

Three-dimensional spatiotemporal optical solitons in waveguide arrays: from theoretical study (2004) to experimental observation (2010)

Dumitru Mihalache

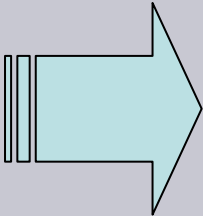
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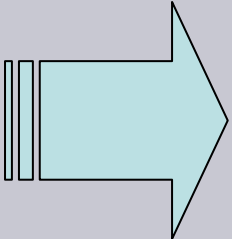
OUTLINE

- ➔ What are spatiotemporal optical solitons (light bullets-LBs)?
- ➔ Varieties of nonlinear optical media
- ➔ Optical spatiotemporal solitons:
seminal experiments in quadratic media
- ➔ Recent theoretical and experimental studies of LBs
- ➔ Conclusions

WHAT ARE SPATIOTEMPORAL OPTICAL SOLITONS?



Packets of electromagnetic radiation confined in space and time: **non-diffracting and non-dispersing wave-packets propagating in nonlinear optical media.** They form as a balance between dispersion, diffraction and self-focusing nonlinear effects.



The spatiotemporal solitons (alias “light bullets”) are ideal bits of information.



They may find application in future all-optical processing devices.

Characteristic lengths: quadratic media

Diffraction length

$$L_d = \frac{\pi w_0^2 n}{\lambda}$$

Parametric gain length - also known as nonlinear length

$$L_{pg} = L_{NL} = \frac{cn}{\omega d_{eff}^{(2)} |a_1|}$$

Coherence length

$$L_c = \frac{\pi}{\Delta k}$$

Dispersion length: pulse compression

$$L_{GVD} = \frac{T_0^2 v_g^2}{|\partial v_g / \partial \omega|}$$

n - refractive index

Δk - wavevector mismatch

w_0 - beam size

T_0 - pulse width

a_1 - fundamental amplitude

v_g - group velocity = $(\partial k / \partial \omega)^{-1}$

B. A. Malomed, D. Mihalache, F. Wise, L. Torner,
J. Opt. B 5, R53-R72 (2005)

Soliton formation

Soliton formation conditions

Spatial soliton: $L_c < L_{pg} \leq L_d$

Temporal soliton: $L_{pg} \leq L_{GVD}$

Spatio-temporal solitons: $L_c < L_{pg} \leq L_{GVD} \simeq L_d$

Crystal length
should be about
 $3 L_d = 3 L_{GVD}$

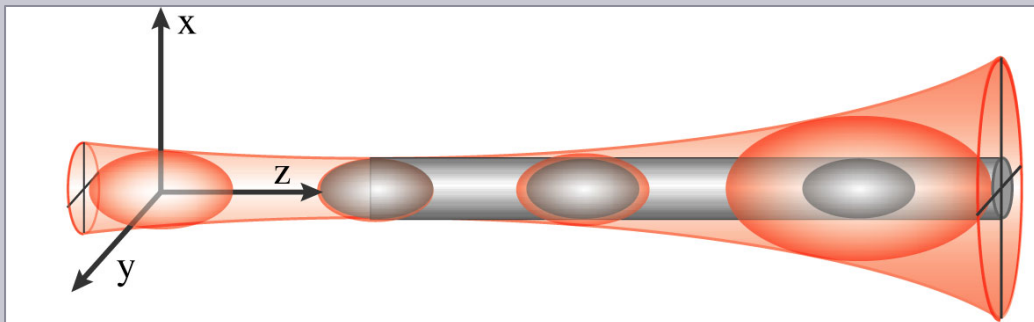


Figure 1. Illustration of the formation of a spatiotemporal soliton due to the simultaneous balance of diffraction and dispersion by nonlinear self-focusing.

Balance of diffraction and dispersion by nonlinear self-focusing

NONLINEAR OPTICAL MEDIA

CUBIC NONLINEAR MEDIA: **collapse of the pulse** in two and three dimensions precludes the formation of stable light bullets; there is a need for a saturable self-focusing nonlinearity.

QUADRATIC NONLINEAR MEDIA:

a saturable self-focusing nonlinearity can be obtained through the process of phase-mismatched SHG ; *multidimensional solitons could be stable in quadratic media.*

Condition: anomalous group-velocity dispersion (GVD) is required at both fundamental and second harmonic frequencies:
very difficult to attain in experiment.

- A possibility to overcome this difficulty is to use periodic layered structures formed by alternating linear and quadratically nonlinear materials (“tandem light bullets”): L. Torner et al., Opt. Commun. 199, 277- 281 (2001)
- Nonlocal nonlinear optical media: liquid crystals, etc. (collapse free nonlinear media)

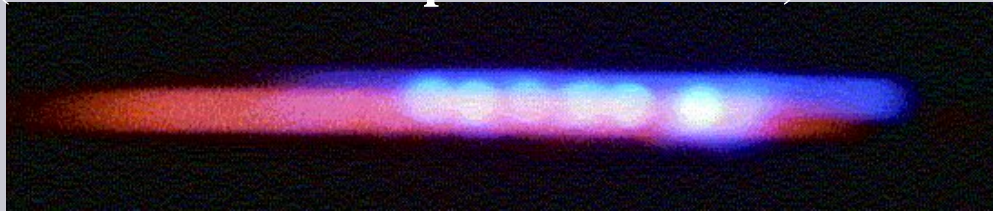
EXPERIMENTS IN QUADRATIC MEDIA: (2+1)D spatiotemporal solitons

Discovery of the **(2+1)-dimensional spatiotemporal solitons** (STS) in quadratic media by Frank Wise *et al.*:

Phys. Rev. Lett. 82, 4631 (1999); Phys. Rev. E 62, 1328 (2000).

<http://people/ccmr/cornell/edu/~fwise/solitons.html>

The solitons are confined in one transverse spatial dimension and time: they are not confined in the second transverse spatial coordinate (“banana”-like shape of the soliton).



The greatest experimental challenge to the generation of STS is the requirement of anomalous GVD at both fundamental and second-harmonic wavelengths. The magnitude of the anomalous GVD should be large enough to produce a dispersion length of the order of 5 mm (the length of the crystal is about 25 mm).

