ICTP-SAIFR school on Nonlinear Optics and Nanophotonics, Dec 2-5, 2013

Broad-area lasers, laser solitons and patterns in optics

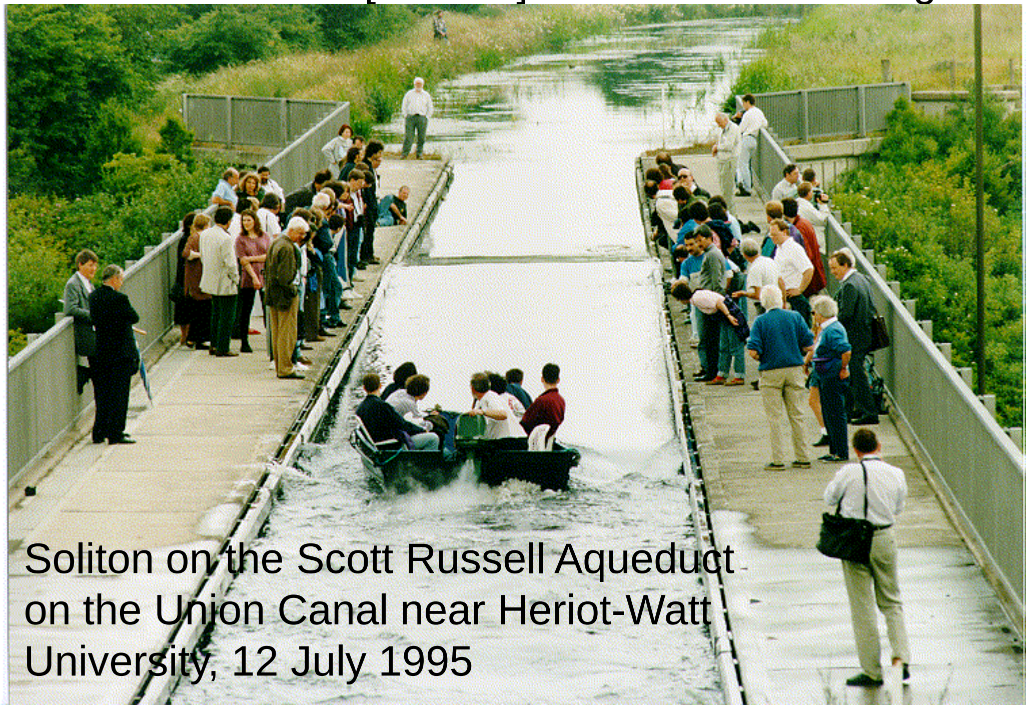
Part II: Laser solitons

Thorsten Ackemann

SUPA and Department of Physics, University of Strathclyde, Glasgow, Scotland, UK

Solitons started in Scotland

"I was observing the motion of a boat which was rapidly drawn along a narrow channel by a pair of horses, when the boat suddenly stopped—not so the mass of water in the channel which it had put in motion; ..., assuming the form of a ***large solitary elevation***, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently ***without change of form or diminution of speed.*** I followed it on horseback, and overtook it still rolling on at a rate of some eight or nine miles an hour [14 km/h], preserving its original figure some thirty feet [9 m] long and a foot to a foot and a half [300−450 mm] in height. Its height gradually diminished, and after a chase of one or two miles [2–3 km] I lost it in the windings of the channel. ... Singular and beautiful phenomenon which I have called the ***Wave of translation***.



Soliton on the Scott Russell Aqueduct on the Union Canal near Heriot-Watt University, 12 July 1995

- Published: 1845
  Russell, ***Report on Waves***.

  Report of the fourteenth meeting of the British Association for the Advancement of Science, York, September 1844.

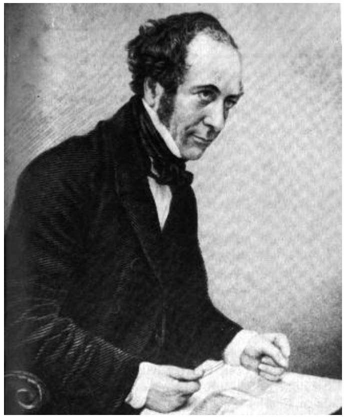
- Impact: 1960s
  computers, plasmas, ...
- Fibre optics: 1970s

http://www.ma.hw.ac.uk/solitons

Solitons started in Scotland

Coast (BBC2 24/04/13)

John Scott Russel



http://www.ma.hw.ac.uk/solitons

1834: "... large solitary elevation, ... without change of form or diminution of speed."

Russell, ***Report on Waves***.
Report of the fourteenth meeting of the British Association for the Advancement of Science,
York, September 1844.

Solitons: Origin

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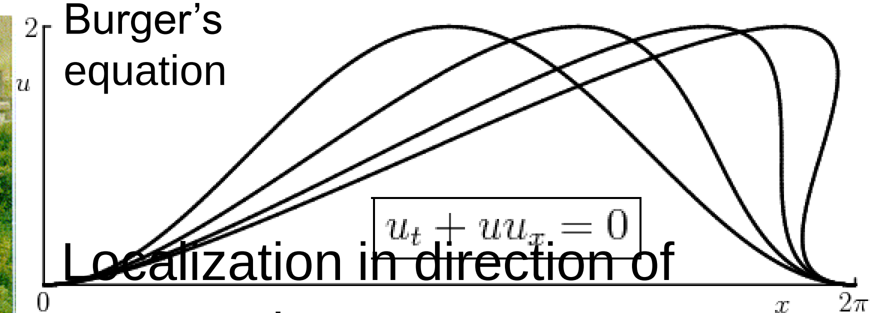
Wave propagation includes ***dispersion*** and ***nonlinearities***

balancing of ***Pulse broadening*** and ***Steepening, shocks, new frequencies***

Soliton = ***wave packet propagating with constant shape***

Burger's equation



Localization in direction of propagation

http://www.eng.fsu.edu/~dommelen/pdes/style_a/burgers.html

$\rightarrow$ ***Temporal soliton***

longitudinal soliton meaning self-localized in direction of propagation

Optical transverse soliton (propagation)

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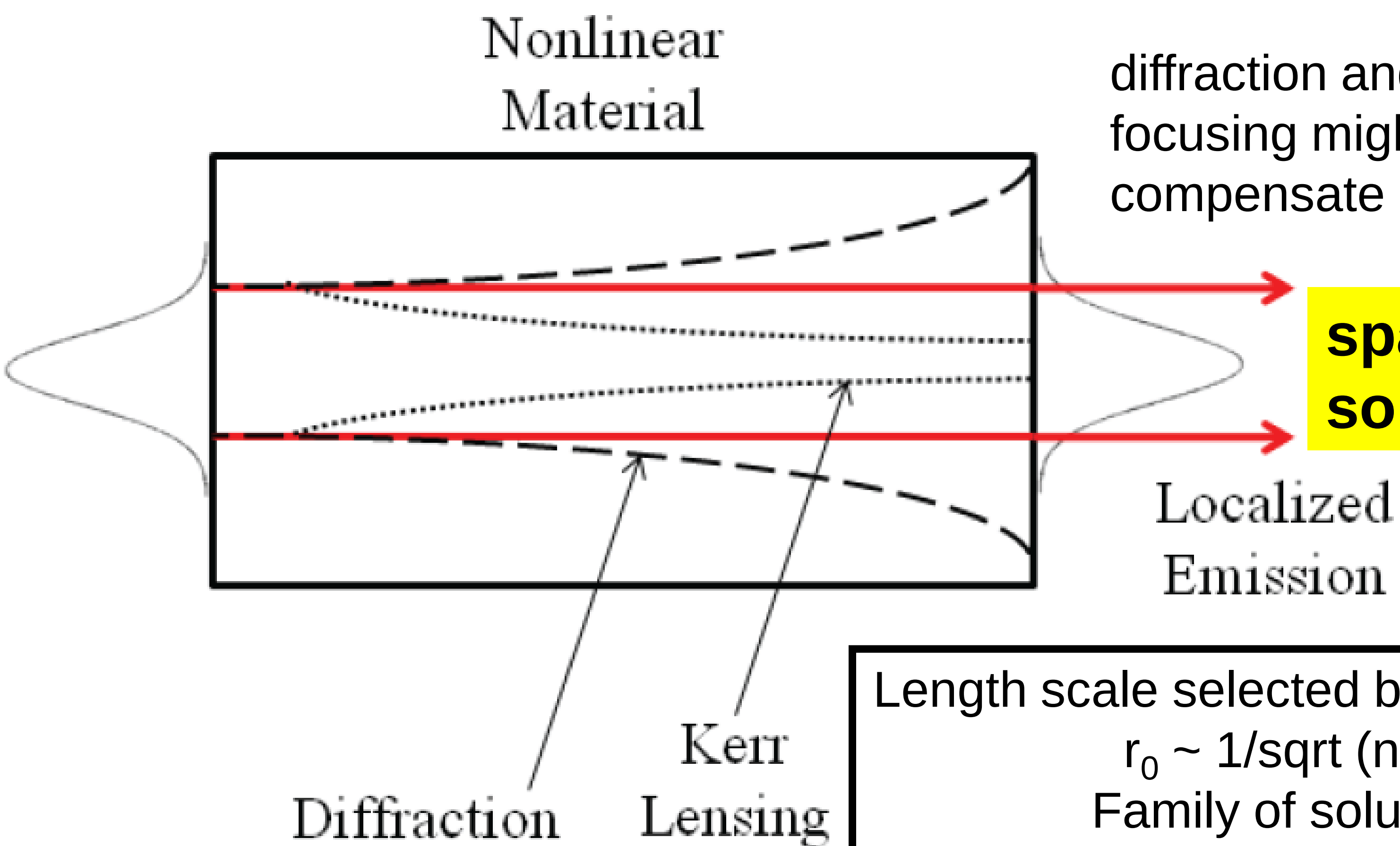
Nonlinear Schroedinger equation (NLS) for propagation in z

$$\frac{\partial}{\partial z}\mathcal{E} = -i\left[\frac{1}{2k_l}\nabla_\perp^2\mathcal{E} + k_l n_2 \,|\mathcal{E}|^2\mathcal{E}\right]$$

conservative



diffraction and self-focusing might compensate ($n_2 > 0$)

spatial soliton

Length scale selected by ***nonlinearity***

$r_0 \sim 1/\text{sqrt}(n_2\, I)$

Family of solutions

Experiment

side view of a cell containing sodium vapor

Na (Bjorkholm and Ashkin 1974)

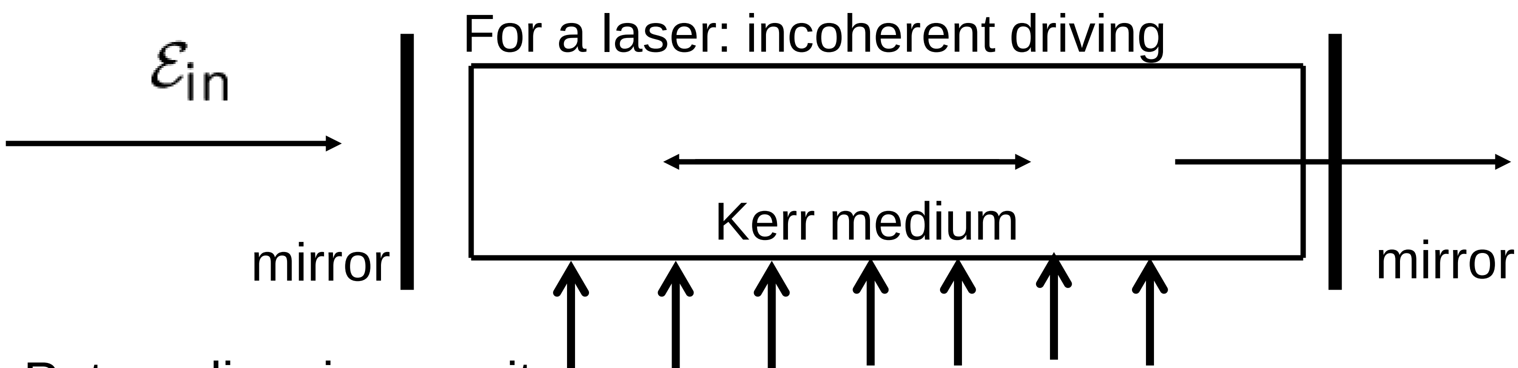
- linear propagation (top): diffractive spreading
- nonlinear propagation (bottom): self-guiding, spatial soliton
- pure $\chi(3)$ Kerr nonlinearity → collapse in 2D

  (need to stabilize by high-order terms,

  e.g. in Na, two-level atom saturable nonlinearity, “saturable Kerr”)

- in a propagation experiment you will never know whether your soliton is long-term stable because you run out of material

Cavity solitons

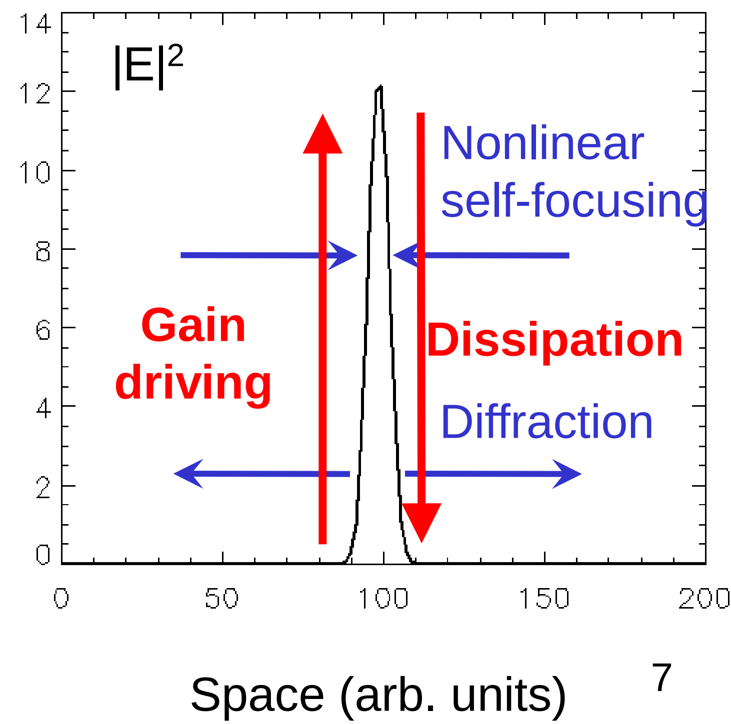


- Put medium in a cavity
  - → propagation replaced by time evolution
- ***Dissipation***: light leaks out of the mirrors
  - → compensate by ***driving***
- second balance condition:
  - → family collapses to single solution
    “attractor”

First approach to cavity solitons:

„soliton in a box“

Firth and Harkness, Asian J. Phys. **7**, 665 (1998)



What is a dissipative soliton?

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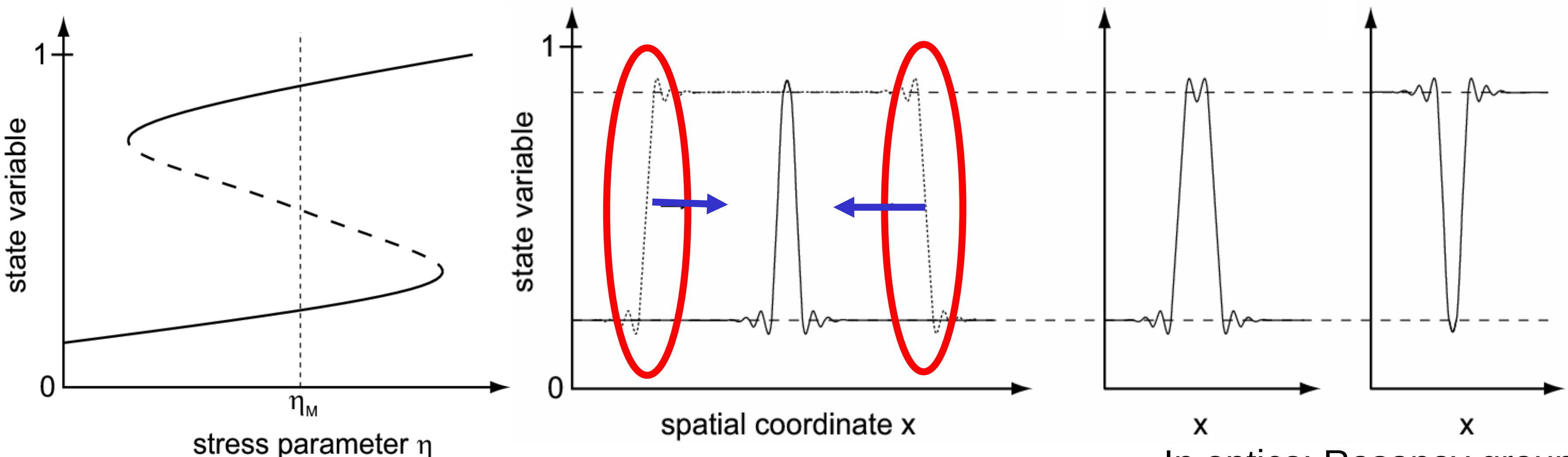
- imagine **bistability** between two states: e.g. low and high amplitude



In optics: Rosanov group

- in a spatially extended system different spatial regions might be in different states → in between there will be a ***front!***
- this front can **move** → one state invades the other and the system becomes homogenous again
- fronts can **lock** and leave an island of one state in the other → ***localized state, localized structure, or dissipative soliton***

Ubiquitous in Nonlinear Science ...

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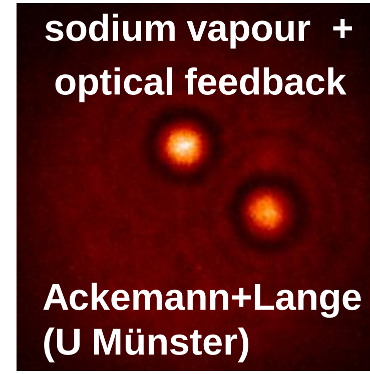
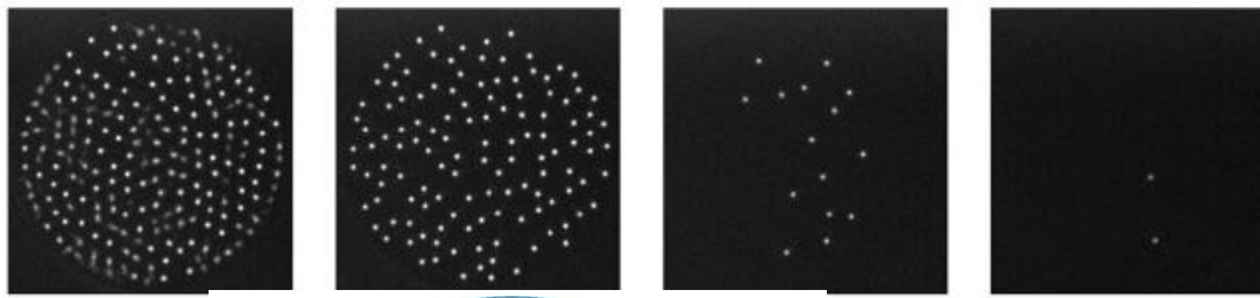
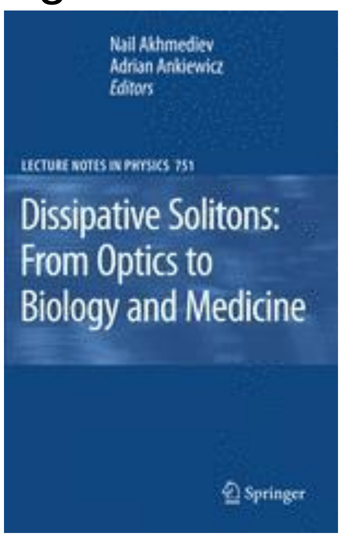
Many aspects of VCSEL patterns and solitons are universal for self-organizing spatially extended systems driven out of thermodynamic equilibrium

- nonlinear optics
- hydrodynamics
- gas discharges
- …



AC gas discharge
Purwins et al., Adv. Phys. 59, 485 (2010)

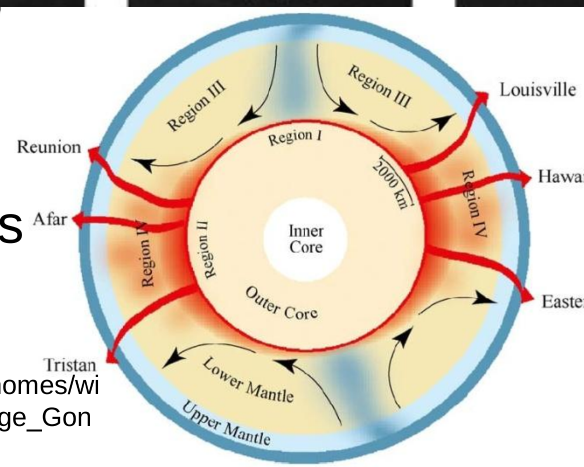




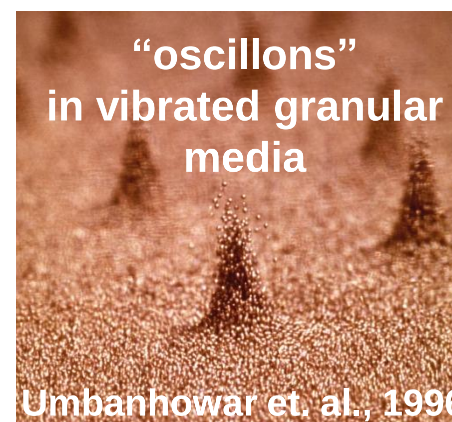
- chemistry
- biology
- nature

➢ Not only structured,
but ***self*-*localized***

plumes



http://www.geos.ed.ac.uk/homes/williams/PlumesCartoon_Helge_Gonnermann.jpg



Cavity soliton laser needs bistability

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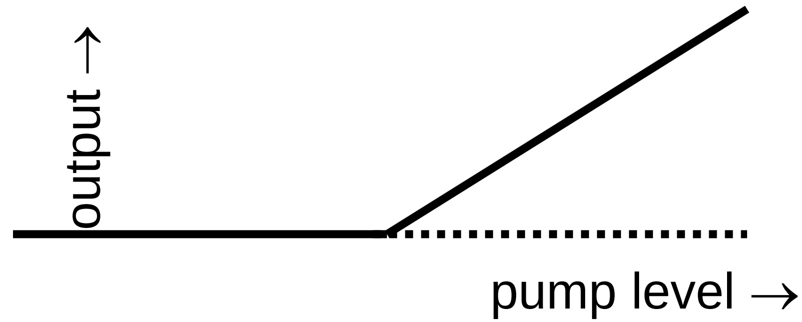
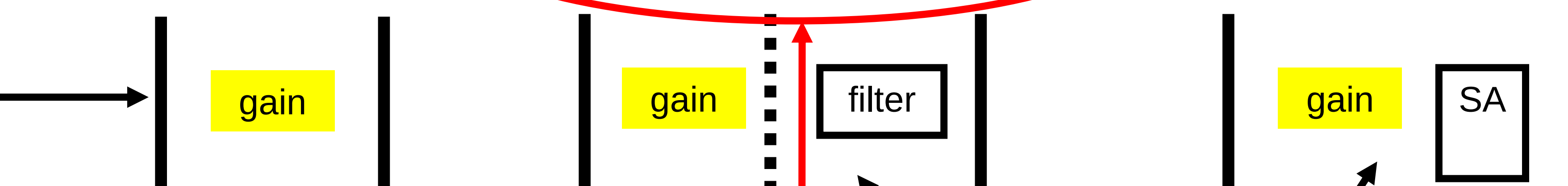
But **normal** laser has a continuous turn-on from threshold: **no** cavity solitons.



bistable laser schemes

laser with injected signal	laser with frequency-selective feedback	laser with saturable absorber



Genevet et al., PRL **101**,123905 (2008)

Hachair et al.,
IEEE Sel. Top. QE **12**,
339 (2006)

Truly free running laser with phase invariance

Go for this!

