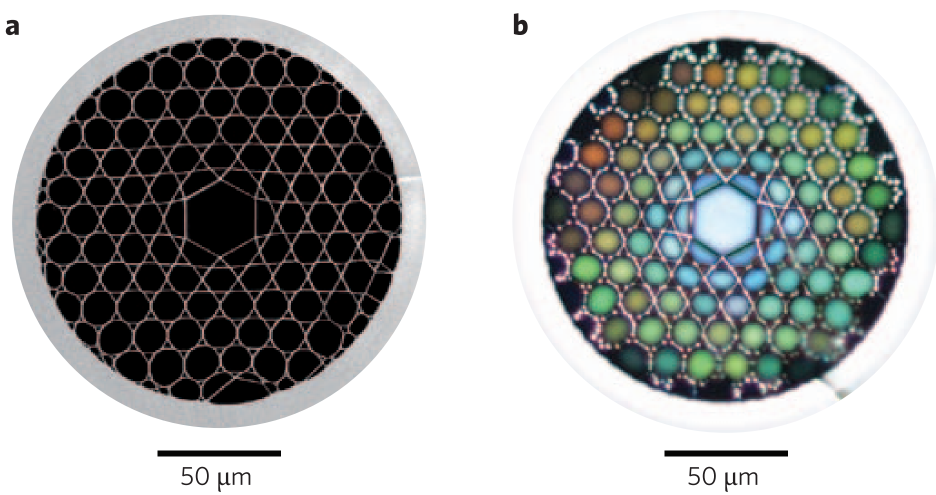


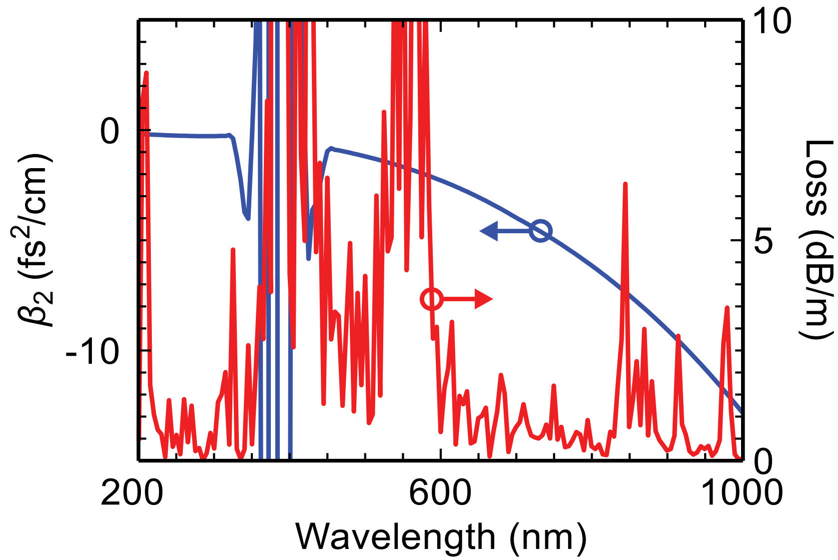


Hollow core photonic crystal fibers

- Kagome fibers
  - Broad guidance

Travers et al., JOSAB 28, 11 (2011)

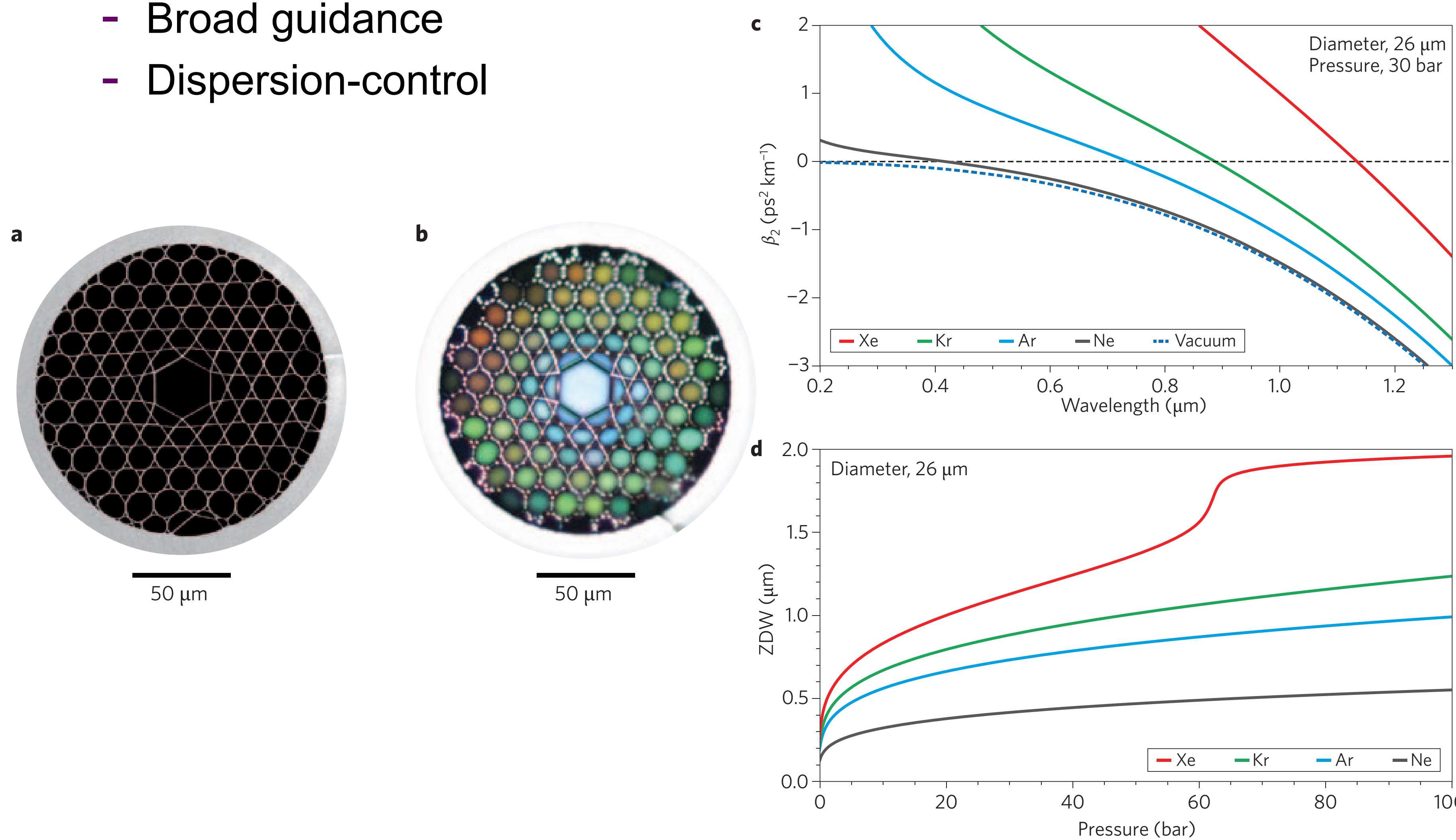




Hollow core photonic crystal fibers

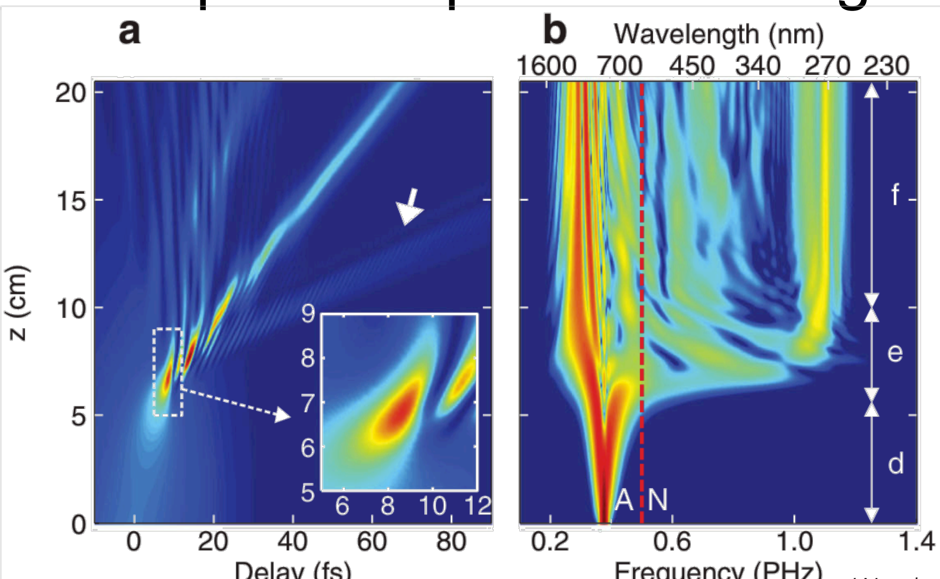
- Kagome fibers
  - Broad guidance
  - Dispersion-control

Russell et al., Nat. Photon. 8, 278 (2014)

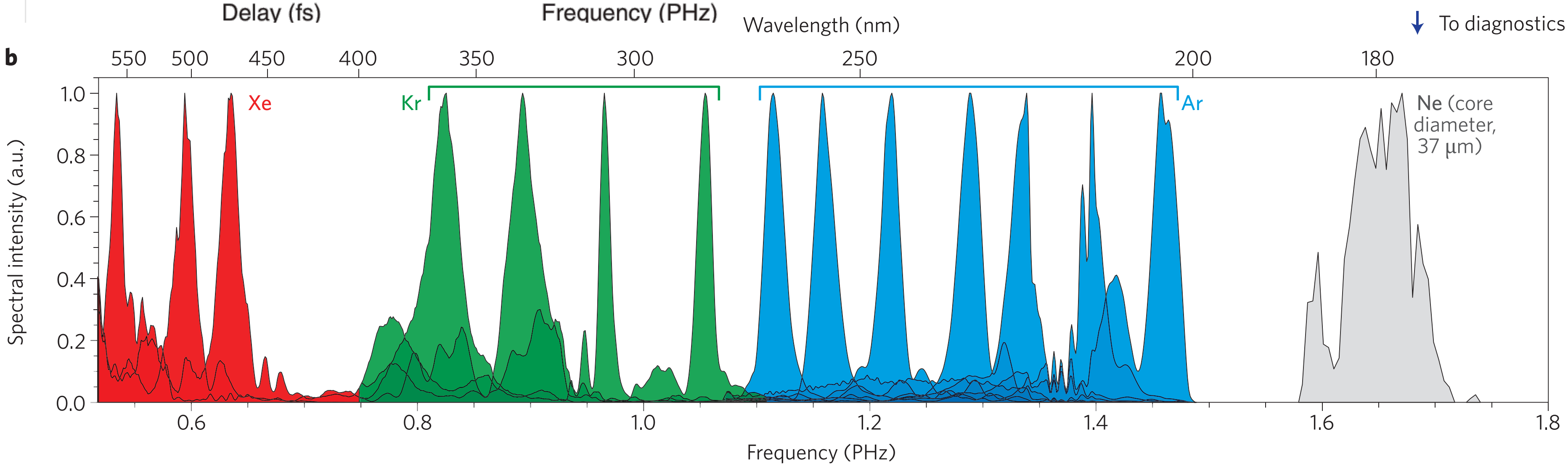


Deep UV generation

- Exploits dispersive wave generation by solitons



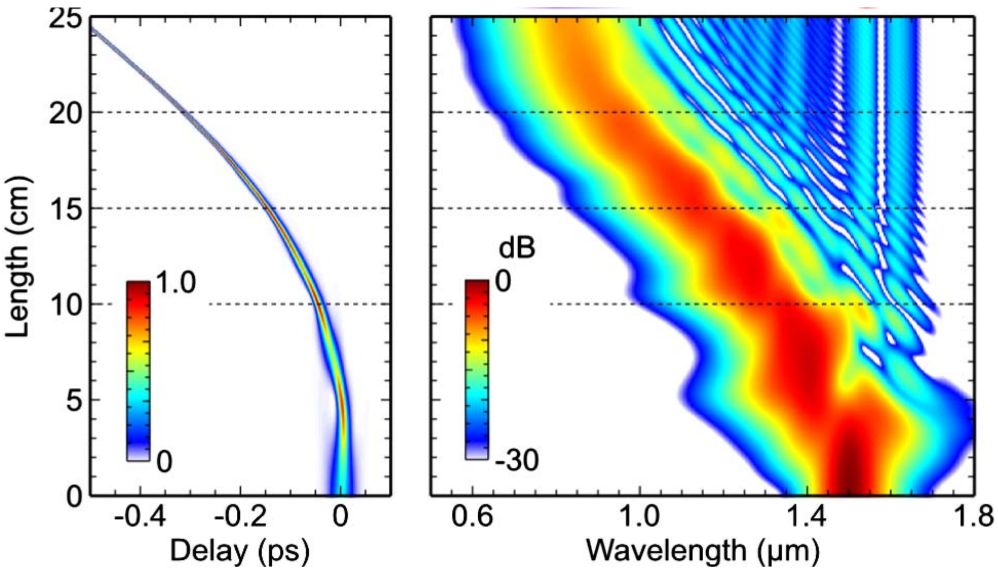
Russell et al., Nat. Photon. 8, 278 (2014)

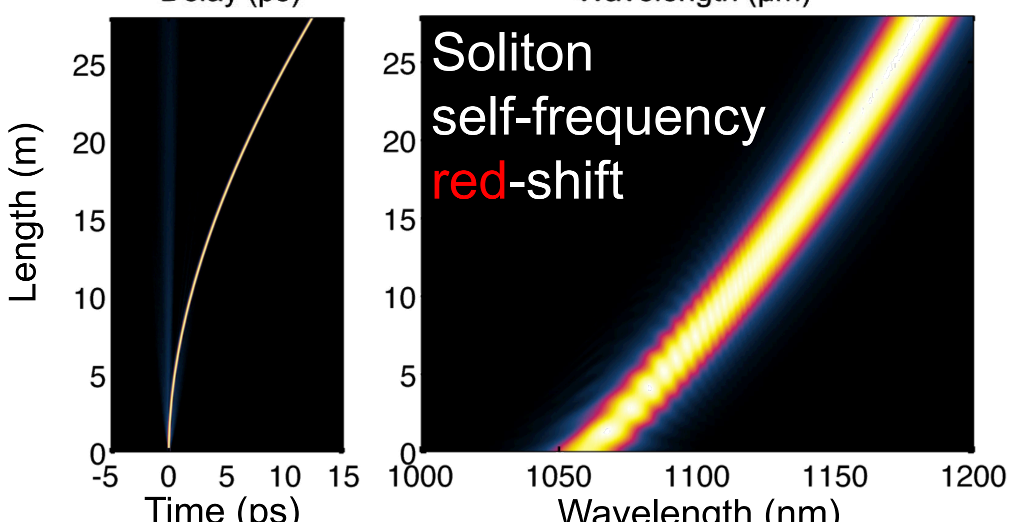


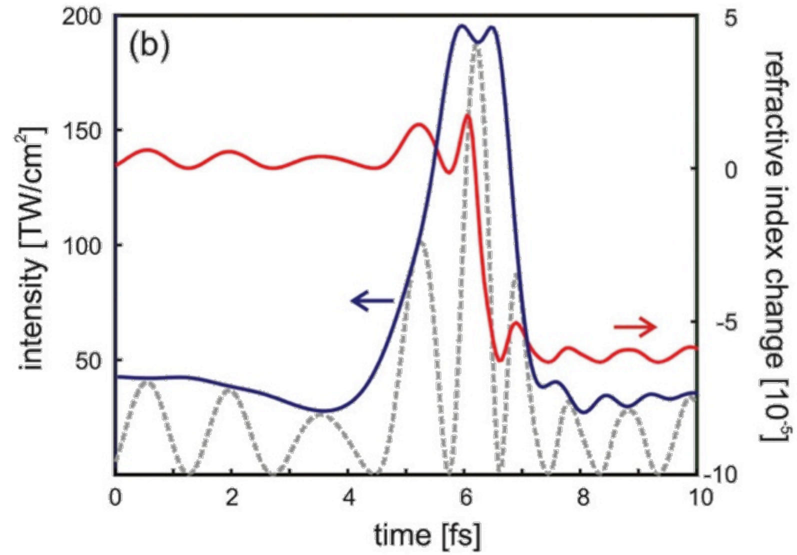
Novel dynamics in the ionization regime

- Solitons self-frequency **blue-**shift

Chang et al., OL 38, 29884 (2013)