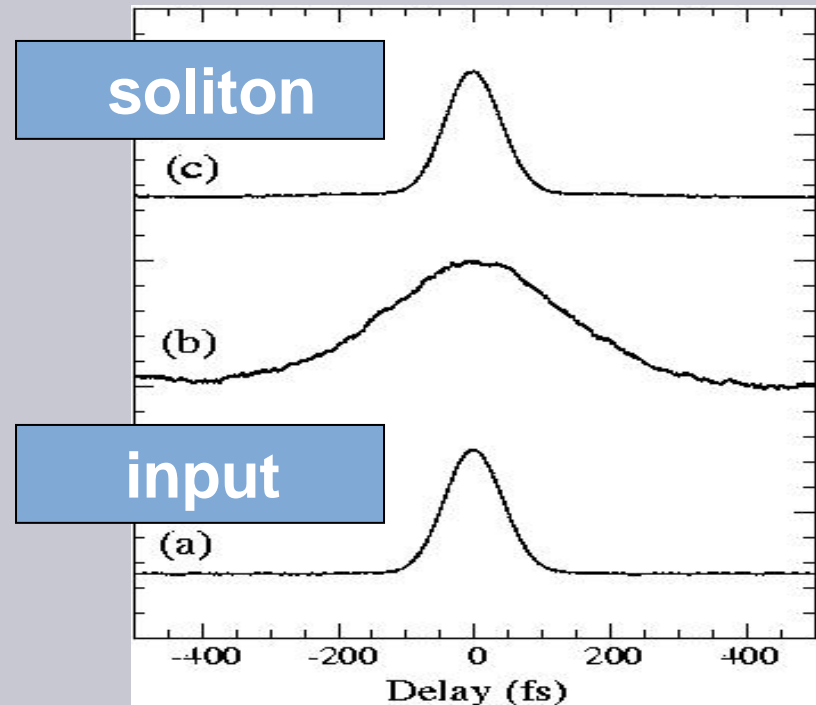
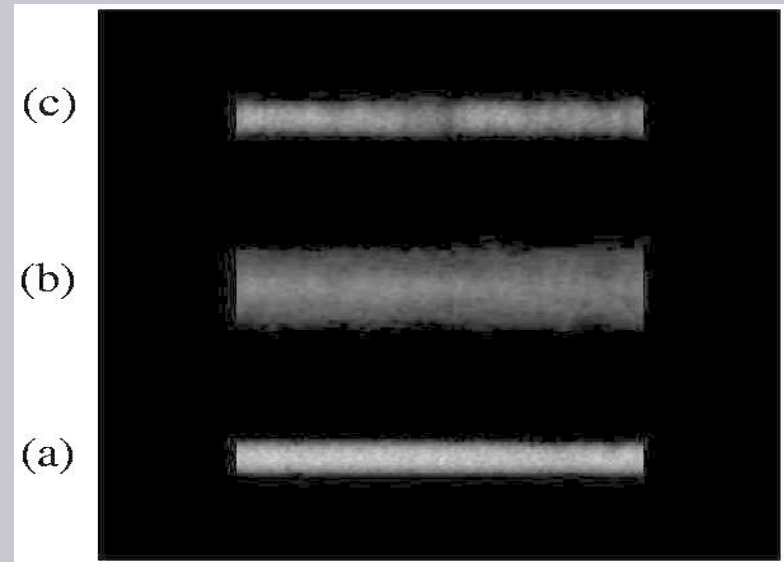
Experiments in
lithium iodate and
barium borate

(Frank Wise group,
1999-2000):

$I \sim 10 \text{ GW/cm}^2$

threshold for STS formation
in lithium iodate.

The threshold for STS
formation in barium borate
is about 8 GW/cm^2 .



The propagation over 5 dispersion lengths in barium borate gives: output at high intensity (*soliton formation*):

w_spatial ~ 50 microns

w_temporal ~ 100 fs

output at low intensity (*diffraction and dispersion, no soliton formation*):

w_spatial ~ 300 microns

w_temporal ~ 500 fs

OTHER DEVELOPMENTS (THEORY)

- **DISCRETE LIGHT BULLETS** (in one- and two-dimensional photonic lattices), including discrete surface LBs:
D. Mihalache et al., Opt. Express **15**, 589 (2007); Opt. Lett. **32**, 3173 (2007)
- **DISSIPATIVE LIGHT BULLETS** (in both continuous and discrete systems, including dissipative surface LBs):
D. Mihalache et al., Phys. Rev. A **77**, 043828 (2008).
- **COLLISIONS BETWEEN LBs**:
D. Mihalache et al., Opt. Commun. **282**, 3000 (2009).
- **DISSIPATIVE LBs IN OPTICAL PARAMETRIC OSCILLATORS**:
N. Veretenov and M. Tlidi, Phys. Rev. A **80**, 023822 (2009).

RECENT THEORETICAL STUDIES

---- **Light bullets in optical tandems (metamaterial structures):** alternating rings made of highly dispersive but weakly nonlinear media and strongly nonlinear and weakly dispersive media:

Torner and Kartashov, Opt. Lett. **34**, 1129 (2009).

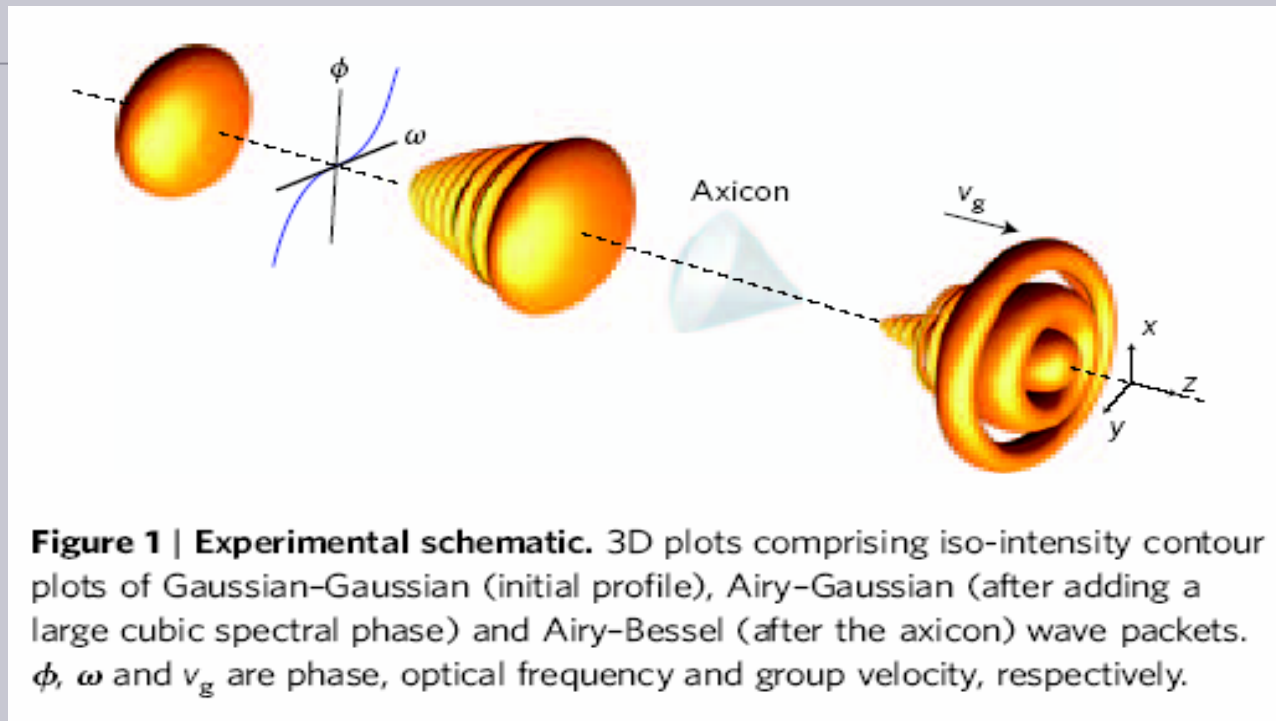
---- **Accessible light bullets via synergetic nonlinearities:** interplay of local electronic and nonlocal reorientational nonlinearities (nonlocal solitons propagating in nematic liquid crystals):

Burgess, Peccianti, Assanto, Morandotti: Phys. Rev. Lett. **102**, 203903 (2009).

