Weierstrass Institute for
Applied Analysis and Stochastics

Leibniz Association

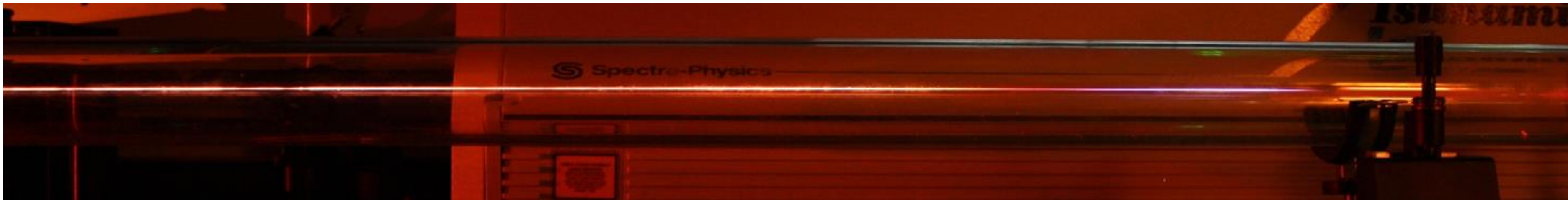
# *Interaction of experiment and numerical simulation in optical filamentation and supercontinuum generation*

Günter Steinmeyer and Carsten Brée

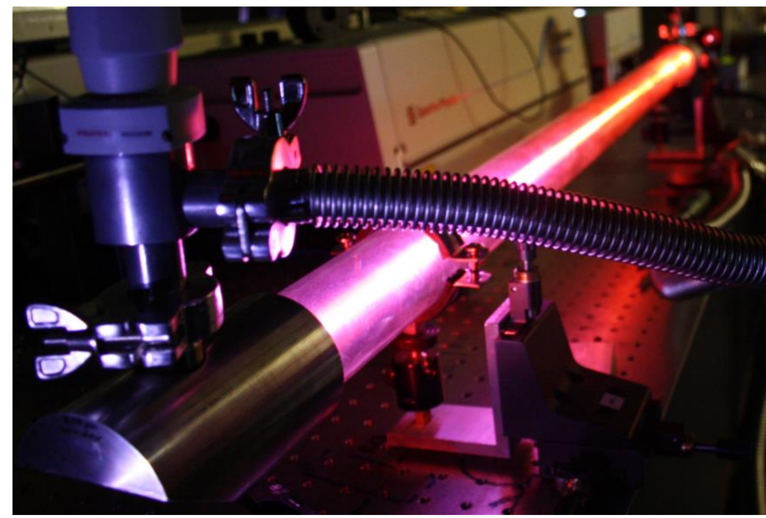
Max Born Institute for Nonlinear Optics
and Short Pulse Spectroscopy

WIAS, January 2016

## What are femtosecond filaments?



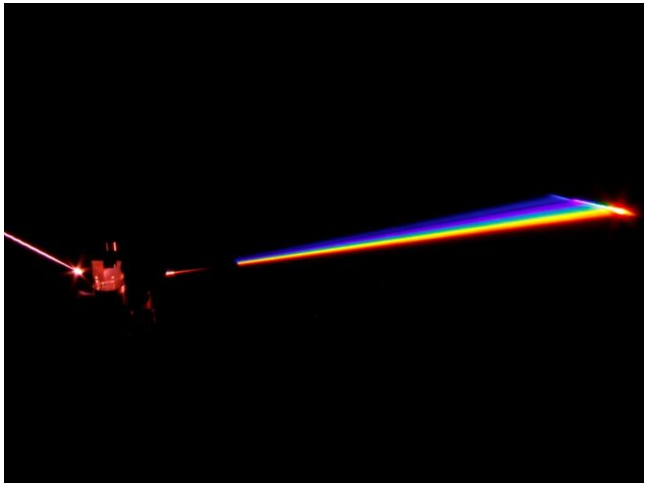
- Narrow channel of light and plasma in transparent medium
- Appears to overcome diffraction
- Ionizing optical intensities ($10^{14}$ W/cm$^2$)
- Ionization proceeds via highly nonlinear mechanisms