First semiconductor based CSL:
Tanguy et al., PRL **100**, 013907 (2008)

Still slaving by external phase reference

first CSL using photorefractives, dyes: Bazhenov et al. (1992); Saffman et al. (1994); Taranenko et al. (1997)

Thanks

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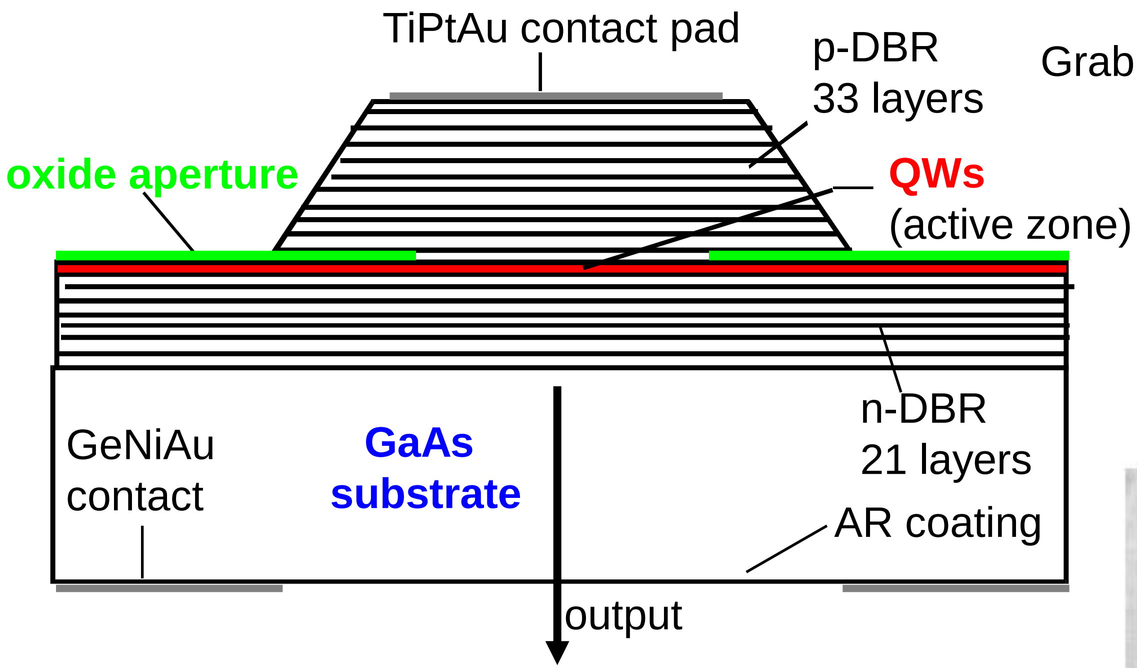
Cavity soliton laser:

- Experiment: Y. Noblet*, J. Jimenez**, N. Radwell*, Y. Tanguy
- Devices: R. Jaeger (Ulm Photonics)
- Theory: C. McIntyre*, W. J. Firth, G.-L. Oppo (Strathclyde), P. V. Paulau (Minsk, Strathclyde, Palma, now University of Oldenburg), D. Gomila, P. Colet (IFISC, Palma de Mallorca), N. A. Loiko (Minsk), N. N. Rosanov (St. Petersburg)

- Funding: *EPSRC DTA, ** Conayt, EU FP6 FunFACS, British Council, Royal Society, DAAD

Our devices: High power VCSELs

Grabherr et al., IEEE STQE **5**, 495 (1999)



- **three InGaAs/GaAs quantum wells**
  (gain maximum ≈ 980 nm)
- **oxide layer**
  → current and optical confinement
- **Emission through substrate**

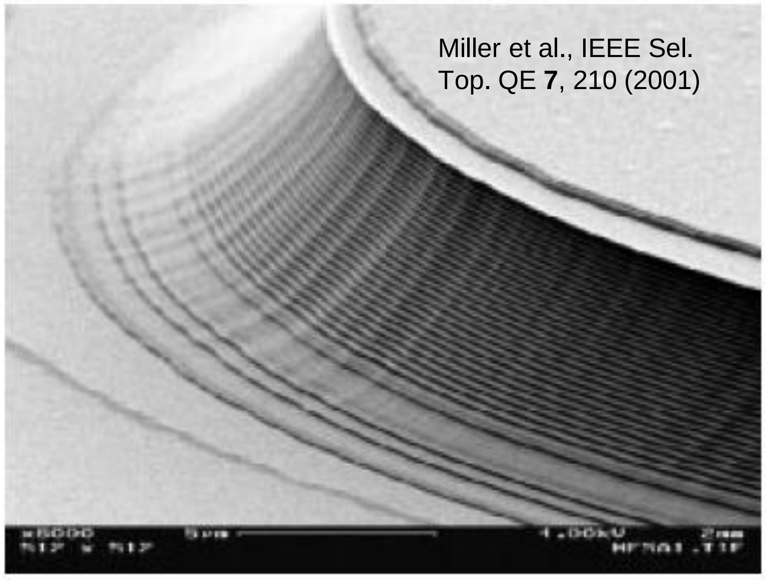
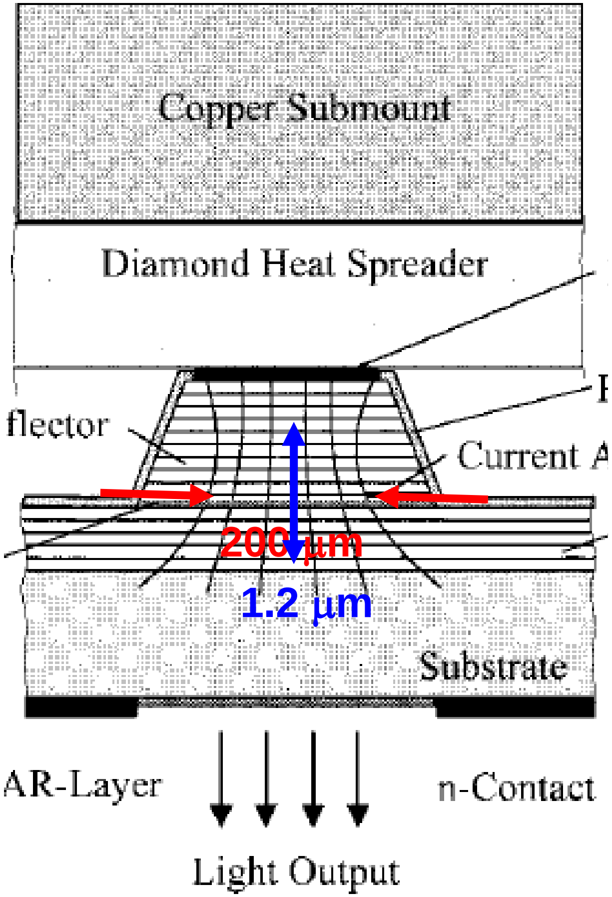


Fig. 2. Wet chemically etched mesa with full p-contact, p-type DBR, and active region.

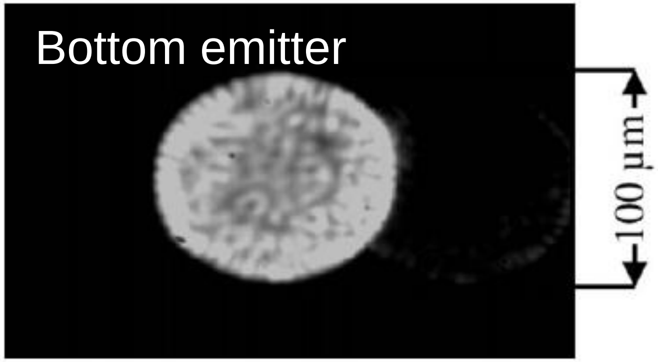
Technology and mounting

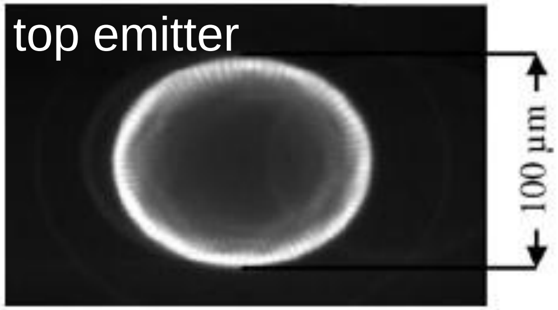
Grabherr et al., IEEE STQE **5**, 495 (1999)



A **disk**, not a tube!

- for wavelength > 880 nm: emission through transparent substrate
  → **bottom emitter**
- heat sinking from top
- much more homogeneous





Setup with volume Bragg grating

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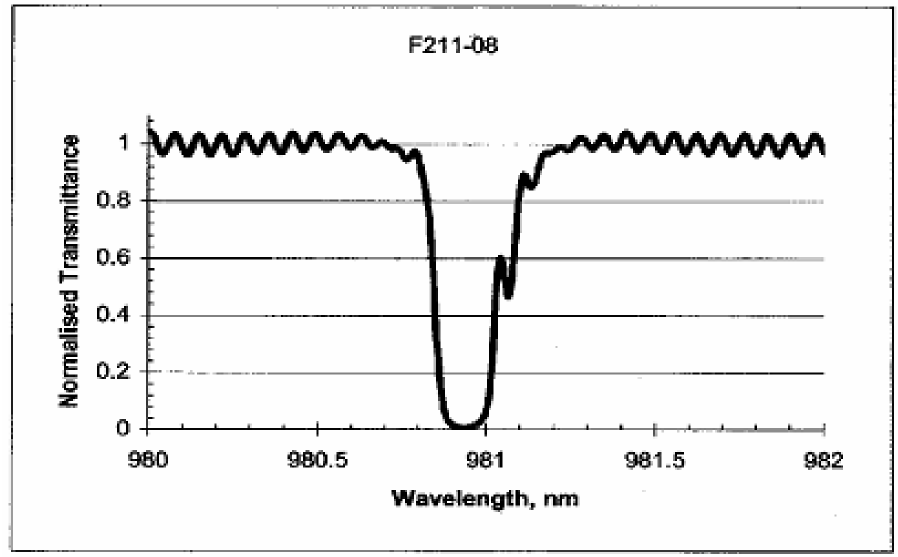
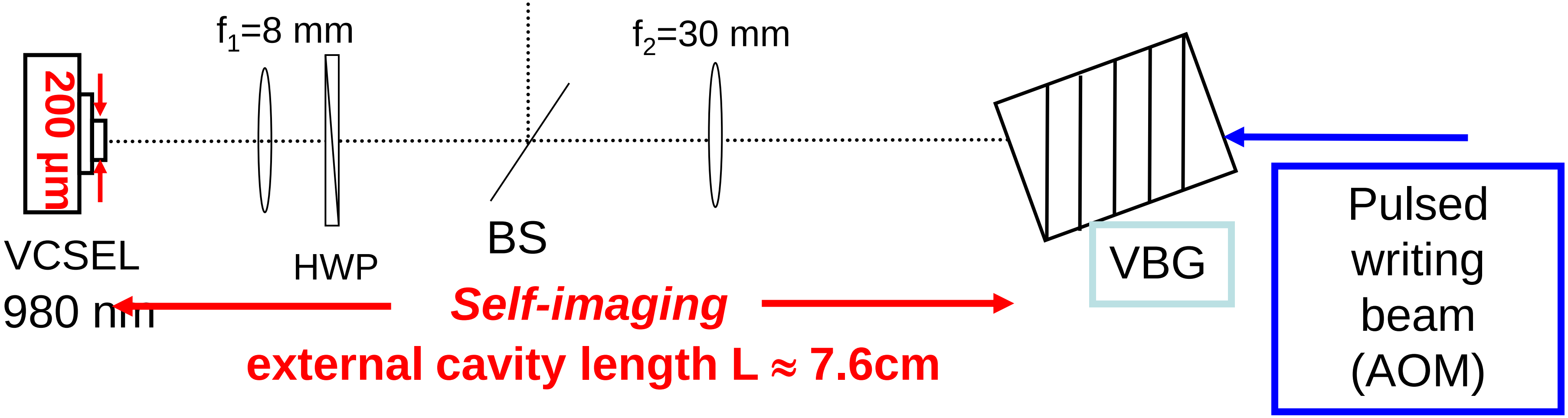
Volume Bragg grating VBG:

Compact frequency-selective element

Radwell+Ackeman, IEEE QE **45,** 1388 (2009)



Detection Branch:

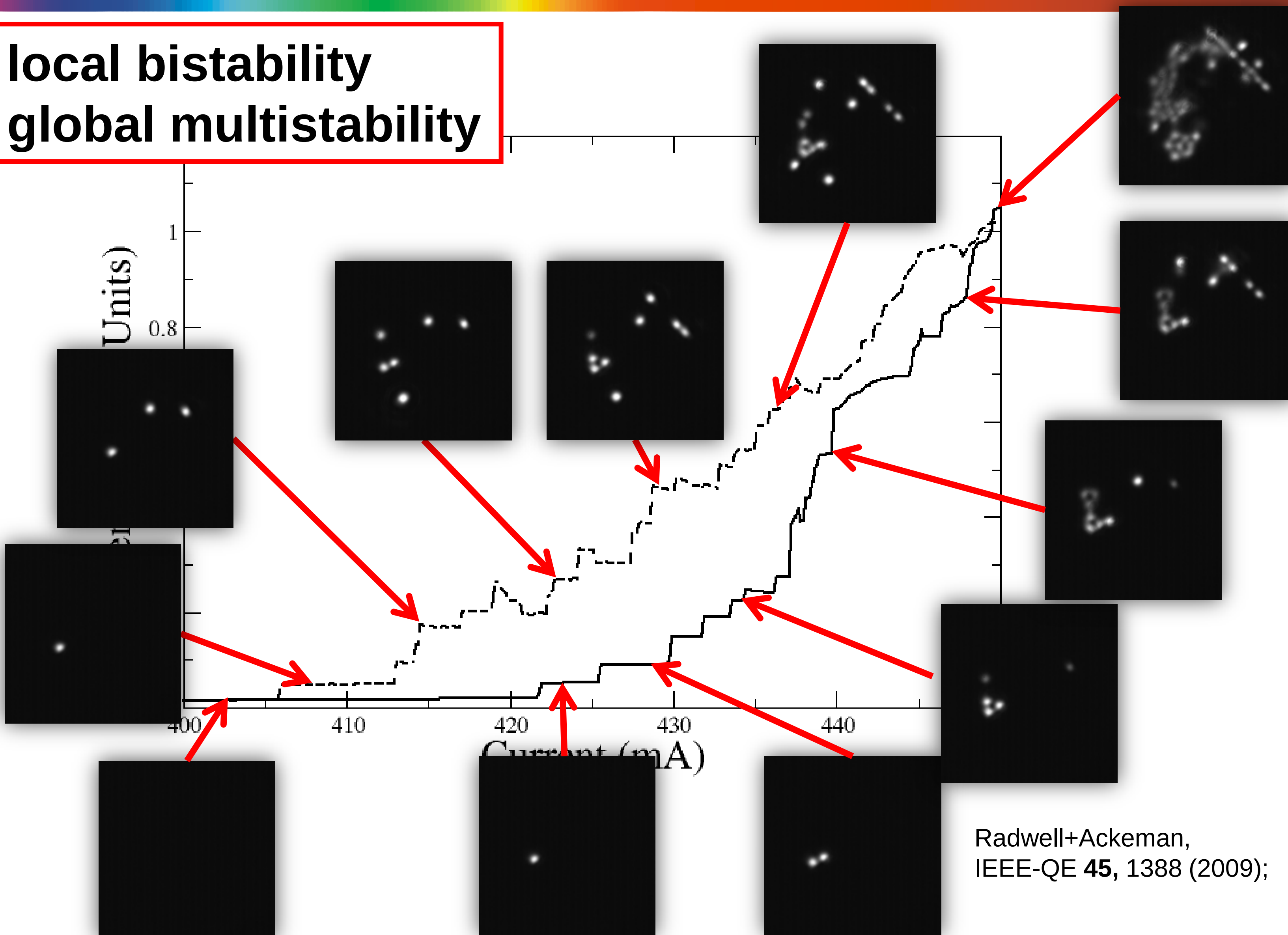


→ maintains high Fresnel number of VCSEL

Experiment: Current ramp

LI-curve of whole device

- ✓ **local bistability**
- ✓ **global multistability**

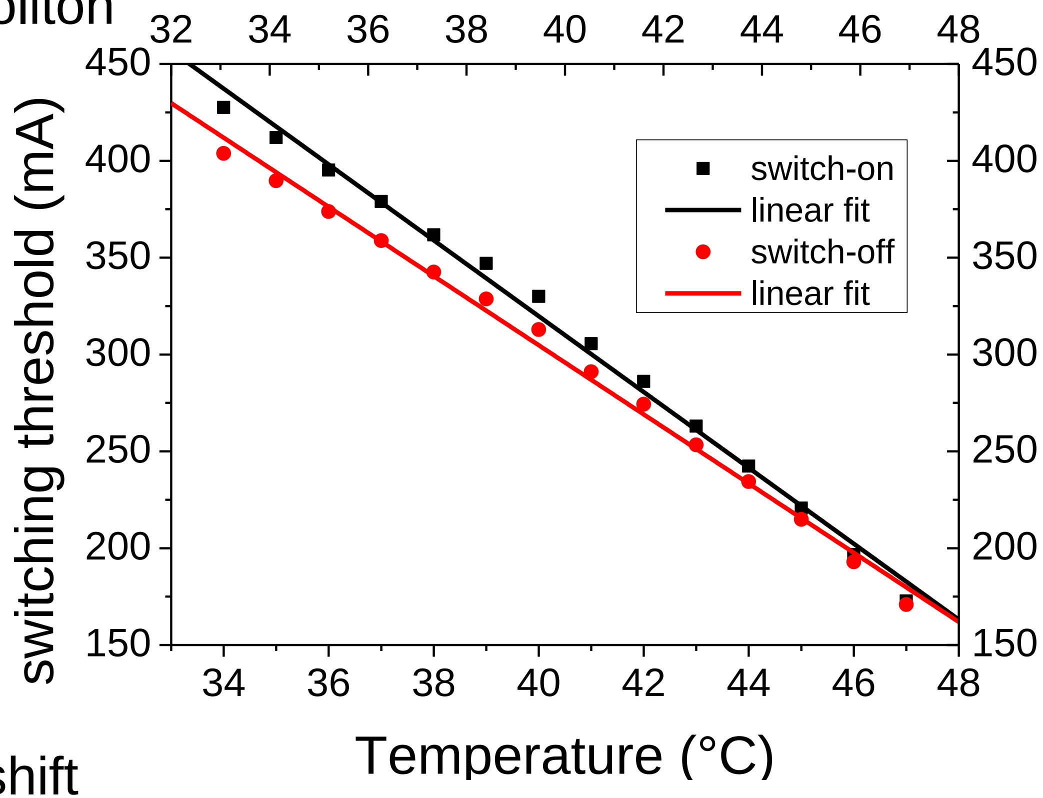


Radwell+Ackeman,
IEEE-QE **45,** 1388 (2009);

Current sweeps detuning, not gain

Switching threshold of first soliton

Switch-on
d I / d T ≈ -19.6 ± 0.4 mA/K
Switch-off
d I / d T ≈ -17.9 ± 0.4 mA/K



From other measurements:

- Shift of cavity resonance with temperature
  d λ / d T ≈ 0.066 nm/K
- Ohmic heating induced shift
  d λ / d I ≈ 0.0035 nm/mA
- Combined
  1 / (d T / d I) ≈ 19 mA/K

Main effect of current is **red-shift of resonance** until **detuning** between cavity and VBG so small that switching occurs via carrier nonlinearity

Bistability: Qualitative interpretation

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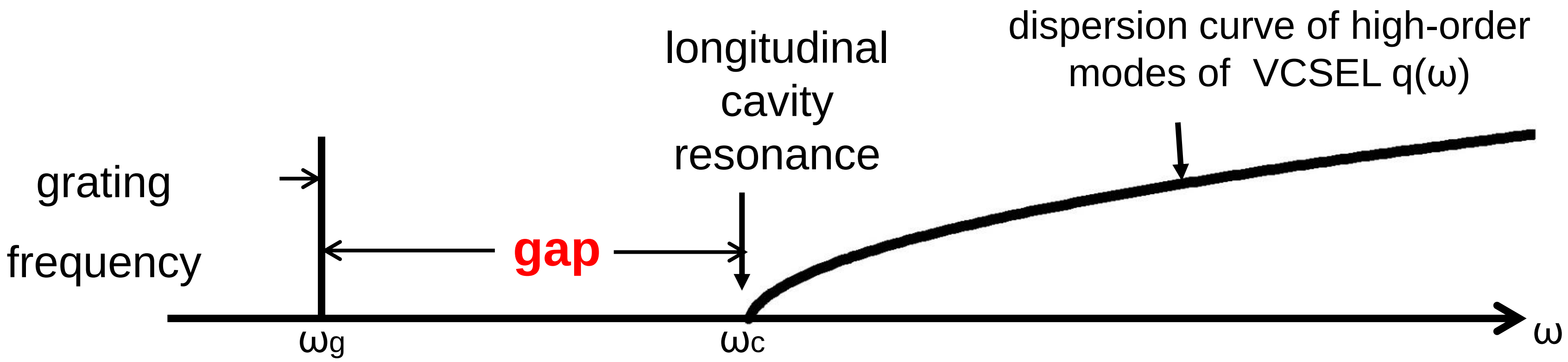
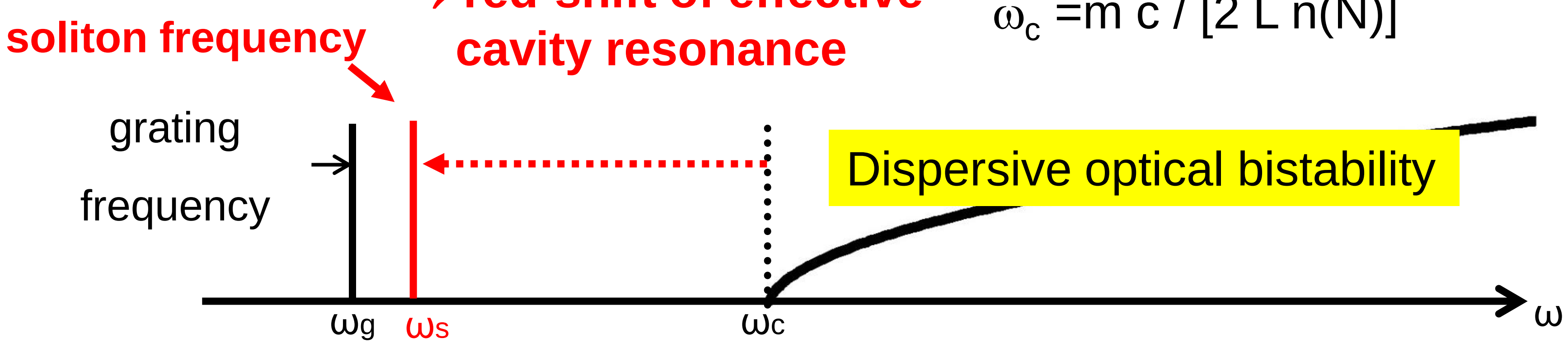
Low-amplitude state: laser off, carrier density high, refractive index low



High-amplitude state: laser on, carrier density low → refractive index high

→ **red-shift of effective cavity resonance**

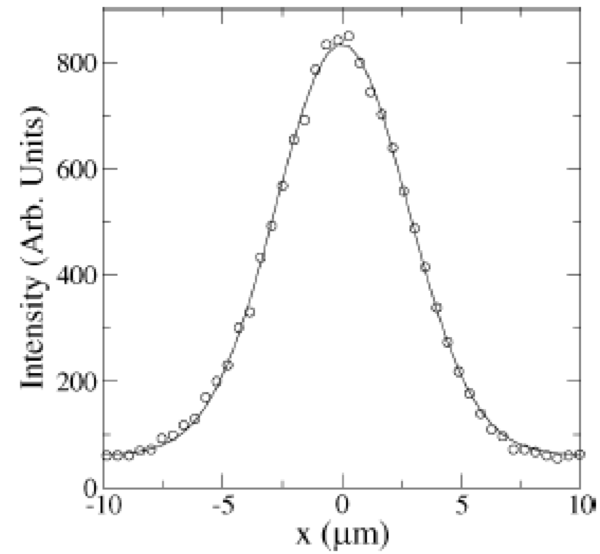
$\omega_c = m\, c / [2\, L\, n(N)]$



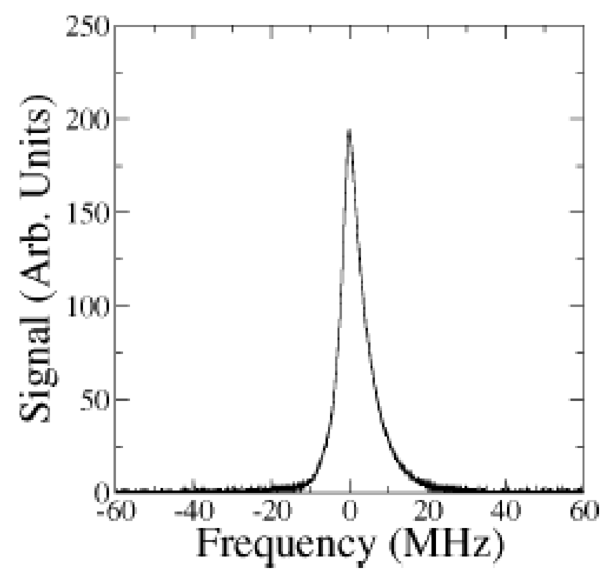
Localized high-amplitude state stabilized by self-focusing