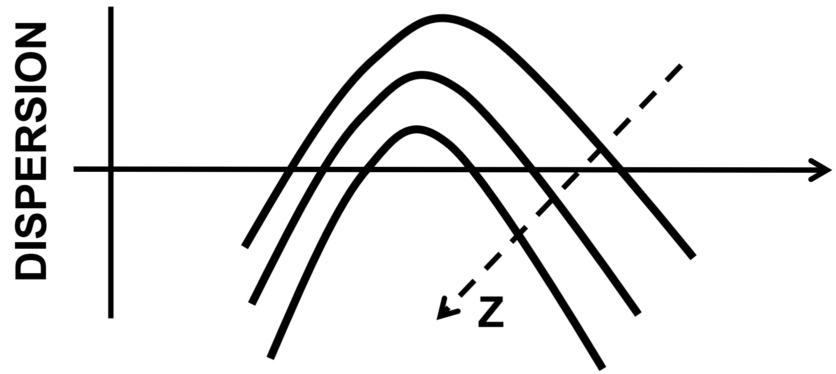


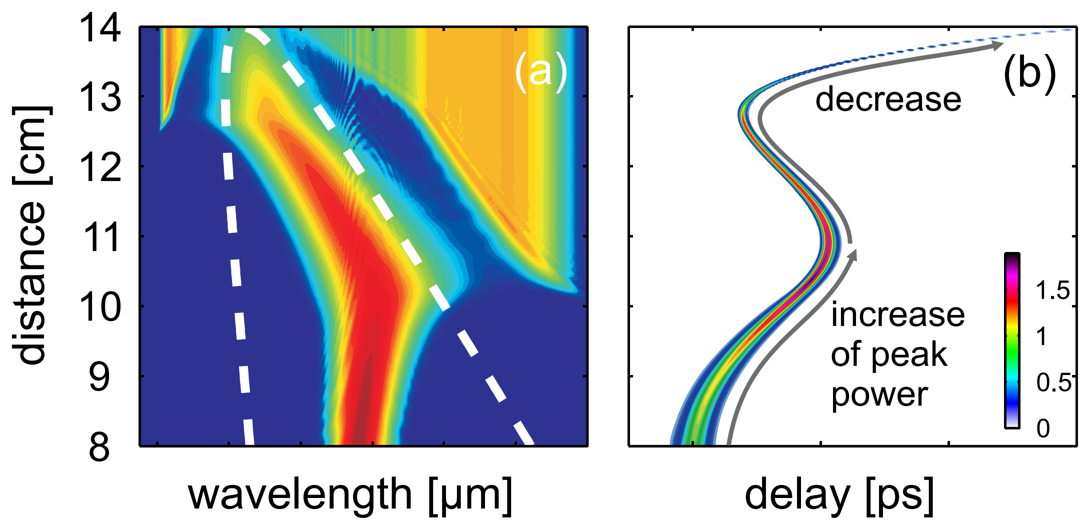




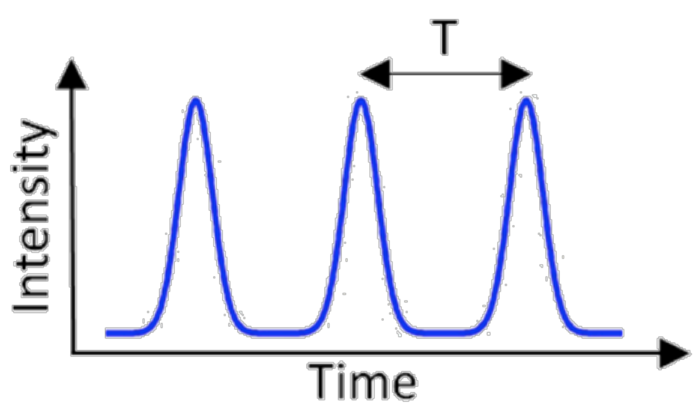
BTW, also possible in tapered fibers

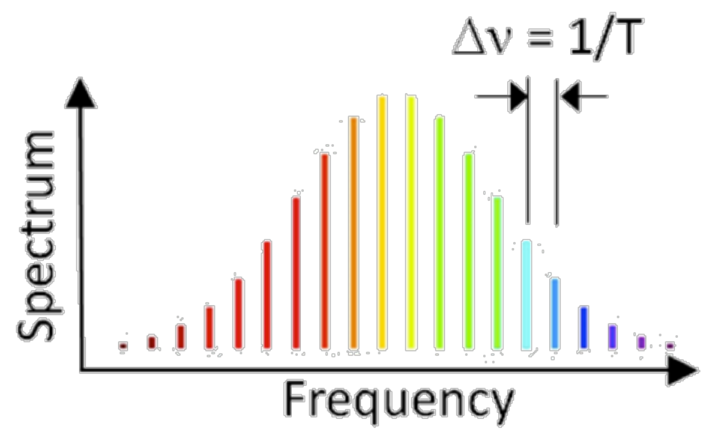
- Solitons self-frequency **blue-**shift Stark et al., PRL 106, 083903 (2011)

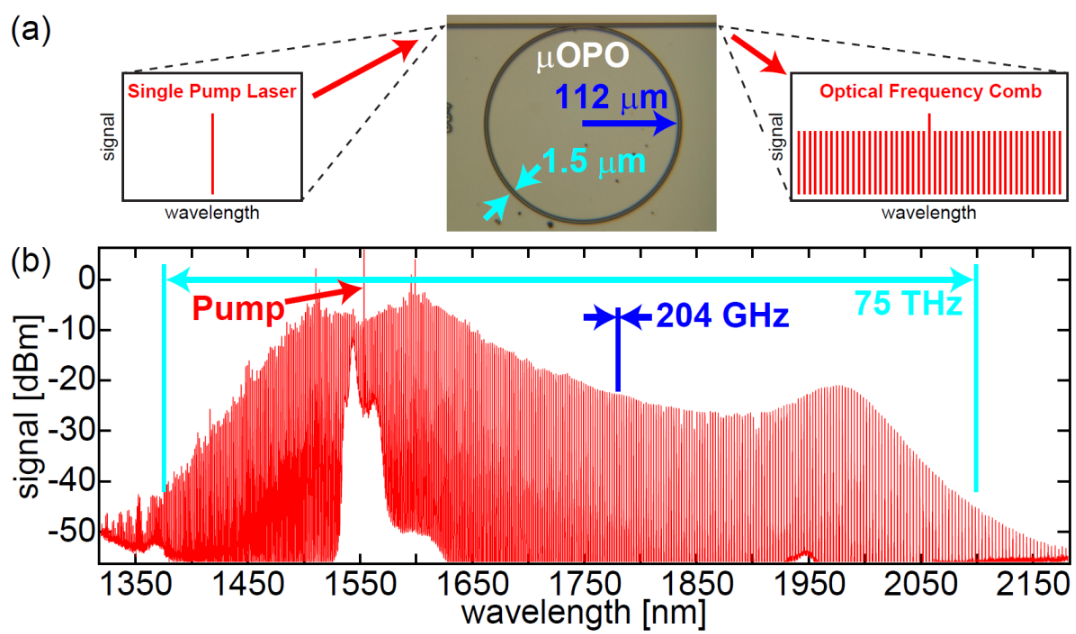




Soliton and frequency combs







Foster et al., Optics Express 19, 14233 (2011)

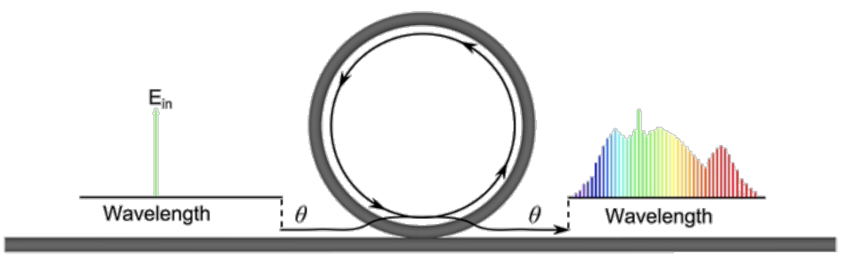
Soliton dynamics at the micron scale

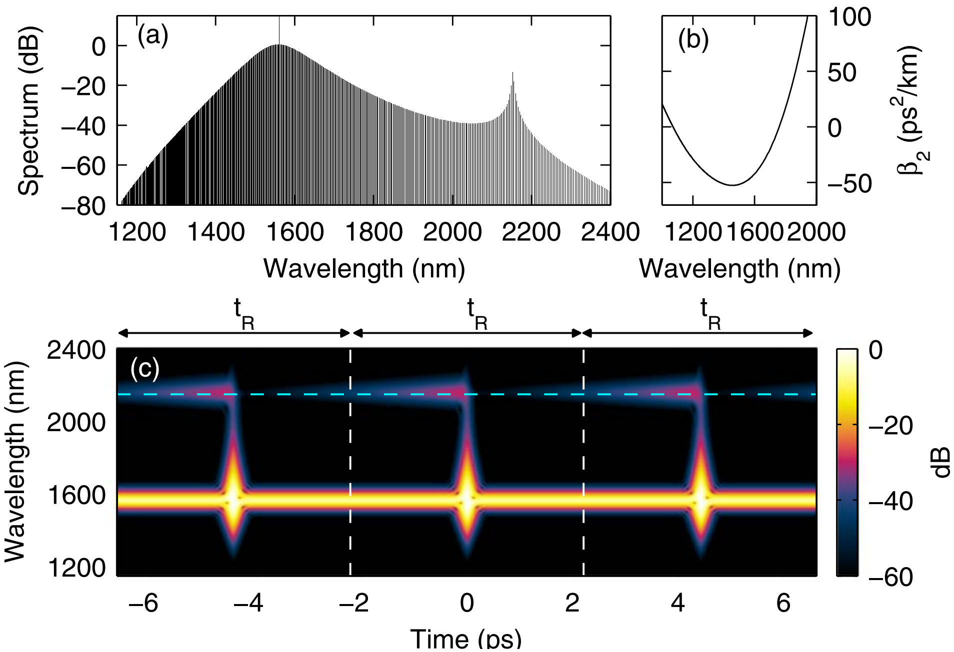
- Soliton dynamics also in microresonator frequency combs

Coen et al., OL 38, 37 (2013)

$$t_R \frac{\partial E(t,\tau)}{\partial t} = \left[-\alpha - i\delta_0 + iL \sum_{k\geq 2} \frac{\beta_k}{k!} \left(i \frac{\partial}{\partial \tau} \right)^k + i\gamma L |E|^2 \right] E + \sqrt{\theta} E_{\mathrm{in}},$$

Lugiato-Lefever model

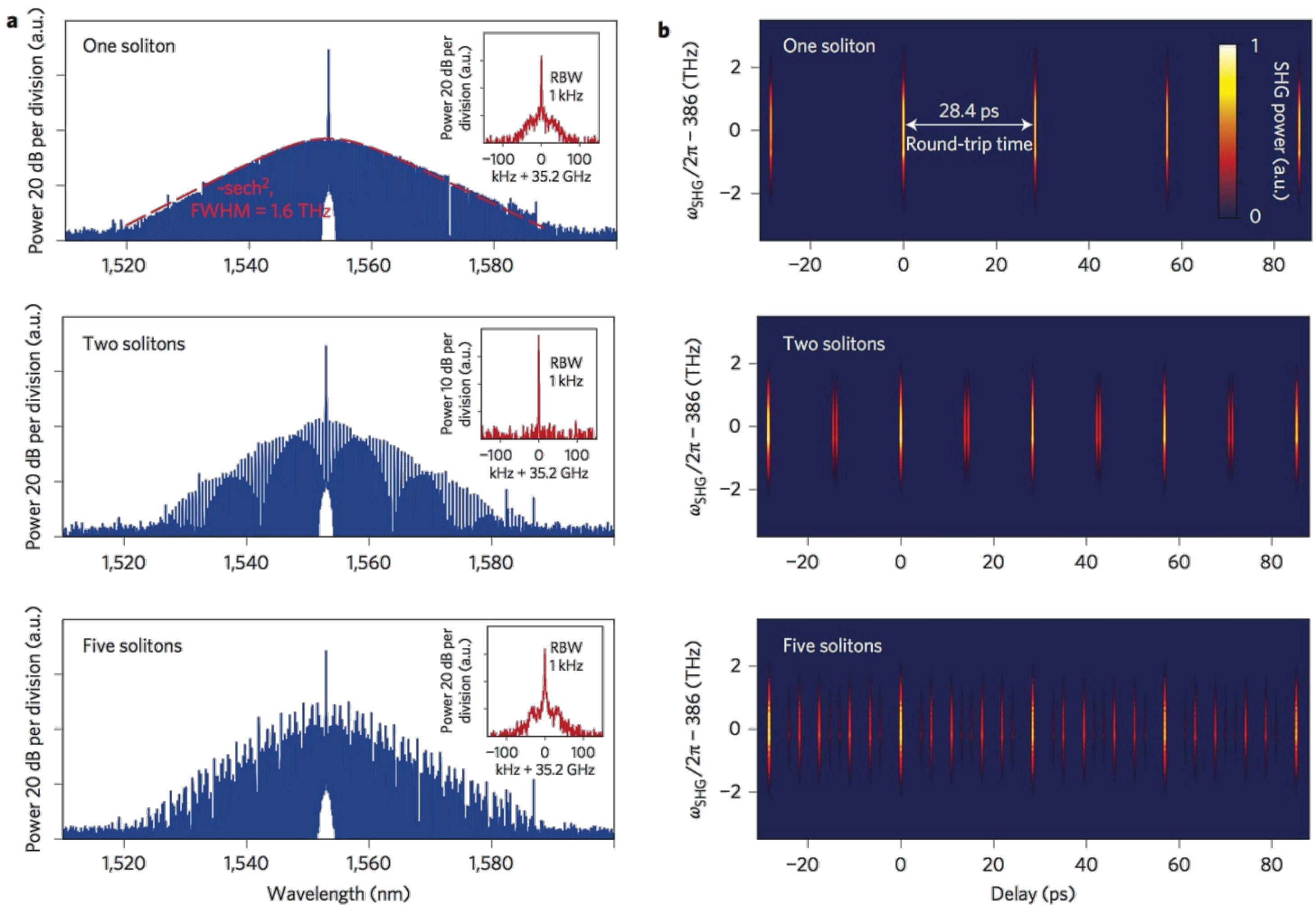




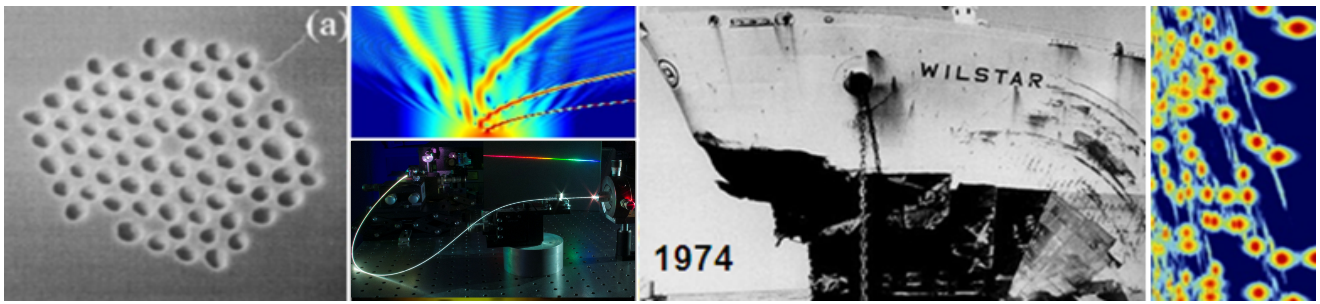
Soliton dynamics at the micron scale

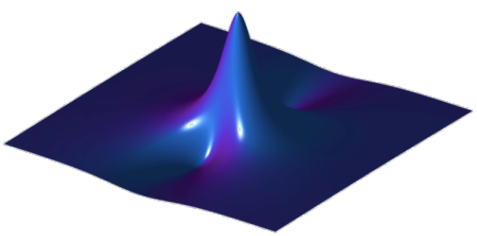
- Soliton dynamics also in microresonator frequency combs

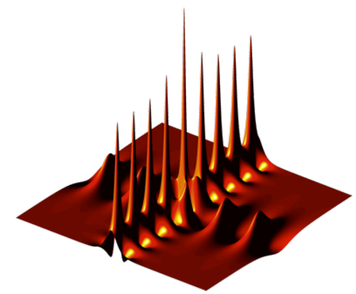
Herr et al., Nat. Photon. 8, 145–152 (2014)



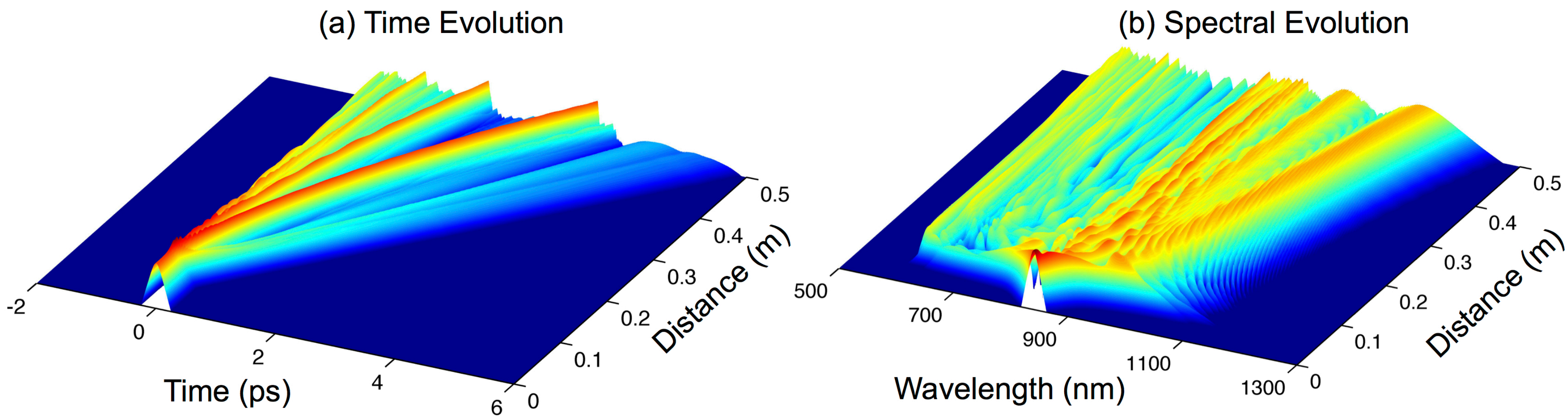
The long pulse regime: nonlinear instabilities et extreme events





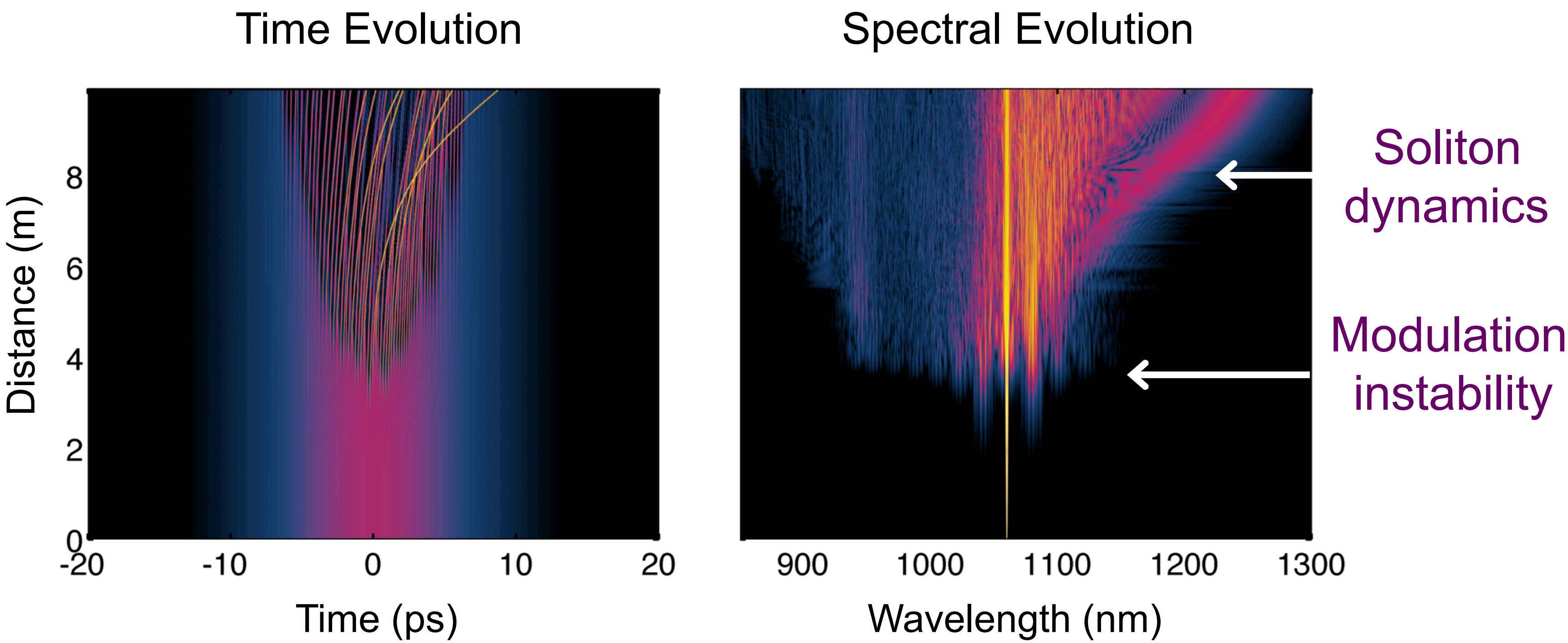


Dynamics are rather complex…



	Short pulses	Long pulses
Anomalous	• Soliton • Dispersive waves	• Modulation instability • Solitons dynamics
Normal	• Self-phase modulation • Four-wave mixing	• Raman scattering • Four-wave mixing