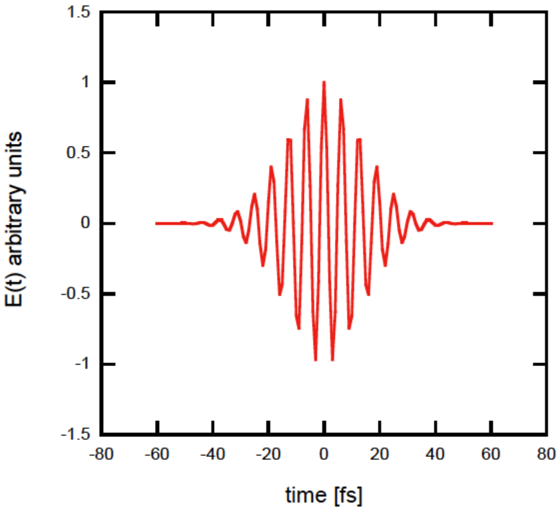
Max Born Institute, Femtosecond Application Lab

# What are they useful for?

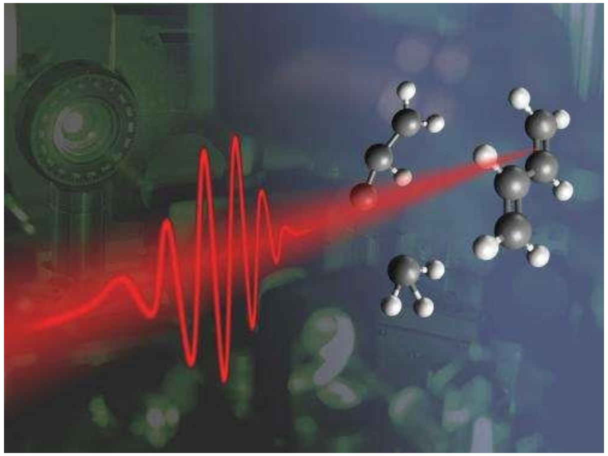
Supercontinuum generation



Generation of ultrashort laser pulses:
Duration of only some few $10^{-15}$ seconds




Studying filaments allows insights into
the fundamental physics of laser-matter interaction



Remote sensing/spectroscopy (remote detection of aerosols, hazardous goods, e.g. explosives)

# Our joint work

- Started as a DFG individual grant (1 PhD Student+ travel and publication expenses)
- Project heads: Günter Steinmeyer from Max Born Institute and
  Ayhan Demircan from Weierstrass Institute
- Aims and scopes of the project:
  - Understand the physical mechanisms behind femtosecond filamentation
  - Understand and optimize the phenomenon of pulse self-compression and supercontinuum generation in femtosecond filaments
- Collaboration successfully continued beyond the end of the project:
  - Supercontinuum generation in optical fibers
  - Nonlinear interaction of laser pulses in fibers

# Our joint work

- Why MBI and WIAS became a succesful partnership:
  - Collaboration of theory and experiment at close locations
  - Combined expertise and benefits of both institutes:

| Max Born institute |
|---|
| Femtosecond application lab of MBI: amplified Ti:sapphire laser delivering intense femtosecond pulses for the generation of filaments |
| Experiment can tell whether theoreticians are misled by numerical artifacts |
| Expertise in the characterization of ultrashort laser pulses |

| Weierstrass Institute |
|---|
| Compute cluster@WIAS: needed for the direct numerical simulation of filaments in a massively parallelized architecture |
| WIAS' expertise in numerical methods: pseudospectral split step, Runge-Kutta, parallel computing,… |

