Soliton Molecules and Optical Rogue Waves

Benasque, October 2014

INSTITUT FÜR PHYSIK

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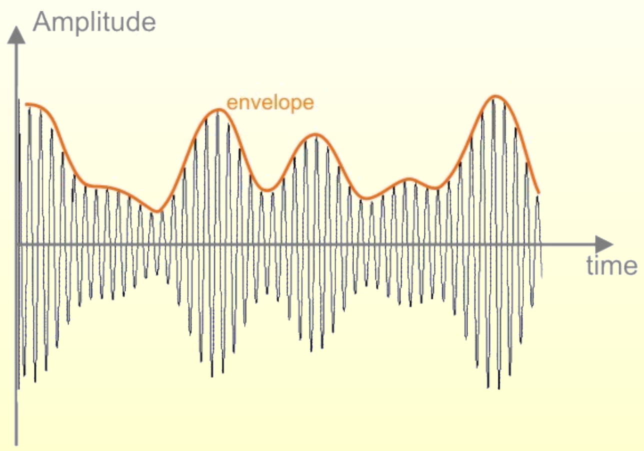
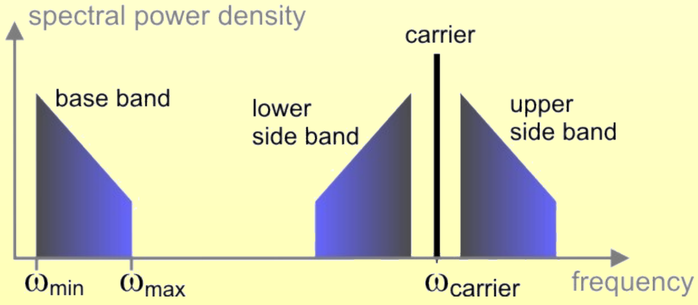
Part IV

State-of-the-Art
Optical Telecommunication:

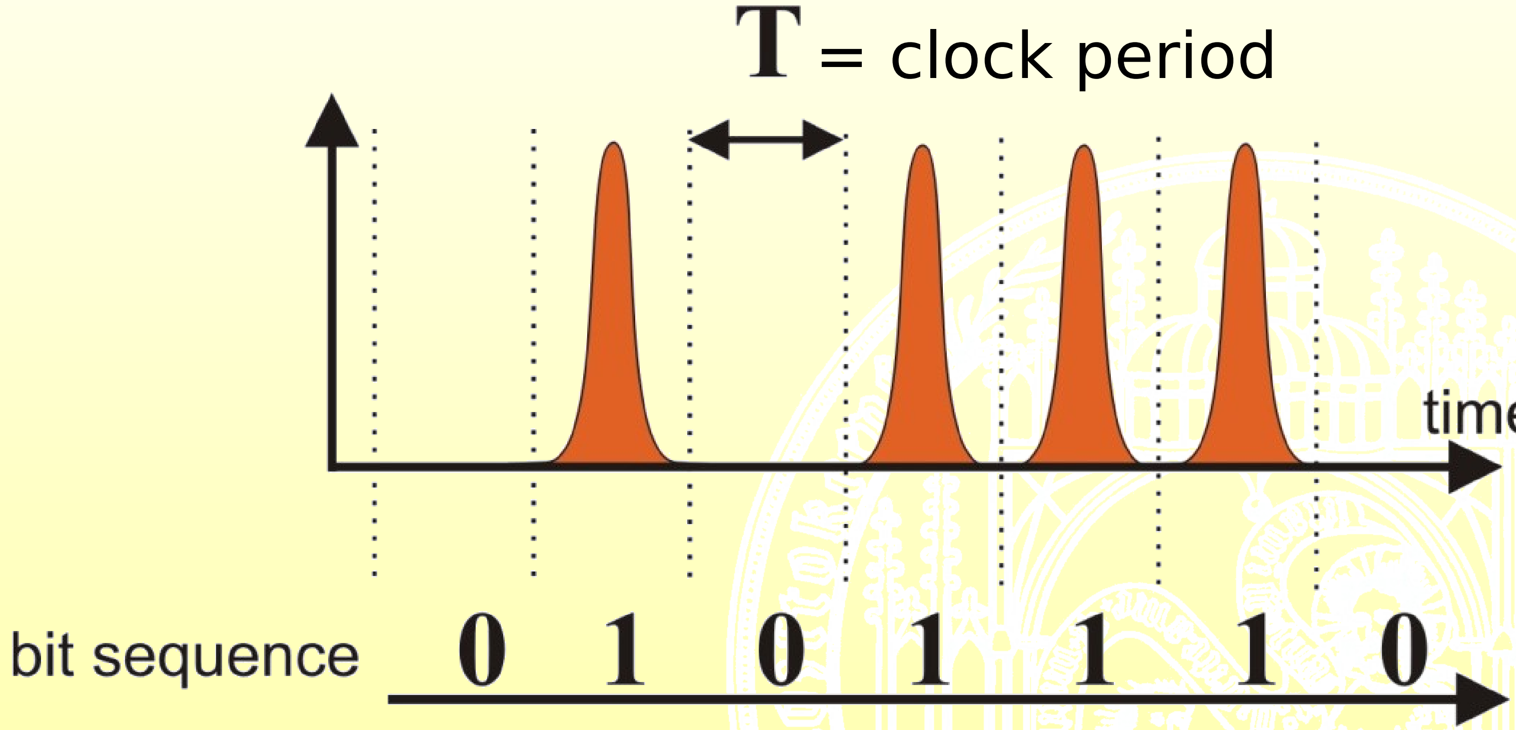
Soliton Molecules etc.

amplitude modulation: sidebands





Coding of Data in Optical Format

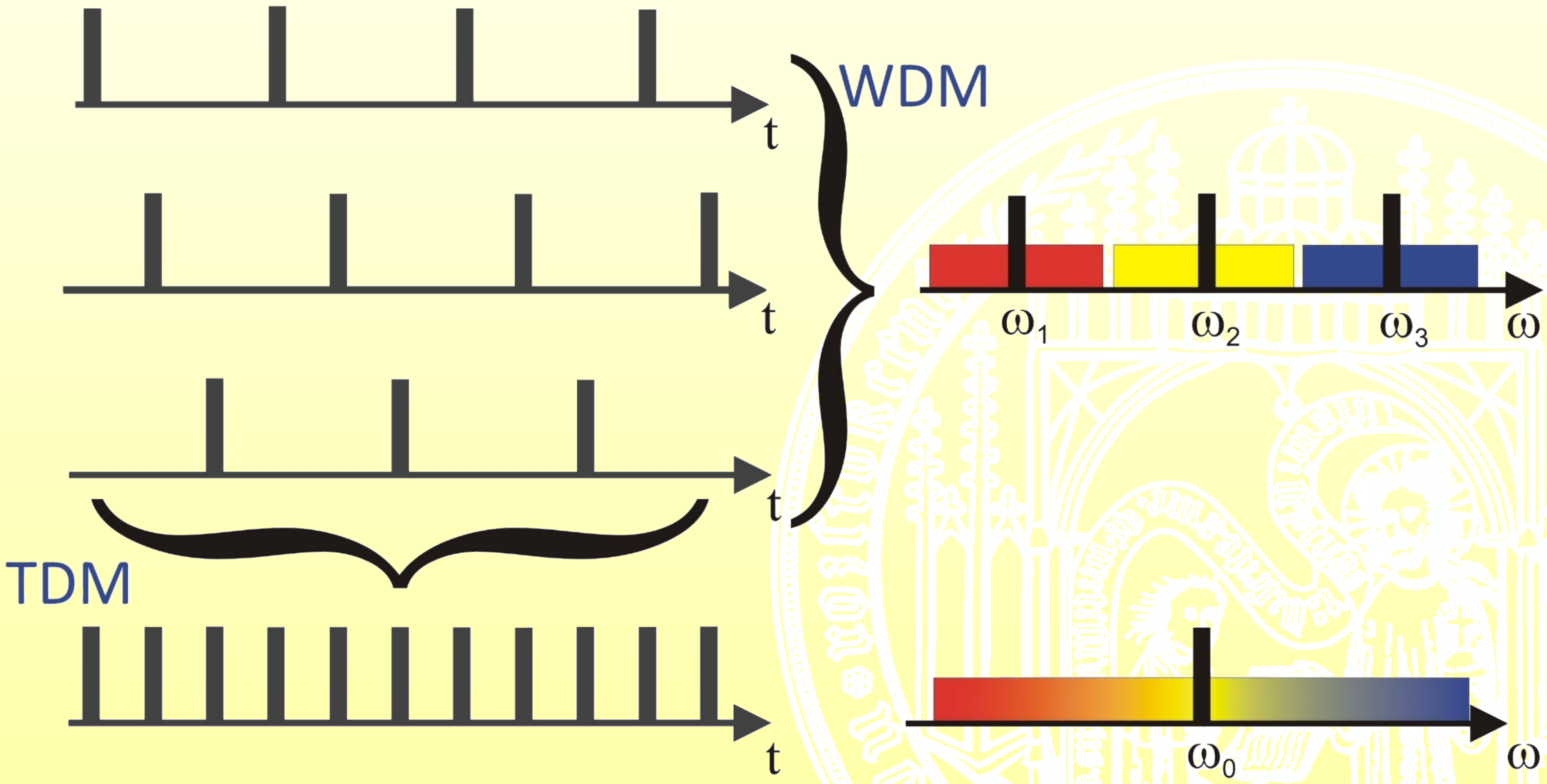


This most straightforward coding is known as OOK, as for *<u>O</u>n-<u>O</u>ff*

transmits one bit per clock period

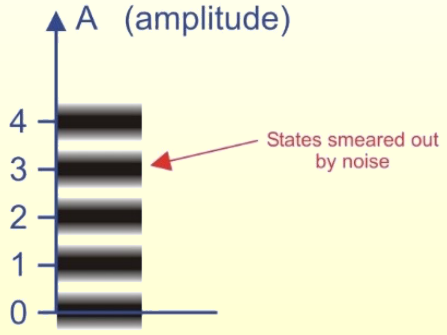
WDM wavelength division multiplex
each bitstream is modulated onto its own carrier frequency

TDM time division multiplex
bit streams are combined, result is modulated onto carrier



How to multiplex several data streams into one

Coding of Data in Optical Format



"Configuration space"
for analog amplitude modulation
as considered by Shannon

$$C = B \cdot \log_2 \underbrace{\left(1 + \frac{S}{N}\right)}_{n}$$

C: capacity, B: bandwidth, n: number of symbols

Claude E. Shannon: *A Mathematical Theory of Communication.* The Bell System Tech. J. 27 (1948)

Coding of Data in Optical Format

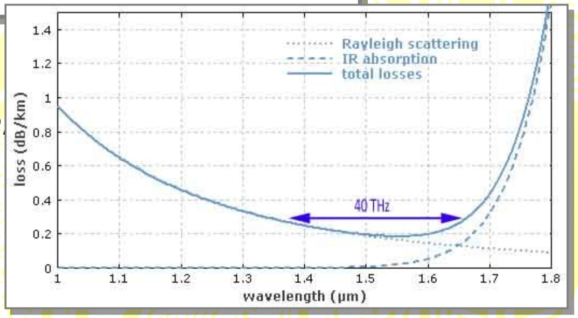
<u>On-off-keying:</u>

Data-carrying capacity subject to Shannon limit

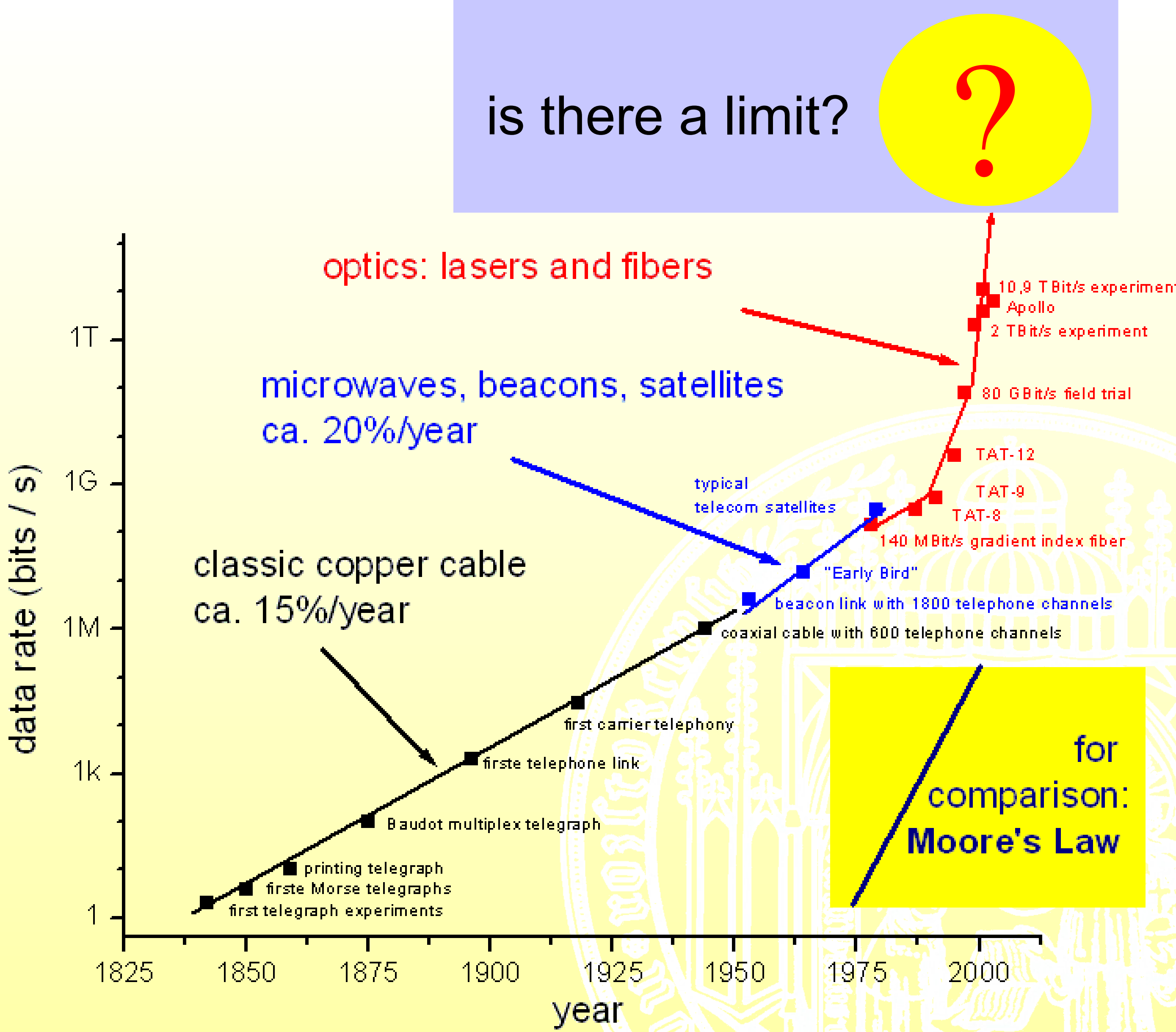
Claude E. Shannon: *A Mathematical Theory of Communication*
The Bell System Tech. J. <u>27</u> (1948)