SC generation with long pulses

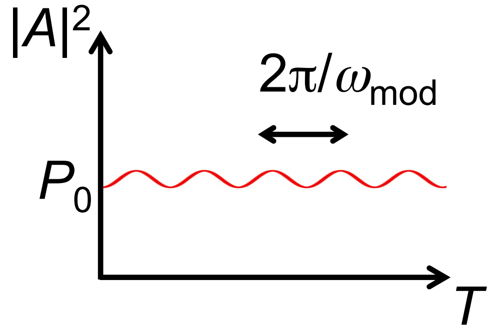


- Modulation instability is seeded by noise (ASE, intensity-noise…etc)

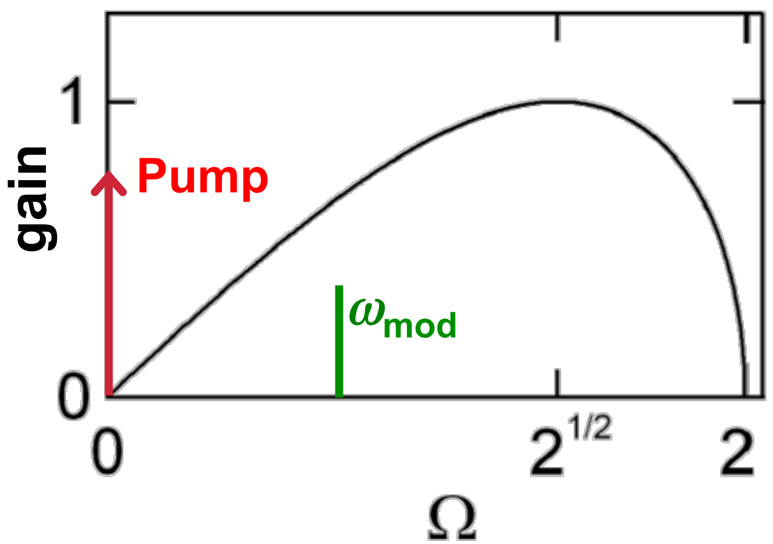
Modulation instability

- Single frequency excitation

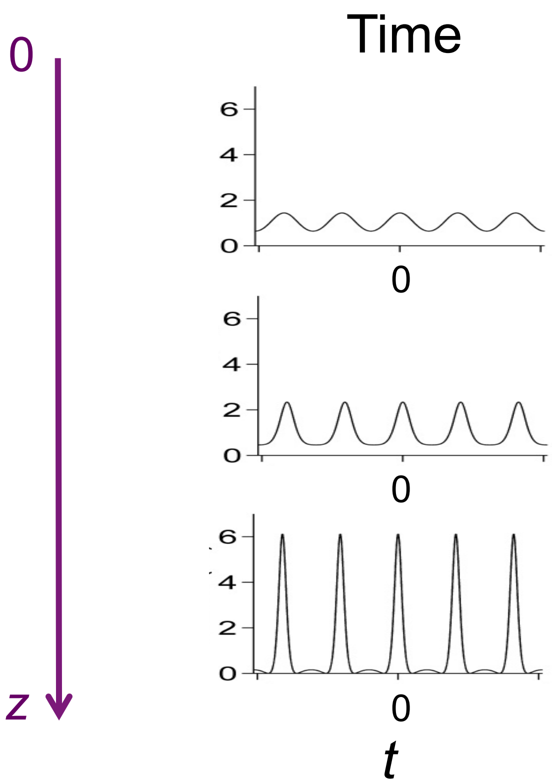
$$A(T) = \sqrt{P_0}\left[1 + \delta\cos(\omega T)\right]$$