OPTICS LETTERS / Vol. 31, No. 2 / January 15, 2006

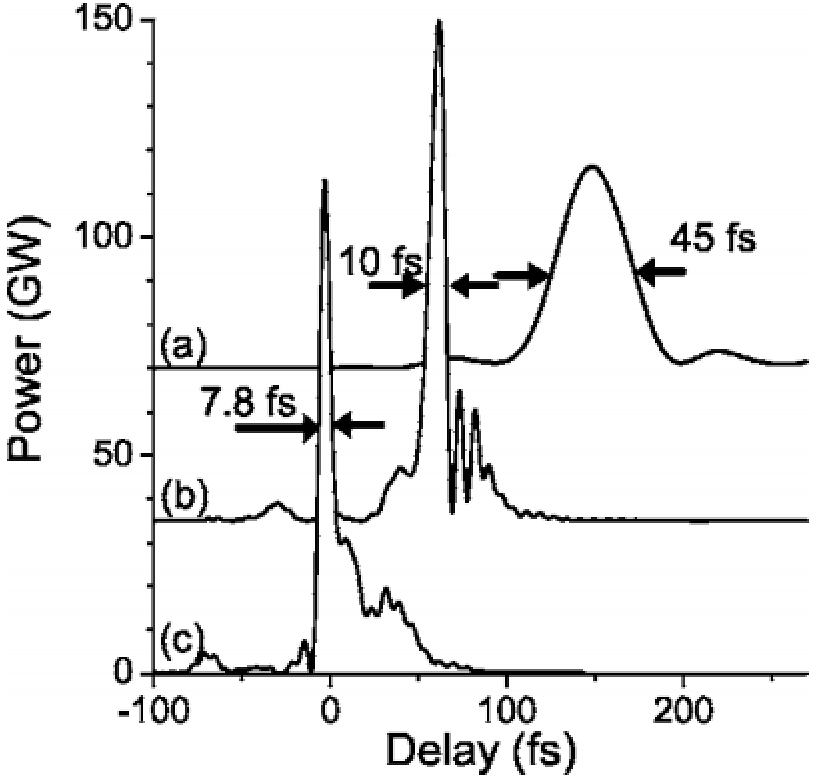
# Self-compression of millijoule pulses to 7.8 fs duration in a white-light filament

**Gero Stibenz, Nickolai Zhavoronkov, and Günter Steinmeyer**

*Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (MBI), Max-Born-Strasse 2a, 12489 Berlin, Germany*

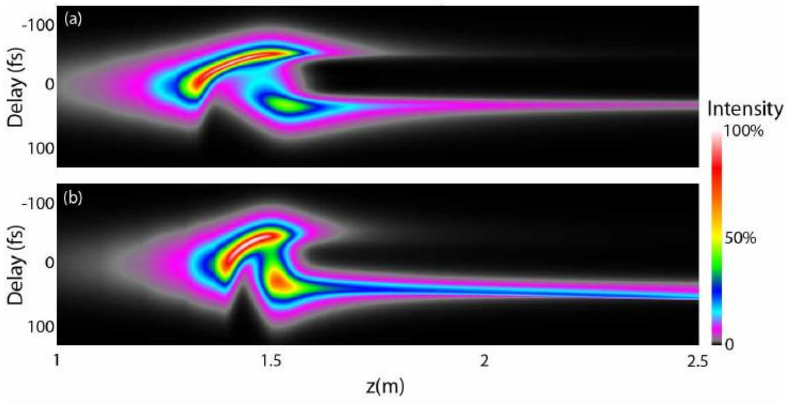
- Compression from 45 fs duration down to 7.8 fs
- Much simpler than hollow-fiber compresssor
- Mechanism completely unclear

  at time of discovery

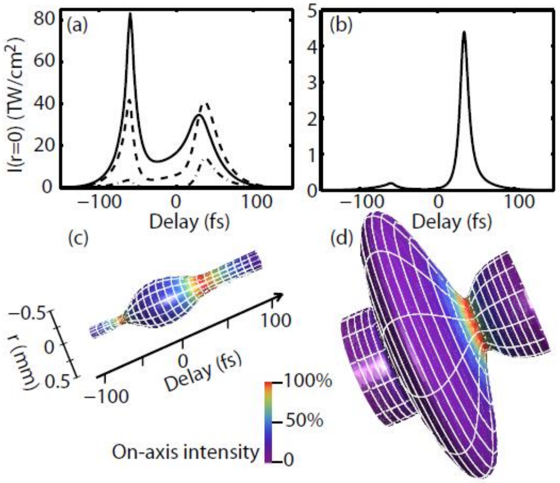


# Some selected results: filamentary self-compression

Revealed the mechanisms behind pulse self-compression in filaments:
Opt. Express 17, 16429 (2009)