- **3D Light bullets by synthetic diffraction-dispersion matching in 2D honeycomb waveguide arrays with out-of-phase periodic longitudinal refractive index modulation in neighboring channels:**
Lobanov, Kartashov, Torner, Phys. Rev. Lett. **105**, 033901 (2010).
- **Trains of light bullets in nonlocal nonlinear media:** Peccianti et al.: Opt. Express **18**, 5934 (2010).
- **Light bullets in Bessel optical lattices with spatially modulated nonlinearity:**
Ye, Kartashov, Hu, Torner, Opt. Express **17**, 11328 (2009).

Airy-Bessel wave packets as versatile linear light bullets

Chong, Renninger, Christodoulides, Wise, Nat. Photonics 4, 103 (2010): combine Bessel beams in the transverse plane with temporal Airy pulses: propagation in BK7 and SF14 highly dispersive glass rods, Corning. Linear LBs: no need for dispersion/diffraction equalization, that is, for any values of radial and temporal widths and for either normal or anomalous GVD.



Propagation of Airy-Bessel wave packet in a Schott SF14 (Corning) glass

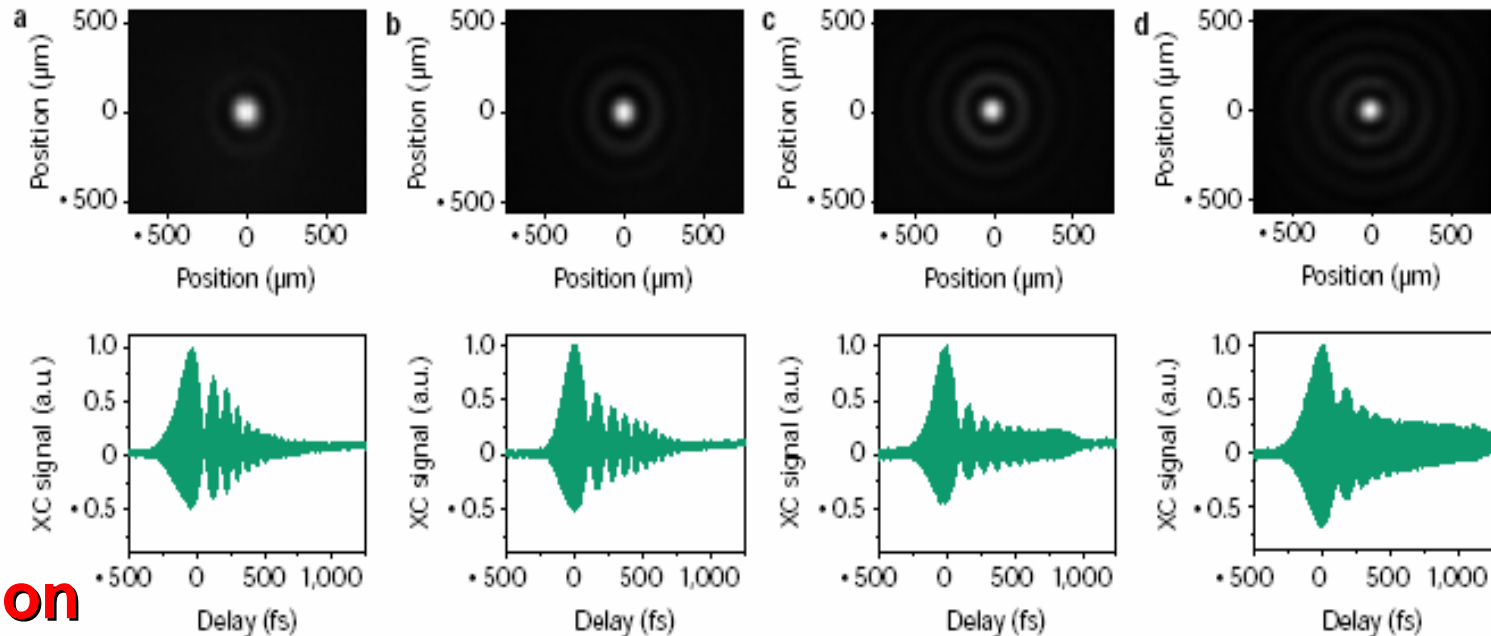
input: $z=0$

$z=5$ cm

$z=10$ cm

$z=15$ cm

CCD camera



Cross correlation

Figure 3 | Propagation of an Airy-Bessel bullet. a, Initial spatial and temporal profiles. b-d, Profiles after propagation through 3.3 diffraction lengths, L_R , and 1.8 dispersion lengths, L_D (b), 5.4 L_R and 3.6 L_D (c) and 7.5 L_R and 5.4 L_D (d). L_R is the diffraction length of a beam with a diameter of 180 mm, and L_D is the dispersion length of a 100-fs pulse.

Important feature of linear LBs:
no need to precisely tailor the diffraction and dispersion lengths

SPATIOTEMPORAL (Ai^3) LBs

PRL **105**, 253901 (2010)

PHYSICAL REVIEW LETTERS

week ending
17 DECEMBER 2010

Spatiotemporal Airy Light Bullets in the Linear and Nonlinear Regimes

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²*Physics Department, University of Crete, 71003, Heraklion, Greece*