$C = B \log_2(n)$ C: capacity, B: bandwidth, n: number of symbols

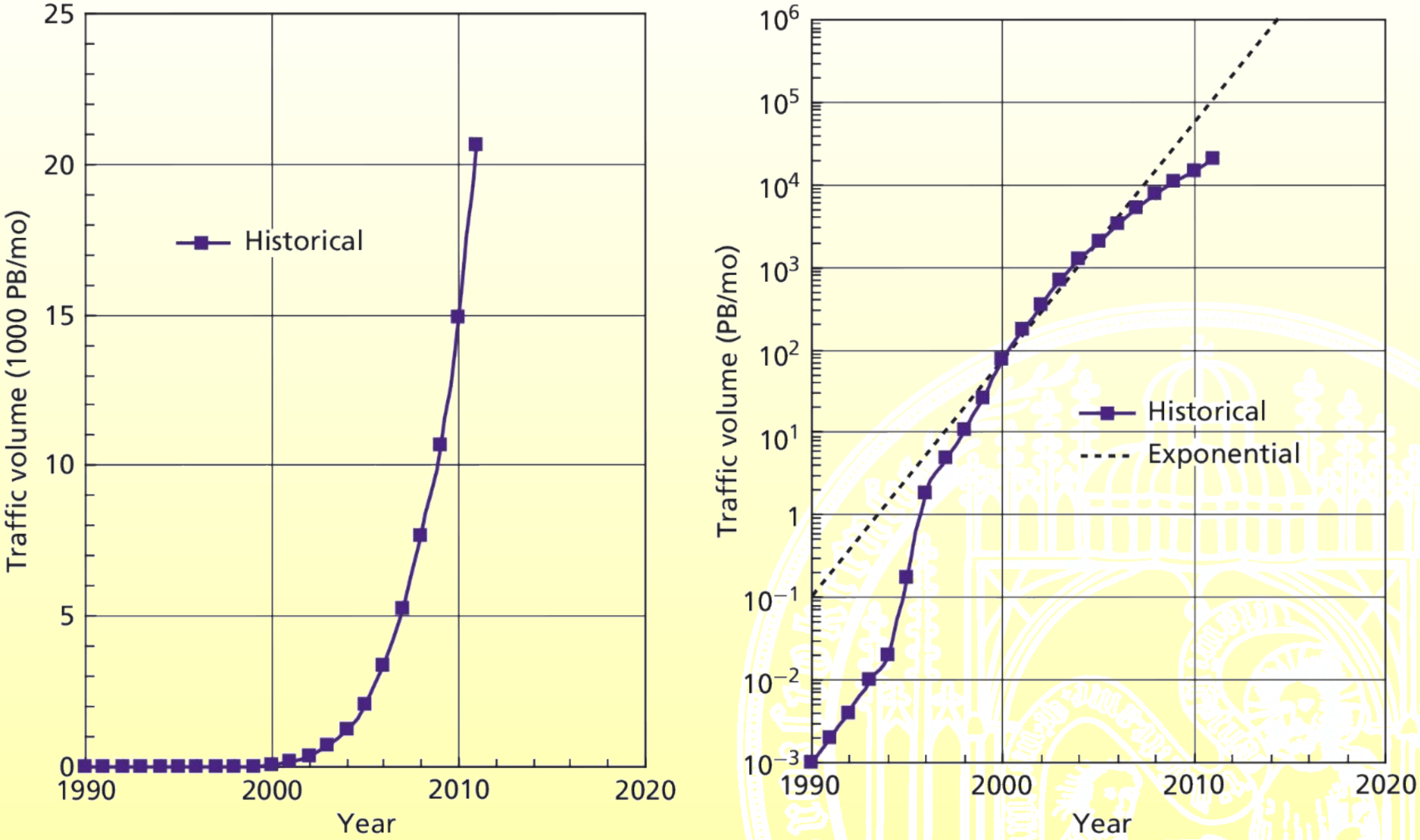
with $n = 2$ and $B \approx$ 40 THz $\Rightarrow$ $C \approx$ 40 Tbits



The Shannon limit for binary signals
has been reached



Historical development of data rates in telecommunication

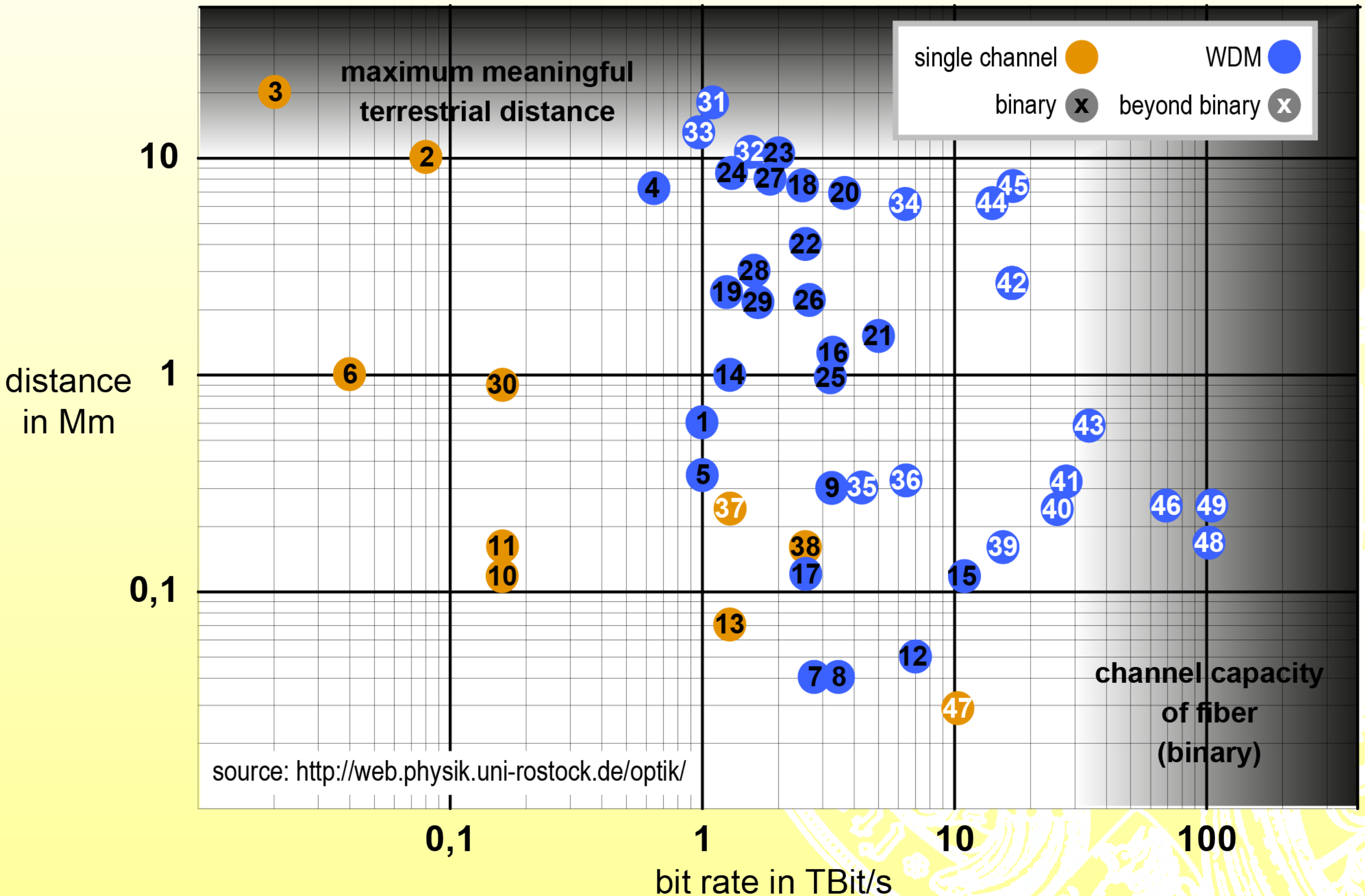


S. K. Korotky, BLTJ **18**, 5 (2913

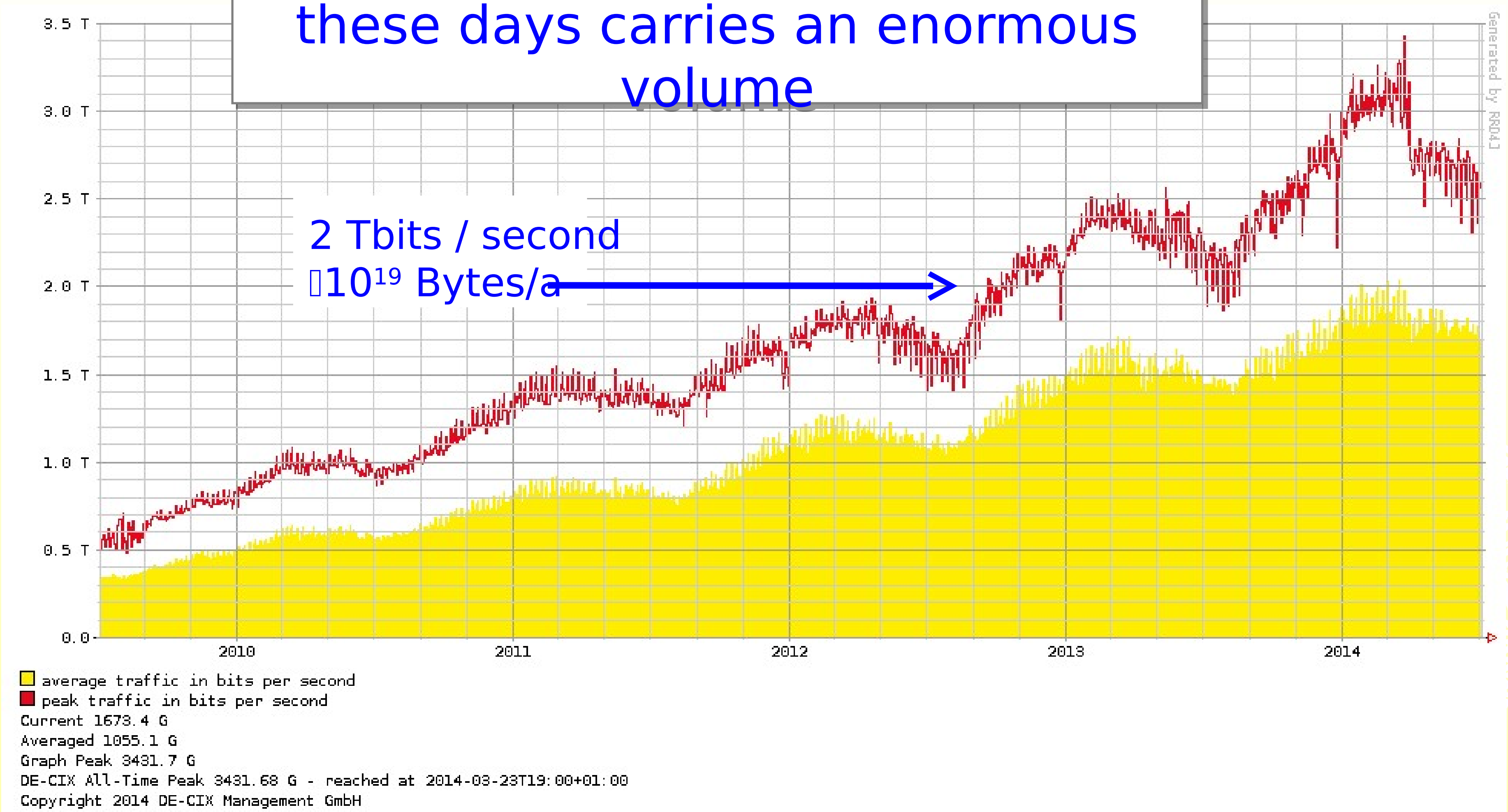
Global Fixed Internet Traffic Volume

Hero experiments, and the Limit to Growth: Data rates and distances achieved over single fiber

Binary coding is no longer up to the task



Fiber-optic data transmission these days carries an enormous volume



2 Tbits / second
≈10^{19} Bytes/a

Internet data traffic volume at German switch „DE-CIX“

as of July 2014

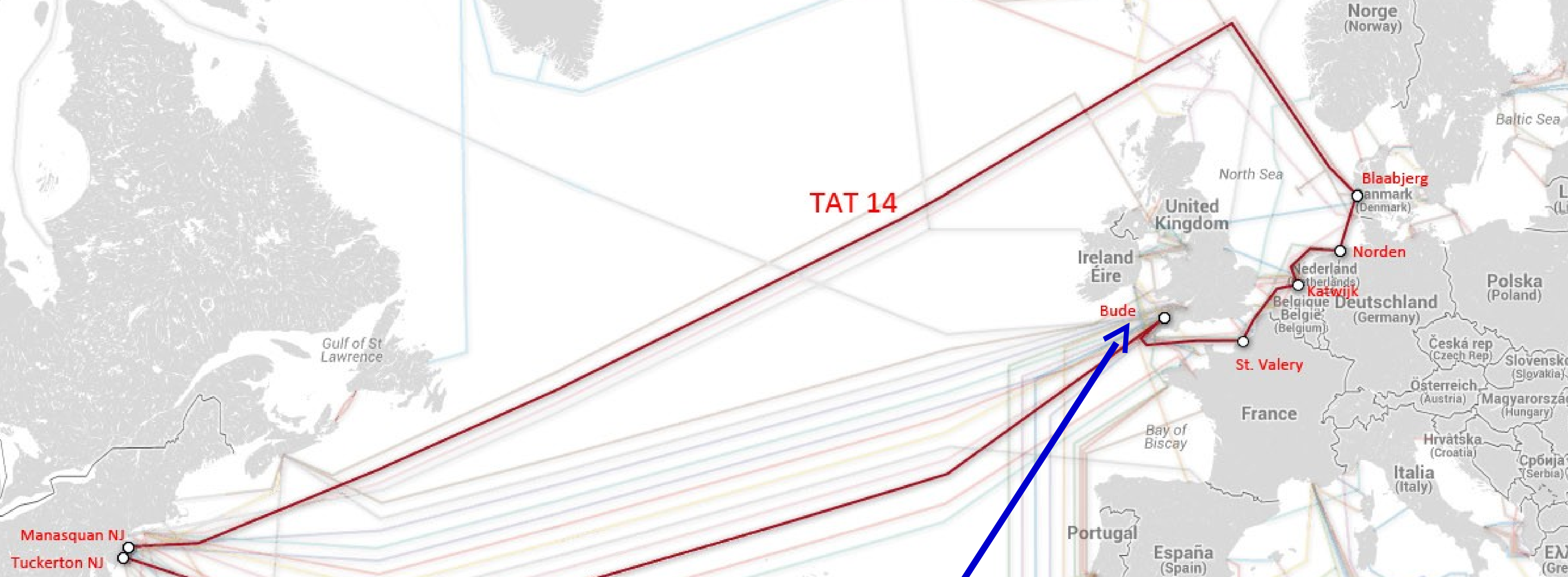
Global IP traffic in 2014 estimated as $8 \cdot 10^{20}$ Bytes/a

Where there is data, it can be tapped. And it is being done.