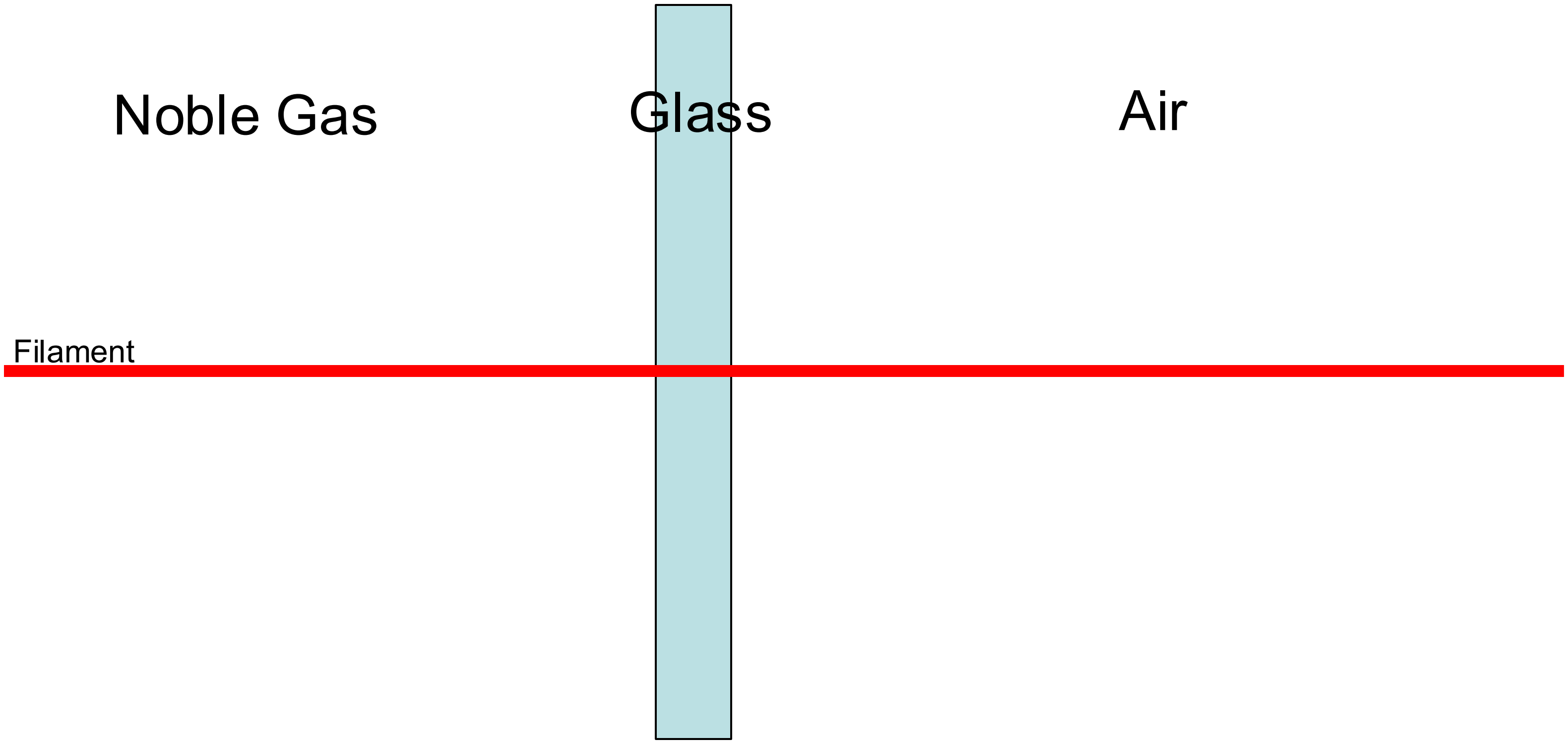

Evolution of temporal pulse shape along filament axis, obtained by solving a generalized nonlinear Schrödinger equation




a) and b) on-axis pulse shapes, c) Spatial intensity Distribution Reveals that self-compression may be regarded as a spatial self-pinching process

Self-compression of optical pulses in filaments results from an intricate interplay of optical nonlinearities and reshapes the pulse both in time and in space.