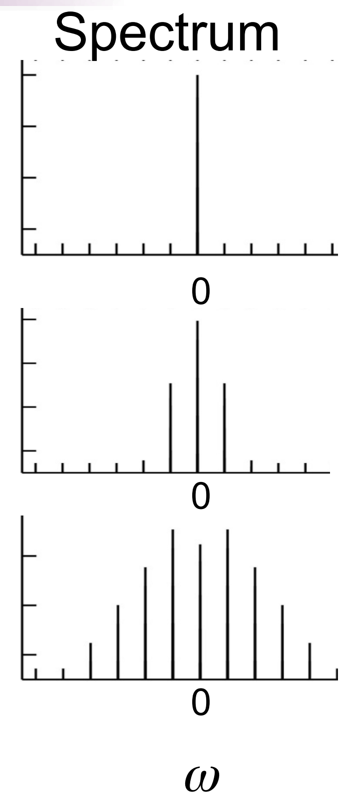
- Gain for a range of frequencies



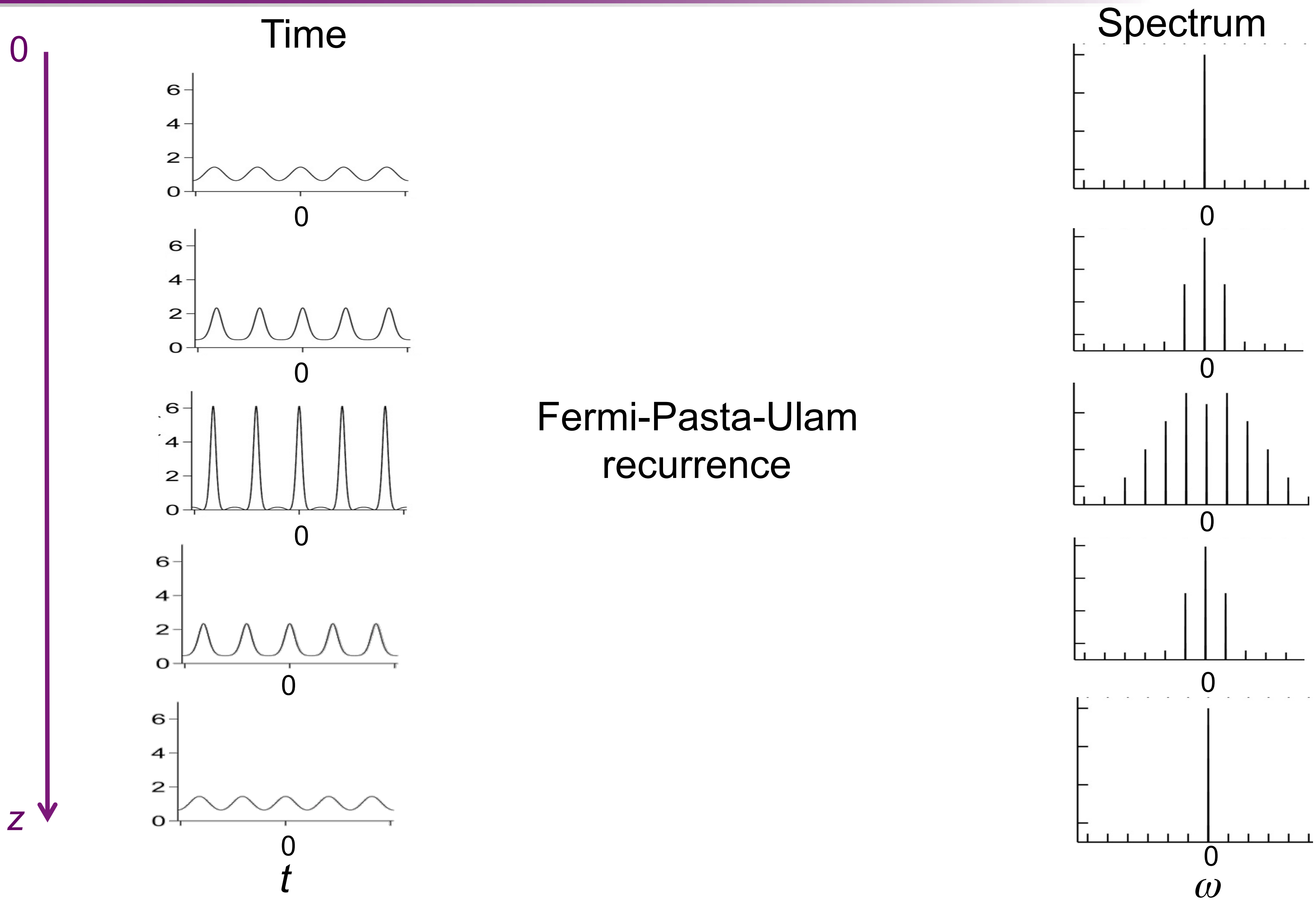
Modulation instability



Modulation grows exponentially

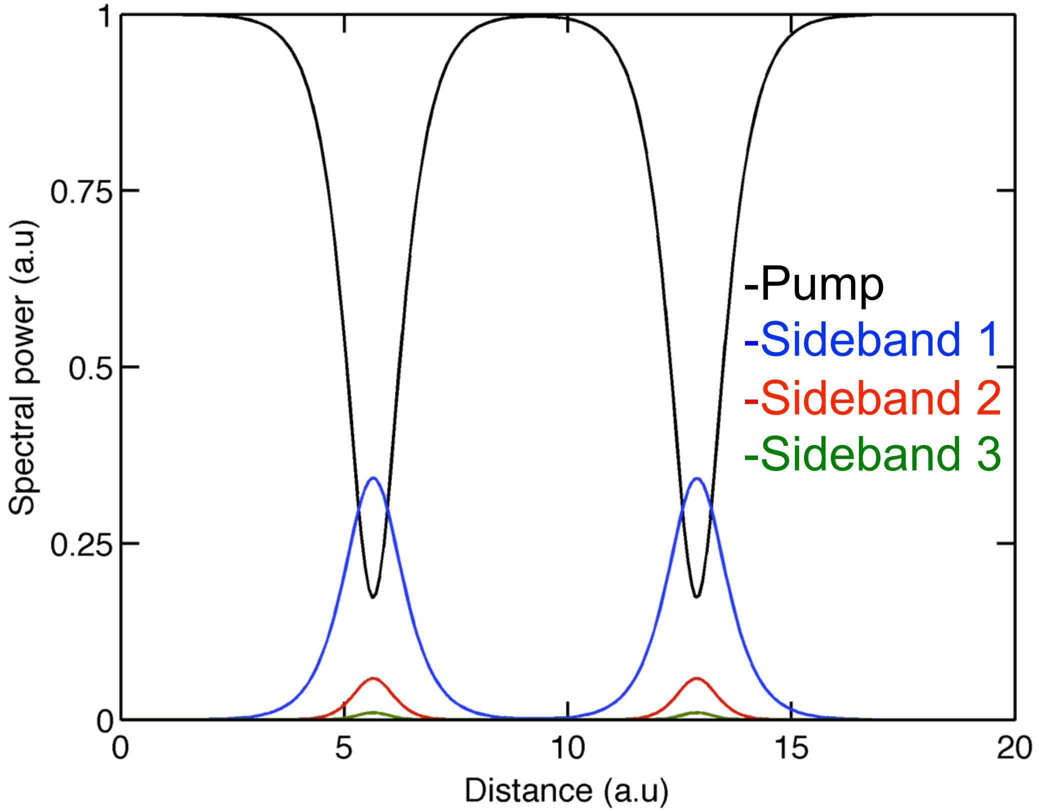


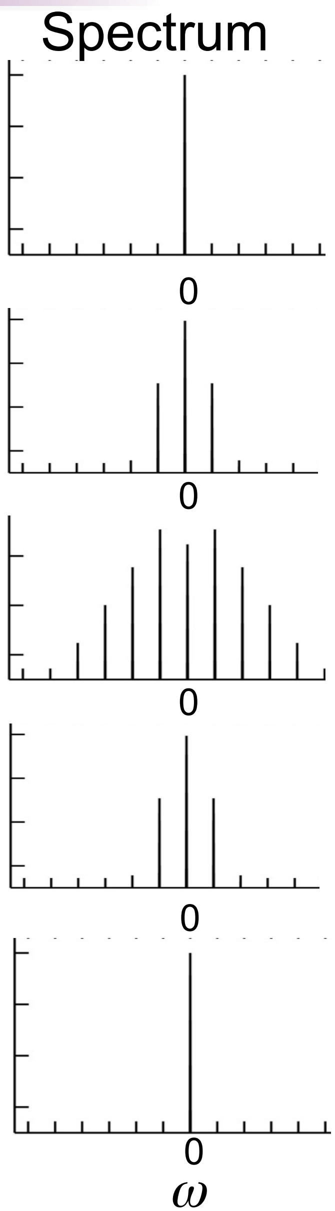
Modulation instability



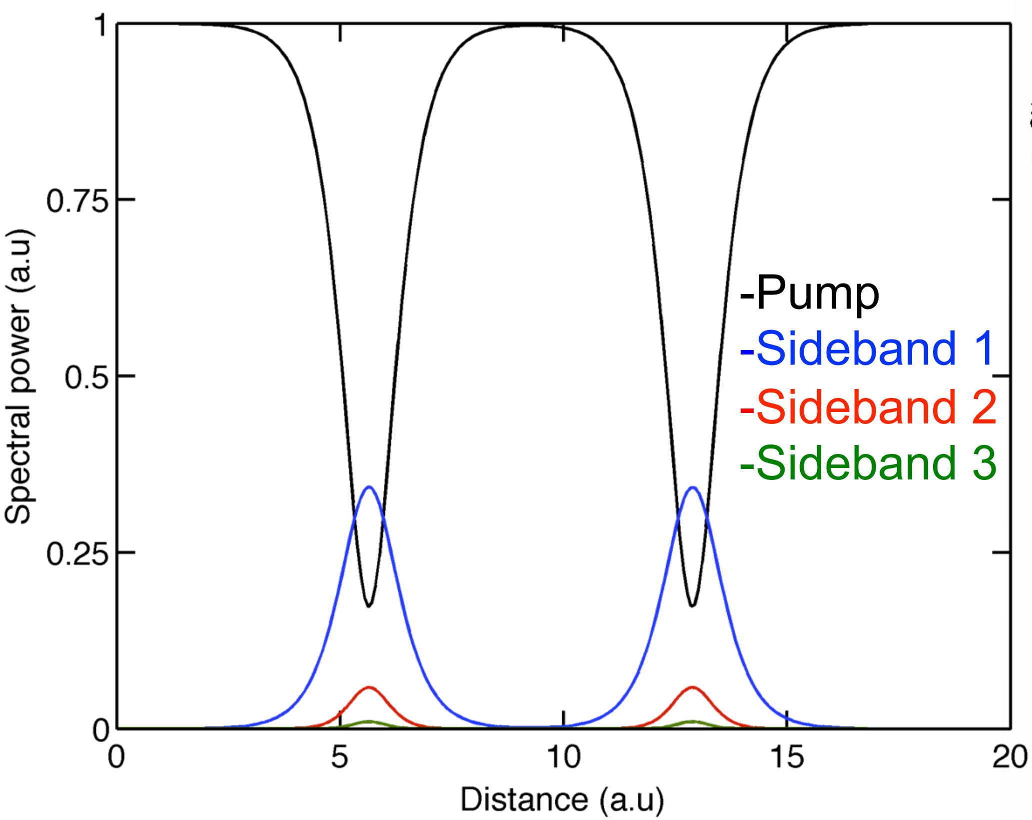
Fermi-Pasta-Ulam
recurrence

FPU recurrence



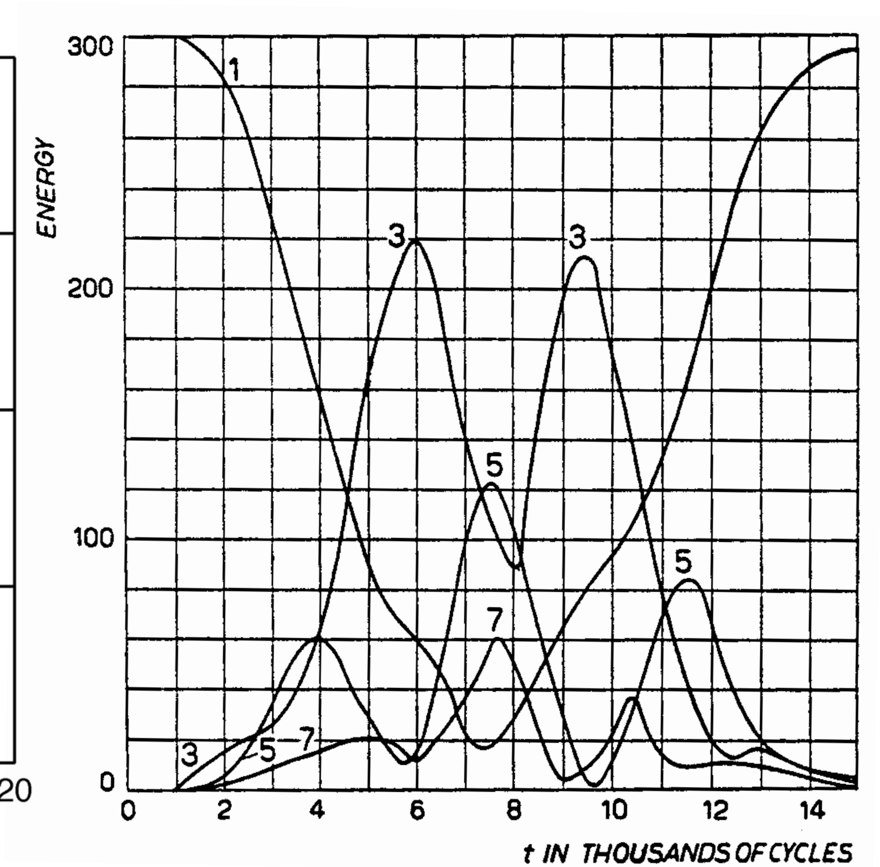


FPU recurrence

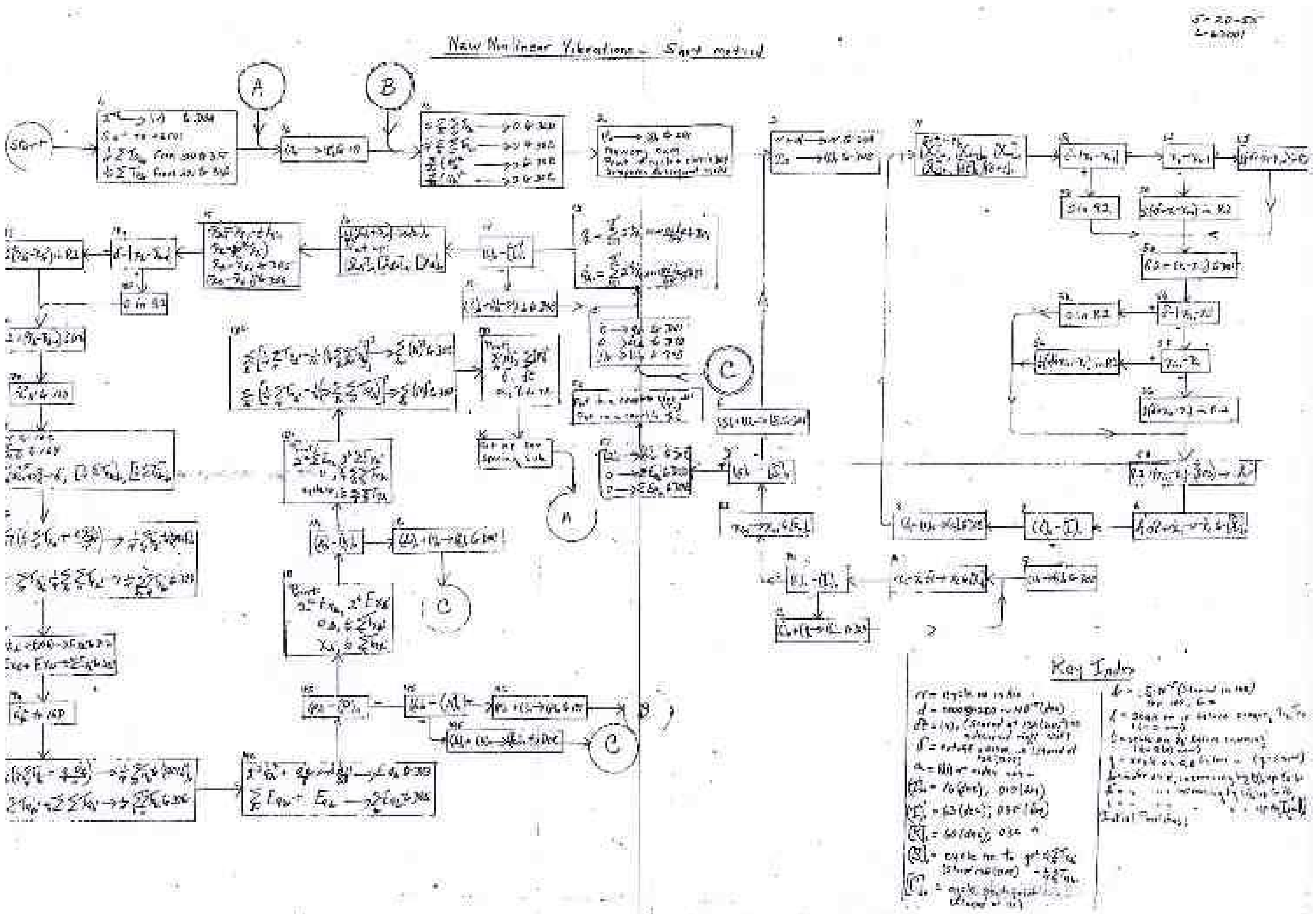


STUDIES OF NON LINEAR PROBLEMS

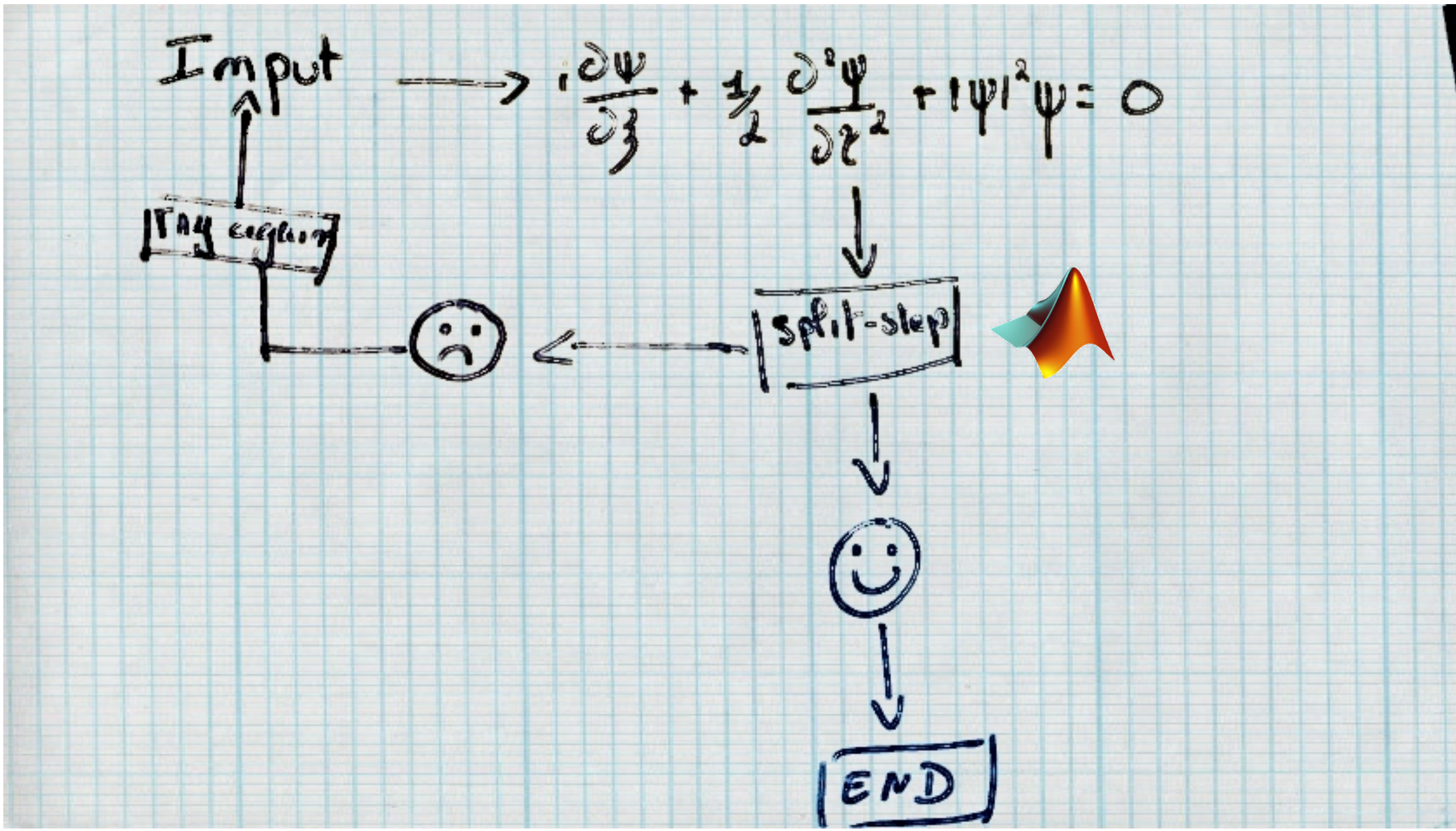
E. FERMI, J. PASTA, and S. ULAM
Document LA-1940 (May 1955).



FPU recurrence

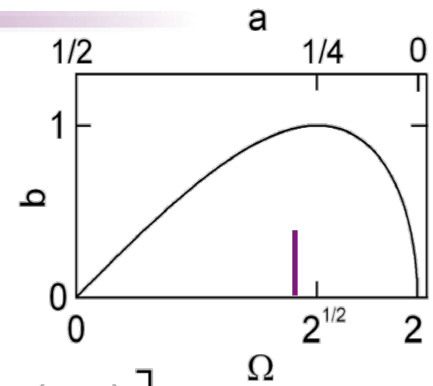


Luckily, it's more simple these days…



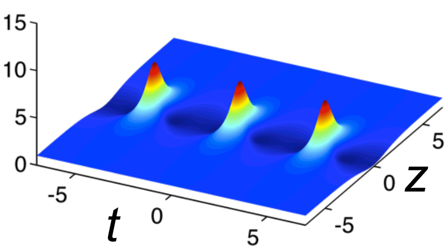
Solitons on finite background (SFBs)

- **Highly localized** solutions of the NLS
- **Single**-parameter family of solutions



$$\psi(\xi,\tau) = e^{i\xi}\left[\frac{(1-4a)\cosh(b\xi) + ib\sinh(b\xi) + \sqrt{2a}\cos(\Omega\tau)}{\sqrt{2a}\cos(\Omega\tau) - \cosh(b\xi)}\right]$$

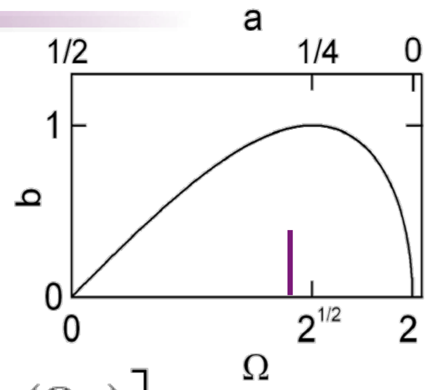
$0 < a < 1/2$



Akhmediev breather (AB)

N. Akhmediev & V. Korneev, Theor. Math. Phys. 69, 1089 (1986)

Solitons on finite background (SFBs)



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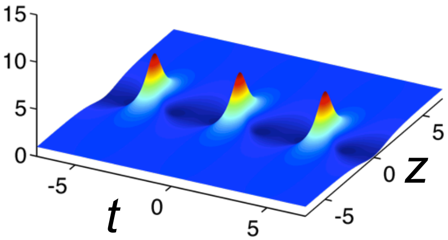
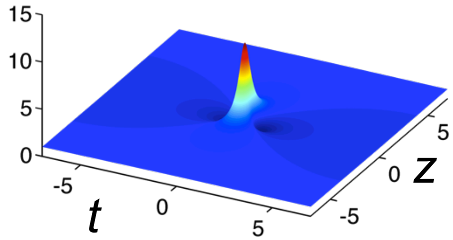


Akhmediev breather (AB)

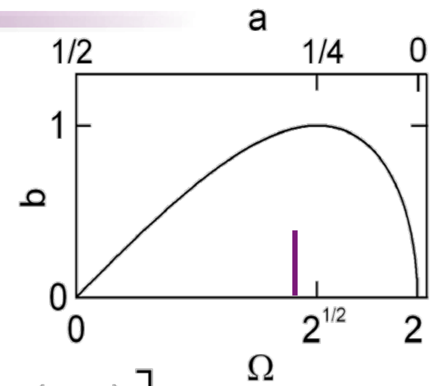
$a = 1/2$



Peregrine soliton (PS)

N. Akhmediev & V. Korneev, Theor. Math. Phys. 69, 1089 (1986)

Solitons on finite background (SFBs)



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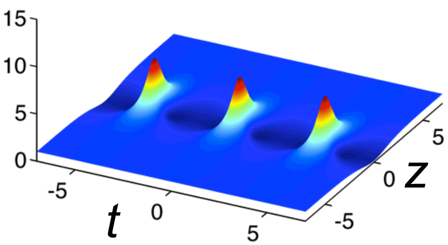
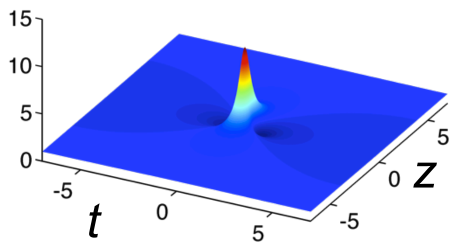


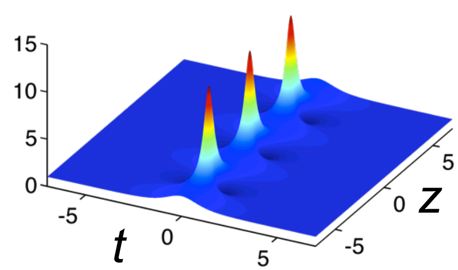
Akhmediev breather (AB)

$a = 1/2$



Peregrine soliton (PS)

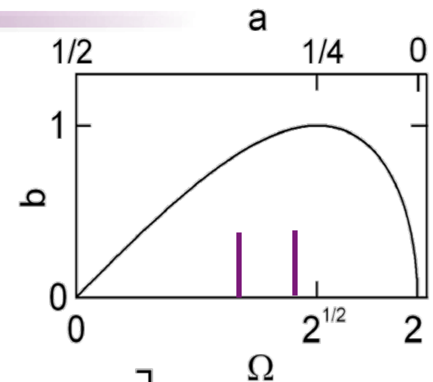
$1/2 < a$



Kuznetsov-Ma soliton (KM)

N. Akhmediev & V. Korneev, Theor. Math. Phys. 69, 1089 (1986)

Solitons on finite background (SFBs)



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- **Single**-parameter family of solutions

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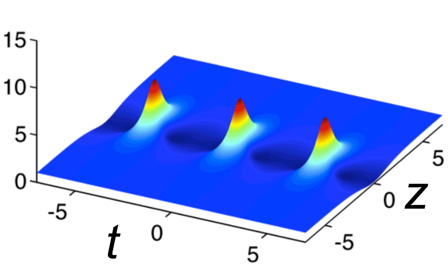
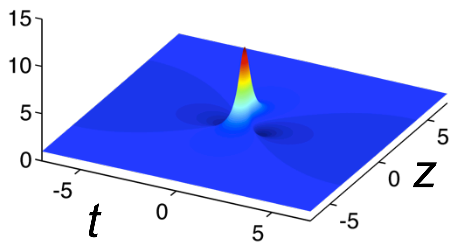
$0 < a < 1/2$



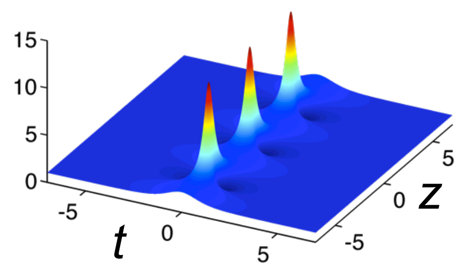
Akhmediev breather (AB)

$a = 1/2$



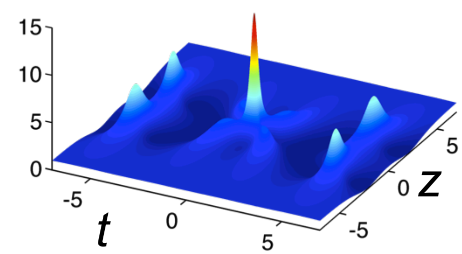
Peregrine soliton (PS)

$1/2 < a$



Kuznetsov-Ma soliton (KM)

$0 < a < 1/2$
$0 < a' < 1/2$



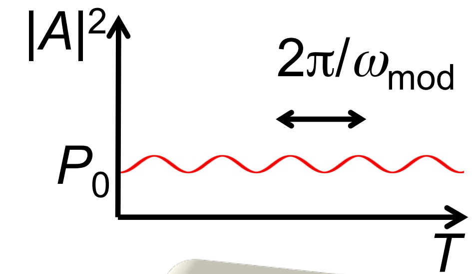
Higher-order AB

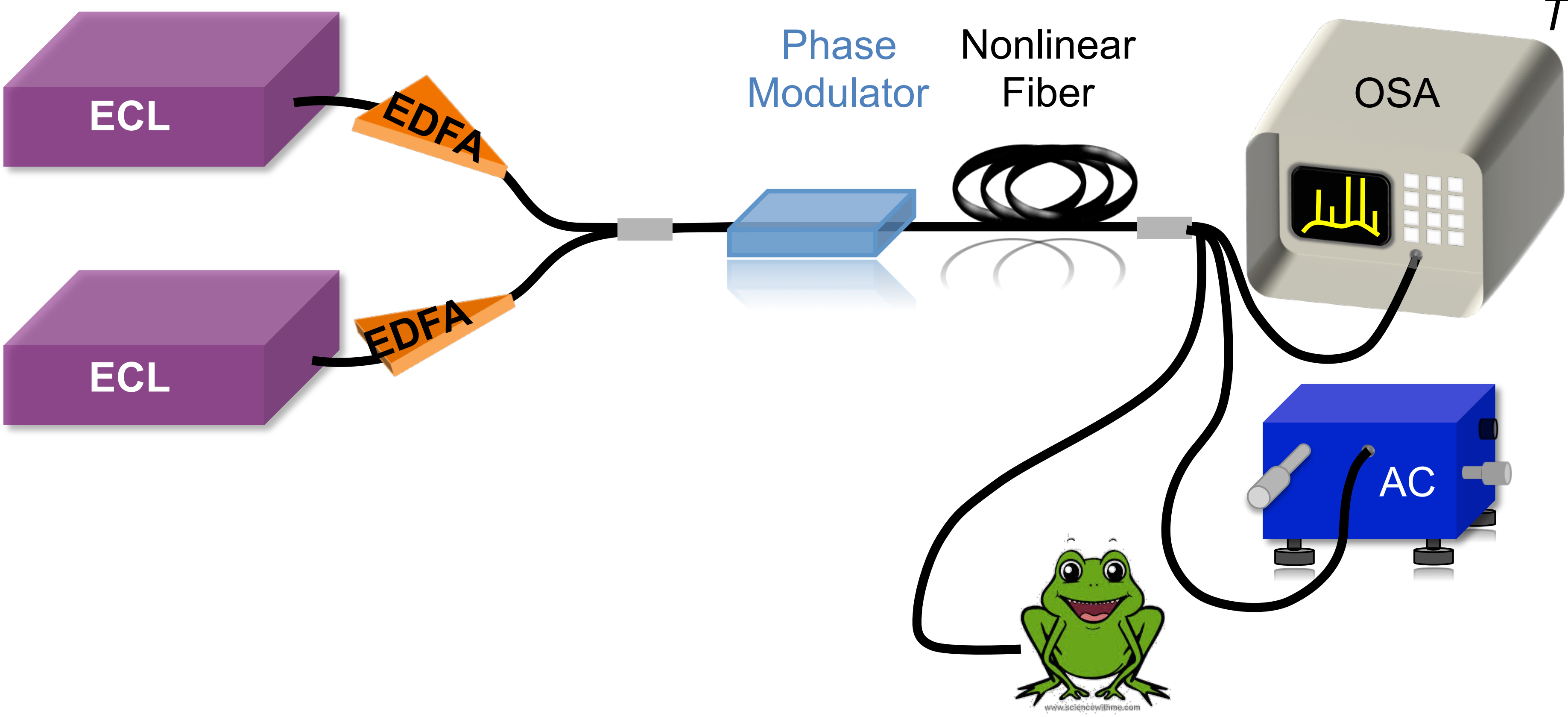
N. Akhmediev & V. Korneev, Theor. Math. Phys. 69, 1089 (1986)