Note: World production of hard disks currently estimated at 10^{20} Bytes/a

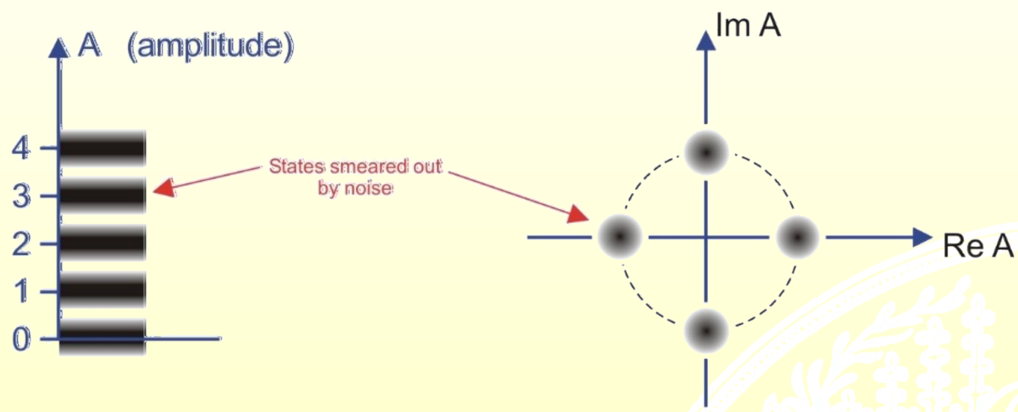
TransAtlantic Telephone Cable 14

in service since 2001
cost 1.3 billion US$
length 15 000 km
data rate 1 Tbit/s



Bude (Cornwall) pop. 9242

Coding of Data in Optical Format



“Configuration space” for analog amplitude modulation as considered by Shannon

Configuration space for QPSK format

Quaternary Phase Shift Keying

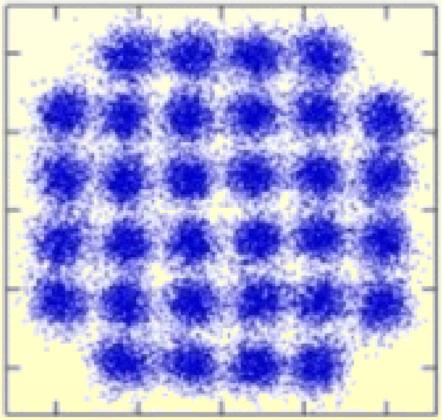
$$C = B \cdot \log_2 \underbrace{\left(1+\frac{S}{N}\right)}_{n}$$

C: capacity, B: bandwidth, n: number of symbols

Claude E. Shannon: *A Mathematical Theory of Communication.* The Bell System Tech. J. 27 (1948)

Coding of Data in Optical Format

Advanced coding formats combine phase and amplitude modulation:
this is known as QAM (*as in quadrature-phase and amplitude modulation*)



32-QAM: Measured configuration diagramm

Akihide Sano *et al*. (21 authors) ,
„409-Tb/s + 409-Tb/s crosstalk suppressed bidirectional MCF transmiss
over 450 km using propagation-direction interleaving“
Opt. Express **21**, 16777 (2013)

transmits 5 bits per clock period

Coding of Data in Optical Format

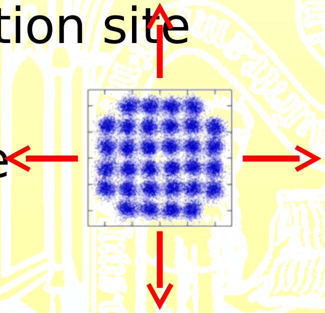
Fiber – any glass – is a nonlinear material.
This is a given.

Conventional wisdom: nonlinearity is bad.
Mainstream approach: keep signal power low
⇒

☺ nonlinear effects are avoided

☹ signal-to-noise ratio issue at detection site

☹ limited configuration space volume



This approach will eventually run into a bottleneck

Now enter…
solitons

The fundamental soliton

$\gamma > 0,\ \beta_2 < 0$ (anomalous dispersion)

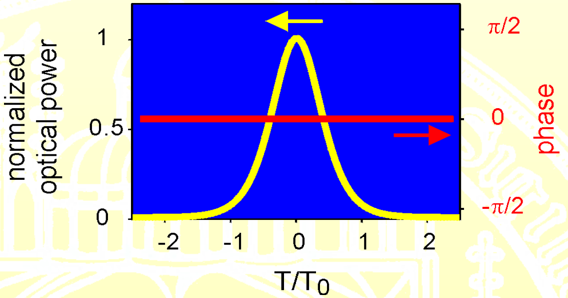
$$A(z,T) = \sqrt{P_1}\ \mathrm{sech}\left(\frac{T}{T_0}\right)\ e^{i\gamma P_1 z/2}$$

with

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

z: position,
T: time (in comoving frame)

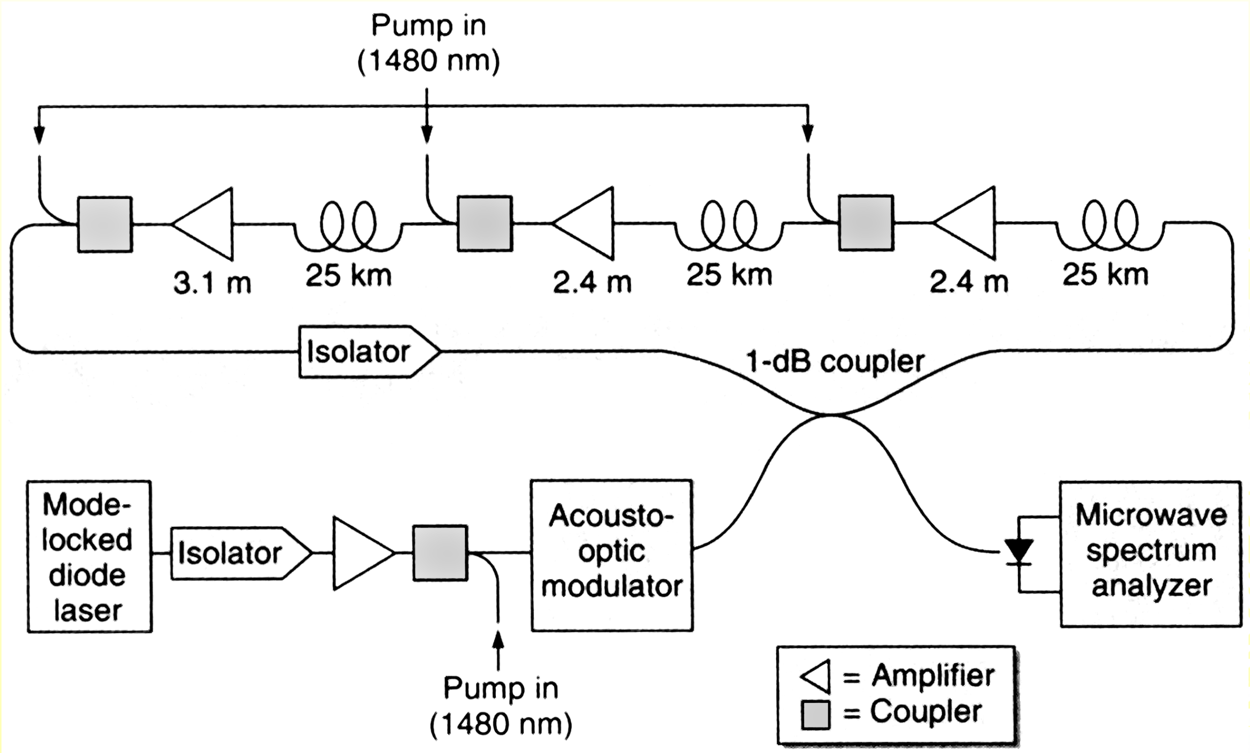
P_1: peak power
T_0: pulse duration



z dependence only in phase $\Rightarrow$ $|A|^2$ is independent of z
T dependence only in envelope $\Rightarrow$ constant phase profile

Solitons are the natural bits of optical data transmission

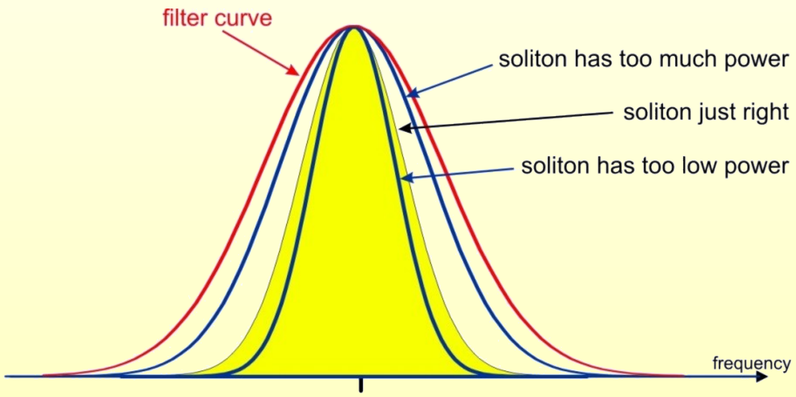
Prediction: Hasegawa, Tappert: Applied Phys. Lett. **23**, 142 (1973)
First demonstration: Mollenauer, Stolen, Gordon: Phys. Rev. Lett. **45**, 1095 (1980)
First commercial deployments: 2001

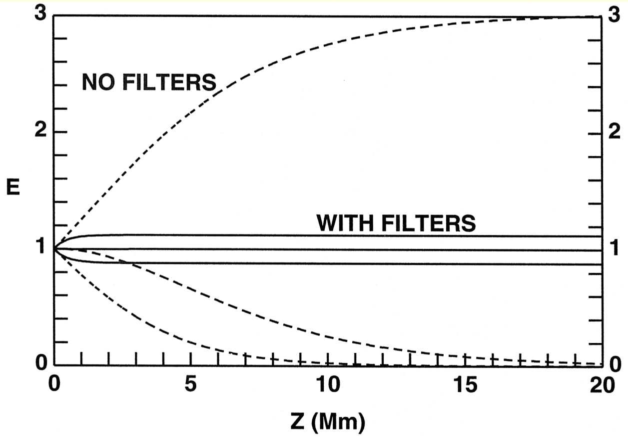


experiment simulating long-distance transmission in the lab

LF Mollenauer *et al*. 1991

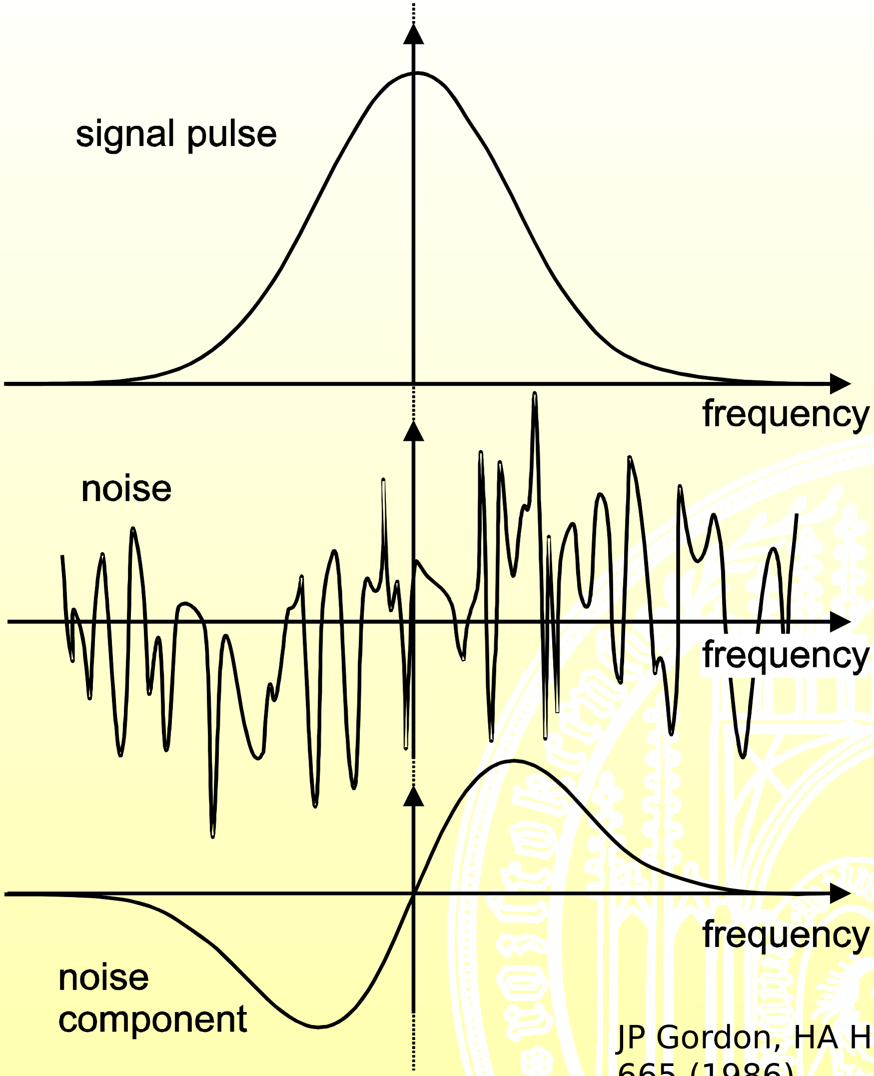
on the effect of in-line spectral filters





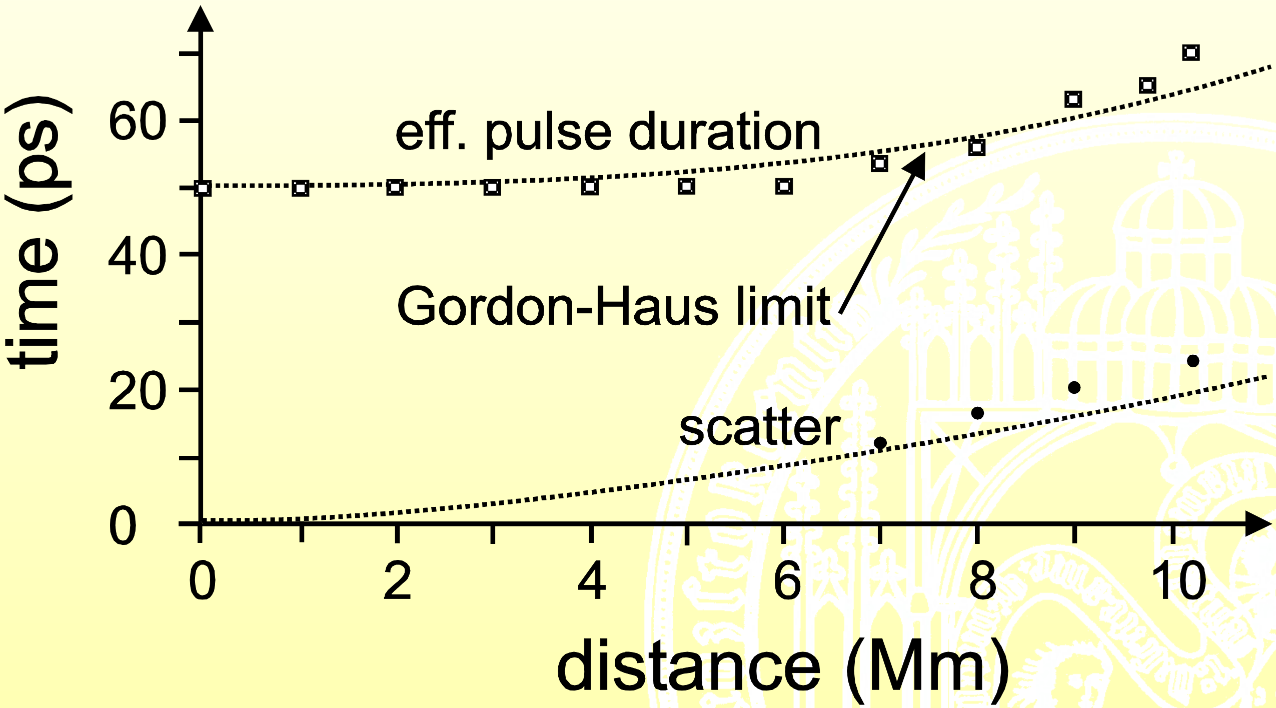
If the soliton has excess power, it becomes narrower
⇒ it becomes spectrally wider and suffers more loss in the filter.