Coherent emitters

- Well defined, **circularly symmetric spots** with size of 4.8-5.8 μm ($1/e^2$-radius of intensity)
- Angular width in far field: 57-69 mrad (centre on-axis within ≤ 18 mrad)
- Close to being diffraction-limited → **high spatial coherence**



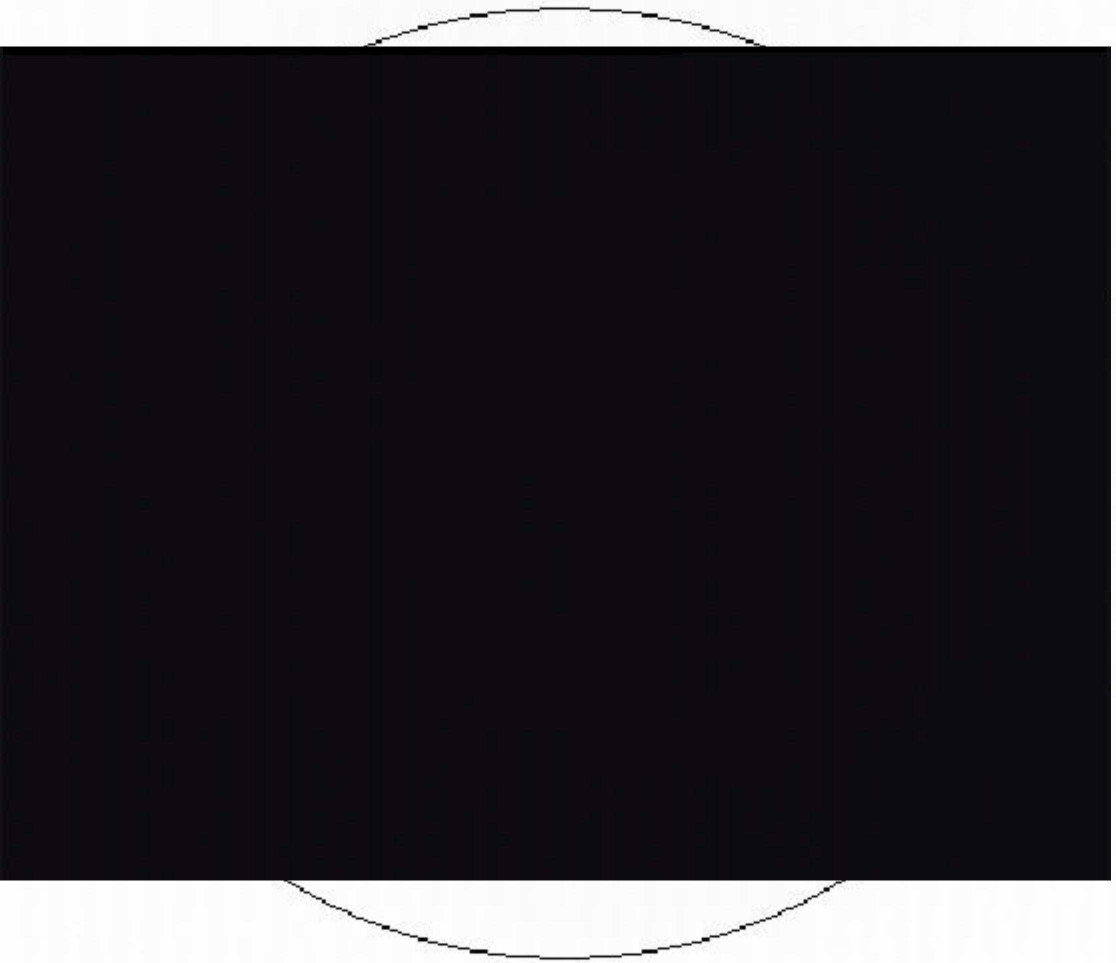
- Linewidth in single-mode: ≈ 6 MHz → **high temporal coherence**
- these are coherent emitters → ***microlasers***



Mutual coherence? -- Later

Spatial solitons: Switch-on/-off

Transverse plane (⊥ cavity axis) of broad-area VCSEL



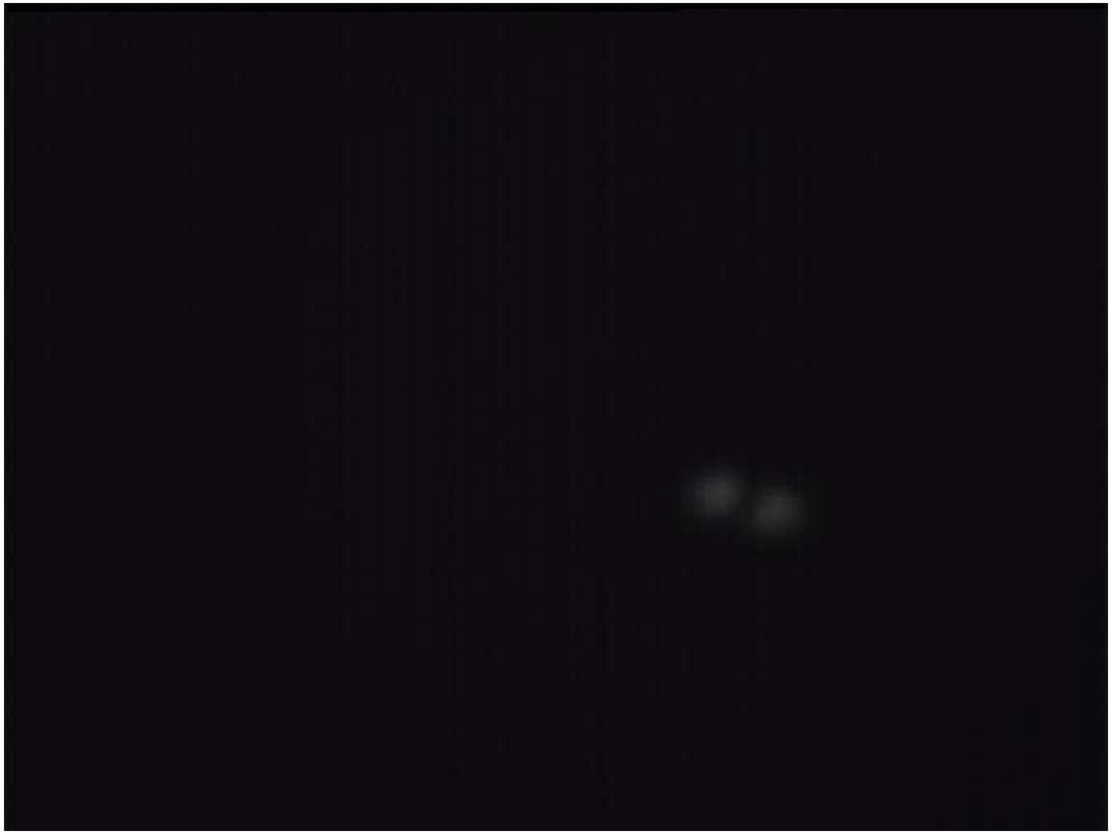
- bright spots much smaller than pumped aperture
- stabilized by nonlinearities
- bistable

demonstration of **independent** writing and erasure:
all 8 possible configurations of 3 bits

→ **solitonic character**

→ Laser (cavity) solitons

Independence and mobility



- *“Stir”* LCS with cw writing beam
- WB attracts LCS and pulls them out of center of trap
- moves them from one trap to another
- pulls them where they can’t exist

→ mechanism for ***erasure***

- VBG isotropic → no preferred direction for switch-on/switch-off
- but symmetry broken by imperfections of device

Frequency of solitons and disorder

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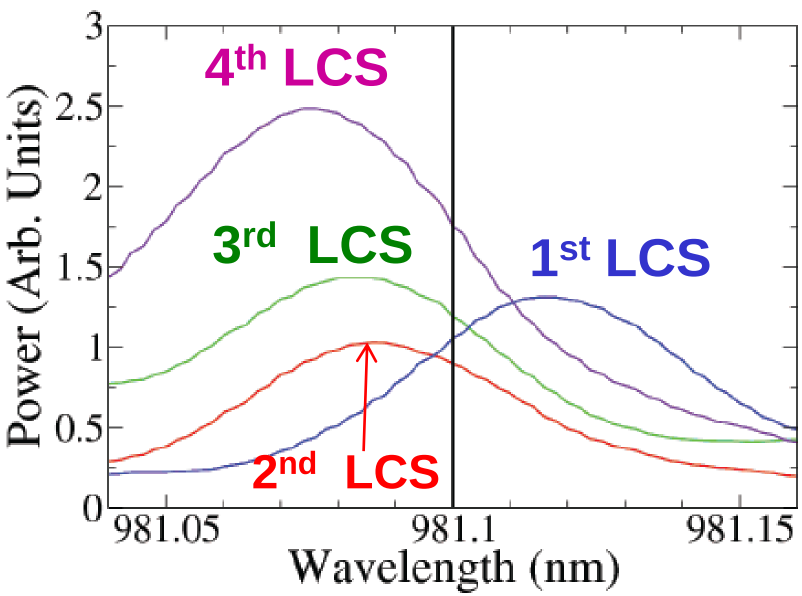
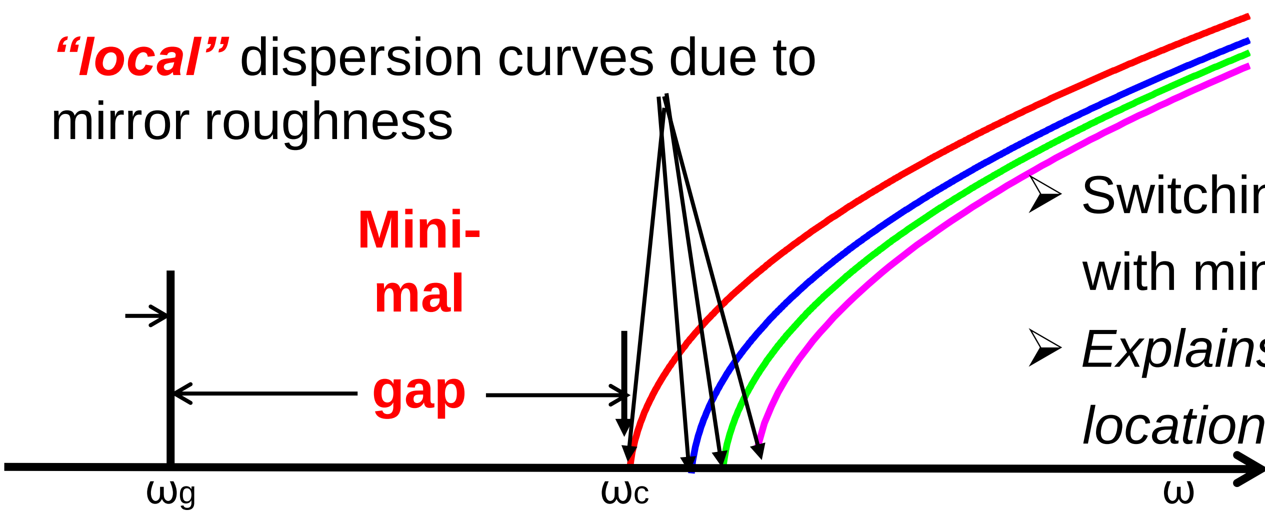


- Different solitons have different threshold frequencies
- The most **reddish** solitons come first!
- Threshold increases with increasing detuning

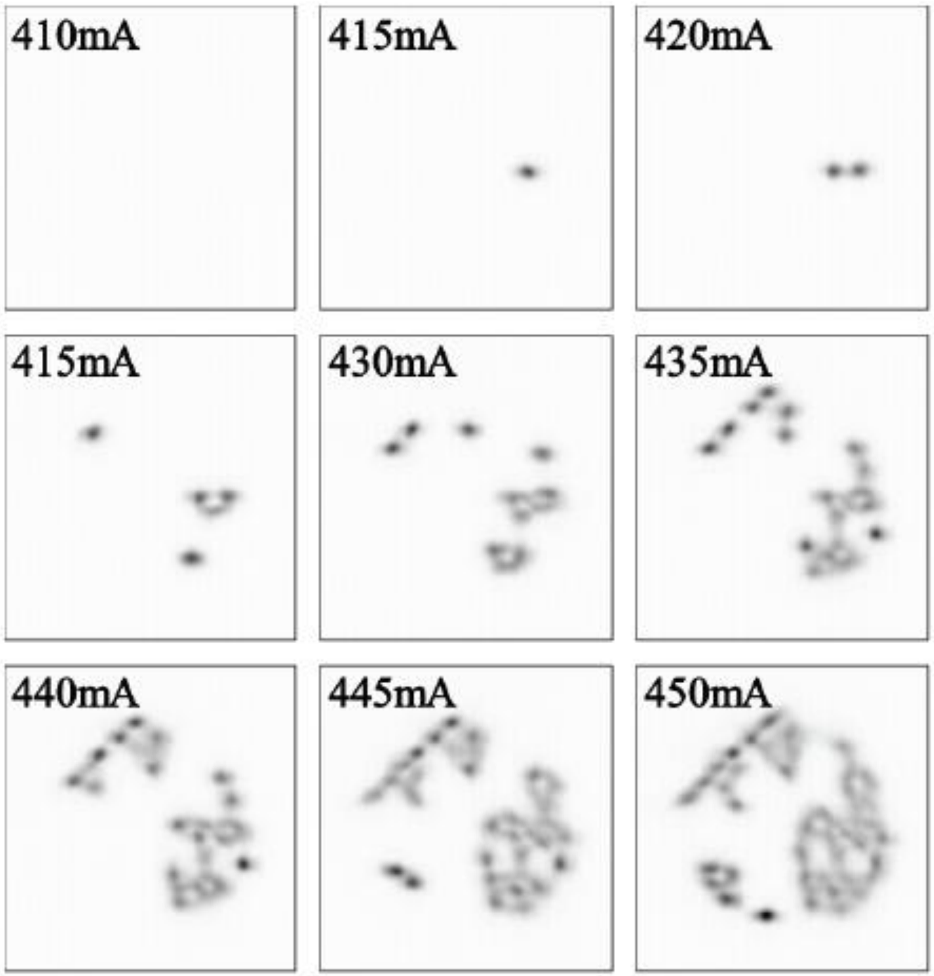
"local" dispersion curves due to mirror roughness

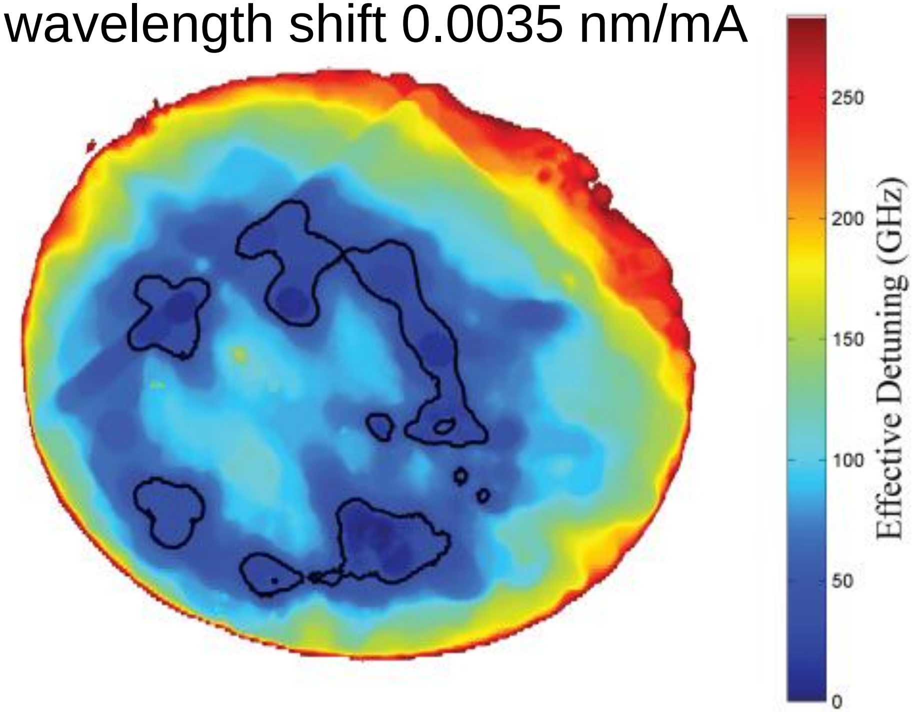


- Switching will occur at locations with minimal gap
- *Explains why most **reddish** locations switch first!*

Application in disorder mapping

Convert threshold value to detuning by wavelength shift 0.0035 nm/mA



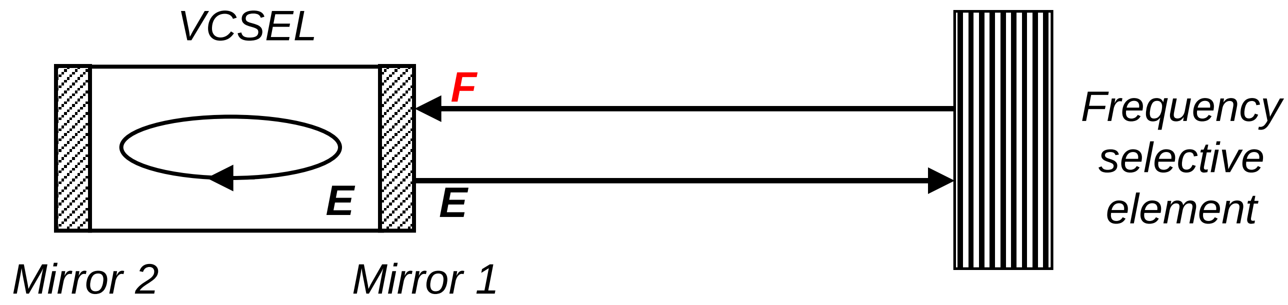


- ➢ potentially useful to characterize disorder in VCSEL on relevant scales with fairly high resolution, Opt. Lett. **37**,1079 (2012)
- ➢ ***monolayer fluctuations***

Theoretical model (class B)

Assume:

- perfect self-imaging
- feedback only dependent on frequency, not on wavevector



feedback

VCSEL field → $$\partial_t E = -(1+i\theta)E + i\nabla^2 E - i\sigma(\alpha+i)(N-1)E + \frac{2\sqrt{T_1}}{T_1+T_2}F$$

carriers → $$\partial_t N = -\gamma\,[N - J + |E|^2\,(N-1) + D\nabla^2 N] \qquad \gamma \approx 0.01$$

external cavity field → $$F(t) = e^{-i\delta\tau_f}\,\hat{G}(t-\tau_f/2)[-r_1 F(t-\tau_f) + t_1 E(t-\tau_f)]$$

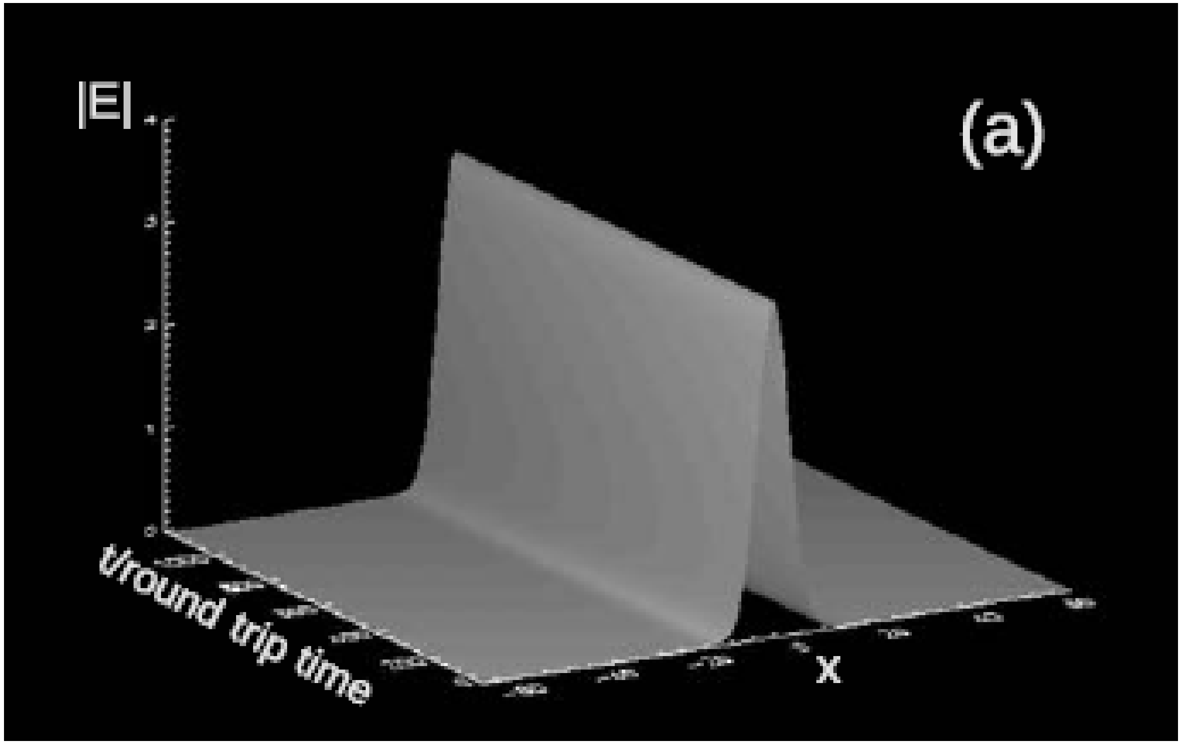
frequency filter → $$\hat{G}(t)[\cdot] = \frac{r_g}{2\beta}\int_{t-2\beta}^{t} e^{i\Delta_g(t'-t)}[\cdot]\,dt'$$

NOT Lang-Kobayashi:
All round-trips

A. J. Scroggie, G.-L. Oppo, W. J. Firth, PRA **80**, 013829 (2009)

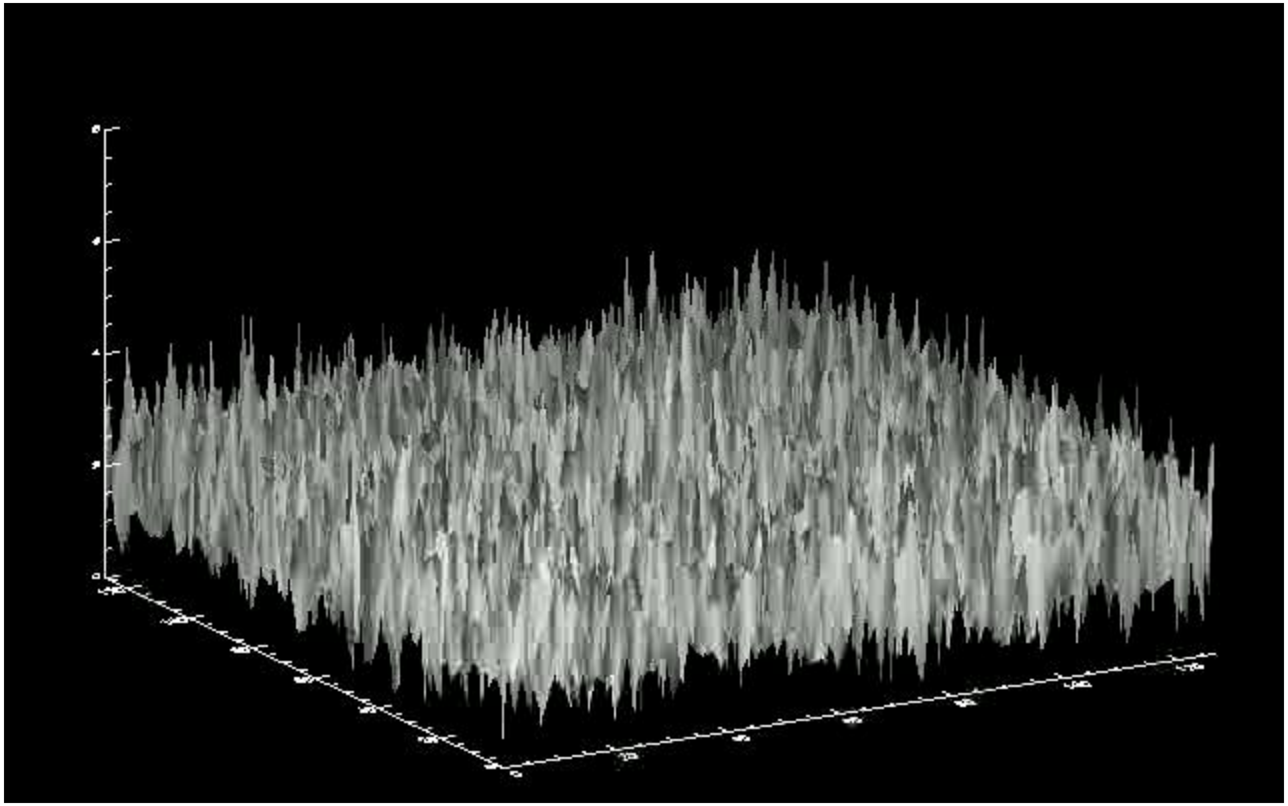
$$\hat{G}(\omega)[h(\omega)] = r_g e^{-i\beta(\Omega_g-\omega)}\,\mathrm{sinc}[\beta(\Omega_g-\omega)]h(\omega)$$

Numerics (1D)



- Stationary LCS, single frequency, one external cavity mode
- Width $\approx 8\ \mu$m

Works also in 2D



- Good reproduction of experimental results
- Applies also to transient dynamics (Radwell et al., Eur. Phys. J. D **59**, 121 (2010))
- Bifurcation structure and instabilities analyzed in simpler Ginzburg-Landau model plus linear filter (Paulau, Firth, ...)