## Some selected results: Nonlinear self-restoration of optical pulses



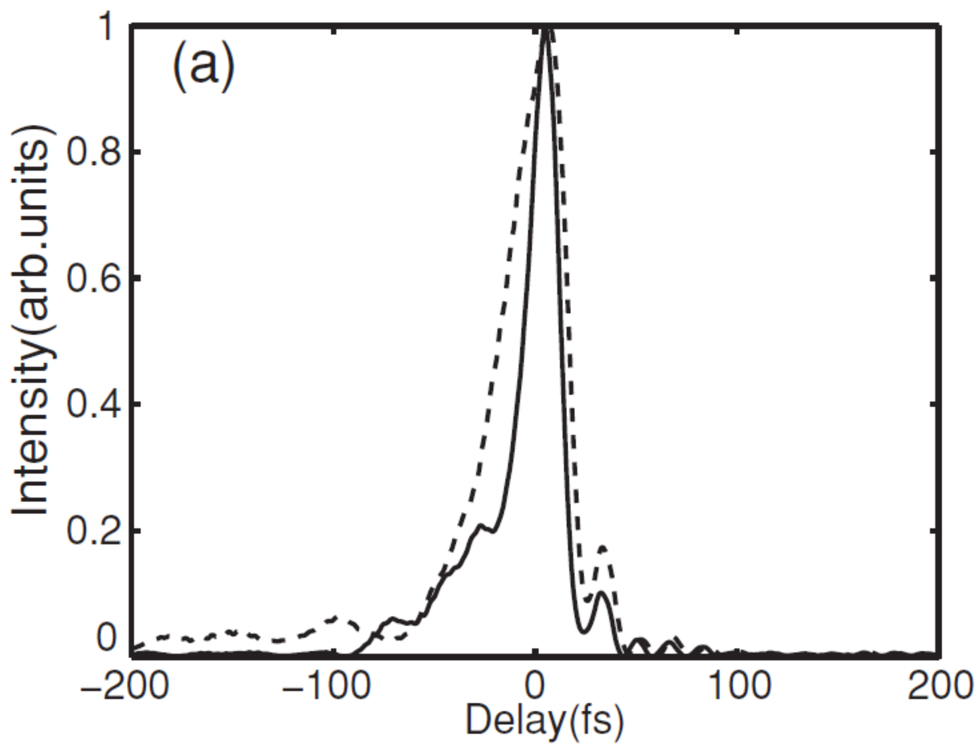

Nonlinearity $n_2$: $10^{-19}$-$10^{-18}$ $cm^2/W$ $2x10^{-16}$ $cm^2/W$ $4x10^{-19}$ $cm^2/W$

Dispersion $\beta_2$: 0.01-0.1 $fs^2/mm$ 30 $fs^2/mm$ 0.02 $fs^2/mm$

## Some selected results: Nonlinear self-restoration of optical pulses

Showed, both theoretically and experimentally, that laser pulses in filaments have spatial and temporal self-healing capabilities:
PRA 83, 043803 (2011)

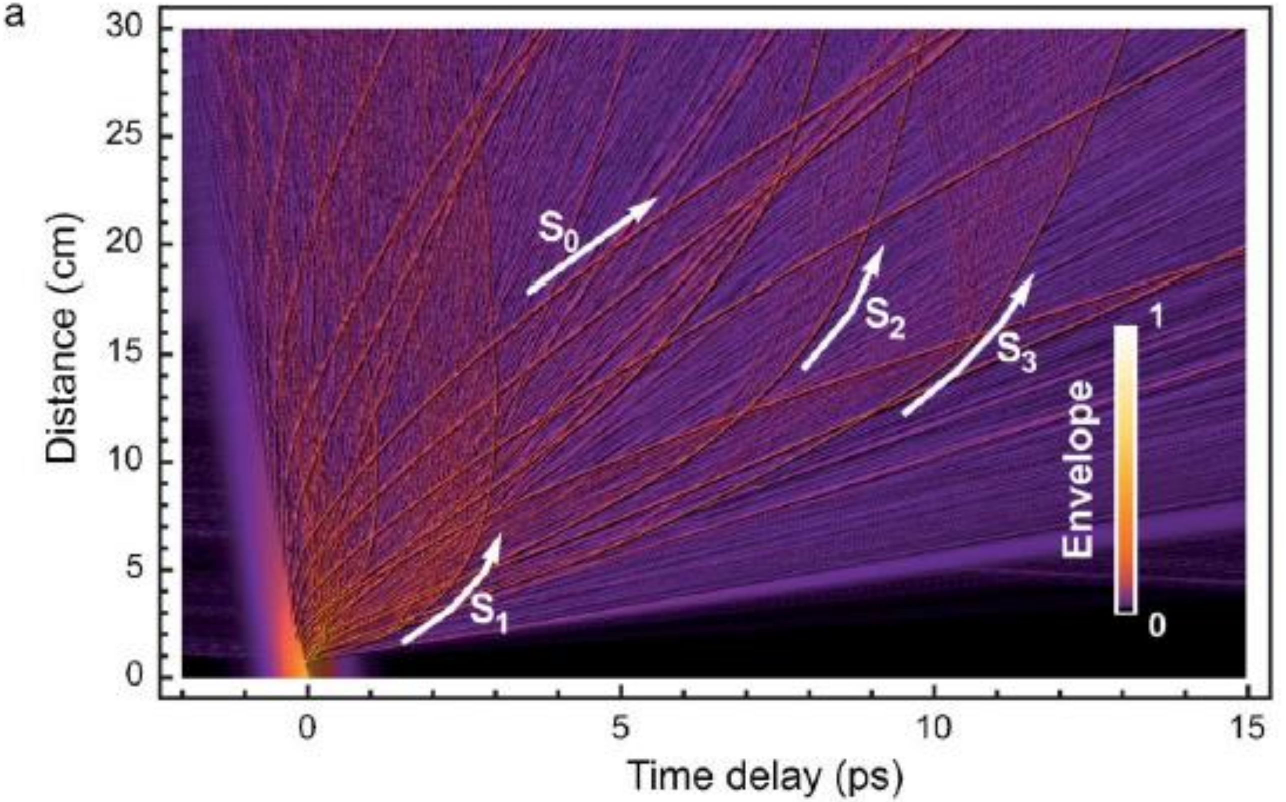
- Spatiotemporal structure of a short laser pulse strongly distorted after passage through a thin silica plate
- Nonlinear optical self-interaction can lead to a self-reconstruction of the original pulse shape
- Building a "window-less cell" for comparison