Filtered line is self-correcting!



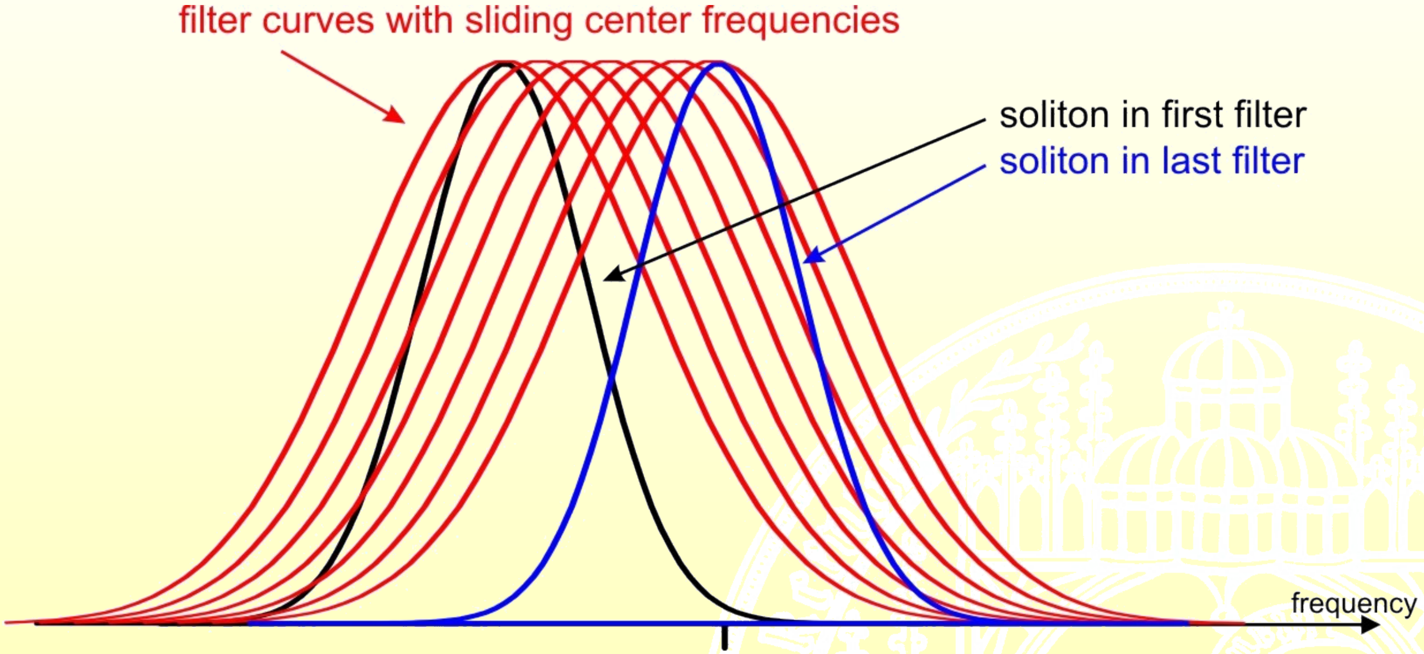
JP Gordon, HA Haus, Optics Letters **11**, 665 (1986)

sketch to explain Gordon-Haus jitter



experimental result for ultralong distance soliton transmission

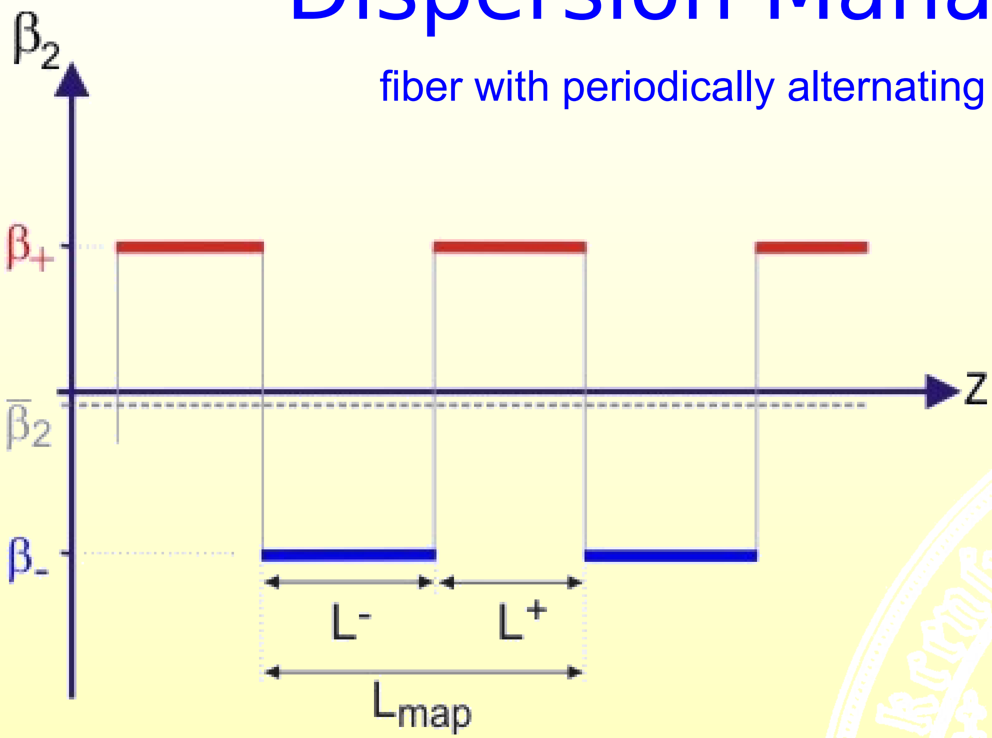
LF Mollenauer *et al*. 1990



- solitons can rearrange themselves and adapt to the next filter
- for linear waves the line becomes opaque

Dispersion Management

fiber with periodically alternating dispersion



modulation strength:

$$S = \frac{(\beta_+ - \overline{\beta})L_+ + (\beta_- - \overline{\beta}_2)L_-}{\tau^2}$$

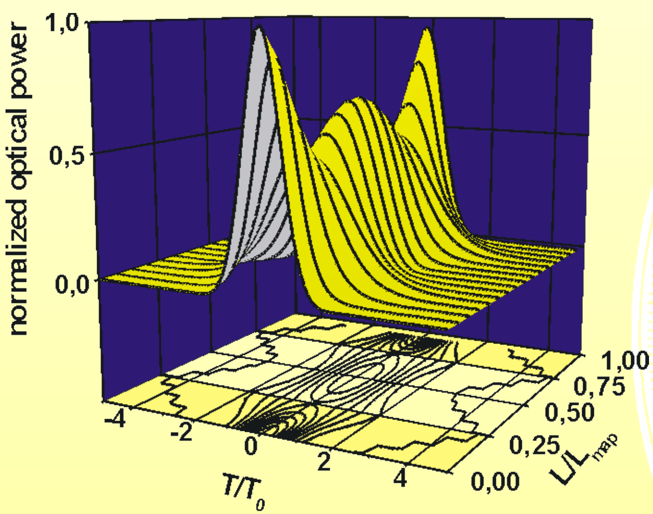
periodically alternating dispersion is advantageous for wavelength division multiplexing:

- low path-average dispersion affords low soliton power
- high local dispersion destroys phase matching for four wave mixing
- more technical benefits...

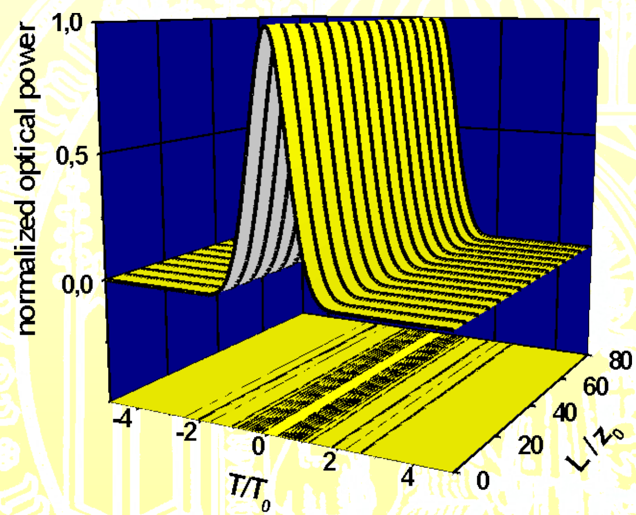
Can solitons exist in dispersion-managed fibers?

Discovery of the DM soliton 1997-98 by five groups almost simultaneously

Nijhof *et al*., Electron. Lett. 33, 1726 (1997)
Chen *et al*., Opt. Lett. 23, 1013 (1998)
Turytsin *et al*., Opt. Lett. 23, 682 (1998)
Kutz *et al*., Opt. Lett. 23, 685 (1998)
Grigoryan *et al*., Opt. Lett. 23, 609 (1998)



propagation of a DM soliton



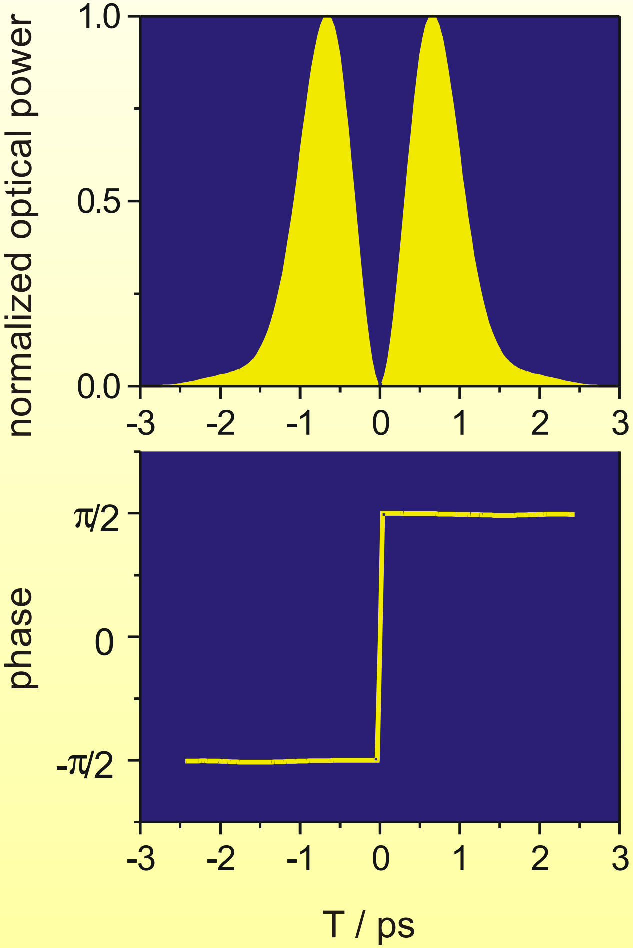
propagation of a DM soliton,
sampled once every dispersion

Now enter…
soliton molecules

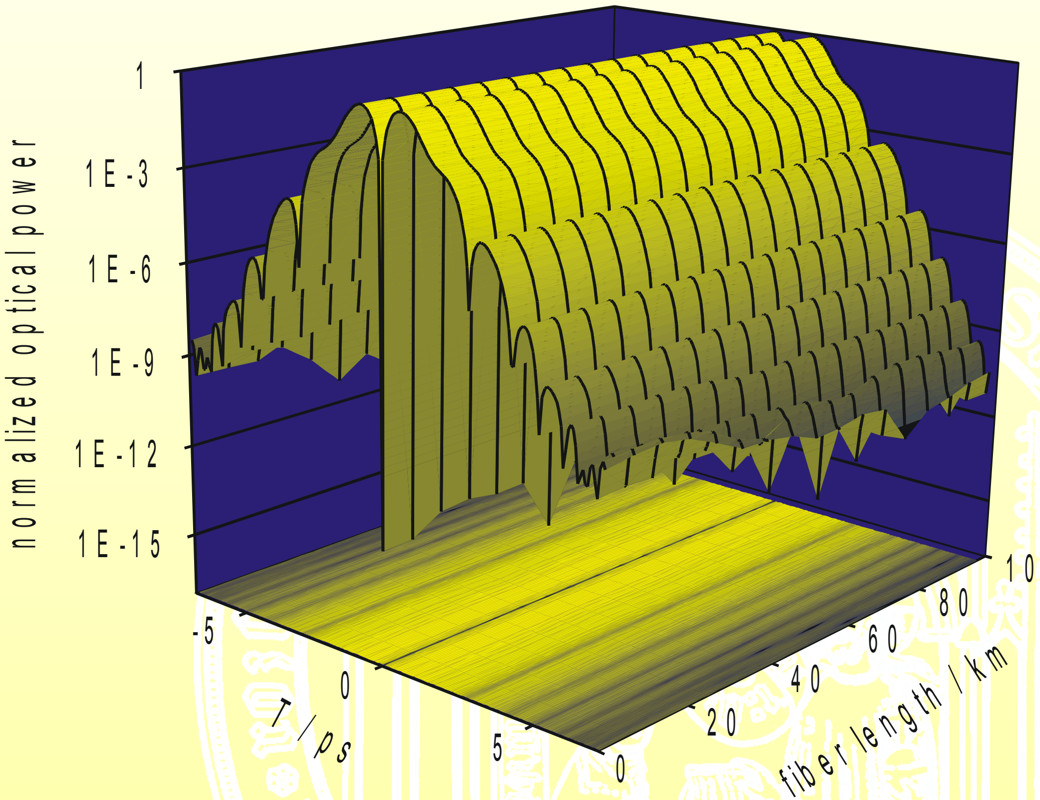
Stable soliton compound

(exists only in DM fibers)

input pulse:



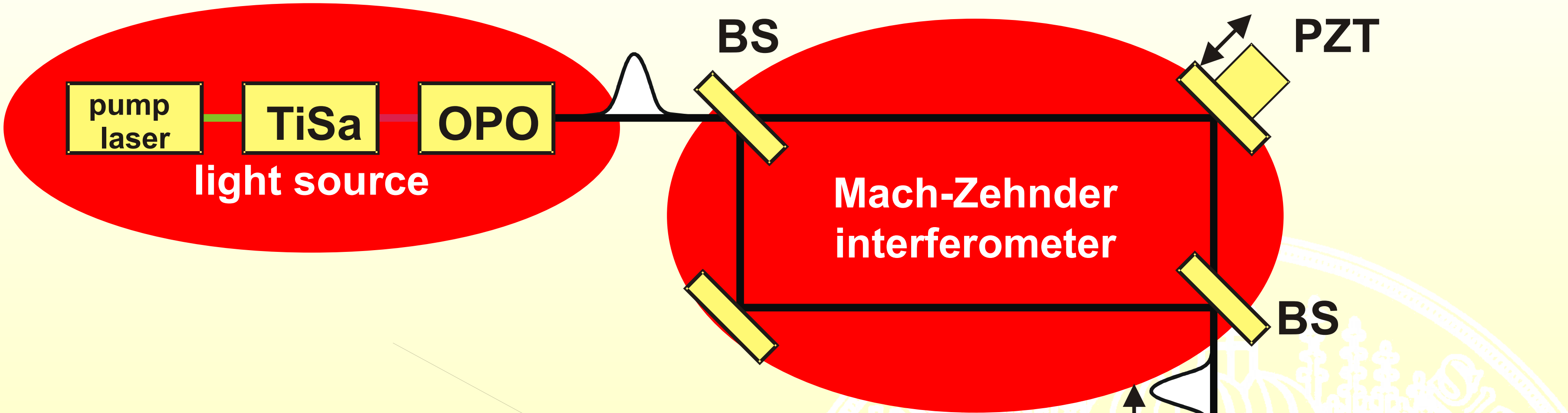
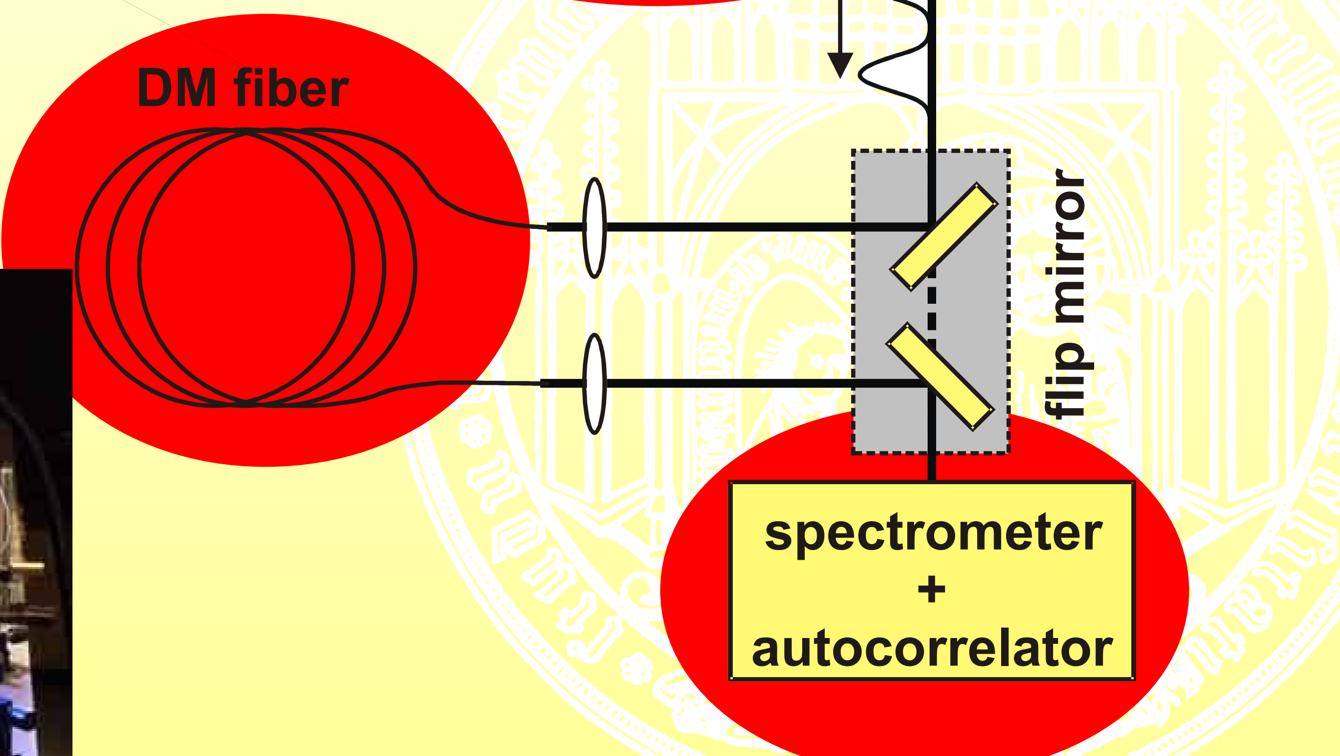
stroboscopic view:



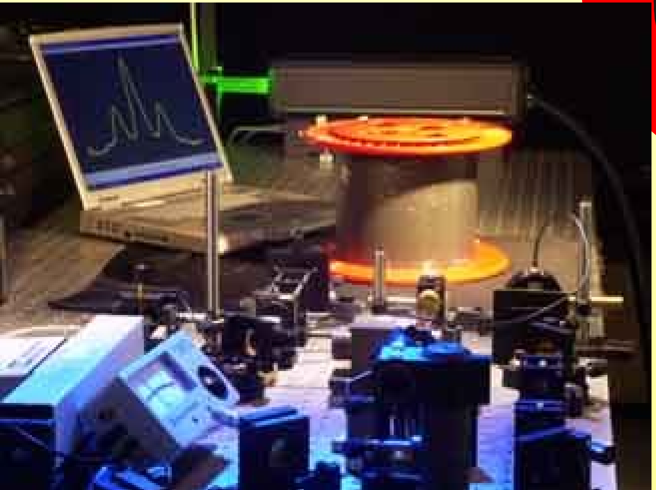
M. Stratmann, T. Pagel, FM: PRL **95,** 143902 (2005)

see also:
Paré, Belanger: Opt. Comm. 1999
Maruta et al: IEEE JSTQE 2002
Feng, Malomed: Opt. Comm. 2004

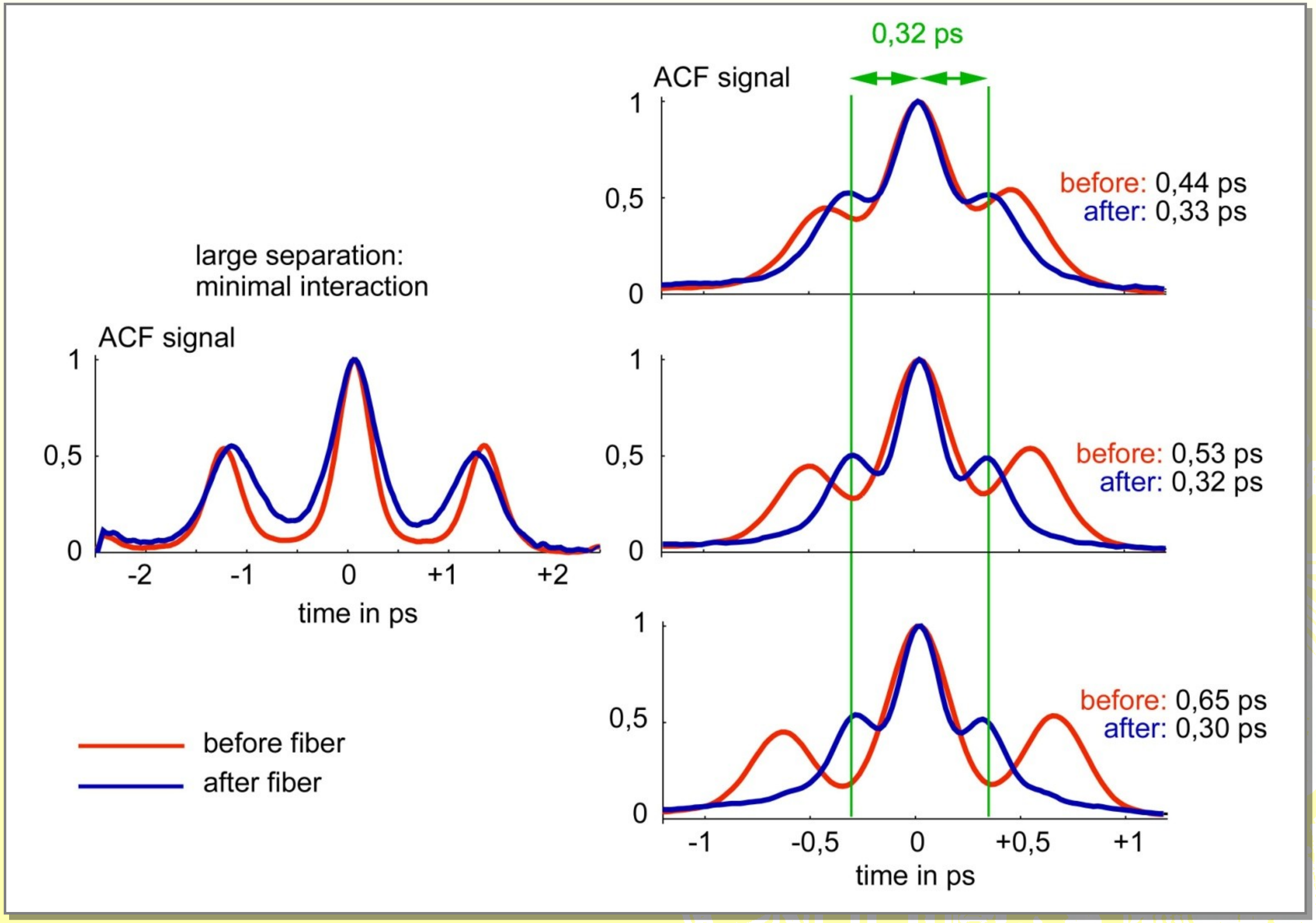
First experiment to demonstrate soliton compounds

M. Stratmann, T. Pagel, FM,
PRL **95,** 143902 (2005)



return to equilibrium separation: experimental data



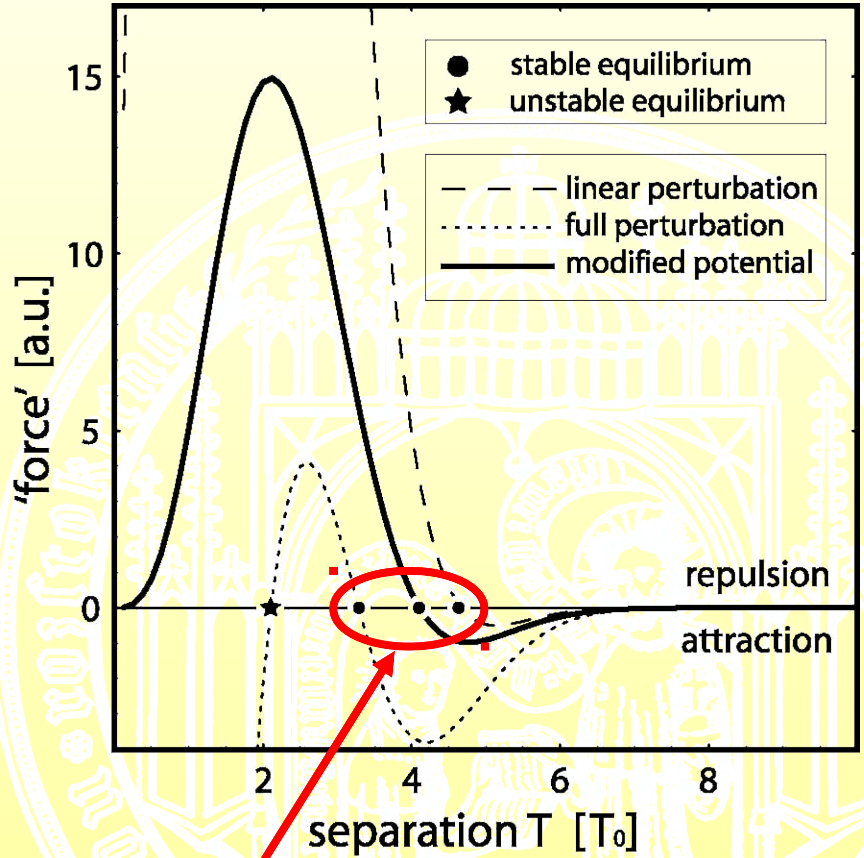
stable equilibrium separation like for nuclei in a diatomic molecule

„soliton molecules“

M. Stratmann, T. Pagel, FM: PRL **95,** 143902 (2005)

binding mechanism understood

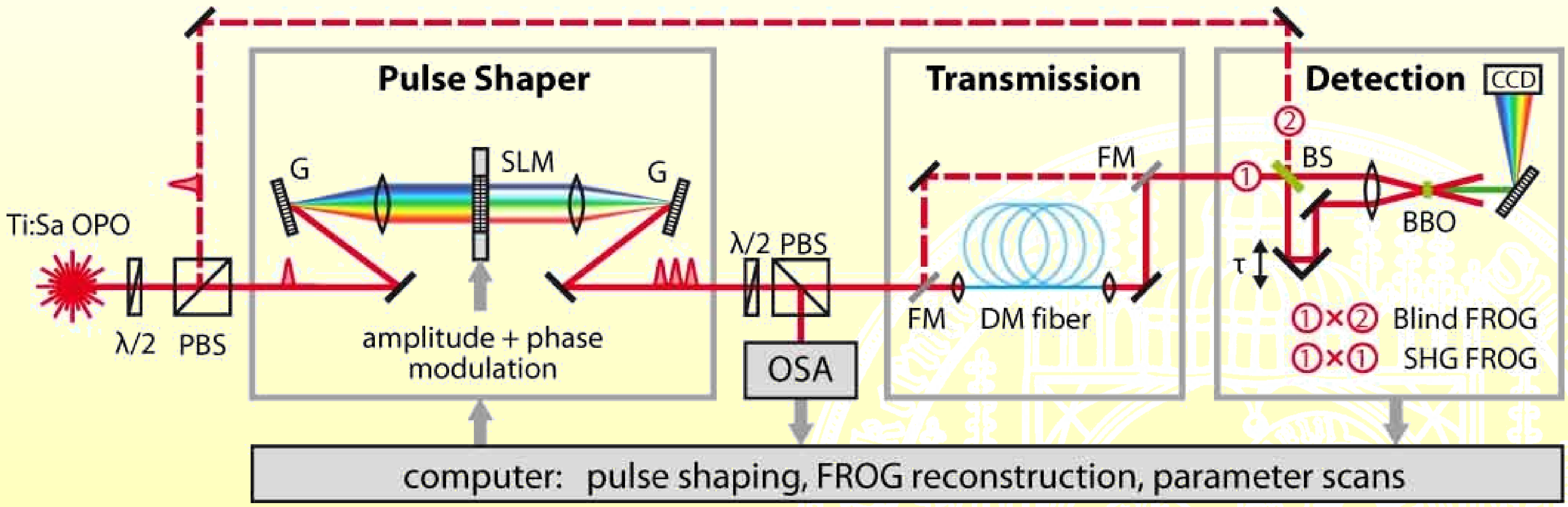
- local forces at different positions inside the double pulse result from the relative phases present in these positions
- integration across whole profile, weighted with local power, yields local net effect
- global net effect is found from integration over a dispersion map period
- this approach pioneered by J. P. Gordon and L. F. Mollenauer



stable equilibrium position

Perturbation treatment:
A. Hause, H. Hartwig, M. Böhm, FM:
„Binding mechanism of temporal soliton molecules",
Phys. Rev. A **78**, 063817 (2008)