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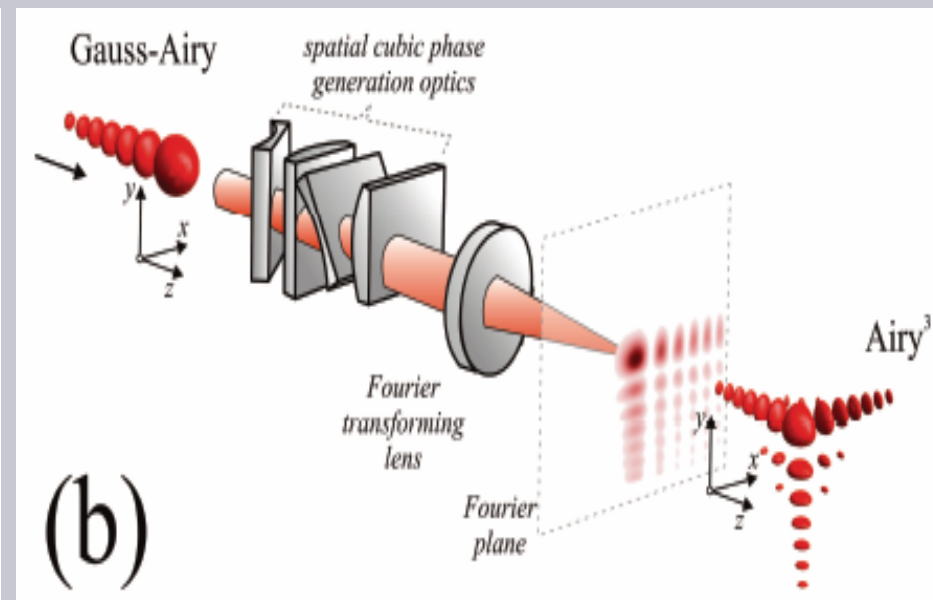
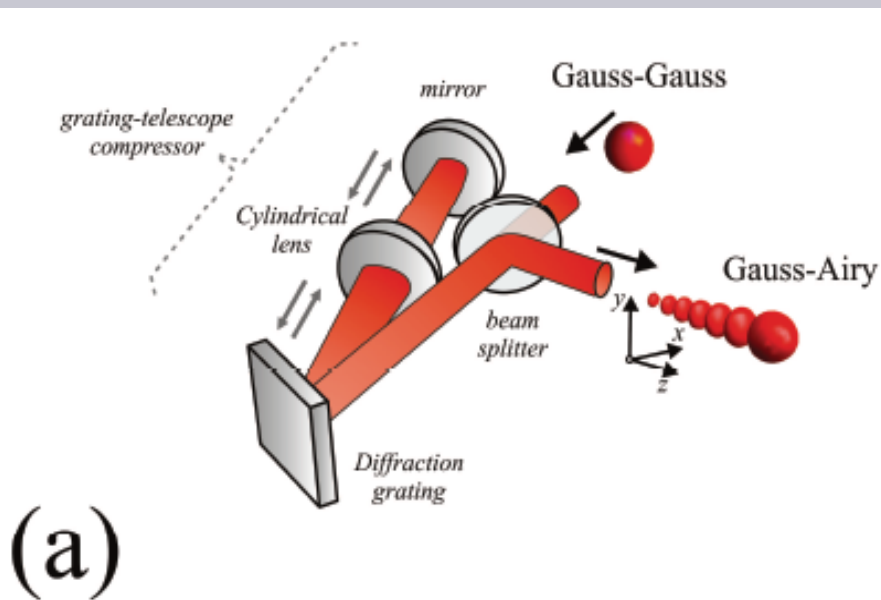
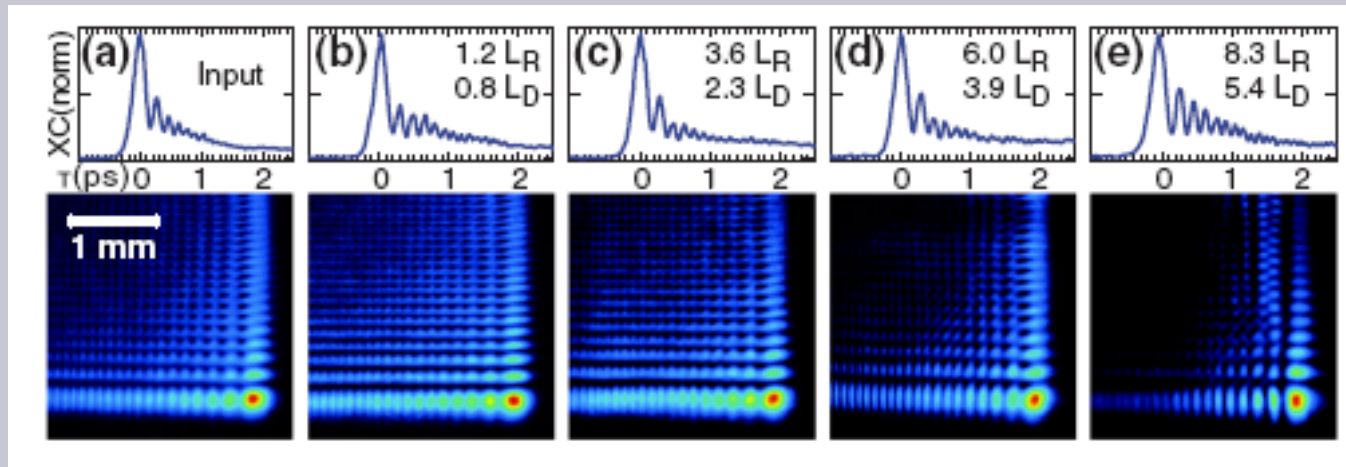
(Received 17 September 2010; revised manuscript received 23 November 2010; published 15 December 2010)

$$I(x, y, z) = I_0 Ai^2\left(\pm \frac{x}{x_0}\right) Ai^2\left(\pm \frac{y}{y_0}\right) Ai^2\left(\pm \frac{\tau}{\tau_0} - \frac{(k_0'')^2 z^2}{4\tau_0^4}\right),$$

$\tau = t - (z/v_g)$ is the reduced time

$k_0'' = \partial^2 k / \partial \omega^2$ is the dispersion coefficient

Transparent material: PMMA (polymethyl metacrylate) at 800 nm (sample length: 20, 60, 100, 140 cm)



RECENT EXPERIMENT ON NONLINEAR X-WAVES

M. HEINRICH et al., Phys. Rev. Lett. **103**, 113903
(2009)

**Observation of 3D discrete-continuous
X-waves in photonic lattices (in femtosecond
laser-written waveguide arrays in fused silica):
the X-waves spontaneously emerge from a
single site excitation due to**

discrete diffraction of the lattice +
normal GVD + cubic (Kerr-like)
nonlinearity of the fused silica

OBSERVATION OF DISCRETE-CONTINUOUS 3D LIGHT BULLETS

F. Eilenberger, S. Minardi, et al., CLEO/EUROPE-EQEC 2009, paper EF1.2 THU

They use time-resolved imaging to observe spatiotemporal localization of nonlinear optical wave packets propagating in a 2D highly regular hexagonal array of Ge-doped fibers.