A simpler class A model

- Adiabatic elimination of carriers
  - same stationary states but stability properties might change
  - but note: carriers slower than field, loss of relaxation oscillations
- Take into account delay or not

$$\frac{\partial E}{\partial t} = -\kappa E + \frac{\kappa \mu E}{1+|E|^2} + \frac{i\alpha\kappa\mu E}{1+|E|^2} - i\Delta_\perp E + F + i\omega_s E - i\alpha\kappa E$$

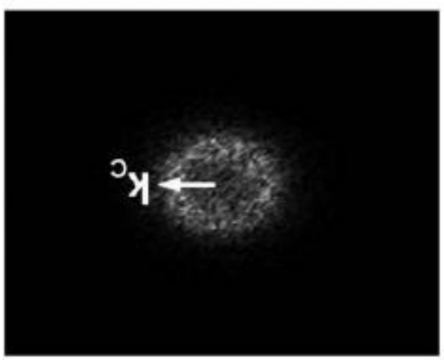
$$\frac{dF}{dt} = -\lambda F + \sigma\lambda E(t-\tau)$$

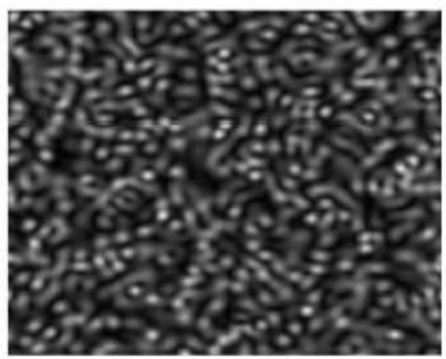
- Lorentzian filter
- Lang-Kobayashi for simplicity

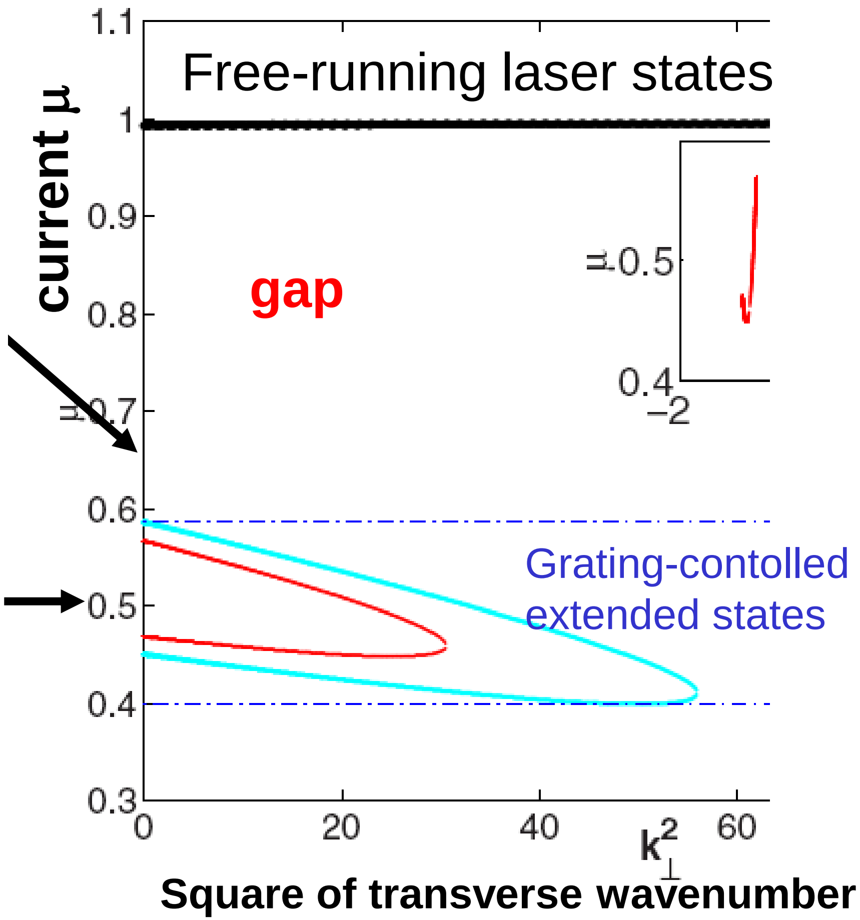
Paulau et al.,PRE **78**, 016212 (2008)

Filamentation vs. solitons

In **gap: solitons** with center on axis





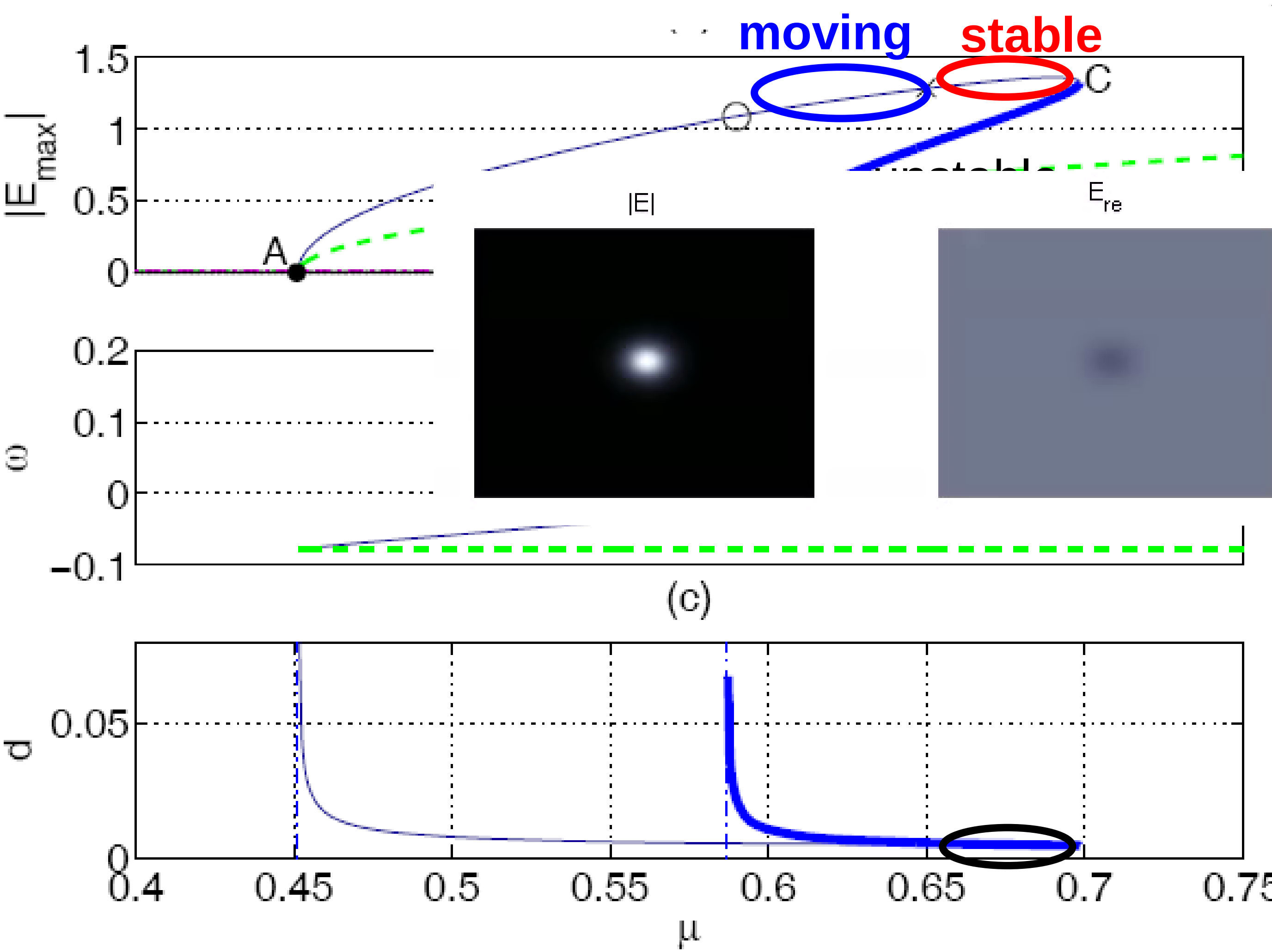


Extended states with

irregular spatio-temporal dynamics

Interpretation: filamentation, modulational instability

Bifurcation diagram



- LCS branches start from homogeneous solution with infinite width, A, B merge in saddle-node bifurcation, C **stable** section:
  - ✓ blue detuning to grating
  - ✓ width 10-13 μm
- spontaneous motion: **drift instability**

Even simpler:Ginzburg-Landau model

University of Strathclyde Science

Ginzburg-Landau model + linear filter, Firth + Paulau, Eur. Phys. J. D **59**, 13 (2010)

Linear loss (gain) and frequency detuning

Nonlinear gain (loss) and self focusing (defocusing)

Diffraction

Filtered Feedback

$$\begin{cases} \frac{\partial E}{\partial t} = g_0 E + g_2 |E|^2 E + i\Delta_\perp E + F \\ \frac{dF}{dt} = -\lambda F + \tilde{\sigma} E, \end{cases}$$

Width of filter

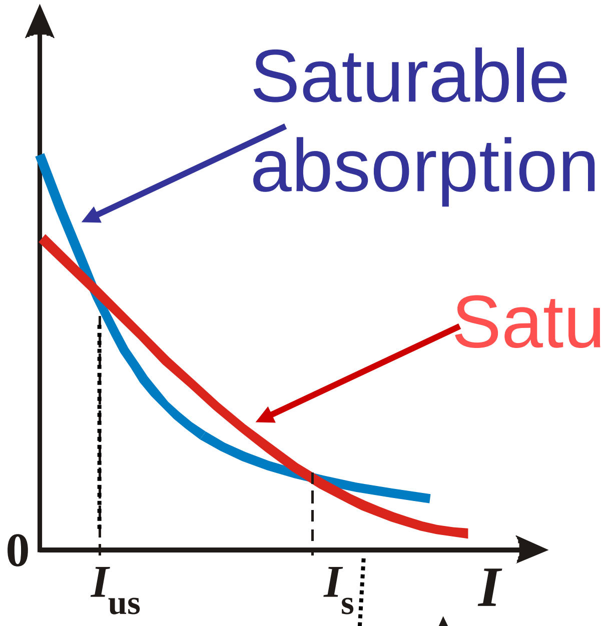
Feedback strength

- in GLE: Chirped-sech soliton solutions known but unstable
- Stabilized by ***coupling to resonant filter*** suppressing background
- simplest model for laser with FSF

L.M. Hocking and K. Stewartson, Proc. R. Soc. Lond., A **326**, 289 (1972); N.R. Pereira and L. Stenflo, Phys. Fluids **20**, 1733 (1977).
P.A. Bélanger, L. Gagnon, and C. Paré, Opt. Lett. **14**, 943 (1989).
C. Paré, L. Gagnon, and P.A. Bélanger, Opt. Commun. **74**, 228 (1989).

$$g_0 = \kappa(1 + i\alpha)(\mu - 1) - i\omega_m,$$
$$g_2 = -\kappa(1 + i\alpha)\mu,$$
$$\tilde{\sigma} = \sigma\lambda,$$

Laser with saturable absorber

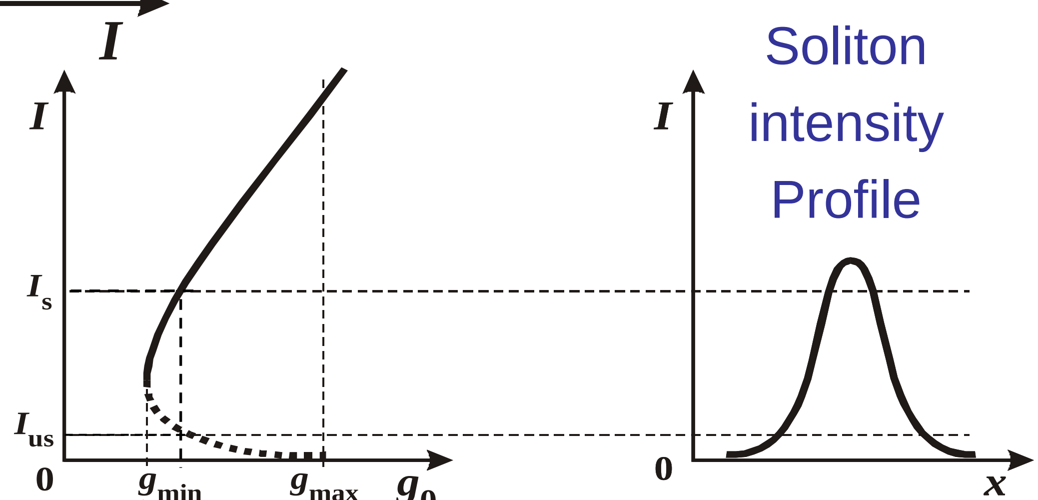


Saturable absorber:
Linear absorption coefficient at low power
Bleaching of absorption at high power

Pioneer: **Rosanov** (St. Petersburg)
Here: Material from Cargese summer school 2006

Bistability for

$$g_{\min} < g_0 < g_{\max}$$



Gain compensates nonsaturable losses

Gain compensates saturable and nonsaturable losses

"Homoclinic Connection"

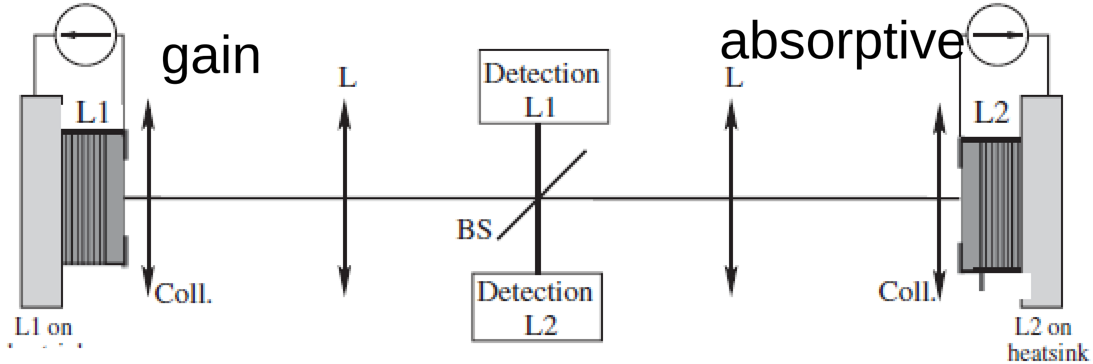
Saturable absorption stabilizes background:

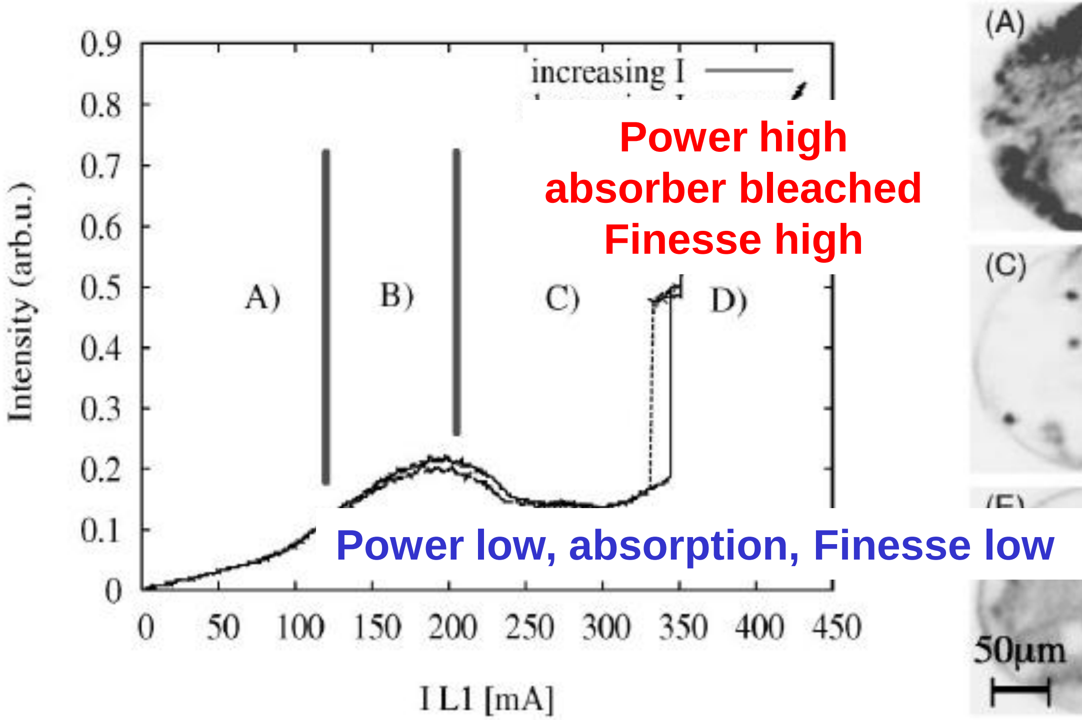
Absorptive bistability

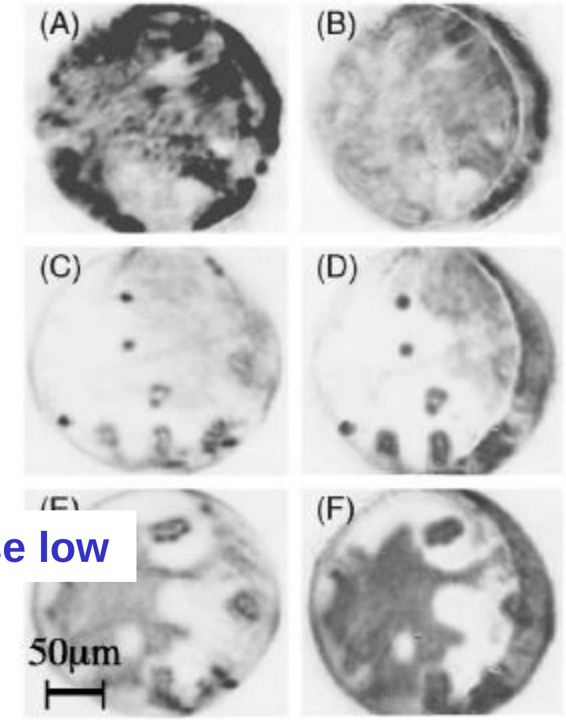
Laser solitons due to saturable absorption

INLN group: Genevet et al., PRL 101, 123905 (2008)

Face-to-face coupled VCSELs







- absorptive optical bistability
  - solitons
  - indepen-dently controllable

For the orbital angular momentum lover

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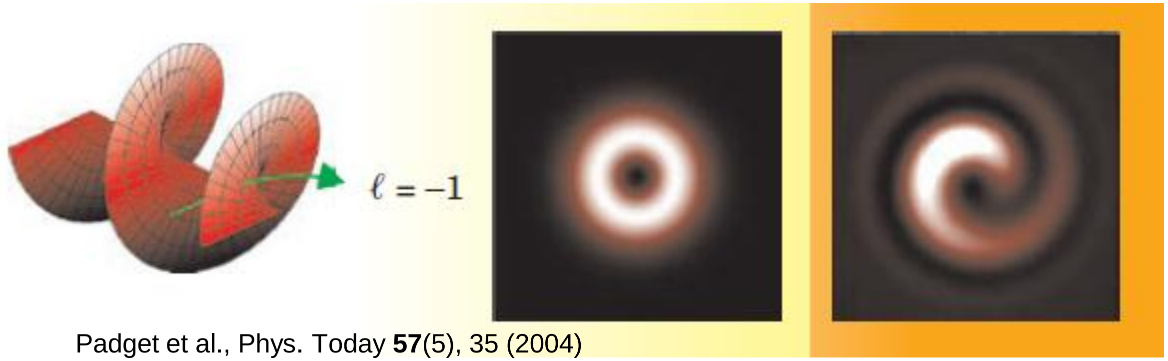
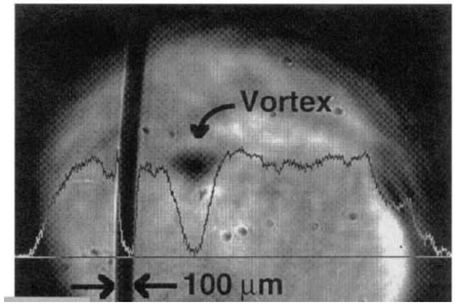
- A doughnut beam or ***optical vortex*** has a spiral phase structure, a singularity at the centre and carries orbital angular momentum



Padget et al., Phys. Today **57**(5), 35 (2004)

- Stable soliton solution for ***self-defocusing*** wave equation

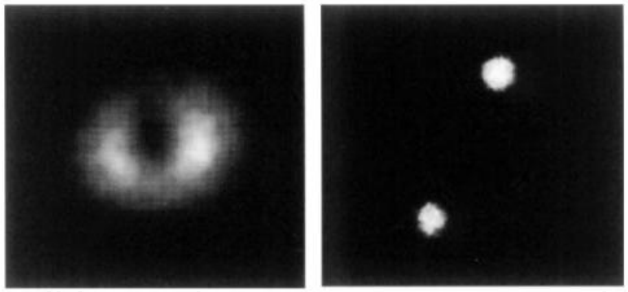


Stable

Swartzlander, OPN **10**, 10 (1993)

(defect in bright homogeneous state)

- But unstable in ***self-focusing*** medium, decays into bright solitons



Tikhonenko, JOSAB 12, 2046 (1995)

Unstable

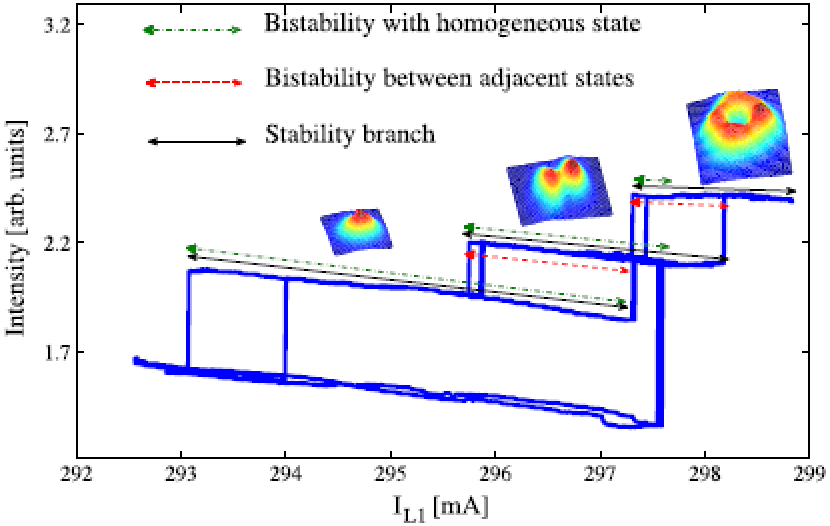
Different for cavity solitons?

self-focusing media ?