Improved experimental setup

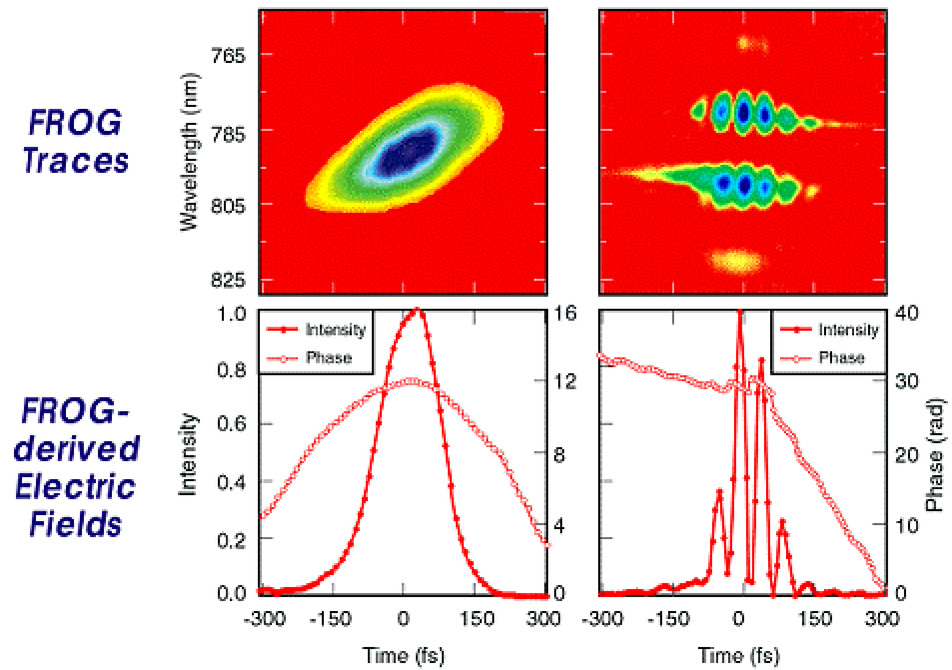


- pulse shaper with spatial light modulator can control both amplitu
- flip mirrors (FM) allow comparison input / output
- auto / cross-correlator with spectral dispersion acquires pulse sha

FROG: Frequency-Resolved Optical Gating

R. Trebino *et al*. 1997

Autocorrelation with spectral dispersion, and a sophisticated reconstruction a
allows to obtain both amplitude and phase profile



a linearly chirped pulse a complex pulse

Bern Kohler, Ohio State University

Improved experimental setup

Fiber types used:

• OFS Fitel TrueWave SRS $\beta_2 = -5.159$ ps²/km 24 m segments

• OFS Fitel TrueWave RS $\beta_2 = +4.259$ ps²/km 22 m segments

Length of dispersion period 46 m

Completed DM fiber line:

10 periods, total length 460 m

Compare with typical commercial system:

40 Gbit/s (25 ps clock period) uses τ = 7.5 ps

This experiment: τ = 250 fs

Pulse duration scaled down by factor of 30

Length scale scaled down by factor of 900

Experiment corresponds to system with total length 410 km

Typical pulse energies here $\approx$ 10 pJ (scaled: 0.3 pJ)

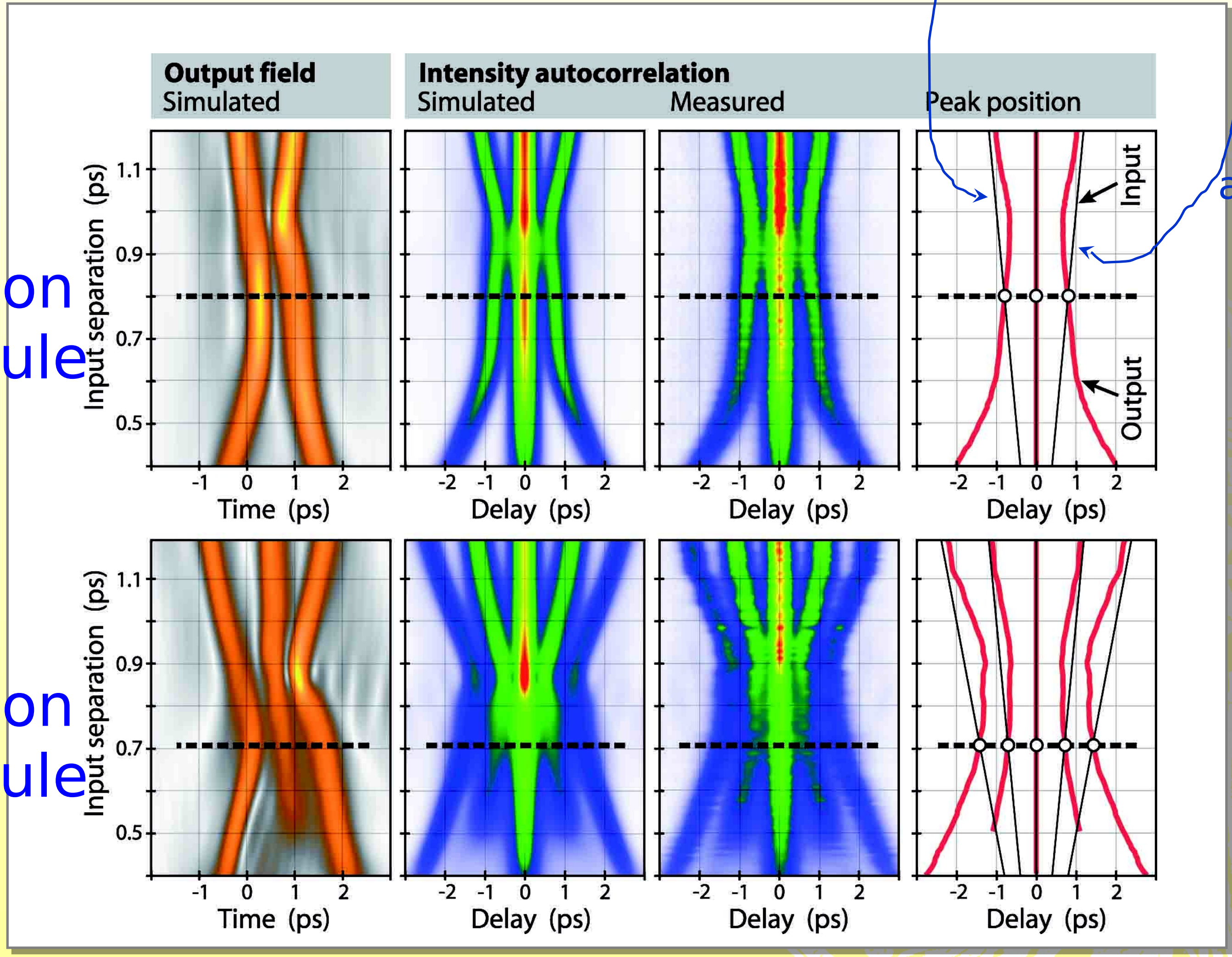
Fiber line has 20 splices, thus power loss of 1.55 dB

Systematic tests

Evaluation of autocorrelation traces to locate equilibrium

2-soliton molecule

3-soliton molecule



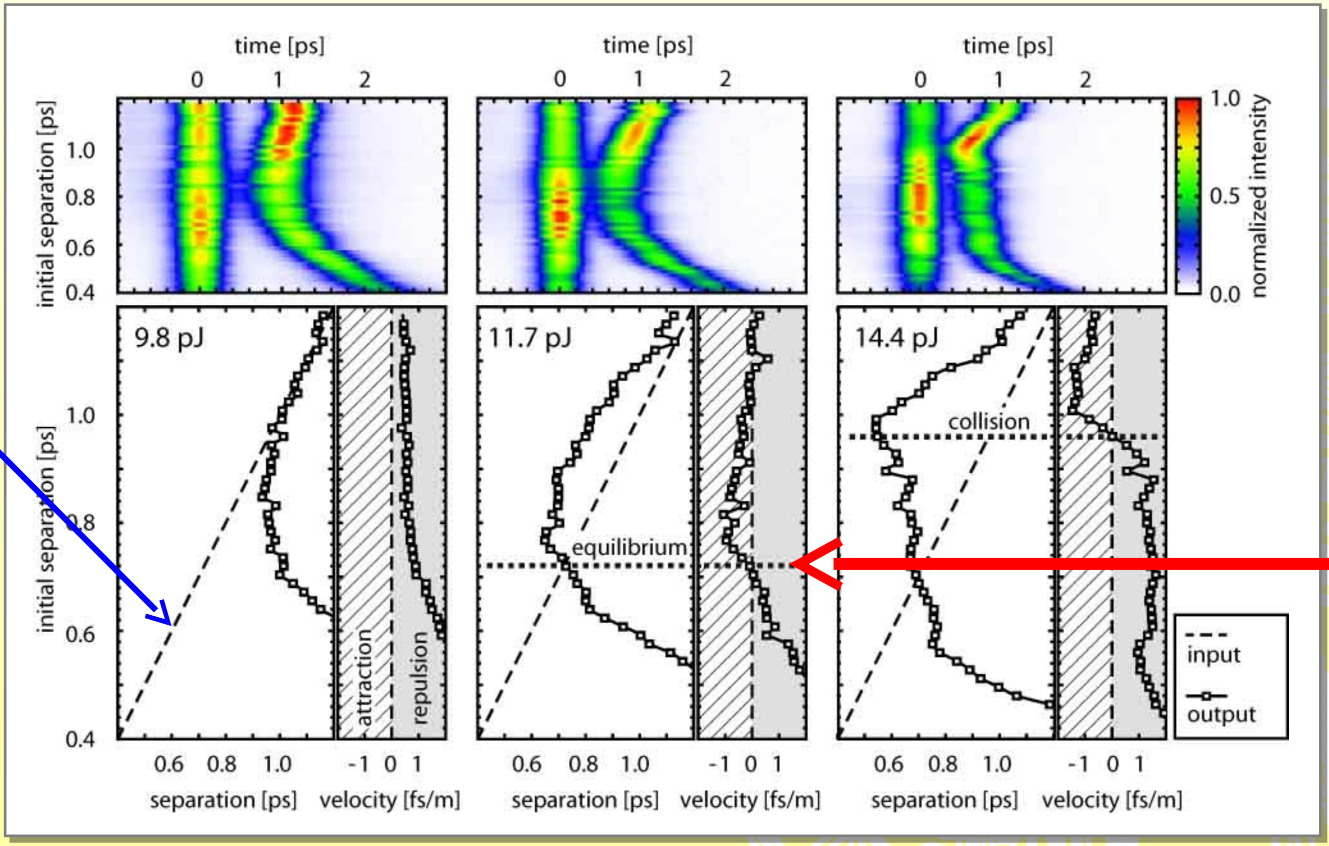
auxiliary lines indicate: input sep. equal to output sep.

Systematic tests

Evaluation of <u>cross</u> correlation traces
to study power and phase dependence of molecule formation

2-molecule

bisector (locus in absence of interaction)



stable equilibrium!

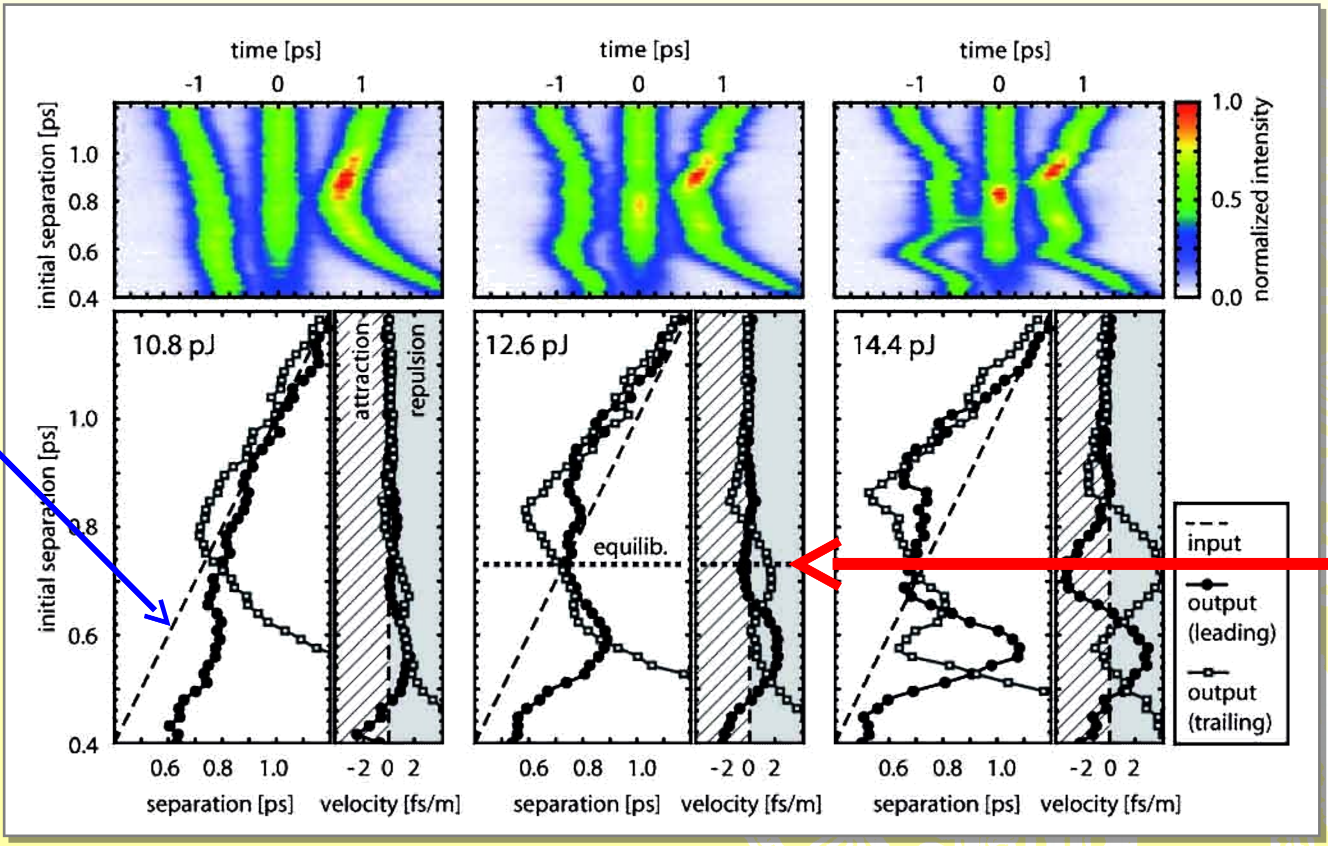
Measured cross correlation FROG data yield relative positions <u>and velocities</u>