NB: The LB can be thought of as a temporal soliton that stays in one waveguide



Three-Dimensional Light Bullets in Arrays of Waveguides

S. Minardi,¹ F. Eilenberger,¹ Y. V. Kartashov,² A. Szameit,³ U. Röpke,⁴ J. Kobelke,⁴ K. Schuster,⁴ H. Bartelt,⁴ S. Nolte,¹
L. Torner,² F. Lederer,⁵ A. Tünnermann,¹ and T. Pertsch¹

We report the first experimental observation of three-dimensional light bullets, excited by femtosecond pulses in a system featuring quasi-instantaneous cubic nonlinearity and a periodic, transversally modulated refractive index. Stringent evidence of the excitation of light bullets is based on time-gated images and spectra which perfectly match our numerical simulations. Furthermore, we reveal a novel evolution mechanism forcing the light bullets to follow varying dispersion or diffraction conditions, until they leave their existence range and decay.

S. Minardi et al., Phys. Rev. Lett. 105, 263901 (2010)

In this Letter, we report the first observation of 3D LBs in a two-dimensional array of coupled waveguides. We have found that due to higher-order effects, LBs evolve following varying dispersion or diffraction conditions until they leave their existence range [7] and decay.

LB can exist (region C). Because of the finite energy threshold for the existence of 3D discrete-continuous LBs [7], this decay scenario is quite generic for experimental systems. Notice that the trajectory of the bullet in

wavelength. Because for longer wavelengths the coupling strength between waveguides increases exponentially, the energy threshold [7] required for the LB propagation grows steeply. Therefore the solitary wave will eventually decay when the dispersively modified energy threshold exceeds the energy of the excitation. The scenario is illustrated in

[7] D. Mihalache *et al.*, Phys. Rev. E 70, 055603 (2004)

Viewpoint

Generation of light bullets

Frank W. Wise

Department of Applied Physics, Cornell University, 212 Clark Hall, Ithaca, NY 14853, USA

Published December 20, 2010

Light pulses injected into an array of waveguides form solitons in time and space.

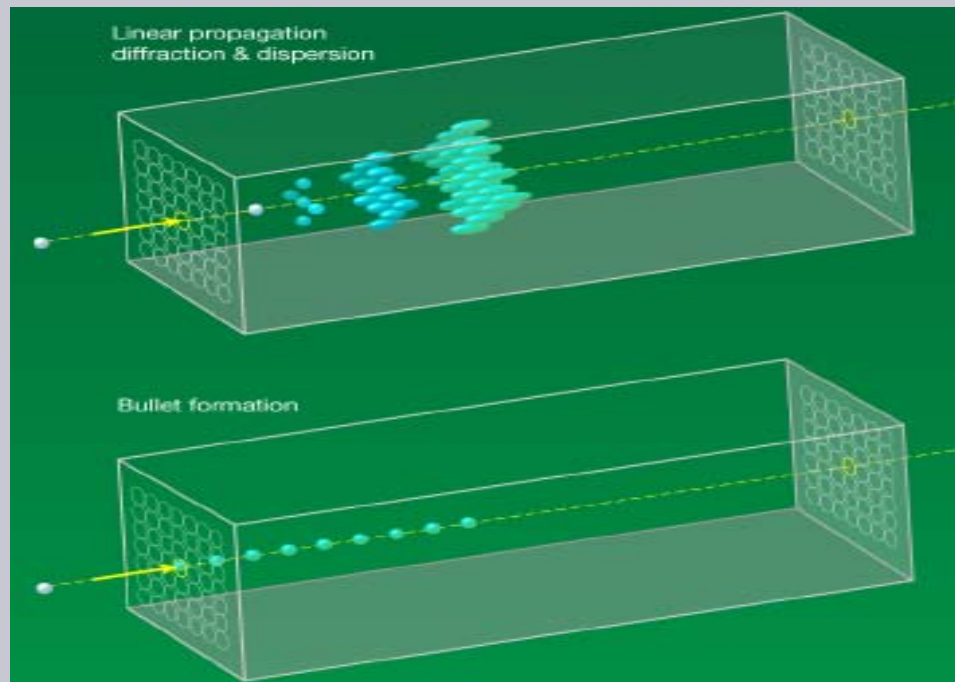
Subject Areas: **Optics, Interdisciplinary Physics**

A Viewpoint on:

Three-Dimensional Light Bullets in Arrays of Waveguides

S. Minardi, F. Eilenberger, Y. V. Kartashov, A. Szameit, U. Röpke, J. Kobelke, K. Schuster, H. Bartelt, S. Nolte, L. Torner, F. Lederer, A. Tünnermann and T. Pertsch

Phys. Rev. Lett. **105**, 263901 (2010) – Published December 20, 2010



$$i \frac{\partial q}{\partial \xi} = -\frac{1}{2} \left(\frac{\partial^2 q}{\partial \eta^2} + \frac{\partial^2 q}{\partial \zeta^2} \right) + \frac{d}{2} \frac{\partial^2 q}{\partial \tau^2} + \sigma q |q|^2 - p R(\eta, \zeta) q$$

d - ratio of the diffraction length to the dispersion length (we used $d = -1$)