Dashed line: experimentally reconstructed laser pulse envelope after passing thin silica plate.
Solid line: undistorted laser pulse

# Rogue waves in optical multifilaments and optical fibers

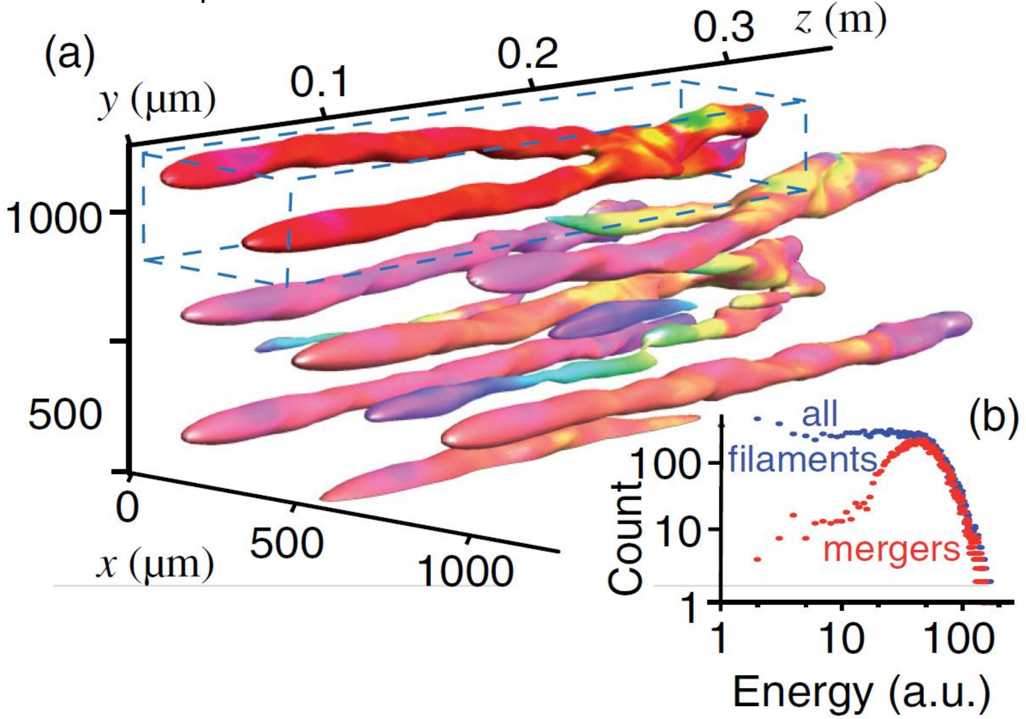
Rogue waves by soliton fission and nonlinear interaction of solitons with dispersive waves