Cavity vortex solitons

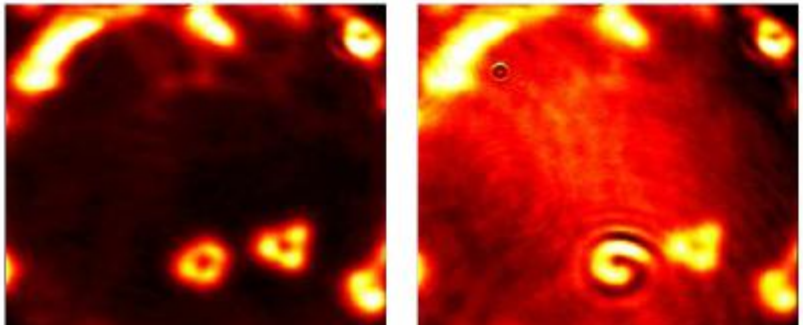
- ***absorptive:***
  - theory: Rosanov group, e.g. Federov et al., IEEE QE **39**, 197 (2003)
  - first experiment: INLN, Genevet et al., PRL **104**, 223902 (2010)

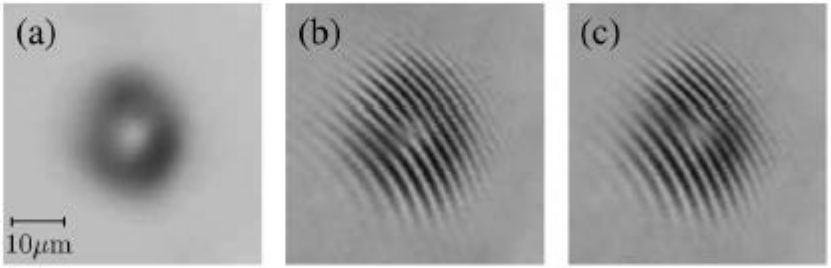
Nested hysteresis curves
Clusters of solitons and “rings”



intensity

Interferogram with magnified part of ring





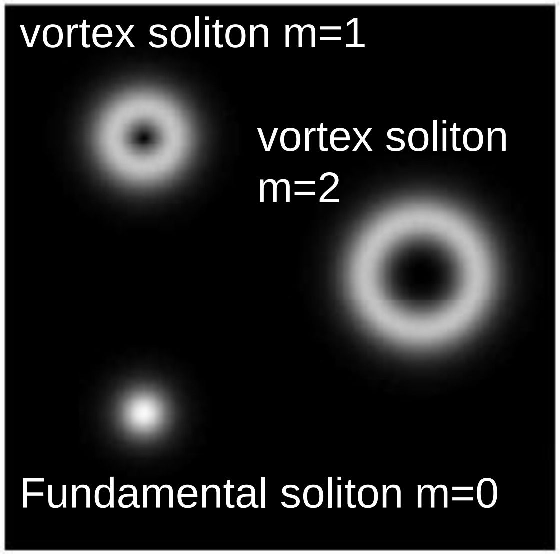
Tilted reference →
forks indicate singularity

Cavity vortex solitons II

- ***self-focusing:***
  - theory: e.g. Crasovan et al., Phys. Rev. E **63**, 016605 (2000)
  - experiment: none to our knowledge
  - specific prediction in a cubic complex Ginzburg-Landau equation with filter

    $\rightarrow$ simplest model for a laser with frequency-selective feedback

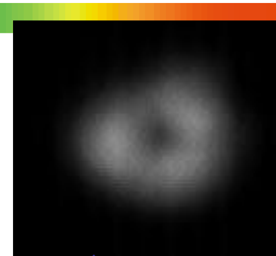
    Paulau et al., Opt. Exp. **18**, 8859 (2010); PRE **84**, 036213 (2011)



Note:

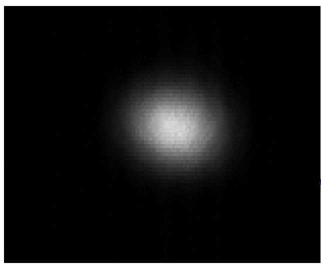
- vortex solitons with integer m form **discrete family of 2D high order solitons**
- this possibility exists only in systems in which the **phase is free**
  i.e. in lasers and other oscillators without coherent injection

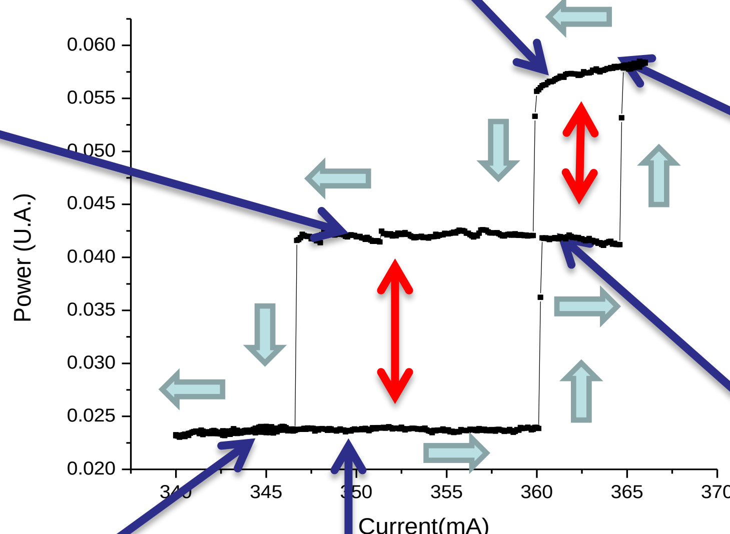
FSF: LI-curve and bistability

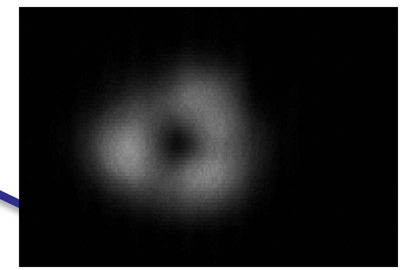


Monitor region of interest around one soliton (not whole aperture!)

(on-state)

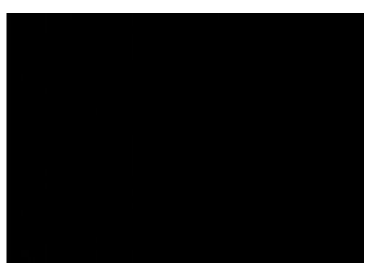


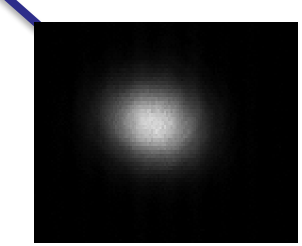




Ring
with three maxima

Background State
(off-state)





Jimenez et al., J. Opt. 15 (2013) 044011 ”singular optics” special issue

Fundamental bright soliton

Interference Patterns (self-interference)

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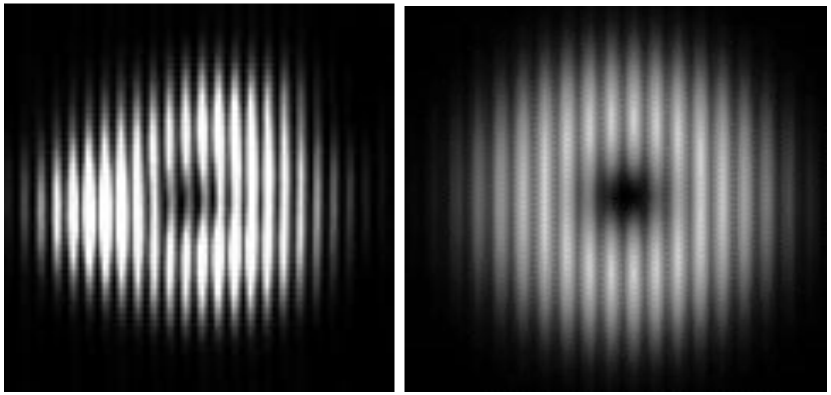
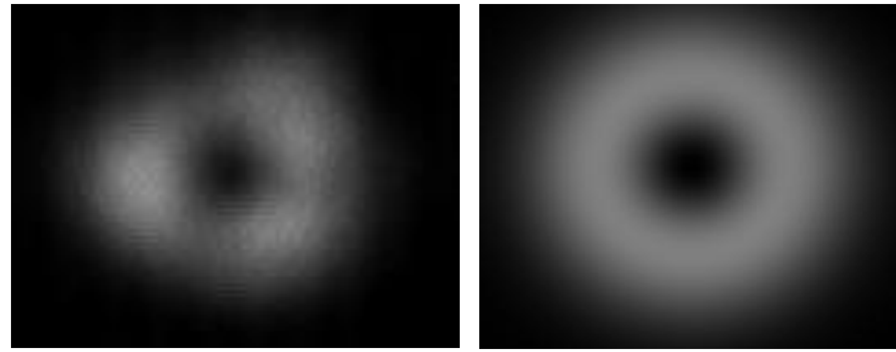
Self-interference (overlapping)



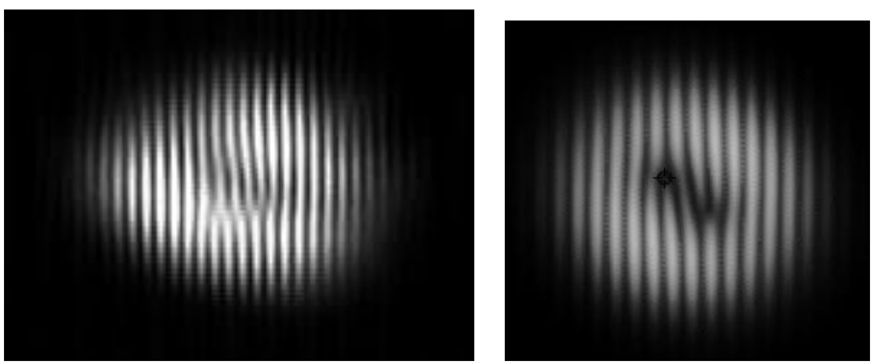
On top of each other

intensity

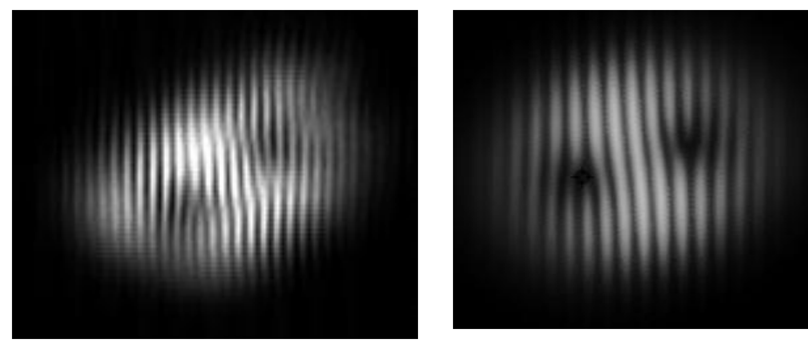


Experimental

Simulation



Shifted sideways, slightly vertically



Stronger shifts

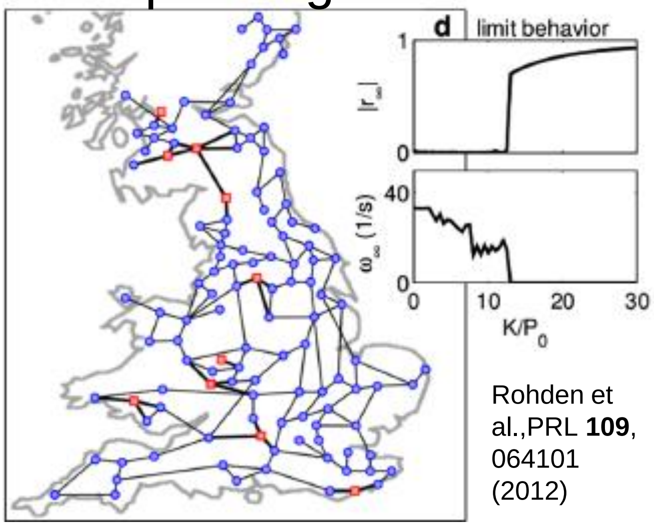
Evidence for one phase singularity with m=1 → vortex

Jimenez et al., J. Opt. 15 (2013) 044011

Synchronization

- We saw that solitons are in generally mutually incoherent due to disorder, i.e. have different frequencies and phases.
- What happens if two are together and interact?

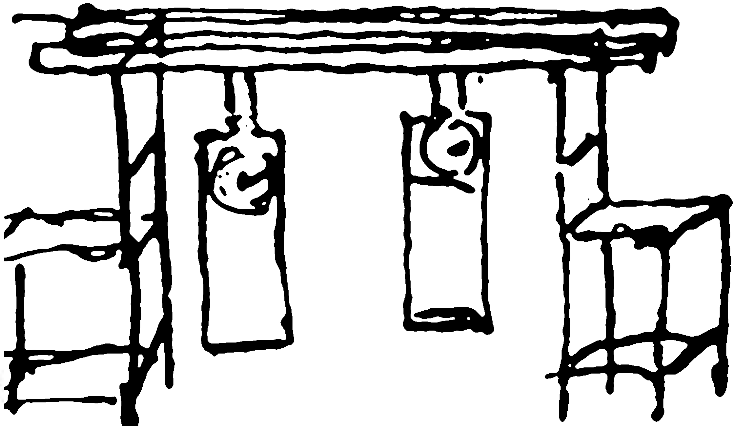
UK power grid



Rohden et al.,PRL **109**, 064101 (2012)

$$\frac{d^2\phi_j}{dt^2} = P_j - \alpha\frac{d\phi_j}{dt} - \sum_i K_{ij}\sin(\phi_i - \phi_j),$$

What about the solitons?



http://www.stat.physik.uni-potsdam.de/~syn-book/H_fig_2.gif

http://en.wikipedia.org/wiki/Christiaan_Huygens

Huygens 1665

Coupled clocks **synchronize:** ***Frequency***- and ***phase-locking***

Adler scenario

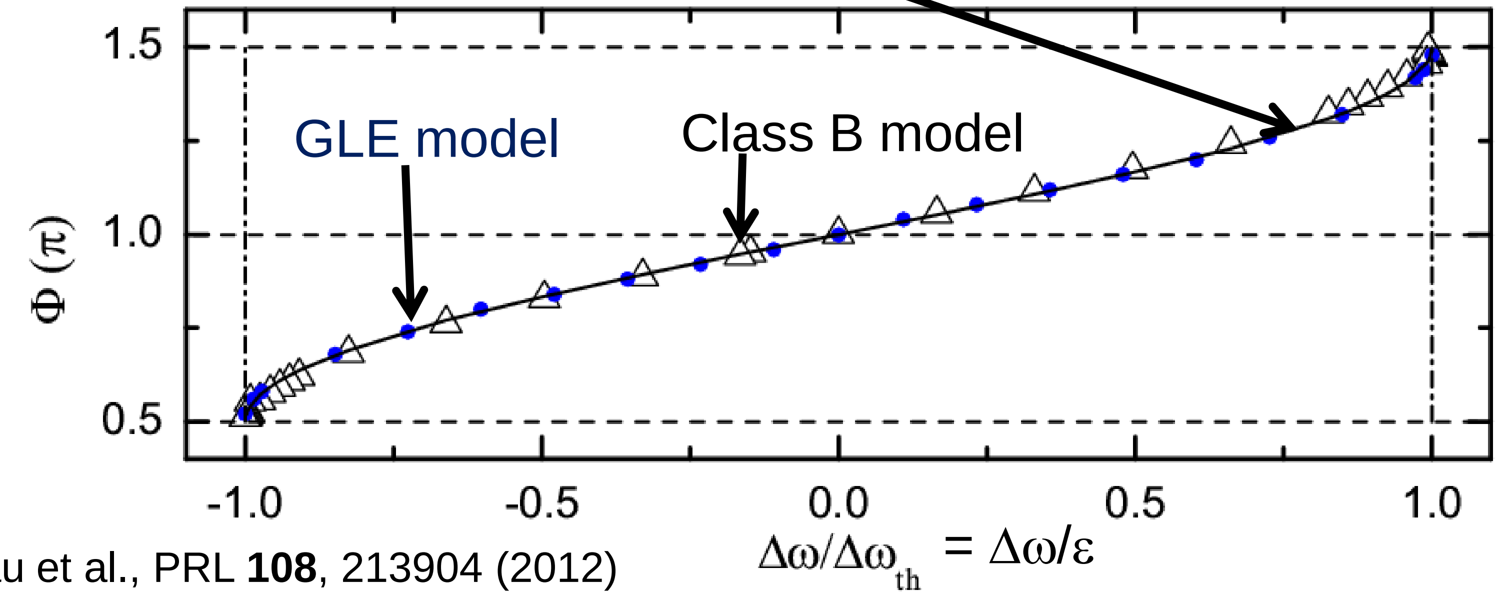
University of Strathclyde Science

- **Adler equation**: Adler, Proc. IRE (1946)

  Archetypical equation for frequency- and phase-locking of nonlinear oscillators in presence of detuning

$$\frac{d\Phi}{dt} = \Delta\omega - \varepsilon \sin(\Phi)$$

- Stable locking at 0 or π for $\Delta\omega=0$
- with detuning still locking for $\Delta\omega < \varepsilon$



Paulau et al., PRL **108**, 213904 (2012)

Experiment: How to control detuning?

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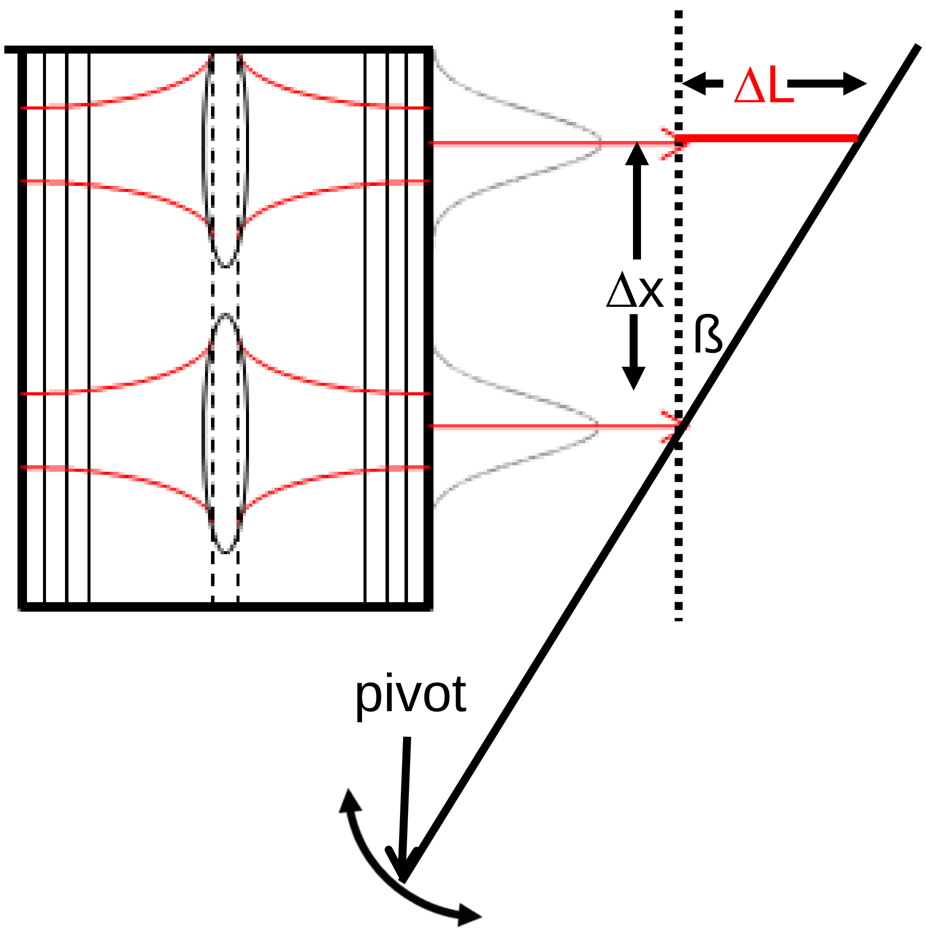

- **Tilt ß of VBG → controls detuning in external cavity (feedback phase)**
- **different arm length ΔL → mutual detuning or offset of combs**

→ align to be "zero" or multiples of free spectral range

- Shift ΔL by a few μm by PZT
  → change detunings by a few tens of MHz
- Near and far field profiles of solitons unaffected but positions are

Similar to control of detuning between coupled microchip lasers (R. Roy et al.)

Experiment: Phase locking

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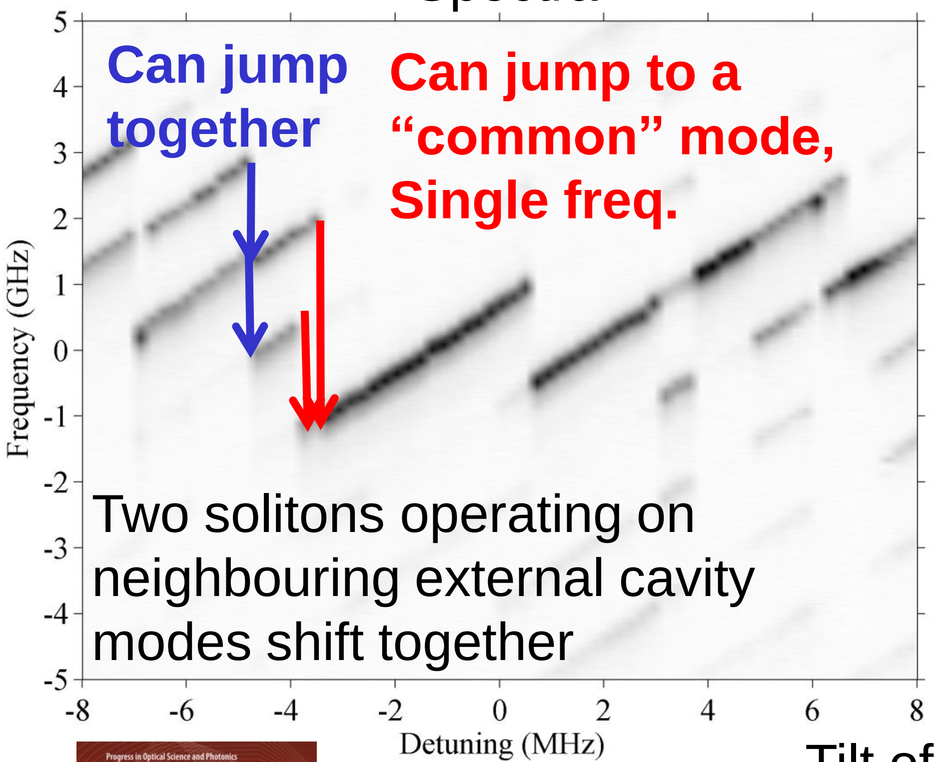
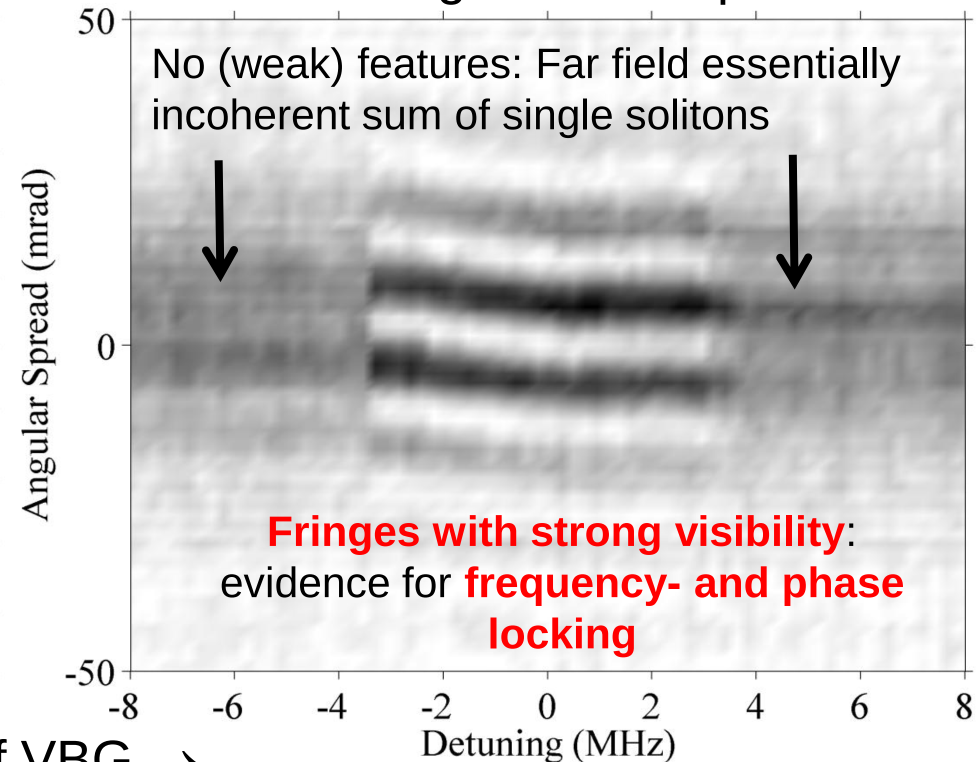
Spectra