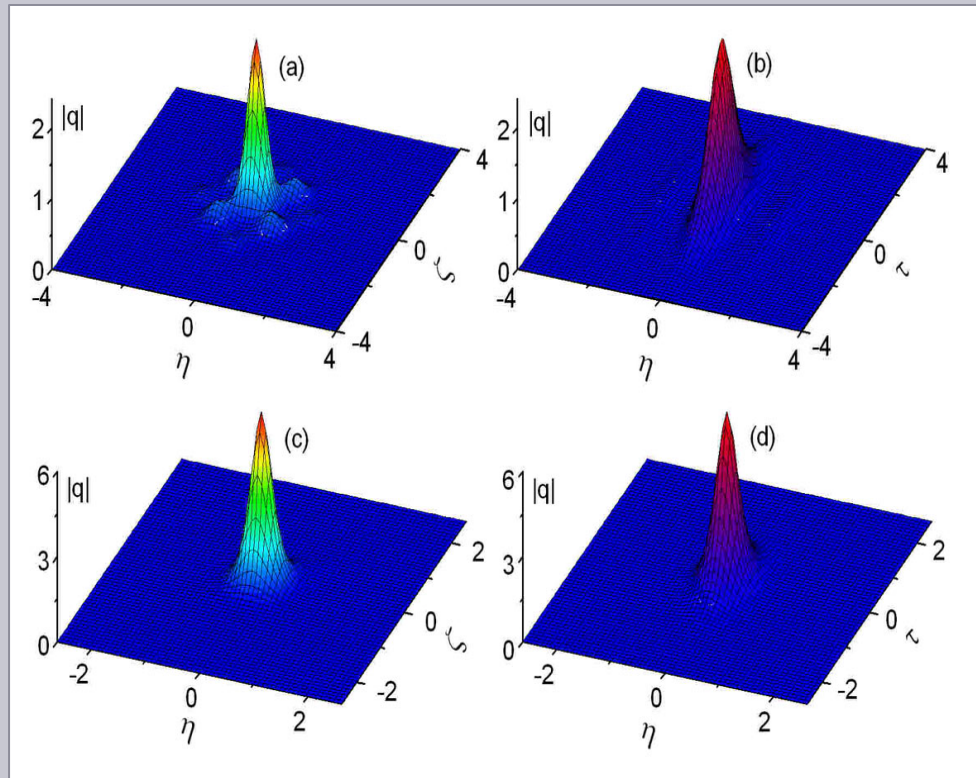
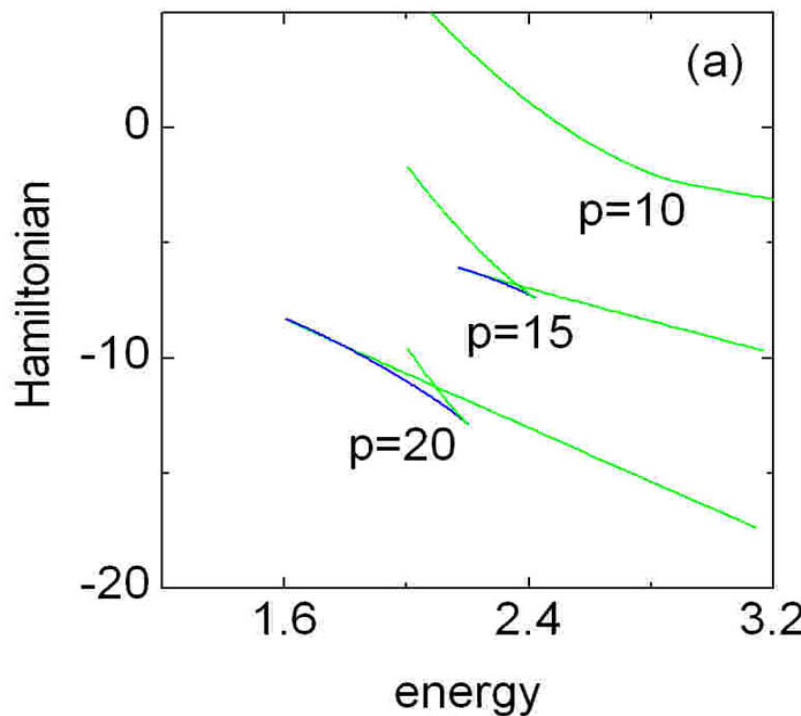
σ - sign of the nonlinearity (we have assumed $\sigma = -1$ – self-focusing)

p - refraction index modulation

$R(\eta, \zeta)$ – lattice potential: $R(\eta, \zeta) = \cos(\Omega_\eta \eta) \cos(\Omega_\zeta \zeta)$, $\Omega_{\eta, \zeta} = 4$

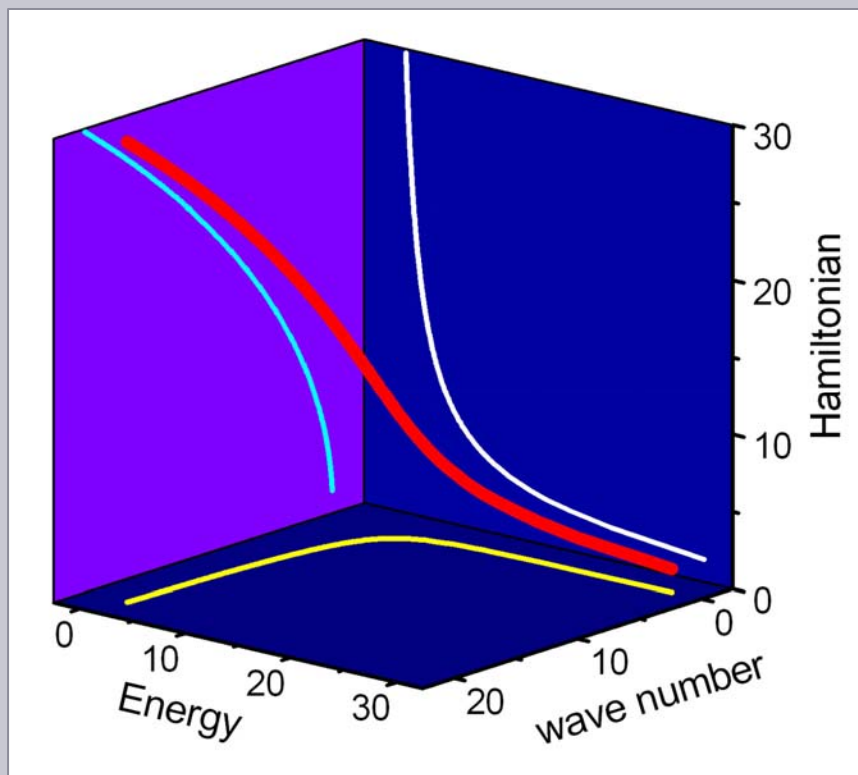
D. Mihalache et al., Phys. Rev. E 70, 055603 (2004)

$\tau = 0$ and $\zeta = 0$ slices for low amplitude ($A = 2.4$, $E = 1.6$) and high amplitude ($A = 6$, $E = 2.17$) stable LBs (for $p = 20$)

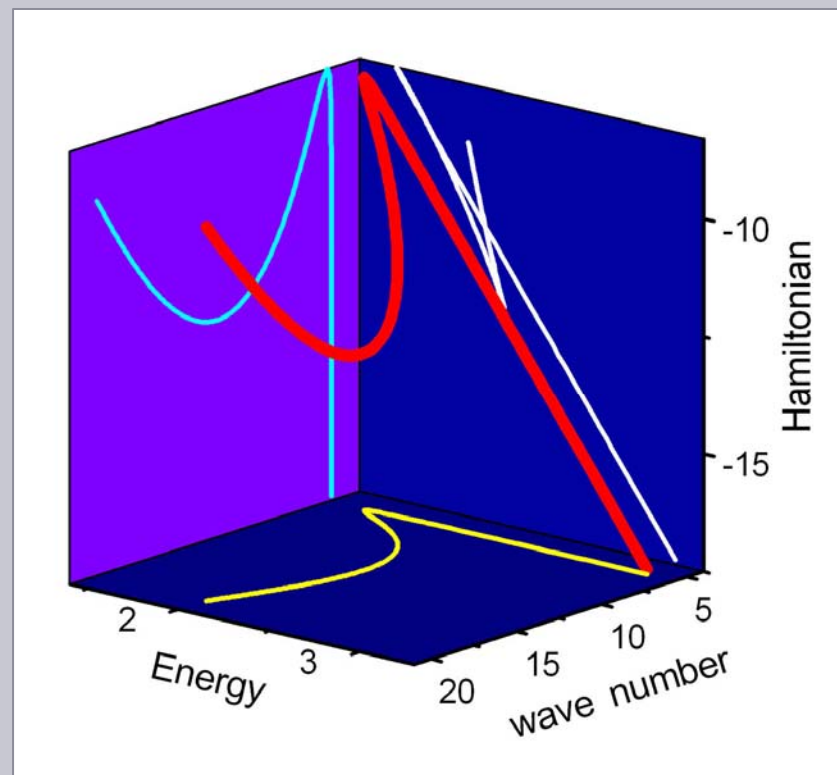


3D LBs in 2D photonic lattices: existence & stability

$H(E,k)$ curves – important hints for stability (Catastrophe theory); for $p=0$, $H(E)=C/E=b(E)E$, $C \sim 44.3$, b =wave number (collapse for $p=0$, cubic nonlinear media, i.e. Kerr media)