Observing experimentally SFBs

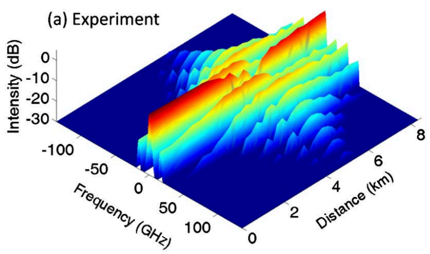
- Use of multi-frequency CW fields to generate a modulated signal

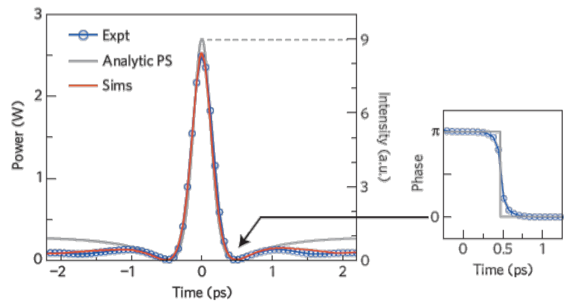
$$A(z=z_0,T)=\sqrt{P_0}[1+\alpha_{\mathrm{mod}}\exp(i\omega_{\mathrm{mod}}T)]$$

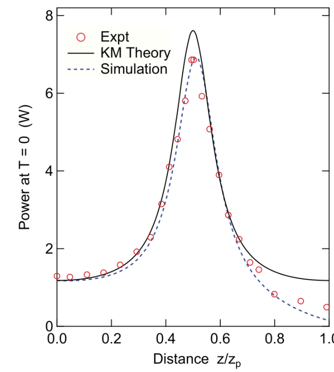


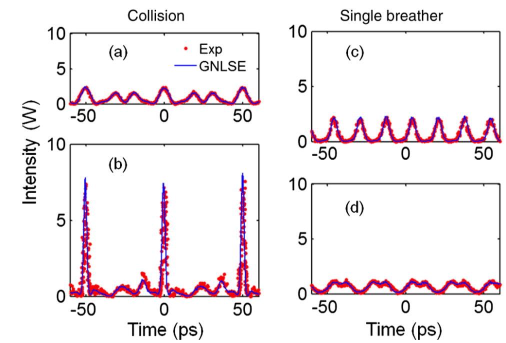


Observing experimentally SFBs

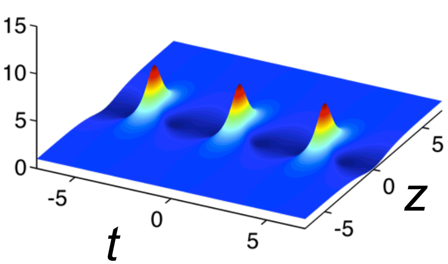








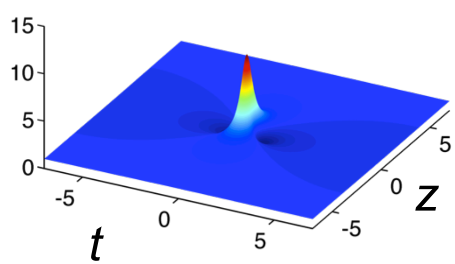
$0 < a < 1/2$



Akhmediev breather (AB)

Hammani *et al.*, OL (2011)

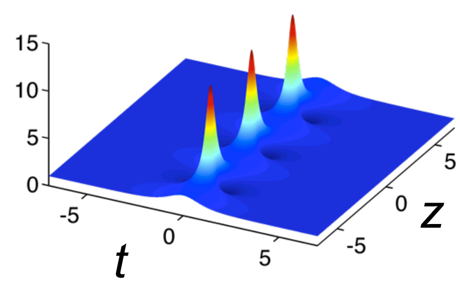
$a = 1/2$



Peregrine soliton (PS)

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

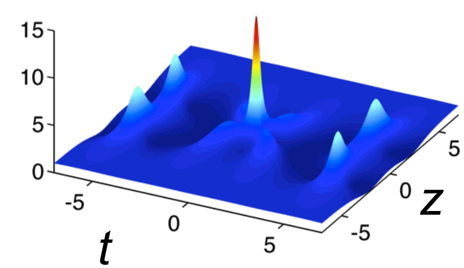
$1/2 < a$



Kuznetsov-Ma soliton (KM)

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

$0 < a < 1/2$
$0 < a' < 1/2$



Higher-order breathers

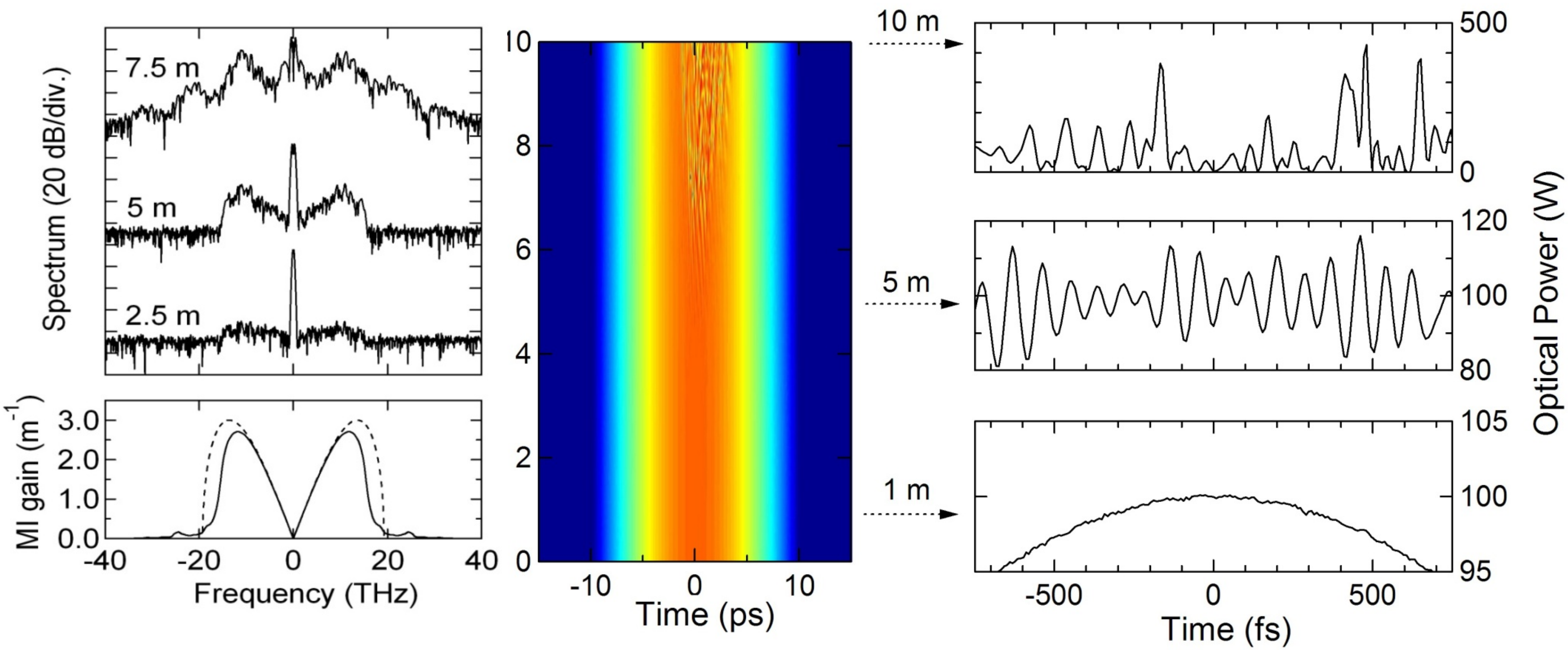
Frisquet *et al.*, PRX (2013)

Initial stage of supercontinuum with long pulses

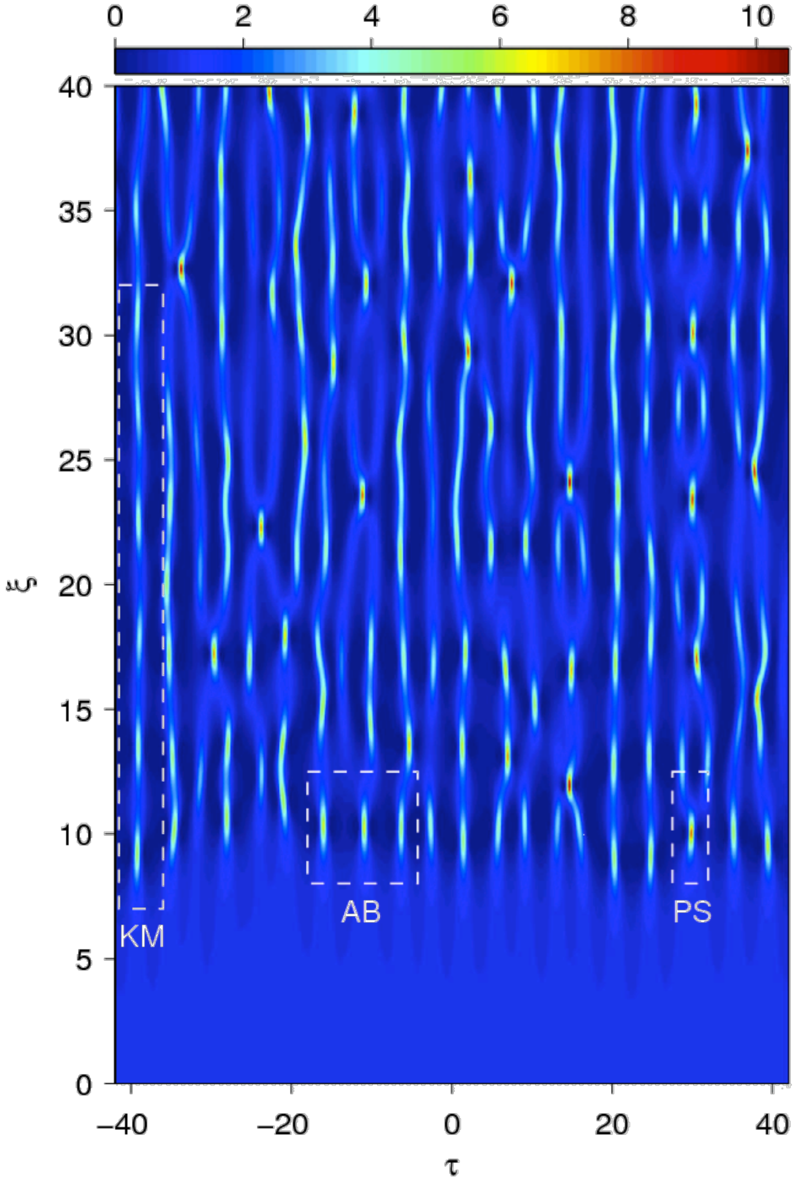
- Modulation instability seeded by noise

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

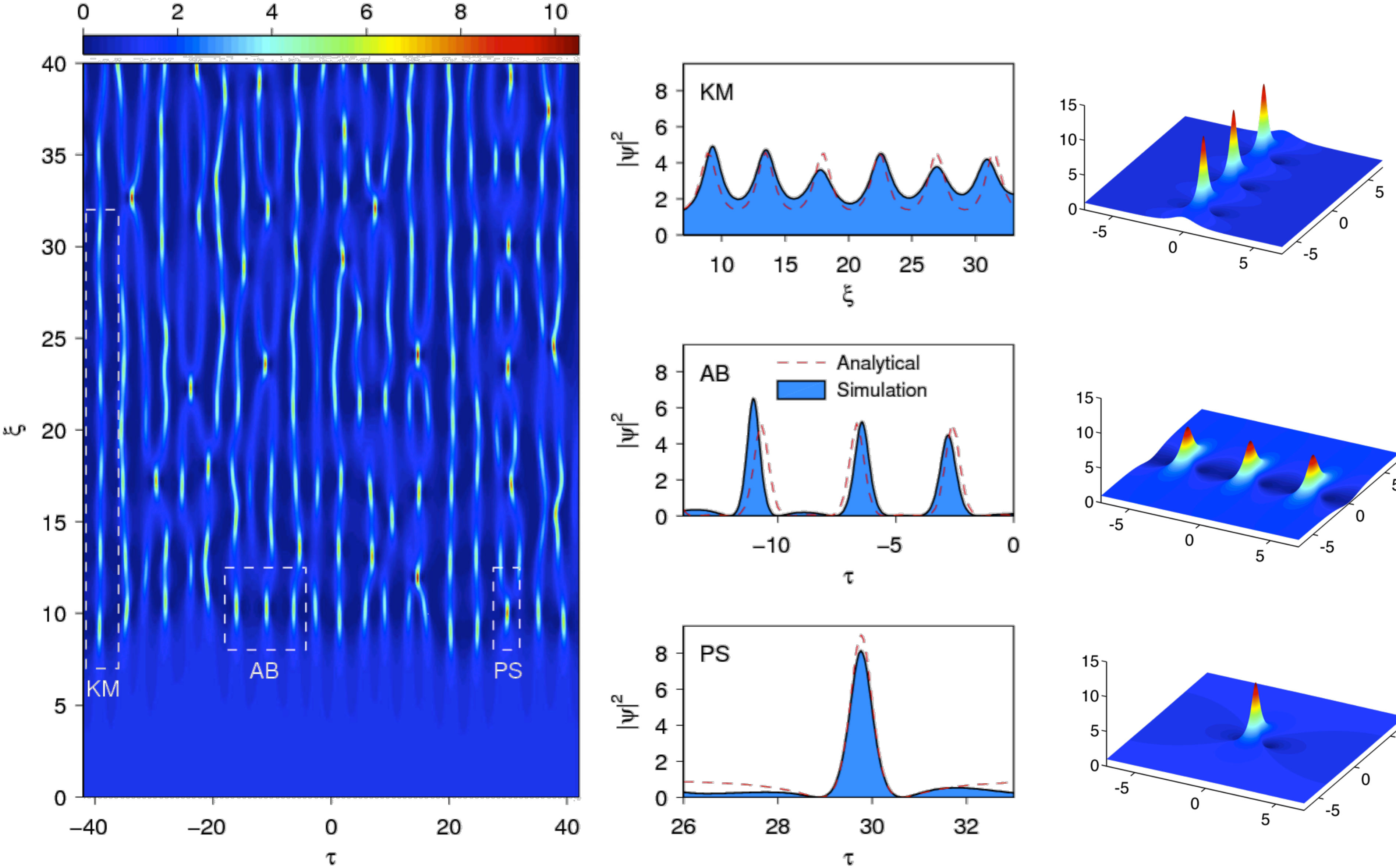
GVD Kerr effect



Signatures of SFBs in noise-seeded MI



Signatures of SFBs in noise-seeded MI



Ocean rogue waves

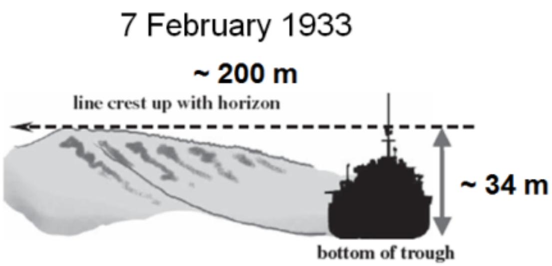
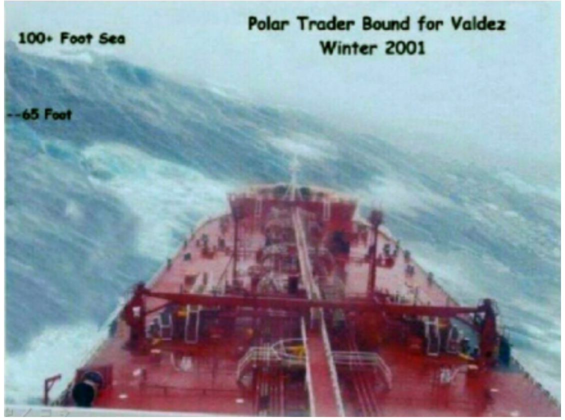
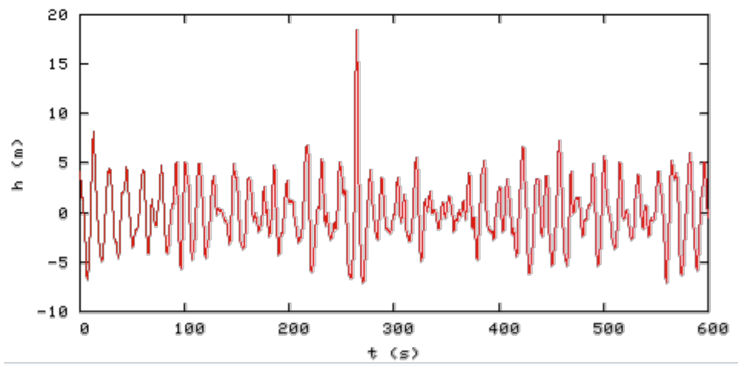


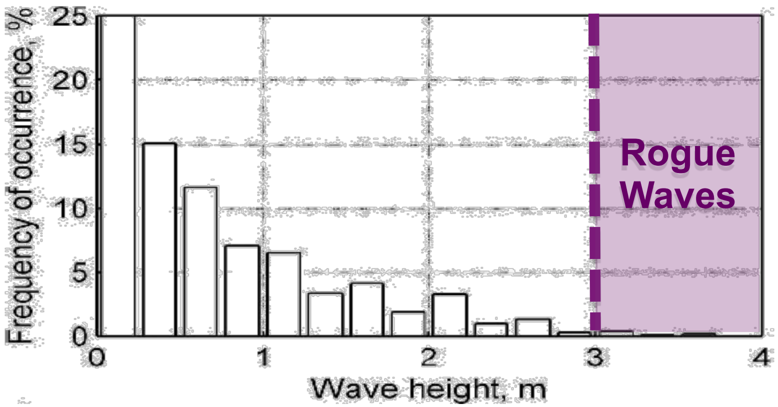
Fig. I.2 Observation of the highest reported wave by the crew members of "Ramapo" (Dennis and Wolff 1996)



Ocean rogue waves

- Rogue waves: statistically-rare wave height





- Possible mechanisms
  - Directional focusing
  - Random superposition of independent wave trains

Linear

  - Amplification of surface noise
  - Localized wave structures

Nonlinear

Linear vs. nonlinear waves

Linear waves

speed is independent of the amplitude

Nonlinear waves

speed depends on the amplitude

Linear → Nonlinear

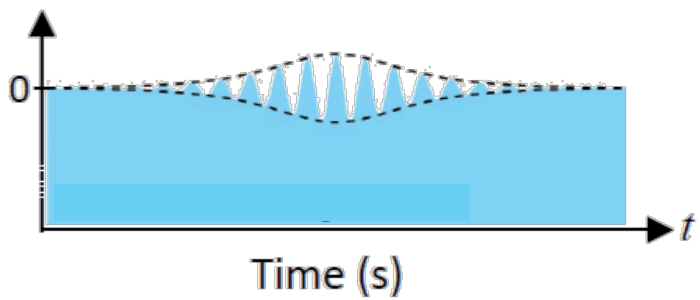
Where is the analogy with hydrodynamics?