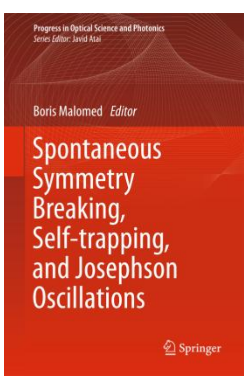


Cut through **far field** patterns



Tilt of VBG →

Shift of fringe pattern → ***change of locking phase***



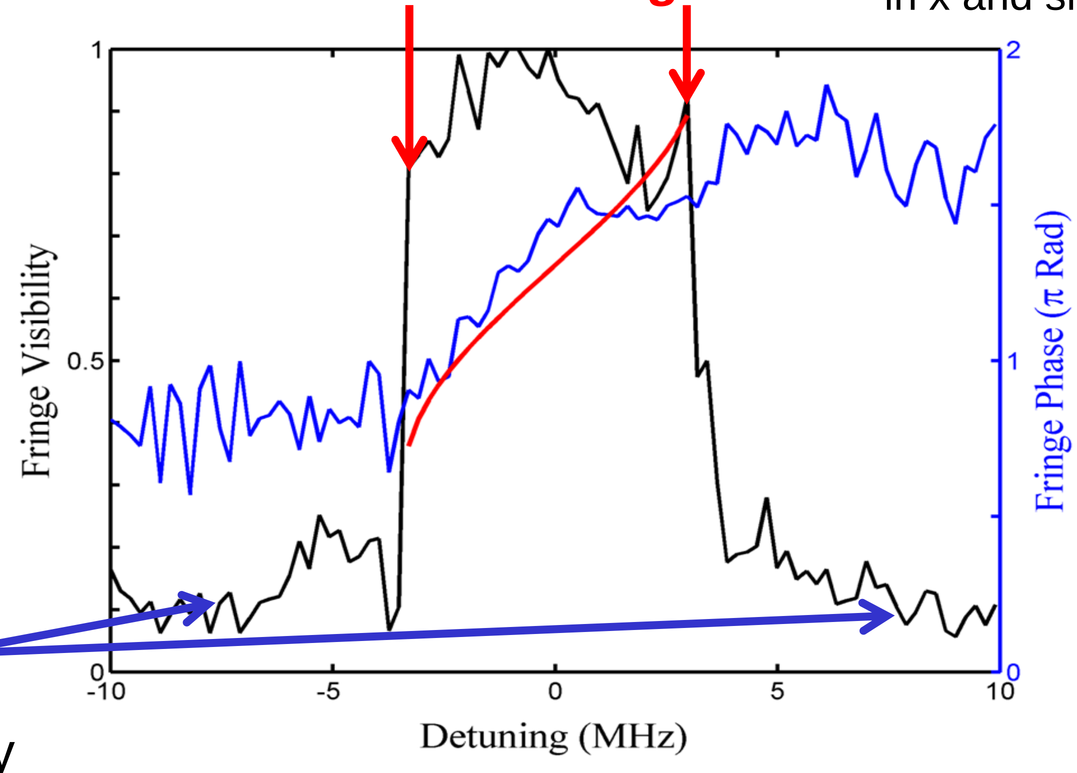
Ackemann et al., Book chapter (2013)

Experiment: Adler

(Nearly) **complete locking:**

(analytical curve (red) scaled in x and shifted in y)

Adler range



partial locking

via some sharing of external cavity modes

- Nice qualitative agreement

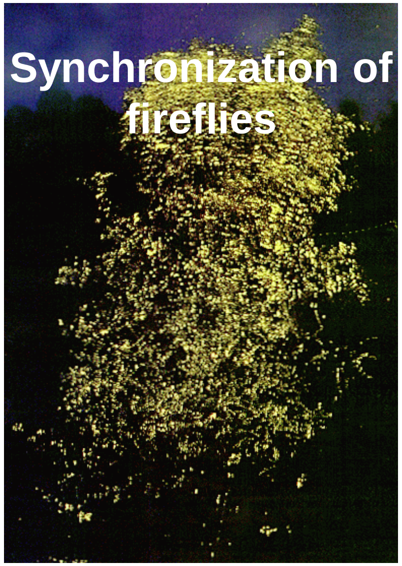
Paulau et al., PRL **108**, 213904 (2012)

Disorder and locking

- Temporal and spatial systems react very different to disorder
- **Temporal (longitudinal):** Bound states with $\pi/2$ phase between constituents predicted for complex cubic-quintic Ginzburg Landau equation are actually observed in mode-locked fiber lasers (Grelut)
  averaging along cavity axis $\rightarrow$ each LCS sees ***all*** disorder

- **Spatial:** Each LCS sees only **local** disorder
  - Translational modes strongly damped
  - ***synchronization dynamics, Adler scenario***
    frequency ***and*** phase locking

- **Nevertheless new features**
  - **self-localized**
  - **bistable**
  - potential of reasonably ***large disordered networks***
- ***Ideas to control disorder locally***



http://www.montefiore.ulg.ac.be/~mauroy/interest.htm

Mode-locking and temporal solitons

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- Pulses in ultrafast, mode-locked lasers can be understood in many (not all!) configurations as temporal dissipative solitons
  - Balance dispersion and self-phase modulation
  - Cavity losses and driving
  - Bistable (self-starting problem)
- Simplified treatment by cubic-quintic Ginzburg-Landau equation

$$i\psi_z + D\psi_{tt}/2 + |\psi|^2\psi + \nu|\psi|^4\psi = i\delta\psi + i\varepsilon|\psi|^2\psi + i\beta\psi_{tt} + i\mu|\psi|^4\psi$$

- Major contributors
  - Fundamental theory: Akhmediev
  - Experiment on molecules, dynamics, ...: Grelu, Cundiff
  - For high-power lasers: Keller, Wise
- Recent review: Grelu, Akhmediev, Nat. Phot. 6, 84 (2012)

Summary: Laser solitons

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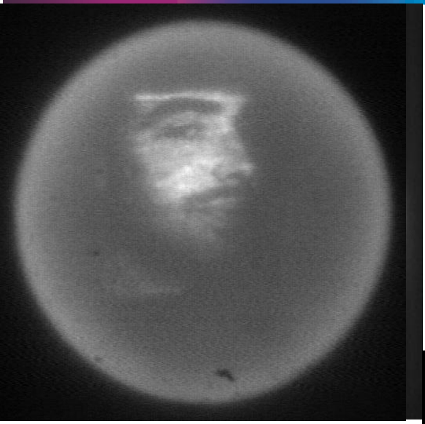
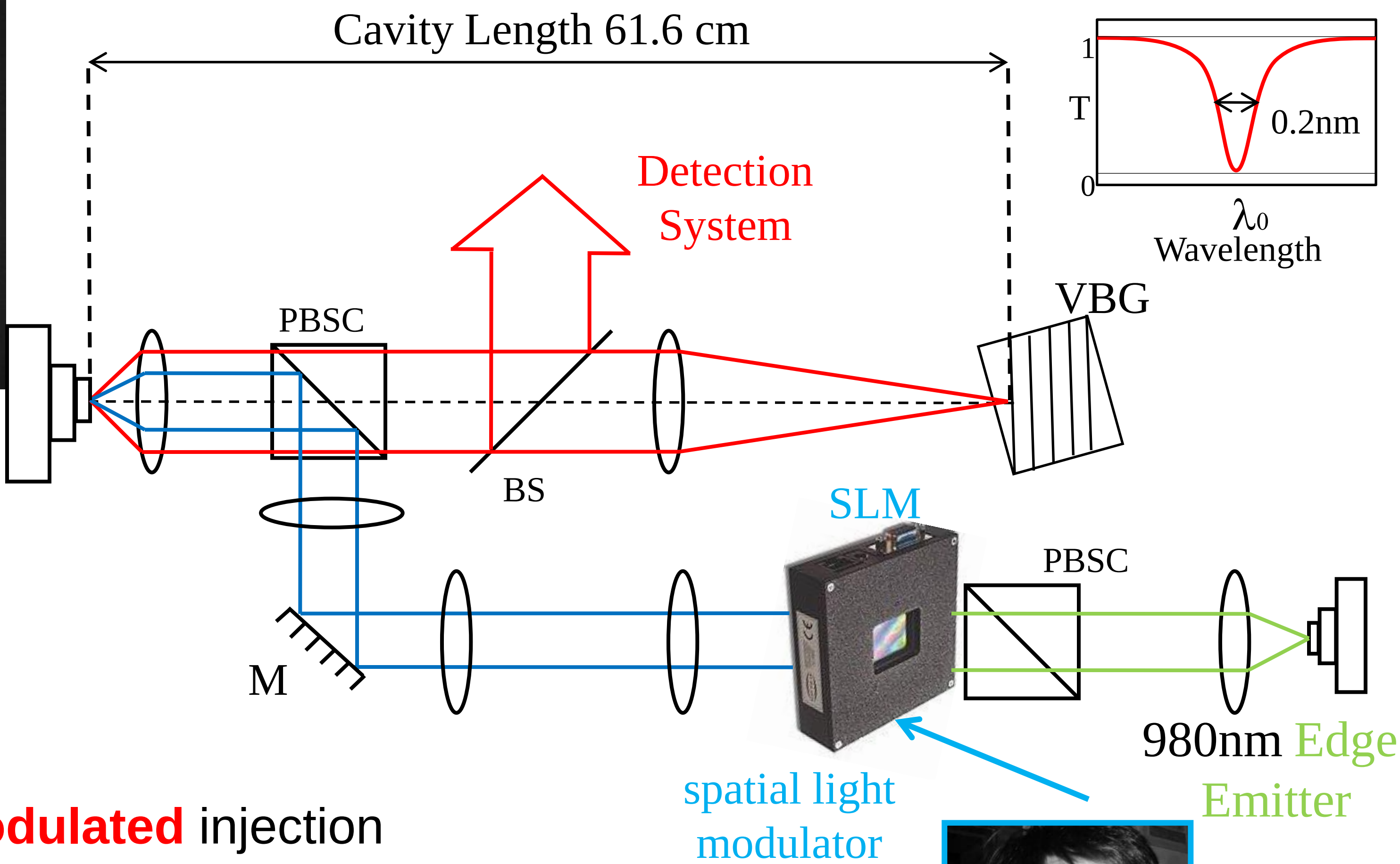
- ***Cavity soliton laser***
  - Optically controllable ***microlasers*** based on ***spatial dissipative solitons!***
  - **Disorder** important in realization (FSF as tool to probe)
  - **Synchronization: Frequency and phase-locking (Adler scenario)**
  - **Vortex solitons as high order states**
- **Different mechanisms, but common features**
  - **Dispersive vs. absorptive optical bistability**
  - **Decisive is that there is a mechanism suppressing lasing in the background (absorptive of off-resonant to filter)**
- **Outlook:** 3D localization, mode-locking of spatial solitons (**Friday**!); networks of phase-locked LCS, local control of inhomogeneities; miniaturization, monolithic integration; cluster of solitons and understanding of connection to high-order solitons and inhomogeneities

Review on CS :
Ackemann, Firth, Oppo, Adv.At. Mol. Opt. Phys. **57**, 323 (2009)

Setup for compensation





- **spatially modulated** injection

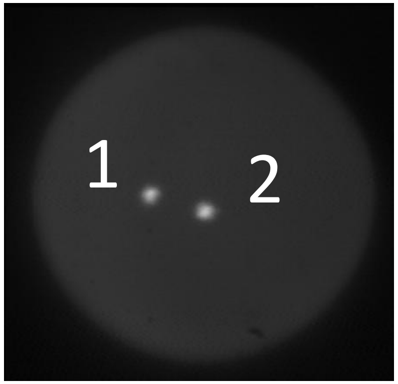
→ spatially modulated carrier distribution

→ spatially modulated refractive index

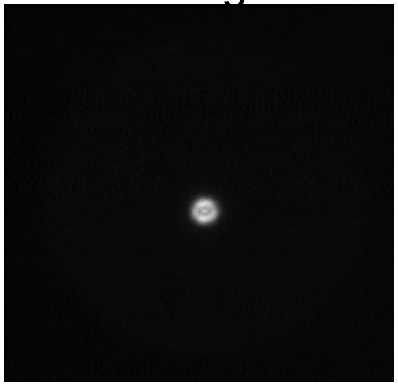
→ **compensation of variations in cavity resonance**

Demonstration of control

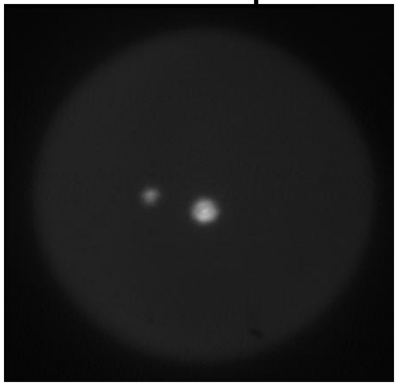
1. Find 2 solitons with similar thresholds

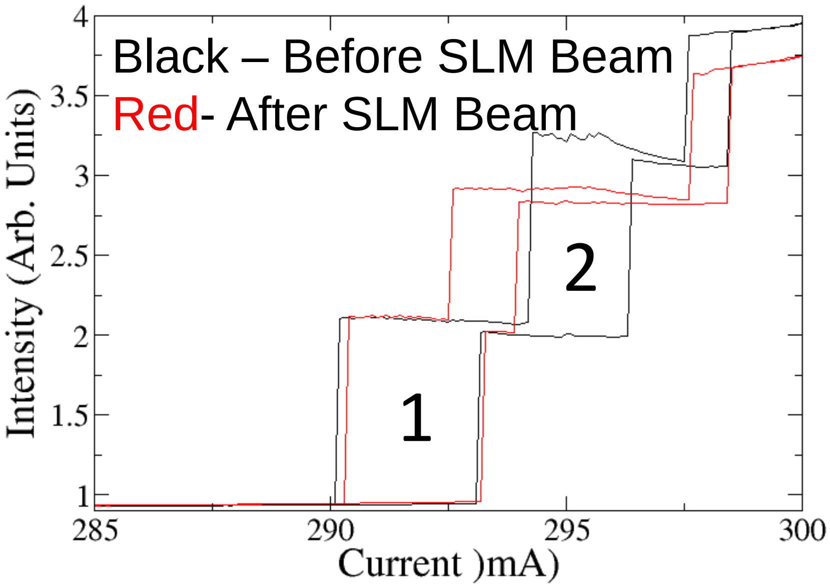


2. Apply SLM beam locally to soliton with higher threshold



3. Soliton thresholds overlap





- SLM for VIS, efficiency in NIR low
  → low power
  → needs to be resonant to microcavity

- **first step towards homogenization**

Large-scale homogeneity

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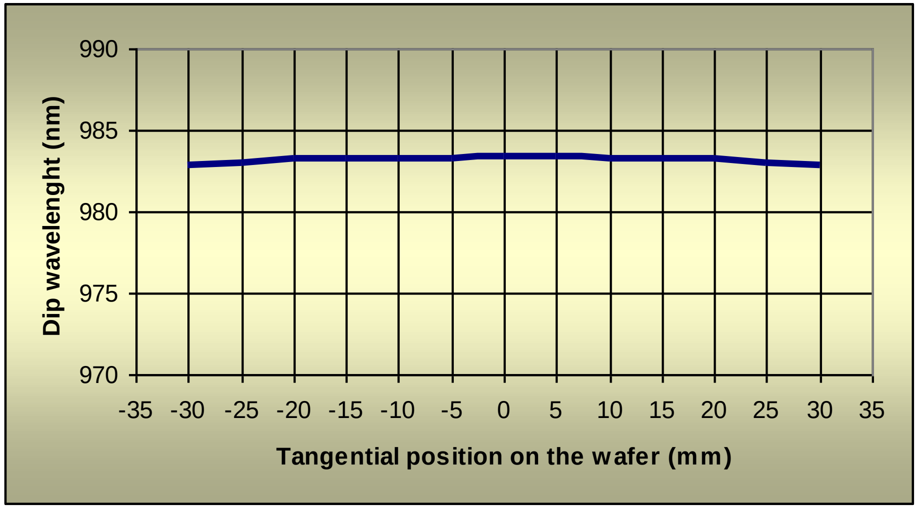
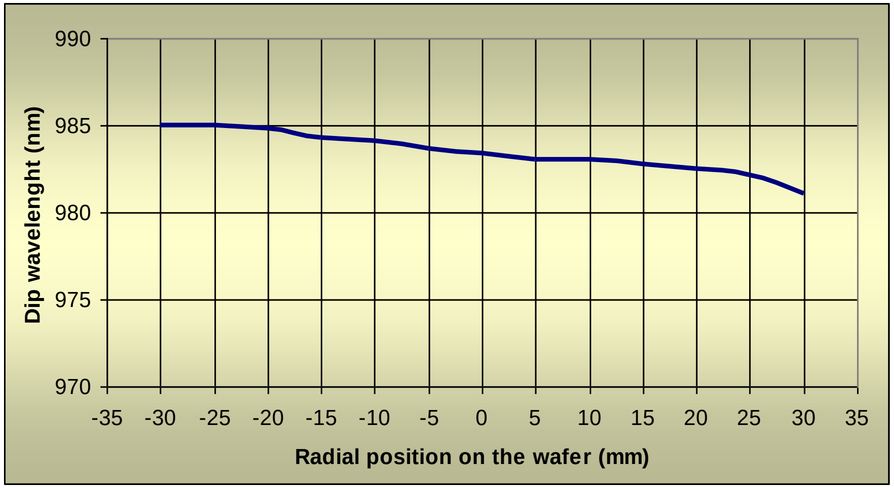
- improve beam shape
  - optimize temperature difference between bottom and top heating filament of the effusions cells
- improve homogeneity of substrate temperature
  - reduce temperature level of growth
  - enhance uniformity of substrate holder rings
- result:
  - **< 0.012 GHz / µm**
  - **< 2.5 GHz / 200 µm**

tangential



radial



R. Jäger et al., Ulm Photonics, unpublished

Time-resolved optical spectrum

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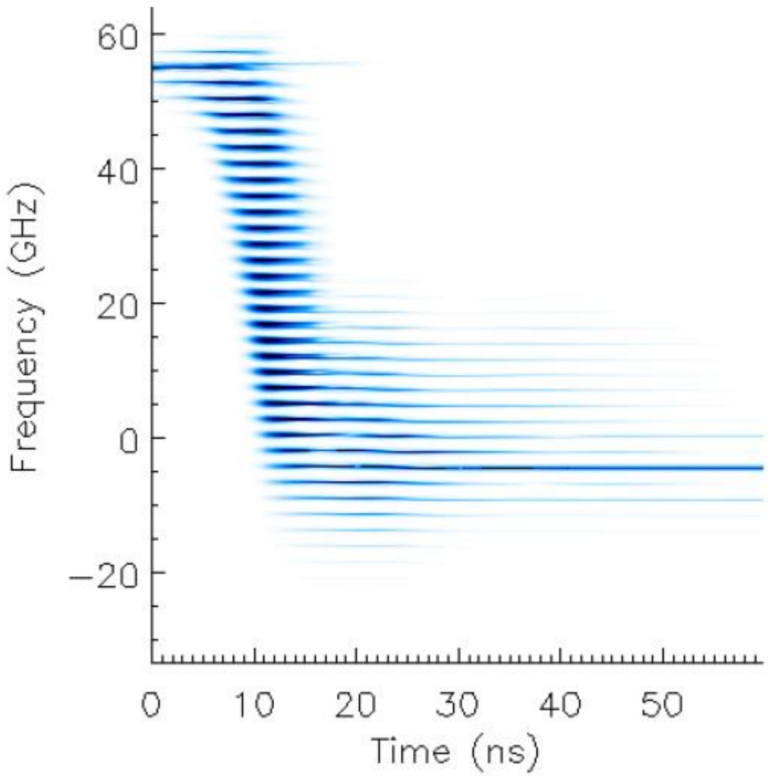
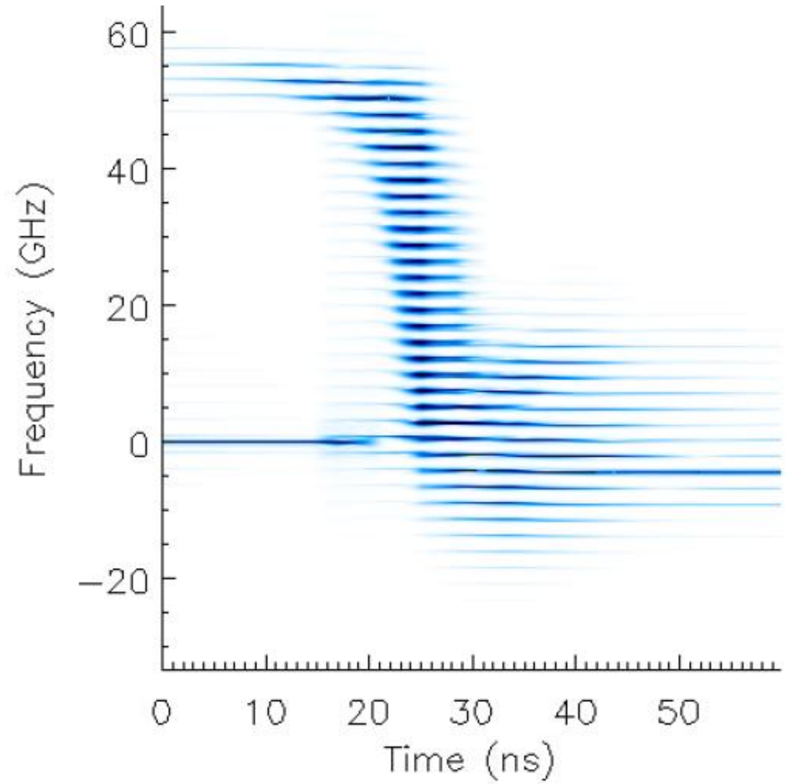
Blue detuned excitation (20 ns pulse)



Excitation at grating frequency



Shift of carrier frequency → evolution via **unstable LCS** → spectral simplification

Still evolution via **unstable LCS**

Even simpler:Ginzburg-Landau model

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Ginzburg-Landau model + linear filter, Firth + Paulau, Eur. Phys. J. D **59**, 13 (2010)

Linear loss (gain) and frequency detuning

Nonlinear gain (loss) and self focusing (defocusing)

Diffraction

Filtered Feedback

$$\begin{cases} \frac{\partial E}{\partial t} = g_0 E + g_2 |E|^2 E + i\Delta_\perp E + F + in(x)E, \\ \frac{dF}{dt} = -\lambda F + \tilde{\sigma} E, \end{cases}$$

Width of filter

Feedback strength

Pinning potential

$$n(x) = \frac{-n_j}{2}\left[cos\left(\frac{\pi(x-x_j)}{W}\right) + 1\right]$$

L.M. Hocking and K. Stewartson, Proc. R. Soc. Lond., A **326**, 289 (1972); N.R. Pereira and L. Stenflo, Phys. Fluids **20**, 1733 (1977).

P.A. Bélanger, L. Gagnon, and C. Paré, Opt. Lett. **14**, 943 (1989).