$p=0$, 3D nonlinear Schroedinger equation
(spatiotemporal collapse)



Stable light bullets: $p=20$
swallow-tail bifurcation,
energy threshold, no collapse

RECENT EXPERIMENT: fluorine doped silica glass (91 silica cores)

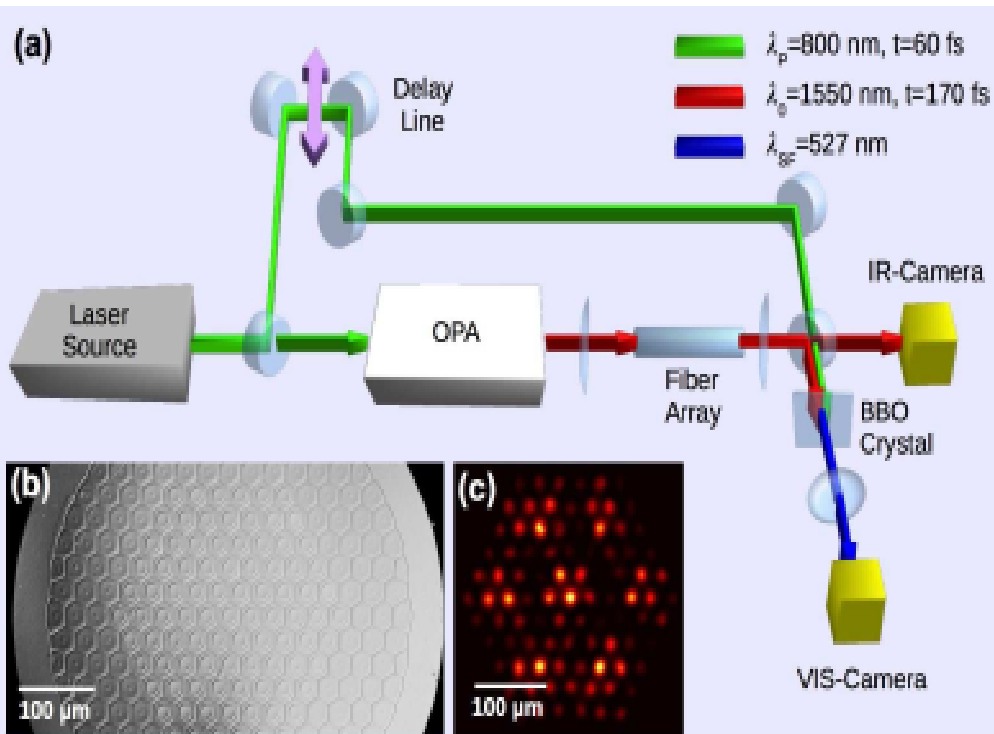


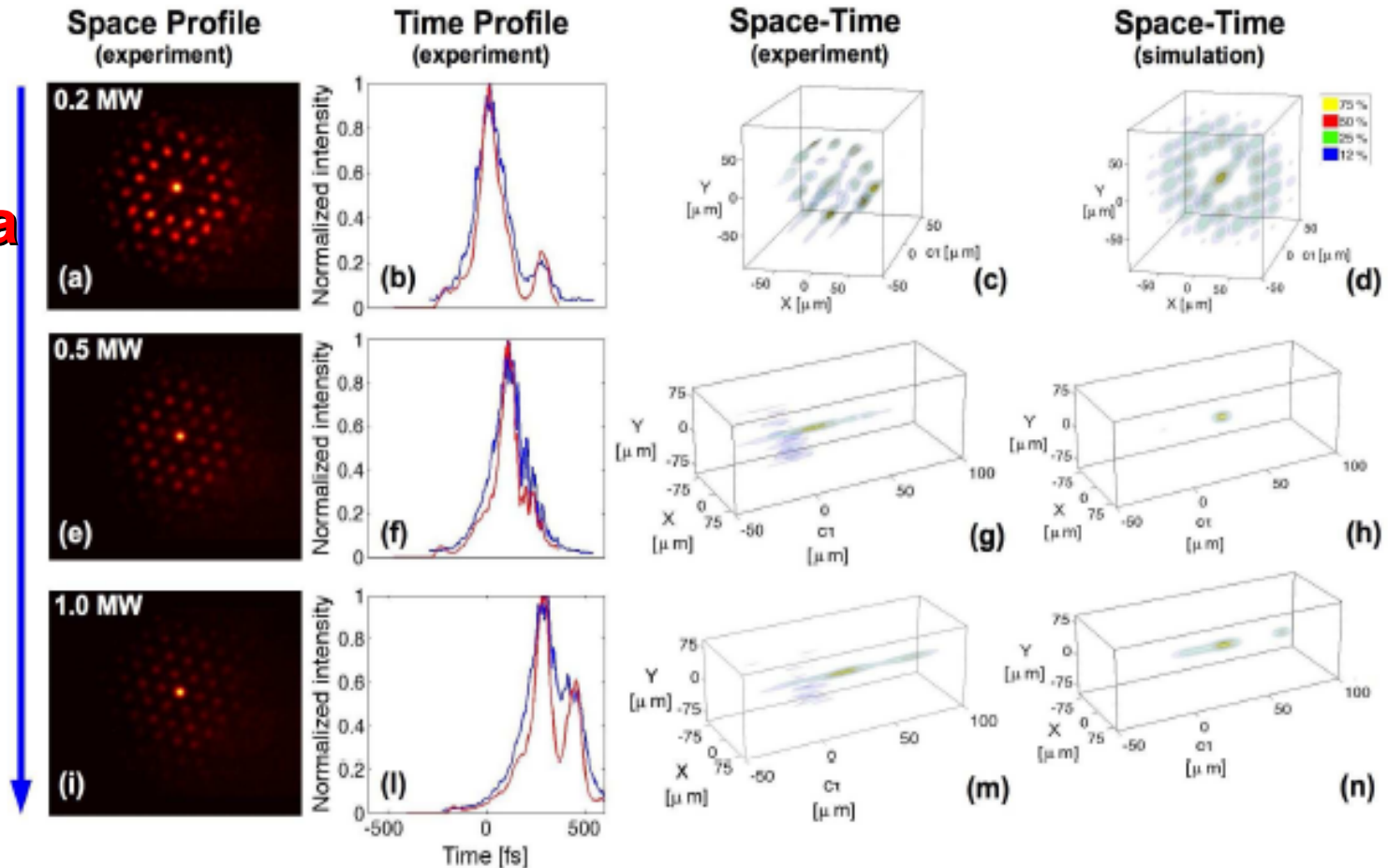
FIG. 1. (a) Layout of the experiment. A focused 170 fs infrared pulse centered at $\lambda_0 = 1550$ nm excites the central waveguide of a sample of the waveguide array (b). The output radiation of the sample is characterized by an infrared camera (IR-Camera) and by a spatially resolved optical gating *via* frequency mixing in a 25- μm -thin BBO crystal with a delayed 60 fs probe pulse at $\lambda_p = 800$ nm. (c) Experimental discrete linear diffraction pattern at the end of a 50 mm-long sample. Parameters of the sample: array made of 91 silica cores embedded in a Fluoride-doped silica glass; lattice period of $d = 33.2 \pm 0.4 \mu\text{m}$, a core radius of $r = 9.8 \pm 0.2 \mu\text{m}$, and an index contrast of $\Delta n = 1.2 \cdot 10^{-3}$.