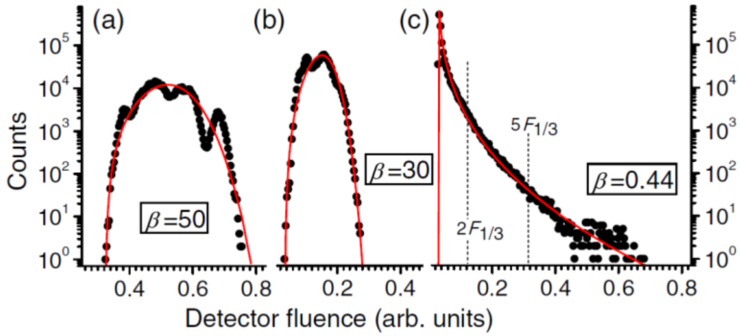

- „Rogue waves“ in fiber optics…
- …probably arise due to the interaction of the continuum and solitons

# Rogue waves in optical multifilaments and optical fibers

Rogue waves by mutual interaction between optical filaments

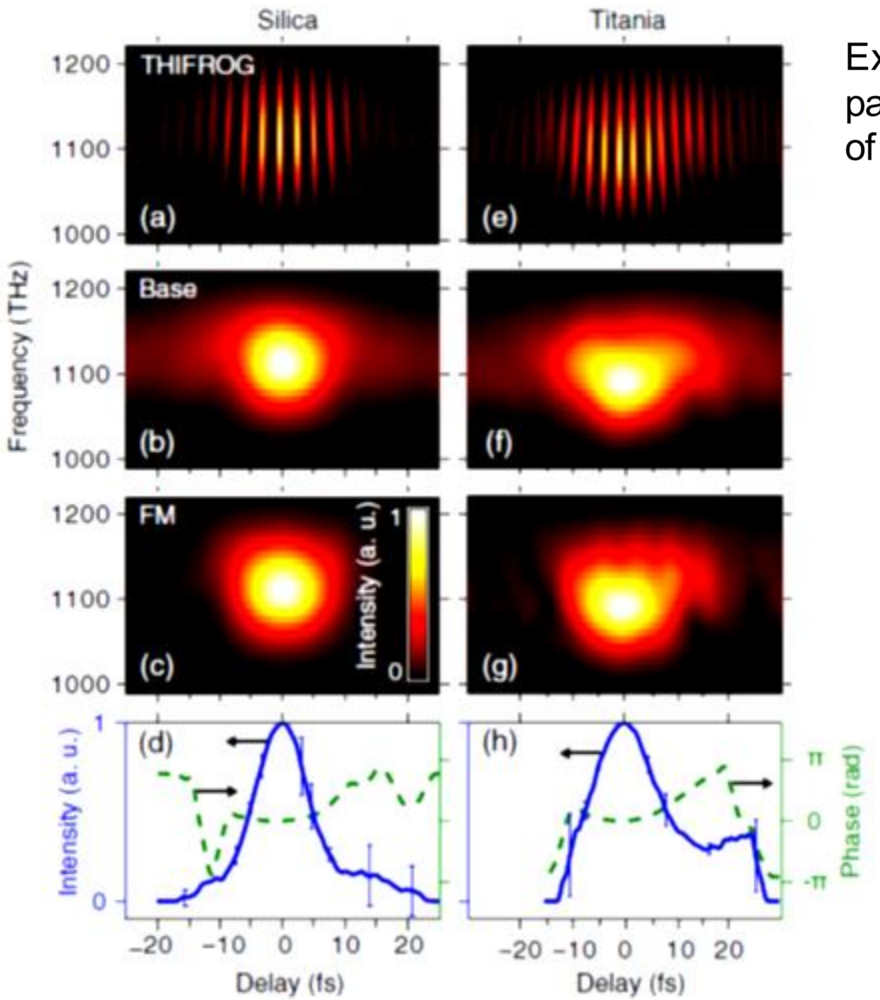



- Mergers between filament strings
- Role of thermodynamic effects in the gas
- „Mirage-like effects




A. Demircan et al., Scientific Reports **2**, 850(2012)
S. Birkholz et al., Phys. Rev. Lett. **111**, 243903 (2013)
S. Birkholz et al., Phys. Rev. Lett **114**, 213901 (2015)

# Delayed dielectric response




Experimental (left panel) and theoretical (right panel) results for the nonlinear optical response of titania