C. Paré, L. Gagnon, and P.A. Bélanger, Opt. Commun. **74**, 228 (1989).

$$g_0 = \kappa(1 + i\alpha)(\mu - 1) - i\omega_m,$$
$$g_2 = -\kappa(1 + i\alpha)\mu,$$
$$\tilde{\sigma} = \sigma\lambda,$$

Homogeneous system

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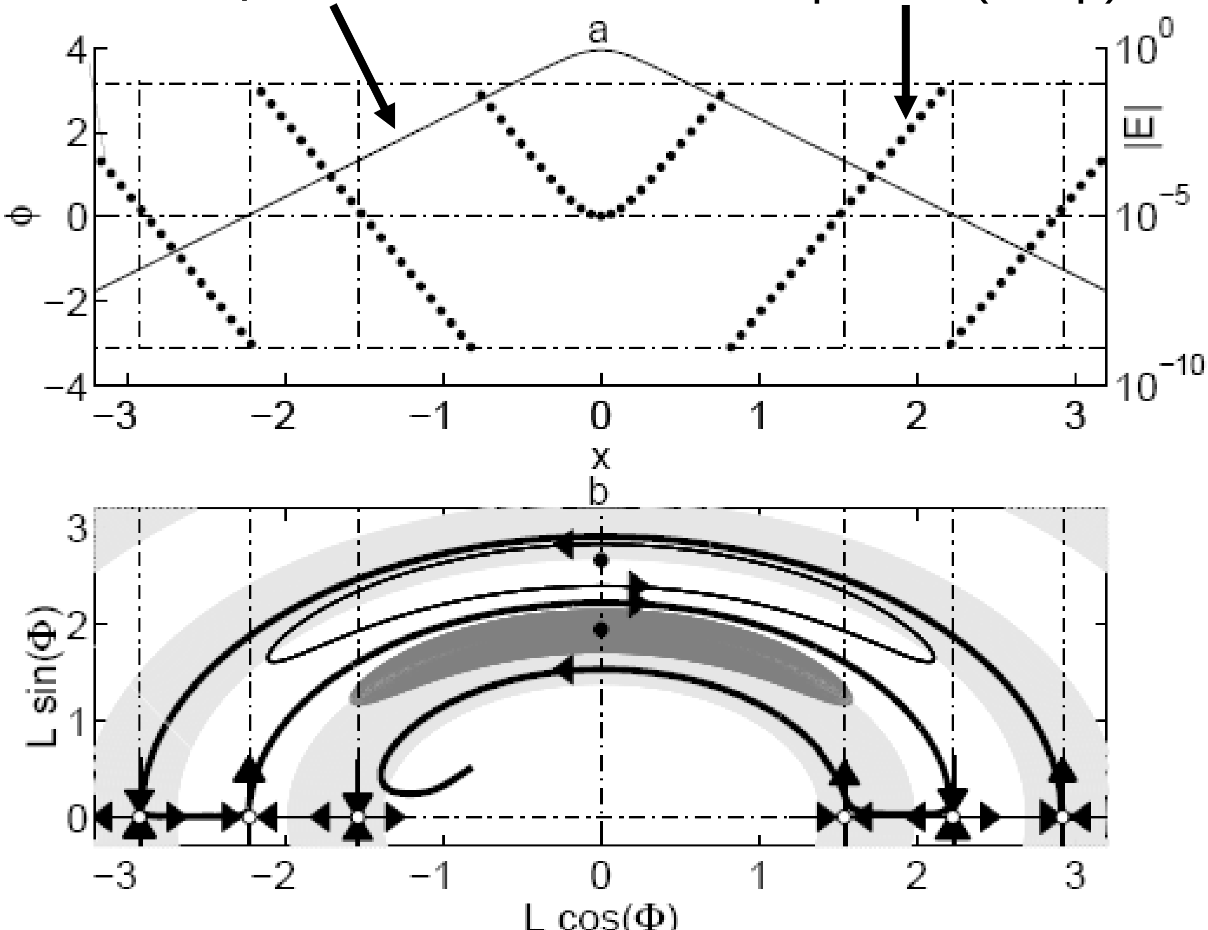
Work by P. Paulau, note $\alpha = 0.5 <<$ than in experimental system $\alpha \approx 5$

Soliton amplitude

Soliton phase (chirp)

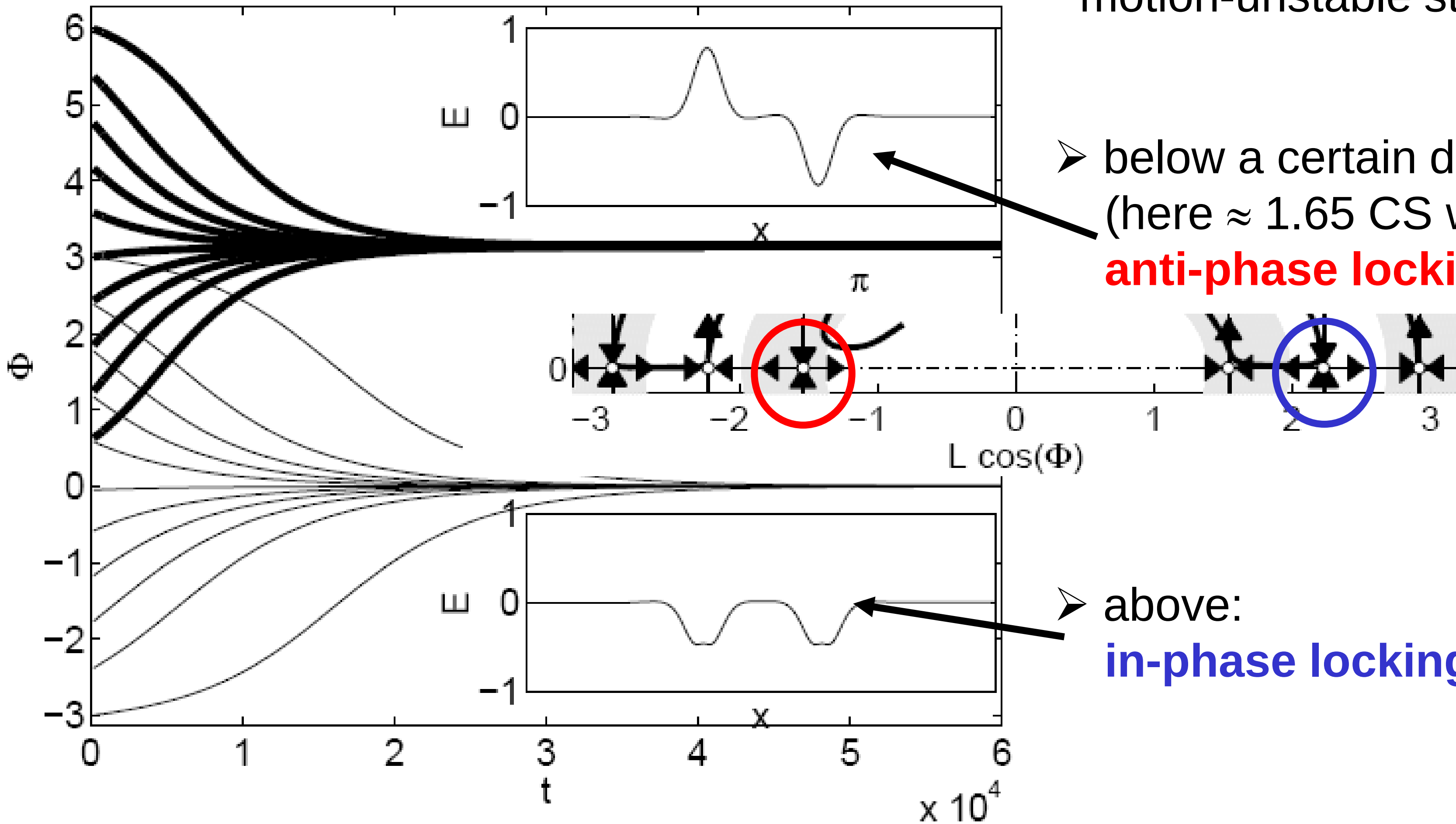


Interaction plane: distance - phase

- **Foci** at phase $\pi/2$ **stable**
- **Saddles** at phases 0 and π ***always unstable***
- qualitatively very similar to perturbatively obtained diagram for cubic-quintic GLE; temporal solitons in fiber lasers; Akhmediev et al, PRL 79, 4047 (1997); Tuarev et al, PRE 75, 045601(R)(2007)

Results with traps of equal depths

Trap depth about 0.48 GHz

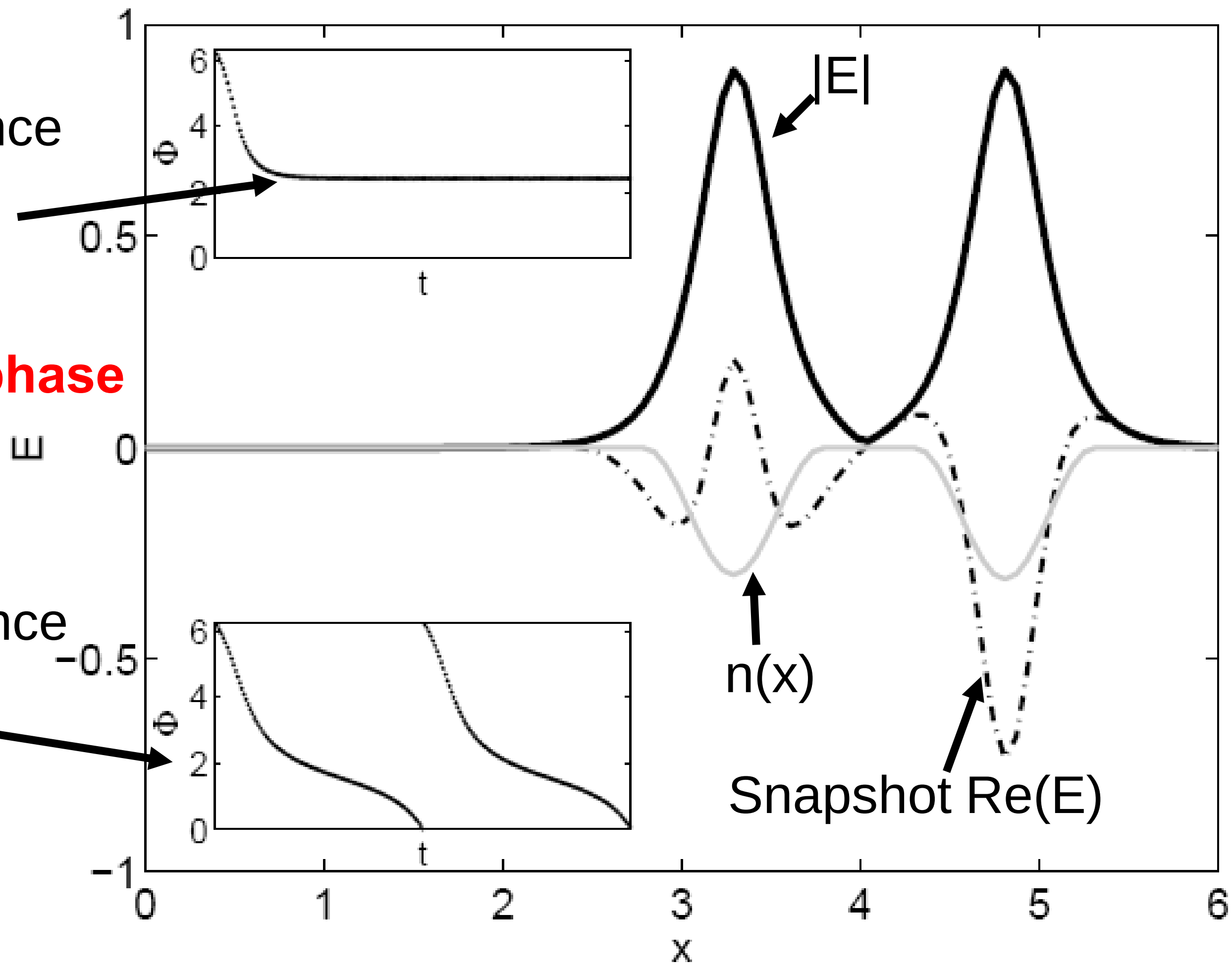


- Traps destroy translational symmetry and stabilize motion-unstable states
  - below a certain distance (here ≈ 1.65 CS width): **anti-phase locking**
  - above: **in-phase locking**

Results with unequal traps

Trap depth different by 3%

- below a certain distance (here 2.06 CS width)
  - **synchronization**
  - **“non-standard” phase**
  - here 2.415



- above a certain distance
  - unlocked

Outlook: Complex networks of LCS

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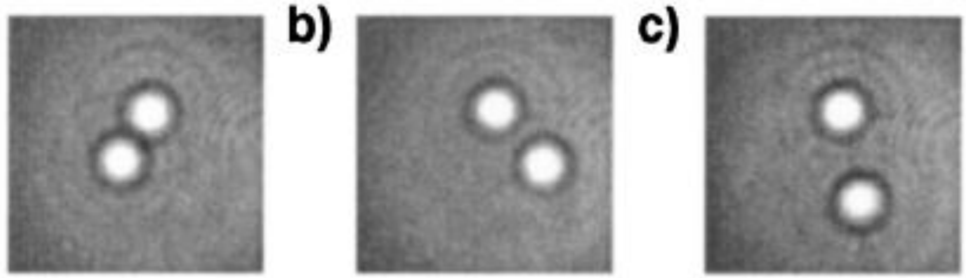
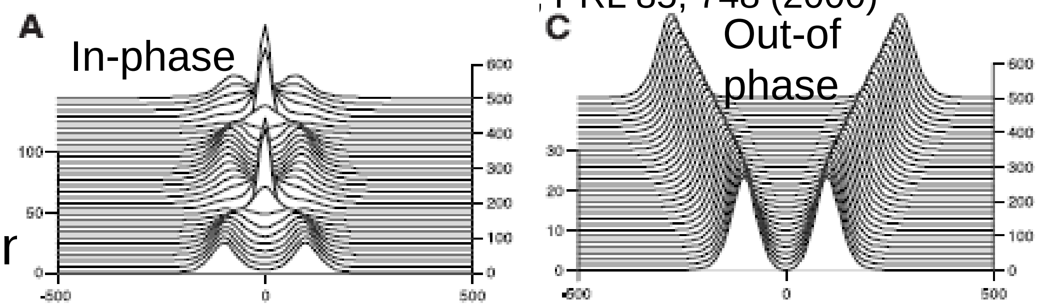
- **Coherently driven systems:** complex interactions via intensity (oscillating tails) but **no** phase dependence



Schaepers et al., PRL 85, 748 (2000)

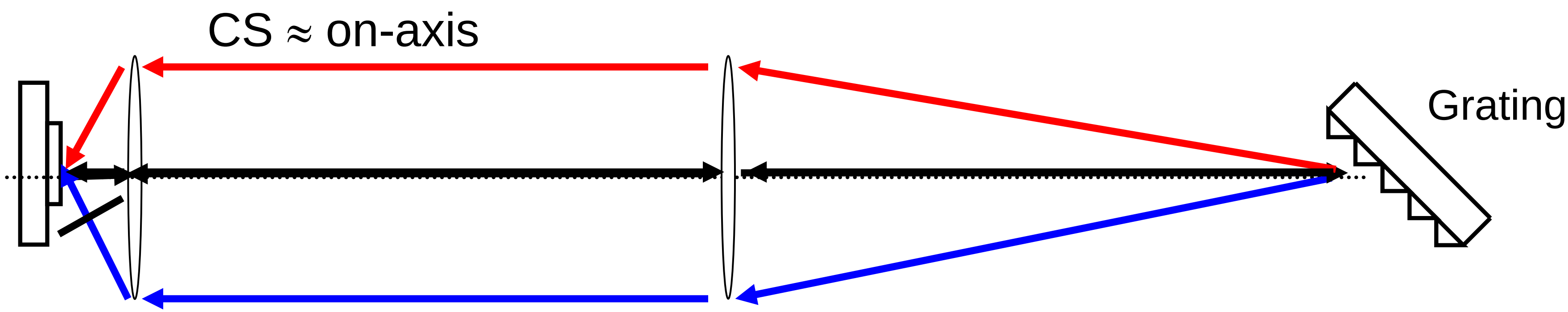
- **Propagational solitons:** **phase sensitive** interactions, depending on launching condition



Stegeman + Segev, Science 286, 1518 (1999)

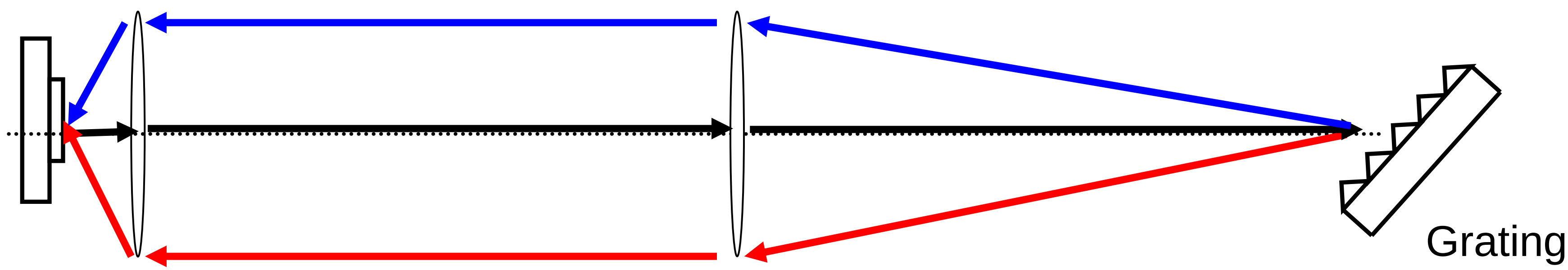
- **Laser cavity solitons** combine features of these two cases and adds new
  - (optical) phase, spatial phase and polarization (phase between x, y comp.) are Goldstone modes
  - **Phase, location, and polarization are free to change during *dynamics***
  - Complex network with many degrees of freedom
  - pioneering work: Akhmediev, Vladimirov, Rosanov, + coworkers

Asymmetry from the grating



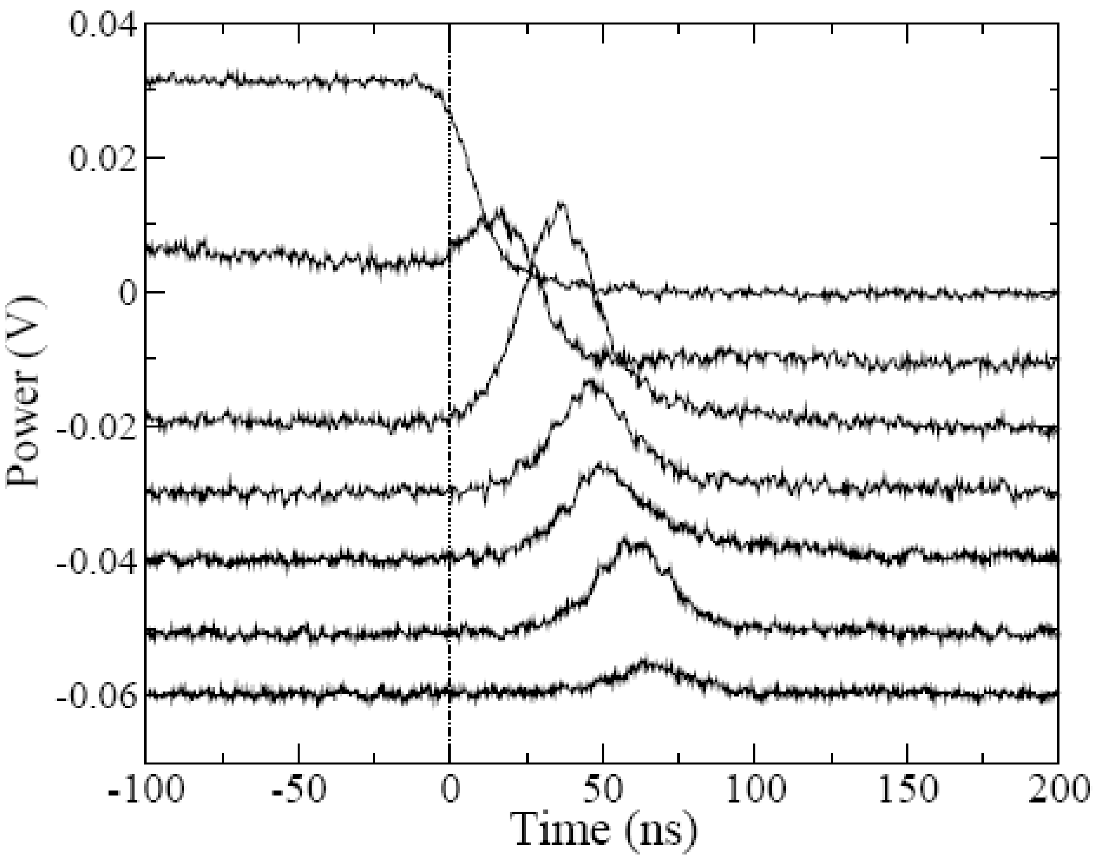
- CS exactly at Littrow freq. → exact retro-reflection
- CS slightly blue detuned → ***angle*** → wavefront tilted to
- CS slightly red detuned → ***angle*** → wavefront tilted to the ***left***

Tilted wavefront induces drift!



Drifting excitations

Ignite CS in a situation, in which it is only transient, monitor by APD array



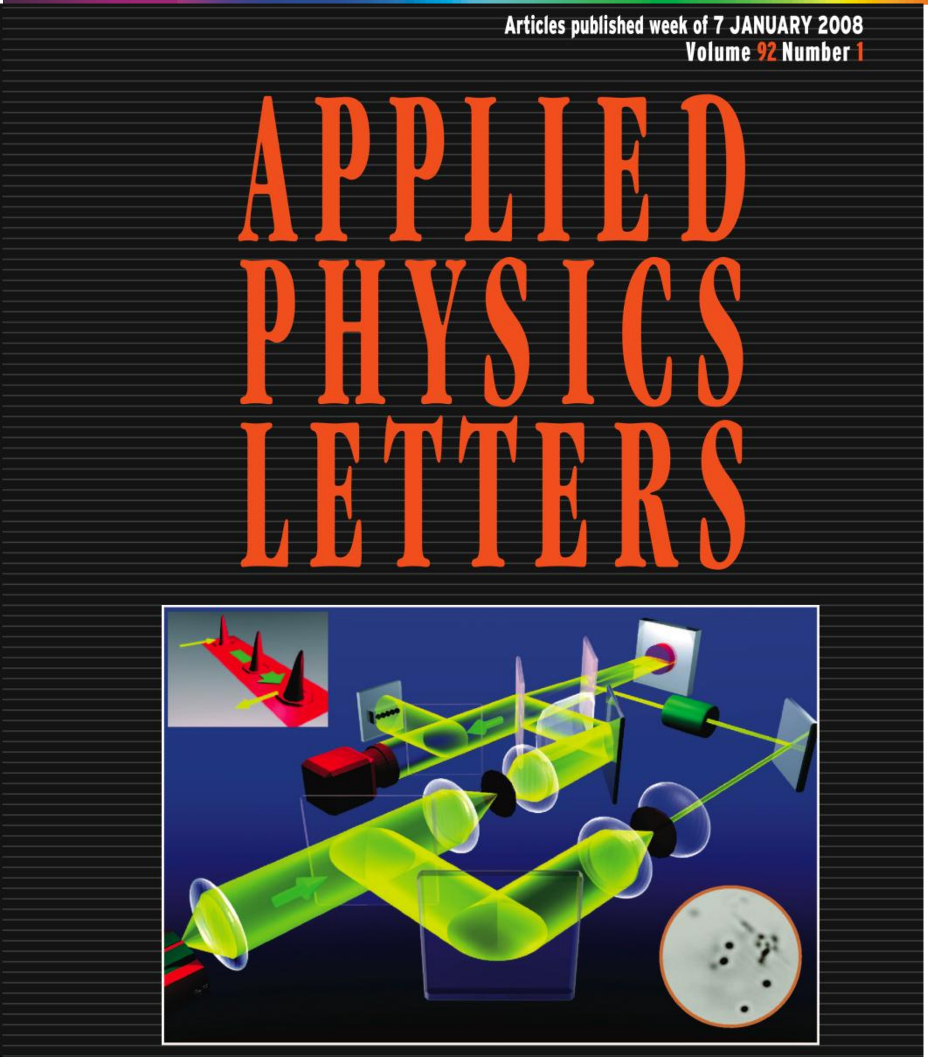
- velocity: 1.4 µm / ns
- drift distance: > 50 µm
- Delay: ~ 40 ns

Caution:
Measurement in far field indicate that angle increase by 2.5º
soliton character likely but needs to be confirmed

Tanguy et al., PRA **78**, 023810 (2008)

CS Application – All-optical delay line

University of Strathclyde Science



In CSL

- velocity: 1.4 µm / ns
- drift distance: > 50 µm
- Delay: ~ 40 ns

In amplifier exp. (Nice)

- velocity: 4.7 µm / ns
- drift distance: 36 µm
- Delay: 7.5 ns

Motivation:

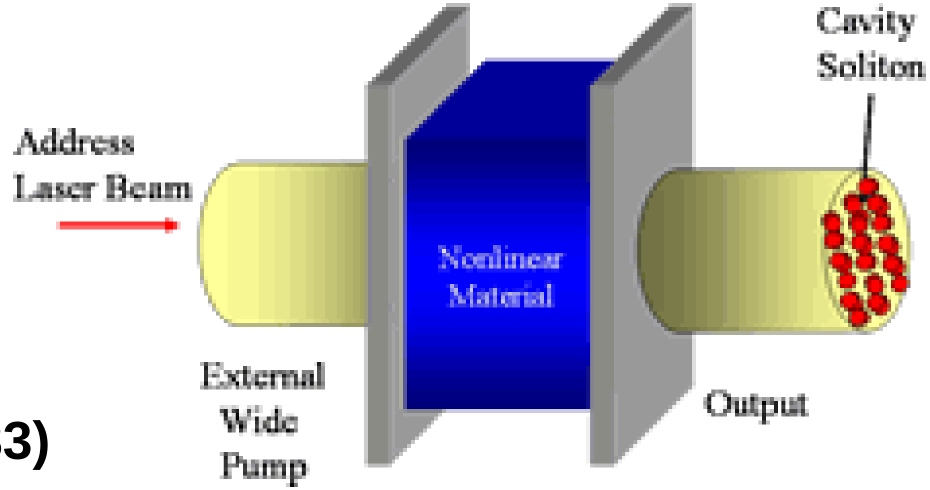
All-optical delay line as buffers in photonic networks

*F Pedaci, S Barland, E Caboche, P Genevet, M Giudici, J R Tredicce, T Ackemann, A J Scroggie, WJ Firth, G-L Oppo, G Tissoni and R Jäger. Appl. Phys. Lett. **92** 011101 (2008)*