First experimental observation of 3D light bullets in 2D photonic lattices (discrete waveguide arrays). Novel evolution mechanism of LBs that force LBs to follow varying dispersion/diffraction conditions, until they leave their existence domain and decay.
LBs with pulse widths = tens of fs and pulse energies = tens of nJ.

LBs SPACE-TIME PROFILES

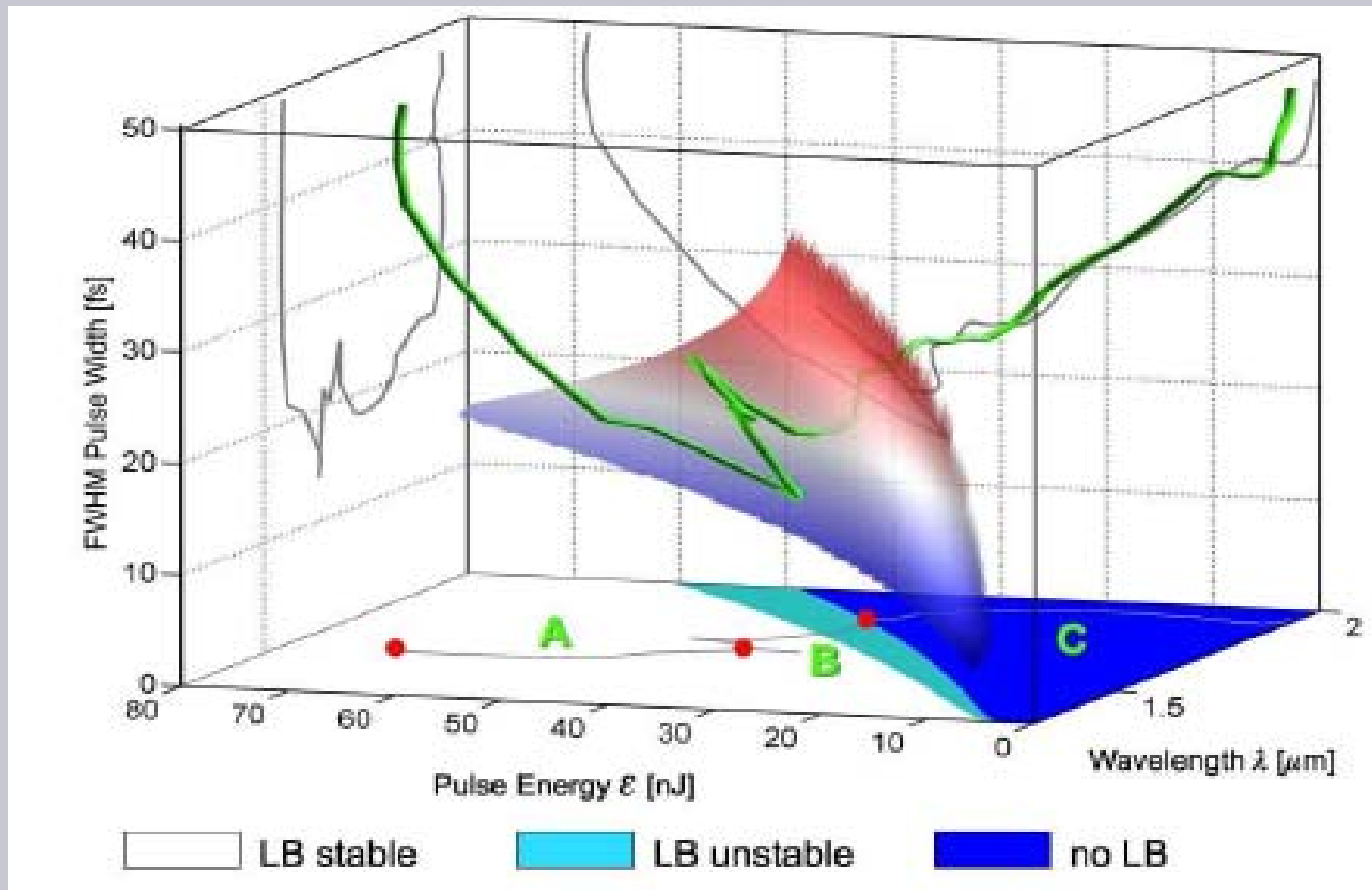
CCD
camera

Power

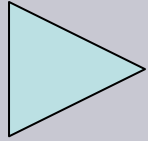


Nota bene: wavelength dependence of the diffraction and dispersion lengths; averaged quantities over the LBs longitudinal path should be introduced

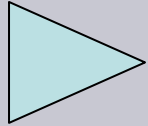
LBs decay mechanism: wavelength dependence of the diffraction and dispersion lengths (averaged quantities over the LBs longitudinal path)



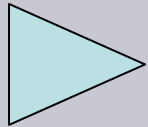
CONCLUSIONS



--The field of multidimensional optical solitons in both conservative and dissipative settings is still in its infancy



--However one can expect many new exciting developments over the next years



--The first observation of (3+1)-dimensional bright spatiotemporal solitons in optical media was a great challenge to the experiment (S. Minardi et al., 2010)

--LBs offer potential for ultrafast digital optical logic with **switching rates of several terahertz.**

**THANK YOU FOR YOUR
ATTENTION!**