- Initial stage: field is narrowband → NLS regime

(a) Deep water wave group envelope

$$i\frac{\partial u}{\partial z}+\frac{1}{g}\frac{\partial^2 u}{\partial t^2}+\frac{\omega_0^6}{g}\frac{\partial^2 u}{\partial t^2}=0$$

GVD **Nonlinearity**

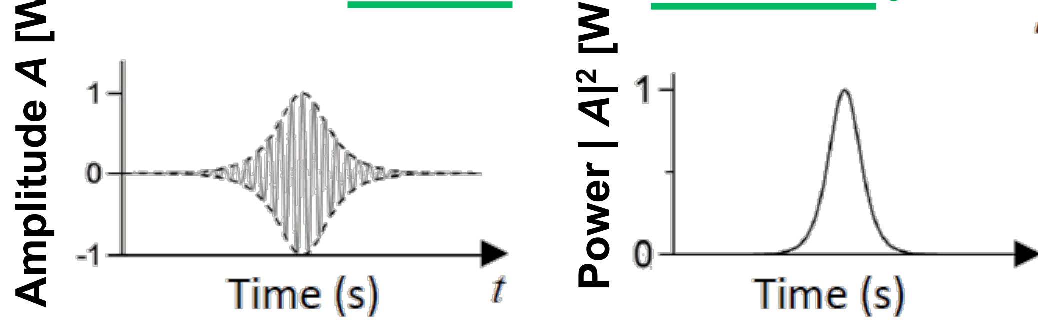


- Envelope modulating the amplitude of a group of free surface waves

(b) Light pulse envelope in fibre

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

GVD **Nonlinearity**

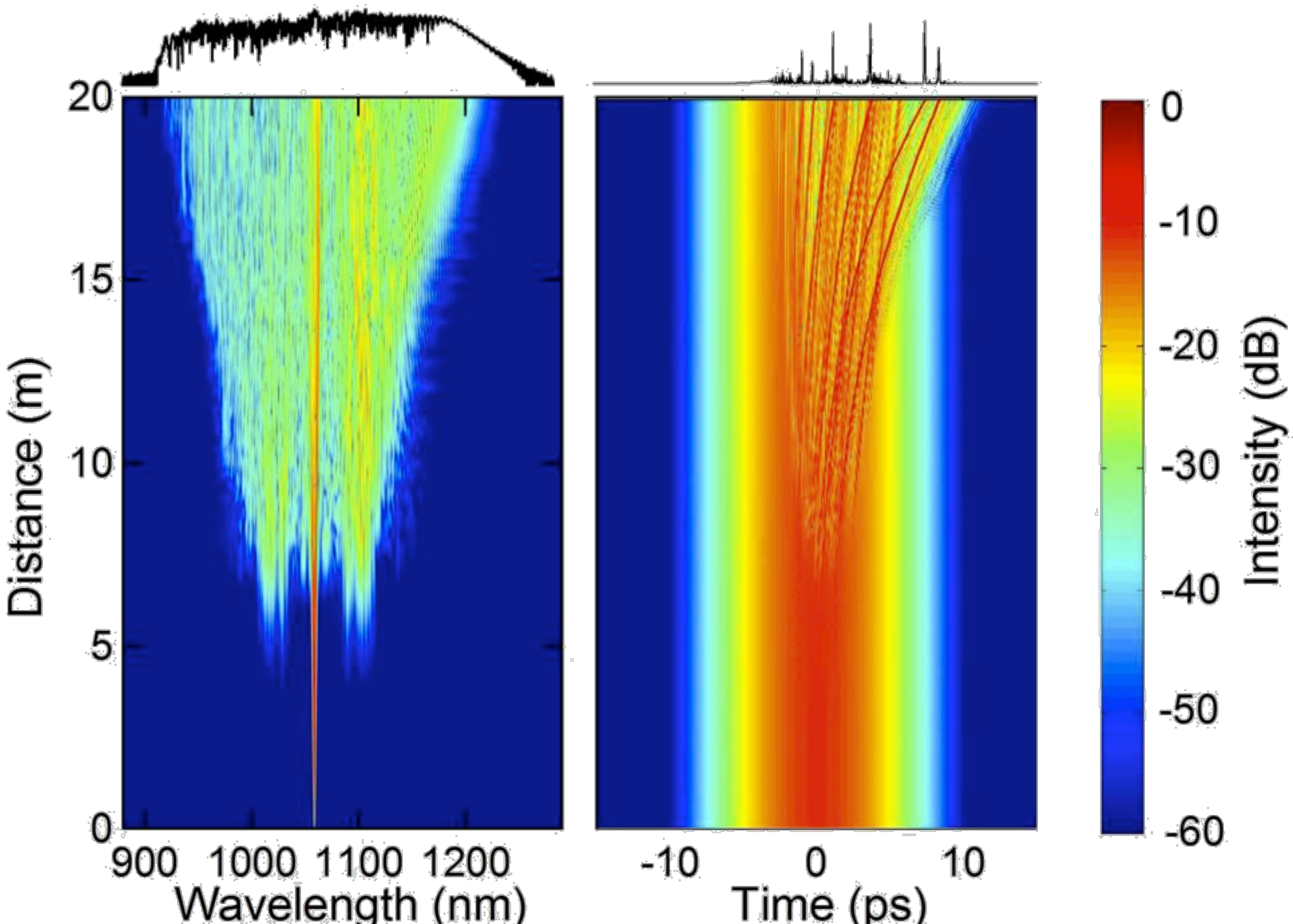


- Envelope modulating the amplitude of a large number of cycles of the electric field

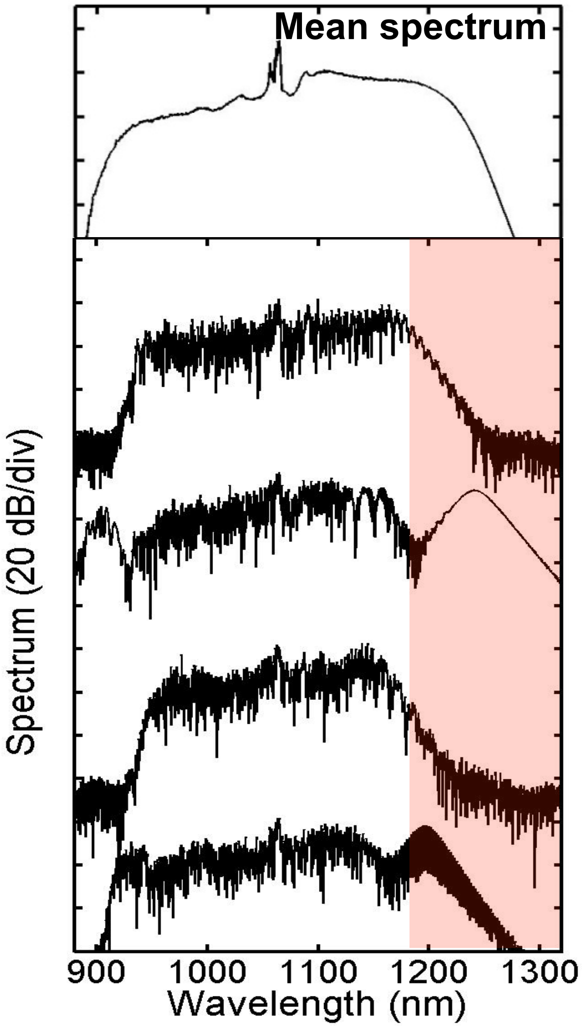
Both cases: anomalous dispersion and self-focussing

Long term soliton dynamics

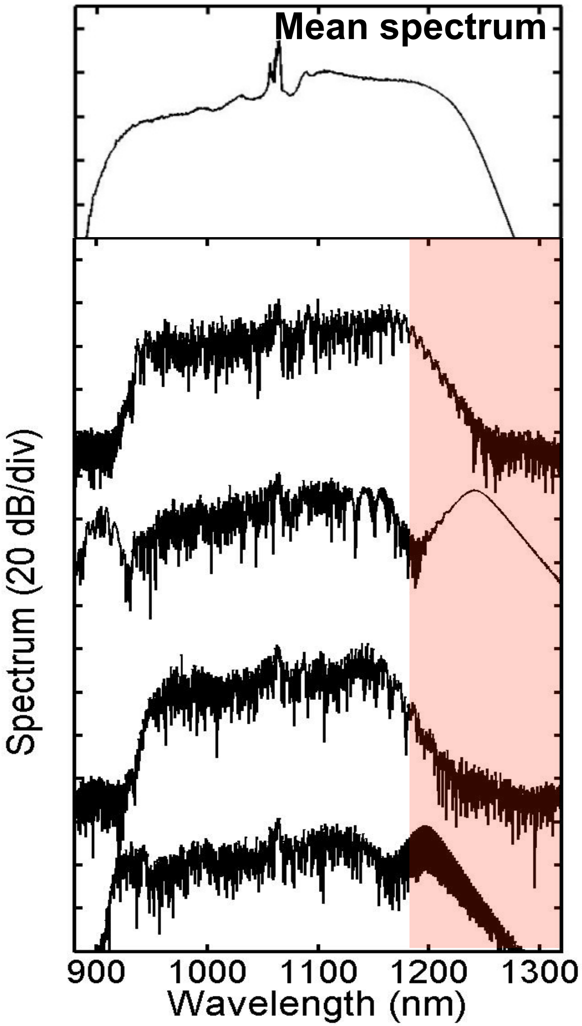
- “turbulent solitons gas”



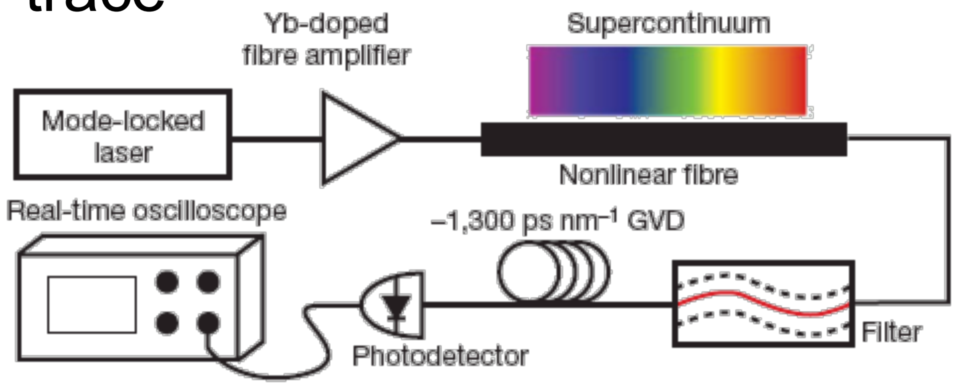
Shot-to-shot fluctuations

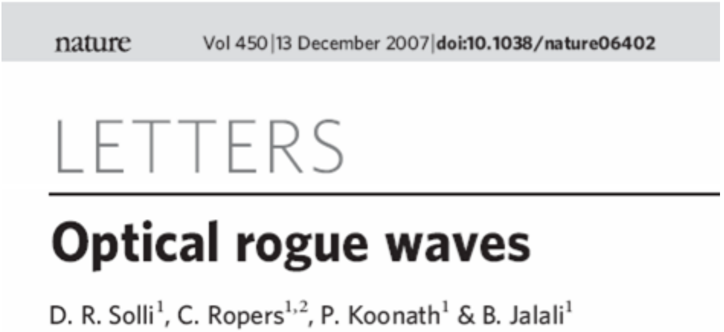


Shot-to-shot fluctuations



- Filtering selects long wavelength edge
- Dispersive fiber stretches the time trace




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

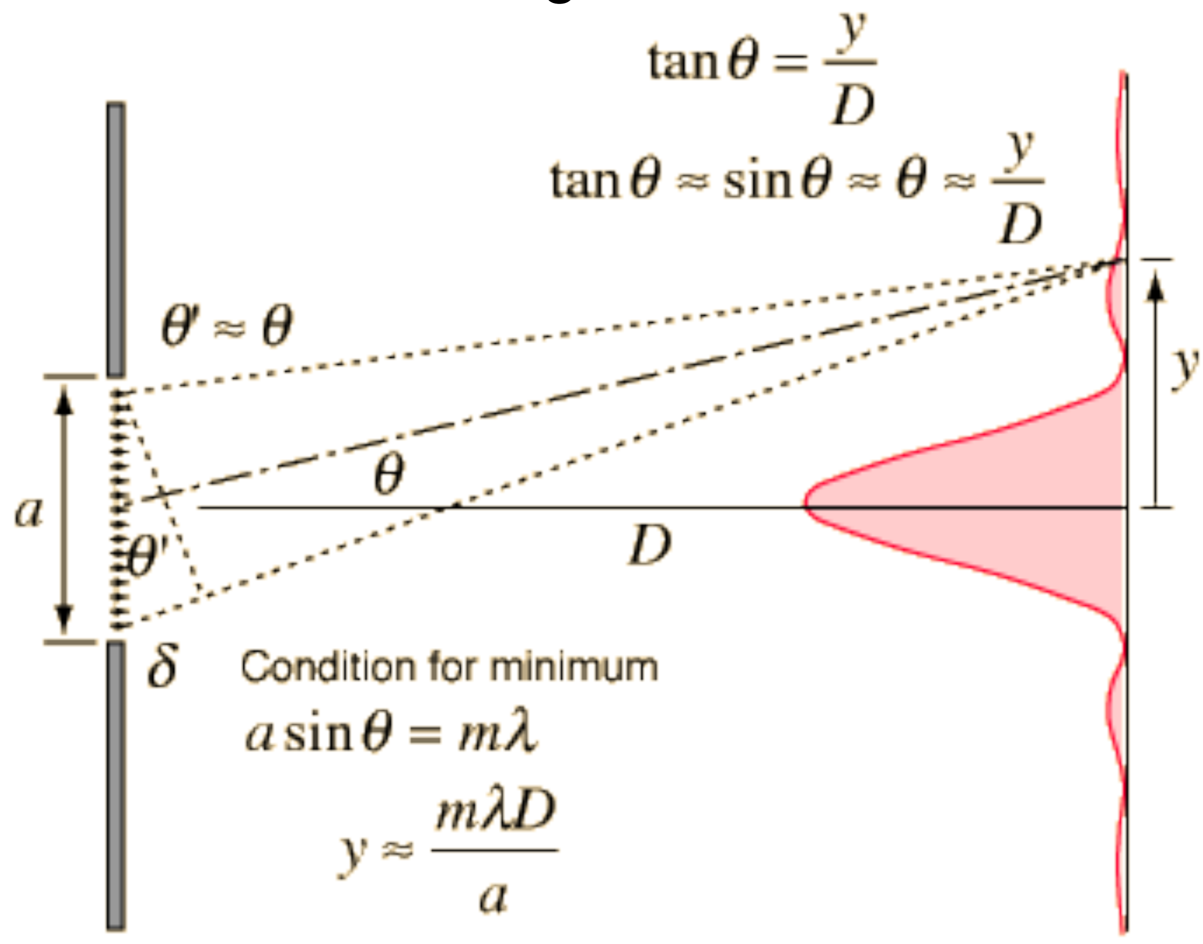
LETTERS

Optical rogue waves

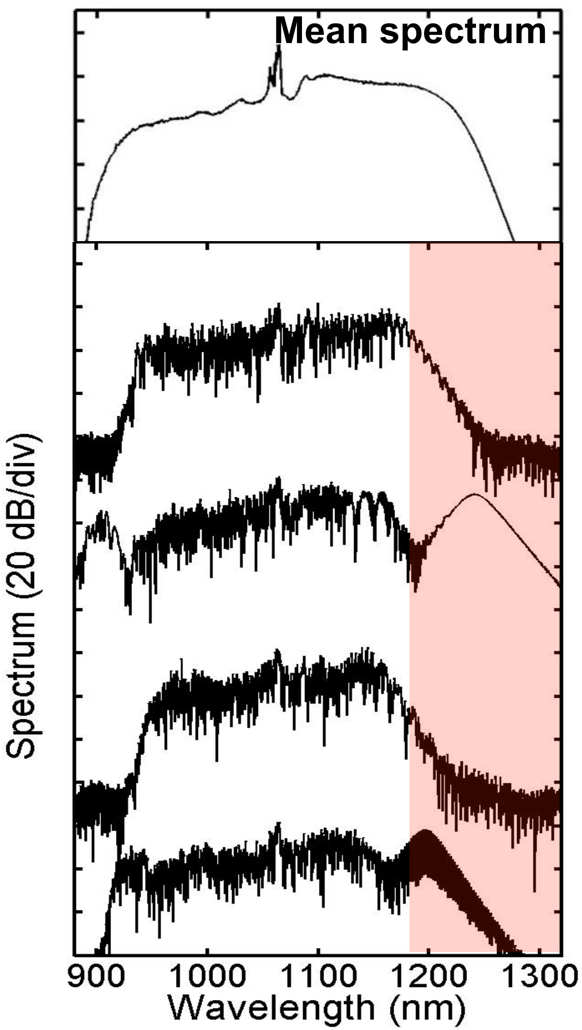
D. R. Solli[1], C. Ropers[1,2], P. Koonath[1] & B. Jalali[1]