Systematic tests

Evaluation of cross correlation traces
to study power and phase dependence of molecule formation

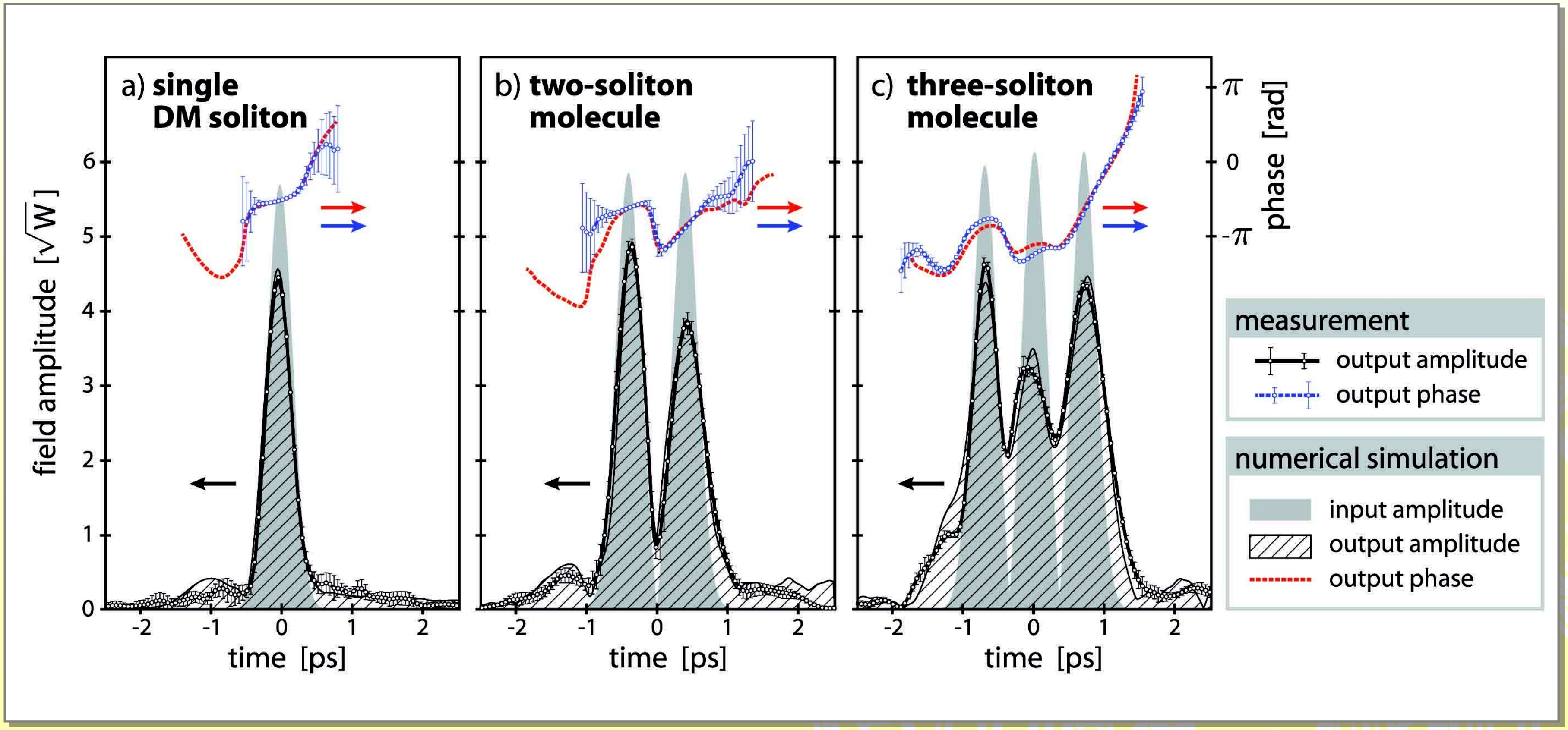
3-molecule

bisector (locus in absence of interaction)



stable equilibrium!

Single soliton, 2-molecule, and 3-molecule



- Loss reduces overall power
- Power oscillates between pulses – imbalance

All symbols could be generated and transmitted successfully

SCIENTIFIC REPORTS

OPEN

Solitons Beyond Binary: Possibility of Fibre-Optic Transmission of Two Bits per Clock Period

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SUBJECT AREAS:
NONLINEAR OPTICS
FIBRE OPTICS AND OPTICAL COMMUNICATIONS
OPTICS AND PHOTONICS
OPTICAL PHYSICS

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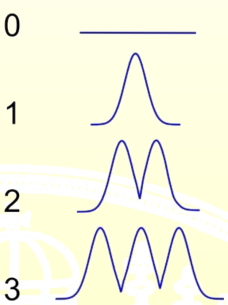
Optical telecommunication employs light pulses travelling down optical fibres; in a binary format logical *Ones* and *Zeroes* are represented by the presence or absence of a light pulse in a given time slot, respectively. The fibre's data-carrying capacity must keep up with increasing demand, but for binary coding it now approaches its limit. Alternative coding schemes beyond binary are currently hotly debated; the challenge is to mitigate detrimental effects from the fibre's nonlinearity. Here we provide proof-of-principle that coding with solitons and soliton molecules allows to encode two bits of data per clock period. Solitons do not suffer from nonlinearity, rather, they rely on it; this endows them with greater robustness. However, they are universally considered to be restricted to binary coding. With that notion now refuted, it is warranted to rethink future systems.

Correspondence and requests for materials should be addressed to F.M. (fedor.mitschke@uni-rostock.de)

Today massive streams of short light pulses are sent down opt
and internet traffic. The fibre's data-carrying rate is by and
with some modifications to take the particular nature of opt
is limited by the available bandwidth (≈ 30 THz) and by a fact
coding a logical *One* is represented by a pulse, and a logical *Zero* b



4 Symbols = 2 bits/clock

Scientific Reports **2**:866 (2012)

Physical Review A **87**, 043834 (2013)

PHYSICAL REVIEW A **87**, 043834 (2013)

Two-soliton and three-soliton molecules in optical fibers

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(Received 12 February 2013; published 25 April 2013)

An experimental study of bound states of two solitons and of three solitons in dispersion-managed fibers is presented. The existence regime and stability of such soliton molecules is investigated. With a programmable pulse shaper we can flexibly shape launch signals; received signals are detected in amplitude and phase, and in relative position and velocity. An equilibrium separation is demonstrated for both two-soliton and three-soliton soliton molecules. It is also shown that stable molecules are possible only with antiphase pulses. Both types of soliton molecule are viable for transmission in the same fiber, at the same wavelength. Together with single solitons this opens the possibility of quaternary data transmission in a soliton-based format.

DOI: 10.1103/PhysRevA.87.043834   PACS number(s): 42.81.Dp, 42.65.Re, 42.79.Sz

I. INTRODUCTION

Today's telephone and internet traffic is accommodated by massive streams of short light pulses passing through optical fibers. To keep up with the ever-increasing demand by data-hungry applications, the data-carrying capacity of fibers

40 Gbits/s channels. However, the demand grows so rapidly that one is now faced with a "capacity crunch" [5]. Economic considerations favor the continued use of existing (legacy) fibers. But then the only option for further improvement is to find coding schemes which go beyond the binary format.

Higher-order equilibrium states

Several authors have suggested that more than a single equilibrium separation exists:

- A. Maruta, T. Inoue, Y. Nonaka, Y. Yoshika, IEEE J. Selected Topics Quant. El. **8**, 640 (2002)
- I. Gabitov, R. Indik, L. Mollenauer, M. Shkarayev, M. Stepanov, P. M. Lushnikov, Opt. Lett. **32**, 605 (2007)
- M. Shkarayev, M. G. Stepanov, Physica D **238**, 840 (2009)

What do we know about the equilibrium separation?

In Phys. Rev. A **78**, 063817 (2008) we had used a perturbative ansatz assuming Gaussian pulses

⇒ Interaction induces frequency shifts which cause velocities ⇒ effective ‚force‘

⇒ Existence of an equilibrium could be established

That approximation is not very good at
... very small separations (perturbation not small)
... large separations (pulse tails not Gaussian)

A. Hause, FM: Phys. Rev. A **88**, 063843 (2013)

In a modified ansatz we now used actual pulse shapes (determined numerically)

Higher-order equilibrium states

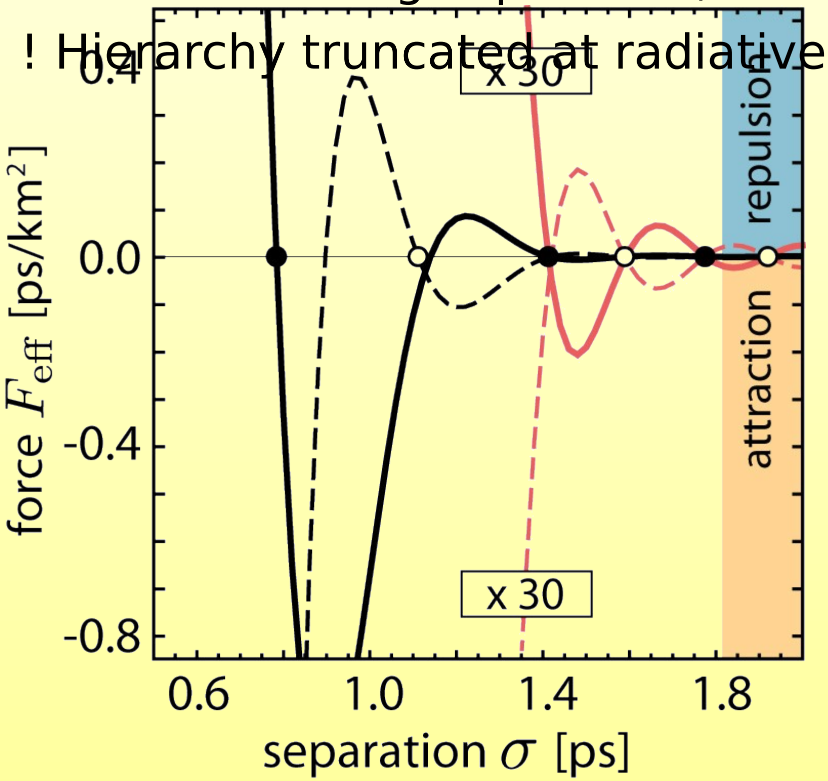
! Hierarchy of equilibrium states

! Alternatingly stable / unstable for both in-phase and opposite-phase pulses

! Globally lowest separation state is for opposite phase pulses, and is always stable

! With increasing separation, the binding energy decreases

! Hierarchy truncated at radiative background level



Circles mark stable equilibrium positions:

! opposite-phase pulses

" in-phase pulses

Unstable equilibria not highlighted

A. Hause, FM: Phys. Rev. A **88**, 063843 (2

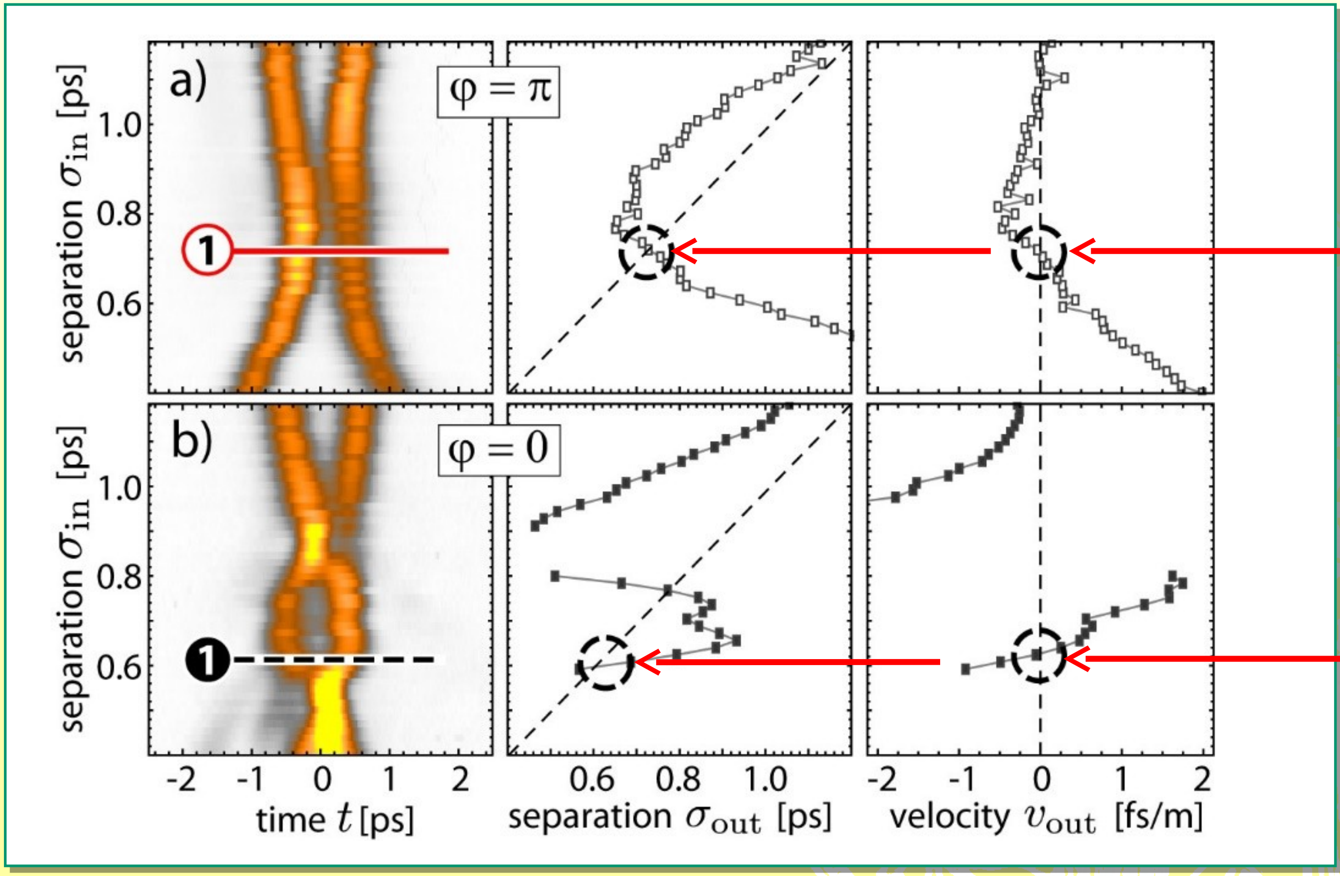
Higher-order equilibrium states

! Opposite phase pulse pairs: lowest state is stable

! In phase pulse pairs: lowest state is unstable

! More states are not observed due to radiative background

cross correlation experimental data



ground state

first unstable state

A. Hause, FM: Phys. Rev. A **88**, 063843 (2013)

Beyond-Binary Coding with Soliton Molecules

Transmits two bits of information per time step

- Enhances data-carrying capacity of fiber twofold
- Can be combined with other advanced schemes