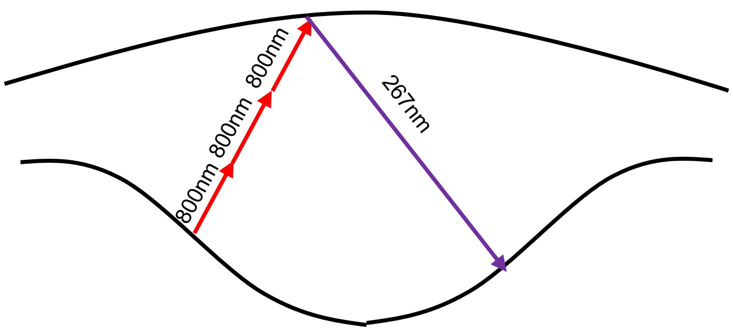
**First evidence for a non-instantaneous nonlinear $\chi^{(3)}$ response of a dielectric material!**

M. Hofmann et al., Optica **2**, 151(2015)

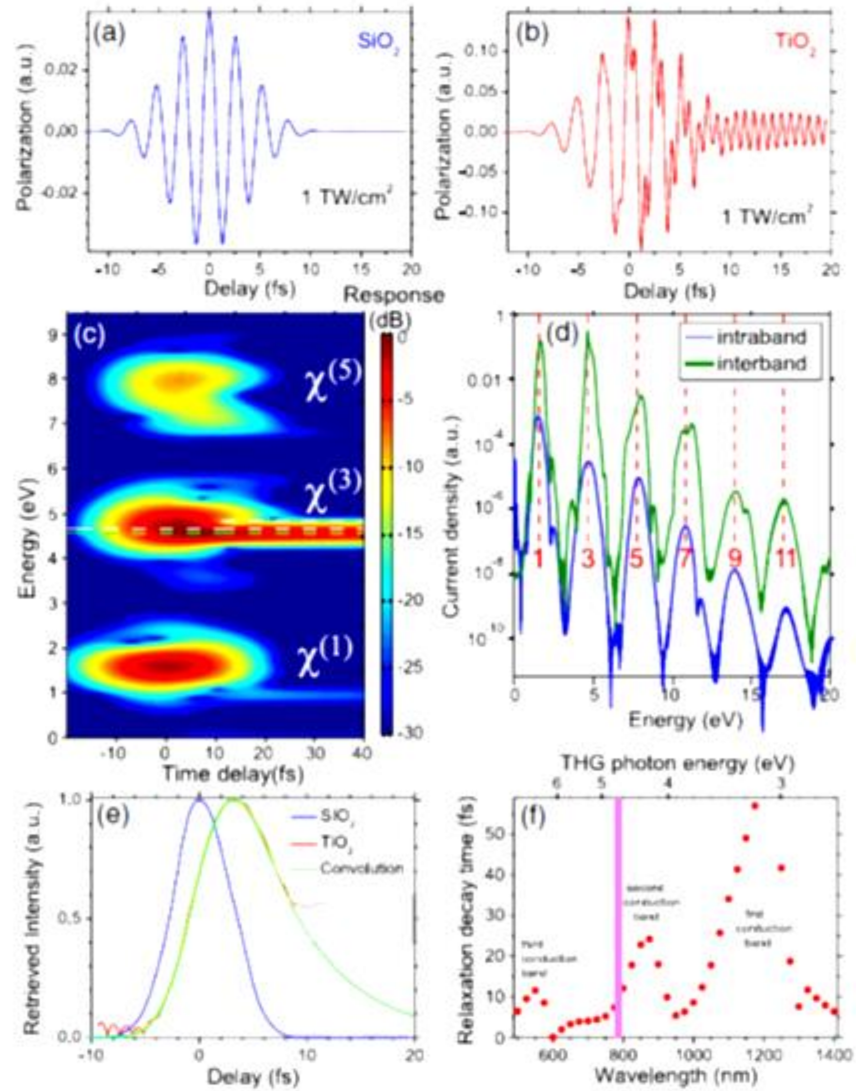
# Delayed dielectric response

Theoretical explanation:
The third harmonic of the incident light is in resonance with a transition between the valence and conduction band.

Theoretical method:
Solve the time-dependent Schrödinger equation in a basis of **Bloch waves**




Three-photon transition from valence into conduction band, followed by emission of the third harmonic radiation




Experimental (left panel) and theoretical (right panel) results for the nonlinear optical response of titania

M. Hofmann et al., Optica **2**, 151(2015)

## Conclusions

- Successful collaboration between two Leibniz-Institutes on filamentation and supercontinuum generation
- Mutually stimulating cooperation: experimental results inspire new theoretical approaches and vice versa
- Proximity of the institutes helpful

# Thank you for your attention!