Space-time duality

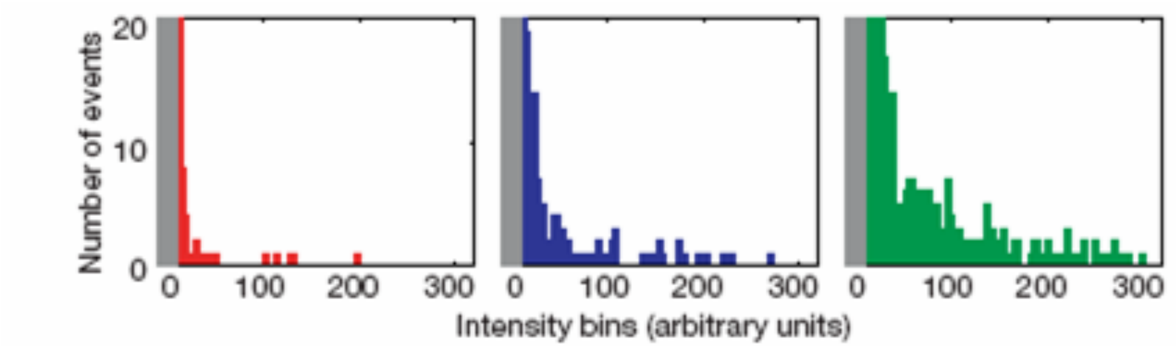
- Field diffraction pattern of an aperture is the Fourier transform of the diffracting mask

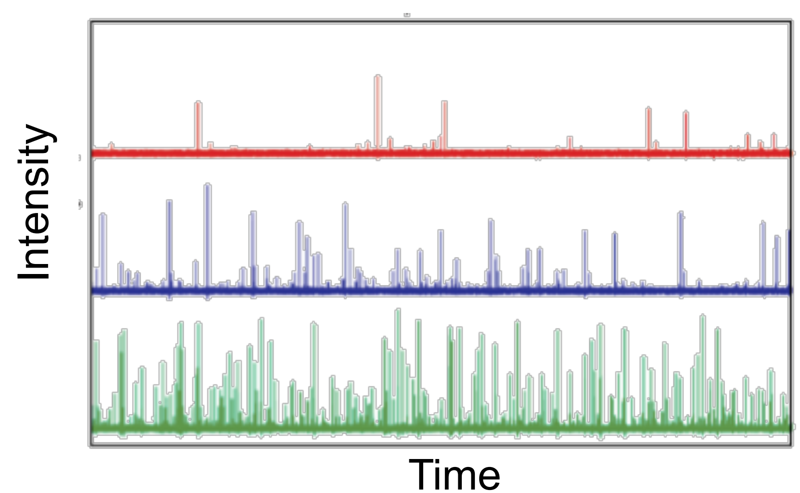


Shot-to-shot fluctuations statistics

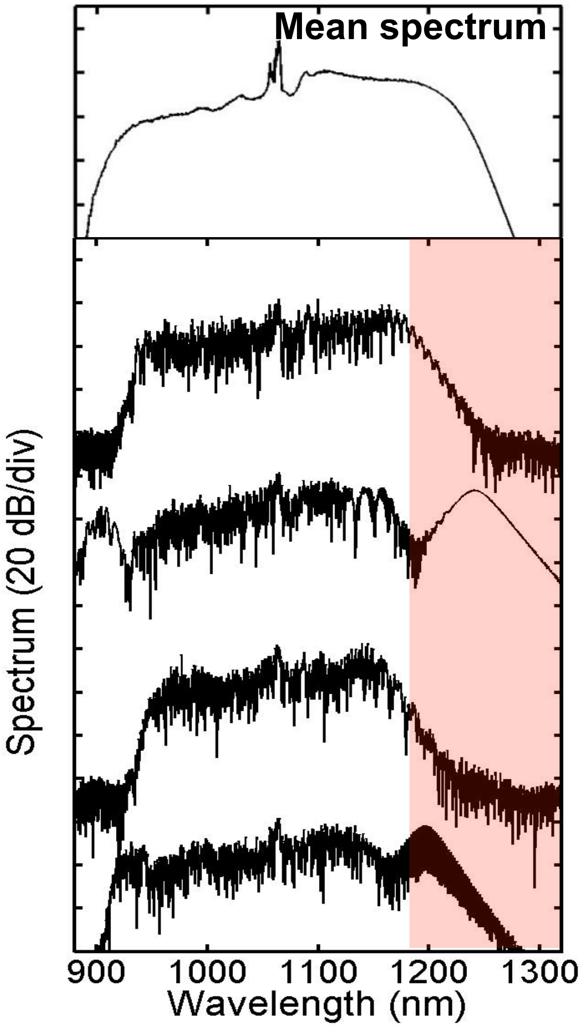


- Long tail statistics at the SC edge

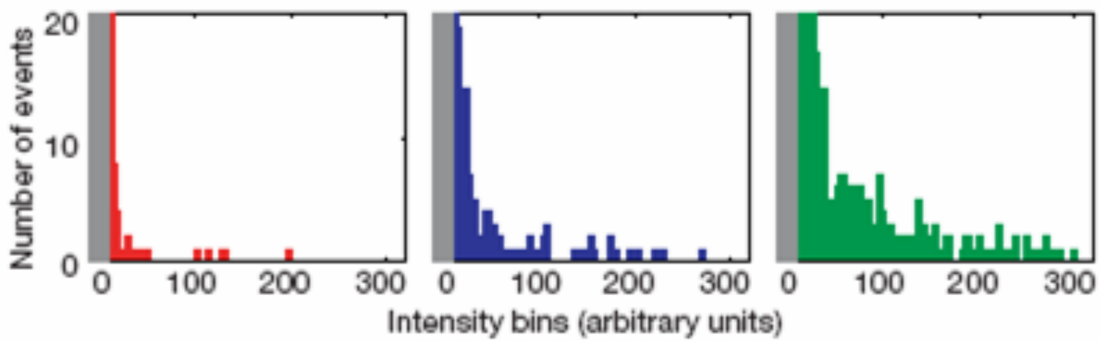


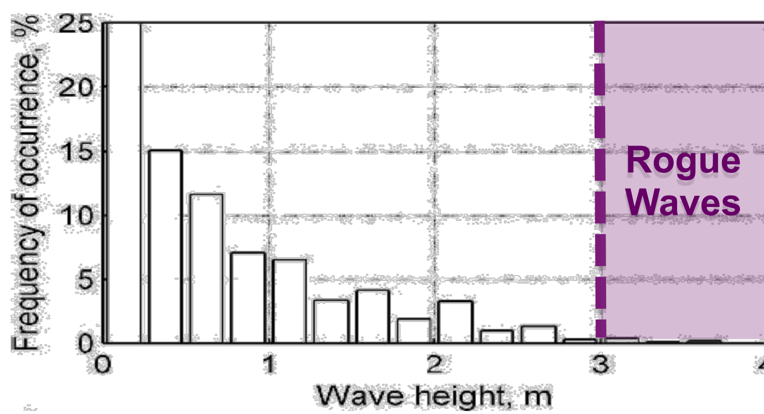


Shot-to-shot fluctuations statistics



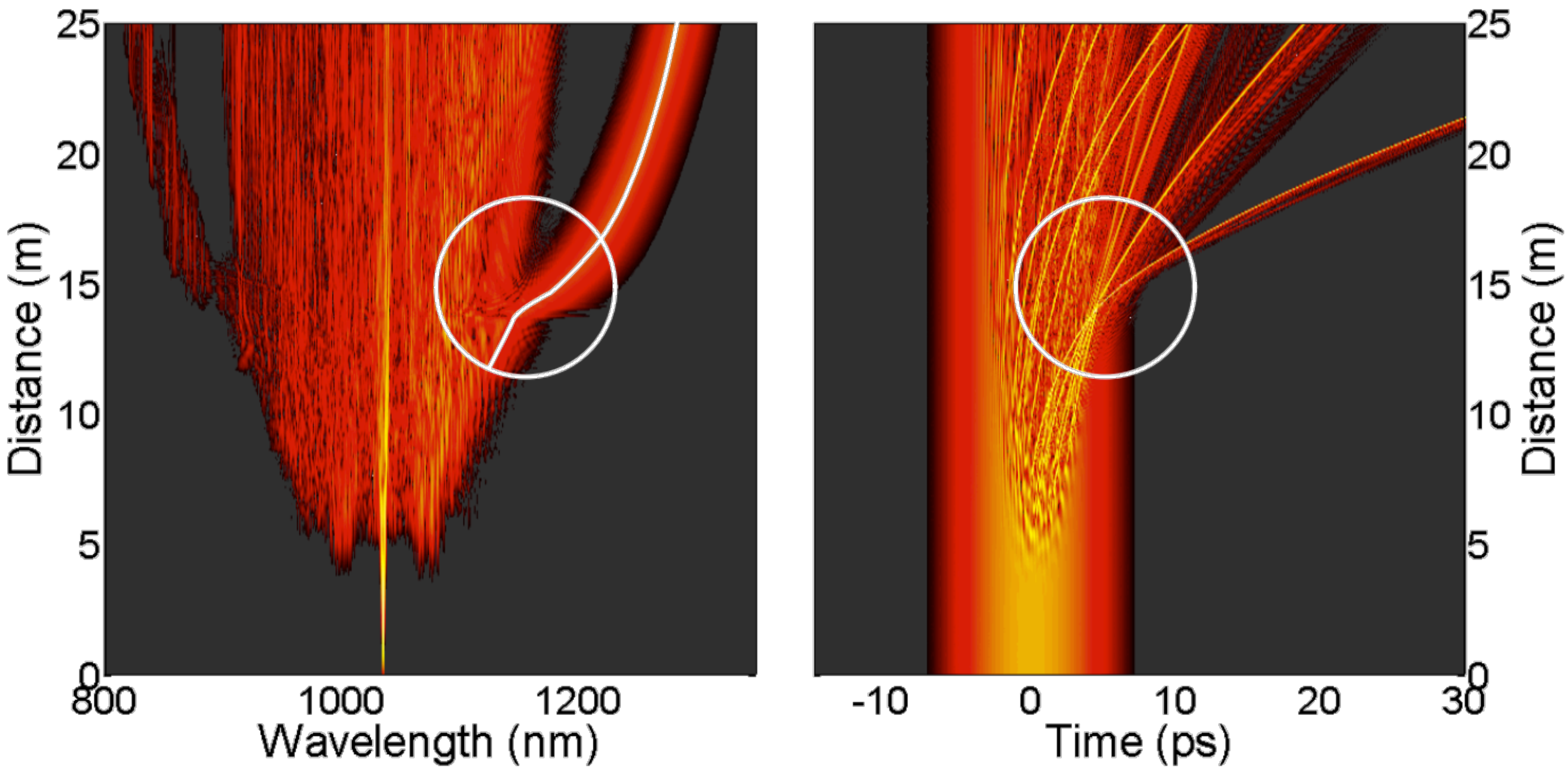
- Analogy with rogue waves?





What causes rogue solitons?

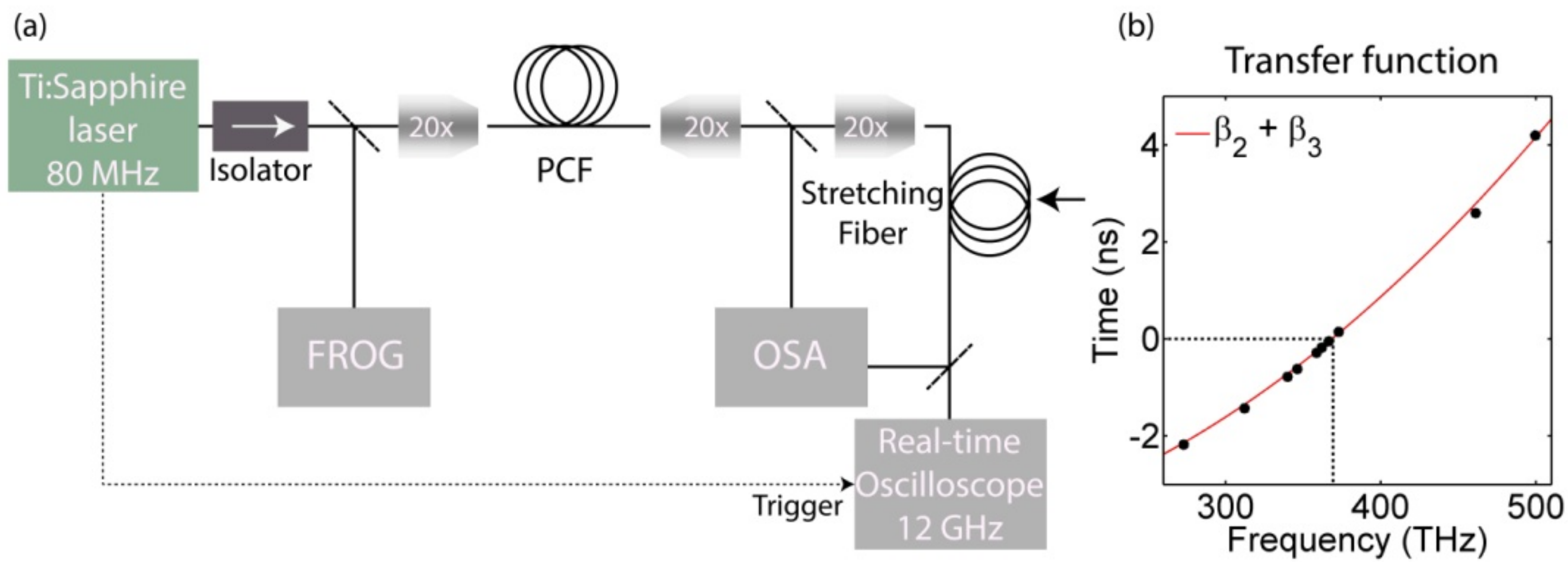
- Collisions between solitons lead to energy exchange and enhanced redshift



Erkintalo *et al.*, EPJ Special Topics 185, 135 (2010)

Capturing single shot spectra

- Real-time measurement of single shot is spectra is possible
- Use dispersive time-to-frequency transformation

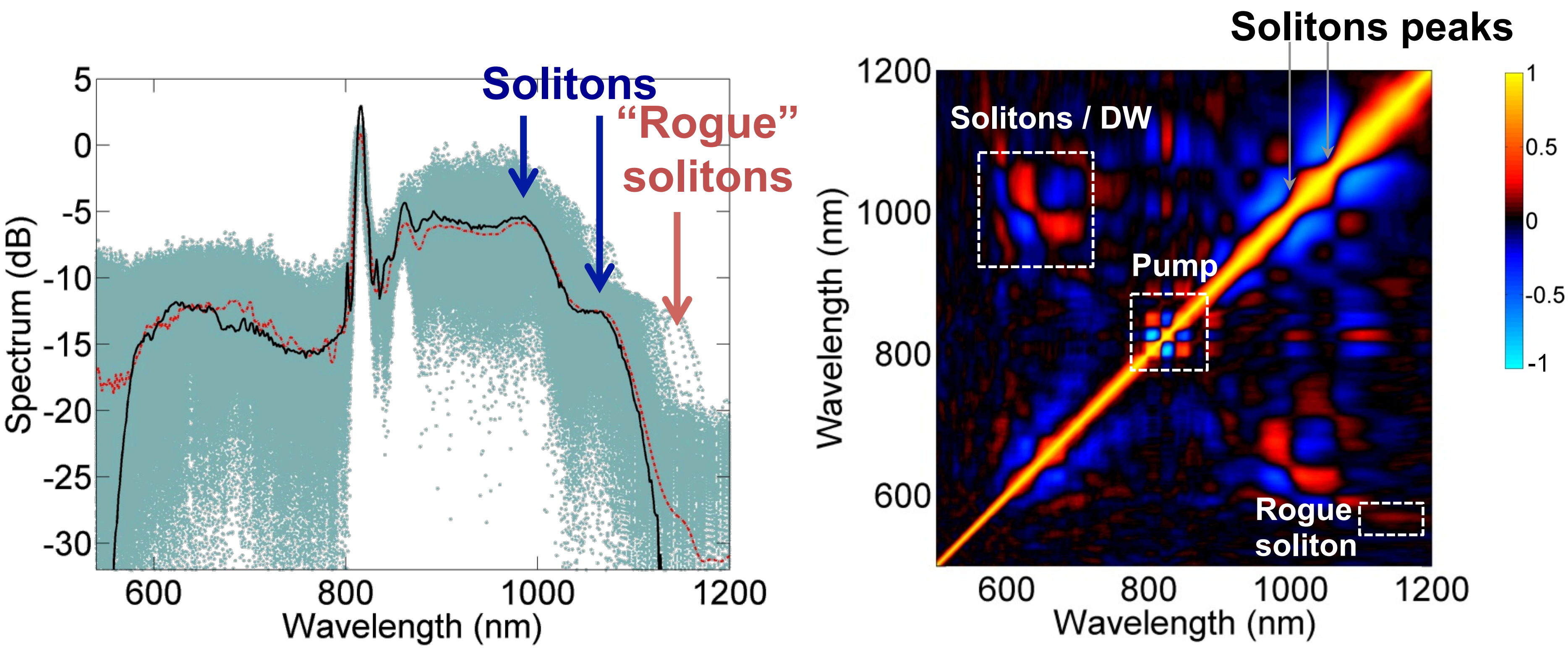


- At large distance in the dispersive fiber, the stretched temporal trace corresponds to the spectrum: analog to far-field diffraction

Goda et al., Nature Photonics **7**, 102–112 (2013)