Nonlinearity taken into account from outset

- No need to keep signal power very low
- Improved robustness against perturbations

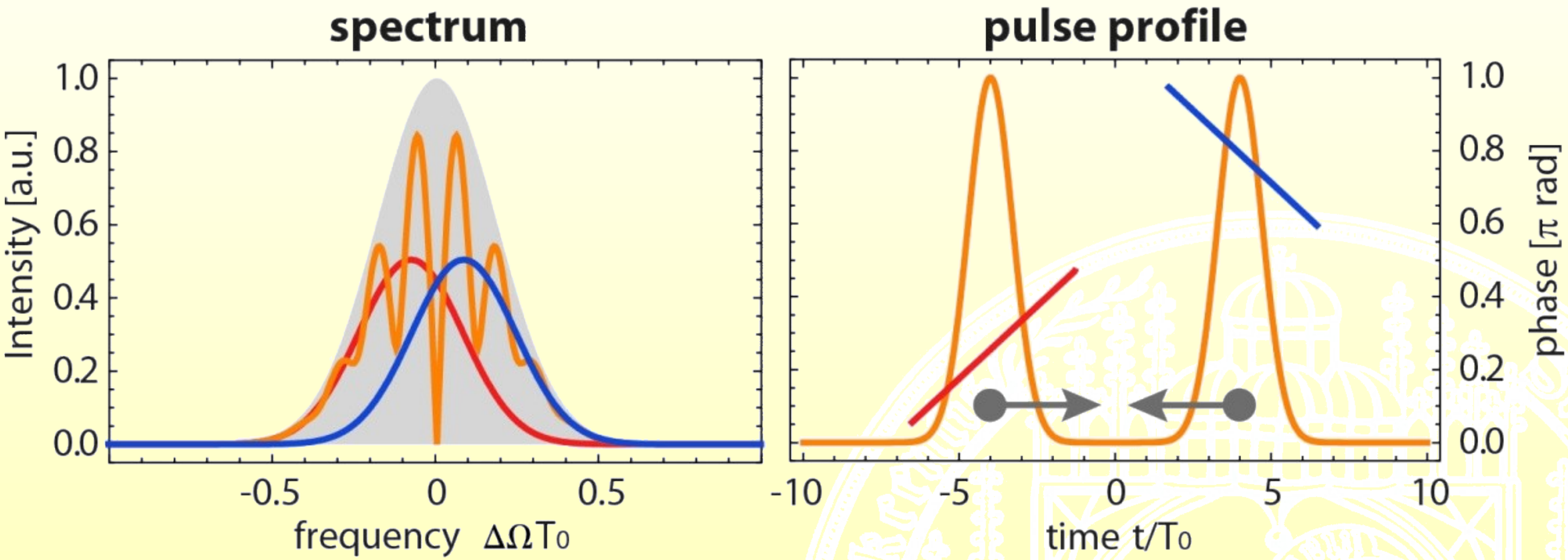
Works with legacy fibers

- Avoids to introduce large-core or multicore fibers

Experiments under way to test...

- ... in-line amplification with Er-doped fiber
- ... collision behavior

Next steps I: Induce collisions



- Carve structures from laser pulses with pulse shaper
- Can simultaneously generate pulses with different frequency and timing
- By dispersion, that amounts to nonzero relative propagation velocities

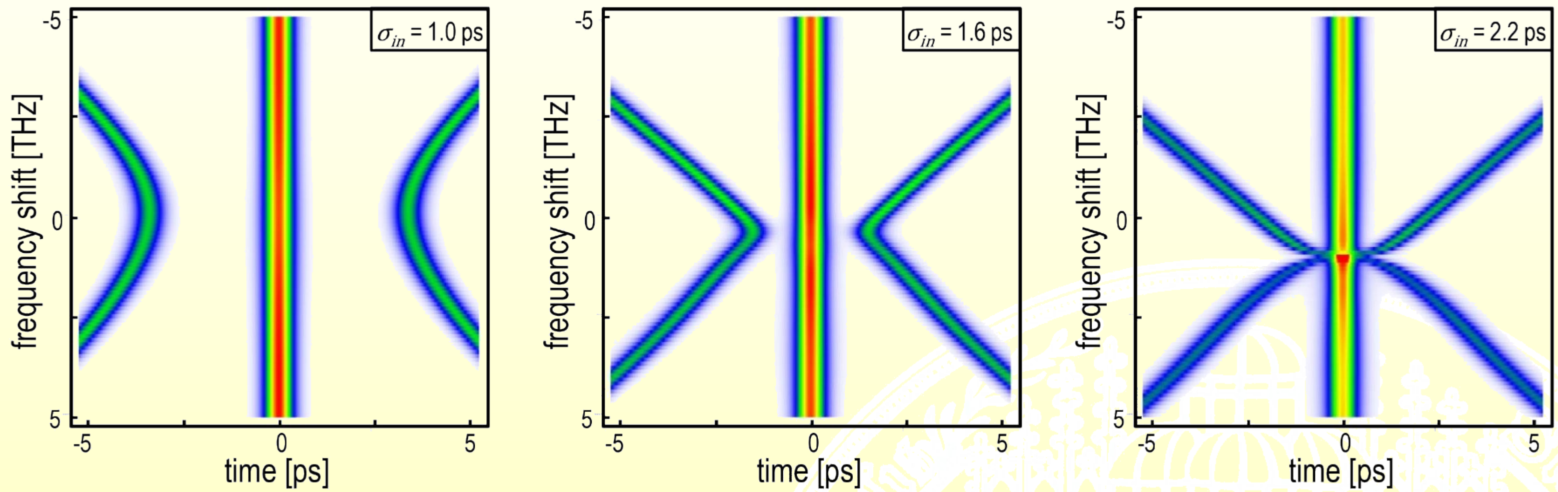
⇒ Pulses are set on collision course!

Collision point can be: at fiber end,
or before,
or beyond

Next steps I: Induce collisions

cooperation: Maria Lubs

autocorr.
simulated

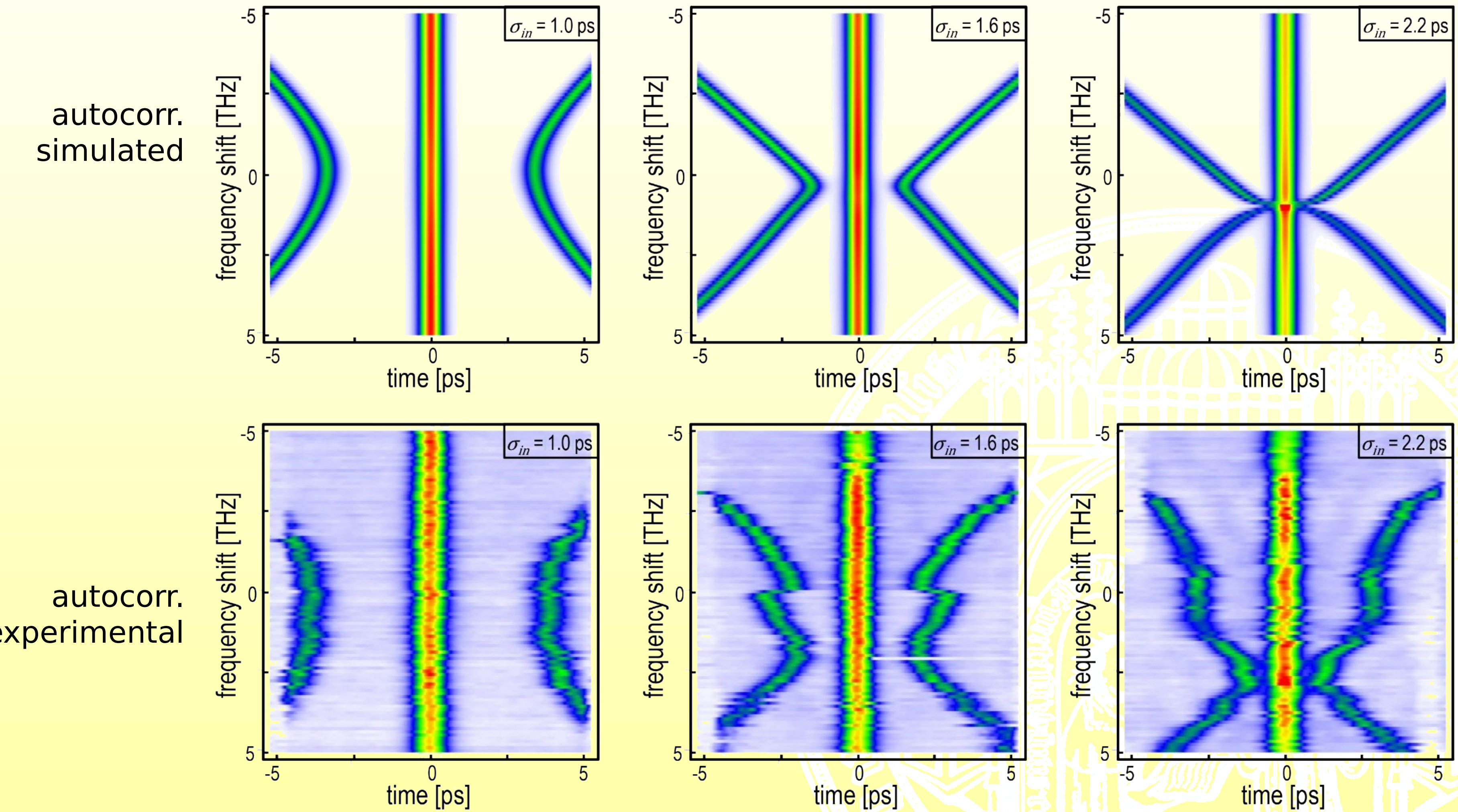


Simulation results for simplest case: NLSE soliton collisions in standard fiber

Frequency difference corresponds to relative velocity
Data as seen at fiber end (fixed position)

Next steps I: Induce collisions

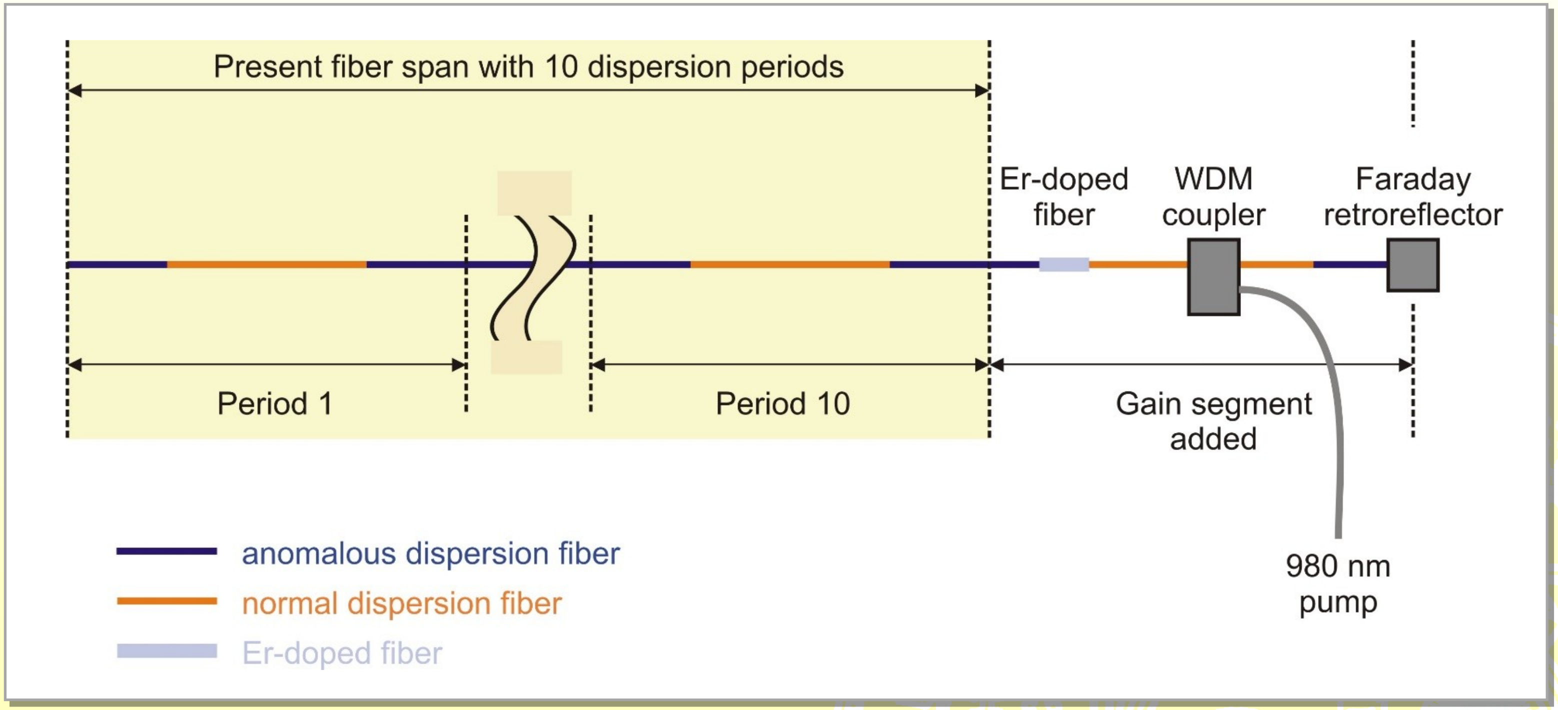
cooperation: Maria Lubs



Corresponding experimental data

Next steps II: Introduce gain

cooperation: Jan Froh



Gain in Er-doped fiber to compensate all loss
Dispersion landscape minimally disrupted
Resulting fiber line ≈ twice as long

- Dispersion values of all fibers have been measured (white-light interferometry)
- Required fiber lengths have been determined
- Gain has been verified, final assembly completed, first data taken
- Evaluation in progress

Take-away messages:

- Optical fiber beats all other data conduits due to large bandwidth and lo
- Traffic growth used to be exponential; may show first signs of slowing gr

Possible reasons:
   * number of users begins to saturate
   * binary coding hits limit; quest for nonbinary coding is on
   * efficiency does not keep up, rising expense

- Linear coding schemes run into new bottlenecks
- Soliton concept is elegant, and can be quaternary

stay tuned....