History: Cavity solitons

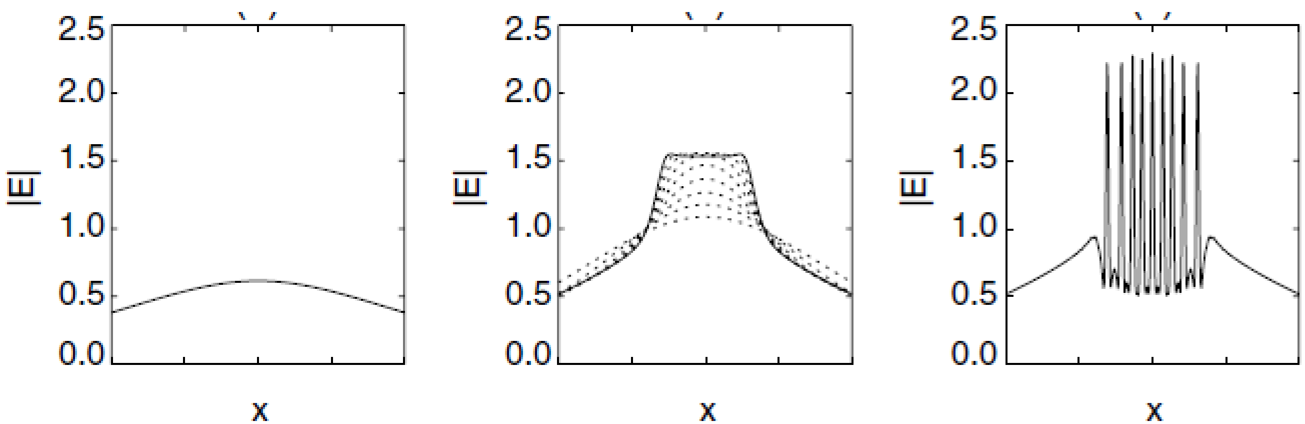
cavity soliton = (spatially) self-localized, bistable solitary wave in a cavity

- stabilized by counteraction of
  - nonlinearity vs. diffraction
  - driving vs. dissipation



driven cavity (optical bistability)

Probably first simulations:
McLaughlin, et al. PRL **51, 758 (1983)**

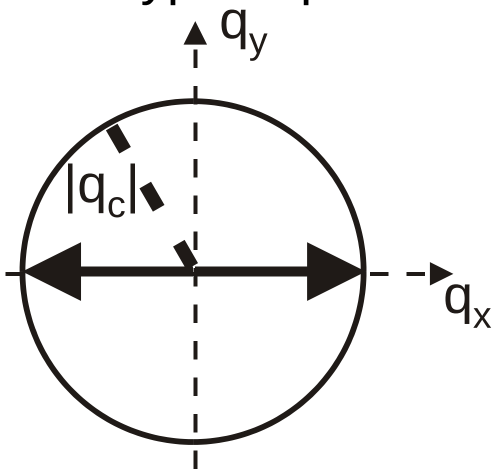


Experiments later

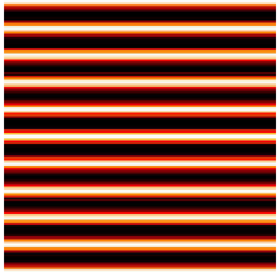
First analysis: Rosanov et al. Opt. Spectrosc. **65**, 449 (1988);
J. Opt. Soc. Am. B **7,** 1057 (1990)

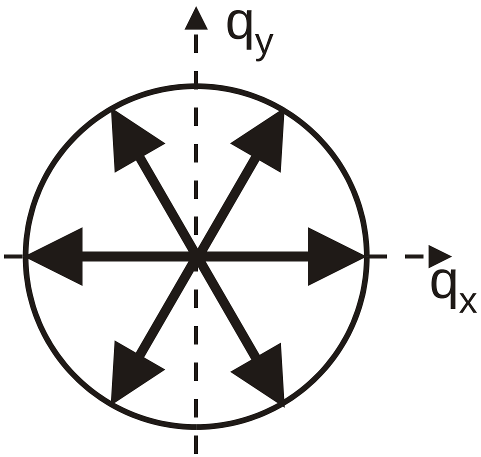
Bifurcations of hexagons

tilted wave argument selects length scale
not type of pattern



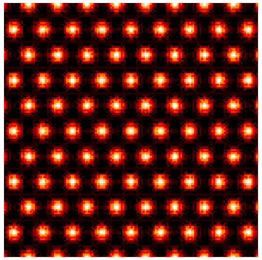
stripes

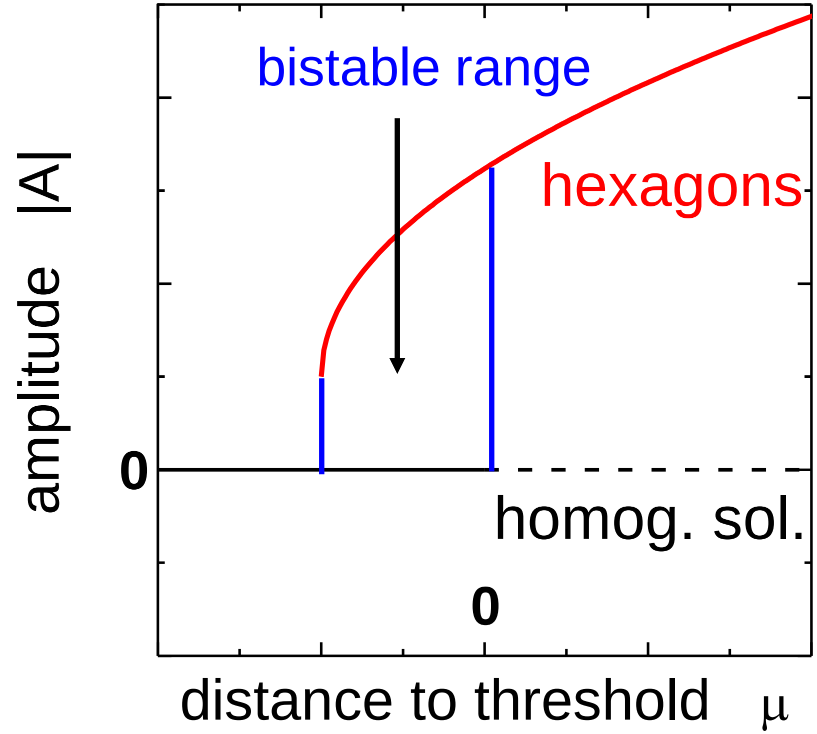




generic in 2D

hexagons



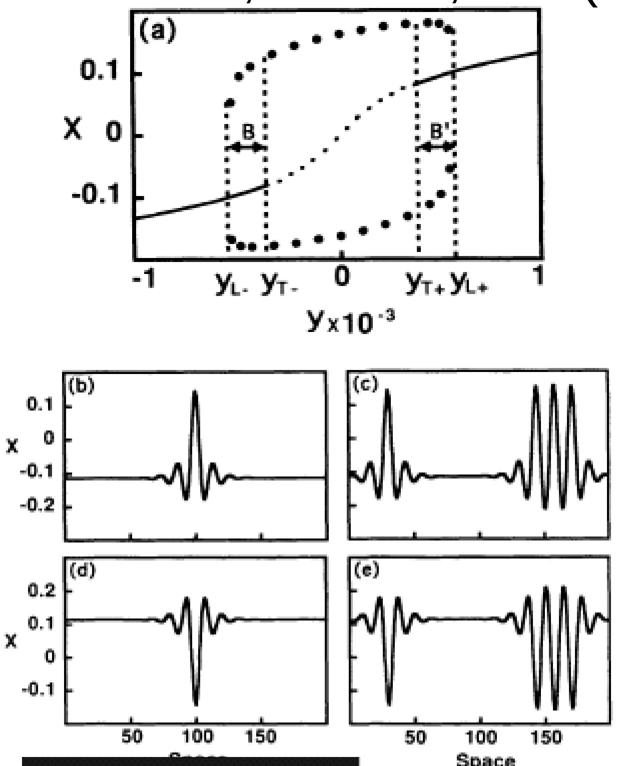


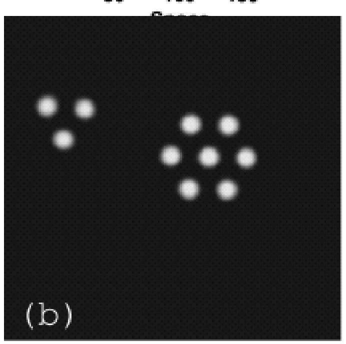
bifurcation to hexagons **subcritical**

region of **coexistence** of
homogeneous solution and hexagons

In bistable range: Cavity solitons and patterns

Tlidi et al., PRL 73, 640 (1994)

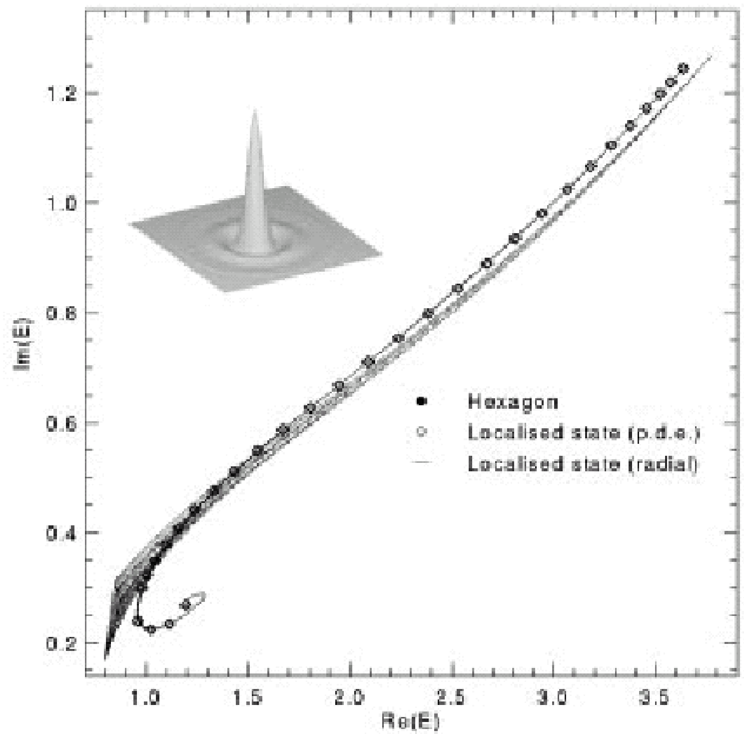




„localized pattern“

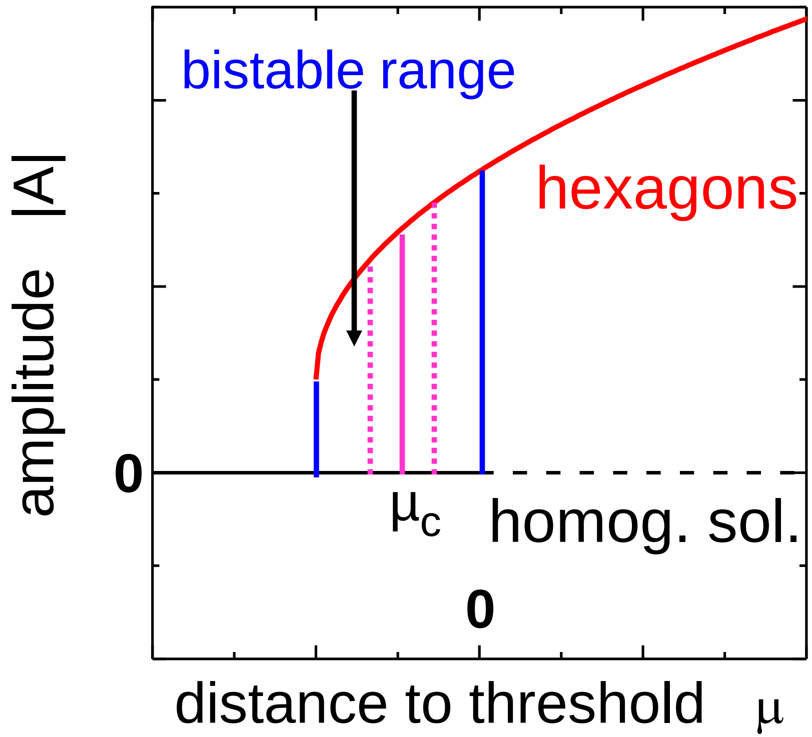
CS very similar to constituent of a hexagon

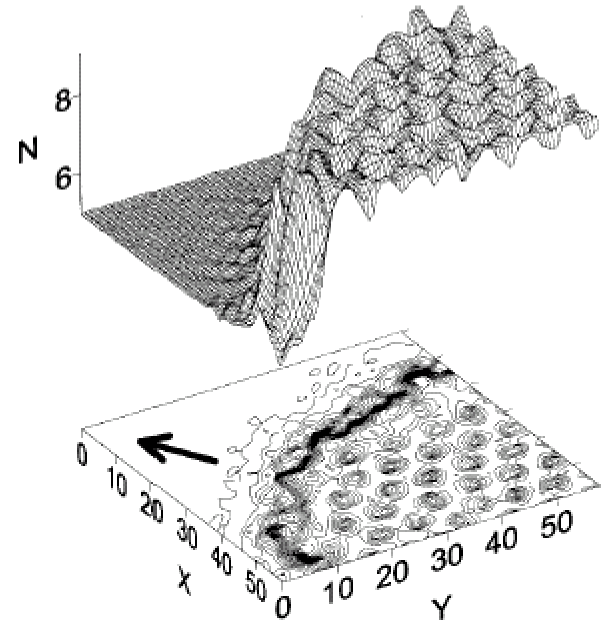
Firth+Scroggie, PRL 76, 1623(1996)



CS (or LS) = part of a pattern

Fronts and cavity solitons





a) **front** between half-plane with hexagons and half-plane with homogeneous solution stationary at ***one*** value of stress parameter

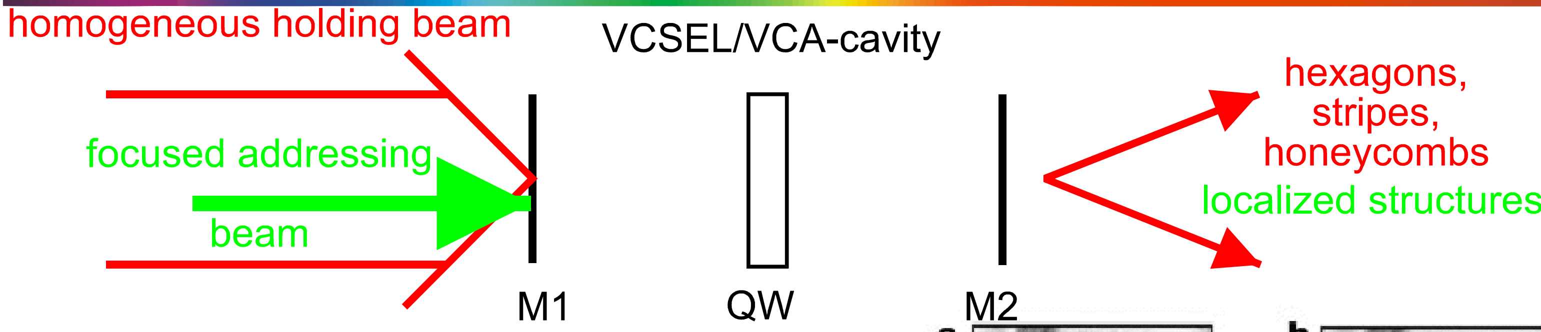
b) **Pomeau-front** stationary for ***finite*** range of stress parameter due to locking at modulated interface

general prediction (1D):

LS / CS occur in vicinity of Pomeau front

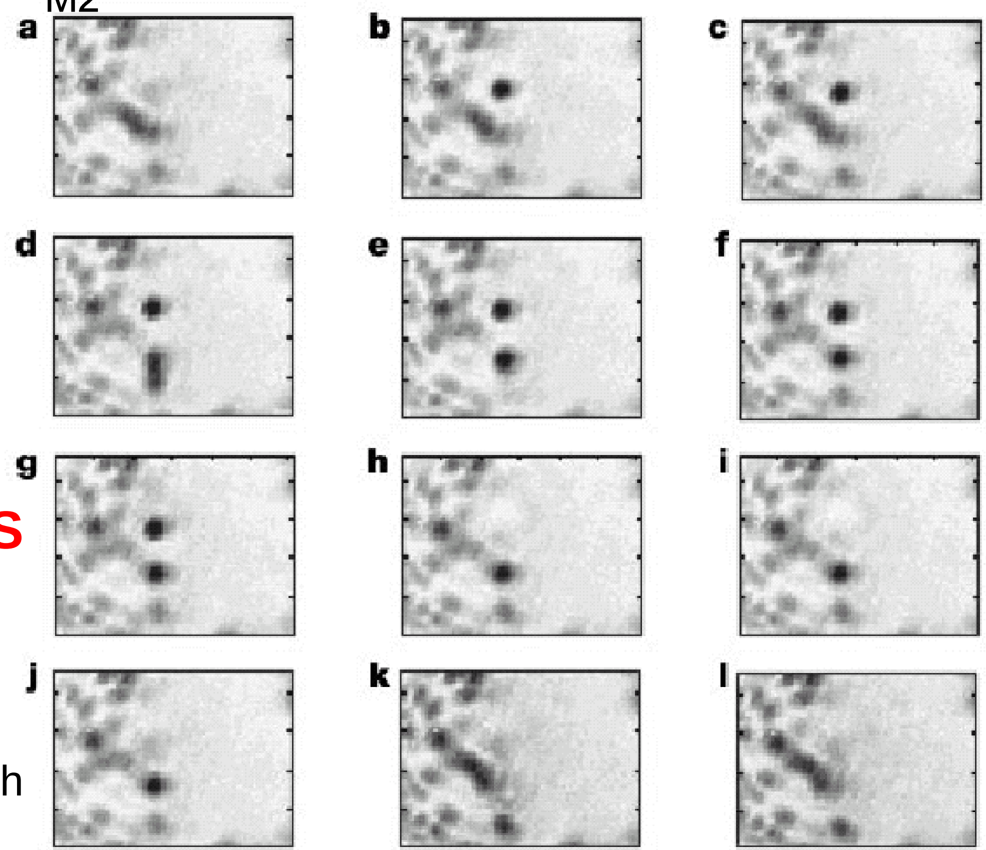
Coullet et al., PRL **84**, 3069 (2000)

Vertical-cavity (regenerative) amplifier



Barland et al., Nature **41**, 699 (2002)

electrical pump



electrically pumped above transparency, but below threshold

VCA = vertical-cavity (regenerative) amplifier

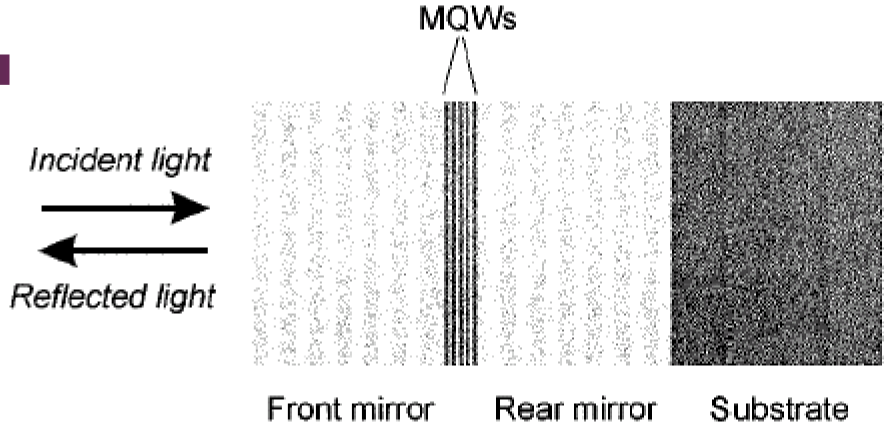
+ homogeneous holding beam

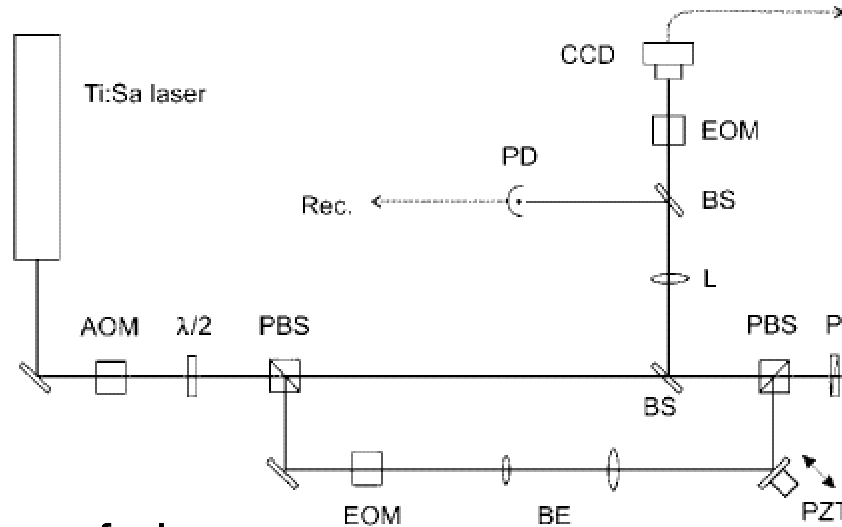
Independent manipulation of two CS

“Cavity solitons as pixels in semiconductor microcavities”

60 × 60 μm²

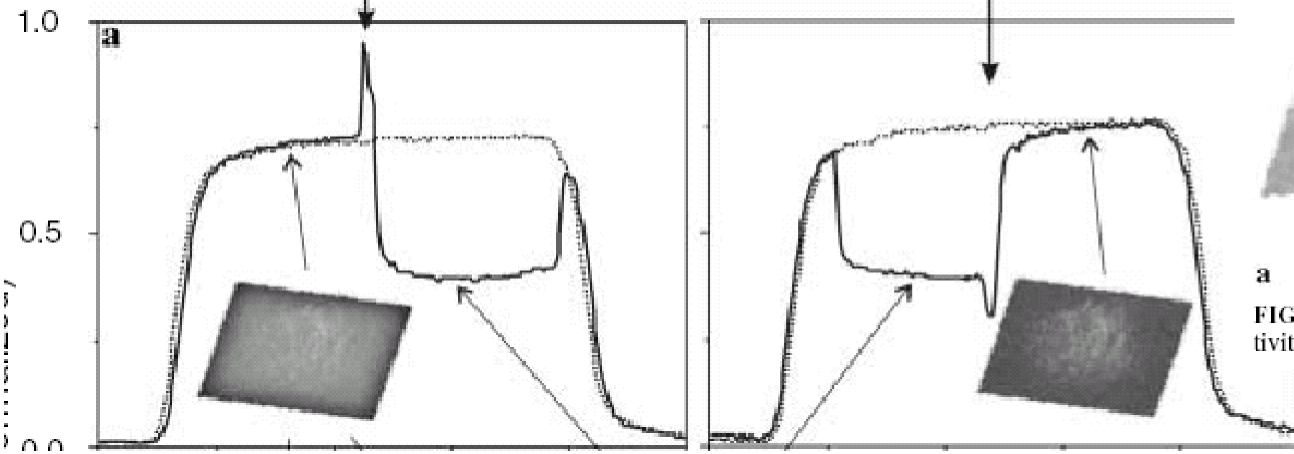
out of a device with diameter 150 μm





pulse, in phase

pulse, out of phase



reflected intensity

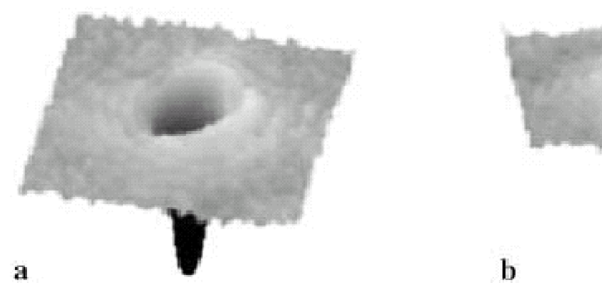


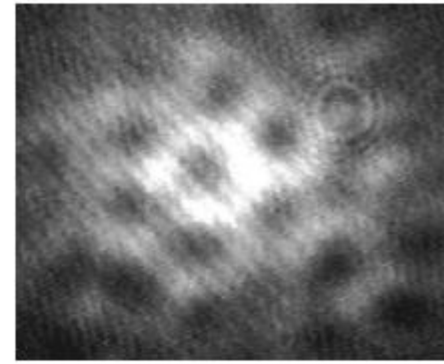
FIGURE 2 Bright soliton (dark in reflection). 3D repr
tivity: a view from above; and b view from below

← 2.5 µs →

time →

switching of a singl

Experiments: CS in cavities



- Kreuzer, Neubecker (Darmstadt): liquid crystals

  Mol. Cryst. Liq. Cryst. 207, 219 (1991); JMO 41, 885 (1994)

  - Bistable single spots; no external control
  - Identification as "self-induced modes"
  - An experiment before its time (later Louvergneaux (Lille))

- Taranenko, Weiss (PTB): absorbing and self-defocusing driven VCSELs

  PRA 61, 063818 (2000); APB 75, 75 (2002) ...

  - Probably first observation of CS in semiconductor microcavity
  - But complete independent manipulation of two not demonstrated