Spectral fluctuations

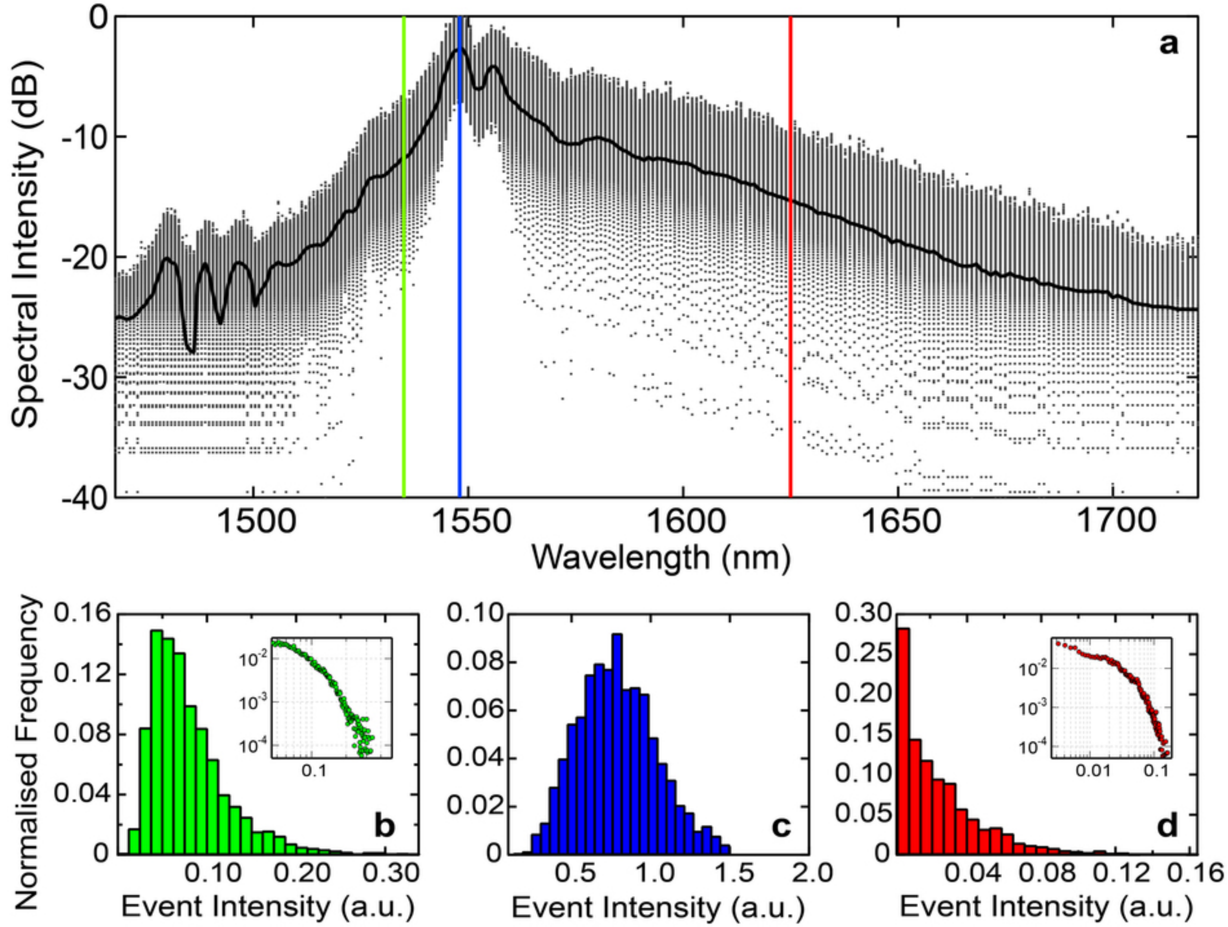
- Octave-spanning fluctuations can be measured



Godin *et al.*Optics Express **XX**, XX (2013)

Capturing single shot spectra

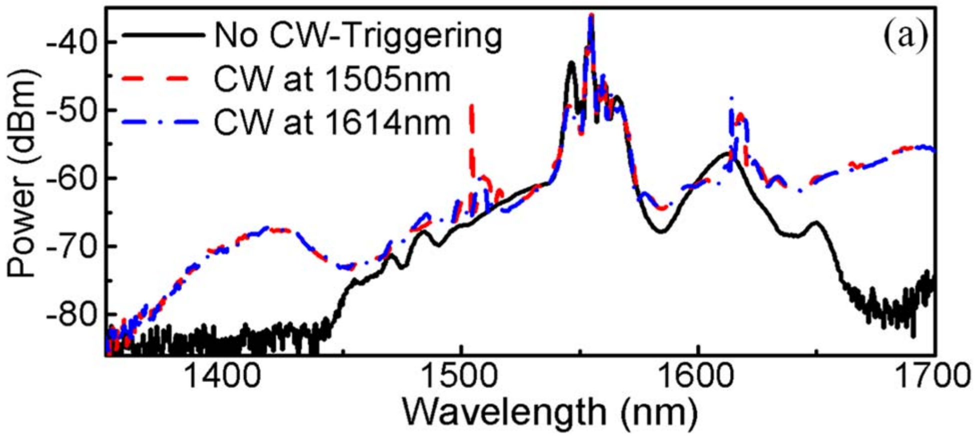
- Direct access to spectral fluctuations at ALL wavelengths



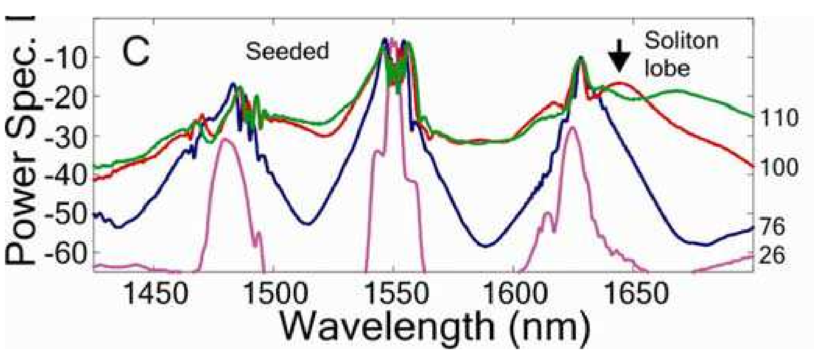
Wetzel et al., Scientific Reports **2**, 882 (2012)

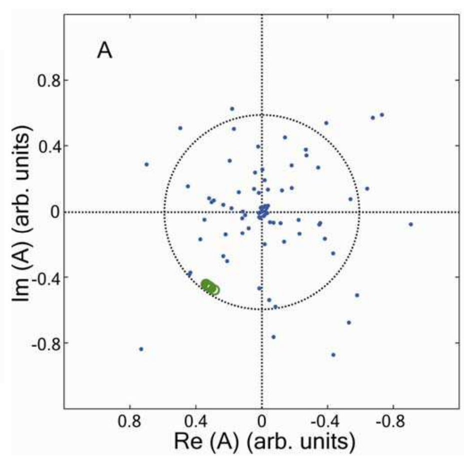
Controlling SC fluctuations and rogue solitons

- Stable SC from long pump pulses
  - Seeding modulation instability



Cheung et al., OL 36, 160-162 (2011)



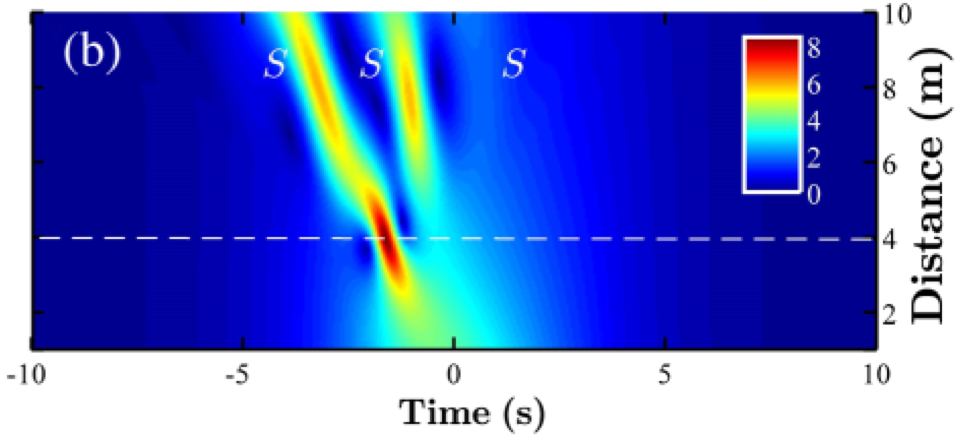


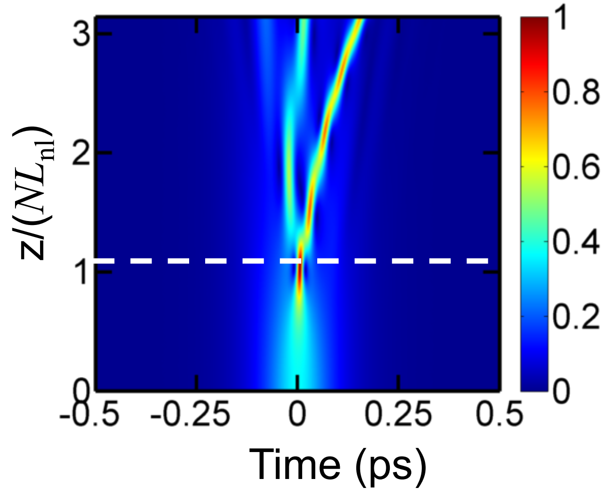
Solli et al., PRL 101, 233902 (2008)

That’s all folks!

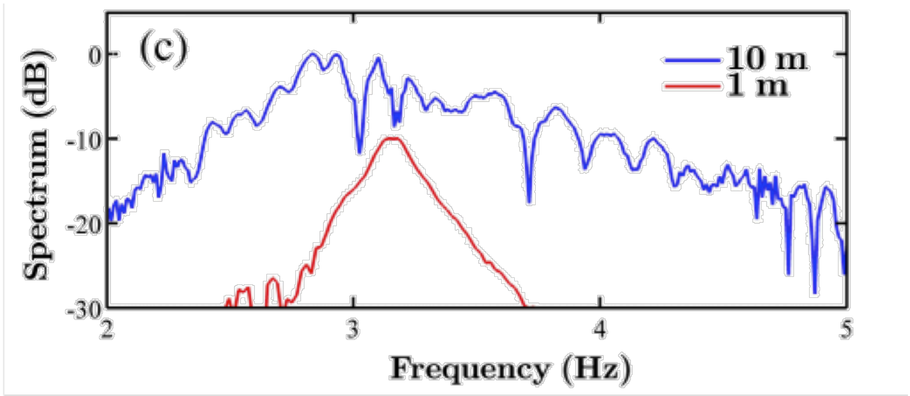
Even SC in water waves!

- Perturbations can also lead to soliton fission, just as in optics…





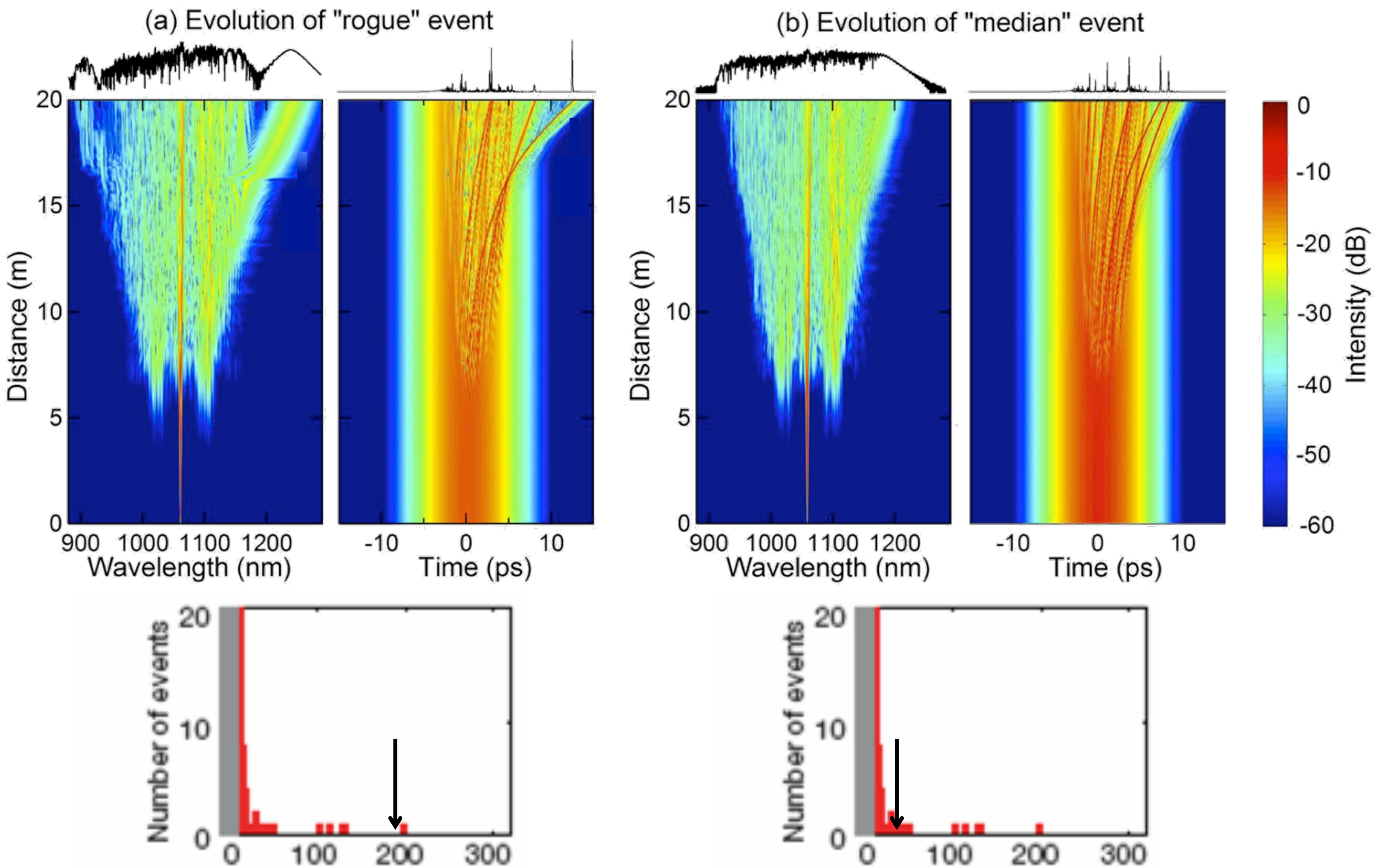
- Fission length $L_{\mathrm{fiss}} \approx L_{\mathrm{d}}/N = N\, L_{\mathrm{nl}}$ is also the same



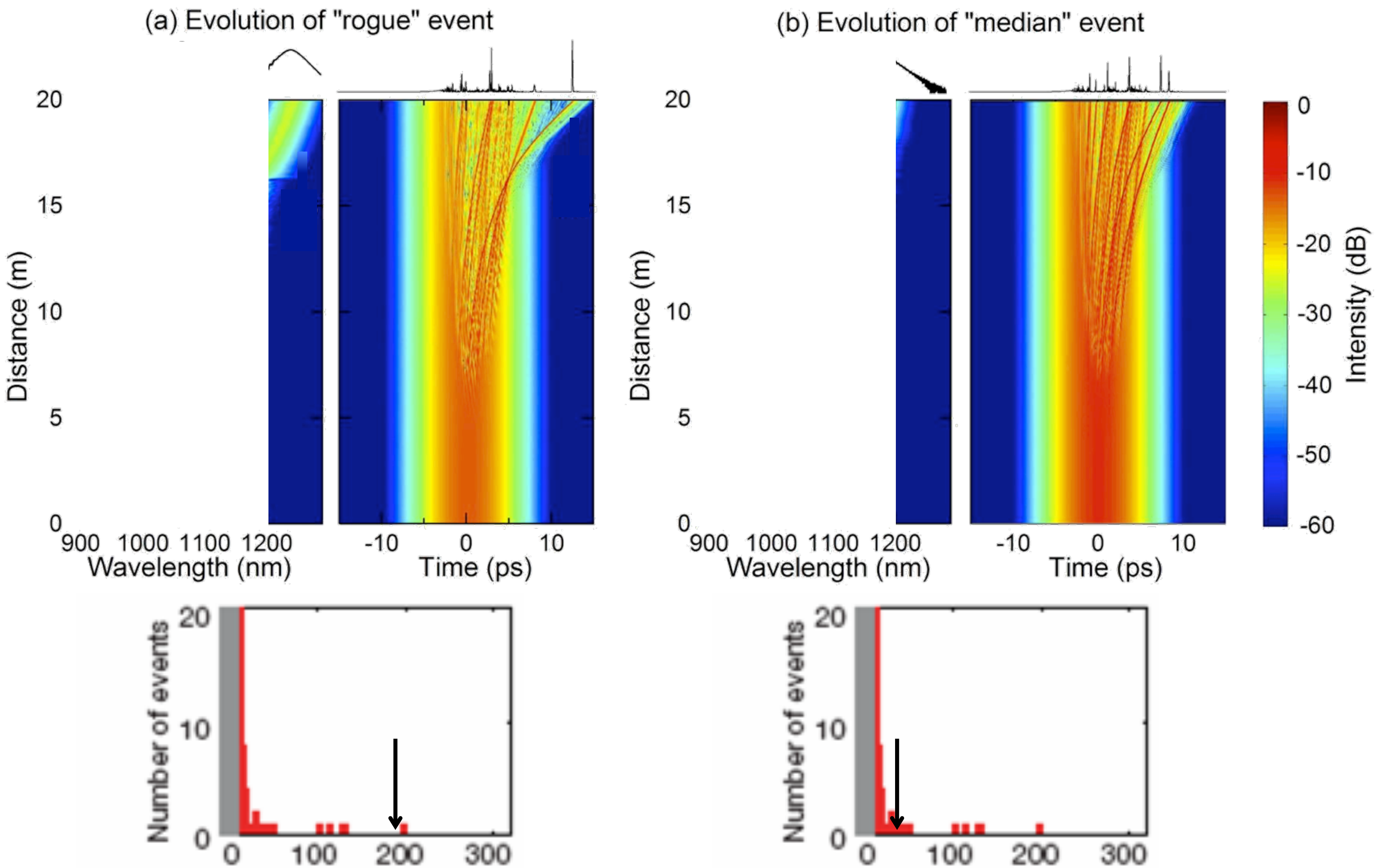
Hydrodynamic supercontinuum

Chabchoub *et al.*, Phys. Rev. Lett. 111, 054104 (2013)

Rogue solitons



Rogue solitons



Rogue solitons